

A FLEXIBLE ACCESS PLATFORM FOR ROBOT- ASSISTED MINIMALLY INVASIVE SURGERY

David Noonan

Department of Surgery and Cancer &
The Hamlyn Centre for Robotic Surgery
Institute of Global Health Innovation

Imperial College London

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Abstract

Advances in Minimally Invasive Surgery (MIS) are driven by the clinical demand to reduce the invasiveness of surgical procedures so patients undergo less trauma and experience faster recoveries. These well documented benefits of MIS have been achieved through parallel advances in the technology and instrumentation used during procedures. The new and evolving field of Flexible Access Surgery (FAS), where surgeons access the operative site through a single incision or a natural orifice incision, is being promoted as the next potential step in the evolution of surgery. In order to achieve similar levels of success and adoption as MIS, technology again has its role to play in developing new instruments to solve the unmet clinical challenges of FAS. As procedures become less invasive, these instruments should not just address the challenges presented by the complex access routes of FAS, but should also build on the recent advances in pre- and intraoperative imaging techniques to provide surgeons with new diagnostic and interventional decision making capabilities.

The main focus of this thesis is the development and applications of a flexible robotic device that is capable of providing controlled flexibility along curved pathways inside the body. The principal component of the device is its modular mechatronic joint design which utilises an embedded micromotor-tendon actuation scheme to provide independently addressable degrees of freedom and three internal working channels. Connecting multiple modules together allows a seven degree-of-freedom (DoF) flexible access platform to be constructed. The platform is intended for use as a research test-bed to explore engineering and surgical challenges of FAS.

Navigation of the platform is realised using a handheld controller optimised for functionality and ergonomics, or in a ‘hands-free’ manner via a gaze contingent control framework. Under this framework, the operator’s gaze fixation point is used as feedback to close the servo control loop. The feasibility and potential of integrating multi-spectral imaging capabilities into flexible robotic devices is also demonstrated. A force adaptive servoing mechanism is developed to simplify the deployment, and improve the consistency of probe-based optical imaging techniques by automatically controlling the contact force between the probe tip and target tissue. The thesis concludes with the description of two FAS case studies performed with the platform during in-vivo porcine experiments. These studies demonstrate the ability of the platform to perform large area explorations within the peritoneal cavity and to provide a stable base for the deployment of interventional instruments and imaging probes.

Tús maith, leath na hoibre...

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List of Acronyms

AESOP – Automated Endoscope Optimal Positioning
AR – Augmented Reality
CABG – Coronary Artery Bypass Grafting
CLE – Confocal Laser Endomicroscopy
cRIO – Compact Reconfigurable Input/Output
CW/CCW – Clockwise/counter clockwise
DC – Direct Current
EMF – Electro Magnetic Force
EPAM – Electroactive Polymer Artificial Muscle
FDA – Food and Drug Administration
FPC – Flexible Printed Circuit
FOV – Field Of View
FPGA – Field Programmable Gate Array
GND – Ground
ID – Inner Diameter
IGI – Image Guided Intervention
IPMC – Ionic Polymer Metal Composite
IREP – Insertable Robotic Effector Platform
L-ASIS – Left Anterior-Superior-Iliac-Spine
MCB – Motor Control Box
MKT – Mauna Kea Technologies
NI – National Instruments
OCT – Optical Coherence Tomography
OD – Outer Diameter
PC – Personal computer
PCB – Printed Circuit Board
PCD – Pitch Circle Diameter
PCI – Peripheral Component Interconnect
pCLE – probe-based confocal laser endomicroscopy
PDD – Photo Dynamic Detection
PEEK - Polyether Ether Ketone
PIC – programmable integrated circuit
PSU – Power Supply Unit
PWM – pulse width modulation
R-ASIS – Right Anterior-Superior-Iliac-Spine

RANSAC – RANdom SAmple Consensus
SMA – Shape Memory Alloy
SIFT – Scale Invariant Feature Transform
TURP – Trans Urethral Resection of the Prostate
UI – User Interface
UV – Ultra Violet
Vcc – Common Collector Voltage
VI – Virtual Instrument
ZIF – Zero Insertion Force

Chapter 1:

Introduction

Few technologies have the potential to revolutionise surgical practice as those in the field of medical robotics. Its fusion of technological innovation and new surgical techniques is already improving patient outcomes in centres around the world. Milestones include procedures such as robot-assisted Totally Endoscopic Coronary Artery Bypass (TECAB) grafting which obviates the trauma of a sternotomy, allowing what would be traditionally a major invasive procedure to be carried out through 4-5 small incisions [1]. Through intraoperative imaging guidance, there is strong evidence to suggest that a specialised robot for CT planned knee replacement surgery is more accurate than conventional surgery [2]. The explosive growth of the field in urology is demonstrated by the uptake of robotic assisted radical prostatectomy [3-5]. One key to the success of robotic systems is their ability to augment a surgeon's existing skills by performing complex procedures using a minimally invasive approach. This reduces patient trauma, blood loss, infection risk and allows for faster hospital discharge. However, while state-of-the-art robotic surgical systems have proliferated into operating theatres and academic institutions around the world, the technology is still in its infancy; indeed, the world's most successful robotic surgical system for soft tissue surgery, the daVinci Surgical System from Intuitive

Surgical Inc, was only launched in 1999. This particular robot is a tele-operated system which provides a surgeon with a stereoscopic view of the operative site and continuously monitors hand and wrist motions in order to replicate such motions in-vivo [6]. Crucially however, while approximately 1400 units have been installed worldwide [7] and the number of operations performed with the system is on the rise year on year, the number of different types of procedures being performed has remained static.

This is due to the fact that although the daVinci has made significant steps towards the initial clinical adoption of a robotic system, it remains unsuitable for many procedures. The long, rigid nature of its instruments limits the areas accessible in-vivo without multiple incisions. Consequently, it is impossible to utilise for cases that involve complex anatomical pathways. Existing robotic devices focus primarily on the task of tissue manipulation in-vivo. Few systems, for example, address the possibility of integrating imaging probes within the robotic platform for the purpose of providing a surgeon with enhanced intraoperative information locally. Although traditional imaging techniques such as Computed Tomography (CT), Magnetic Resonance (MR) and Ultrasound are being integrated for anatomical localisation and navigation, limited work has been conducted on the use of new imaging probes for in-situ tissue characterisation. Specifically, imaging techniques such as probe-based Confocal Laser Endomicroscopy (pCLE), Optical Coherence Tomography (OCT) and Fluorescence Lifetime Imaging (FLIM) offer the potential to probe tissues to identify underlying pathologies intraoperatively without the need for biopsy. Finally, the significant capital expense of systems such as the daVinci, coupled with the large footprint within the operating theatre, limits its uptake in many hospitals and healthcare systems. Many laparoscopic surgeons argue that similar results can be obtained by traditional means but at a fraction of the cost. In order to make robotics technology truly accessible and seamlessly integrated with normal surgical workflows, it is important to address the pitfalls of current systems and identify when conventional means fail to deliver the required precision, consistency and safety.

The technical contribution of this thesis is the development of a new type of medical robotic device for minimally invasive interventions. Rather than the more ‘traditional’ approach of developing full robotic systems to cover an entire surgical procedure [8] [9], the system described here focuses on developing a flexible access platform to be used for parts of the surgical workflow when robotic assistance is required. In this configuration, a small diameter articulated robot is used to provide access to areas of the body which are currently difficult or

impossible to reach with rigid instrumentation. While at such locations, the robot will utilise advanced imaging and sensing techniques, combined with instrumentation passed through the device to perform early diagnosis and interventions. Example applications of such a device include transvaginal fallopian tube ligation, identification and removal of pre-cancerous polyps or lesions during diagnostic laparoscopy and endometrial ablation.

By developing the platform to be compatible with diagnostic imaging and sensing techniques, and coupling this with simple interventional instrumentation, it is envisaged that such future devices will leverage advances in imaging and treatment at a cellular level. In turn this will integrate diagnosis, characterisation and interventional steps into the existing surgical workflow. The ultimate goal is to provide a surgeon with the ability to diagnose and treat early rather than ‘cutting to cure’ when pathologies or conditions have become too advanced and irreversible damage has already occurred.

1.1 Key Objectives and Technical Challenges

The evolution of Minimally Invasive Surgery (MIS) from the gold-standard of open procedures has had a major effect on the way in which many procedures are now undertaken. Throughout its journey, advances in technology and instrumentation have played a crucial role. Thus far, MIS has reached a certain level of maturity, and new approaches such as Natural Orifice Surgery (NOS) and Single Incision Laparoscopic Surgery (SILS), are being promoted as the next potential step in the surgical evolution. From a technical standpoint, these terminologies share many common instrumentation and navigation requirements, and henceforth will be referred to as Flexible Access Surgery (FAS). For the purposes of this thesis, the term Flexible Access Surgery will be defined as follows:

Flexible Access Surgery is a term to describe surgical procedures where the flexible nature of the instrumentation used provides a surgeon with the flexibility to access the target anatomy from an incision considered impractical or impossible using rigid instrumentation alone.

Example procedures include the use of flexible instruments for trans-umbilical single port cholecystectomy or trans-oral endoscopic sub-mucosal dissection within the stomach. In the former example articulated instruments provide a surgeon with the flexibility to access the gallbladder using only a single incision which can be hidden within the folds of the umbilicus, while in the latter an augmented flexible endoscope can be used to access the stomach and perform the procedure without any incision in the peritoneal or stomach lining. However, for

such procedures to achieve similar levels of success and adoption as MIS, technological advances must continue in their critical function of solving unmet technical challenges. This will allow ever more complex clinical procedures to be performed. Such solutions need to not just address the difficulties presented by the complicated access routes of FAS, but must also build on advances in both pre- and intraoperative imaging techniques. These techniques offer to increase the information flow to surgeons in-theatre, and facilitate both diagnostic and interventional decision making processes.

The field of robotics is ideally placed to address many of these issues. This thesis aims to present solutions to some of the challenges that will enable FAS to be successfully performed. More specifically, these challenges include:

Challenge 1: To provide controlled, multiple degree-of-freedom (DoF) flexibility along curved pathways in a spatial environment, such as the peritoneal cavity, with a minimal footprint within the operating theatre so as to seamlessly integrate into the existing surgical workflow.

Challenge 2: To improve the ergonomics and controllability of multiple degree-of-freedom robotic instrumentation and to reduce the number of specialists required to perform complex flexible access procedures.

Challenge 3: To improve the intraoperative information flow - and hence the diagnostic capabilities of a surgeon - by integrating multi-spectral imaging modalities or by providing consistent functional probe-based multi-spectral imaging within flexible devices capable of performing large area visualisation along curved pathways.

Challenge 4: To provide a stable platform to target minor interventional instrumentation or imaging probes at any location within the peritoneal cavity from a single incision and to facilitate rapid instrument exchange when at the operative site.

Challenge 5: To provide controlled bimanual tissue manipulation and triangulation along curved pathways in a spatial environment through a single incision.

Challenge 6: To provide high quality visualisation and reduced operator disorientation when operating along curved pathways in a spatial environment, such as the peritoneal cavity.

Challenge 7: To achieve safe, consistent and repeatable closure of transrectal and transgastric incisions to facilitate further surgical exploration via these pathways.

This thesis will focus on addressing some of the technical issues related to the first four of these unmet clinical challenges. In the following chapters, a detailed account of the instrument design, system modelling and configuration, as well as in-vitro and in-vivo validation will be presented. **Chapter 2** will provide an overview of existing medical robotic systems with an emphasis on flexible robotic devices and ‘focused’ robotic systems designed for specific tasks within the operating theatre.

Chapter 3 will investigate preliminary solutions to both *Challenge 1* and *Challenge 3* through the introduction of an articulated robotic device which is capable of multi-spectral imaging. A key element facilitating the multi-spectral imaging is the use of a tunable supercontinuum laser illumination source and a flexible fibre image guide as the optical transmission mechanism to pass light from the distal tip of the device to an external image acquisition system. The purpose of using such an optical configuration is to investigate its suitability for meeting the flexibility requirements and limited cross-sectional area available in articulated robotic devices. It allows the operator to seamlessly switch between ‘white light illumination - reflected image acquisition’ and ‘fluorescence light illumination - autofluorescence image acquisition’ without the need for bulky optics or rigid optical transmission media. The key contribution of this chapter is the demonstration of a dual-modality imaging instrument that provides a surgeon with the ability to perform large area robotically controlled scans of a spatial environment using synchronised white light and tunable fluorescence light in a minimally invasive manner.

While the multi-spectral imaging robot described in Chapter 3 provides preliminary solutions to the *Challenges 1* and *3* outlined above, further improvement of the platform is necessary.

Specifically, while it is undoubtedly advantageous to have the ability to perform both white light and fluorescence imaging using the same optical system, the challenges of the limited bending radius, resolution and field of view of the fibre image guides hinders their practical deployment within an articulated robotic platform. Additionally, with the ongoing development of both commercial multi-spectral imaging probes and CCD micro-cameras, the clinical need has shifted towards a requirement for a flexible robotic device that is capable of taking standard instrumentation; either integrating them within the device or facilitating passage of such probes down through internal channels in a manner similar to an endoscope. **Chapter 4** will introduce a modular mechatronic joint design which has been developed to meet these requirements and maintain a minimum footprint within the operating theatre. Each degree of freedom within the joint module features a novel, hybrid micromotor-tendon actuation scheme. Multiple modules can then be assembled to create a 7-DoF flexible access robotic device. This system specifically addresses *Challenge 1* and *Challenge 4* above by providing controlled flexibility along multiple degrees of freedom, a small footprint within the operating theatre and the provision of three internal working channels. The key contribution of this chapter is the demonstration of a modular mechatronic joint design that can be used to create novel multiple degree-of-freedom instruments suitable for use as a research platform to investigate many of the challenges facing the adoption of flexible access surgery.

As identified in *Challenge 2*, crucial to the usability of any robotic device intended for use within an operating theatre is the issue of the control interface. **Chapter 5** will introduce two different control methodologies developed to control the flexible access platform. These methodologies include both ‘standard’ joystick based interfaces, whose primary aim is to provide the operator with a simple yet ergonomically improved environment, and an ‘experimental’ gaze contingent control interface, whose aim is to investigate whether intuitive hands-free control of a multiple degree-of-freedom instrument was possible through the eye gaze of a surgeon. A key contribution of this chapter is the demonstration that gaze contingent control is suitable for controlling flexible mechatronic devices and the introduction of an adaptable, intuitive user interface suitable for rapid deployment in an operating theatre.

Chapter 6 will describe a system designed to improve the intraoperative information flow to a surgeon, as identified in *Challenge 3*, through the use of robotic-assisted probe-based multi-spectral imaging. Specifically, this chapter will introduce a force adaptive linear servoing mechanism which clamps a multi-spectral imaging probe at its proximal end (as it enters an

internal channel of the flexible access platform) and adjusts its insertion length within the platform based on the measured interaction force between the distal tip and the soft tissue. This effectively eliminates the need for the operator to manually manipulate the imaging probe, and thus simplifies the ergonomics of the procedure while simultaneously improving the consistency of the acquired multi-spectral imaging data. The validity of this work is demonstrated through an investigation of the effect of probe contact force on excised stomach tissue. Key contributions of this chapter include the demonstration of a system suitable for consistent probe based multi-spectral imaging, and the ability to provide a surgeon with co-registered white light and multi-spectral images.

Chapter 7 will describe the in-vivo deployment results obtained with the flexible access platform. Specifically, the results described in this chapter will demonstrate how the system was successfully deployed during multiple transvaginal Single Incision/Natural Orifice Surgery procedures under pneumoperitoneum in live porcine models. These procedures were used to evaluate and improve the system design. They included user trials of different control interfaces, a diagnostic peritoneoscopy examination using both white light and probe based confocal endomicroscopy and a transvaginal tubal ligation procedure performed entirely using the platform. The key contribution of this chapter is the demonstration of the ability of the flexible access platform to gain access from a single incision and to provide sufficient dexterity to explore the peritoneal and pelvic cavities. Once at the target location, the system is capable of providing a stable platform for the deployment of interventional instrumentation and probe-based optical imaging systems.

Finally, **Chapter 8** will summarise the main technical achievements of the thesis and the potential pitfalls of the existing approaches. Future research directions for the flexible access platform will also be outlined.

The original technical contributions of this thesis include:

- demonstration of a dual-modality imaging instrument that provides a surgeon with the ability to perform large area robotically controlled scans of a spatial environment using synchronised white light and tunable fluorescence light in a minimally invasive manner

- development of a modular mechatronic joint design that can be used to create a novel multiple degree-of-freedom instrument suitable for use as a research platform to investigate many of the challenges facing the adoption of flexible access surgery
- implementation of gaze contingent control methodologies suitable for controlling multiple degree-of-freedom mechatronic devices in a hands-free manner
- evaluation of a system suitable for consistent probe based multi-spectral imaging and the ability to provide a surgeon with co-registered white light and multi-spectral image information
- in-vivo validation of the ability of the flexible access platform to gain access from a single incision through a standard trocar port, to retroflex within the pelvic cavity and to provide a stable platform for the deployment of interventional instrumentation
- the demonstration of the ability of the flexible access platform to target a confocal imaging probe at multiple locations within the peritoneal cavity from a single incision

The work presented in this thesis has resulted in the following publications in peer-reviewed engineering and clinical journals as well as international conferences:

- 1) Noonan DP; Elson DS; Mylonas GP; Darzi A; Yang GZ. (Mar 2009). **Laser-induced fluorescence and reflected white light imaging for robot-assisted MIS**. IEEE Transactions on Biomedical Engineering. vol. 56 3:889-892.
- 2) Noonan DP; Mylonas G; Shang; Payne C; Darzi A; Yang GZ. **Gaze Contingent Control for an Articulated Mechatronic Laparoscope**. IEEE International Conference on Biomedical Robotics and Biomechatronics (BIOROB), Tokyo, Japan. 759-764. IEEE (2010).
- 3) Noonan DP; Payne C; Shang J; Sauvage V; Newton R; Elson D; Darzi A; Yang GZ. **Force Adaptive Multi-spectral Imaging with an Articulated Robotic Endoscope**. Medical Image Computing and Computer Assisted Intervention (MICCAI), Beijing, China. 245-252. Springer (2010).

- 4) Noonan DP; Mountney P; Elson DS; Darzi A; Yang GZ. **A Stereoscopic Fibroscope for Camera Motion and 3D Depth Recovery during Minimally Invasive Surgery.** IEEE International Conference on Robotics and Automation (ICRA), 3274-3279. IEEE (2009).
- 5) Noonan DP; Mylonas GP; Darzi A; Yang GZ. **Gaze Contingent Articulated Robot Control for Robot Assisted Minimally Invasive Surgery.** IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 1186-1191. IEEE (2008).
- 6) Shang J; Noonan DP; Payne C; Clark J; Sodergren M; Darzi A; Yang G.-Z; **An Articulated Universal Joint Based Flexible Access Robot for Minimally Invasive Surgery.** IEEE International Conference on Robotics and Automation (ICRA). Shanghai, China. 1147-1152. IEEE (2011).
- 7) Clark J; Sodergren M; Noonan DP; Darzi A; Yang GZ. (Apr 2009). **The natural orifice simulated surgical environment (NOSsE): exploring the challenges of NOTES without the animal model.** Journal of Laparoendoscopic & Advanced Surgical Techniques. 19:211-214.
- 8) Tun-Latt. W; Newton R.C; Visentini-Scarzanella M; Payne C; Noonan DP; Shang J; Yang G.-Z. (2011). **A Hand-held Instrument to Maintain Steady Tissue Contact during Probe-Based Confocal Laser Endomicroscopy.** IEEE Transactions on Biomedical Engineering. 9:2694-2703
- 9) Newton RC; Noonan DP; Payne C; Andreyev J; DiMarco A. **Probe Tip Contact Force and Bowel Distension Affect Crypt Morphology during Confocal Endomicroscopy.** British Society of Gastroenterology. GUT (2011)
- 10) Newton RC; Noonan DP; Payne C; Clark J; Sodergren M; James D; et al. **LB86: Towards diagnostic peritoneoscopy with a force adaptive probe-based confocal endomicroscope via a transvaginal robotically controlled articulated endoscope.** National Cancer Research Institute. Liverpool, 2010.
- 11) Sodergren M; Clark J; Noonan DP; Shang J; Payne C; James D; Athanasiou T; Teare J; et al. **Feasibility of Transvaginal Peritoneoscopy using a Novel Articulated Stereo-Laparoscope Robot.** 2010 Annual Meeting of the Society of American Gastrointestinal and Endoscopic Surgeons. Sup 1:S689. (Apr 2010).
- 12) Clark J; Sodergren M; Noonan DP; Shang J; Payne C; James D; Teare J; Athanasiou T; et al. **A Novel Articulated Robotic Laparoscope for Single Incision and Natural Orifice Surgical Applications: Preliminary usability trials in a live porcine model.** 2010 Annual Meeting of the Society of American Gastrointestinal and Endoscopic Surgeons. Sup 1: S690. (Apr 2010).

- 13) Atasoy S; Noonan DP; Belhimane S; Navab N; Yang GZ. **A Global Approach for Automatic Fibroscopic Video Mosaicing in Minimally Invasive Diagnosis**. Medical Image Computing and Computer Assisted Intervention (MICCAI). 1:850-857. Springer (2008).
- 14) Patent Application, Yang, G-Z., Noonan, DP, Shang, J, Vitiello, V., **WO 2010/149969 Joint Arrangement**

In press at time of thesis submission:

- 15) Noonan DP; Vitiello V; Shang J; Payne C; Yang G.-Z. **A Modular, Mechatronic Joint Design for a Flexible Access Platform for MIS**. *International Conference on Intelligent Robots and Systems*, IEEE/RSJ (2011).
- 16) Clancy N; Clark J; Noonan DP; Yang G.-Z; Elson D. (2011). **Light sources for single access surgery**. Surgical Innovation.
- 17) Warren A; Mountney P; Noonan DP; Yang GZ. (2011). **Horizon Stabilized – Dynamic View Expansion for Robotic Assisted Surgery (HS-DVE)**. Computer Aided Radiology and Surgery (CARS).
- 18) Sodergren MH; Clark J; Purkayastha S; Noonan DP; Farthing A; Mason P; Teare J; Darzi A. (2011). **United Kingdom First Transvaginal Hybrid NOTES Cholecystectomy**. Journal of Laparoendoscopic & Advanced Surgical Techniques & Part B: Videoscopy.

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Chapter 2:

Robot Assisted Minimally Invasive Surgery

2.1 Introduction

In its simplest terms, minimally invasive surgery (MIS) can be described as major or minor surgery performed through small incisions. During laparoscopic surgery a needle is inserted into a patient and the abdominal cavity inflated using CO₂ gas. Multiple incisions of 5-12mm are then made and trocar ports passed through the incisions. A fibre optic transmission lens or CCD camera at the tip of a rigid shaft called a laparoscope is passed through to provide the surgeon with an illuminated field of view. This is typically displayed on a patient side monitor. Various additional laparoscopic instruments are then passed through one or more trocar ports and used to perform the procedure. The CO₂ insufflation provides the surgeon with the space to view the operating site and manipulate the instruments.

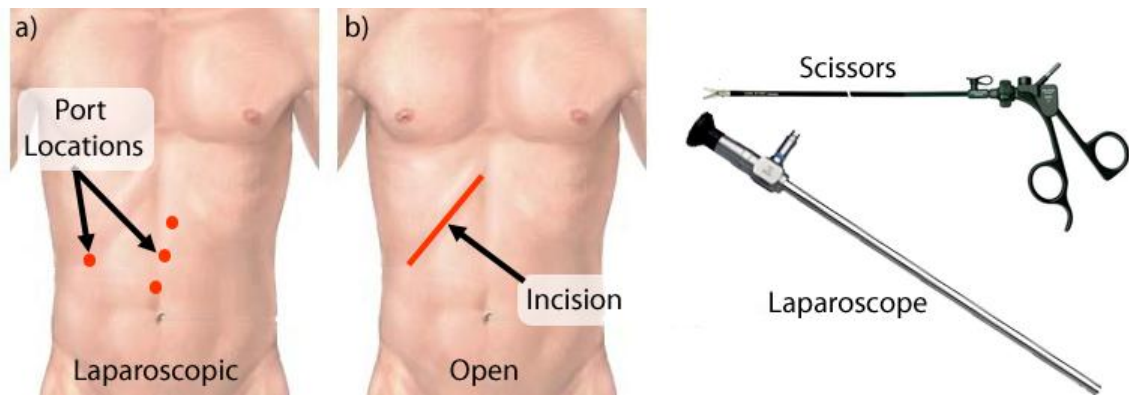


Figure 2.1: (left) The approximate location of the small incisions required for a multi-port laparoscopic cholecystectomy (a) and the large incision required to perform an open cholecystectomy (b). (right) Some traditional laparoscopic instruments including a laparoscope and scissors from Karl Storz GmbH

As evident from Figure 2.1, the primary benefit of the MIS approach is the use of small incisions resulting in less trauma to the patient [10], and thus decreasing recovery time and hospitalisation costs. There is also a reduced risk of infection during the procedure. However, these advantages are offset by the sharp increase in the technical difficulty of any surgical procedure carried out using the MIS approach. Due to the fact that the procedure is performed from outside the body, the surgeon loses the ability to both directly see and touch the operative site. This is compounded by the fact that the tip of an instrument is constrained to the arcs of a sphere whose fulcrum is the insertion point [11]. Due to this ‘fulcrum effect’, tasks such as suturing and knot tying require extensive training as directions are reversed in-vivo [12]. Manual dexterity is also impaired due to the use of long, rigid instruments introduced through a fixed point (Figure 2.1 (right)). This loss of direct visual, haptic and tactile feedback, coupled with dexterity problems, can lead to accidental damage of tissue [13]. Furthermore, when performing delicate procedures such as beating heart surgery, the destabilisation induced by respiratory and cardiac motion affects precise tissue-instrument interaction [14].

The latest evolution of minimally invasive surgery is the new experimental area of flexible access surgery (FAS). In FAS, surgeons are moving the incisions away from what would traditionally be considered the ‘optimum’ location. They must then rely on the flexibility of new instrumentation to reach the desired operative site. Subsidiary elements of FAS include Single Incision Laparoscopic Surgery (SILS) and Natural Orifice Translumenal Endoscopic Surgery (NOTES). In SILS surgery, typical procedures performed include cholecystectomies and appendectomies via the umbilicus [15]. Currently no procedures are routinely performed using the NOTES technique, however exemplar procedures also include hybrid cholecystectomies and

peritoneoscopies [16]. Both of these techniques advance the original concepts of MIS by reducing the number of incisions and therefore the levels of patient trauma. However, as with MIS, the negative consequence of SILS and NOTES is the increase in the technical difficulty of carrying out procedures using such techniques. Challenges include sub-optimal location of the incisions, surgeon disorientation and inappropriate instrumentation [17, 18]. Table 2.1 presents a comparison of open, minimally invasive and flexible access surgery from the perspectives of patient trauma and technical difficulty for the surgeon. The table is adapted from [19] and extended to include the potential effects of flexible access surgery. A (-) indicates a negative effect for the patient or surgeon while a (+) indicates a positive effect for the patient or surgeon.

Table 2.1: A comparison of the different effects of open surgery, minimally invasive surgery and flexible access surgery from both patient and surgeon perspectives. A (-) indicates a negative overall effect and a (+) indicates a positive overall effect. Adapted from [19].

Feature	Open Access Surgery		Minimally Invasive Surgery		Flexible Access Surgery	
	Patient	Surgeon	Patient	Surgeon	Patient	Surgeon
Wound	-		+		++	
Hospital stay	-		+		++	
Operation complexity		+		-		- -
Wound infection	-		+		++	
Assistants required		+		-		- -
Training required		+		-		- -
Treatment cost	-	-	+	+	++	++

It can be seen that while the MIS and FAS approaches to surgery have many benefits, there are many challenges to their widespread clinical adoption. However, many of these challenges are related to the complexity of the approach and the levels of training required for performing the

procedures. Medical robotics has the potential to make a significant contribution to solve these problems by fusing the miniaturisation, dexterity and precision of mechatronically controlled instruments with the ingenuity of a surgeon. To date, many systems have been developed to meet these challenges for MIS, however many problems still remain unsolved and the new challenge of flexible access surgery has yet to be fully addressed. In the rest of this chapter, a brief history and overview of medical robotic systems is provided. The discussion will focus on three different categories of medical robotics. The first of these categories deals with medical robotic systems for soft tissue surgery. The second introduces devices for surgical assistance, such as camera positioning systems or systems for tool guidance. Finally, the third category describes several state-of-the-art research prototypes of flexible robotic devices for minimally invasive surgery.

2.2 Medical Robotics

Although the concept of medical robotics has a long history, influenced by parallel industrial and military applications, the practical use of robotics within the operating theatre started in the early 1980s. In 1985 Kwoh et al [20] used an adapted Unimation PUMA 200 6-axis robot to obtain precise positioning of a biopsy needle during a neurosurgical procedure via an interfaced computed tomography (CT) scanner. This work, first published in 1988, and other papers from Taylor [21] and Davies [22, 23] in 1989, represent some of the early work in medical robotics from a system level. These original systems described by Kwoh and Taylor were passive devices which were locked into position with power removed to facilitate the accurate holding of biopsy probes, drills, fixtures, etc. during surgery. It was Davies who first carried out a “robotic assisted” surgical procedure when he used a robot to actively remove prostatic adenoma during a transurethral resection of the prostate (TURP) procedure. The goal of these systems was to improve the overall efficacy of the surgical procedure in which they were deployed. This same goal underpins the medical robotics systems that are at the forefront of technological innovation almost two decades later. However, one key point in the evolution of the surgical robots we see today is that, as per a classical definition, they are not robots at all. Instead of automated systems performing surgery, what have developed are robotic-like systems that allow a surgeon to perform “robot-assisted” surgery. These systems complement the existing skills of a surgeon to allow him or her to perform procedures in a manner that would not be possible before the advent of computer aided surgery.

For the purposes of providing an overview of the current state-of-the-art in medical robotics for MIS, a list of notable devices and systems has been compiled. This list is split into three categories to reflect the nature of the work to be described in the later chapters of this thesis. The first category lists existing systems capable of carrying out full procedures involving manipulation and dissection of soft tissue (as opposed to systems for orthopaedic or neurosurgical procedures which assume a static target anatomy). Systems on this list include commercially available platforms which aim to enhanced laparoscopic surgery and experimental systems which are attempting to solve some of the challenges posed by flexible access surgery.

The second category lists robotic devices designed to assist surgeons during surgery. The systems listed in this category are more ‘focused’ robotic devices which have a specialised skill but are not suitable to carry out full procedures. Again, systems on this list include commercially available platforms designed for laparoscopic surgery and experimental devices which can be applied to flexible access surgery.

The final category lists articulated or flexible robotic devices which are capable of actuating along curved pathways. Many of these systems are still in the prototype stage. The purpose of including this list is to provide the reader with an understanding of what technology currently exists and why a flexible access platform capable of addressing *Challenge 1* to *Challenge 4* in Chapter 1 is necessary.

2.2.1 Robot-Assisted Soft Tissue Surgical Systems

The term ‘soft tissue surgical system’ is defined as a system which is used to carry out an entire procedure. This is as opposed to an assistive device used to help the surgeon during only part of the procedure. Table 2.2 provides an overview of existing medical robotic systems for soft-tissue surgery. The undisputed success story in this area is the *daVinci Surgical System* from Intuitive Surgical Inc, as shown in Figure 2.2. Although its description as a ‘robotic surgery system’ implies a level of autonomous operation, it is important to note that no actions are performed autonomously by the system nor does it feature any decision making software to replace direct surgeon control. Rather, it is a tele-operation platform which allows a surgeon to control the motion of miniature tools inside a patient’s body from an external location. The system consists of two main sections: a patient side ‘slave’ unit and a surgical ‘master’ console.

The patient side cart has a maximum of four arms, one of which holds a stereoscopic laparoscope, and the remainder of which hold interchangeable surgical instruments known as *EndowristsTM* [24]. Both the camera and instruments pass through specialised trocar ports of diameter 12mm and 8.5mm respectively. In order to generate the large gripping forces required for MIS, the instruments are tendon driven with the actuators located outside the body.

Table 2.2: List of Soft Tissue Surgical Systems

System Name	Company / University	Type of Surgery	Human Use	References
daVinci	Intuitive Surgical	Laparoscopic	Yes	[5, 8]
Zeus	Computer Motion	Laparoscopic	Yes	[9, 25]
MIROSURGE	DLR	Laparoscopic	No	[26, 27]
Raven	University of Washington	Laparoscopic	No	[28, 29]
Kawashima Lab	Tokyo Institute of Technology	Laparoscopic	No	[30, 31]
-	University of Hawaii	Laparoscopic	No	[32]
ViaCath	EndoVia Medical	Flexible Access	No	[33, 34]
CoBRASurge	University of Nebraska	Flexible Access	No	[35-37]
MASTER	Nangyang Technological University	Flexible Access	No	[38, 39]
IREP	Columbia University	Flexible Access	No	[40]
-	Waseda University	Flexible Access	No	[41]
SPRINT	Scuola Superiore de Sant'anna	Flexible Access	No	[42]

While operating, the surgeon places their head inside the master console and sees a magnified 3D image of the operative site projected through mirrored overlay optics. The surgeon's hands are placed into position measuring devices which record the seven degrees of freedom (DoF) possible at the human wrist, i.e. x , y , z translation, roll, pitch, yaw and grip [43]. The surgeon's position at the console is such that the view of the surgical tools is aligned with their hands. This

ensures that the registration of hand motions to the motion of the tools is both visual and spatial. Any motion of the surgeon's hands is captured at a frequency greater than 1kHz. The controller then transforms the spatial motion of the tools into the camera frame of reference so that the surgeon feels as if their hands are inside the patient's body [8]. The fact that the surgeon closes the servo control loop allows for compensation of the soft tissue motion and deformation.

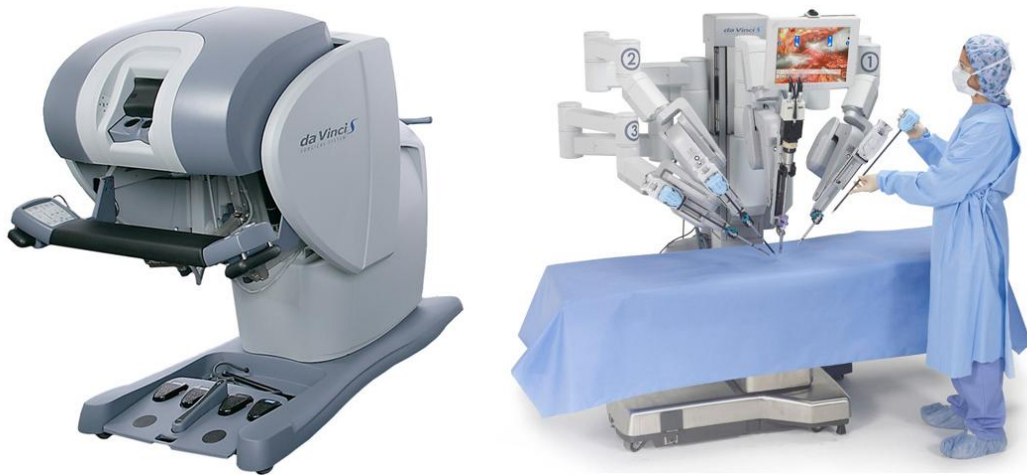


Figure 2.2: daVinci S Master Console (left) with patient side Slave Unit (right). The surgeon sits at the master console and their hand motions are mapped to the miniature instruments on the slave. The large footprint of the system can be clearly seen. Image source: Intuitive Surgical Inc.

The primary advantages of the system are that it restores the degrees of freedom lost during conventional laparoscopy and provides an ergonomic working position for the surgeon. The controller also filters out hand tremor above 6Hz and allows for motion scaling. Disadvantages include a large footprint within the operating theatre, high initial and running costs, a steep learning curve and the absence of haptic feedback. Currently, the primary application of the system is for Radical Prostatectomy [3]. However, as was mentioned in the Chapter 1, while the number of prostate related procedures being performed each year is increasing, the system has seen only limited uptake in other surgical fields. Aside from the expense and large footprint in theatre, technically, another limitation is that the rigid shaft of the *EndowristTM* tools restricts their workspace inside the body to a direct line of sight from the incision point. These limitations restrict the ability of the daVinci for performing flexible access surgery in its current configuration.

Another notable system for soft tissue surgery is the Zeus Surgical Robot. This system was developed in parallel to the daVinci by Computer Motion Inc. It is also a tele-operated system with a patient side slave robot featuring three arms and a master console, as shown in Figure

2.3. The position of the camera is controlled via voice commands from the surgeon and the image from the operative site is displayed on a 2D monitor. The surgical instruments are 5mm in outer diameter and are actuated via a serial linkage mechanism, again with the actuators located outside the body. One comparative disadvantage over the daVinci is that the Zeus instruments only feature four motorised degrees of freedom (and two passive degrees). However the smaller diameter results in a correspondingly smaller incision. The system was involved in a number of world firsts – including the first robot-assisted totally endoscopic beating heart bypass graft procedure in 1999 [44] and the first trans-Atlantic “Lindbergh” operation in 2001 [45]. However, following a legal battle over patent rights, Computer Motion was acquired by Intuitive Surgical in 2003 and the manufacture of the Zeus was discontinued shortly afterward.

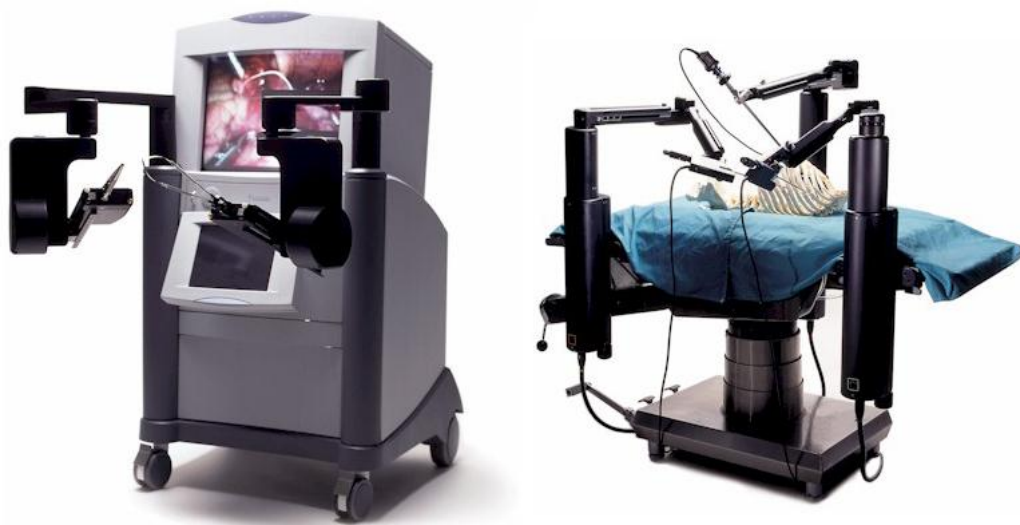


Figure 2.3: Zeus Master Console (left) and Patient Side Slave (right). This system also operates as a tele-manipulator with the operator sitting at the master console and manipulating instruments which control the tool tips of the slave located inside the patient. Image source: Computer Motion Inc

While neither the daVinci nor the Zeus is suitable for interventions along curved pathways, development work is ongoing to reengineer the daVinci for single incision laparoscopic surgery. However, the system configuration is not particularly well suited to the approach. Problems such as instrument clashing, limited triangulation and challenging ergonomics indicate that a more flexible system is required [46]. The latter six systems listed in Table 2.2 aim to provide such flexibility and the triangulation necessary to perform clinically relevant tasks. These systems are directly addressing *Challenge 5* outlined in Chapter 1. Each offers bimanual tissue manipulation through the use of instruments which emerge from the system after insertion through an incision, as can be seen for the IREP [40] and ViaCath [33] conceptual designs in Figure 2.4. Still, none of the systems listed in Table 2.2 address *Challenge 1* to *Challenge 4*

outlined in Chapter 1. This is because they do not offer controlled flexibility along curved pathways or the ability to pass interventional instruments. Additionally, none of the systems listed incorporate intraoperative multi-spectral imaging techniques.

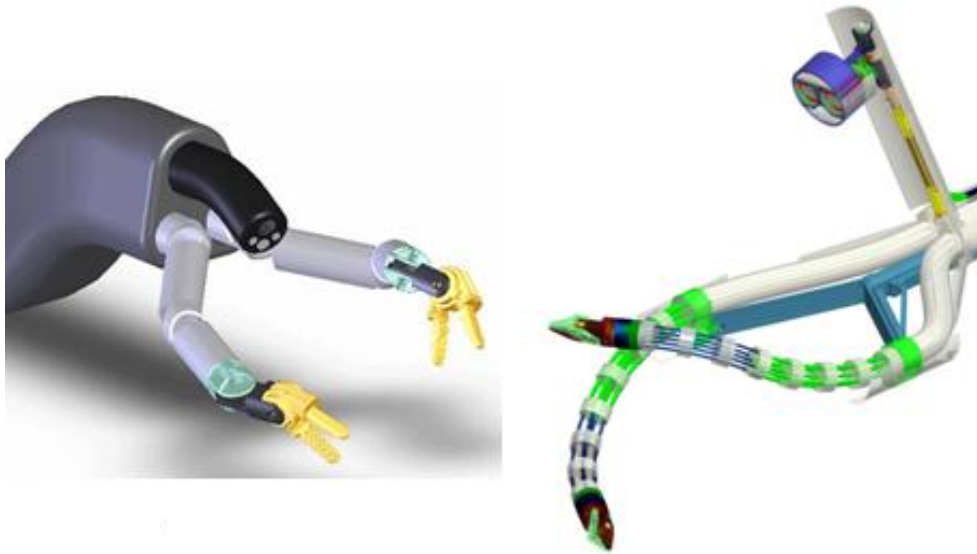


Figure 2.4: Conceptual CAD models of the ViaCath (left) and IREP (right) systems for single incision laparoscopic surgery. Both systems enter the body via a single incision and extend manipulators for bimanual triangulation to perform the procedure. Image Source: [33] and [40]

2.2.2 Assistive Robotic Devices for MIS

The second category of robotic devices to be described is that of assistive robotic devices for minimally invasive surgery. These are listed in Table 2.3 and represent many different application areas within the field of surgery. Several of the systems will be described in greater detail owing to their importance to the overall evolution of medical robotics as a field, or based on their potential relevance to flexible access surgery.

Table 2.3: List of assistive robotic devices for minimally invasive surgery

System Name (Author)	Company / University	Purpose	Human Use	References
AESOP	Computer Motion	Laparoscope manipulation	Yes	[47-49]
EndoAssist	Prosurge	Laparoscope manipulation	Yes	[48, 50- 52]
Freehand	Prosurge	Laparoscope manipulation	Yes	[53]

Viky	Endocontrol	Laparoscope manipulation	Yes	[54]
Probot	Imperial College London	Prostate resection	Yes	[22, 23]
Neuromate	Integrated Surgical Systems	Neurosurgery	Yes	[55]
Pathfinder	Prosurgics	Neurosurgery	Yes	[56]
Acrobot	Acrobot Company	Orthopaedics	Yes	[57]
RoboDoc	Curexo Technology	Orthopaedics	Yes	[58]
Masor	Masor Robotics Ltd	Orthopaedics	Yes	[59]
CyberKnife	Accuray Ltd	Oncology	Yes	[60]
Various in-vivo robotic devices (Rentschler)	University of Nebraska	In-vivo visualisation, exploration and assistance	No	[11, 61, 62]
Various in-vivo visualisation devices (Allen)	Columbia University	In-vivo visualisation	No	[63-66]
Robotic pill cameras (Dario)	Scuola Superiore de Sant'anna	Legged locomotion in the colon	No	[67, 68]
Heartlander	Carnegie Mellon University	Locomotion on the surface of the heart	No	[69, 70]
Micron	Carnegie Mellon University	Microsurgery	No	[71]
Steady Hand	Johns Hopkins University	Microsurgery	No	[72-75]
RAMS	NASA Jet Propulsion Laboratory	Microsurgery	No	[76, 77]

Smart Instrument (Dario)	Scuola Superiore de Sant'anna	Athroscopy	No	[78, 79]
MRBot	Johns Hopkins University	MRI interventions	No	[80, 81]
MCI	Harvard University	Cardiac surgery	No	[14]

At an early stage the potential for using robotic systems to hold and position laparoscopes during minimally invasive surgery was identified. The first such system to gain Food and Drug Administration (FDA) approval was the AESOP, or Automated Endoscope Optimal Positioning, system from Computer Motion [49] shown in Figure 2.5. It is operated via pre-calibrated voice commands and its primary benefit is a stable, tremor free mounting of the laparoscope over which the surgeon has control. However, problems include errors with the voice commands, speed of actuation, setup time and the large footprint of the system in theatre.



Figure 2.5: The AESOP voice controlled laparoscope positioning system which was the first FDA approved robotic device to be routinely used within operating theatres. The system held the laparoscope and provided the surgeon with a stable field of view and reduced the number of operators required in the operating theatre. Image source: Computer Motion Inc.

Additional systems to offer laparoscope holding abilities include the EndoAssist and FreeHand Surgeon which were commercialised by ProSurgics in 1999 [51] and 2008 respectively [53]. These systems utilise a head mounted infrared (IR) emitter in conjunction with a foot switch to track the surgeon's head movements and actuate the camera in the desired direction. While none of these systems are suitable for operation along curved pathways, the evolution of the designs from the large floor mounted systems, such as the AESOP and the EndoAssist, to the

compact and mobile Freehand, demonstrates the clinical importance of reducing the footprint of robotic devices in theatre.



Figure 2.6: The EndoAssist (left) and Freehand Surgeon (right) laparoscope positioning systems which use a surgeon mounted IR tracker to control the laparoscope field of view. Image source: Prosurgics Inc.

The concept of further reducing the footprint of visualisation and assistive tools has been adopted by the University of Nebraska, Lincoln and Columbia University through the development of fully insertable robotic devices. These are intended to be inserted through an incision and left in-vivo for the duration of the procedure. This then allows other instruments to be passed through the original incision. Examples include an insertable pan-tilt camera, as shown in Figure 2.7 (left), and a mobile robot for traversing the peritoneal cavity, as shown in Figure 2.7 (right).

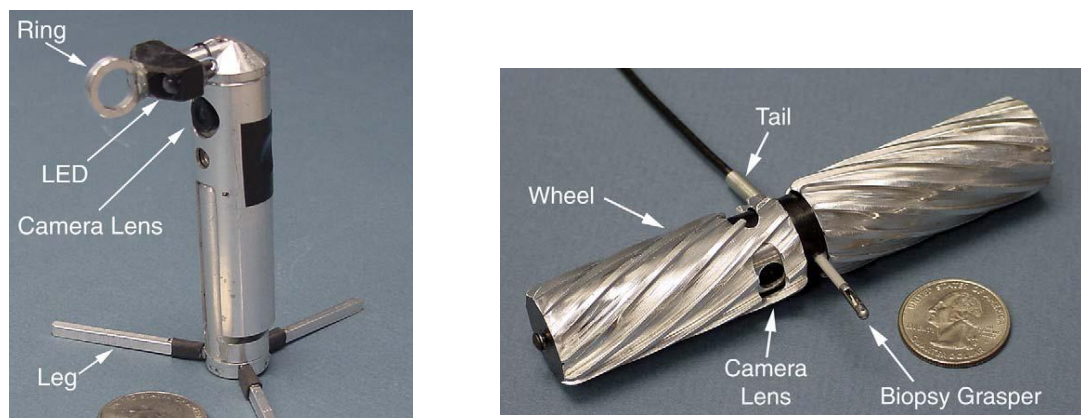


Figure 2.7: (left) Insertable Pan-Tilt Camera for laparoscopy. Illumination is provided by an embedded LED and the ring is to facilitate retraction. (right) Mobile robot for traversing the peritoneal cavity, providing visual feedback and minor interventional capabilities. Image source: [62]

This latter system is designed to be inserted through a trocar port to provide visualisation of the operative site. Its ability for in-vivo exploration allows for it to be employed for additional off-axis visualisation in conjunction with a standard laparoscope. Alternatively, it can be utilised as the sole means of visualising the operation to reduce the number of incisions required [62]. It is an innovative approach to facilitate flexible access surgery which offers to reduce the invasiveness of procedures. However, these devices have limited means of deploying interventional instruments and do not provide controlled flexibility within the peritoneal cavity.

2.2.3 Flexible Robotic Devices for Medical Applications

A key limitation of existing medical robotic systems is the constraint imposed by the use of long, rigid instruments introduced through a fixed point. As a consequence, the workspace of these tools is limited to a hemisphere of which the trocar port is the origin. This inability to follow curved pathways limits the number and type of procedures which are suitable for robotic assistance. This section will present an overview of currently available flexible medical robotic devices. The devices are listed in Table 2.4. Several offer significant potential for deployment within the field of flexible access surgery and their advantages and disadvantages will be discussed in greater detail.

2.2.3.1 Flexible Robotic Devices for Endoscopy

Before introducing notable flexible robotic devices for endoscopy, it is worthwhile to provide a description of the flexible endoscope itself. Although the standard flexible endoscope does not have any robotic features, it is currently the primary device used for flexible access surgery; in particular in its NOTES embodiment. The first reported human NOTES cholecystectomy described in [82] utilised a dual channel videogastroscope from Karl Storz Endoskope GmbH similar to that shown in Figure 2.8. The key feature of the device is the ability to steer its distal tip in two orthogonal degrees of freedom (deflection up 200°, deflection down 100°, deflection left and right 120°). This actuation is achieved using tendons which terminate at the distal tip and pass through the flexible shaft of the device to two control wheels mounted at the proximal end. By rotating the control wheels the operator is able to steer the distal tip. The device has an outer diameter of 12mm and enables passage of endoscopic instruments through two internal channels with diameters of 3.4mm and 2.8mm. The device also features a tip mounted image sensor and fibre optic light carriers to provide visual feedback. Additional functionality provided by the endoscope includes the ability to pump CO₂ to insufflate and create space within a lumen or saline to flush any material (such as blood or tissue) which is obscuring the

field of view of the camera lens. The system is also capable of providing suction through an additional channel.



Figure 2.8: A dual-channel videogastroscope with the steerable tip, control wheels, image sensor, two internal channels and flexible shaft highlighted. Image source: Karl Storz Endoskope GmbH.

The primary advantage of the device is its ability to follow curved pathways inside the body. When operating in a tubular lumen, such as the colon or oesophagus, its flexibility can be exploited to visualise organs which would be impossible to reach using rigid instruments. However, even skilled endoscopists can have difficulty navigating the device along the tortuous path from the rectum to the cecum during a full examination of the colon. The highly deformable nature of the environment coupled with the difficulty in accurately controlling the endoscope along its entire length can lead to considerable patient discomfort or even perforation in worst case scenarios [83]. To overcome such difficulties, several robotic-assisted devices have been proposed. The two main categories such devices fall into are those which aim to provide robotically controlled flexibility along their entire length or those which aim to robotically locomote through the colon using an onboard propulsion mechanism. Notable examples of both categories will be briefly described below.

An early example of a medical robotic device which offers controlled flexibility along curved pathways is the Active Endoscope proposed by Ikuta et al. [84] in 1988. A schematic of the system is shown in Figure 2.9. It features five segments, each of which is 13mm in diameter,

40mm in length and is capable of actuating 60° in one plane. Actuation is provided by antagonistic pairs of shape memory alloy (SMA) coil springs arranged around a central stainless steel coil spring. Water cooling is used to improve the system response and overall safety. A novel contribution of this system is that while the actuators for each segment are mounted mechanically in parallel, the wiring structure is connected in series. This allows for measurement of the angular displacement of each segment via the electrical resistance. Consequently, this solves a considerable challenge facing all medical robotic devices: how to provide on-axis position measurement given the limited space available for traditional position measurement devices. The device does provide image feedback from an integrated fibroscope, however there is insufficient space for the passage of interventional instruments. While this active endoscope represented many technological achievements, ultimately its applicability was limited due to the reduced number of degrees of freedom and difficulties in accurately controlling the SMA actuators. However, it represents one of the earliest flexible devices for medical applications available in the literature.

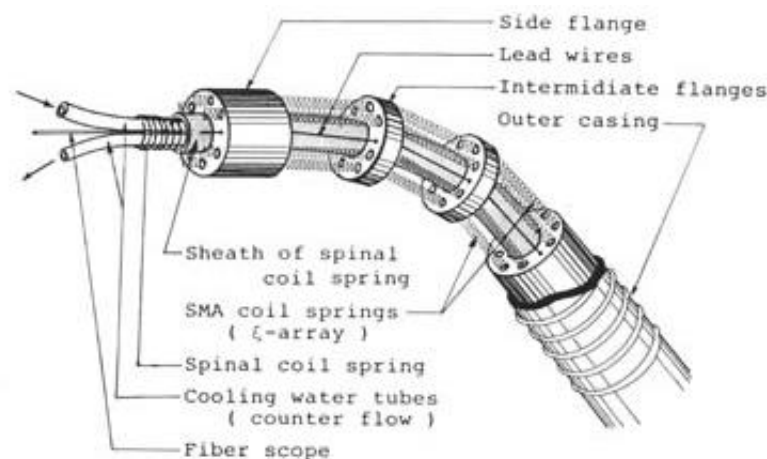


Figure 2.9: Configuration of the shape memory alloy actuated ‘Active Endoscope’ which provides five degrees of in-plane actuation from its proximal joint segments and two degrees of freedom at its distal segment. Image source: [84]

The concept of an ‘Active Endoscope’ has been further explored by several companies and universities. Of these, the NeoGuide Endoscopy system from Neoguide Systems Inc offers a highly dexterous tendon driven system for colonoscopy. The device features sixteen steerable segments which ‘follow-the-leader’ as the tip is steered through the colon [85]. This dexterity and provision of an internal channel (3.2mm in diameter) would be very suitable for flexible access surgery, however the system is optimised for travelling the length of the colon. The result is a long, heavy device with a support cart which has a considerable footprint in-theatre. An alternative flexible approach to colonoscopy is that of using un-tethered robots which

effectively climb through the colon using an onboard propulsion mechanism. Examples include the bio-inspired ‘inchworm’ style propulsion exhibited by the systems developed by Phee et al. [86] and Slatkin et al. [87]. Both use alternative clamping and extension strategies to grip the colon wall and advance inside its lumen. However, both are too flexible for applications in a surgical environment as they do not have the ability to pass instrumentation and require a lumen through which to operate.

2.2.3.2 Flexible Robotic Devices for Cardiac Interventions

The attraction of developing flexible devices to perform minimally invasive cardiac surgery is driven by the extensive trauma a patient undergoes during any procedure requiring a sternotomy. Providing a surgeon with the ability to intervene at the heart without such an incision would result in greatly reduced invasiveness. However, the anatomical location of the heart between the lungs and protected by the rib-cage presents limited direct lines of approach. One device was developed in an attempt to perform anastomoses during Coronary Artery Bypass Grafting (CABG) [88]. The device is shown in Figure 2.10 and is unique amongst the devices presented thus far in that it utilises embedded brushless DC motors to achieve actuation along five degrees of freedom. The outer diameter of the device is 10mm so that it can pass through the intercostal spaces. Motor rotation is converted to joint rotation via a worm gear, and position feedback is provided by integrated hall-effect sensors. This configuration is well suited to the applications of flexible access surgery as it has the potential to provide a very small footprint in-theatre due to no requirement for external actuator packs. However, the device is optimised for CABG and so only features 5-DoF and does not provide any internal channels for the passage of instrumentation or control wiring.



Figure 2.10: Dexterous Robotic Arm for Cardiac Artery Bypass Grafting. The system features embedded actuation which offers significant advantages for reducing the footprint in-theatre, however the design does not provide any space for internal channels to pass instruments or control wires. Image Source: [88]

A second device designed for cardiac surgery is the Highly Articulated Robotic Probe (HARP) [89, 90] which is in the process of commercialisation under the name of CardioArmTM [91]. This system aims to provide an access route to perform flexible access surgery on the heart via a single subxiphoid incision. The version shown in Figure 2.11 is 300mm in length and 12mm in diameter. It consists of concentric inner and outer tubes which can alternate between rigid and limp configurations. The clinical variation of the system has an internal channel capable of passing instruments up to 8 French (2.7mm) in diameter. Each tube is constructed of serially connected cylindrical links joined by a spherical joint. Forward locomotion is achieved by making one tube rigid, thus forming a ‘backbone’, and advancing the other tube by the length of one link. This tube is then made rigid and the tube which previously provided the backbone support is made limp and advanced along the pathway defined by the other tube. This process is repeated to facilitate locomotion and the definition of a three dimensional path, as can be seen in Figure 2.11. Four tendons actuate the device, three to allow for steering of the outer tube and one to allow the inner tube to be made rigid.

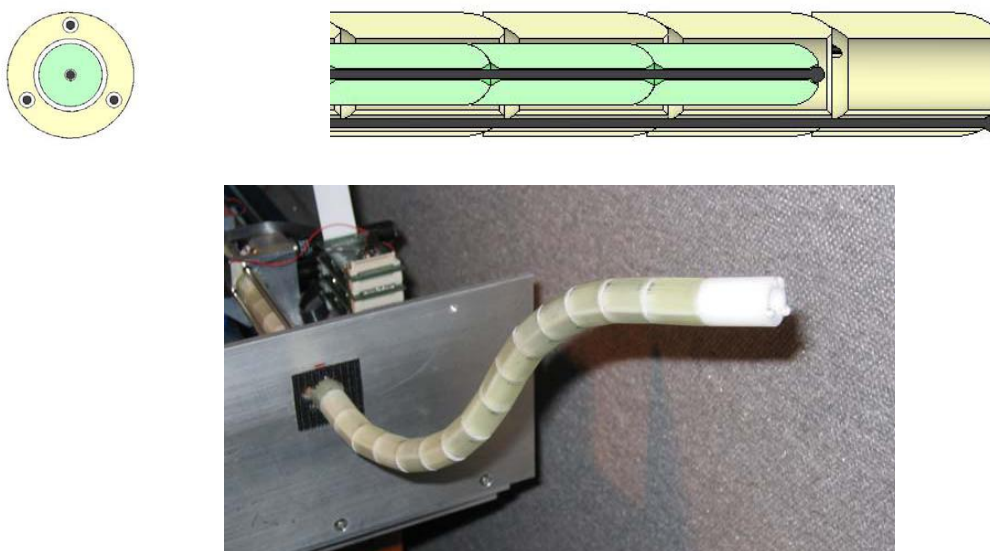


Figure 2.11: (top) Front and cross sectional view of HARP showing inner (green) and outer tubes (yellow), and four actuating tendons (black); (bottom) the HARP demonstrating its ability to maintain an arbitrary 3D shape. Image source: [89]

The key advantages of this system include the ability to define and hold an arbitrary shape in 3D, its small diameter and ability to convert from rigid to flexible should the need arise. However, each joint cannot be independently actuated, which limits the re-configurability of the device and does not exploit the redundancy of having so many degrees of freedom. The consequence of this feature is that while the system presents excellent characteristics for following a curved pathway, deviations from that pathway are difficult to achieve without

retracting the device and restarting the manoeuvre. As such, the system is well suited to exploration of restricted spaces, like the thoracic cavity, but not for the peritoneal cavity where the ability to explore a large area in a short space of time would be more beneficial. Additionally, although the diameter of the system is small, a large external feeding mechanism is required.

The flexible robotic system shown in Figure 2.12 is the commercially available ArtisanTM Control Catheter from Hansen Medical. It provides precise control over the insertion, positioning and manipulation of electrophysiological catheters when inside the heart. The system features a tendon driven, two-stage flexible tip. The first stage uses two guide tendons to achieve bending in one plane, while the second stage features four tendons and provides two degrees of freedom for the distal tip. An internal channel allows for the passage of up 8.5 French (2.85mm) instruments. The system is steered from the SenseiTM Robotic Control System which provides the operator with fluoroscopic images taken during the procedure, as well as a superimposed rendering of the catheter configuration. This combination of flexibility and integrated imaging provides many of the attributes desirable for flexible access surgery, however it is optimised for use during intra-luminal cardiology procedures and so is unable to support itself outside of a lumen.



Figure 2.12: The Artisan Control Catheter from Hansen Medical demonstrating the dexterity provided by the catheter tip. Image source: Hansen Medical Inc.

2.2.3.3 Flexible Robotic Devices for Laparoscopic Surgery

The ‘Hyper Finger’ [92], also from Ikuta et al. at the Tokyo Institute of Technology is another example of a flexible robotic system for minimally invasive surgery (see Figure 2.13). The system again features a remotely sited actuation pack with force transmission via tendons passing through the shaft of the device. It features identical master and slave ‘finger’ units which each consist of four links serially connected via a universal joint. A ninth degree of freedom is provided by a detachable gripper unit operated by an embedded DC micromotor.

Each joint is actuated by four tendons operating in antagonistic pairs with two for each DoF. A contribution of the system design is that it attempts to overcome some of the fundamental design difficulties which affect tendon drive mechanisms. This includes placing each axis and the corresponding tendon connection points in the same plane so that one rotational drive system is decoupled from the other (see Figure 2.14) and compensating for tendon elongation by ensuring the route length is kept constant during actuation. However, the system does still suffer from non-linear tendon dynamics caused by routing the actuation lines for distal links through the more proximal joints [93].

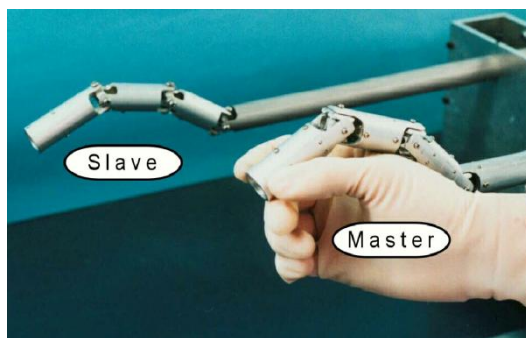


Figure 2.13: Hyper Finger Mk1 Master and Slave units. This version of the Hyper-Finger features 6-DoF. The later version features 8-DoF of joint articulation and a micromotor actuated gripper. Image Source: [92]

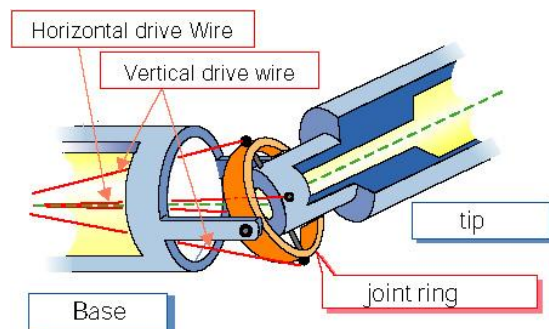


Figure 2.14: Schematic of the Hyper Finger joint mechanism detailing the decoupled universal joint which serves to eliminate some of the problems produced by the long tendon transmission paths. Image source: [92]

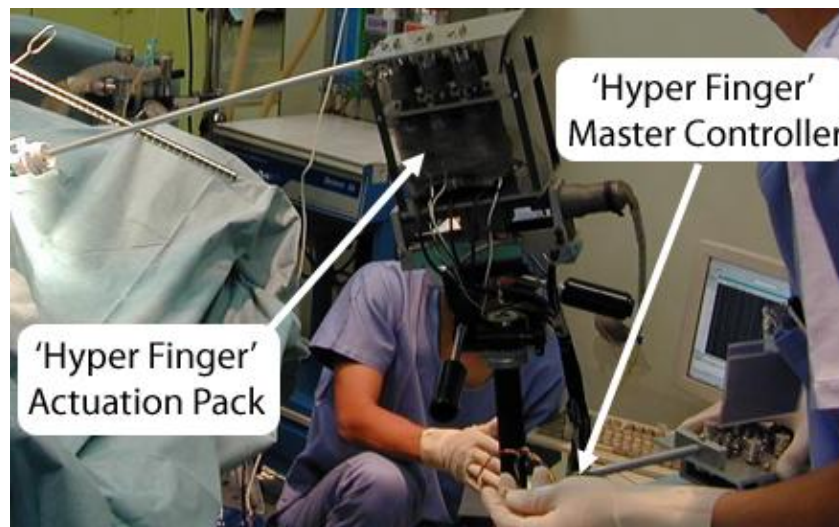


Figure 2.15: The view in the operating theatre during a pre-clinical porcine experiment using the 'Hyper Finger'. The external actuation pack is marked along with the master controller which is an unactuated replica of the slave unit. Image source: [92]

Additionally, due to the nature of the design it is impossible to pass instruments through a central channel. The authors also claim to have made significant efforts to reduce the footprint

of the actuation pack in-theatre. However, as can be seen in Figure 2.15, the pack still represents a considerable volume which could potentially obstruct surgeons intraoperatively. This large in-theatre footprint of the device is an inherent problem of systems which feature remote actuation and limits their suitability for rapid integration into the surgical workflow.

Other notable flexible systems for laparoscopic surgery include the modular system developed as part of the ARES project [94-96], and the Direct Screw Drive (DSD) Forceps manipulator [97]. This latter system uses universal joints and flexible shafts to achieve high force transmission and deflections of the tip through $\pm 90^\circ$ in any direction. However, neither is suitable for addressing *Challenge 1* to *Challenge 4* as outlined in Chapter 1.

2.2.3.4 Flexible Robotic Device for Laryngeal Surgery

The final flexible robotic system to be discussed in this section is for laryngeal surgery. It is a shape memory alloy (SMA) actuated ‘snake’ robot from Columbia University and Johns Hopkins University [98] [99]. This system differs from those previously described in that it provides multiple degrees of freedom through the push-pull action of super-elastic Nitinol tubes. The prototype shown in Figure 2.16 is 4.2mm in diameter and features four super-elastic SMA tubes (arranged with one central backbone and three secondary backbones spaced equidistant from this central backbone), a base disk, an end disk and several spacer disks. The central backbone is attached to all disks (base, end and spacer) while the secondary backbones are attached only to the end disk and are free to slide and bend through suitably dimensioned holes in the base and spacer disks. Varying the lengths of the SMAs allows for bending in 2-DoF. The system is designed to provide enhanced dexterity in the restricted environment of the throat and provides several advantages in this setting. However, as can be seen from the tip mounted gripper in Figure 2.16, the robot is designed for manipulation tasks and does not feature the dexterity for large area explorations or internal channels to pass instrumentation.

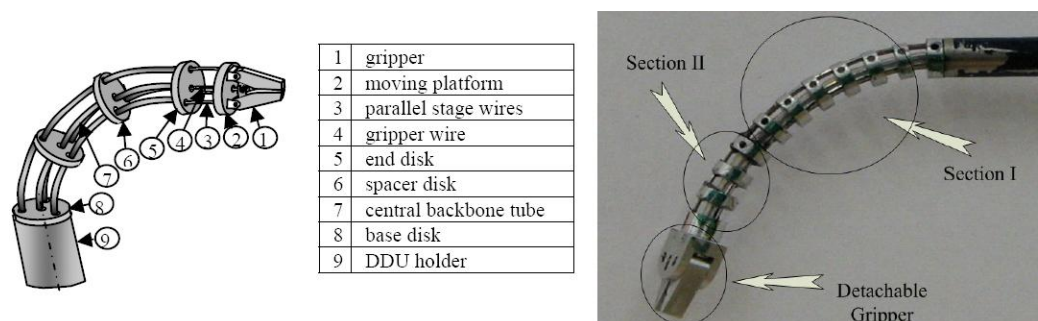


Figure 2.16: SMA based snake robot showing (left) schematic of internal components and (right) the actual device with two bending sections clearly marked. Image source: [98]

Table 2.4: List of flexible and articulated robotic devices designed for minimally invasive interventions

System Name (Author)	Company / University	Purpose	System Diameter (mm)	Total DoF	Actuation Type	On-Joint Position Sensing	Internal Channels	Reference
Active Endoscope	Tokyo Institute of Technology	Endoscopy	13	5	SMA wire	Electrical Resistance	-	[84]
HARP/CardoARM	Carnegie Mellon University	Cardiac Surgery	12 and 10	3	Tendon	-	Yes	[89-91, 100]
Hyper Finger	Nagoya University	Laparoscopic	10	8	Tendon	-	-	[92]
Neoguide	Neoguide Systems Inc	Endoscopy/Flexi ble Access	14	16	Tendon	-	Yes	[85, 101]
Distal Dexterity Unit (Simaan et al.)	Johns Hopkins & Columbia University	Laryngeal Surgery	4.2	4	super-elastic NiTi tubes	-	-	[98, 99, 102]
Tool Guiding System (Peirs et al.)	Katholieke Universiteit Leuven	Laparoscopic	5	2	Tendon	-	Yes	[103]
Artisan Control Catheter	Hansen Medical	Cardiology	4.7	Intra- luminal	Tendon	-	Yes	[104, 105]
High dexterity instrument (Salle et al)	University of Paris & Genoa University	Cardiac Surgery	12	5	Motor	Hall effect	-	[88, 106]

Endoscope Manipulator (Peirs et al.)	Katholieke Universiteit Leuven	Endoscopy	12.4	2	Motor	-	-	[107, 108]
Inchworm Device (Phee et al.)	Scuola Superiore de Sant'anna	Endoscopy	24	Intra-luminal	Pneumatic	-	-	[86]
Inchworm Locomotion (Slatkin et al.)	California Institute of Technology	Endoscopy	22	Intra-luminal	Hydraulic	-	-	[87]
Ares Project	Scuola Superiore de Sant'anna	Flexible Access Surgery	16	4	Motor	Motor back EMF	-	[94-96]
MINIR	University of Maryland	Neurosurgery	12	Currently 2	SMA wire	-	Yes	[109]
Continuum Robot (Yoon et al.)	Hanyang University	Flexible Access	8	4	Tendon	-	Yes	[110]
DSD	Kogakuin University	Laparoscopic	10	2	Flexible Shaft	-	-	[97, 111, 112]
Concentric Tubes (Dupont et al.)	Boston University	Percutaneous therapy	2.77	/	Super-elastic tube	-	Yes	[113, 114]

From Table 2.4 and the overview of flexible devices for MIS presented above, it is clear that while many innovative, high quality devices are available, none are suitable for addressing each of the challenges outlined in Chapter 1. A gap exists for a small footprint, flexible device which can provide independently controllable multiple DoF dexterity, stability along curved pathways and facilitation of the passage of instruments through internal channels. It is also important to point out that although the use of CT and MRI image guidance is established for use with robotic devices, none of the systems described in the literature discuss the integration of multi-spectral imaging techniques within robotic devices.

The next section will review the different actuator technologies compatible with minimally invasive surgery and briefly discuss the merits of different transmission mechanisms for use with a flexible robotic device.

2.3 Actuation Technologies

Key elements of any flexible robotic system for minimally invasive surgery are the actuator and transmission mechanism used to provide controlled joint motion. The selection of the actuators is largely dictated by design criteria such as:

- System dimensions (link diameter, link length, workspace, cross section)
- Desired actuator placement (embedded, remote)
- Joint torque requirement, τ
- Joint actuation speed requirement, ω

The majority of flexible robotic systems described in Section 2.2 utilise remotely positioned actuators (DC motors, current amplifiers, tendon spools, shape memory alloys) with long transmission lines passing through more proximal links to reach the distal units (examples include SMA wires [69, 70, 98, 102, 109, 113, 115] and tendons [28, 33, 39, 76, 85, 89, 92, 103, 104, 110]). This approach has one key advantage and one key disadvantage. The advantage is that by placing the actuators remotely vital space is saved within the robot itself and high force transmission can be achieved. However, the disadvantage of the approach is that the long transmission lines introduce nonlinearities and transmission inefficiencies due to frictional losses, changing path lengths, indirect position sensing and the joint coupling that can occur in flexible systems. Additionally, as the number of joints increases so too does the number of transmission elements taking up the cross sectional area. This eventually limits the final number

of links that can be serially connected. A secondary drawback of remote actuation is that the actuator pack must be located outside of the patient. This often results in the pack being between the patient and the surgeon, which physically separates the surgeon from the operative site and can limit the space available for surgical assistants.

Table 2.5 summarises several of the available actuator modalities that provide sufficient miniaturisation capabilities for integration into a flexible robotic device. All were carefully considered for integration within the flexible access platform, however shape memory alloys, pneumatics and piezoelectrics were discarded at an early stage. The key reasons for this are listed in the “Disadvantages” section of Table 2.5. Additionally, current state-of-the-art in artificial muscles (IPMC: Ionic Polymer Metal Composite and EPAM: Electroactive Polymer Artificial Muscle) were also initially considered. These technologies offer great potential for the future, in particular since they can act as both an actuator and a sensor. However, the current availability of robust and tested products is limited and the high voltages (EPAM) and high power (IPMC) required represent hurdles for implementation within a medical robot. The remaining two transmission technologies (remote tendon and DC motor) will be discussed in greater detail.

Table 2.5: Comparison of potential actuator technologies which are compatible with the size constraints of minimally invasive surgery [31, 106, 109, 116, 117]

Actuation Type	Advantages	Disadvantages
Tendon (remote)	Good force transmission	Transmission inefficiencies
	Support miniaturisation	Require remote actuation
Shape memory alloy	High force	Response time
	Support miniaturisation	Modelling and control issues Cooling required
Pneumatics	High force transmission	Difficult to miniaturise
	Simple	Precise control difficult
Piezoelectric/Ultrasonic	High torque at low speed	High voltage required
	High bandwidth	specialised waveform
	Good holding force	Difficult to integrate
Brushless DC	Embedded actuation	Limited torque
	Easy to control	Brushless only

2.3.1 Remote Actuator with Tendon Transmission

As was mentioned in Section 2.3, the advantages of employing a tendon drive mechanism are the good force transmission characteristics and small cross sectional area taken up within the link units. Additionally, the advantages of pre-tensioned tendons for providing low friction and backlash have led to their integration within high precision haptic interfaces such as the Whole Arm Manipulation (WAM) Arm from Barrett Technologies [118], the PHANTOMTM from Sensable Technologies [119] and the Omega/Delta systems from Force Dimension [120]. However, for the flexible access platform, many of the design requirements are not ideally suited to the capabilities of tendons. Reasons for this include:

- As the number of degrees of freedom increases, the number of tendons required to actuate the degrees of freedom also increases. Each additional tendon takes up more cross sectional area within the link segments and hence reduces the space available to pass instruments;
- As the number of tendons increases, so too does the number of actuators located at the proximal end of the system leading to a greater footprint in the operating theatre;
- The efficiency and performance of a pre-tensioned tendon transmission system would be reduced over long transmission distances and when passing along tortuous path lengths. A potential solution to this would be to employ compensatory mechanisms, as provided by the daVinci or demonstrated in [121]. The effects of friction along the route can also be modelled to improve performance [122]. However, implementing such a routing system for each tendon would take valuable space within the platform;
- Remote actuation is not compatible with a modular design approach.

2.3.2 Embedded DC Motors

The major advantage of DC motors is the straightforward digital controllability that they provide. They are also widely available. However, only miniature brushless DC motors offer the dimensions compatible with the size restrictions of MIS compatible devices. Only a limited number of such miniature motors exist and as they scale down in size the torque available also reduces. Thus any embedded DC motor implementation requires an efficient transmission mechanism to convert motor rotation to joint motion. Two different brands of miniature DC motors were evaluated as part of this project: a 4mm diameter motor (Namiki Precision Jewel Ltd.) with two different gearbox combinations (337:1 and 79:1) and a 3.4mm diameter motor

from Faulhaber GmbH with a 125:1 gearbox. These represent the smallest motors available that could be of practical use for implementation within a medical robotic device. Smaller brushless DC motors available from Namiki include a 1.9mm diameter and a 0.9mm diameter motor. However, the torque of these motors is measured in μNm and so is insufficient for integration within robotic devices constructed on a *mm* scale. Essential comparative information is listed in Table 2.6 below.

Table 2.6: Comparison of miniature brushless DC motors from Namiki Precision Jewel Ltd and Faulhaber GmbH

	Namiki SLB04-0829 PG337	Namiki SLB04-0829 PG79	Smoovy 0308 03A
Diameter (mm)	4	4	3.4 (gearhead) 3 (motor)
Gear ratio	337:1	79:1	125:1
Stall torque (mNm)	5.7	2.92	1.32
Nominal voltage (V)	3	3	3

The data in this table indicate that the 4mm motor from Namiki with a 337:1 gearbox provides the optimum trade-off between torque and size.

2.4 Conclusion

In this chapter, a brief overview of existing medical robotic systems is provided. The principal part of the chapter is about flexible robotic devices and actuation technologies that could potentially be utilised in any new design. In particular, analysis of the systems described in Section 2.2.3 allows the identification of several key opportunities within the area of medical robotic systems. While many systems which fit into the broad description of ‘flexible medical robotic device’ exist, none fulfil the requirements of a flexible access platform as was described in Chapter 1. The purpose of such a device would be to access difficult to reach internal structures, and facilitate early diagnosis/intervention through the use of visible and functional imaging combined with interventional instruments. Existing systems either do not have the necessary dexterity to access the internal structures from a single incision or do not have the ability to pass probes to image and intervene at the target site. Additionally, many of the systems described in Section 2.2 feature large footprints within the operating theatre. This may

appear to be a minor issue, however to ensure repeated use of a system, it is critical that rapid deployment and removal from the operative site can be achieved in order to minimise disruption of the surgical workflow.

As such, any potential flexible access platform would be required to incorporate most if not all of the following features:

1) *Biopsy channel(s)*

To ensure compatibility with third party interventional instrumentation and imaging probes any flexible access platform should integrate dedicated biopsy channel(s) to facilitate the passage of instrumentation.

2) *Visual Feedback*

If the purpose of the flexible access platform is to reach inaccessible areas, a key requirement is to provide visual feedback to the operator. This is vital unless an additional imaging technique such as fluoroscopy or MRI is used to make both navigational and diagnostic decisions. Many of the systems described in Section 2.2.3 omitted visual feedback as a design feature.

3) *Functional imaging*

The emerging technique of using functional imaging to perform ‘optical biopsies’ for in-vivo, in-situ tissue characterisation perfectly complements the flexible access provided by articulated robotic systems. To fully leverage the strengths of both technologies, any robotic system should consider integration of the functional imaging techniques at the design phase. This combination of access and diagnostic ability offers the possibility of greatly increasing the intraoperative information available to the surgeon.

4) *Small footprint*

A problem with the daVinci Surgical System and many of the articulated robotic designs in Section 2.2.3 is their large footprint in the operating theatre. Although systems such as the daVinci clearly have a different design specification, an articulated device which aims to facilitate flexible access surgery should aim to be small, easy to setup, lightweight and portable.

5) *Intuitive control paradigm*

Any articulated system must have an intuitive control paradigm which allows the operator to easily control the multiple degrees of freedom. Similarly, many of the systems described in Section 2.2.3 did not address the issue of how their multiple degrees of freedom are controlled.

Each of these features will be addressed in the design of the flexible access platform to be described in the following chapters. The mechatronic joint module to be described in Chapter 4 contains three internal channels suitable for passage of interventional instruments, optical imaging probes and miniature cameras. The joint module design also ensures that the flexible access platform only requires a minimum of space within the operating theatre. Chapter 5 will present two intuitive control paradigms for controlling the flexible access platform, and Chapter 6 will describe how the platform can be used to improve the consistency of probe based optical biopsy imaging. The practical benefits of each of these features will be demonstrated in Chapter 7 with results from in-vivo trials. Firstly however, in Chapter 3 the feasibility of integrating functional imaging techniques into a flexible robotic imaging probe will be investigated.

Chapter 3:

An Articulated Multi-Spectral Imaging Robot for MIS

Chapter 2 reviewed existing flexible robotic devices for minimally invasive surgery and outlined their current technical limitations and advantages. The purpose of this chapter is to present an articulated, robotic probe capable of providing enhanced intraoperative information to a surgeon during MIS. This enhanced information is achieved through the provision of both white light and fluorescence imaging using a supercontinuum laser source. Although imaging probes have significantly enhanced the capabilities of in-vivo in-situ imaging, their high resolution and small field of view represent practical challenges in clinical use. Specifically, the small field of view offered by these probes requires a large number of images to be acquired in order to provide a functional map of a large area. This is a time consuming and difficult process. Additionally, most probes are deployed through endoscopes and attempting to use them in a spatial environment, such as an insufflated abdomen, is challenging. There is a clear

need for a flexible robotic device with integrated dual modality imaging that can acquire targeted multi-spectral images of a large region in a simple and effective manner. The articulated design presented here allows the device to explore behind fixed structures, or to trace overlapping tip trajectories such that an expanded field of view (panorama) can be generated. These reconstructed image sequences can be used to provide clinicians with improved navigation cues and simultaneous fluorescence functional mapping that would not be possible with current devices.

However, the results presented in this chapter represent the initial attempt to develop a flexible access platform with multi-modal imaging capabilities and, as will become clear in Section 3.5 Discussion and Conclusion, the design approach was ultimately deemed to be incompatible with the overall goals of the platform. This resulted in a change in design strategy from remote tendon actuation to embedded micromotor actuation; detailed design details of which will be provided in Chapter 4. Consequently the results in the subsequent chapters are considered to be more relevant to the overall contribution of the thesis than Chapter 3. Nonetheless, the results reported in this chapter are important to include on the basis that several crucial lessons which influenced the design of the modular mechatronic joint were learnt during development of the multi-spectral imaging robot. To reflect this, the chapter documents key elements of robot and its imaging system but the more detailed engineering information is included in Appendix I, rather than within the main text of the chapter. Such results include the assembly steps, (Appendix I.A), mechatronic design details (Appendix I.C), device repeatability analysis (Appendix I.D) and the steps required for image mosaicing (Appendix I.E). However, the significant results obtained with the robot, including a demonstration of synchronised white light and autofluorescence characterisation of phantom and ex-vivo tissue samples, are provided. The key contribution of this chapter is the integration of multi-spectral imaging techniques within a flexible robotic device compatible with the constraints of minimally invasive surgery.

3.1 Robot-Assisted Multi-Spectral Imaging

One of the recent advances in biophotonics for minimally invasive surgery is the introduction of fluorescence imaging for real-time, in-vivo tissue characterisation. This ability of fluorescence imaging to provide additional information to clinicians is the result of the autofluorescence emission exhibited by all biological tissues when excited by ultra-violet (UV) or visible light. Critically, this emission spectra differs between healthy and cancerous tissues and thus offers

the potential to identify the precursors of cancer [123, 124] and metastatic disease [125]. There has consequently been an increase in clinical demand for systems which provide clinicians with functional information regarding tissue structure which is not available when imaging under white light illumination alone. An advantage of having systems that combine white light and fluorescence imaging capabilities is that the former can provide navigational cues and traditional evaluation of the tissue surface while the latter can provide enhanced functional information through analysis of the autofluorescence images. An example demonstrating the different types of images that can be obtained under white and fluorescence illumination is shown in Figure 3.1 and Figure 3.2.

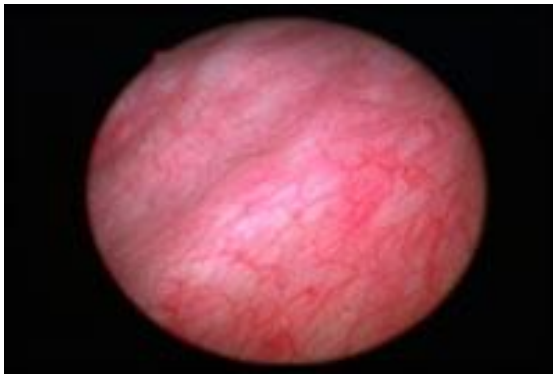


Figure 3.1: Cystoscopy image acquired under white light. Credit: Prof. Maximilian Burger, University of Regensburg

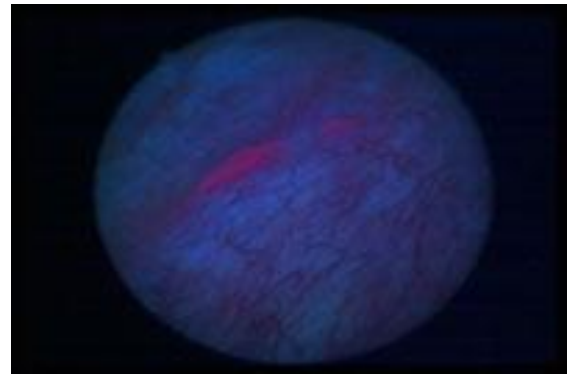


Figure 3.2: Cystoscopy image acquired under blue light illumination. The pink areas of the image indicate abnormal tissue structures. Credit: Prof. Maximilian Burger, University of Regensburg

Two images of the same tissue region obtained during a cystoscopy examination are shown. An optical imaging agent (CysviewTM (hexaminolevulinate HCl)) is used to amplify the autofluorescence effect and highlight abnormal tissue structures in conjunction with a dual modality imaging system (Karl Storz D-Light C Photodynamic Diagnostic (PDD)). The image on the left was acquired under white light illumination, while the image on the right was acquired under blue light illumination. The pink region which can be seen in Figure 3.2 indicates a tissue abnormality not visible under white light. Providing such information intraoperatively offers the potential to increase the accuracy and speed at which diagnoses are performed and thus appropriate treatment administered.

Examples of multi-modal (fluorescence and white light) imaging systems that have been commercially developed include the Karl-Storz D-Light [126], Richard Wolf Combilight PDD 5133 [127], Pentax SAFE-1000 [128] and the Xillix Onco-LIFE [129]. However, each of these systems is incorporated into either a rigid laparoscope or flexible endoscope and thus has limited actuation capabilities and must be manipulated by the clinician in order to perform

exploratory scans of target anatomy. The multi-spectral imaging robot to be described in this chapter incorporates dual mode imaging capabilities similar to those mentioned above but within a small diameter, articulated robotic platform. The advantage of the robotic platform is that it can be used to image behind fixed structures by fixing its proximal joints and scanning with the distal tip alone. Alternatively, it can employ controlled joint actuation to trace overlapping trajectories with the distal tip to generate an extended field of view of the target scene. This ability to pre-define trajectories offers the potential for the device to generate functional maps with synchronised white light and tissue autofluorescence information.

3.2 Mechatronic Design

The proposed device consists of two core design elements – the mechatronic design required to provide access, support and controlled articulation at the target site, and the optical design required for the illumination of the target and capturing of the reflected image. Although clearly separate elements, it was necessary to carry out the design work in parallel due to the size constraints imposed by the restrictions of minimally invasive surgery. Specifically, the cross-sectional area available for the structural, actuation and optical components is limited by the requirement to minimise the incision diameter. A schematic of the overall design can be seen later in the chapter (Figure 3.5).

3.2.1 Mechanical Design

In order to achieve large area scans with overlapping tip trajectories, the multi-spectral imaging robot features four links serially connected via three 1-DoF revolute joints (J_1, J_2, J_3). These joints are attached to the distal end of a rigid, hollow shaft 310mm in length, as can be seen in Figure 3.3. Each link unit is 30mm in length and the diameter of both the links and shaft is 8.5mm. This diameter is compatible with existing trocar ports. The links feature two internal channels, the larger of which is used to pass the actuation tendons and a flexible fibre image guide. The smaller channel is used to pass an illumination fibre. The fibre image guide and the illumination fibre will be described in greater detail in Section 3.4 and Appendix I.B. This entire unit (shaft and link segments) is connected to a fourth revolute joint which is capable of providing rotation along the principal axis of the shaft, J_4 (Figure 3.3). This combination of the three joints providing in-plane articulation and the fourth rotational joint allows the device to point its tip in any direction through 90°.

Each of the serially connected joints is independently actuated by a 0.5mm diameter steel wire tendon. To reduce the number of tendons required for actuation, each joint is returned via an embedded torsion spring, as is marked in Figure 3.3. The tendon fixation point is offset from the joint axis of rotation so that when the tendon length shortens, the joint experiences a turning force. If this turning force is greater than the torque exerted by the torsion spring, the joint rotates. Similarly, when the tendon length adjusts so that it is no longer applying a turning force on the joint (i.e. the tendon is slack), the torque stored in the torsion spring rotates the joint in the opposite direction. This torque must be of a sufficiently high magnitude to overcome any friction in the system. Bearings and washers are used to reduce the effects of friction where possible. The joint will stop rotating once the tendon is placed under tension. In this manner, the angular displacement of each joint can be controlled by adjusting the length of its tendon. Using this configuration, only three tendons are required to control the three degrees of in-plane articulation of the robot. These pass down the central channel within the multi-spectral imaging robot; the tendons for the more distal links pass through the proximal links. Each link n also features an internal ‘*Tendon Channel*’ that allows the actuating tendon for the link $n+1$ to pass through the link n to the tendon fixation point located on link $n+1$. Further details on this design, including actuator selection and the geometrical relationship between tendon translation and joint displacement, can be found in Appendix I.C. Other mechanical components of each link unit include a ball bearing (inner diameter 1mm, outer diameter 3mm), an axle (outer diameter 1mm), washers and spacers.

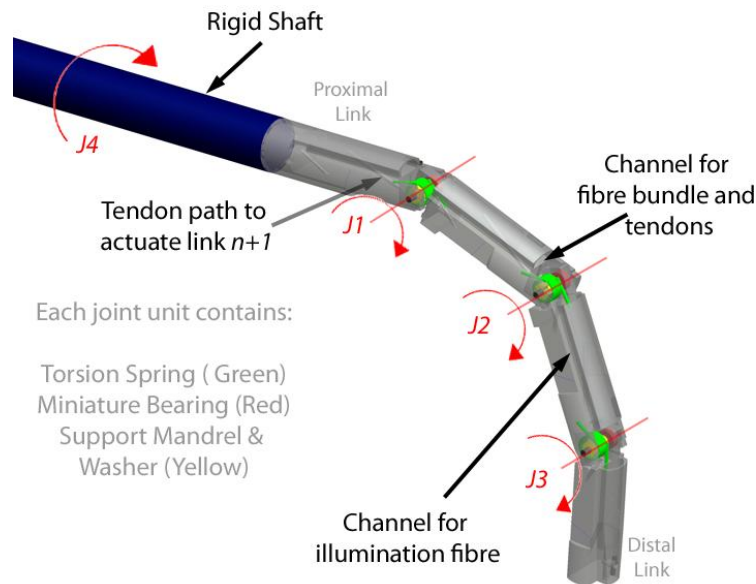


Figure 3.3: A CAD schematic showing the key components of the articulated section of the multi-spectral imaging robot. The three axes of in-plane articulation ($J1$, $J2$ and $J3$) and the axial rotation ($J4$) are marked in red. This articulated section is attached to a rigid shaft 310mm in length. The rigid shaft is then connected to an actuator pack.

3.2.2 Electronics and Control Design

Motor control is achieved using an OOPic-R programmable integrated circuit (PIC). The PIC is interfaced to a computer via the serial port and a custom user interface. The user interface is designed to allow an operator to easily implement large area imaging scans and to capture synchronised multi-modality images. Given the robot architecture, the most straightforward way to achieve this is to trace a series of concentric circles with the distal tip using J_4 to rotate through 360° . To define the radius of each circular trajectory, the operator sets the required angular displacements of J_1 , J_2 and J_3 and saves these values to the system memory. Once the desired robot configurations have been saved by the operator, the system is programmed to automatically rotate through 360° twice for each saved configuration. As will be discussed in Section 3.3, the purpose of performing two scan runs is to capture reflected white light information on the first run and the autofluorescence information on the second run.

The steps performed by the operator to execute these imaging scans are as follows:

1. The desired angular position for each of the three joints (J_1 , J_2 , J_3) is entered in a dialog box on the user interface;
2. The positions can be entered independently, and once entered the respective joint moves to the desired position;
3. The positions are fine-tuned until the operator is satisfied with the position and orientation of the distal tip;
4. The robot configuration is saved as *Configuration_X*;
5. The above procedure is repeated until the desired number of configurations has been obtained;
6. The operator clicks a *Scan* button at which point the system servos the robot to each configuration in turn and automatically rotates through 360° twice at each configuration;
7. These pre-programmed trajectories can be recalled and executed at a later stage if required.

The commands entered in the dialog boxes are sent to the PIC via the serial port. The PIC then generates the pulse width modulated (PWM) signal to control each motor. A detailed position

repeatability analysis was carried out to ensure that the robot was capable of performing imaging scans in a consistent and repeatable manner using the protocol described above. Details of this analysis can be found in Appendix I.D.

3.3 Integration of Dual Mode Imaging Abilities

A significant technical challenge facing the integration of a dual modality optical imaging system into an articulated robotic device is the limited cross-sectional area available once all structural and actuation elements are in place. In medical endoscopes and laparoscopes, reflected white light imaging is typically achieved using an incandescent or arc lamp illumination source coupled into a fibre bundle or series of lenses for delivery to the target tissue. However, the incoherent and extended nature of these light sources typically requires a transmission fibre bundle with a diameter of several millimetres in order to get sufficient light to the target. Integrating such an imaging bundle into the multi-spectral imaging robot would necessitate an increase in the overall diameter, thus limiting its applicability for MIS. The multi-modal (white light and fluorescence) medical instruments mentioned earlier in this chapter (Karl-Storz D-Light, Richard Wolf Combilight PDD 5133, Pentax SAFE-1000 and Xillix Onco-LIFE) utilise such illumination systems. When switching to the fluorescence imaging modality various filtering optics are used to select the desired wavelength from the light spectrum.

3.3.1 Illumination System

Since incorporating such an illumination system into the multi-spectral imaging robot was not possible, a novel optical configuration was developed in collaboration with Dr. Daniel Elson from the Biophotonics and Surgical Imaging Lab at the Hamlyn Centre [130]. This utilised a coherent white supercontinuum fibre laser (Fianium SC450-2) to provide sequential white light and fluorescence illumination within the multi-spectral imaging robot instead of the traditional Xenon light source. The laser is capable of emitting light over a broad spectrum and so can be tuned to emit white light or a specific wavelength as required. Additionally, the coherent beam of the laser can be focused into a single multi-mode fibre, thus reducing the effective footprint required for the illumination from mm to μm . As such, this illumination source is ideally suited to the size and flexibility constraints of the robot. Although the application of this laser device for fluorescence and fluorescence lifetime imaging has previously been demonstrated [131, 132], to the knowledge of the author it has not been utilised for standard or robotic assisted laparoscopic white light or fluorescence illumination.

The laser is capable of emitting broadband (450-1800nm) pulsed light generated in a highly nonlinear holey fibre. The output was passed through a computer controlled spectral filter consisting of a dispersive prism (SF2) and a motor controlled slit to allow different wavelength ranges to be selected automatically. The spectrally filtered light was then coupled into 2m of high numerical aperture polymer clad 200µm core diameter optical fibre (Thorlabs BFL37-200) using a ×20 achromatic microscope objective, as shown in Figure 3.5. It is this fibre which passes down the ‘illumination fibre channel’ of the robot. Uniform illumination of the field was achieved through the use of a tip mounted optical diffuser.

3.3.2 Image Acquisition System

In rigid laparoscope systems reflected white light images are typically acquired using a series of rod lenses to form an image on the proximal end or using a miniature tip mounted CCD camera. However, the flexible nature of endoscopes precludes the use of rigid rod lenses and consequently standard endoscopes typically acquire images with distally mounted cameras or flexible fibre bundles which transmit the reflected light to external camera systems. An advantage of the flexible fibre bundle approach is that any additional optical components required for specialised operation (such as multi-modal imaging) do not need to be miniaturised and co-located with the camera(s) at the distal tip. Table 3.1 outlines the properties of the different image acquisition techniques suitable for integration with devices designed for minimally invasive surgery.

Table 3.1: Properties of different image acquisition techniques suitable for minimally invasive surgery

Image Transmission Type	Flexibility	Image Quality	Distal Tip Complexity
Rod Lens	None	Excellent	Simple
Flexible fibre bundle	Good	Average	Simple
Distal CCD	Good	Very good	Complex

To account for the articulated nature of the design, the limited cross sectional area available and to facilitate seamless switching between white light and fluorescence image acquisition, a flexible coherent fibre image guide (Sumitomo IGN-05/10, 10.000 fibres, length 1.5 m, outer

diameter 0.59mm. The datasheet is provided in Appendix I.B) was selected for integration with the multi-spectral imaging robot. A graded index (GRIN) lens (Grintech GmbH) was cemented onto the end of the image guide (diameter 0.5mm, working distance 10mm, NA 0.5). This uses a variable refractive index to focus incoming light, and images a circular area of 20mm diameter at a working distance of 35mm onto the distal end of the image guide. This was then passed down the central channel of the robot (as indicated in Figure 3.3) and exits at the distal tip. The proximal end of the image guide was imaged onto a CCD camera (QImaging Retiga Exi) using an achromatic $\times 10$ microscope objective and 100mm focal length lens. In order to obtain colour images, a liquid crystal tunable filter was placed in front of the CCD camera. This was switched between red, green and blue filters in synchronisation with image acquisition by the camera. The three colour channels were calibrated under white light illumination from the supercontinuum laser, and 300×275 pixel images were acquired with exposure times of 20ms for each channel at 6Hz. When the system switches to the fluorescence intensity imaging modality, the electronically controllable slit is adjusted to only pass light shorter than 500nm, and a 500nm longpass interferometric filter (Thorlabs FEL0500) is introduced between the microscope objective and the 100mm lens. Images are acquired with an exposure time of 200ms and a frame rate of 5Hz. The actual acquisition setup can be seen in Figure 3.4 and the overall system schematic (as used for the experimental testing) in Figure 3.5.



Figure 3.4: Image acquisition system used with the multi-spectral imaging robot including fibre clamp, liquid crystal tunable filter and CCD camera.

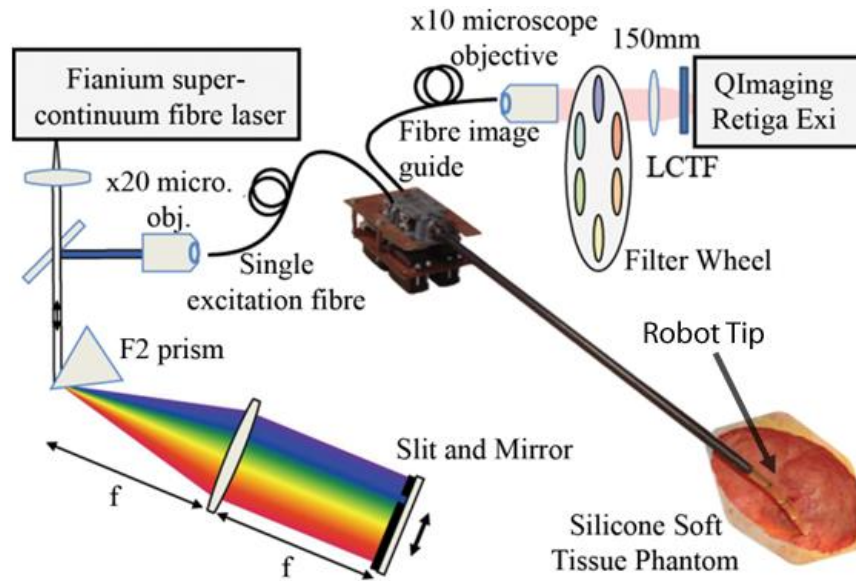


Figure 3.5: Schematic of the entire multi-spectral imaging robot system used during the dual mode imaging scans. The supercontinuum laser illumination source and its associated optical components, the robotic probe, image acquisition equipment and silicone tissue phantom are shown.

3.4 Experimental Setup and Results

Two different experimental tests were carried out with the robot in order to demonstrate its ability to:

- Perform sequential white light image acquisition and fluorescence image acquisition
- Characterise a large field of view through controlled joint motion

These tests were carried out using a silicone tissue phantom and excised ovine liver, both of which were infiltrated with fluorescein dye. Examples of static images captured under both white light and fluorescence illumination of the silicone phantom are shown in Figure 3.6 and Figure 3.7 respectively. These clearly demonstrate the ability of the system to acquire ‘standard’ white light images and to both excite and detect the autofluorescence signal from the fluorescein. Similar images from an ex-vivo liver sample are shown in Figure 3.8 and Figure 3.9. The mottled surface of the liver can be identified in the white light image, while the autofluorescence from the fluorescein can be seen in the image acquired using fluorescence illumination. These images clearly demonstrate the ability of the multi-spectral imaging robot to acquire different information about the target tissue when switching between acquisition modalities.

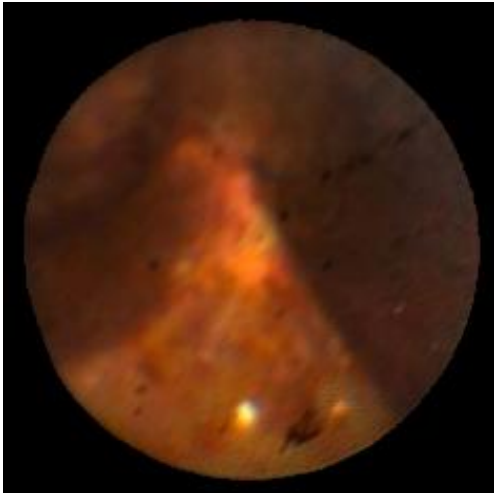


Figure 3.6: Sample image showing the fluorescein stained silicone phantom under white light illumination.

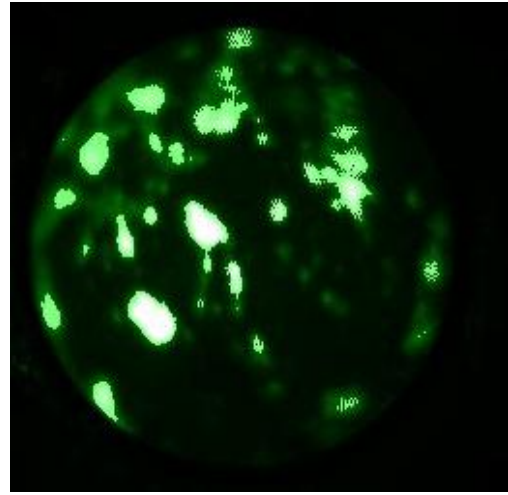


Figure 3.7: Sample image showing the fluorescein stained silicone phantom under fluorescence illumination. Pseudo-colour has been added to the image.

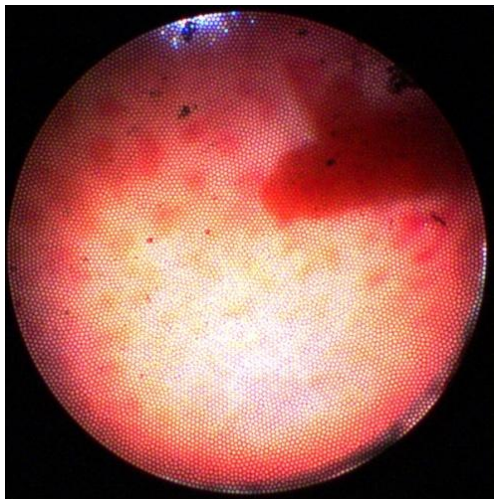


Figure 3.8: Sample image of the liver surface under white light illumination. The mottled pattern of the liver surface can be clearly seen and the fluorescein dye is not visible.

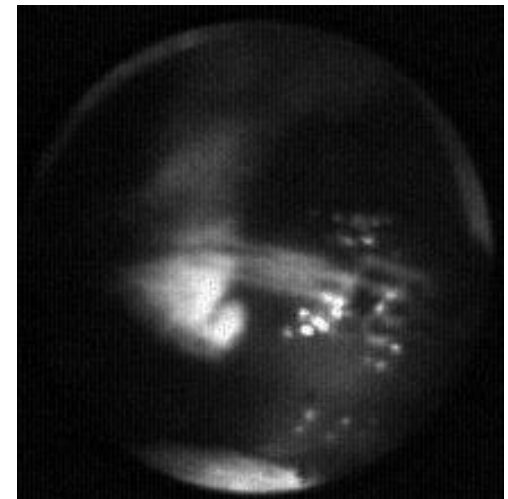


Figure 3.9: Sample image of the fluorescein stained liver auto-fluorescing under fluorescence illumination.

The experimental protocol for demonstrating the ability of the device to characterise an extended field of view involved tracing concentric circular trajectories. This operation was performed in a manner similar to that described in the repeatability analysis which can be found in Appendix I.D. The tip of the device was set at four different angular displacements and rotated through circular trajectories at each position. At each tip position, two rotations of the device through 360° were carried out at a speed of 36° per second. The first rotation captured

reflected white light images and the device was then set to capture fluorescence images during the second rotation. By keeping the tip angular position fixed between runs, the white light and fluorescence image sequences can be synchronised.

To illustrate how these synchronised dual mode images can potentially be employed to provide a clinician with enhanced visual information, a pair of panoramic views of the phantom tissue surface were reconstructed from the individual images captured during the robot scans. This was performed using the Autostitch image mosaicing software, which is freely available online [133]. The algorithm is capable of generating fully automatic panoramic image stitching from an image dataset irrespective of rotation, scale and illumination changes. As such, it is ideally suited to take the individual images acquired by the multi-spectral imaging robot and to generate an extended field of view. It performs this task in four main steps which are described in Appendix I.E. Full details of can be found in [134] and [135]:

A total of 145 individual images captured during the four rotations of the multi-spectral imaging robot (under both white light and fluorescence illumination) were used as the input images for the algorithm. Examples of both the reconstructed white light and autofluorescence panoramas are shown in Figure 3.10, along with a sub-sample of the input images.

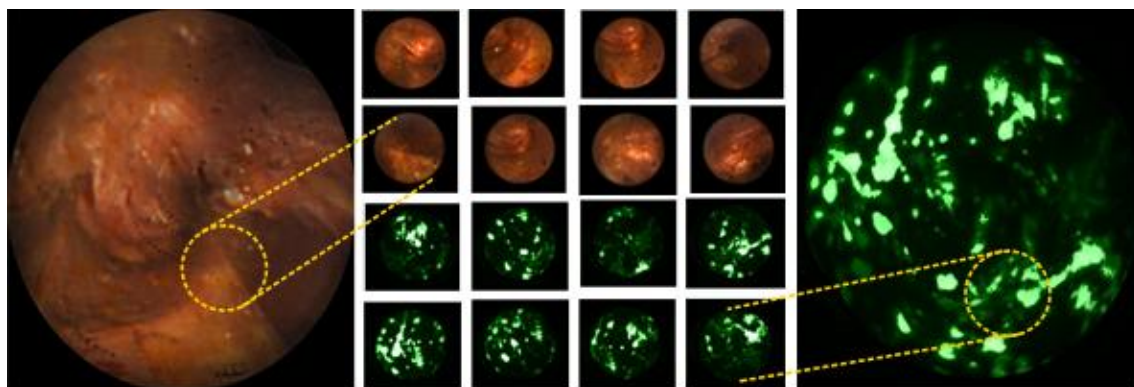


Figure 3.10: Fused panorama from 145 combined white light (*left*) and fluorescence images (*right*) generated using the Autostitch image stitching algorithm [133]. Pseudo-colour has been added to the fluorescence images. (*middle*) Samples of white light and fluorescence images indicating the relative field of view of each image acquisition.

Each panorama shows images acquired from the same region of the silicone phantom. The reconstruction increases the effective field of view of the fibre bundle from a circle of diameter 20mm to approximately 70mm. The total time taken for image acquisition was 100 seconds

(including 20 seconds to transition between imaging modalities) and 20 seconds for panorama reconstruction. The fidelity of the white light reconstruction was validated visually; however, it was not possible to validate the fidelity of the fluorescence panorama. In theory a larger panorama could be generated. However, with the configuration described here it was not possible for the robot to trace a larger circular trajectory without damaging the fibre bundle. It should be noted that the information contained in the individual images can be used without reconstruction, as would be the case in standard endoscopy or laparoscopy.

A similar protocol was utilised when imaging the fluorescein stained liver sample (i.e. four rotations for both acquisition modalities using controlled joint articulation). A panoramic reconstruction of this scene is not presented as the Autostitch program is unable to identify and match sufficient features between images to estimate the camera motion. This is because a typical image of biological soft tissue contains a limited number of features. This is due to conditions such as free-form tissue deformation, specular highlights and inter-reflecting lighting conditions [136]. The author has been involved in a project attempting to solve some of these challenges in order to improve the generation of fibroscopic panoramas [137], however description of this work is beyond the scope of this thesis.

This entire dual mode surface characterisation is achieved without requiring external manipulation of the robot, as would be necessary to obtain similar results with a traditional laparoscope or endoscope. Additionally, it is achieved with minimum intervention from the operator. These two features demonstrate how the multi-spectral imaging robot can be employed to improve the intraoperative information flow to a surgeon (*Challenge 3*). Additionally, the results verify the ability of the supercontinuum laser source to provide dual mode illumination whilst adhering to the miniaturisation requirements of robotic-assisted MIS tools.

However, as was mentioned at the introduction to this chapter, the experiments carried out with the robot also highlighted the limitations of the fibre image guide based imaging system. Qualitatively, the image quality, resolution and field of view are poor with respect to CCD based devices on the market; a problem which would potentially preclude the use of the device for navigation and exploration. Practically, the system could only be deployed under guidance from an additional laparoscope. In this instance, the onboard white light visualisation would

only be used for targeting and co-registration of the fluorescence data. While such a system might have utility as a ‘stand-alone’ multi-spectral imaging instrument, its overall usefulness for a clinician is somewhat limited.

A second limitation of the fibre bundle is the requirement to restrict the range of motion of the robot joints. This is necessary so as not to go beyond the minimum bending radius of the image guide. Exceeding this radius would result in damage to the individual fibres within the bundle. This in turn would reduce the image quality further. Realistically, the flexible fibre image guide is more suited to a continuum style bending, similar to that exhibited by an endoscope where deflection of the distal tip is achieved as a smooth curve rather than discrete articulating joint units. A solution for increasing the resolution and image quality would be to use a fibre image guide with a larger number of pixels. However, this would have a detrimental effect on the minimum bend radius of the fibres. As the number of pixels in a fibre image guide increases, so too does the minimum bending radius. The next size larger than the 10,000 pixel bundle integrated with the robot is the 30,000 pixel IGN-08/30. This has a bending radius of 40mm which would further reduce the ability of the system to characterise an extended field of view.

3.5 Discussion and Conclusion

The multi-spectral imaging robot has successfully demonstrated its ability to perform robot-assisted white light and fluorescence imaging in a simulated MIS environment. By adhering to the space restrictions prevalent in MIS compatible devices, it demonstrates the feasibility of integrating dual modality imaging with articulated robotic probes. It also illustrates the potential for enhancing the intraoperative information flow to the surgeon by effectively increasing the field of view. Having a flexible robotic device with these imaging and sensing capabilities complements the identified clinical demand outlined in *Challenge 3*. It brings multi-spectral imaging capabilities to an in-situ, in-vivo setting and thus allows for large area, real-time tissue characterisation and functional assessment.

The lessons learnt from the development of the system were quite clear. While it is undoubtedly advantageous to have the ability to perform both white light and fluorescence imaging using the same optical system, the challenges of the limited bending radius, resolution and field of view of the fibre image guide hinders their practical deployment within an articulated robotic platform. Additionally, with the ongoing development of both third party multi-spectral imaging

probes and CCD micro-cameras, the clinical need has shifted towards the requirement for a flexible robotic device compatible with such third party instrumentation. This compatibility may include integration within the device, or allow passage through internal channels in a manner similar to an endoscope.

Improvements are also required in the mechatronic design of the system. Specifically, while the 4-DoF provided by the robot successfully demonstrated the ability to scan over an extended field of view, the dexterity of the device is limited. More degrees of freedom are necessary to perform tasks such as retroflexion or an intra-abdominal exploration. However, simply expanding the current spring loaded, tendon based actuation scheme would take up more of the cross sectional area within the 8.5mm diameter. Such an expansion would also introduce new control challenges due to the tendon path length changes and joint coupling that would occur during actuation.

In conclusion, following the development and testing of the multi-spectral imaging robot, it is clear that while functional, in its current configuration the instrument is not yet ready for clinical deployment as a tool to provide controlled flexibility and increased intraoperative information. It therefore does not fit the overall design goals of the flexible access platform and a new system architecture and design is required to more specifically target the challenges outlined in Chapter 1. To deal with these challenges, while incorporating the lessons learnt from the multi-spectral imaging robot, a modular micromotor driven mechatronic joint was designed. This new design will be described in Chapter 4.

Chapter 4:

Joint Design for a Flexible Access Robot

The previous chapter introduced an articulated robotic device that featured the ability to actuate along curved pathways and to provide multi-modal imaging. However, the system did not meet many of the requirements for a flexible access platform as set out in Chapter 1. This chapter will introduce a modular mechatronic joint design which has been developed to meet these requirements whilst adhering to the principal of maintaining a minimum footprint within the operating theatre. Each degree of freedom within the joint module features a novel hybrid micromotor-tendon actuation scheme. Different modules can be assembled together to create a multiple DoF flexible access robotic device. A 7-DoF version of such a device is presented. This system specifically addresses *Challenge 1* and *Challenge 4* described in Chapter 1 by

providing controlled flexibility along multiple degrees of freedom, the provision of three internal channels through which third party instrumentation may be passed and a minimum footprint within the operating theatre. Detailed analysis of the joint design including tendon path length analysis, backlash compensation techniques and torque transmission characteristics are presented. A system level description of the 7-DoF flexible access platform will also be presented. The key contribution of this chapter is the demonstration of a modular mechatronic joint design that can be used as the building block to create novel multiple degree-of-freedom instruments.

4.1 Design Requirements

The primary aim of any surgical robotic design is to improve a surgeon's ability to perform a given procedure or to enable new procedures to be carried out. Although the flexible access platform is envisaged as a generic flexible device and not procedure specific, for the purpose of establishing a clear set of design requirements and goals, a target clinical application was identified. The procedure selected was a transvaginal tubal ligation as described in [138]. Given the overall vision of the flexible access platform as a low cost, 'focused' robotic device, this procedure provides an ideal initial clinical focus. Specifically:

- The transvaginal approach requires a full retro-flexion within the pelvic cavity to visualise and intervene at the fallopian tubes. Therefore, a high degree of flexibility and stability is required.
- The procedure is relatively minor surgery and can be performed with endoscopically compatible interventional instruments [138]. Such instrumentation can be used to perform the procedure if deployed through the internal channels of the platform.
- The procedure can be carried out under general or local anaesthesia as either an inpatient or an outpatient [139]. Therefore, to provide the flexibility to integrate into different standards of operating theatres, the system should be lightweight and not require large infrastructural support to operate.

In addition to these procedure specific technical requirements, the transvaginal tubal ligation also represents an ideal target application due to the potential patient benefits and the unsuitability of existing instrumentation. From a patient perspective, the procedure is elective and can be carried out via a laparoscopy, mini-laparotomy, standard laparotomy or in a natural

orifice approach via a transvaginal colpotomy. The option of a transvaginal approach offers several advantages due to the lack of external incisions, reduced post-operative pain and rapid convalescence. However, to carry out the procedure from this approach is technically difficult and requires extensive surgical training if performed without special apparatus [140]. The procedure has been attempted using an endoscope to provide the necessary flexibility to visualise the fallopian tubes [138]. However, the authors report that the suitability of the endoscope for the task is limited. Specific problems include difficulties controlling the endoscope due to its inherent flexibility and difficulties controlling instruments passed through the device due to the disorientation induced when operating the endoscope in a retroflexed configuration. A flexible, robotically controlled device would be ideally placed to solve these problems by providing a stable platform through which instruments can be passed. Additionally, a robotic platform could leverage its ‘drive-by-wire’ architecture and software algorithms to improve the overall ergonomics and controllability when compared with the traditional endoscope. Finally, tubal ligation is one of the most commonly performed surgical procedures. In the United States 643,000 cases were performed in 2006 [139] thus offering a significant commercial market for any potential device.

Using transvaginal tubal ligation as the clinical focus, a set of system requirements were derived. These were based on the estimated anatomical requirements, robotic system and dimension requirements, 3rd party instrumentation requirements and theatre requirements. The details of these specifications can be found in Table 4.1 – Table 4.4 respectively. The estimated measurements listed for anatomical requirements Table 4.1 were identified by Dr. James Clark from a series of eight Magnetic Resonance Imaging (MRI) scans of female pelvises. The measurements are used to represent the pelvic volume as a truncated cone where the distance between the right ASIS (Anterior Superior Iliac Spine) and left ASIS represents the diameter of the base (widest part) of the cone (marked *B* in Figure 4.1). The distance between the sacral promontory and the pubis symphysis is considered the pelvic floor and represents the top (narrowest part) of the cone (marked *T* in Figure 4.1). The height of the cone is given by the distance between the pelvic floor and the line joining the ASIS’s (marked *H* in Figure 4.1). The flexible access platform will enter the truncated cone at a point within the area defined by the pelvic floor and should be able to achieve retroflexion within the volumetric constraints of the truncated cone. The approximate locations of these measurements and the anatomical features are shown in Figure 4.1.

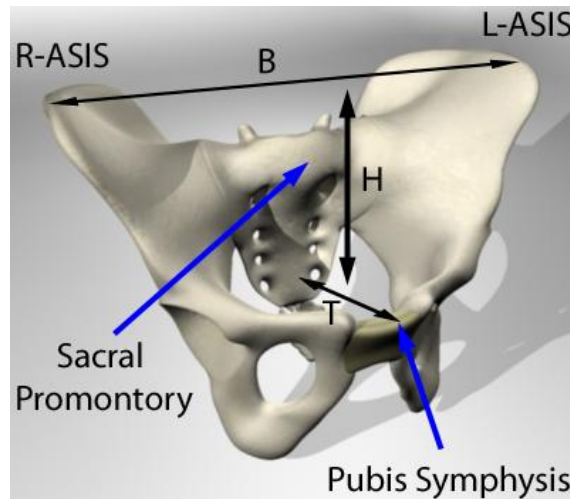


Figure 4.1: Approximate location of the measurements in the pelvis used to define the volumetric constraints for the flexible access platform. The truncated cone is defined by B, H and T. Image Source for 3D model of the pelvis: [141].

Table 4.1: Estimated specifications based on anatomical requirements derived from 8 pelvic MRI images

Constraint	Anatomical Measurement
L-ASIS* to R-ASIS§	$21.7 \pm 0.42\text{cm}$
Diameter of pelvic floor	$9.86 \pm 1.24\text{cm}$
Height of pelvic volume	$8 \pm 1.8\text{cm}$
Position of fallopian tubes in pelvis	Below the sacral promontory bilateral from midline
*L-ASIS: Left-Anterior Superior Iliac Spine	
§R-ASIS: Right-Anterior Superior Iliac Spine	

Table 4.2: System specifications related to robot system and dimensions

Robot and System Dimensions		
Constraint	Design Goal	Reason
Diameter	$<15\text{mm}$	Based on standard trocar ports
Flexibility (individual joints)	$\pm 45^\circ$	To enable large region scanning with individual joints
Flexibility (combined joints)	$>180^\circ$	Based on transvaginal incision and a requirement to approach the fallopian tubes from above
Max diameter of retroflexion	110mm	Based on anatomical dimensions
Length (individual joints)	$\approx 40\text{mm}$	Function of joint flexibility, number of joints required for retroflexion and the anatomical constraints.
Footprint in theatre (robot)	Minimal	Handheld or simple table mounting to seamlessly integrate into surgical workflow

Table 4.3: System specifications related to 3rd party instrumentation

Instrument Dimensions		
Constraint	Design Goal	Reason
Channels required	1 min, 2 ideal	At least one channel is required to pass interventional instrumentation
Channel dimensions	2.8mm min, 3.5mm ideal	Based on standard endoscopic instrument dimensions
Visualisation	Tip mounted camera	So additional laparoscopic instruments are not required
Lighting	Tip mounted illumination	As above

Table 4.4: System specifications based on theatre requirements

Theatre Requirements		
Constraint	Design Goal	Reason
Setup time	<20mins	Standard theatre setup time
Total operative time	<30mins	For transvaginal tubal ligation faster than existing techniques
User interface	Handheld or tele-operated. Single person operable	To provide optimum ergonomic configuration and minimise the number of people in-theatre

Based on these requirements, a mechatronic joint design was developed. The future integration of the design into a multiple degree-of-freedom flexible access platform was considered at all stages of its development to ensure that the design goals are met. This development will be described in the next section.

4.2 Mechatronic Considerations of the Joint Design

The joint design described in this chapter represents the evolution of a novel actuation design that has been refined and improved over the course of the project. While these refinements have altered the physical appearance of the joint, the initial conceptual design has not changed. The proposed solution is to take the core benefits identified during the evaluation of Actuator Technologies carried out in Chapter 2 and to combine them in an architecture tailored to the requirements of the flexible access platform. The resulting actuation scheme is a hybrid system which combines brushless DC micro-motors with a pre-tensioned tendon drive mechanism. In the proposed configuration each robot link would house an embedded brushless DC micro-

motor which transmits rotary motion to the joint via a short pre-tensioned tendon transmission stage. The rotary motion is converted to joint rotation through the use of a ‘ring gear’ transmission element. The system is analogous to a biological muscle actuation system where the DC motor is the muscle and the mechanical tendon is the biological tendon which connects the muscle to the actuating bone.



Figure 4.2: CAD schematic illustrating the key elements of the conceptual design utilising the hybrid micromotor-tendon actuation scheme.

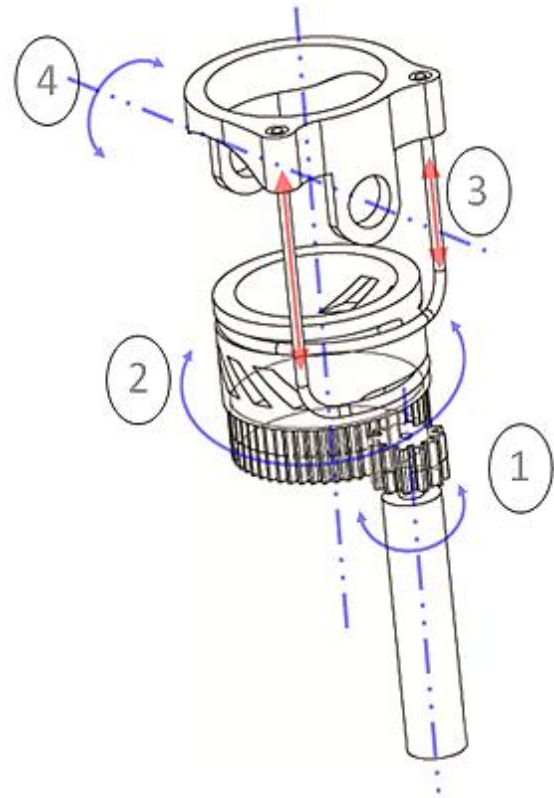


Figure 4.3: CAD schematic illustrating the axes of rotation for the hybrid micromotor-tendon actuation scheme.

The conversion from rotary motion at the motor output shaft to joint rotation at the rotatable stage is illustrated in Figure 4.2 and Figure 4.3. Its operation for anti-clockwise rotation of the motor is outlined below:

- **Step 1:** The brushless DC micro-motor, marked ‘1’, rotates anti-clockwise;
- **Step 2:** The micro-motor rotation causes rotation of the ‘ring gear’, marked ‘2’, clockwise. The upper external surface of the ‘ring gear’ acts like a capstan around which a pre-tensioned tendon is wound;
- **Step 3:** As the ‘ring gear’ rotates clockwise the tendon marked ‘3’ pulls down, and exerts a turning force on its fixation point, which is located on the joint's rotatable stage;

- **Step 4:** The moment exerted by the tendon pulling down on the rotatable stage causes the stage to rotate about the axis marked '4' in Figure 4.3.

The advantages of using this hybrid transmission mechanism include:

- Each link can be developed as a separate stand alone module with a motor(s), tendons, internal channels and electrical connections;
- By actuating the tendons locally within each link they will not be subject to long transmission routes or joint coupling as the robot changes orientation;
- The design can be implemented with the module having a single degree of freedom (pitch or yaw) or can be expanded and implemented with two degrees of freedom (pitch and yaw). These degree of freedom would be located at opposite ends of the module;
- Each degree of freedom can be independently addressable;
- Using the tendon transmission is a space efficient method of converting the rotary motion of the motor into a linear motion at the point of connection to the joint frame. It means that the motor or gears do not need to be placed directly at the joint, as would be required in a direct drive system (for example a worm gear and wheel as shown in [88]). Instead, the motor can be located back down the link, where space is more available;
- The placement of the motor away from the rotating axis results in a large free volume between the actuating members of individual degrees of freedom. This is important for ensuring that sufficient cross-sectional area remains available for the internal channels to pass instruments as the joint rotates through its range of motion;
- With careful design and pretension the tendons can be used to achieve low friction transmission and torque amplification. This will be demonstrated in Section 4.4.

There are however some disadvantages of employing such an actuation scheme. The main problem is that of the small torque developed by the micromotors. As a consequence of this, the overall link mass must be as low as possible, friction must be rigorously reduced where possible and additional gearing incorporated where space allows.

A prototype one degree-of-freedom joint module was constructed as a proof-of-concept for the actuation scheme and is shown in Figure 4.4 below. The prototype features an 'external ring

gear’ in which the ring gear and tendon run around the outside of a large central channel. The tendon runs from the surface of the ring gear to the tendon fixation points via two idler pulleys.

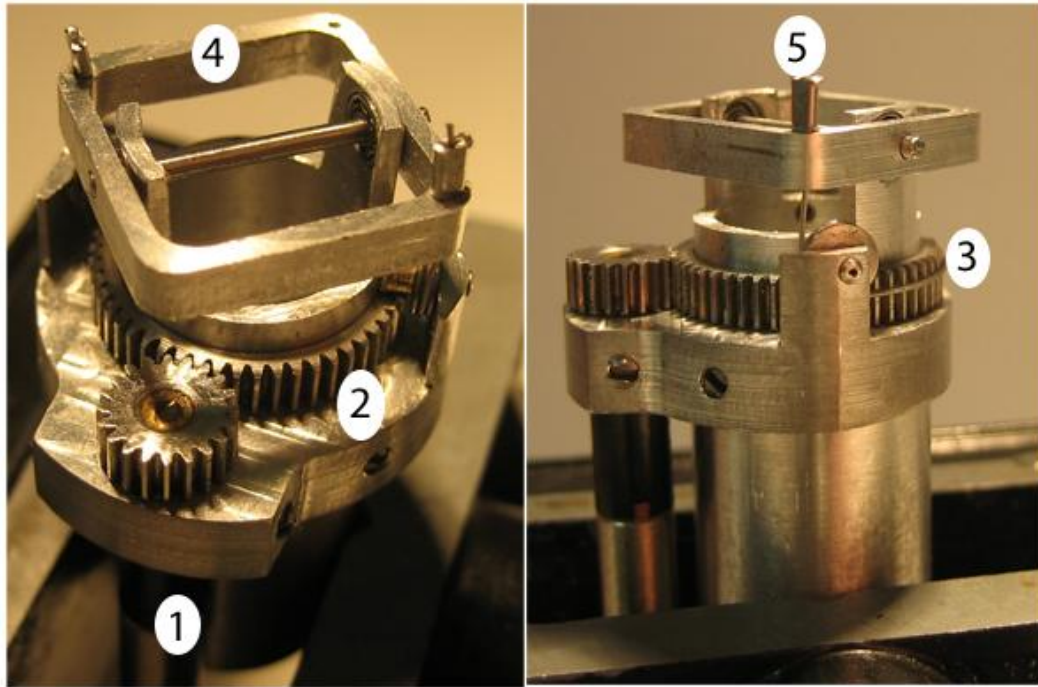


Figure 4.4: Images of the first joint prototype featuring the proposed hybrid actuation scheme. The core elements of motor (1), ring gear (2), tendon (3), rotatable frame (4) and tendon fixation point (5) are marked.

Over the course of this project five different joint designs were developed and implemented into the different versions of the flexible access platform. The changes made at each design iteration reflect the lessons learnt from the practical deployment of the system in laboratory and in-vivo tests. These changes were carried out in collaboration with Dr. Jianzhong Shang of the Hamlyn Centre. The details of these changes and how the flexible access platform performed with the different design iterations can be found in Appendix II. However, the overall conceptual architecture of a hybrid micromotor-tendon actuation scheme remained consistent throughout all designs. The next section will describe the fifth and final iteration of the joint design. This design was integrated into a 7-DoF flexible access platform and used for the in-vivo case studies presented in Chapter 7 of this thesis.

4.3 Joint Design Prototype

The conceptual actuation scheme introduced in Section 4.2 was constantly refined in order to address the requirements of dexterity, modularity and functionality as defined in Table 4.2 and

Table 4.3. In its final configuration, the proposed mechatronic joint design has the following key features:

Table 4.5: Key features of the mechatronic joint design

Feature	2-DoF Module	1-DoF Module
Outer diameter	12.5mm	12.5mm
Total length	43mm	34mm
Weight	10.1g	7.1g
Degrees of freedom	2	1
Range of motion	$\pm 45^\circ$ per DoF	$\pm 45^\circ$ per DoF
Modular	Yes	Yes
Channel 1	1×3.5mm; (instruments)	1×3.5mm; (instruments)
Channel 2	1×3.0mm; (camera and illumination)	1×3.0mm; (camera and illumination)
Channel 3	1×1.8mm; (motor power & signal)	1×1.8mm; (motor power & signal)

A CAD schematic of the joint module is shown in Figure 4.5 below. Figure 4.6 shows the module from the same perspective except that the aluminium body has been rendered transparent. This allows more of the internal components to be visualised. Conceptually the design is identical to that shown in Figure 4.4 with the exception that instead of the ‘ring-gear’ having teeth on its external surface (an ‘external ring gear’), the teeth are located on its inner surface (an ‘internal ring gear’). Consequently the micromotor is now located inside the ‘ring-gear’ and the gear itself sits inside the joint body. This change was implemented for the dual benefits of protecting the actuating elements (i.e. motor, pinion gear and ‘ring-gear’) inside the joint body and providing a smooth external surface. This joint module design can be easily modified to provide a single DoF (pitch or yaw) through the removal of a motor and the actuation elements at one end of the module.

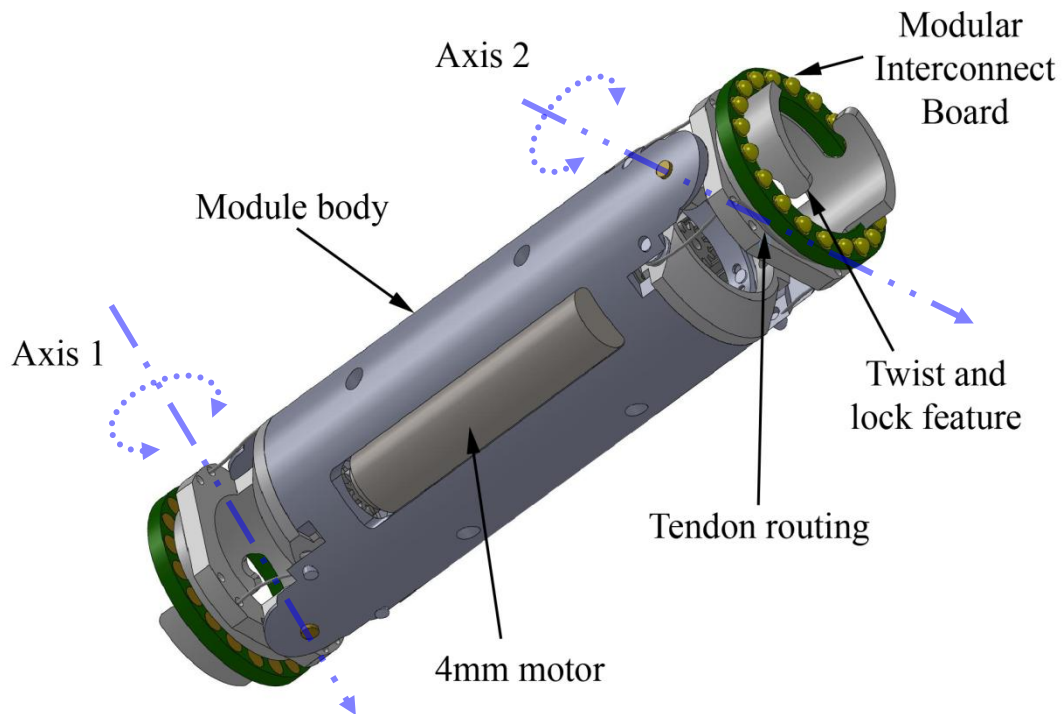


Figure 4.5: CAD schematic illustrating a 2-DoF joint module which features two orthogonal degrees of freedom at opposite ends of the joint segment. Actuation is achieved via a hybrid “micromotor-tendon” transmission scheme and the module contains three internal channels ($1 \times 3.5\text{mm}$, $1 \times 3\text{mm}$, $1 \times 1.8\text{mm}$). The module can be integrated as shown (with 2-DoF) or as a single DoF module with one of the DoFs removed.

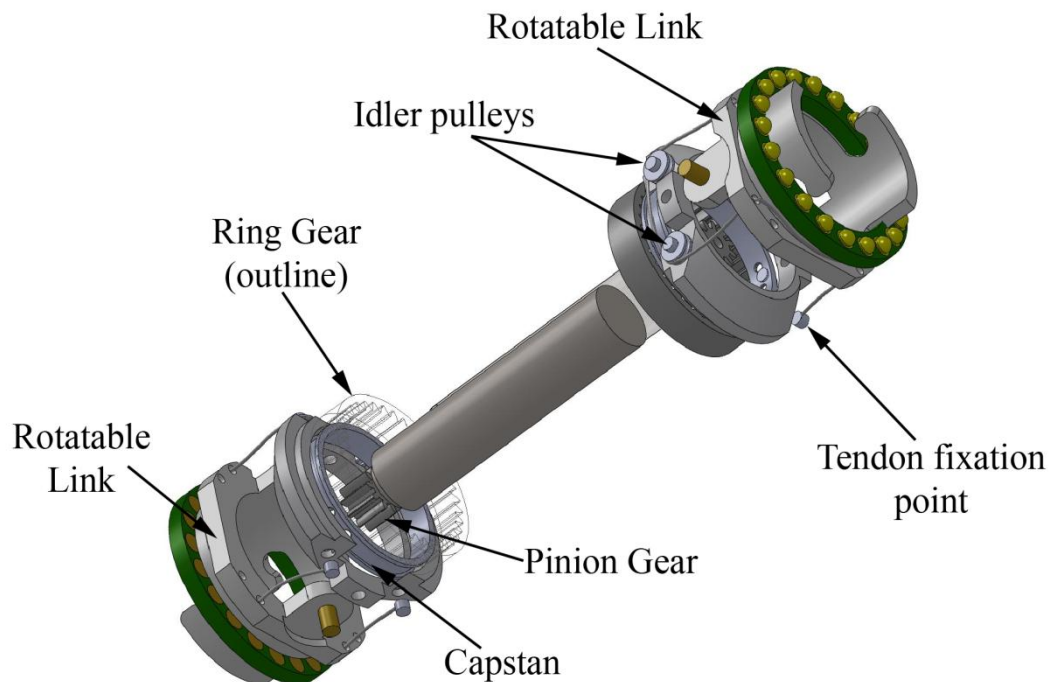


Figure 4.6: CAD schematic identical to that shown in Figure 4.5 but with the aluminium body of the joint rendered transparent so that the internal components can be visualised

Given the limited torque available from the embedded micromotor, significant effort was made to reduce the losses due to friction between moving parts, to reduce the overall weight and to reduce the module length. The negative effects of friction were addressed through the use of an array of micro ball bearings (diameter 0.5mm) placed between the ring gear and the inner wall of the module housing. To stop the ring gear translating axially, a stopper component was manufactured from Polyether Ether Ketone (PEEK) which is lightweight and self-lubricating. The modular interconnect board and rotatable link were also manufactured from PEEK. Aluminium was used as the housing of each module and SpectraFibre™ was used as the tendon owing to its small radius of curvature and high-strength properties. Both gears were manufactured from stainless steel and the pinion gear features a module of 0.25, 10 teeth and a Pitch Circle Diameter (PCD) of 2.5mm. The ring gear features an identical module, 36 teeth and a PCD of 9mm. When attempting to shorten the overall module length, the motor (20.4mm from base to top of output shaft) was the primary restricting factor. Additionally, from a design perspective it is necessary to ensure that sufficient clearance exists to pass instrumentation through the internal channel(s) when at the maximum angle of displacement (i.e. $+45^\circ$ or -45°).

An example of a real implementation of a single DoF module is shown in Figure 4.7. The individual elements of the module design, including actuation, motor electrical wiring, modularity and position feedback will now be described in greater detail.

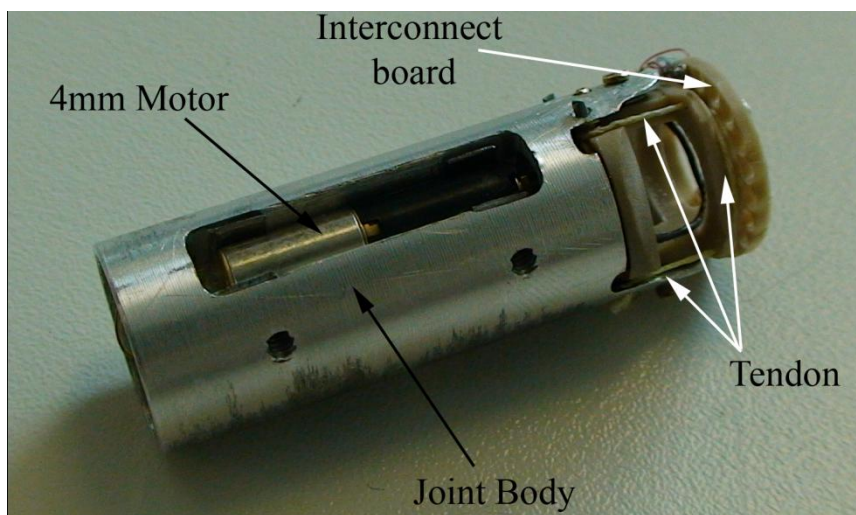


Figure 4.7: A single degree-of-freedom joint module. The embedded 4mm motor, the joint body, tendon routing and the interconnection board can be clearly seen.

4.3.1 Actuation

Actuation of each degree of freedom is achieved via a 4mm brushless DC motor (SBL04-0829, Namiki Precision Jewel Ltd, Japan) which outputs 5.7mNm of torque via a 337:1 planetary gearbox (PG04-337). As shown in Figure 4.6, a pinion on the motor output shaft drives a ball raced ‘internal ring gear’ onto which a capstan is attached. The tendon (SpectraFibre™, Honeywell International Inc) is wrapped around the capstan for one complete rotation and fixed at one point. The two free ends of the tendon then pass over idler pulleys (brass, diameter 2.25mm) before running to the rotatable link of the joint module. The tendons then pass around the edge of this link before returning to the joint segment where they are terminated. In this configuration, the tendons act as an antagonistic pair such that when the ring gear and capstan rotate in one direction, the tendon on one side is pulled in while the tendon on the other side is reeled out. The pulling motion of the tendon serves to apply a moment about the joint axis and thus causes joint rotation. By routing the tendons in this manner, the effective torque of the design shown in Figure 4.5 is doubled when compared to the tendon routing shown in Figure 4.4. This is because the tendon is now pulling on the rotatable link from two locations. This torque amplification feature is important due to the small torque provided by the micromotors and will be discussed in greater detail in Section 4.4. Schematic diagrams of the module design with key dimensions can be found in Appendix II.

4.3.2 Motor Electrical Wiring

One of the integration challenges when designing the joint module was how to connect the power and signal lines of each micromotor to their respective drive electronics units. Due to size restrictions within the joint module these drive electronics units are located remotely in a Motor Control Box, which will be described in Section 4.6. Each motor requires four connections (phases U, V, W and Common, see Appendix II) and needs to be connected to a 3-phase sensorless drive circuit (SSD04, Namiki Precision Jewel Ltd). A standard SBL04-0829 motor features a short Flexible Printed Circuit (FPC) which connects to the SSD04 via a Zero Insertion Force (ZIF) tab. The length and width of this FPC preclude its placement within the joint module. In order to facilitate a fully integrated wiring architecture, a customised version of the SBL04-0829 was developed in conjunction with Namiki. In this customized version, the FPC is replaced by a flexible, 0.5mm diameter, 2m long, 4-core wire. Given the cross sectional area of the wire it is possible to fit approximately 9 inside the 1.8mm channel of the joint module and thus control 9 motors without additional circuitry. Naturally, if multiple joint modules are

connected sequentially the number of wires passing through the proximal module(s) will be greater than the number of wires passing through the distal module(s).

4.3.3 Modularity Considerations

While it would be possible to hardwire each motor directly to the drive electronics by threading multiple 4-core wires through the 1.8mm channel, such approach would not allow adjacent joint modules to be linked up in a modular manner. To address this requirement, the rotatable link on each end of the module features a custom ‘twist and lock’ interconnection board. This board features a circular array of spring loaded contact pins (PD8JS-2.1, Coda Systems Ltd) which allow electrical connections to be made between adjacent joint segments. Using this architecture, the electrical connections between the drive circuits and motors are carried over 4-core wires when inside the joint modules and through the contact pins when passing between adjacent joint modules. Three contact pins (and one ground pin common to all motors) are required for each motor and so a limit exists on the total number of motors that can be supported in this manner. The current configuration, with the contact pins listed above, can support up to seven motors within a 12.5mm outer diameter. A CAD model of the modular interconnect can be seen in Figure 4.6 and a real implementation can be seen in Figure 4.7. This figure shows an example of a 1-DoF module designed to be connected as the distal module of the flexible access platform.

4.3.4 Position Feedback

A significant design challenge addressed when developing the joint design was that of how to measure the angular displacement of each degree of freedom given the space and wiring restrictions inside the joint module. In the final design this position feedback is provided by a miniature potentiometer (3203X103P, Tyco Electronics) mounted on the joint axle, as can be seen in Figure 4.8. In order to measure a rotation of the joint along its axis, the outer casing of the potentiometer is fixed to the housing while the inner rotating wiper of the potentiometer is fixed to the joint axle. Therefore as the joint rotates, the axle causes the wiper to rotate and the resistance of the potentiometer is changed. By measuring this resistance the angular displacement of the joint can be calculated. This particular mounting configuration is advantageous as it provides direct ‘on-axis’ position readings and thus is not susceptible to any backlash introduced by the gearbox or the tendon transmission stage. The advantages of the sensor when compared to other sensing techniques include the following:

- Small footprint: The small volume of the sensor ($3.4\text{mm} \times 3.4\text{mm} \times 2\text{mm}$) allows for integration inside the joint module;
- No additional circuitry is required: Potentiometers are stand-alone electrical components and do not require additional circuitry which would take up space within the joint unit;
- Efficient wiring architecture: Power and Ground lines can be common for multiple sensors which means that only one signal line is required per joint axis;
- Modularity: The power and signal lines for the potentiometer are compatible with the modular architecture of the module design.

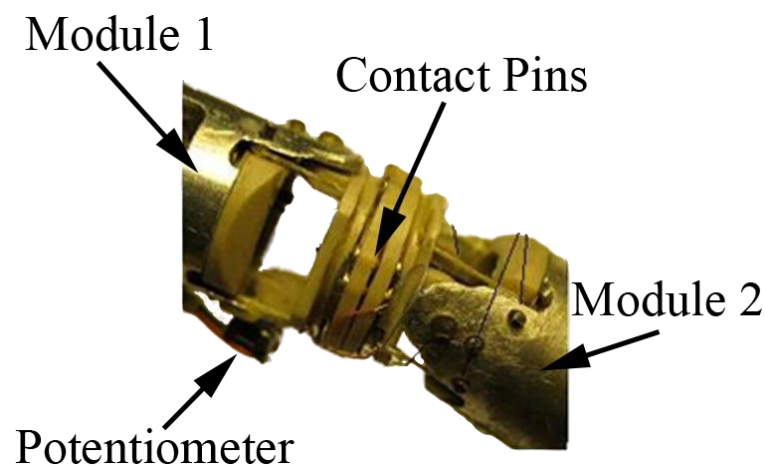


Figure 4.8: Image of two connected joint modules with orthogonal axes of rotation. The potentiometer used for position sensing can be seen. The modular interconnect and some contact pins can be clearly identified.

The potentiometer shown in Figure 4.8 was fitted to the joint module after the module was constructed. As a result it is located on the outside of the module housing. However, sufficient space does exist to integrate the potentiometer inside the module.

It is worth noting that the joint position feedback from the potentiometers was not used during the experiments carried out for this thesis. However, they have been integrated into the flexible access platform *Version_4* and an assessment of the repeatability of this position feedback mechanism is outlined in Appendix III. The system is currently being used as a test-bed by other researchers and preliminary closed loop control algorithms have already been implemented [142]. The implications for the use of closed loop position feedback control with the platform will be further discussed in Chapter 8.

4.3.5 Module Design Iterations

The joint module design introduced in Section 4.3 is the result of multiple design iterations which took place during this project. At each iteration a new flexible access platform was constructed. Five versions of the platform were constructed in total and their technical differences are documented in Appendix II. The design iterations were driven by technical and clinician feedback from both laboratory and in-vivo trials, and the module design changed three times during this process. A list of the key differences in the module iterations can be found in Table 4.6 and technical schematics can be found in Appendix II.

Table 4.6: Key differences in joint characteristics between design iterations

Platform Version	Diameter (mm)	Channel(s) diameter (mm)	Range of motion (°)	Axis to Axis Length (mm)	Motor Wiring	Modular Interconnect
<i>Version_1</i>	11	1×2.5	±30°	42	External FPC	No
<i>Version_2</i>	11	1×2.5	±30°	42	Integrated	No
<i>Version_3</i>	12.5	1×1.8 2×3.0	±30°	40	Integrated	No
<i>Version_4</i>	12.5	1×1.8 2×3.0	±45°	35	Integrated	Yes
<i>Version_5</i>	12.5	1×1.8 1×3.0 1×3.5	±45°	35	Integrated	Yes

The joint module design introduced in this section addresses many of the requirements of the flexible access platform. It provides a building block for constructing multiple degree-of-freedom robotic devices which are capable of actuating along curved pathways. It also allows for the passage of minor interventional instruments and imaging probes. Placement of the motor away from the rotating link within the body of the module provides a large unrestricted space between the capstan and the rotatable link which is important to allow the passage of instrumentation through the joint when at extreme angles of rotation. Additionally, the use of

an embedded actuation scheme means that no external actuation components are required. The next section will present an engineering analysis of the joint module.

4.4 Joint Analysis

A limitation of the joint module design presented in Section 4.3 is the presence of backlash introduced because the tendon paths on each side of the joint unit (between the pulley and the rotatable link) do not add up to a constant path length as the joint rotates. This manifests itself as a slackening on the side that is not driving the joint rotation thus causing backlash. To demonstrate the effect of this backlash, two iterations of the joint module design introduced in Section 4.3 have been analysed. The first iteration of the design highlights the negative effects of this backlash. The second iteration presents a method for compensating for the change in tendon path length and reducing the backlash. An additional advantage of this iteration is that its tendon routing also amplifies the joint torque. This second design iteration is the implementation used in flexible access platform Version_5 and shown in Figure 4.2. Geometric and schematic representations of the two design iterations were developed in order to aid the derivation of equations necessary to carry out this analysis. A simplified schematic representation of Design Iteration 1 (DI_1) joint is shown in Figure 4.9. In this iteration the tendon terminates on the rotatable link.

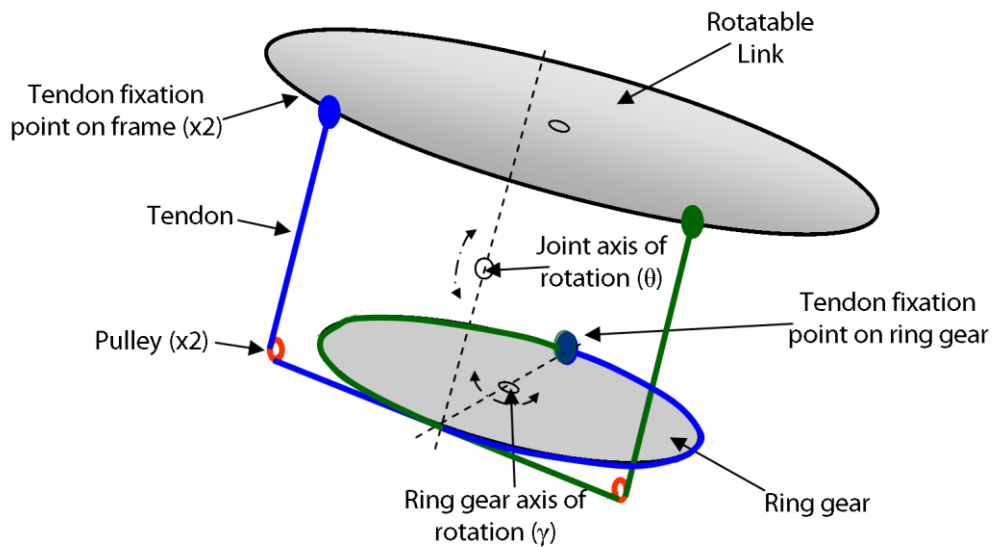


Figure 4.9: Schematic illustrating the key components used for joint analysis. The tendon path is shown in blue and green with the transition between colours taking place at the tendon fixation point on the ring gear. The two primary parameters of γ and θ , which represent the rotation of the ring gear and the rotatable link respectively are shown set equal to 0° .

4.4.1 Tendon Path Length Analysis - Design Iteration 1

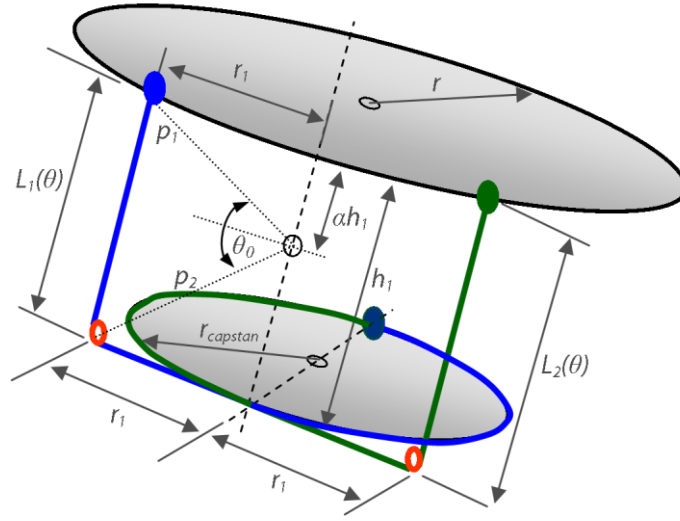


Figure 4.10: Schematic illustrating the constants and variables used to calculate the lengths L_1 and L_2 for Design Iteration 1

Figure 4.10 shows a schematic with the key variables required to calculate the variation in tendon lengths between the pulley and the rotatable link (i.e. lengths L_1 and L_2). From Figure 4.10 the following relationships can be defined:

$$p_1 = \sqrt{(\alpha h_1)^2 + r_1^2} \quad (4-1)$$

$$p_2 = \sqrt{h_1^2(1-\alpha)^2 - r_1^2} \quad (4-2)$$

$$\theta_0 = \cos^{-1} \left(\frac{p_1^2 + p_2^2 - h_1^2}{2p_1p_2} \right) \quad (4-3)$$

Where $2r_1$ is the distance between the tendon fixation points on the rotatable link (7.6mm), h_1 is the distance between the plane of the ring gear and the plane of the tendon fixation points on the rotatable link (6.4mm) and α represents the fraction of the total length h_1 which defines the distance between the joint axis of rotation and the plane of the tendon fixation points ($\alpha = 0.39$). For a given clockwise rotation of the joint, θ , where $\theta > 0^\circ$, the lengths of tendons connecting the rotatable link to the pulleys L_1 and L_2 vary according to:

$$L_1(\theta) = \sqrt{p_1^2 + p_2^2 - 2p_1p_2 \cos(\theta_0 + \theta)} \quad (4-4)$$

$$L_2(\theta) = \sqrt{p_1^2 + p_2^2 - 2p_1p_2 \cos(\theta_0 - \theta)} \quad (4-5)$$

Given these parameters, it is possible to calculate the variation in tendon path length as the joint unit rotates. Figure 4.11 illustrates how the tendons move as this rotation occurs and depicts the variables required to calculate the change in tendon path length from the tendon fixation point on the ring gear to the pulleys (i.e. s_1 and s_2).

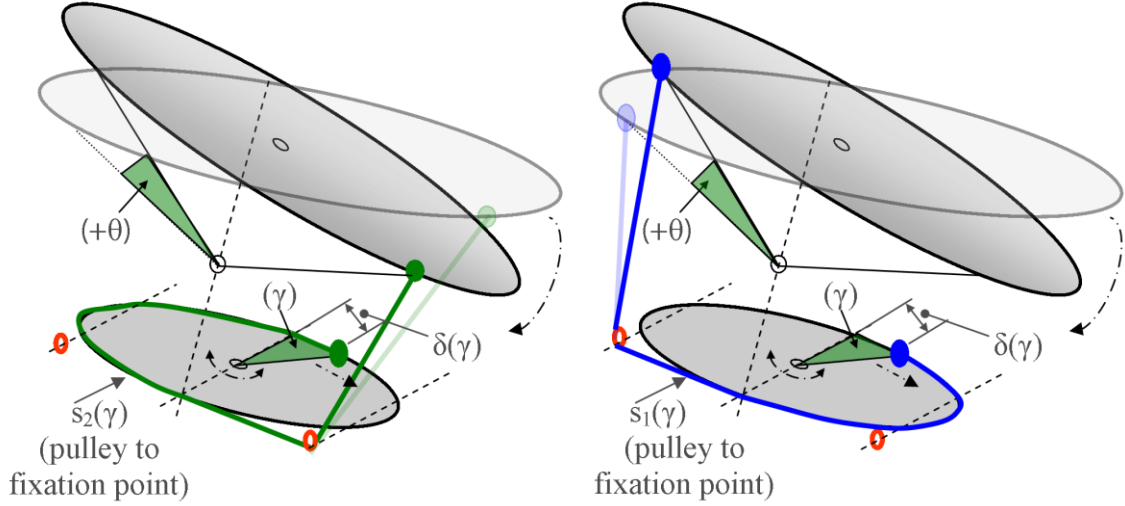


Figure 4.11: (left) Schematic illustrating the path of the driving tendon during clockwise rotation for $\theta > 0^\circ$ (right) Schematic illustrating the path of the driving tendon during anti-clockwise rotation of the joint unit for $\theta < 0^\circ$

As can be seen in Figure 4.11, for a clockwise rotation of the joint ($\theta > 0^\circ$), as the ring gear rotates with an angular displacement, γ , the lengths of the tendons connecting the pulleys to the fixation point on the ring gear, s_1 and s_2 , vary according to:

$$s_1 = r_1 + r_{capstan}(\pi - \gamma) \quad (4 - 6)$$

$$s_2 = r_1 + r_{capstan}(\pi + \gamma) \quad (4 - 7)$$

Where $r_{capstan}$ is the radius of the capstan (4.45mm). When the ring gear is driving the joint module and the link is rotating, the driving tendon is under tension and does not change its physical length. For example, when the link is rotating clockwise, the right tendon (length $L_2 + s_2$) is driving the joint (see Figure 4.11 (left)) and the variation of L_2 is by definition equal to the variation in s_2 ($\Delta L_2 + \Delta s_2 = 0$). Therefore, for clockwise rotations of the rotatable link where $0^\circ < \theta < 45^\circ$ the relationship between the angular displacement of the ring gear, γ , and the angular displacement of the rotatable link, θ , is defined by the geometry specified in Figure 4.10 and Figure 4.11 and is given by:

$$\gamma(\theta) = \left(\frac{L_{2_0} - L_2(\theta) + s_{2_0} - r_1}{r_{capstan}} \right) - \pi \quad (4 - 8)$$

Where L_{2_0} is the value of L_2 when $\theta = 0^\circ$ and s_{2_0} is the value of s_2 when $\theta = 0^\circ$. As the ring gear rotates anti-clockwise back towards 0° , the left hand tendon becomes the driving tendon and therefore ($\Delta L_1 + \Delta S_1 = 0$). This allows a new relationship between γ and θ for anti-clockwise rotations of the ring gear (where $0^\circ < \theta < 45^\circ$) to be defined as:

$$\gamma(\theta) = \pi - \left(\frac{L_{1_0} - L_1(\theta) + s_{1_0} - r_1}{r_{capstan}} \right) \quad (4 - 9)$$

Similarly, L_{1_0} is the value of L_1 when $\theta = 0^\circ$ and s_{1_0} is the value of s_1 when $\theta = 0^\circ$.

The tendon path length variations, as a result of a clockwise rotation between 0° and 45° followed by an anti-clockwise rotation between 45° and 0° , are shown in Figure 4.12 with respect to the angular displacement of the ring gear, γ . In Figure 4.13 the same rotation is shown with respect to the angular displacement of the rotatable link, θ . Figure 4.12 clearly demonstrates that while the ‘driving tendon’ does not undergo any change in path length as the joint rotates, the ‘non-driving’ tendon does undergo a variation. Since the tendon used when constructing the joint unit is of a finite length, it must be at least as long as the longest path length for all possible angular displacements of the joint. Therefore backlash will occur when the ring gear changes its direction of rotation until the path length variation of the tendon has been recovered and the tendon is in tension. This can be seen in Figure 4.13 at the transition between directions of rotation at 45° . Here, the tendon must recover the change in length before θ will change and the link rotates.

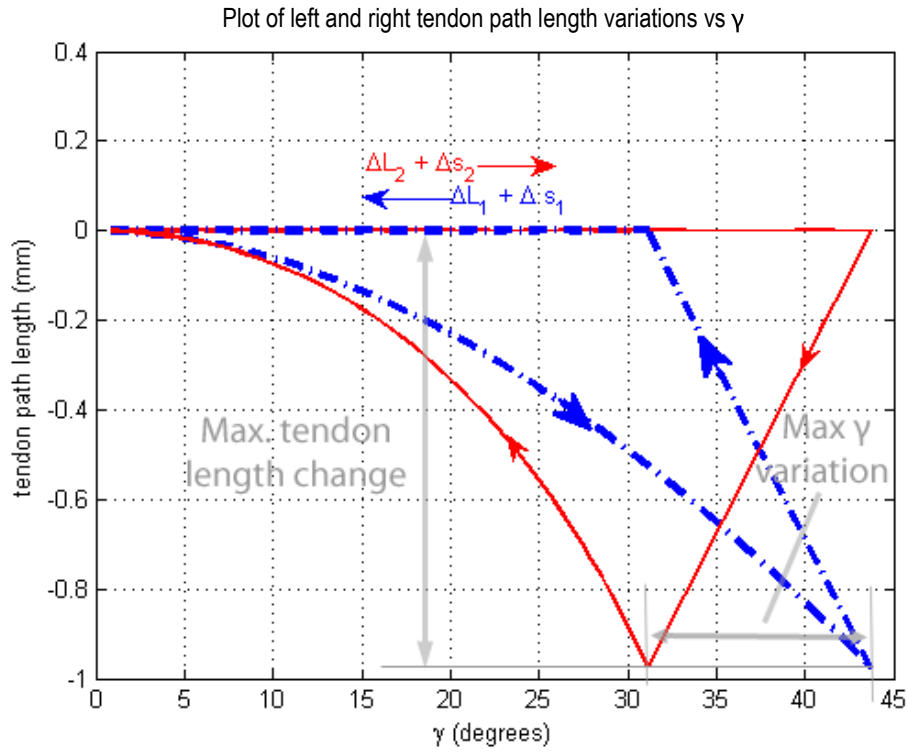


Figure 4.12: Tendon path length variations plotted with respect to ring gear rotation. The maximum change in tendon length and the region of rotation where maximum backlash occurs are marked.

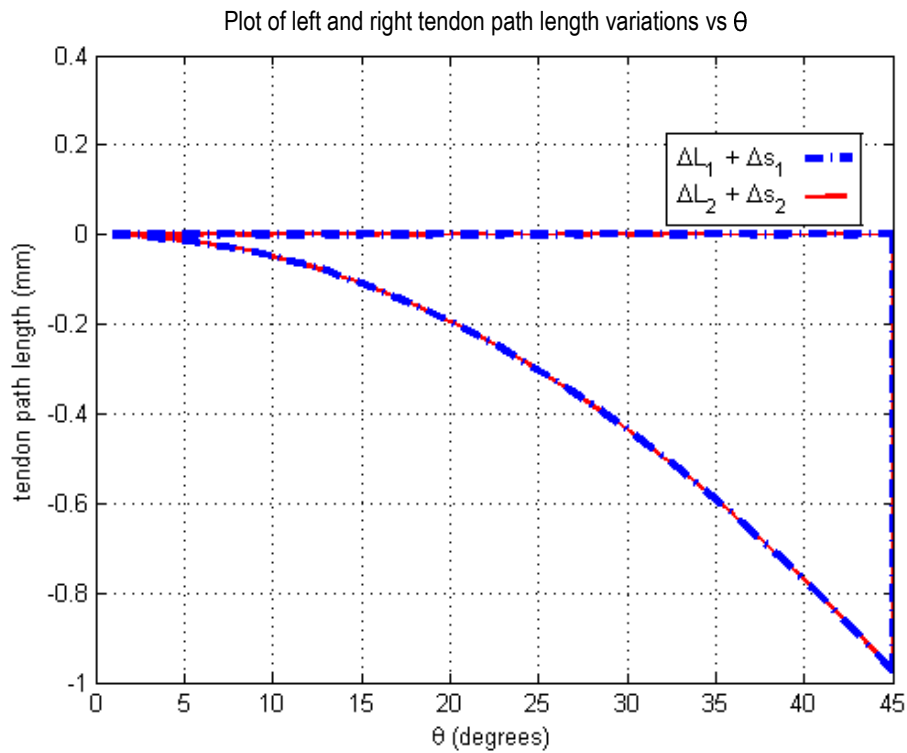


Figure 4.13: Plot of left and right tendon path length variations with respect to theta. The backlash zone, where the tendon path lengths are changing but theta is not can be seen at $\theta=45^\circ$

From these plots the maximum variation in tendon path length can be measured as 0.97mm. This corresponds to a maximum backlash for the ring gear rotation (γ) of 12.55°. Plotting γ against θ allows the maximum backlash of the joint unit to be calculated. This value is 14° at $\theta = 45^\circ$. Given the proposed application area of the joint module, such a large backlash would potentially preclude its use on safety grounds. In particular, the cumulative error that would result with multiple joint modules connected together would be significant. The next section will show *Design Iteration 2* which incorporates a compensation scheme for reducing the effect of this path length variation while simultaneously amplifying the torque applied to the joint by a factor of approximately two.

Note: A similar set of derivations can be calculated for joint rotations for $0^\circ > \theta > -45^\circ$.

4.4.2 Tendon Path Length Analysis – *Design Iteration 2*

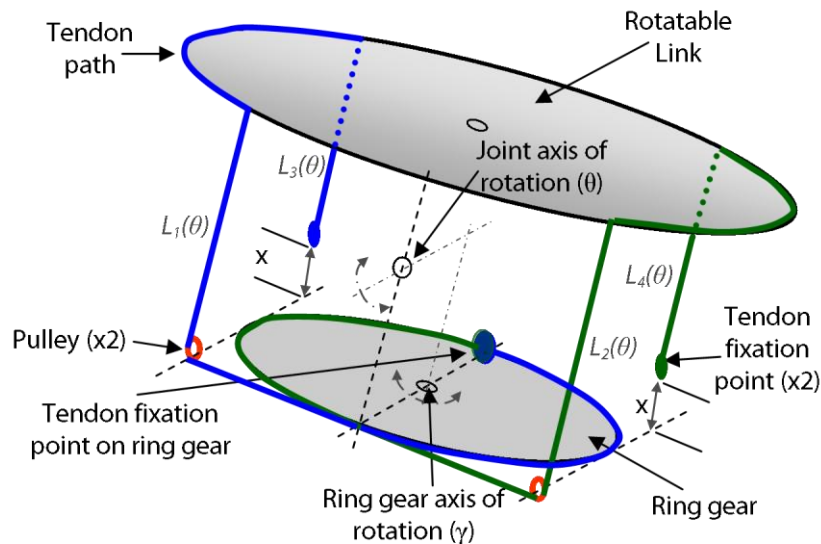


Figure 4.14: *Design Iteration 2* illustrating the enhanced tendon routing method whereby the tendon passes around the edge of the rotatable link and then passes down to a fixation point on the joint body. This fixation point is displaced a distance x from the pulley axis of rotation. This displacement allows for some of the changes in tendon path length to be compensated.

In Figure 4.10 the tendon can be clearly seen terminating on the edge of the rotatable link. However, an alternative tendon routing scheme involves passing the tendon around the edge of the rotatable link and back down to the frame of the joint body. This provides two advantages over simply terminating the tendon on the edge of the rotatable link:

- The position of the tendon termination point on the frame can be optimised to minimise the overall variation in tendon path length as the joint rotates. This can be seen by the tendon displacement x in Figure 4.14.
- The output force applied by the ring gear, F_{outs} is effectively doubled since there are now two tendons applying a moment about the joint axis of rotation. This output force will be further discussed in Section 4.4.3.

Moving the tendon fixation point from the rotatable link back to the main body of the module housing provides a new parameter, x , which represents a displacement of the tendon fixation point off the axis of rotation of the idler pulleys. This displacement is along the path of the tendon when $\theta = 0^\circ$. By adjusting x it is possible to compensate for some of the changes in L_1 and L_2 with two new tendon segments, L_3 and L_4 . The geometric relationship between each of these parameters is shown in Figure 4.15. The parameters required to calculate the length of L_1 and L_2 are shown in Figure 4.15 (left) while Figure 4.15 (right) illustrates the parameters required to calculate the length of L_3 and L_4 .

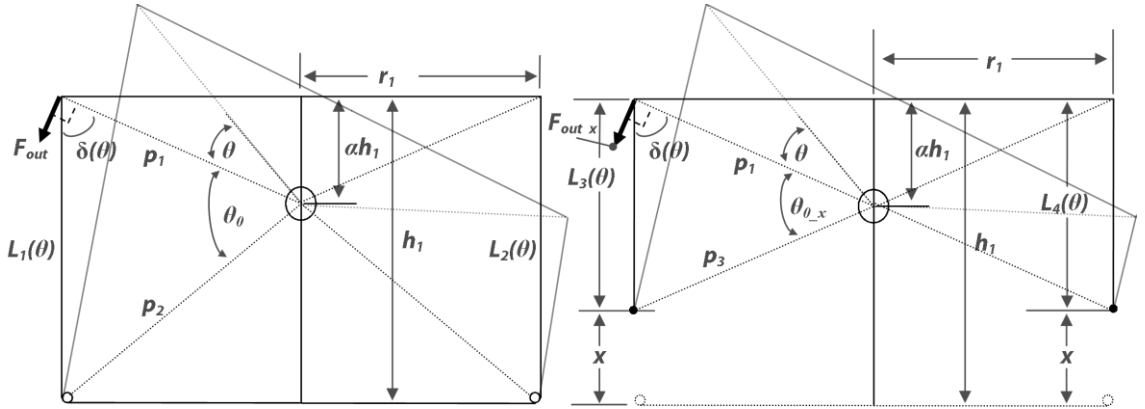


Figure 4.15: Schematic representation of the joint illustrating the parameters required to calculate the variation in tendon length for (left) tendon segments L_1 and L_2 and (right) tendon segments L_3 and L_4 . The variables used to calculate the resolved output force are also shown.

When calculating the new variation in overall path length, the values previously calculated for L_1, L_2, s_1 and s_2 do not change. However, although previously when the driving tendon was under tension for clockwise rotation of the joint (given $\theta > 0^\circ$), the relationship ($\Delta L_2 + \Delta S_2 = 0$) was true. This relationship is now replaced by ($\Delta L_2 + \Delta S_2 + \Delta L_4 = 0$). From Figure 4.15 the following values can be defined:

$$p_3 = \sqrt{r_1^2 + [h_1(1 - \alpha) - x]^2} \quad (4 - 10)$$

$$\theta_{0_x} = \cos^{-1} \left(\frac{p_1^2 + p_3^2 - (h_1 - x)^2}{2p_1p_3} \right) \quad (4 - 11)$$

$$L_3(\theta) = \sqrt{p_1^2 + p_3^2 - 2p_1p_3 \cos(\theta_{0_x} + \theta)} \quad (4 - 12)$$

$$L_4(\theta) = \sqrt{p_1^2 + p_3^2 - 2p_1p_3 \cos(\theta_{0_x} - \theta)} \quad (4 - 13)$$

This results in a new relationship between the angle of rotation of the ring gear, γ , and the rotatable link, θ , for clockwise rotation between 0° and 45° as:

$$\gamma(\theta) = \left(\frac{L_{4_0} - L_4(\theta) + L_{2_0} - L_2(\theta) + s_{2_0} - r_1}{r_g} \right) - \pi \quad (4 - 14)$$

Where L_{4_0} is the length of L_4 when $\theta = 0^\circ$. Similarly, for anti-clockwise rotations between 0° and 45° where $(\Delta L_1 + \Delta S_1 + \Delta L_3 = 0)$, the relationship is given by:

$$\gamma(\theta) = \pi - \left(\frac{L_{3_0} - L_3(\theta) + L_{1_0} - L_1(\theta) + s_{1_0} - r_1}{r_g} \right) \quad (4 - 15)$$

Where L_{3_0} is the length of L_3 when $\theta = 0^\circ$. The resulting plot of $(\Delta L_2 + \Delta S_2 + \Delta L_4)$ with respect to γ and $(\Delta L_1 + \Delta S_1 + \Delta L_3)$ with respect to γ is shown in Figure 4.16.

The plot clearly illustrates that the maximum variation in path length has been reduced from 0.97mm to 0.63mm. This is due to the fact that the new tendon lengths L_3 and L_4 are varying in opposition to L_1 and L_2 . The variable x may be adjusted in order to match this compensatory effect with the aim to reduce the cumulative variation in tendon path lengths as much as possible. The value of x is set to 2.85mm for the plot shown in Figure 4.16. Additionally, the plot clearly shows that as the effective tendon path length increases, the range of motion of the ring gear also increases. The ring gear, γ , must now rotate through approximately 66° so that θ will rotate through 45° . Figure 4.17 illustrates the variation in tendon length with respect to θ and it can be seen that the maximum backlash experienced by the joint unit now occurs when $\theta = 43^\circ$.

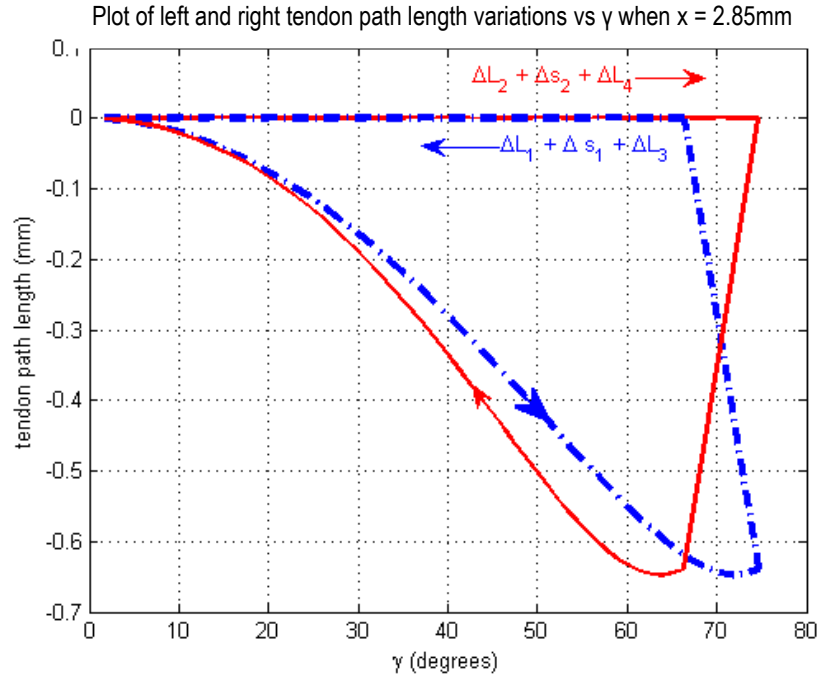


Figure 4.16: Plot of tendon path length variations for both clockwise and anti-clockwise rotations of the joint unit with respect to the ring gear rotation, γ , when tendons L_3 and L_4 are incorporated. The position of the fixation point on the frame is set $x = 2.85\text{mm}$ in order to compensate for the variation in length of L_1 and L_2 as the joint unit rotates.

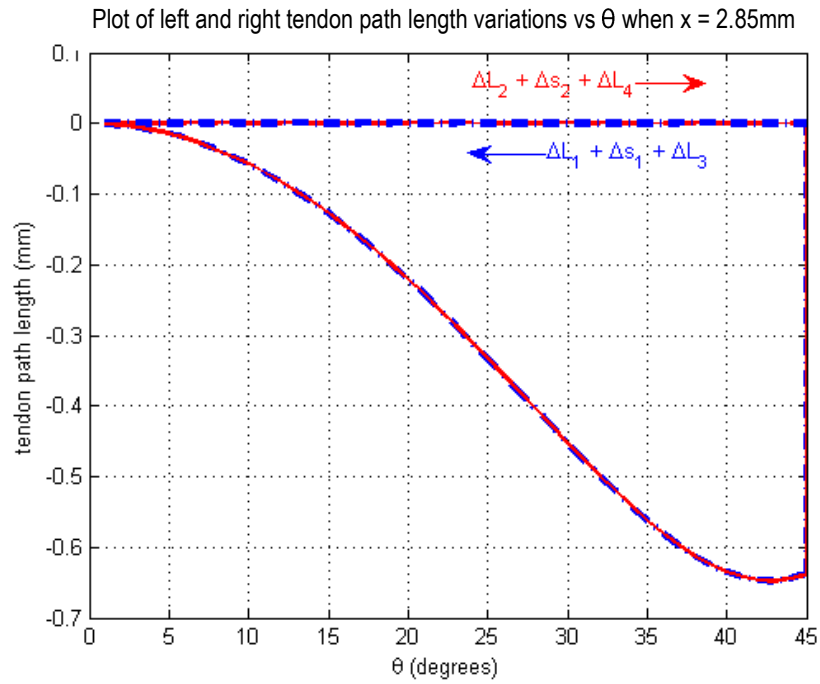


Figure 4.17: Plot of variation in tendon length with respect to theta. This indicates that the greatest backlash will occur when $\theta = 43^\circ$. However, the variation in path length at this location is 0.63mm which represents a backlash within the ring gear, γ_b , of 9.62° and a resulting backlash at the joint of θ_b of 4.7°

Given the capstan radius, $r_{capstan}$, of 4.45mm and a maximum variation of 0.63mm, the maximum angle of backlash on the ring gear, γ_b , is given by:

$$r_{capstan}\gamma_b = (\Delta L_2 + \Delta S_2 + \Delta L_4)_{max} \quad (4 - 16)$$

This gives $\gamma_b = 8^\circ$ which results in a maximum backlash of the joint, θ_b of 4.7° . This represents a significant improvement over the maximum backlash of 14° calculated for *Design Iteration 1* and is deemed acceptable for the flexible access platform. It is also worth noting that $x = -2.85mm$ was selected as the optimum solution for a configuration considered ‘manufacturable’ in the context of existing workshop machine tools at the Hamlyn Centre and within the other design criteria, such as minimising the overall link length and diameter. If such restrictions were not in place, it is possible that alternative optimum solutions could be found.

4.4.3 Joint Torque Transmission Analysis

The previous section analysed the tendon routing scheme of the joint module from the perspective of variation in tendon path lengths and backlash. Equally important is the ability of the design to transmit the output torque from the micromotor through the ring gear and pre-tensioned tendons to the rotatable link. In the design, the original output torque of the motor was maximised through the use of a small diameter pinion gear and a slight difference in diameter between the ring gear and the capstan.

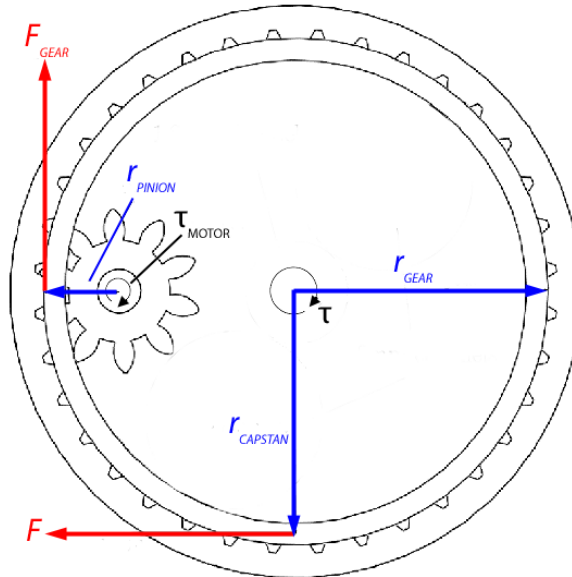


Figure 4.18: Schematic diagram of the gearing mechanism showing the joint torque transmission parameters. For clarity, the internal channels and the locations of the 4mm motors are not shown.

The transmission is split into three sections, the key variables of which can be seen in Figure 4.18 (a schematic showing a cross section through the joint unit taken on the plane of the capstan):

1. A pinion gear which meshes with the ‘ring gear’ to generate a force, F_{gear} .
2. The capstan that is welded to the ring gear but which has a different diameter to the ring gear and is rotated with a torque, τ .
3. The tendon which is wound around the capstan and which exerts a force, F , as the motor rotates.

Given parameters: $\tau_{motor} = 5.7mNm$, $r_{gear} = 4.5mm$, $r_{pinion} = 1.25$ and $r_{capstan} = 4.45mm$, the output force of the tendon, F , can be calculated from:

$$F = \frac{\left(\frac{\tau_{motor} * r_{gear}}{r_{pinion}} \right)}{r_{capstan}} = 4.61N \quad (4 - 17)$$

This is the force exerted by the driving tendon on the rotatable link. However, given the joint configuration, the moment exerted by the tendon about the axis of rotation will depend on the angle of the tendon segment with respect to the rotatable link. For $x = 0mm$ the resolved force will be identical for all driving tendons; however, for $x \neq 0mm$, tendons L_1 and L_2 will have a different resolved force to tendon segments L_3 and L_4 . Figure 4.19 shows the variables necessary to calculate this value when tendon $L_1L_3s_1$ is the driving tendon.

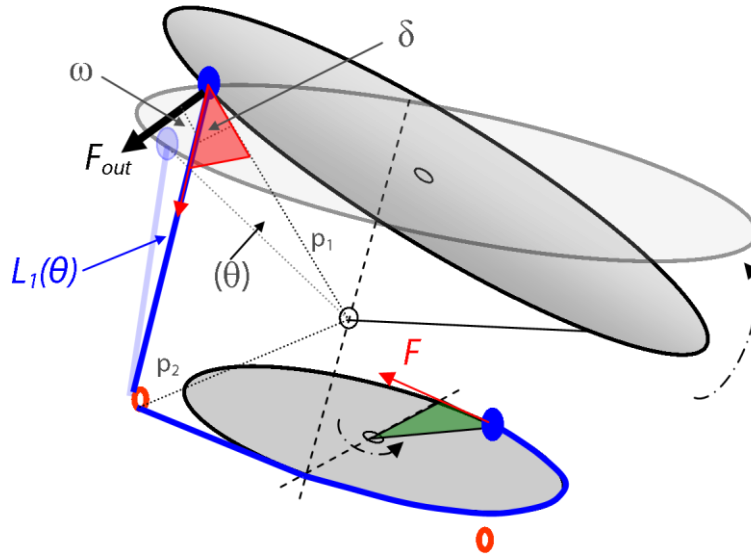


Figure 4.19: Schematic illustrating the variables required to calculate the resolved force from tendon segment L_1 when that segment is the driving tendon. The variables required to calculate the resolved force for tendon segment L_3 have been omitted for clarity, however, they can be found in Figure 4.15.

Where the output force exerted by the tendon on the joint unit is given by:

$$F_{out} = F * \cos(\omega) \quad (4-18)$$

$$\omega = \left| \frac{\pi}{2} - \delta \right| \quad (4-19)$$

$$\delta = \cos^{-1} \left(\frac{p_1^2 + L_1(\theta)^2 - p_2^2}{2p_1L_1(\theta)} \right) \quad (4-20)$$

For $45^\circ > \theta > 0^\circ$ as the rotatable link rotates.

Similarly, from Figure 4.15, when $x \neq 0$:

$$F_{out_x} = F * \cos(\omega_x) \quad (4-21)$$

$$\omega_x = \left| \frac{\pi}{2} - d_x \right| \quad (4-22)$$

$$\delta_x = \cos^{-1} \left(\frac{(L_3(\theta) + x)^2 + p_1^2 - p_3^2}{2p_1(L_3(\theta) + x)} \right) \quad (4-23)$$

Therefore the total torque, τ , experienced by the joint is given by:

$$\tau = p_1(F_{out} + F_{out_x}) \quad (4-24)$$

Figure 4.20 shows the torque values for clockwise and anti-clockwise rotations of the joint unit for an input force, F , of 4.61N.

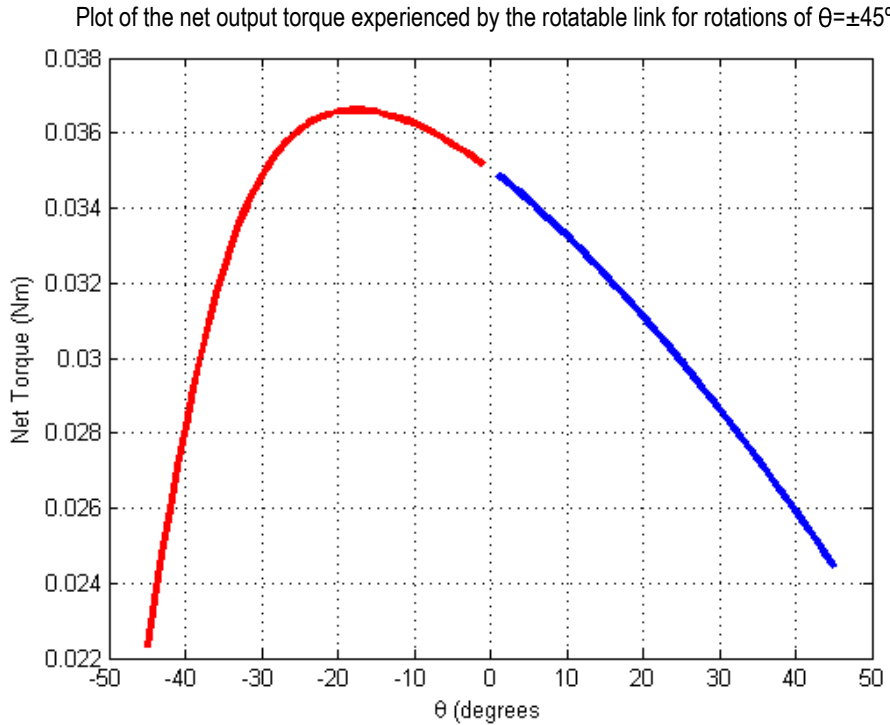


Figure 4.20: Plot of the net output torque experienced by the rotatable link as it rotates through -45° to 0° (red) and from 0° to 45° (blue)

This plot clearly shows the asymmetrical nature of the force transmission, however, the important feature to note is that the minimum torque the joint is capable of developing is 22.3mNm. Theoretically, this torque value is sufficient to cantilever lift (i.e. the lift required in the worst loading scenario possible) three of the 2-DoF joint modules. This is based on a calculation similar to that performed in Appendix I.C to compute the torque required to actuate the multi-spectral imaging robot. In this case, the link mass, $m = 10.1g$, the link length, $l = 43mm$ (axis to axis length plus the length of the interconnect frame) and the number of links, $n = 3$.

$$\tau = F * d \quad (4 - 25)$$

Where:

$$F = (n * m) * 9.81 \quad (4 - 26)$$

$$d = \frac{(n * l)}{2} \quad (4 - 27)$$

In this case, the theoretical torque required is 18.9mNm. However, this calculation does not take the effect of friction or any transmission inefficiencies into account. To investigate the ‘real-world’ actuation capabilities of the system, a 7-DoF flexible access platform was constructed. The next section will describe how this was achieved.

4.5 Mechatronic Configuration of a 7-DoF Flexible Access Platform

This section provides a system level description a 7-DoF mechatronic flexible access platform constructed through the combination of two universal joints (pitch and yaw) and three 1-DoF yaw joints, as can be seen in Figure 4.21. To minimise the torque required to cantilever lift the distal tip in the worst case loading scenario (i.e. a cantilever lift from a horizontal position), the universal joints are aligned at an angle of 45° with respect to the gravity vector. The yaw joints are aligned with the gravity vector so as to actuate in the horizontal plane. This configuration effectively maximises the number of degrees of freedom that the system can have given the 5.7mNm torque available from the 4mm micromotor. The distal 1-DoF module is 32.5mm in length and the proximal 1-DoF modules are 34mm in length. The 2-DoF module is 43mm in length and features rotatable links orientated orthogonally at both ends. The distal 1-DoF module is very similar to the proximal 1-DoF modules, differing only because the proximal 1-DoF modules need connection points on both ends. Each DoF is capable of actuating $\pm 45^\circ$. As

will be demonstrated in Chapter 7, the system is capable of retroflexing with a maximum bending radius of 91mm, which is within the volumetric constraints outlined in Section 4.1.

This version of the flexible access platform was the fifth constructed during this project. The details of the other four systems can be found in Appendix II.

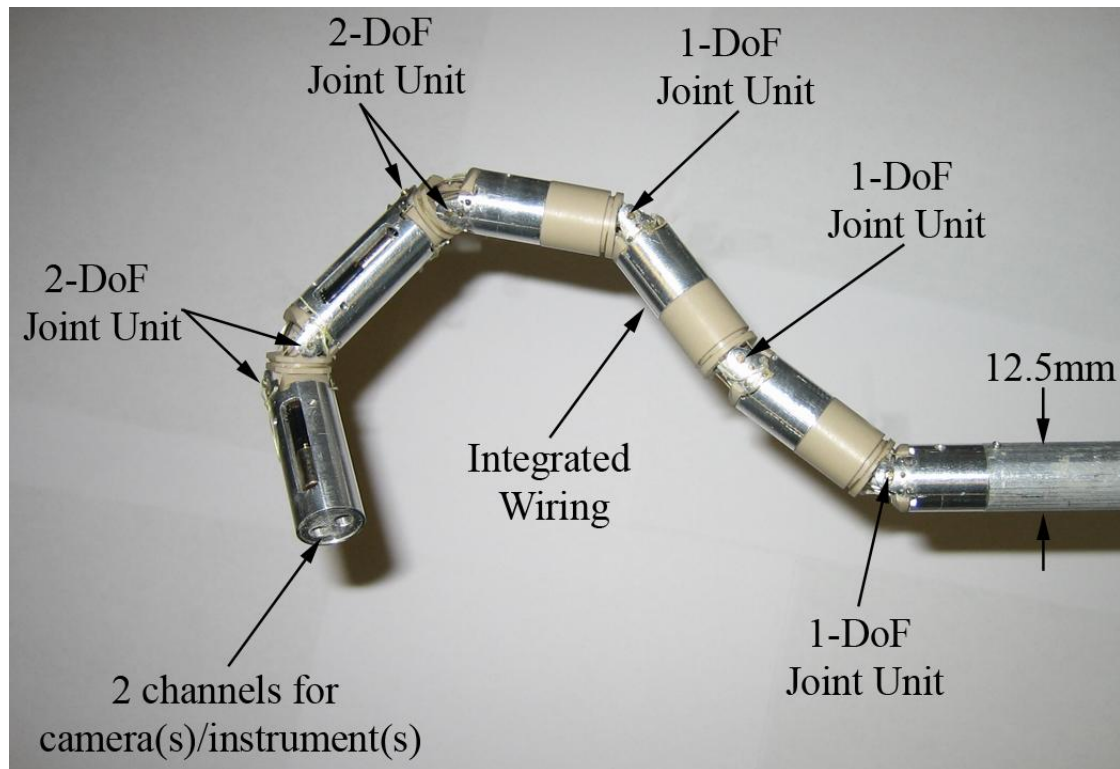


Figure 4.21: The flexible access platform without external sheath. This version of the platform features seven degrees of freedom arranged into two serially connected universal joints and three single degree of freedom yaw joints. Three internal channels of 3.5mm, 3mm and 1.8mm diameters run through the system. Its outer diameter is 12.5mm.

4.6 Flexible Access Platform System Architecture

Previous sections have described the joint module design, introduced the mechatronic configuration of the articulated segments and documented the advantages of using embedded micromotors. However, equally as important for ensuring that the platform has a small footprint in-theatre is the overall system architecture. The key elements of the system are shown in Figure 4.22 and those which have not already been addressed will be described briefly. These elements include the motor control box, the connection unit, the user interface and the graphical user interface (GUI).

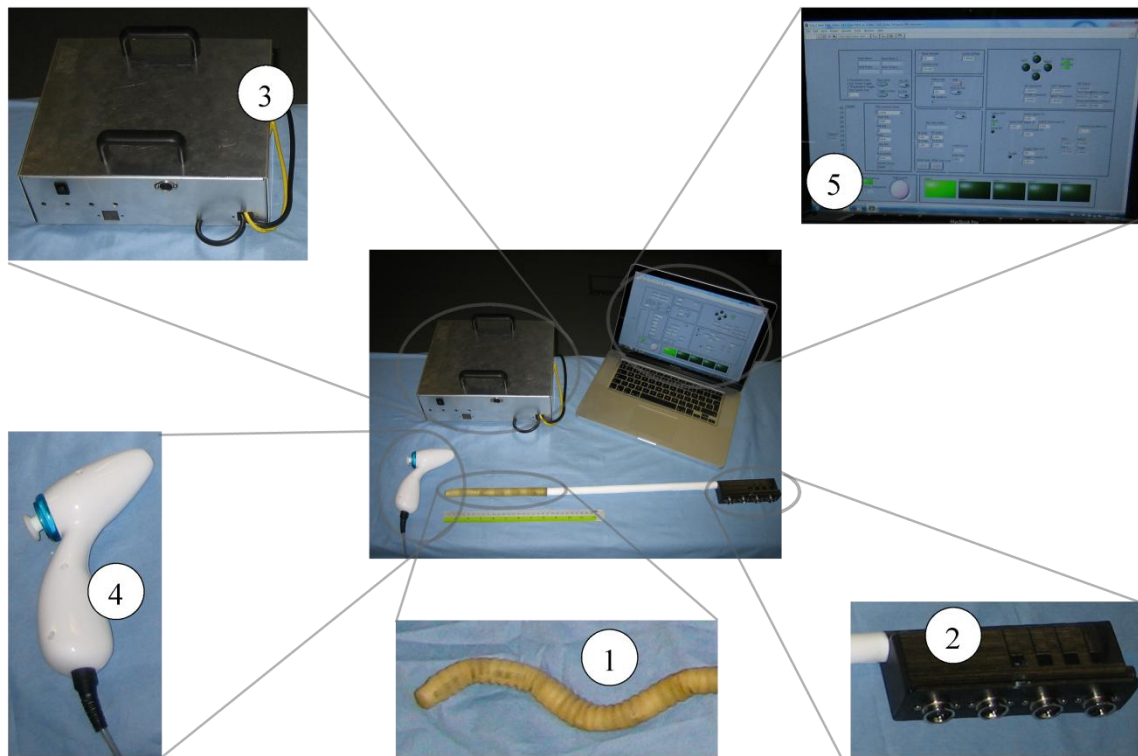


Figure 4.22: The overall system architecture of the flexible access platform including 1: the articulated distal tip covered in a custom latex sheath; 2: The connection unit on the rigid shaft; 3: The motor control box; 4: The handheld controller; 5: The GUI

As with the joint module design, five iterations of the system were developed during this project. The material described below relates to the fifth iteration. Specific details, advantages and disadvantages of the four previous iterations can be found in Appendix II.

4.6.1 User Interface

The user interface developed to control the 7-DoF flexible access platform is a handheld controller with an integrated thumb-stick. It was designed in collaboration with Christopher Payne of the Hamlyn Centre. It is decoupled from the flexible access platform, as can be seen in Figure 4.23. This allows the operator to position the platform in any location and orientation that is suitable for the particular surgical procedure, and then hold the controller in an ergonomically comfortable position. The operator is also free to move around the operating table and/or to manipulate additional instruments as required. This feature is of particular importance considering the potential for integrating the platform into the existing surgical workflow without disruption. The ‘decoupled thumb-stick’ controller represents the evolution of several user input devices constructed and tested for this project. More detail of these devices will be presented in Chapter 5. Alternative designs tested include a fully ‘handheld’ flexible

access platform, in which a thumb-stick was located in line with the robot shaft, and a fully ‘decoupled joystick’ in which the controller was decoupled from the platform but needed to be clamped to a rigid structure in order to operate. While the handheld system was advantageous from the perspective that surgeons are familiar with handheld instruments, the inherent ergonomic limitations of minimally invasive surgery can result in such a device proving difficult to operate. The decoupled system overcame this limitation by separating the controller from the platform, however the need to clamp the joystick to the table was found to be difficult to achieve in a theatre environment. It also does not fully exploit the advantages of the small footprint provided by the platform. Consequently, the ‘decoupled thumb-stick’ controller was developed to combine the advantages of both systems. It provides the operator with the ability to both locate the flexible access platform in the most appropriate location, and allow for control from any necessary position around the operating table.

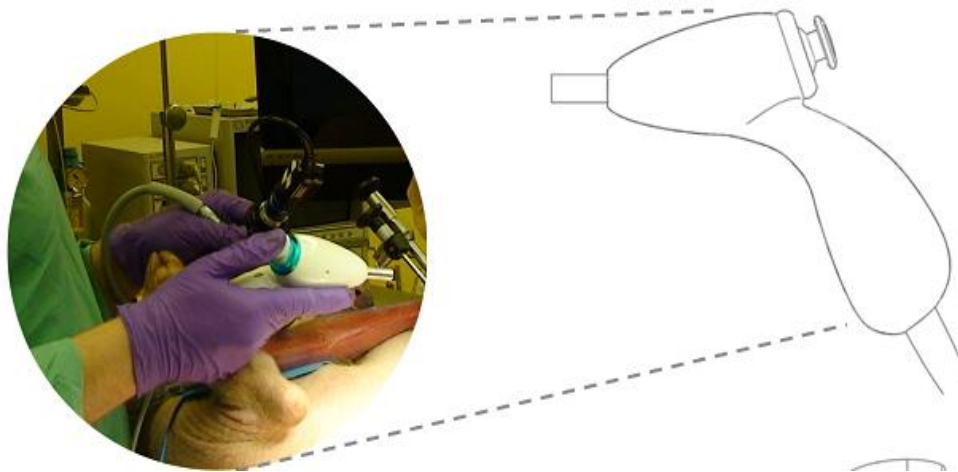


Figure 4.23: Schematic of the decoupled, handheld controller. It features an embedded thumb-stick and integrated push-switch. An image of the device being used during an in-vivo pre-clinical trial is also shown.

Movement of the thumb-stick causes variations in resistance of two orthogonally arranged potentiometers. It also features an embedded push-button which activates when the thumb-stick is depressed. In order to achieve intuitive control of a multiple degree of freedom system, a direct ‘joint-to-joint’ control scheme was implemented. Under this scheme, a movement along one axis of the thumb-stick results in a corresponding movement along one of the seven joint axes in the flexible access platform. Relative positioning is used to change the desired joint angle with a velocity proportional to the change in resistance of the potentiometer. Naturally, an input-output asymmetry exists (2-DoF in the thumb-stick compared to 7-DoF in the platform). To overcome this, the operator must switch between each joint unit sequentially to actuate the device. This switching between joint units is achieved by depressing the thumb-stick. When

initially powered up, the default configuration maps the two axes of the thumb-stick to the two axes of the distal universal joint (*Joint 1*). When the thumb-stick is depressed, the mapping is switched to the next universal joint (*Joint 2*). Subsequent depressions of the thumb-stick will result in the control switching to the three single DoF joints in turn (*Joints 3, 4 and 5*) and then back to *Joint 1*. This process is schematically illustrated in Figure 4.24.

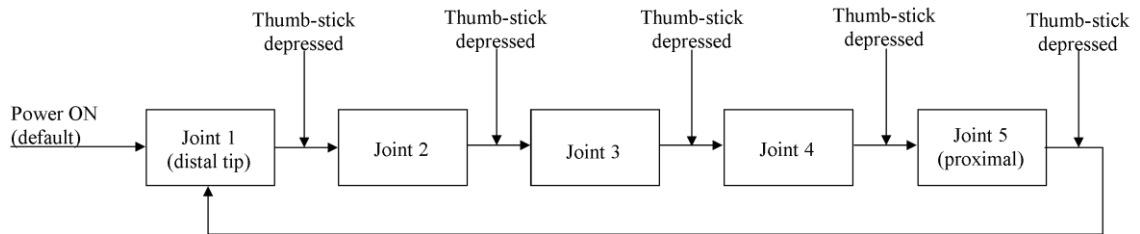


Figure 4.24: Schematic illustrating the joint switching functionality of the thumb-stick. As the operator depresses the thumb-stick, the control is transferred to the next joint unit in sequence

When the 1-DoF joints are active, only one axis of the potentiometer is mapped. In this manner, each of the seven degrees of freedom can be controlled using the handheld controller. Further experimental results demonstrating the efficacy of this control strategy will be discussed in Chapter 5.

4.6.2 Motor Control Box

Due to the size constraints within the joint module it was necessary to locate the 3-phase brushless drive electronics remotely from the motors. However, since the system is effectively ‘drive-by-wire’ it is possible to place the drive electronics in a motor control box which can be located away from the operating table and connected to the flexible access platform via electrical cables. Thus the additional footprint of the platform infrastructure directly at the operating table is limited to the electrical cables required to connect the motors to the motor control box. In order to ensure portability and robustness, and to facilitate rapid setup in the operating theatre, the motor control box was constructed from sheet aluminium (see Figure 4.22). Suitable connectors on its external surfaces allow for easy connection of the flexible access platform, the handheld controller and the GUI to the internal control hardware. The internal elements of the control box are shown in Figure 4.25 and a photograph can be found in Appendix II.

4.6.2.1 Embedded Controller

To allow for real-time control of the flexible access platform and its associated inputs/outputs, the main component of the control box is a CompactRIO (cRIO) (National Instruments Corp.).

This consists of a real-time controller (cRIO-9014) and a field programmable gate array (FPGA) backplane (cRIO-9113) which are connected via a high speed data bus. The real-time controller carries out processing while the FPGA backplane performs low-level operations on the input/output lines. Software to control the platform was developed in the *LabView* development environment and three programs (or VIs – Virtual Instruments) are required; one each for the real-time controller, the FPGA and a computer to host a GUI. The software deployed to the real-time controller is a dedicated real-time program which features two deterministic control loops. The first handles any high priority calculations required for motor control while the second, less critical control loop, handles non-essential tasks such as communication with the GUI or data logging. This program is compiled on a separate computer and is downloaded to the cRIO. The program for the FPGA is also developed in the *LabView* environment. When compiled, a configuration file, or bitstream, is generated. This reconfigures the FPGA digital logic based on the desired task. For the flexible access platform, all analogue and digital input signal acquisition and output signal generation are hardware timed and run in parallel loops at 25kHz. Acquired signals are passed to the real-time controller via the high-speed bus, processed and then the signals to be generated are passed back to the FPGA. Although a host computer is required to develop and compile the software, the cRIO is capable of controlling the flexible access platform as an embedded controller without the need for a separate computer. However, in order to display the system state to the operator and to allow for parameters to be adjusted during operation, a third program runs on a laptop to display an interactive GUI. Communication takes place over Ethernet. The GUI displays key information such as motor selection, motor power, joystick position and sensor thresholds. During pre-clinical in-vivo trials the GUI was fed from the laptop to a display on a laparoscopic stack. This allowed the operator to monitor system parameters during the procedure. Signal acquisition and generation are carried out using C-Series modules (National Instruments Corp.) which plug into the backplane. Specifically, a NI-9264 16-channel module was used to generate analogue outputs, a NI-9205 32-channel module acquired analogue inputs and an 8-channel NI-9401 handled digital inputs and outputs.

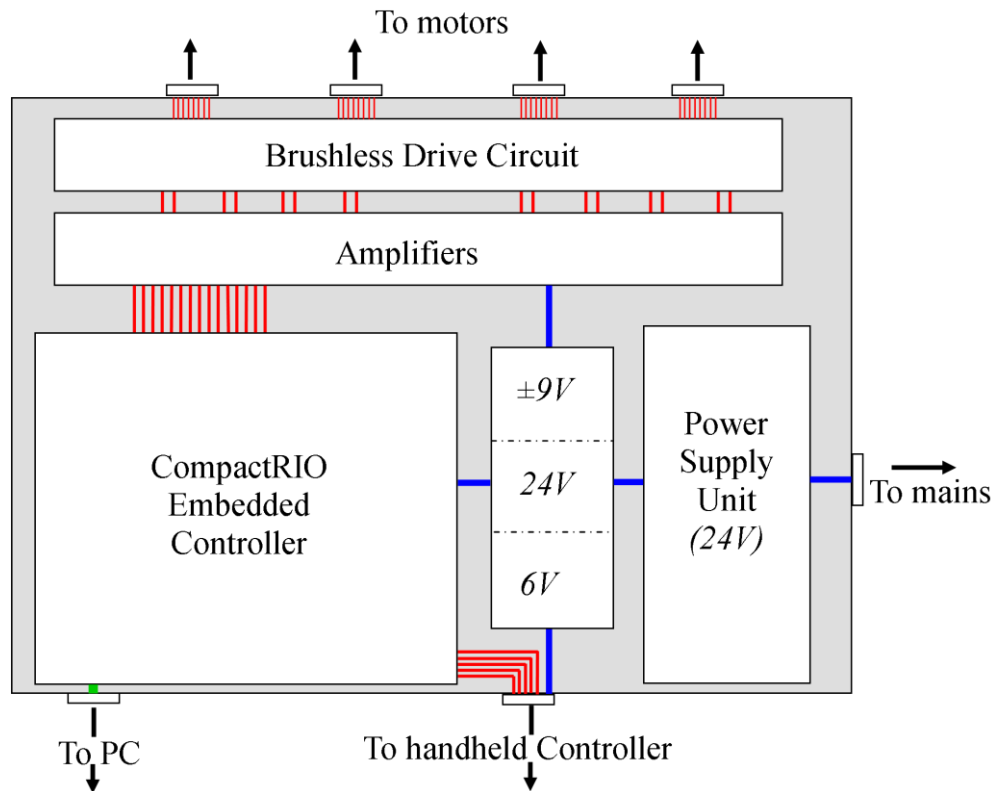


Figure 4.25: Schematic of the internal components of the motor control box. The cRIO embedded controller, the power supply unit, voltage regulators and drive electronics can be seen.

4.6.2.2 Drive Electronics

As can be seen in Figure 4.25, between the outputs on the cRIO and the motors are an amplifier section and a motor drive electronics section. The former is required due to low current drive from the NI-9264 (4mA per channel typical) while the latter is required to generate the three phases to drive the brushless DC micromotors. The drive electronics units used were the SSD04 from Namiki Precision Jewel Ltd. These are sensorless drive circuits which commutate based on the back EMF generated from one of the phases in the micromotor. They feature three input terminals (Vcc, GND and CW/CCW) and one SSD04 is required for each motor. Therefore, seven SSD04 units are required to control the seven degrees of freedom. Two analogue outputs are required per motor (one to power the motor clockwise and one to turn it anti-clockwise when required). Thus 14 of the 16 channels in the NI-9264 are required. Current amplification is achieved using high-current operational amplifiers (OPA551PA) arranged in a voltage follower configuration for each of the 14 channels. This amplifier was chosen for its high speed and high current capability. For stable operation, the OPA551PA requires both positive and negative voltage rails. This required implementing a switched capacitor voltage convertor to obtain a negative output voltage from a positive input voltage. This was achieved using ICL7660 ICs and 10uF capacitors. The overall circuit schematic for a

single motor is shown in Figure 4.26. This circuit was repeated seven times to control all motors.

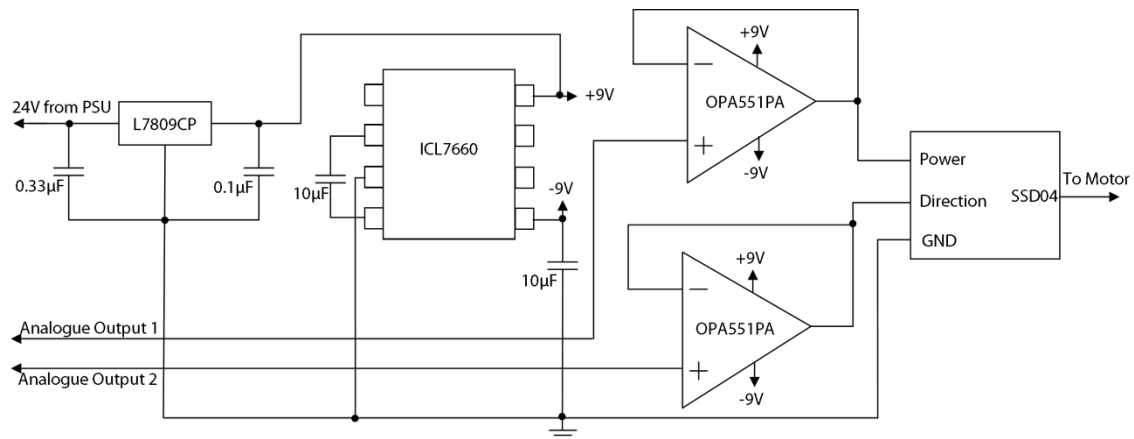


Figure 4.26: Electrical schematic for one motor. The voltage regulator, charged pump capacitor circuit and current amplifiers and 3-phase drive electronics are shown. The circuit must be repeated for each motor (with the exception of the voltage regulator).

A power supply unit was integrated within the motor control box. This unit (Recom RCA40-24SA) is an AC-DC convertor that plugs into a mains power supply and outputs 24V up to a power limit of 40W. The 24V powers both the cRIO (directly, no voltage regulation required) and two voltage regulators. These regulators step the 24V down to voltages of 6V (L7806ACV) and 9V (L7809CP) to power the handheld controller and amplifiers respectively. The result is that the motor control box is simply plugged into a mains supply to power all elements of the system.

4.6.2.3 Connection Unit(s)

As was described in Section 4.3.2, each motor is wired via a 0.5mm diameter, 4-core wire when inside the flexible access platform. Due to the high resistance of these wires they are terminated in the connection unit on the proximal end of the rigid shaft (Figure 4.22). This connection unit is then connected to the control box using four 9-core wires (Maplin, Part No: XR27E) with 8-way DIN plugs on each end. Four 8-way DIN sockets located in the connection unit and the motor control box allow for all elements to be securely connected. These cables are each 3m in length, thus allowing the control box to be located away from the operating table.

4.6.2.4 Handheld Controller

The handheld controller described in Section 4.6.1 connects directly to the control box via an 8-way DIN connector on a 3m cable. When this connector is plugged into the control box, power

from the 6V rail inside is fed to the thumb-stick and the necessary sensing lines are connected to the cRIO.

4.7 Additional Components

Additional components required to complete the flexible access platform include a camera, an illumination system, an external sheath and an internal sheath to guide any instruments passed through the device. Image feedback from the distal tip is achieved using an IntroSpicoTM 115 Micro CCD video camera (Medigus Ltd, Israel) which is threaded through the 3mm channel of the platform. Illumination is provided by two tip mounted light emitting diodes (LED) (LUXEON® Rebel LXML-PWC1-0120) mounted on a custom aluminium printed circuit board (PCB). The purpose of the PCB is to dissipate any heat generated by the LEDs back to the aluminium housing of the distal joint module. This feature is essential to ensure that the LEDs don't overheat during continuous operation. The LEDs are connected serially, and their power and ground lines also pass through the 3mm channel. The internal sheath is spiral reinforced tubing (OSCO Ltd, UK) which has sufficient flexibility to bend as the joint units articulate but sufficient strength to re-direct the passage of any instrument passed through its lumen. These three components can be seen in Figure 4.27. Finally, the overall system is covered in a custom 'bellowed' latex sheath to protect the inner workings from contamination. The purpose of the bellows is to minimise the mechanical impedance of the sheath as the joint units actuate.

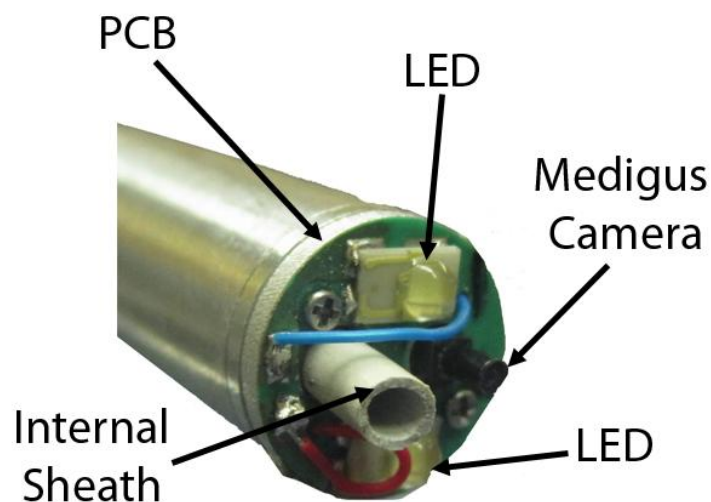


Figure 4.27: The distal tip of the flexible access platform illustrating the internal sheath to ease the passage of instrumentation, the camera for visual feedback and the LEDs for illumination

Three different images of the 7-DoF flexible access platform are shown in Figure 4.28. The bellowed sheath can be seen in the upper and lower images.

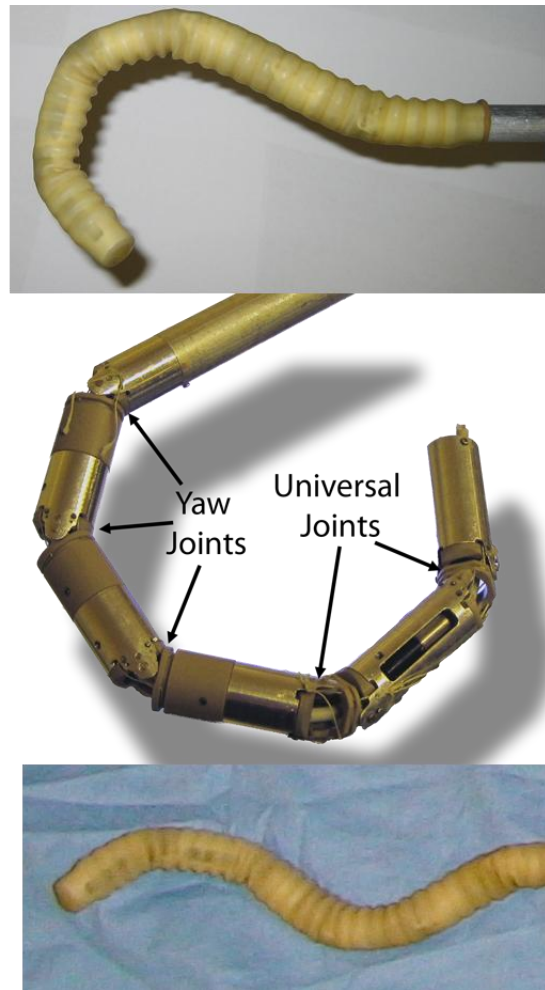


Figure 4.28: Images of the flexible access platform to demonstrate its flexibility and degrees of freedom. The customised latex sheath is also shown in the top and bottom images.

4.8 Discussion and Conclusion

The purpose of this chapter was to introduce a new mechatronic joint design suitable for integration within a flexible access platform which can address some of the challenges outlined in Chapter 1. In that chapter the requirement for a ‘focused’ mechatronic device was outlined. The key challenge addressed by this chapter is that of *Challenge 1* – the ability to provide stable, controlled actuation along multiple degrees of freedom and to ensure passage of interventional instrumentation and optical imaging probes. The modular joint design described here is capable of this and its efficacy will be demonstrated in the following chapters.

Additional advantages of the joint design include the use of embedded actuation within the link segments to reduce the external actuation requirements. It also presents the possibility of providing joint modules which can be interconnected as required. This ‘modularity’ feature could potentially be used to construct different configuration flexible access platforms depending on the requirements of a given procedure. By keeping the central elements of the link segments free for the passage of instruments, the device is effectively compatible with all existing endoscopic instrumentation. This eliminates the need for ‘specific’ instruments to be developed. Another clear advantage of the system is the redundancy provided by the seven actuated degrees of freedom – a feature which will be further discussed in Chapter 7 – and the practical usefulness of this dexterity for tasks in the pelvic and peritoneal cavities.

However, if more degrees of freedom are required then optimisation of the design will be necessary. This is due to the fact that there is insufficient torque available from the 4mm micromotor to support any more degrees of freedom than the current seven. This lack of torque is also evident from the fact that the system is only capable of actuating the three proximal joints when their axes are aligned with gravity. However, during laboratory and in-vivo trials with the system this has not proven to be a problem since the un-actuated roll and translation axes (along the shaft of the flexible access platform) can be manipulated manually to extend the workspace of the device. A potential element of future work would be to actuate these two degrees of freedom.

Other future work which offers many exciting possibilities is the integration of robotic control algorithms with the flexible access platform. The system described here is primarily a mechatronic device. Its utility can be greatly improved by building on the potential offered by the joint position sensors to integrate ‘robotic’ features. Such features might include automatic manoeuvres such as straightening for removal from the patient, shape conformance matched to tissue deformation or the tracing of specific trajectories with an optical imaging probe. It is anticipated that such robotic control algorithms will be able to greatly enhance the ability of a clinician to perform tasks with the flexible access platform. Chapter 8 will provide further discussion on this topic.

Finally, in its current form, the flexible access platform is a test-bed for exploring and addressing the challenges outlined in Chapter 1. From an engineering perspective, it can be

used to explore how the ergonomics and control of flexible devices can be improved so as to be made suitable for deployment in-theatre. This will be further investigated in Chapter 5. From the perspective of improving the intraoperative information flow to a surgeon, the platform can be used to experiment with probe-based optical imaging techniques. This will be further investigated in Chapter 6. Lastly, from a surgical perspective, the platform can be used to experiment with clinical applications of flexible access surgery. Two such applications were explored and the results of preliminary case studies will be outlined in Chapter 7.

Chapter 5:

Control Strategies for the Flexible Access Platform

The previous chapter introduced the main mechatronic elements of the flexible access platform. The purpose of this chapter is to use the platform as a test-bed to develop and explore two different experimental control strategies. The first strategy utilises a physical ‘joystick style’ user interface to allow the operator to control the platform in a manner suitable for rapid deployment in a clinical environment. The evolution of this user interface over three different configurations will be described. Its design criteria include providing intuitive control of the platform given its multiple degrees of freedom, and providing an adaptable, ergonomic interface for use in an operating theatre. Time based user trials were performed to ensure that users could successfully navigate the device using the direct ‘joint-to-joint’ control scheme proposed in Chapter 4. The second control strategy that will be introduced is a method of controlling the flexible access platform through the eye gaze of a surgeon. Results of a study to test the feasibility of this approach will be presented. The goal of this experimental user interface is to provide an operator with the ability to control flexible robotic devices in a hands-free manner

and thus allow one or more standard instruments to be simultaneously manipulated. The gaze contingent control technique uses monocular image feedback from the camera mounted in the tip of the platform and a commercial eye tracking unit. Interfacing these components allows the operator to servo the platform's joints by linking the operator's fixation point with the control software. Two different variations of the gaze contingent control technique were trialled and results from user studies will be presented. The key contribution of this chapter is a demonstration of the feasibility of controlling a flexible robotic device through the eyes of a surgeon.

5.1 Existing User Interface Strategies for Robot-Assisted MIS

As was explained in Chapter 2, many current state-of-the-art robotic devices for minimally invasive surgery are not necessarily robots in the true sense of the definition. Instead of carrying out automated, repetitive tasks, as would occur in a manufacturing plant, medical robots are mainly master-slave tele-manipulators where movements of the robotic end effectors are directly controlled by the surgeon. In this partnership, the 'slave', or end-effector, is only one element. The 'master' control element is equally as important and careful design is required in order to ensure that the overall system complexity is masked from the operator. One of the key successes of the daVinci Surgical Robot is the fact that the master console is very intuitive to use. Features such as an immersive operating environment and visual-spatial alignment of the surgeon's hand motions to instrument motion results in an intuitive man machine interface [8]. Similar master control stations have been developed for other surgical robotic platforms such as the Zeus [9] or the ViaCath [33]. However, as can be seen in Figure 5.1, a limitation of this master console architecture is the substantial footprint within the operating theatre and the fact that the surgeon is physically separated from the patient.



Figure 5.1: Typical master consoles for controlling tele-operated surgical robotic devices. (Image Sources: Intuitive Surgical Inc, Computer Motion Inc and EndoVia in [33])

This type of architecture is not compatible with the design goals for the flexible access platform since the operator would be separated from the patient, and rapid deployment would be problematic due to the size of the sub-systems involved. What is required for the flexible access platform is a small footprint, adaptable user interface that allows the operator to interact directly with the patient and control all of the degrees of freedom of the system.

A further extension of a small footprint user interface is the concept of controlling the platform in a totally 'hands-free' manner. This approach has been described for several laparoscope manipulation systems such as the Freehand [53] and the EndoAssist [48], which are controlled by head movements, and the AESOP [49], which is controlled by voice commands. In these cases, the user interface is effectively transparent to the operator thus allowing direct hands-on interaction with the patient while simultaneously providing the ability to control the field of view of the laparoscope. However, the input resolution of voice or head-movement commands are limited and so controlling a flexible device would be challenging. An alternative 'hands-free' control strategy is that of gaze contingent control. In this control paradigm the surgeon is perceptually docked with the robotic system through their gaze fixation point [143-147]. Example applications of this technique which have been developed by Dr. George Mylonas at the Hamlyn Centre include gaze contingent depth recovery, motor channelling and motion stabilisation. Gaze contingent depth recovery can be used to extract information about the tissue surface in-vivo which can aid surgical navigation [143]. Gaze contingent motor channelling can be used to dynamically prescribe and update safety boundaries [145]. Gaze contingent motion stabilisation can be used to automatically provide a stable frame of reference during complex procedures which suffer from tissue motion [146]. These examples demonstrate that the technique offers the potential for a surgeon to intuitively interact with a robotic device. A higher input resolution can be achieved than is possible with voice or head movement controlled systems. To investigate the feasibility of controlling the flexible access platform in this manner, an experimental gaze contingent control framework was developed in parallel with the more traditional master controller.

The following sections will introduce and describe both control strategies. However, it is important to note that the design goals for each were quite different. The purpose of the first strategy was to facilitate rapid testing of the system for flexible access surgery applications within an in-vivo environment, while the purpose of the second strategy was to investigate the feasibility of an experimental control technique.

5.2 User Interfaces Suitable for Controlling the Flexible Access Platform

Three different ‘physical’ user interface designs suitable for deployment during in-vivo trials were developed and tested in parallel with the different versions of the flexible access platform. The specific details of the ‘User Interface - Platform Version’ pairings can be found in Appendix II. The relative merits of each interface design will now be briefly discussed. A significant advantage of the embedded micromotor based actuation scheme is that the system is extremely lightweight. This compact, lightweight design presented several opportunities for different interfaces. The first interface developed was a fully handheld device with a thumb-stick embedded into a pistol grip located at the proximal end of the rigid shaft. The second interface was a self-centring joystick which is decoupled from the rigid shaft and could be clamped at any location around the operating table. The third interface is that described in Chapter 4 and is a handheld controller which features an embedded thumb-stick. The advantages and disadvantages of each interface are listed in Table 5.1.

Table 5.1: Advantages and disadvantages of the different user interface designs

Interface Type	Advantages	Disadvantages
Handheld Integrated Thumb-stick	Minimal footprint (no clamp required to hold the flexible access platform)	Poor ergonomics
Decoupled Joystick	Small footprint Good ergonomics, if suitable location for joystick can be found	Difficult to attach to operating table Operator must stay near joystick Mechanism required to hold the flexible access platform
Handheld Thumb-stick	Best ergonomics Small footprint Operator free to move around operating table	Mechanism required to hold the flexible access platform

Note: The ‘Advantages’ and ‘Disadvantages’ listed were derived from personal experience when using the different interfaces during testing. As such, they should be considered specific to the interfaces and the requirements of the tasks described in this thesis.

Each of these interfaces were deployed with the flexible access platform during laboratory and in-vivo user trials designed to test the usability of the direct ‘joint-to-joint’ based control scheme introduced in Chapter 4. The purpose of these trials was to assess if operators could successfully navigate the platform around a spatial environment given the limitations of the system. These limitations include the requirement to switch between joint units to exploit the degrees of freedom, the lack of position information feedback to the operator and the orientation of the distal universal joints at 45° with respect to the proximal degrees of freedom. Only image feedback from a tip mounted camera was provided during these trials.

5.2.1 Usability of the ‘Joint-to-Joint’ Control Scheme

Multiple user trials were carried out in an abdominal simulator [148] in order to evaluate if users could successfully navigate the device. The difficulties facing the users include the direct ‘joint-to-joint’ control and the misalignment between the joystick axes and the axes of the universal joints. This axis misalignment is a result of the torque optimisation detailed in Section 4.5 where the axes of the universal joints were offset by 45° with respect to the gravity vector.

These trials were carried out using both the ‘handheld thumb-stick’ and the ‘decoupled joystick’ user interfaces. To further assess the usability of the joystick in an in-vivo setting, additional user trials were performed during a live porcine experiment. Unfortunately the thumb-stick was not available for use during this in-vivo trial.

5.2.1.1 User Trials in a Simulated Abdominal Exploration

HYPOTHESIS

Users can effectively navigate the flexible access platform to perform a large area visualisation using the direct ‘joint to joint’ control paradigm in a simulated or live surgical environment using both user interfaces.

THE TASK

Five targets (T2 to T6) were placed at specific locations within the simulated abdominal cavity. The locations of the targets can be seen in Figure 5.2. *Version_2* of the flexible access platform (see Appendix II) was used during these experiments and features 5-DoF. The task was to navigate the device to visualise each of the targets using only the feedback from the onboard camera. The locations of the targets were selected such that T2 and T3 could be visualised by only actuating the 2-DoF of the distal tip, T2 – T5 required both the distal and medial joints (i.e.

4-DoF) to be actuated and T6 required all three joint units (and hence 5-DoF) to be actuated. The order in which the targets must be visualised required the operator to traverse the flexible access platform from one side of the simulated abdomen to the other three times. A target was considered visualised when the target marker was fully inside the camera field of view, as can be seen in Figure 5.3. Both user interfaces connect to the motor control box via identical 8-way DIN connectors and are capable of being hot-swapped without requiring a system restart.

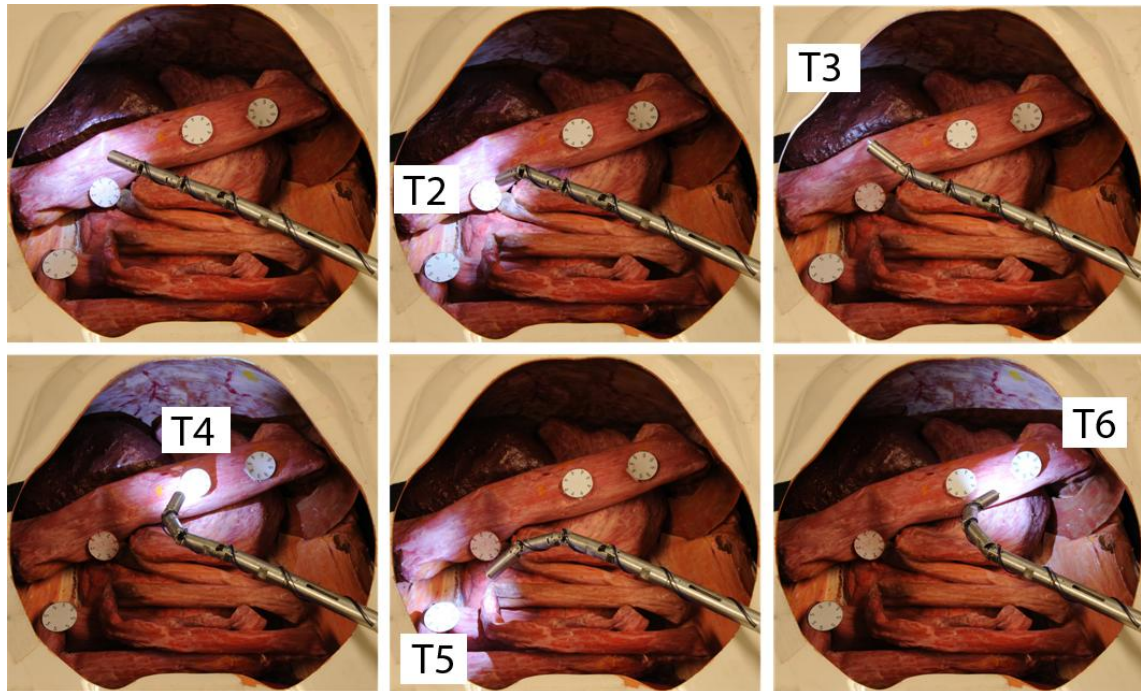


Figure 5.2: The abdominal exploration experiments showing marker positions and the robot visualising each marker. (top, left) robot in default start position, (top, mid) visualising T2, (top, right) visualising T3 (out of sight), (bottom, left) visualising T4, (bottom, mid) visualising T5, (bottom, right) visualising T6.

TEST USERS

The flexible access platform was clamped into position and fourteen users were randomly assigned to complete the task using either the thumb-stick or the joystick (seven users each). All of the users were considered novices who had no prior experience controlling the platform.

EXPERIMENTAL DESIGN

Each user was given five minutes to familiarise themselves with the actuation characteristics before performing three timed trials navigating the platform between the targets. A total time limit of three minutes was imposed. The system was reset to a default ‘straight’ position (Figure 5.2, top left) between trials. The abdomen was open during the familiarisation stage but fully covered during the timed trials.

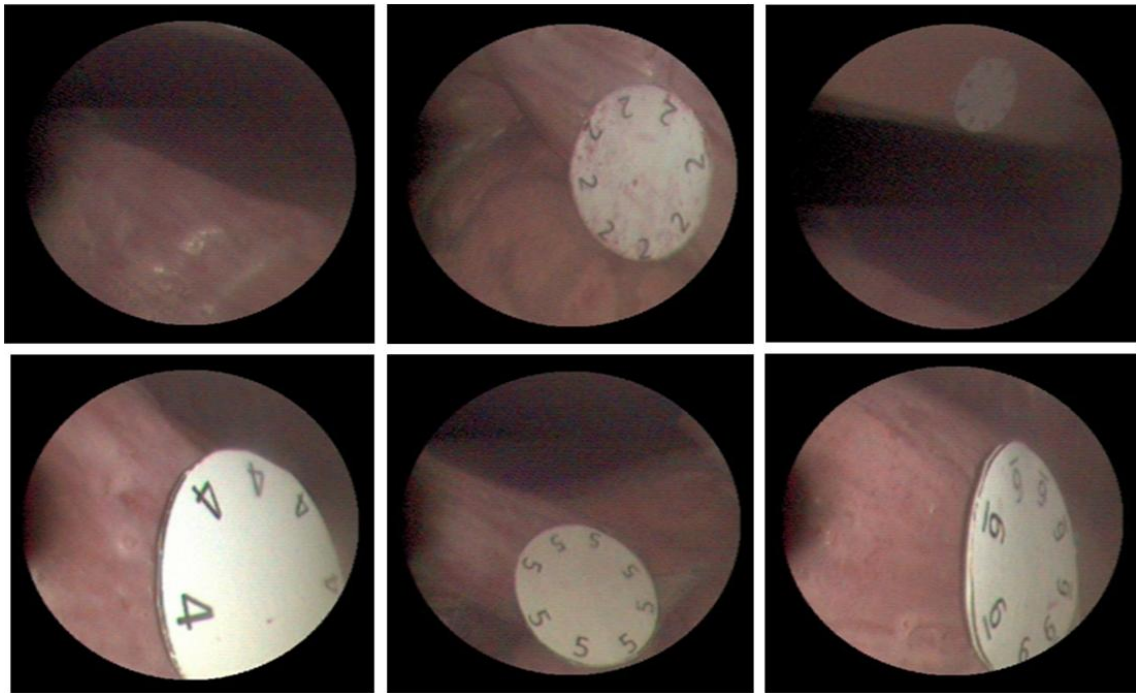


Figure 5.3: Feedback from the onboard camera showing the visualisation of the individual targets. Clockwise from the top left shows the view when the flexible access platform is in the default straight position, visualising T2, visualising T3, visualising T6, visualising T5 and almost visualising T4.

RESULTS

The average time and fastest time for each operator to complete the three trials for the joystick are shown in Figure 5.4, while similar results for each of the users when using the thumb-stick are shown in Figure 5.5. The results show that all fourteen users were successfully able to complete the task within the time allowed. This indicates that the ‘joint-to-joint’ control scheme is suitable for controlling the multiple degrees of freedom provided by the flexible access platform. Additionally, it was found that twelve of the operators recorded their fastest times on the third trial. This improvement between the average time and the fastest time indicates that the operators became more familiar with the system characteristics with practice and therefore were able to complete the task in a shorter period of time. The plots would also indicate that operators performed better when using the joystick. This was a result which was not expected, however given the small numbers of participants in the study it is difficult to state conclusively that one user interface was more intuitive to use than the other.

Plot of Average and Fastest Times for Joystick Users

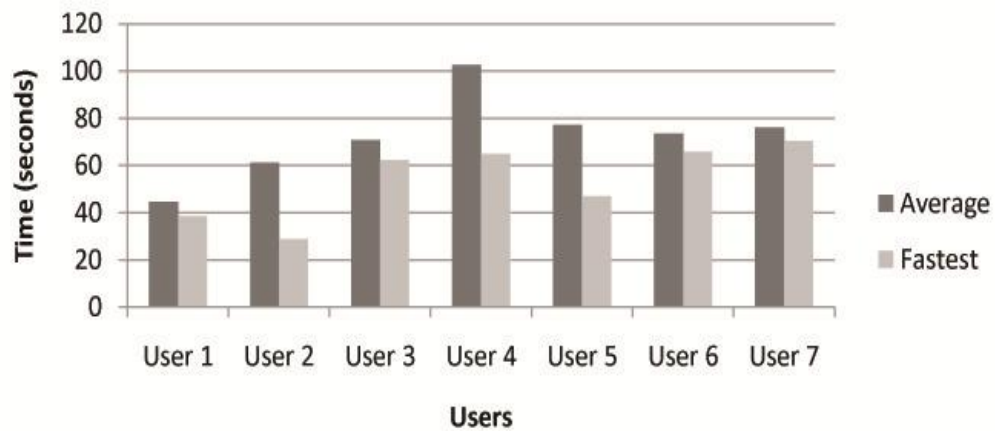


Figure 5.4: Plot of the average and fastest times taken to complete the task over three attempts using the joystick interface in a simulated environment.

Plot of Average and Fastest Times for Thumbstick Users

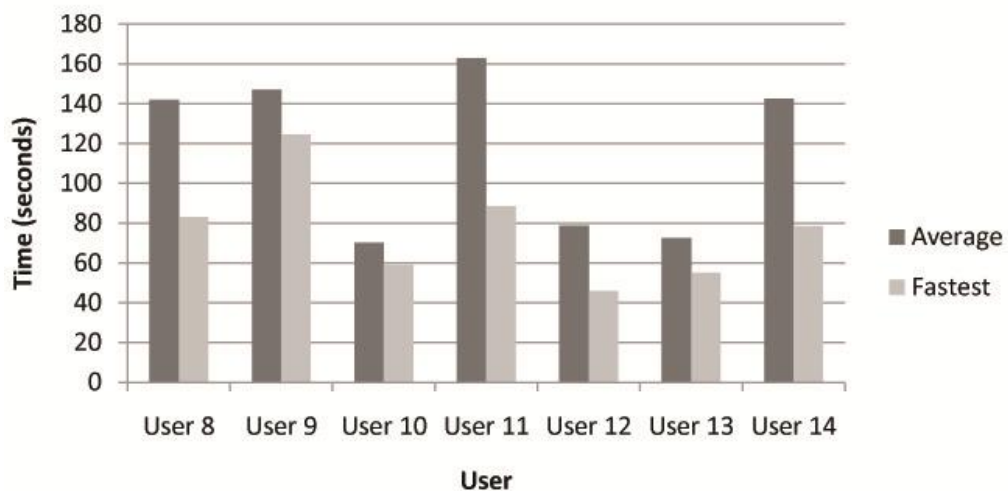


Figure 5.5: Plot of the average and fastest times taken to complete the task over three attempts using the thumb-stick interface in a simulated environment.

DISCUSSION

The trials also revealed the limitations of the overall control scheme. Specifically, these limitations relate to the ease with which an operator can get disorientated due to a lack of knowledge of the configuration and orientation of the articulated sections of the platform. When this occurred the operator was unable to complete the task until re-orientation using a visual cue

could be achieved. Naturally, this disorientation-reorientation phase resulted in longer overall times (in particular Users 8, 9, 11 and 14 in Figure 5.5). This disorientation occurred when the operators only had five degrees of freedom to control and it is anticipated that the difficulties with disorientation would increase with increasing degrees of freedom. A solution to improve the overall controllability of the system would be to provide the operator with a graphical representation of the overall joint configuration with respect to a fixed frame of reference, as is provided by the Sensai Platform of Hansen Medical [104]. Such a graphical representation would use angular displacement information from the joint potentiometers described in Chapter 4 to update the configuration of a computer generated model of the entire platform. However, carrying out such an implementation and reassessing the controllability of the platform when used in conjunction with it is beyond the scope of this thesis.

In conclusion, the results of these user trials demonstrate that the technique of controlling the individual joints for navigation is suitable for controlling the multiple degrees of freedom in an experimental environment. To validate these results the controllability experiments were repeated in-vivo as part of a live porcine experiment.

5.2.1.2 User Trials in an In-vivo Porcine Experiment

The purpose of the in-vivo user trials was to validate the findings outlined in Section 5.2.1.1 and the hypothesis that the ‘joint-to-joint’ control methodology is suitable for controlling the flexible access platform in an in-vivo environment.

THE TASK

To perform the procedure the platform was inserted through an adapted 15mm trocar port (Applied Medical Resources Corp.) and pneumoperitoneum established at 15mmHg (a more thorough description of the in-vivo experiments appears in Chapter 7). A task similar to that performed in the abdominal simulator was carried out. Due to the difficulties associated with inserting identical target markers to those previously used, four targets were defined using features that could be easily identified inside the abdominal cavity. These targets were as follows:

1. T1 – A trocar port located to the left of the flexible access platform’s insertion point
2. T2 – A clip on the abdominal wall specifically placed to provide a target on the featureless abdominal wall
3. T3 – the gallbladder
4. T4 – a trocar port located to the right of the platform’s insertion point.

Visualising T1 from the default ‘straight’ position could be achieved using the distal joint alone, T2 and T3 required the distal and medial joints to be actuated, while T4 required all joints to be actuated.

TEST USERS

Only four operators were able to undertake the task due to the restrictions on the use of animals for medical research purposes under the Animals (Scientific Procedures) Act (ASPA) 1986. Each of the users had a surgical background and were novices with no prior experience controlling the flexible access platform.

EXPERIMENTAL DESIGN

Each user navigated the device ten times between the default position and the targets using the ‘decoupled joystick’ user interface. No additional illumination was provided except for a pulsed laser diode mounted at the distal tip of the device and, as before, the operators could only use feedback from the tip mounted camera for navigation purposes. A time limit of three minutes was imposed and the system was reset to a default ‘straight’ position between trials. Figure 5.6 shows six separate views of the flexible access platform within the abdominal cavity (*Note: the laparoscope was removed during the user trial*). Figure 5.7 shows the view from the onboard camera during this user trial. As with the laboratory trial, *Version_2* of the flexible access platform was used. This version featured a stereo-camera pair as can be seen in Figure 5.7.

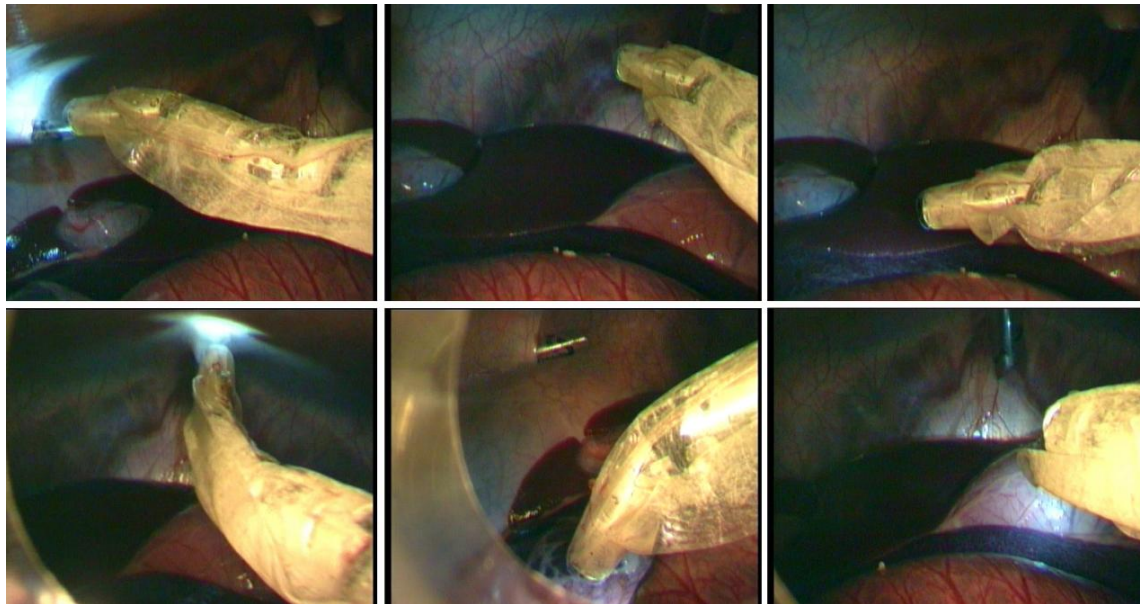


Figure 5.6: Images captured from a separate laparoscope during the in-vivo porcine user trials. Clockwise from top left, the flexible access platform visualising T1, visualising T2, visualising T3, a disorientated operator to the right of T4, a disorientated operator to the left of T1, visualising T4.

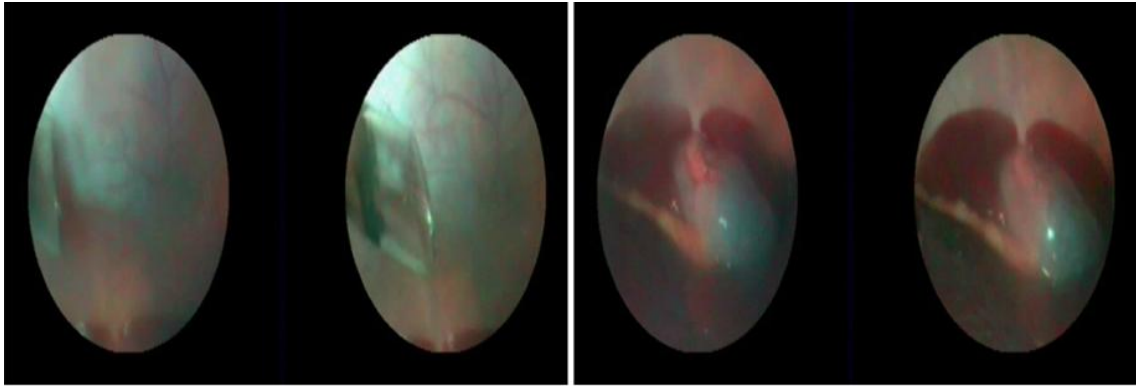


Figure 5.7: Images from the onboard stereo-camera pair captured during the in-vivo user trials. (left) Visualising target T1 – the tip of a trocar port and (right) Visualising target T3 – the gallbladder.

RESULTS

The results for the average time taken by each operator to complete the task along with their fastest time to complete the task are shown in Figure 5.8.

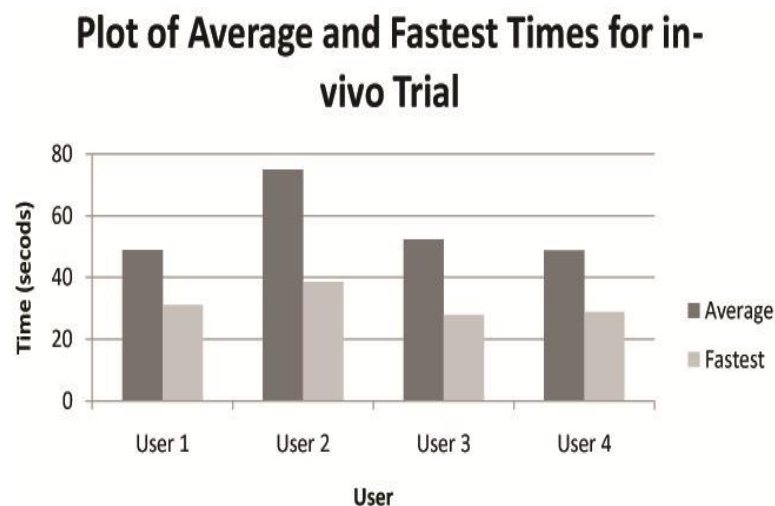


Figure 5.8: Plot of the average and fastest times when using the joystick user interface over 10 attempts during the in-vivo user trials.

DISCUSSION

The results derived are encouraging as they again indicate that the device is controllable using the direct ‘joint-to-joint’ control technique. However, both simulator and in-vivo trials show a large difference between the average and fastest times of the operators. It was also clearly observed by the author during these trials that the fastest times were recorded when the operator did not get disorientated. Conversely, the slowest times were often a direct result of disorientation. This indicates that the user input strategy does allow for the system to be successfully and quickly navigated around a spatial environment only if disorientation does not occur. However, the lack of positional information (and thus information regarding the joint

configurations) provided to the operator can result in disorientation which subsequently makes the task difficult to complete.

5.2.3 Conclusion

The user trials presented in this section have demonstrated that the direct ‘joint-to-joint’ control strategy allows the flexible access platform to be successfully navigated around a spatial environment. Additionally, from the data contained in Table 5.1, the ‘decoupled thumb-stick’ has been identified as the most suitable interface for deployment in a clinical environment. These results are important as they allow other elements of the flexible access platform (such as motor performance, flexibility/dexterity, robustness, instrument deployment, etc.) to be tested in both laboratory and in-vivo settings.

However, the user trials exposed the limitations of the overall system in its current form. Improvements could be obtained by implementing control features which utilise the position feedback in order to develop new user interface elements such as:

- A graphical display of the flexible access platform joint configuration which is presented to the operator.
- An option to utilise kinematic control of the flexible access platform or direct ‘joint-to-joint’ control. Should this be implemented, the operator would not be required to constantly switch between joints and the misalignment between the joystick axes and the axes of the universal joints could be eliminated.

With the incorporation of the position feedback potentiometers into the final design iteration of the joint module, both of these features have been implemented. Further discussion of the implementation is outside the scope of this thesis however.

While the user interfaces described above represent a practical solution to facilitate experimental trials with the flexible access platform, a second experimental user interface was also developed as part of this project. The purpose of developing an additional user interface was to investigate a potential solution to *Challenge 2* outlined in Chapter 1. Specifically, this involves providing a surgeon with enhanced intraoperative capabilities and reducing the number of specialists required to perform complex procedures. In this case, the use of gaze contingent control offers the potential to allow a surgeon to control the flexible access platform in a ‘hands-

free' manner. The next section will introduce two different gaze contingent control strategies and demonstrate the feasibility of the approaches for controlling the flexible access platform.

5.3 Gaze Contingent Control of the Flexible Access Platform

The handheld controller only takes up a small amount of space within the operating theatre. However, it still represents an additional piece of equipment which the surgeon must physically use in order to control the flexible access platform. Eliminating this requirement through the use of a 'hands free' control mechanism would further reduce the impact of the platform in-theatre. The purpose of this section is to introduce such a 'hands free' control mechanism whereby the joints of the platform are controlled by the location of the operator's fixation point on a monitor displaying the image feed from the onboard camera. The feasibility of intuitively controlling the flexible access platform in this manner will be demonstrated. As was mentioned above, this gaze contingent control concept addresses *Challenge 2* outlined in Chapter 1, as the technique offers the potential to both improve the controllability of flexible robotic instrumentation and to reduce the number of operators required in theatre. A key potential advantage of the technique is that it allows an operator to control the platform in a hands-free manner, thus allowing other instrumentation to be controlled simultaneously. In the case of a diagnostic laparoscopy, this could potentially allow an operator to control the movements of the platform while simultaneously retracting or moving organs using traditional instrumentation. Alternatively, during a minor interventional procedure, the technique potentially simplifies the overall ergonomics by allowing the operator to easily feed and deploy any instruments (endoscopic clips, biopsy forceps, diathermy tools) through the internal channels without needing to simultaneously manipulate the handheld controller.

This section will introduce two different gaze contingent control techniques compatible with the flexible access platform. The first technique provides joint level control with functionality similar to that of the 'decoupled thumb-stick' controller. The second technique uses current feedback from the micromotors embedded within the joint modules to automatically select the most suitable degree of freedom to actuate based on the direction in which the operator desires to servo the distal tip. The advantage of the former technique is that it provides the operator with explicit control over each joint unit and therefore allows full exploitation of the multiple degrees of freedom available. The advantage of the latter technique is that it further simplifies the overall control of the system by eliminating the need for the operator to consider which joint unit should be selected at any given time. Results of multiple user trials performed with both

techniques will be used to demonstrate the feasibility of deploying gaze contingent control strategies with the flexible access platform. The flexible access platform *Version_3* featuring 5-DoF was used during the gaze contingent control studies. Please see Appendix II for specific details of this version.

5.3.1 Eye Tracking Unit

Both gaze contingent control techniques utilise a Tobii x50 (Tobii Technologies AB, Sweden) stand-alone eye tracker positioned underneath a 1280x1024 screen displaying a graphical user interface (GUI). The x50 performs infrared video-based remote eye tracking and records 2D fixations on the screen at 50Hz with an accuracy of 0.5° and drift $<1^\circ$ across the work plane. The system allows for head movement within a working volume of $30 \times 16 \times 20 \text{ cm}^3$ (at 60cm from the unit) [149]. Subject specific calibration is required prior to operation, and during operation the raw data (i.e. the location of the fixation point) was median filtered with a window of 140ms to eliminate erroneous readings before transmission to the control software. Such readings can be introduced due to saccadic eye movement or blinking. The S-video output from the Medigus IntroSpico115TM camera control box is digitised and imported into the GUI. The right hand side of the GUI also features several command buttons required to operate the gaze contingent control techniques, as can be seen in Figure 5.9. The following sections will describe how the flexible access platform and the eye tracking unit were interfaced, along with the method of operation of the two gaze contingent control techniques.

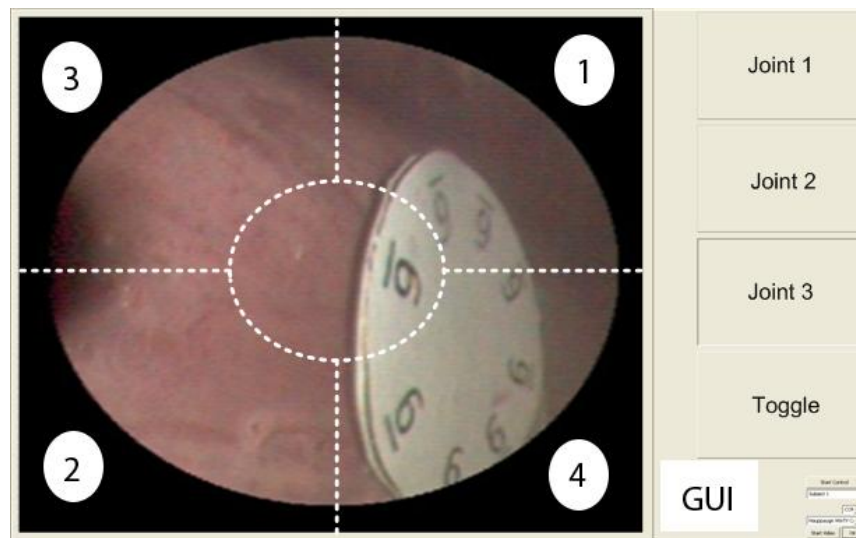


Figure 5.9: The GUI used for the experiments. The main feature of the GUI is the image feedback from the onboard camera. The white lines on this image illustrate the five segments used to identify which direction the user wishes to servo the system. The four buttons required to implement the two gaze contingent control techniques are shown on the right hand side of the screen. These buttons are selected when the user's fixation dwells on the button area for more than 300ms.

5.3.2 Flexible Access Platform – Eye Tracking Unit Interfacing

In the context of the overall flexible access platform system architecture, the eye tracking unit essentially replaces the handheld controller as the user interface. In order to provide the same functionality as the thumb-stick, a protocol was required to convert the user fixations from an xy coordinate on the screen to a control input for the motors. To achieve this, the image from the onboard camera was divided into five regions, as can be seen marked 1-4 in the image feed in Figure 5.9. The configuration of the segments was chosen so as to reflect the configuration of the universal joints of the flexible access platform, which are offset 45° from the gravity vector. By fixating in the relevant quadrant the operator can indicate in which direction they want the platform to move and give a proportional indication of what speed they want it to move at. The relationship between quadrant fixation and the resulting motor rotation for a typical universal joint can be seen in Table 5.2. The proportional gain is calculated from the measurement of the Euclidean distance between the fixation point and the centre of the camera image, and mapped linearly to a motor output voltage. Fixating on the central segment indicates that the user does not want the flexible access platform to move. In this manner, when the quadrants are mapped to a universal joint, a fixation in a given quadrant will result in the rotation of one of the motors of that universal joint with the following relationship:

Table 5.2: Truth table illustrating the relationship between quadrant fixations and resulting motor rotations for a single universal joint on the flexible access platform

Fixation Point	Motor 1 Rotation	Motor 2 Rotation
Quadrant 1	Clockwise	-
Quadrant 2	Anti-clockwise	-
Quadrant 3	-	Clockwise
Quadrant 4	-	Anti-clockwise
Central Segment	-	-

The above example holds for a universal joint, however the 1-DoF yaw joint units only have two possible directions in which to servo. In the case that the gaze contingent control is controlling a yaw joint, the image feed is only segmented into two segments, left and right of the centreline (i.e. a fixation in Quadrants 1 and 4 indicates that the operator wishes to servo the

system to the right while a fixation in Quadrants 2 and 3 indicates that the operator wishes to servo the system to the left).

This information is transmitted from the eye tracking application to the cRIO in the motor control box via an RS232 port at 30Hz. The cRIO then interprets which motor should be turned on, in which direction it should rotate and how much voltage to deliver to the motor. Thus, in order to move the flexible access platform in a specific direction, the operator fixates on a point in the relevant quadrant and the platform servos in that direction until the fixation point falls within the central region. In this manner the control loop is closed by the user's fixation point based on the image feedback from the onboard camera. A block diagram representation of this is shown in Figure 5.10. The white quadrant demarcation lines shown in Figure 5.9 were not visible to the users during the experiments. As an additional safety feature, in practice the system could be engaged via a footswitch (or similar device) when the operator requires the flexible access platform to be controlled by eye gaze. This effectively allows the operator to lock the field of view in order to fully observe all areas of the image when required.

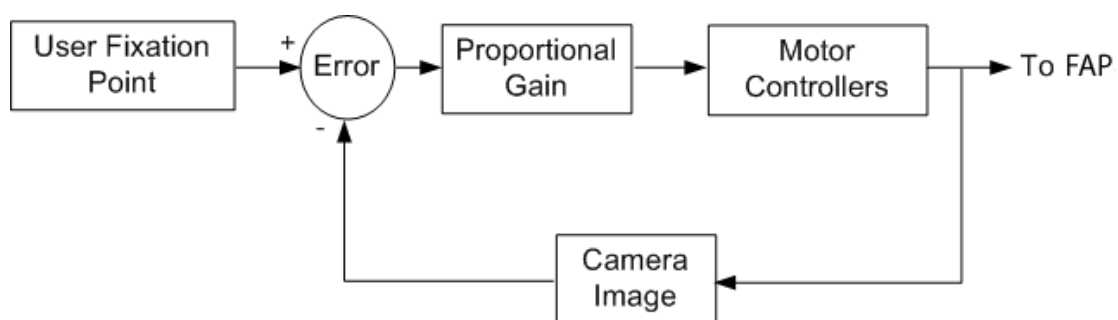


Figure 5.10: Block diagram of the gaze contingent control loop utilised in this study

Naturally, segmenting the screen into five regions is only suitable for controlling a 2-DoF robot. To enable full control of the 5-DoF of the platform, further features are required within the eye tracking application. How this input-output asymmetry was addressed will be described in Section 5.3.2.1 and Section 5.3.2.2. Each of these sections introduces a different gaze contingent control technique which was implemented during this study. The first provides the operator with the ability to control each degree of freedom independently, while the second uses an algorithm to select the most appropriate degree of freedom automatically. It was anticipated that the latter technique would provide a more intuitive control interface, as the operator does not need to consider which degree of freedom should be selected, while the former would provide more low level controllability and thus fully exploit the five degrees of freedom offered by the device.

5.3.2.1 Gaze Contingent Technique 1: Individual Joint Selection

To facilitate switching between the five degrees of freedom in a straightforward manner, it is necessary to define three joint units, only one of which may be actively controlled at any one time. Given the configuration of the flexible access platform *Version_3* used for these experiments, these joint units correspond to the distal universal joint (*Joint_1*), the medial universal joint (*Joint_2*) and the proximal yaw joint (*Joint_3*). Three buttons on the right hand side of the GUI allow the operator to switch between the joints by fixating on the relevant button for 300ms or longer. These buttons can be seen in Figure 5.9. When *Joint_1* is selected, fixations in each of the four quadrants map directly to motions of the distal universal joints (i.e. fixating in the upper left quadrant will actuate the joint module up and left). Similarly, when *Joint_2* is selected, control is passed to the medial joint. When *Joint_3* is selected, fixations left and right of the camera image centre servo the proximal joint to the left or the right. The speed at which the motor moves is proportionally scaled based on the distance between the centre of the image and the operator's fixation point. This scaling means that small movements of the flexible access platform can be obtained by fixating just outside the circumference of the central segment (Figure 5.9), while fast movements can be achieved by fixating close to the edge of the camera image. This direct "joint-to-joint" control paradigm is analogous to the toggling scheme introduced in Chapter 4 and allows many potential configurations to be obtained. However, servoing the robot over a large area requires multiple switching between the different joint units which can be time consuming.

5.3.2.2 Gaze Contingent Technique 2: Automatic Joint Selection

The second control strategy developed for the flexible access platform obviates the joint switching function so that the operator only has to fixate in the desired direction and a control algorithm will automatically select the degree of freedom to be activated. This is achieved by sensing the current drawn by each motor as it is actuating and automatically switching to the next suitable degree of freedom (which will continue motion in the desired direction) if the current drawn exceeds a predefined threshold. This threshold is set just under the current at stall torque and so provides a crude measurement of when a given motor is no longer free to rotate and has thus reached its actuation limit. This limit varied for each degree of freedom but was within the range 85-95mA at 4.8V. Measurement of the motor current is carried out by measuring the voltage drop across a 10 Ω shunt resistor. The algorithm initialises by defaulting to the distal universal joint and resets when the operator fixates in the central region. Thus, if the operator fixates in the lower left quadrant but the desired point to be visualised is outside the workspace of the distal joint, the algorithm will automatically switch to the medial joint and

then the proximal joint in sequence. Once at the desired location, the operator fixates in the central region and control is passed back to the distal joint for continued scanning in that configuration.

5.3.3 Results

The purpose of the user trials described in this study was to demonstrate the feasibility of using both gaze contingent techniques to control the flexible access platform in tasks similar to the user trials described in Section 5.2. A secondary goal was to identify any clear differences between the two techniques. To evaluate the ability of novice users to use the device for large area visualisation, five targets (T1 to T5) were placed at specific locations within an abdominal simulator [148], as shown in Figure 5.11. As before, the task was to actuate the flexible access platform to visualise each of the targets solely using feedback from the onboard cameras. The “target visualisation” condition was satisfied when the target was fully inside the field of view of the camera, as demonstrated in Figure 5.11. The locations of the targets were selected such that T1 could be visualised by only actuating the 2-DoF of the distal joint, T2 required both the distal and medial joints (i.e. 4-DoF) to be actuated and T3 – T5 required all three joints (i.e. 5-DoF) to be actuated. Additionally, with the exception of T5, sequential targets were placed in locations such that multiple traverses of the abdominal cavity were required to complete the task.

To standardise the trials and achieve a stable field of view, the flexible access platform was clamped to the table at a location which simulates the lower abdominal access typical for a SILS or NOTES procedure. Five novice users who had no experience in controlling the platform were selected and given five minutes to familiarise themselves with the system actuation characteristics and control strategies before performing two timed trials navigating the platform between the targets. A time limit of three minutes to complete the task was imposed and each user controlled the flexible access platform once with the *Individual Joint Selection* technique and once with the *Automatic Joint Selection* technique; the order of which was assigned randomly. The platform was reset to a default ‘straight’ position between trials, as shown in Figure 5.11, (*top, left*). The operators could not see the flexible access platform during the trials. Sample images showing two of the targets under visualisation from the onboard camera are shown in Figure 5.12. All users successfully completed the task using both gaze contingent control strategies. In order to differentiate between the strategies two variables were used to

evaluate their efficacy – the time taken for each operator to navigate between the targets and the distribution of the gaze fixations on the screen when navigating between targets.

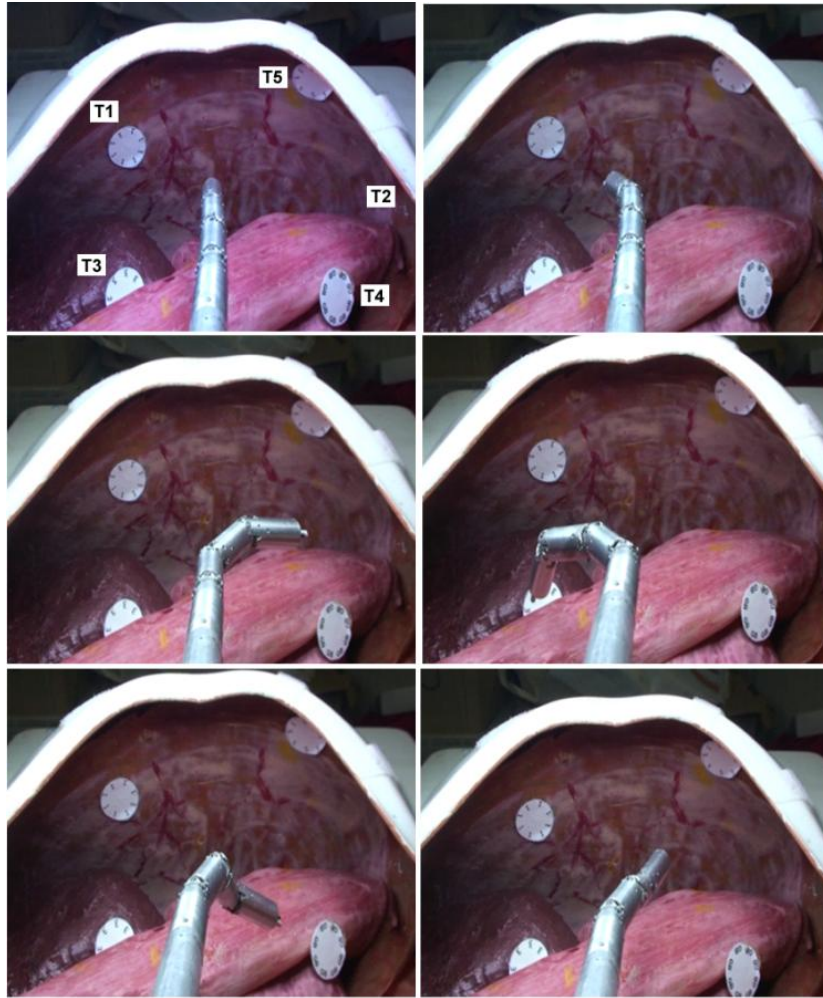


Figure 5.11: Images illustrating the robot in various poses during the user trials for gaze contingent control. (top, left) robot in the default start position, (top, right) visualising target T1, (middle, left) visualising target T2 (target not visible in image), (middle, right) visualising target T3, (bottom, left) visualising target T4, (bottom, right) visualising target T5.

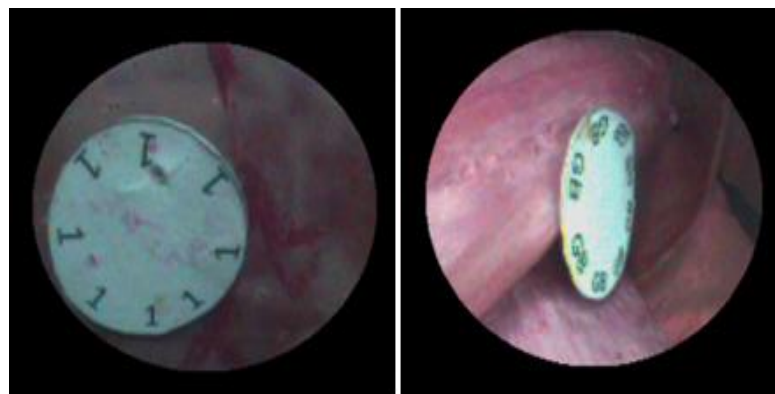


Figure 5.12: Sample images from the onboard camera showing the robot visualising T1 (left) and T4 (right).

5.3.3.1 Time Based Analysis

The times taken for each user to successfully complete the task using the Individual Joint Selection technique and the Automatic Joint Selection technique are shown in Table 5.3 and Table 5.4 respectively.

Table 5.3: Gaze contingent control user times: Time taken for each user to navigate between the targets when using the individual joint selection technique

	User 1	User 2	User 3	User 4	User 5
Target 1	4.3	4.0	4.5	6.2	6.6
Target 2	16.6	12.8	35.3	13.0	19.0
Target 3	9.9	8.15	19.0	16.7	14.1
Target 4	20.1	13.6	14.1	15.8	8.2
Target 5	7.4	4.5	3.7	8.75	8.8
Total	58.3	43.1	76.6	60.3	56.7

Table 5.4: Gaze contingent control user times: Time taken for each user to navigate between the targets when using the automatic joint selection technique

	User 1	User 2	User 3	User 4	User 5
Target 1	4.0	3.8	4.1	2.6	6.0
Target 2	10.1	6.7	10.7	7.2	8.3
Target 3	7.3	7.3	8.2	8.1	22.6
Target 4	13.2	10.1	7.3	8.3	6.7
Target 5	6.9	7.2	8.4	3.2	8.7
Total	37.5	35.1	38.7	29.4	52.3

The results indicate that even with minimum training on how to use the system, the five operators were able to successfully complete both tasks within the time allowed. With the exception of one user, all users completed the task in 60 seconds or under. Given the unfamiliarity of the operators with both the gaze contingent control techniques and the multiple degrees of freedom of the flexible access platform, these results are encouraging and clearly show that the control strategies are intuitive and straightforward to use. Additionally, the data listed in the *Total* columns of each table highlight that each user completed the task quicker

when controlling the platform using the *Automatic Joint Selection* technique. Analysing the average task completion time for all users shows a 35% decrease when using this technique. To illustrate this in more detail the average time taken for all users to reach each target using both techniques was extracted from the data and plotted. The results are shown in Figure 5.13.

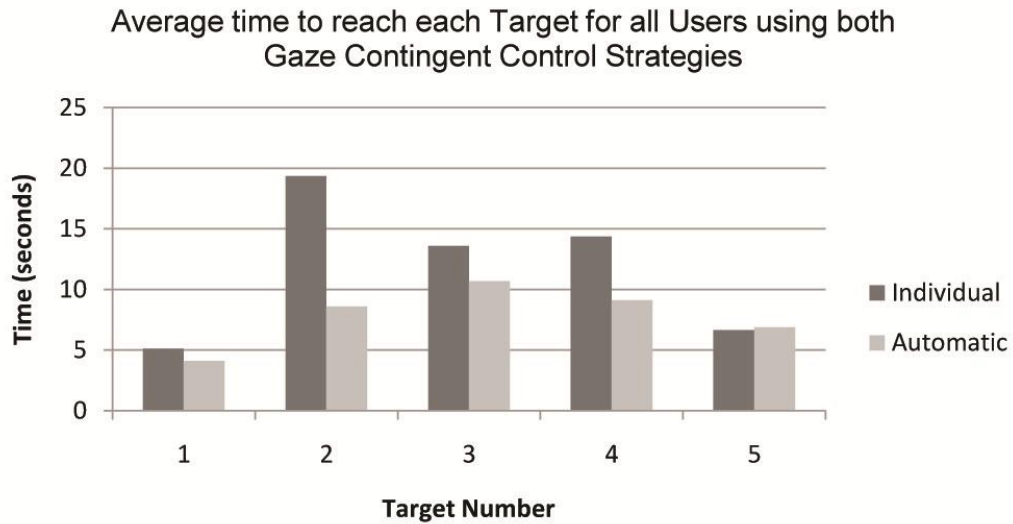


Figure 5.13: Average time taken for all users to reach each of the five targets. Times for both control strategies are shown.

This figure again illustrates that for all targets, the time taken to complete the task is faster when using the *Automatic Joint Selection* technique. This can be attributed to the fact that the operator does not lose time directing their fixation point to the joint selection buttons and pausing to select a joint. Additionally, the cognitive workload is reduced as the operator does not have to consider the robot configuration and make a decision regarding which joint unit should be actuated next. It is also notable that the quickest targets to be acquired are those where only limited actuation is required (i.e. from the default position to T1 and from T4 to T5). For these targets there is very little difference between the times for the two techniques. This reinforces the hypothesis that delays are introduced when the user is transitioning between targets which require multiple degrees of freedom to be actuated and hence multiple switches between joint units. This additional time spent fixating on the buttons can be further examined by analysing the fixation point distributions between targets.

5.3.3.2. Gaze Fixation Distribution

To illustrate the difference in fixation distribution between the two strategies, the corresponding fixations of User 1 for targets T1 - T4 are shown in Figure 5.14 (*Individual Joint Selection* technique) and Figure 5.15 (*Automatic Joint Selection* technique). Each subplot displays the

fixations on the entire area of the screen while searching for a given target. In Figure 5.14 the *x-axis* of the subplots are 1280 pixels wide and the *y-axis* is 1024 pixels high. The *Joint* selection buttons are located at pixel values greater than 1000 on the *x-axis* and their approximate locations are marked with grey rectangles. These *Joint* selection buttons are disabled in the *Automatic Joint Selection* technique and so the *x-axes* of the subplots in Figure 5.15 only run to 1000 pixels.

When comparing the fixation distributions as the user controls the platform to visualise the same targets (i.e. Target 1 in both Figure 5.14 and Figure 5.15, Target 2 in both Figure 5.14 and Figure 5.15, etc) it is clear that the additional effort required to fixate on the different joint selection buttons, significantly increases the time taken to complete the task. Looking initially at T1 for both control techniques – this particular target is relatively easy to visualise as it does not require multiple joint units to be actuated. As a result, few fixations should be required to visualise the target. However, when using the *Individual Joint Selection* technique, the operator must initially select the relevant joint unit (this action which can be seen by the single fixation point over the *Joint_1* selection button on the right hand side of the plot) which delays the operator in reaching the target. This delaying effect of the *Individual Joint Selection* technique is amplified when looking at the fixations performed in order to visualise T2. This action requires the flexible access platform to servo from a straight position to observe the target on the right wall of the simulator as shown in Figure 5.11 (*middle, left*). In this case the operator makes multiple selections of the different joint units, as evidenced by fixations on each of the three joint buttons, even though only the distal and medial joints are required to visualise the target. In comparison, the fixations of the same operator (when employing the *Automatic Joint Selection* technique) are located in a focused cluster on the right hand side of the plot. The operator does make two fixations back in the centre of the plot, which would imply that the flexible access platform had reached the limit of its travel in a given direction and the operator was passing control back to the distal joint. This tighter clustering of the fixations in the known direction of the target indicates that when using the *Automatic Joint Selection* technique, the system is easier to control and more efficient than when using the *Individual Joint Selection* technique.

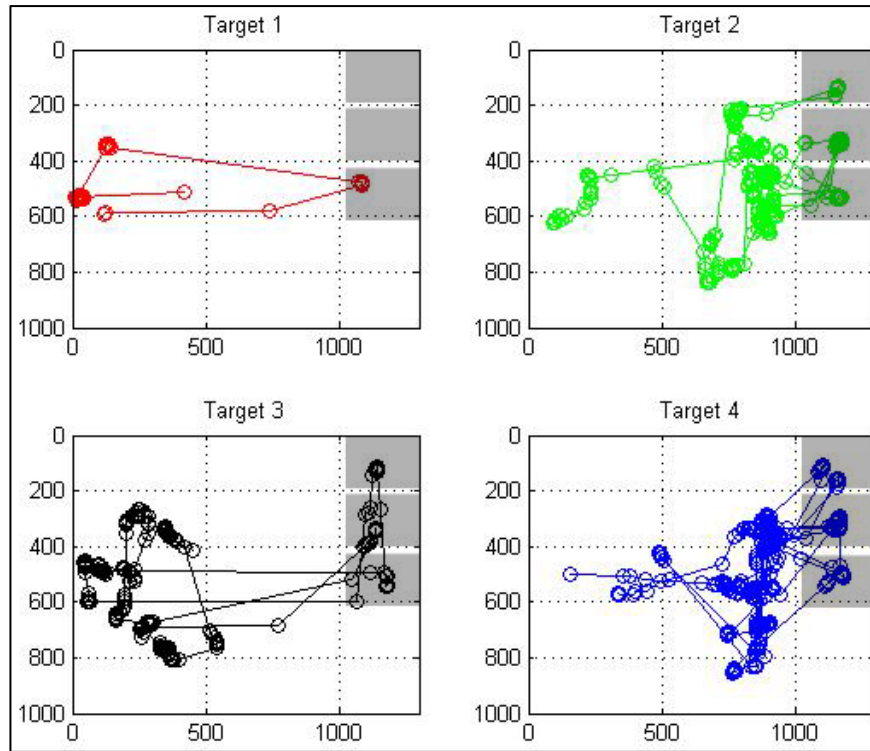


Figure 5.14: User 1 fixations for Individual Joint Selection when serving the robot to (top, left) Target 1, (top, right) Target 2, (bottom, left) Target 3 and (bottom, right) Target 4. All units are in pixels. The grey rectangles in each plot correspond to the approximate locations of the Joint Selection Buttons in the GUI.

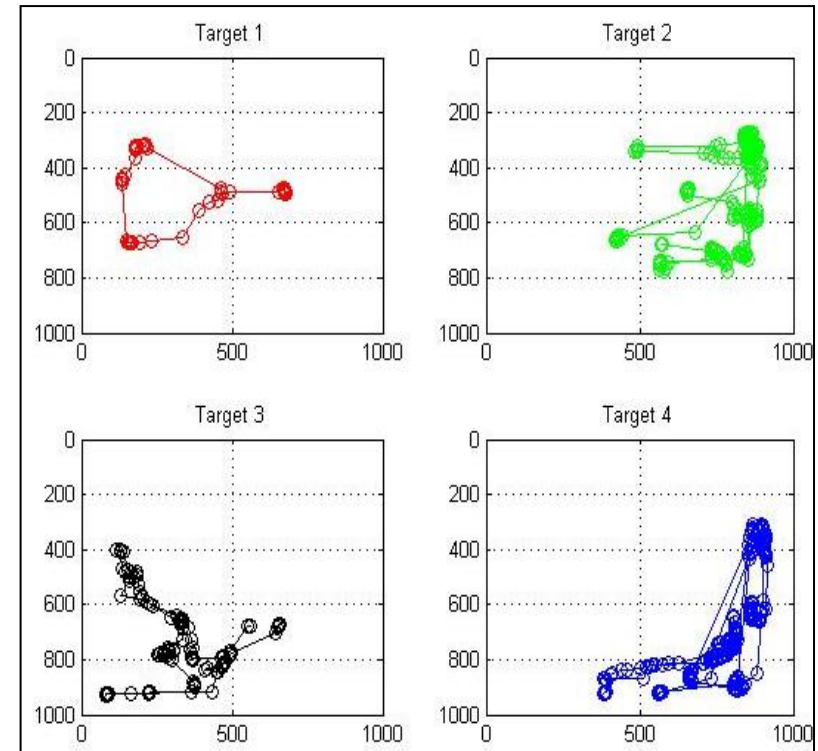


Figure 5.15: User 1 fixations for Automatic Joint Selection when serving the robot to (top, left) Target 1, (top, right) Target 2, (bottom, left) Target 3 and (bottom, right) Target 4. All units are in pixels.

This same pattern is repeated when looking at the fixations used to servo the platform to visualise both T3 and T4. These targets are located in the lower left and lower right of the abdominal simulator. When using the *Automatic Joint Selection* technique, the location of the fixation clusters are clearly seen to be co-located in the quadrants known to contain the target markers. However, in the case of the *Individual Joint Selection* technique the fixation distribution is more diffuse and multiple user fixations on the *Joint* selection buttons are required. As expected, this indicates that the latter technique requires more user interaction than its automatic counterpart and therefore more time is required to complete the task.

5.3.4 Conclusion

This section demonstrates the feasibility of controlling a flexible robotic device through the eyes of the operator. The provision of controlled distal dexterity to facilitate large area visualisation and targeting in an intuitive, hands-free manner offers the potential to free the operator from directly controlling the system with the handheld controller. This capability could be used, for example, during the transvaginal tubal ligation procedure introduced in Chapter 4. In this scenario, the operator could target the flexible access platform using the gaze contingent interface and simultaneously manipulate any interventional instruments inserted through the internal channel(s) with both hands. This could eliminate the need for a surgical assistant to manipulate such instruments and potentially provides a solution to *Challenge 2* outlined in Chapter 1 by reducing the overall number of operators required to perform flexible access surgery.

However, the studies presented in this chapter only represent preliminary feasibility results and further work is required to fully characterise operator performance during more complex user trials. Issues such as potential visual fatigue introduced by the system over longer periods need to be investigated. Additionally, the practical challenges of deploying the eye tracking system in-theatre should be considered. In that environment a direct line-of-sight between operator and monitor is not always possible and the operator might need to move out of the pre-defined volume where accurate tracking can be achieved. A potential solution to this issue is to use a wearable eye tracking system; however, this introduces new challenges with regard to locating the fixation point of the wearer on the monitor and the cumbersome nature of such systems.

5.4 Discussion and Conclusion

This chapter provided a detailed description of two different user interface platforms suitable for controlling the flexible access platform. The first user interface provides the operator with the ability to control each degree of freedom of the system using a direct ‘joint-to-joint’ control paradigm via a handheld controller. Given the lack of position feedback available in the early versions of the platform, this approach offered the functionality required for rapid deployment and testing in laboratory and pre-clinical settings. It also provides the low level control over individual joints which is necessary to take full advantage of the dexterity of the platform. In addition, the ‘decoupled thumb-stick’ design offers flexibility within the operating theatre through its portability and adaptability – attributes essential for the future deployment of ‘focused’ robotic devices into operating theatres. While the direct ‘joint-to-joint’ control paradigm has proven to be successful for controlling the flexible access platform in a clinical setting, the results of the usability trials indicate that additional features are required to fully leverage the potential of the robotic platform. This is a similar conclusion to that identified in Chapter 4. It is anticipated that features such as the option to utilise kinematic control to eliminate the need for switching between joint units, and a graphical representation of the joint configurations to reduce operator disorientation, will build on the existing success of the interface.

The use of gaze contingent control represents a novel user interface for the control of a flexible robotic device. The combination of the onboard camera and a monocular eye tracking system offers controlled distal dexterity and the ability to perform large area visualisation and targeting in an intuitive, hands-free manner. This technique aims to directly address elements of *Challenge 2* by reducing the number of operators required to perform flexible access procedures while also improving the usability of the systems deployed. The addition of the *Automatic Joint Selection* technique provided users with a simplified interface, and this simplification was demonstrated in the reduction in time taken to complete the user trials. However, it is acknowledged that any future deployment of the technique would require further trials and system characterisation.

The next chapter in this thesis will switch from presenting solutions to the challenges posed by the controllability and ergonomics of the flexible access platform and move to address the issue

of how to provide surgeons with enhanced intraoperative imaging capabilities via robotically controlled instruments, as identified in *Challenge 3* in Chapter 1.

Chapter 6:

Intraoperative Force Adaptive Imaging with the Flexible Access Platform

The previous two chapters introduced a seven degree-of-freedom flexible access platform and two different control methodologies designed to address *Challenges 1, 2 and 4* as outlined in Chapter 1. These challenges relate to the provision of controlled flexibility along curved pathways, simplified ergonomics and the ability to pass interventional instrumentation. However, the issue raised by *Challenge 3* – improving the intraoperative information flow through the integration of multi-spectral imaging techniques – has yet to be addressed using the flexible access platform. In this chapter, an additional device designed to be used in conjunction with the platform will be described. The new device aims to provide enhanced functionality and to improve a surgeon’s ability to deploy in-vivo optical imaging probes in a minimally invasive manner. The goal is to facilitate the acquisition of accurate and repeatable ‘optical biopsy’ images in an ergonomic and controllable manner. By decoupling the operator from the complex manipulations required to target such optical imaging probes in-vivo, the system offers the

potential to improve the intraoperative information flow and simultaneously provide more time for therapeutic and interventional decision making. The additional device developed for this task is a force adaptive linear servoing mechanism which is capable of automatically holding and translating an optical imaging probe while maintaining a consistent contact force between the probe and the target tissue. The combination of the flexible access platform and the force adaptive linear servoing mechanism allows an optical imaging probe to be easily navigated and targeted in-vivo using only the handheld controller described in Chapter 5. Details of the effect of a changing contact force on image consistency will be described for an ex-vivo tissue sample. Additionally, detailed ex-vivo experiments to demonstrate the efficacy of the system for maintaining a consistent contact force between a multi-spectral fluorescence imaging probe and a tissue sample will be provided. Although primarily addressing *Challenge 3* as outlined in Chapter 1, the force adaptive linear servoing mechanism also addresses elements of *Challenge 2* and *Challenge 4*, by providing a clinician with the ability to target optical imaging probes along curved instrument pathways in a repeatable, controllable and ergonomic manner.

6.1 Flexible Access Surgery and Probe-Based Optical Imaging

Some of the earliest proposed intraperitoneal applications of the NOTES component of flexible access surgery were for diagnostic peritoneoscopy [150, 151], tumour staging [152] and minor interventions, such as liver biopsy and tubal ligation [153, 154]. Many pre-clinical and clinical trials have been performed using existing endoscopic equipment, and although generally successful, the authors have commented that improvements in technology would increase the usefulness and efficacy of the approach. The challenge of ‘improvements in technology’ can be viewed from two (or more) perspectives. The first is that of improved instrumentation. The papers cited above mention that although successful in navigating around the peritoneal cavity, the inherent flexibility of the endoscope can result in problems targeting and obtaining tissue biopsies. The flexible access platform presented in this thesis is ideally suited to provide surgeons with the necessary dexterity and platform stability to perform such tasks – a feature that will be further discussed in Chapter 7. However, a second perspective on improving the technology available is that of the incorporation of real-time optical imaging techniques into the operating platform. Emerging techniques such as probe-based confocal endomicroscopy (pCLE) [155], fluorescence spectroscopy [156] and optical coherence tomography (OCT) [157] each offer the potential to provide real-time, near histopathological grade information to a clinician without the delays, risks or discomfort posed by standard biopsy. The combination of the reduced patient trauma possible via a flexible access surgery approach and the facilitation of

simultaneous virtual histology, could potentially offer significant benefits during many of the procedures mentioned above. However, it is essential to note that at this stage the techniques listed above are experimental and their future uptake will be reliant on the clinical community developing methodologies and protocols which allow ‘optical biopsy’ images to be interpreted as accurately as the current gold standard of histopathology. Further discussion of this topic is beyond the scope of this thesis but it is important to note that the optical biopsy images contained in the following chapters are provided for illustrative purposes only and are not intended to be viewed for diagnostic purposes.

A challenge of using optical imaging probes in an in-vivo environment, and hence providing high quality images, is the difficulty of deployment and ergonomic control. Such probes are typically deployed using conventional endoscopes, which are designed for intra-luminal interventions and not navigation within a spatial environment such as the peritoneal cavity. Tasks such as navigating the endoscope to create a mosaic or representative video sequence of a lesion or abnormality require steady contact between the probe and the tissue and a slow translation over a few millimetres. This is further complicated by tissue deformation due to the contact and/or respiratory and cardiac motion. Additionally, from an ergonomic perspective, the operator is required to simultaneously control the insertion depth and axial roll of the endoscope with one hand, control the deflection of the distal tip via the control wheels with the other hand and still insert the imaging probe through the biopsy channel of the device. As was mentioned above, the dexterity and controllability of the flexible access platform provide solutions for the challenges posed by the endoscope as an instrument. However, a research niche exists to also improve the control and ergonomics with which the optical imaging probe is deployed. This in turn can lead to improvements in the consistency and repeatability of the images acquired. Of particular relevance is the issue of probe-tissue contact force and how it is controlled in an in-vivo setting. In [158] it was found that variations in contact force between an ex-vivo tissue sample and optical spectroscopy probes induced major profile alterations in the diffuse reflectance spectra and significant intensity increases in the fluorescence spectra. These changes can be attributed to:

1. The coupling efficiency between the tissue and the fibres.
2. The change in optical scattering properties due to compression.
3. The increase in signal from deeper tissue layers with increasing pressure due to the displacement of surface layers.

These results indicate that in order to obtain accurate and repeatable optical biopsy images, the contact between the imaging probe and the tissue should be controlled where possible [159].

The force adaptive linear servoing mechanism presented here has two purposes. The first is to provide a straightforward probe advancement device which simplifies the ergonomic challenges experienced by clinicians when attempting to deploy optical imaging probes through endoscopes. The second purpose is to facilitate a more advanced robotically assisted system that aims to improve the accuracy and repeatability of probe-based optical imaging by maintaining a consistent contact force between the probe and the tissue during image acquisition. The system also synchronises the image capture from the optical imaging probe with the onboard camera and the trajectory of the joints as the flexible access platform actuates. This can potentially improve the intraoperative information flow for the clinician by allowing seamless localisation of the optical biopsy images within the surgical field of view. The following sections will describe the system configuration and provide detailed ex-vivo results demonstrating the importance of maintaining a consistent contact force. The ability of the flexible access platform to target an imaging probe, while both maintaining a consistent contact force and synchronising the image and tip trajectory information, will also be demonstrated. In addition, the ability of the system to perform ‘hands-free’ probe advancement during an in-vivo diagnostic peritoneoscopy will be discussed in Chapter 7.

6.2 Force Adaptive Linear Servoing Mechanism

The key design requirements of the force adaptive linear servoing mechanism are as follows:

- To attach to the shaft of the flexible access platform
- To safely and securely clamp the proximal end of any optical imaging probe that can pass through the flexible access platform
- To measure relative changes in the axial force imparted onto the imaging probe by contact at its distal tip
- To provide fast, accurate linear translation of the imaging probe based on the feedback from the axial force measurement or the operator

The key hardware and software elements of the mechanism will now be described.

6.2.1 Hardware

Each of the key hardware components of the force adaptive linear servoing mechanism can be seen in the CAD schematic shown in Figure 6.1. The mechanism is attached to the shaft of *Version_3* of the flexible access platform via the ‘Shaft Clamp’ at a location proximal to the opening of the ‘Internal Channel’. This allows the optical imaging probe to be secured into place using the ‘Probe Clamp’ and threaded through the ‘Internal Channel’ of the platform. The probe then passes through the channel and exits from the distal tip of the platform. The probe clamp is directly attached to the ‘Slider’ of a ‘Rack and Pinion’ (24 teeth, Module 0.25) translation mechanism which is driven by a brushed DC motor (Maxon RE10 6V, 16:1 gearhead, MR Type Integrated 256cpr Quadrature Encoder). The rack and pinion configuration was chosen for its simplicity, back-drivability and fast response time. The construction of the slider is such that the imaging probe translates into the internal channel as the motor rotates anticlockwise, and out of the channel as the motor rotates clockwise.

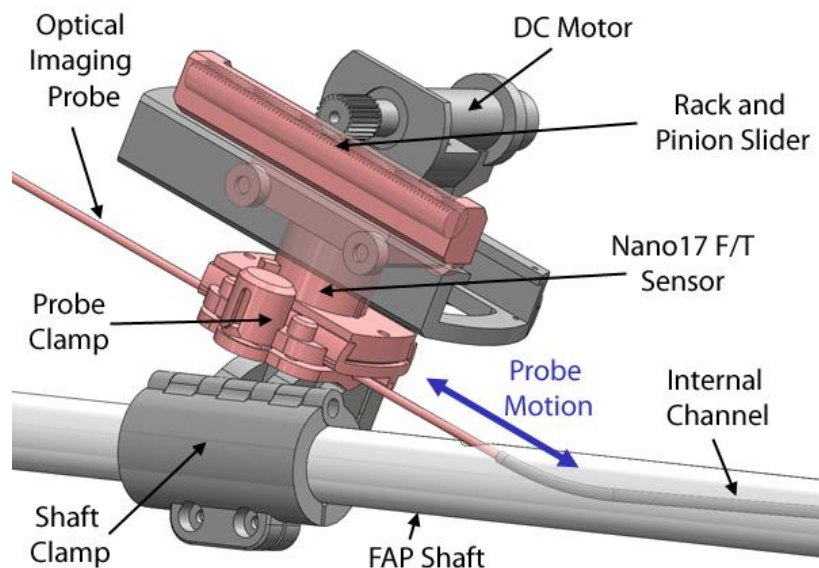


Figure 6.1: Schematic illustrating the force adaptive linear servoing mechanism. The components which translate to servo the probe (rack, slider, force/torque sensor, clamp and optical imaging probe) are marked in red and the probe translation motion is marked with a blue arrow.

The axial load along the central axis of the probe is measured by an embedded Nano17 (calibration SI-12-0.12) 6-axis Force/Torque sensor (ATI Industrial Automation, USA). Given proximal positioning of the sensor at a distance of approximately 500mm from the tip of the flexible access platform, the force measured by the sensor will not be representative of the absolute contact force between the distal tip of the probe and the tissue surface. This absolute

measurement will be masked by interferences; these are introduced due friction and backlash in the internal channel, the tortuosity of the flexible access platform (due to changes in the frictional interference effects along the length of the probe as it is required to pass through the articulating links) [160] and some buckling as the probe enters the internal channel. However, the purpose of the system is not to provide the operator with an accurate absolute force measurement between the tissue and the imaging probe, but rather to advance the probe until tissue contact is identified and then to maintain the relative force at a consistent level during image acquisition. It is assumed that if the distal tip of the flexible access platform only undergoes small amounts of translation during image acquisition, then the force measured remotely from the tip (and transmitted through the probe) is sufficiently representative of the tip interaction force to drive the controller. Further investigation into this assumption will be detailed in Section 6.4.2.

6.2.2 The Control Hardware and Software

In order to measure the probe-tissue interaction force and control the translation of the probe, a closed loop force control scheme was created in the *LabView* development environment. The Nano17 F/T sensor is mounted such that the axial force transmitted along the centreline of the probe is measured by the *x-axis* of the sensor. This signal is acquired using a NI-6221 Analogue Input acquisition card (National Instruments Corp., USA). This signal forms the feedback to the force controller which utilises proportional control to generate an output signal for a differential operational amplifier via a NI USB-6009 Multi-function DAQ board (National Instruments Corp., USA). The differential amplifier generates a signal suitable for bipolar control of the motor. This signal then forms the input to a Pulse Width Modulation (PWM) based speed controller (LSC 30/2 linear 4Q Servo amplifier, Maxon Motor AG, Switzerland) for the brushed DC Maxon motor. The speed of the DC motor is measured by an integrated quadrature encoder and regulated by the speed controller. A block diagram of the overall control system is shown in Figure 6.2 below.

In addition to the force adaptive linear servoring mechanism, a joint position estimation scheme was implemented to measure the position of the two distal degrees of freedom of the flexible access platform. This was achieved by counting a pulse output from the SSD04 drive electronics chip for each full rotation of a motor. Counting the number of pulses and the direction of rotation of the two motors allows for the position of the distal tip to be estimated. Full details of the implementation can be found in Appendix II (*flexible access platform Version_2*).

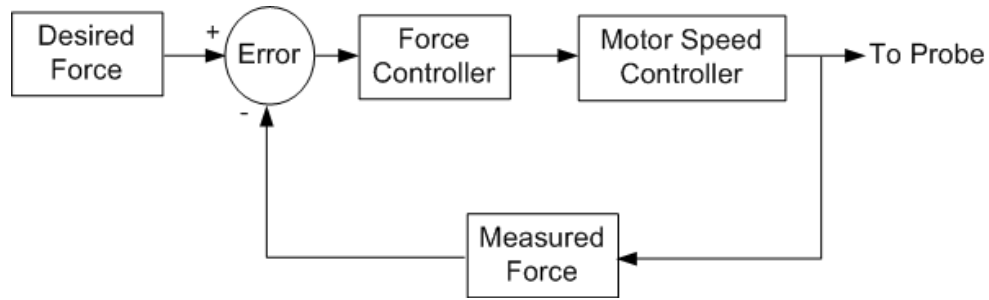


Figure 6.2: Block diagram of the control loop running the force adaptive linear servoing mechanism. Key components include a ATI Nano17 F/T sensor and NI-6221 data acquisition card, the RE10 Maxon motor and LSC 30/2 servo amplifier, a NI USB-6009 and differential amplifier, and a computer running the *LabView* software.

6.3 Optical Imaging probes

Two different optical imaging probes were deployed with the flexible access platform during these experiments. These were a research fluorescent imaging probe under development at the Biophotonics and Surgical Imaging Lab of the Hamlyn Centre [130] (described in [159]), and a commercial system from Mauna Kea Technologies [161]. Both are compatible with the platform and the force adaptive linear servoing mechanism and demonstrate the overall adaptability of the architecture. In the interest of completeness, both imaging probes will be briefly described below.

6.3.1 Fluorescent Imaging Probe

Fluorescence emission measurements were taken using a 2mm diameter flexible fibre-optic probe (Romack, V.A., USA) consisting of 7 hexagonally assembled fibres, each having a 200 μ m core diameter and a 0.22 numerical aperture. Excitation light was provided by a 375nm laser diode collimated with a 4.6mm focal length lens and focused into a central excitation fibre with an 8mm focal length lens. The fluorescence emission light collected by the six fibres surrounding the central fibre was arranged into a linear array which was imaged onto the 80 μ m wide slit of a spectrograph (Specim Ltd, Finland). A 405nm longpass filter was inserted to block the reflected excitation light, and the light was dispersed by a prism-grating-prism element of the spectrograph and detected with a cooled CCD camera (Retiga EXI, QImaging, 1392 $\times$ 1040 pixels). The camera and the beam shutter were also controlled through *LabView* (exposure time phantom, 1ms; exposure time liver, 10ms; region of interest 1392 $\times$ 110) and the autofluorescence spectrum was acquired in a single shot with a frame-rate of 130ms. Image acquisition from the onboard Medigus camera is also synchronised with the autofluorescence signal acquisition, which allows the immediate localisation of the probed site within the camera

field of view. A sample image showing the intensity of the fluorescence emission light from the six sensing fibres when not in contact with a tissue sample is shown in Figure 6.3.

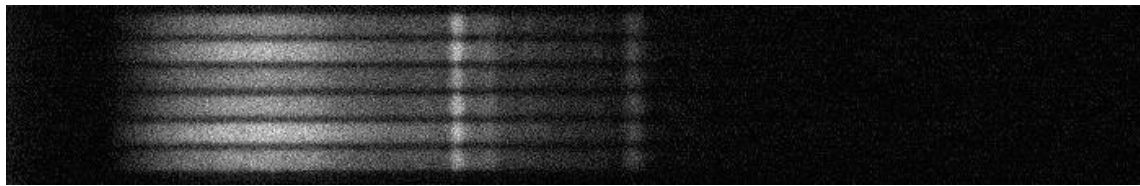


Figure 6.3: Sample spectral images from the six sensing fibres showing the non-contact condition. Image source: Vincent Sauvage, Imperial College London.

6.3.2 Micro-confocal Endomicroscopy

The CellVizio probe-based Confocal Laser Endomicroscopy (pCLE) system from Mauna Kea Technologies was deployed with the flexible access platform during the in-vivo studies and the experiments to qualitatively evaluate the effect of contact force on tissue samples. The system is capable of providing high-resolution, real-time, in-vivo images or ‘optical biopsies’. The specific probe used during the studies mentioned above was the CellVizio GastroFlex™ ‘Z’ Probe (Mauna Kea Technologies, Paris, France). It uses a 488nm laser focused on a confocal plane at a tissue depth of 100µm, and the reflected fluorescence is acquired at 12 frames per second with a resolution of 3.5µm and 15µm in the lateral and axial resolutions respectively. It has a 600µm diameter field of view. Example images captured with this probe are shown in Section 6.4.1.

6.4 Validation Steps

Two validation experiments were performed prior to carrying out the experimental assessment of the force adaptive linear servoing mechanism. The purpose of these experiments was to:

- demonstrate the effect of contact force on an ex-vivo tissue sample using a pCLE imaging probe (GastroFlex™, Mauna Kea Technologies, Paris, France) in a controlled environment;
- validate the assumption that the force measurement from the F/T sensor mounted in the servoing mechanism (at proximal end of the platform shaft) is sufficiently representative of the actual contact force between the probe tip and the tissue to drive the force controller.

In the first experiment, the probe is used without the flexible access platform to demonstrate qualitatively how changing the contact force affects the images obtained from an ex-vivo porcine stomach sample in a controlled environment. The second experiment utilises the same

imaging probe in a simulated clinical scenario with *Version_5* of the flexible access platform. In this experiment the probe is passed down the internal channel of the platform and engaged with a second F/T sensor to assess the differences between the forces measured at the force adaptive linear servoing mechanism and at the tip.

6.4.1 Effect of Contact Force on pCLE ‘Optical Biopsy’ Images

In order to assess the effect of contact force on the resulting optical biopsy image, the force adaptive linear servoing mechanism was mounted orthogonal to an ex-vivo stomach tissue sample, as can be seen in Figure 6.4. The system was not integrated with the flexible access platform for these experiments so that the effects of friction between the probe and the internal channel would not affect the readings. Since the pCLE probe is clamped into position orthogonal to the tissue sample in this controlled environment, it can be assumed that the force measured by the F/T sensor is representative of the absolute interaction force between the probe and the tissue sample.

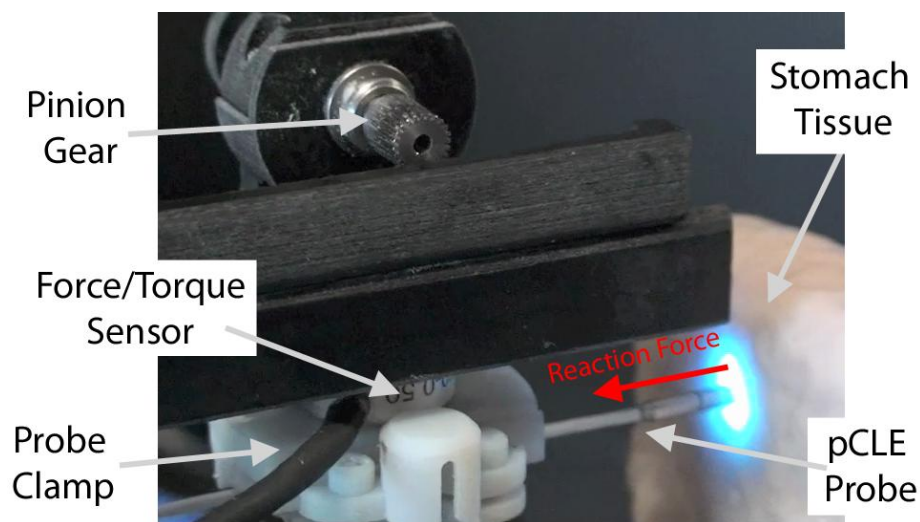
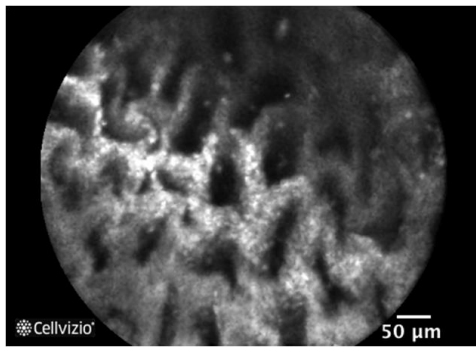


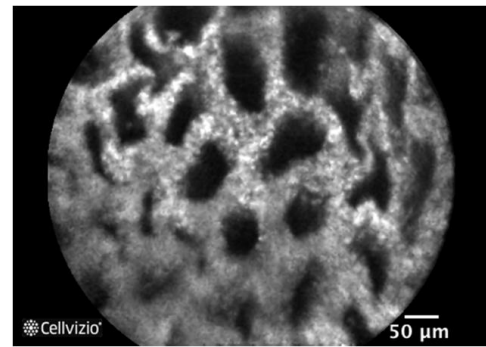
Figure 6.4: The ex-vivo test rig constructed to evaluate the effect of contact force on the optical biopsy image. The F/T sensor, probe clamp, probe and ex-vivo tissue can be clearly seen. The force adaptive linear servoing mechanism was not attached to the flexible access platform during these experiments so as to eliminate the effects of friction on the force reading as the probe passes through the internal channel. Therefore, the reaction force measured by the F/T sensor can be assumed to be representative of the absolute contact force between the probe and the tissue.

The protocol employed for these tests was to advance the probe into contact with the tissue and to increase the contact force in increments of 5mN from 0N to 35mN. The resulting images recorded at each force increment are shown in Figure 6.5. The magnitude of the forces required to generate a noticeable change in the tissue were found heuristically, and it is interesting to

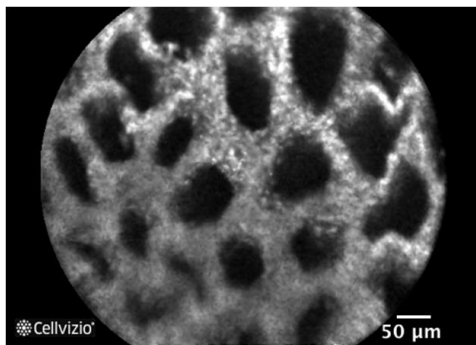
note the small magnitudes involved. The resulting images clearly display the underlying crypt (glandular structures located in the epithelial lining of the small intestine and colon) based architecture of the tissue. The reason for using this particular tissue type is that changes in crypt architecture are being proposed as a tool for in-vivo assessment of ulcerative colitis and intraepithelial neoplasias using CLE techniques [162] [163]. The metric on which the different grades of inflammation are assessed include the crypt diameter, regularity of shape and inter-cryptal distance. Qualitatively, it is clear from the images shown in Figure 6.5, that as the contact force increases, the shape and diameter of the crypts change. So too does the inter-cryptal distance. These images indicate that if using pCLE as a diagnostic tool, a system such as the force adaptive linear servoing mechanism should be employed to ensure that a consistent contact force is maintained between the probe and tissue surface; thus guaranteeing that comparable images are obtained. The ability of the force adaptive linear servoing mechanism to achieve this goal will be demonstrated with detailed ex-vivo experiments with the fluorescence spectroscopy probe in Section 6.5.



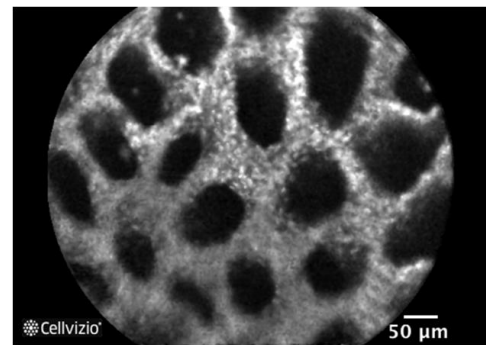
Contact force = 5mN



Contact force = 10 mN



Contact force = 15mN



Contact force = 20mN

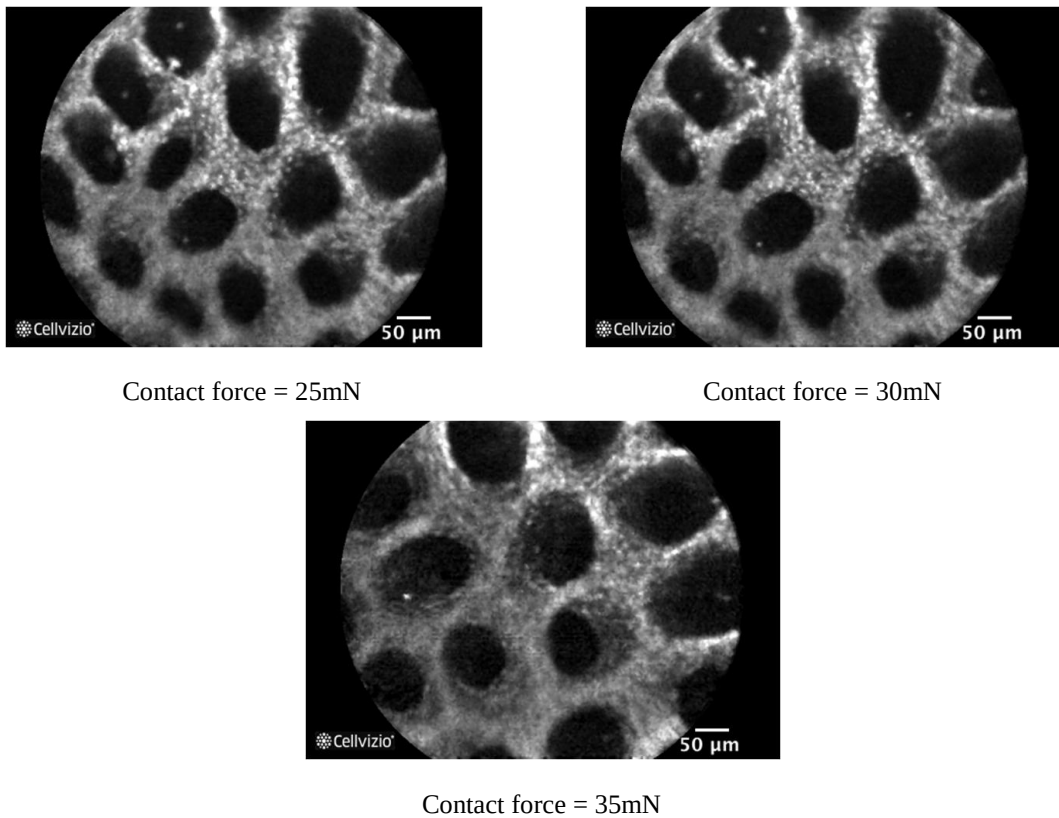


Figure 6.5: Multiple probe-based confocal endomicroscopy images taken at different contact force levels on ex-vivo porcine stomach. These images demonstrate the effect that varying contact force has on the optical biopsy images, and the importance of maintaining a consistent force if used for diagnostic purposes.

6.4.2 Validation of the Relative Force Measurement Principal

The second experiment carried out before testing the force adaptive linear servoing mechanism in a simulated MIS environment was to validate the assumption that the force measurement from the F/T sensor at the proximal end of the platform shaft is sufficiently representative of the probe tip contact force to drive the force controller. As was discussed in Section 6.2.1, the purpose of the system is not to provide the operator with an absolute force measurement of the tip interaction force. Measurement of this force is not possible with the current configuration given the interference effects of friction between the probe and the sheath, and how this would vary at different angles of joint displacement. Instead the system is designed to measure any relative changes in force as the probe is servoed over the tissue surface, and to adjust the position of the probe accordingly. To demonstrate that the system is capable of measuring this relative change in contact force and using this measured value to drive the force controller, a experimental test was performed with a second Force/Torque sensor (ATI Nano17, calibration SI-12-0.12). This sensor was mounted so that as the probe exited the distal tip of the flexible access platform it contacted the sensor along its *z-axis*, as can be seen in Figure 6.6. The

setpoint of the force adaptive linear servoing control software (which sets the desired contact force between the probe tip and the tissue surface) was then adjusted to oscillate in a sinusoidal manner about a contact force of 0.1N. Thus when the mechanism is engaged, the probe advances into contact with the second F/T sensor and then applies a varying contact force onto the sensor. By synchronising acquisition between the two F/T sensors, the measurement of the ‘Proximally Mounted’ F/T sensor (measuring relative contact force) can be compared against the second ‘Tip Mounted’ F/T sensor (measuring the absolute contact force). The difference between the two sensors represents the losses in force transmission between the tip and the probe clamp. The frequency and amplitude of the sinusoidal input function were varied to demonstrate that the force measured by the ‘Proximally Mounted’ F/T sensor is representative of the actual force applied by the distal tip of the imaging probe onto the ‘Tip Mounted’ F/T sensor irrespective of such variations. *Version_5* of the flexible access platform and an Alveoflex™ Confocal Miniprobe™ (Mauna Kea Technologies, Paris, France) were used during this experiment.

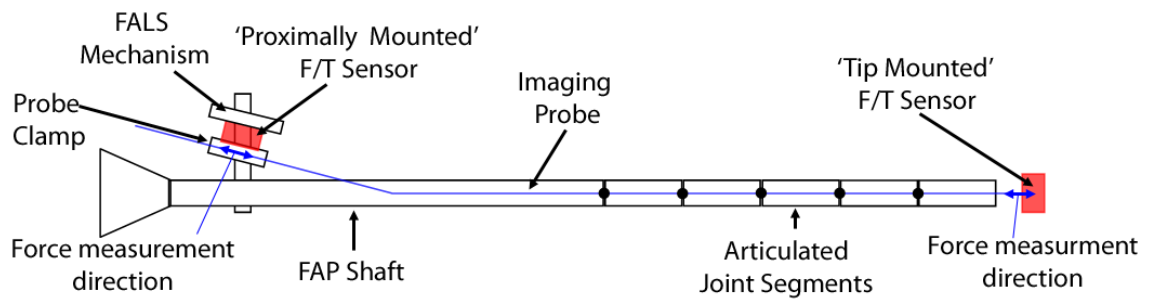


Figure 6.6: Schematic illustrating the experimental setup for the assessment of the force transmission and measurement. The measurements from the proximally mounted F/T sensor and the tip mounted F/T sensor are compared to demonstrate that the proximally mounted sensor is capable of measuring relative changes in the tip interaction force.

Figure 6.7 (top) shows the input sine wave (green) which is driving the force adaptive linear servoing controller, the force measured by the ‘Proximally Mounted’ sensor (blue) and the actual force imparted by the tip of the imaging probe onto the ‘Tip Mounted’ sensor (red). The parameters of the sine wave result in an oscillation about a mean contact force of 0.1N with a peak-to-peak amplitude of 0.2N and a frequency of 0.25Hz. The mean contact force of 0.1N was chosen to ensure that the probe was advanced with sufficient force to overcome the frictional losses within the system. The measurement from the ‘Proximally Mounted’ F/T sensor can be clearly seen to track the input sine wave in terms of frequency, phase and amplitude. The measurement from the ‘Tip Mounted’ F/T sensor can also be clearly seen to match the measurement from the ‘Proximally Mounted’ F/T sensor in terms of frequency, although

attenuation in amplitude and a limited phase shift are also evident. Although the force magnitudes are different, the measurement of the ‘Proximally Mounted’ sensor is clearly representative of the actual force imparted by the imaging probe onto the ‘Tip Mounted’ F/T sensor. An example of how relative changes in contact force are detected by both sensors can be seen after approximately 82 samples (as marked on Figure 6.7 (*top*)), when a sudden force change can be seen in both traces. Figure 6.7 (*bottom*) illustrates that this result is independent of frequency, as the measurement from the ‘Tip Mounted’ F/T sensor can still be seen to track the sine wave measured by the ‘Proximally Mounted’ F/T sensor when its frequency is doubled to 0.5Hz.

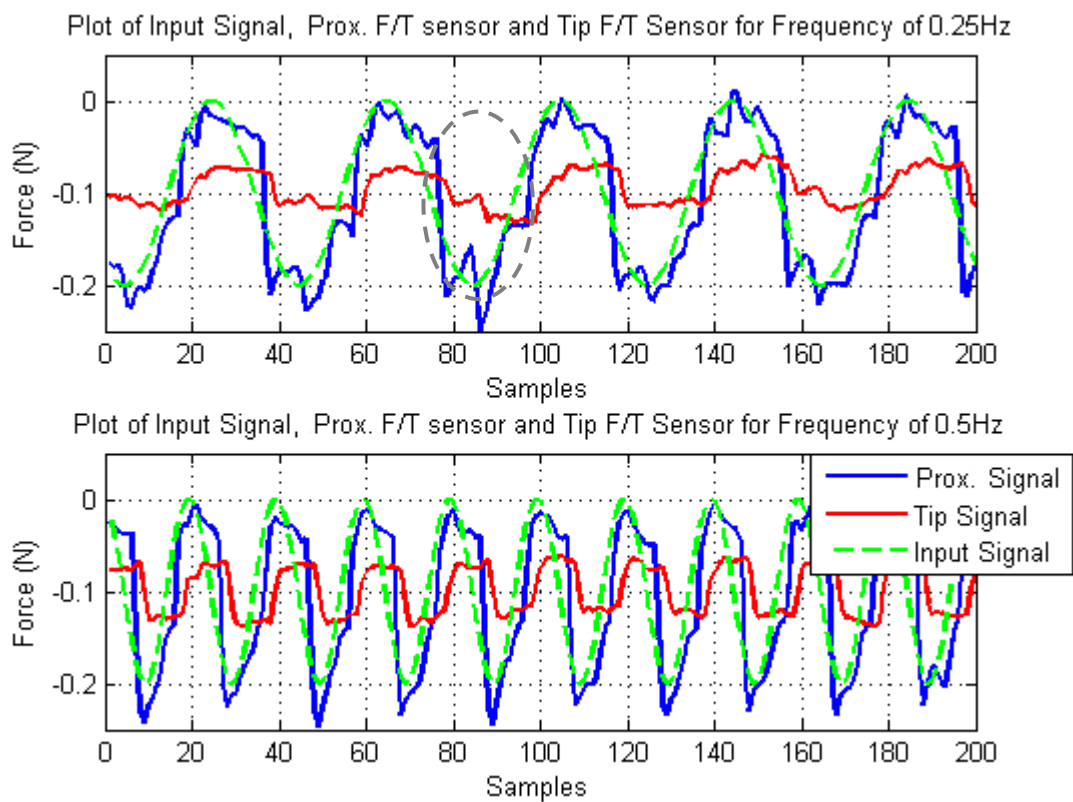


Figure 6.7: Demonstration of the ability of the force adaptive linear servoing mechanism to measure the relative changes in probe tip contact forces given the proximal mounting of the F/T sensor for different input frequencies. The input signal to the controller is shown in green, the force measured by the proximally mounted F/T sensor is shown in red and the force measured by the distally mounted F/T sensor is shown in blue. (*top*) Force measurements for a sinusoidal input of 0.25Hz; (*bottom*) force measurements for a sinusoidal input of 0.5Hz.

Similarly, the invariance of the system response to amplitude is shown in Figure 6.8. In this plot the frequency of oscillation was set at a constant 0.2Hz and the amplitude was increased from 0.1N to 0.2N in 0.01N increments after every two wavelengths. As before, values measured by

the ‘Tip Mounted’ F/T sensor (red) can be clearly seen to track the ‘Proximally Mounted’ F/T (blue) sensor, although with an attenuated value.

These results indicate that although errors in measurement of the absolute contact force do exist, the force measured by the F/T sensor located in the force adaptive linear servoing mechanism is representative of the probe-tissue interaction force. However, although suitable for the task described in this chapter, the attenuation in the measured force signal also highlights the limitations of the system. The effects of friction within the internal sheath and probe bucking within the internal channel would need to be modelled in order to improve the overall system performance. These features will be further discussed in the conclusion to this chapter.

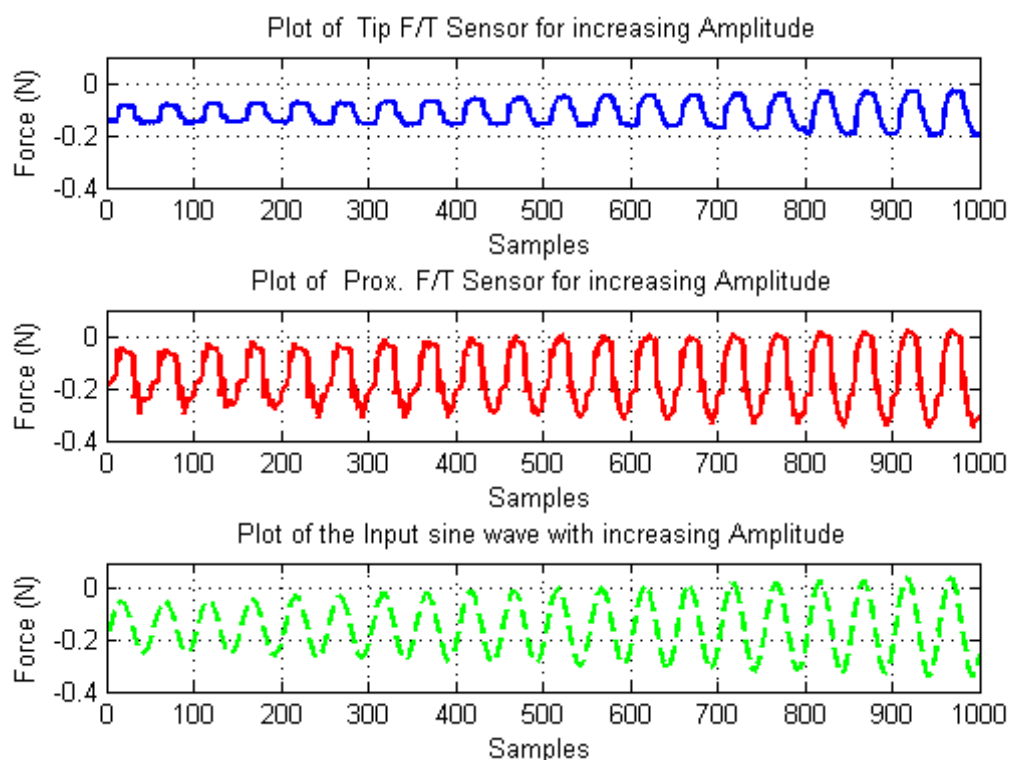


Figure 6.8: Demonstration of the ability of the force adaptive linear servoing mechanism to measure the relative changes in probe tip contact force for increasing amplitude of input signal. The input signal to the controller is shown in green, the force measured by the proximally mounted F/T sensor is shown in red and the force measured by the distally mounted F/T sensor is shown in blue. The amplitude of the sinusoidal input was increased in increments of 0.01N from 0.1N to 0.2N.

6.5 Experimental Setup and Results

In order to fully assess the efficacy of the system, four experiments were performed with the fluorescence spectroscopy probe described in Section 6.3.1. The first experiment was a system characterisation to identify the force required to initially advance the imaging probe (and

therefore overcome friction between the probe and the internal channel) for different deflections of the distal tip of the flexible access platform. The second experiment is similar to that described in Section 6.4.1 and aims to characterise the effect of different contact forces on the autofluorescence signal measured using the fluorescence spectroscopy probe on the ex-vivo soft tissue. The third experiment was designed to validate the ability of the system to reconstruct a multi-spectral map of a known fluorescent pattern using a stained silicone phantom. Finally, the fourth experiment was designed to demonstrate the ability of the system to acquire autofluorescence spectra while maintaining contact with an ex-vivo tissue sample as the platform servos the probe tip over the tissue surface. *Note:* It was not possible to also carry out these experiments with the Cellvizio system due to a technical fault with the system.

6.5.1 Effect of Contact Force on Fluorescence Intensity Spectra

In order to simulate a clinical environment, the force adaptive linear servoing mechanism was attached to the flexible access platform and the fluorescence probe passed through an internal channel, as can be seen in Figure 6.9. The tissue sample used during these experiments was an ex-vivo fowl liver, and the flexible access platform used was *Version_3*.

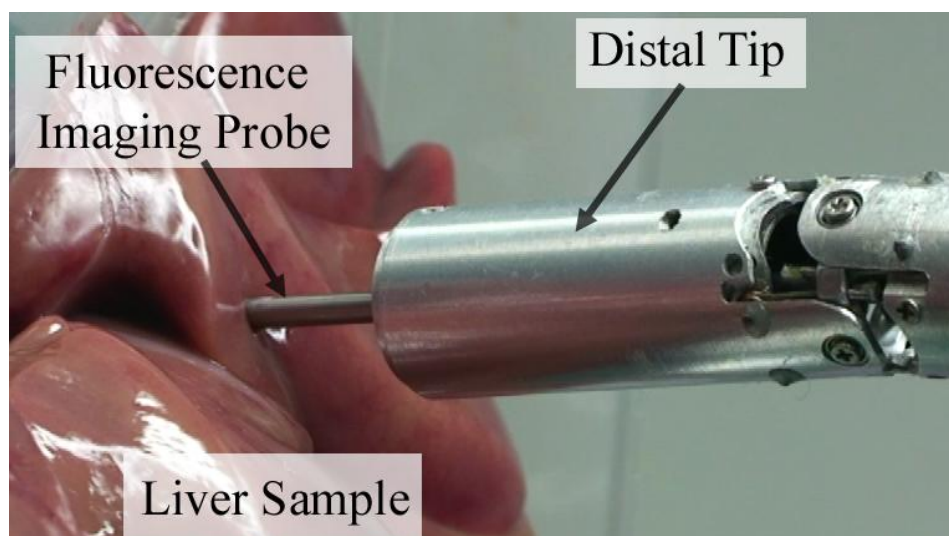


Figure 6.9: Experimental setup for testing the effect of contact force on reflected autofluorescence intensity. The ex-vivo liver tissue sample, fluorescence imaging probe and the distal tip of the flexible access platform are marked. The force adaptive linear servoing mechanism is located at the proximal end of the platform shaft, approximately 500mm to the right of the probe tip as shown in the image.

With the flexible access platform in a straight configuration (i.e. no angular displacement on any degree of freedom), the force adaptive linear servoing mechanism was used to advance the probe into contact with the tissue. Due to the limiting effects of the long transmission distance

and proximal location of the force sensor, a minimum setpoint of 20mN was required to advance the probe into contact with the tissue. Once touching the tissue, the force was increased in 10mN increments up to 150mN and spectroscopic images were acquired at each increment. A sub-sample of the plots of autofluorescence intensity versus wavelength are shown for four force increments (0mN, 40mN, 90mN, 150mN) in Figure 6.10.

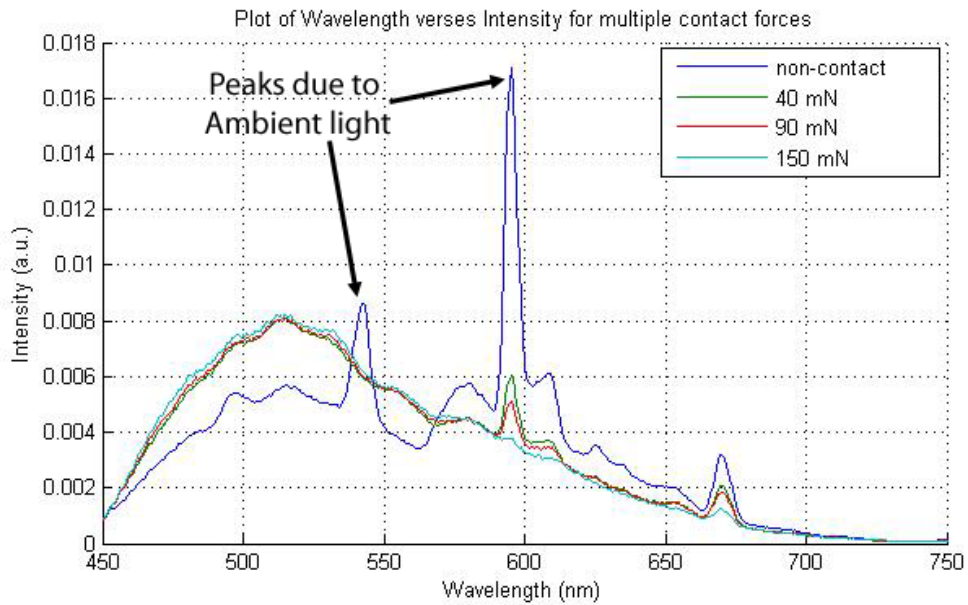


Figure 6.10: Plot of intensity versus wavelength for contact forces of 0mN, 40mN, 90mN and 150mN. The 0mN increment represents a non-contact condition where the distal tip of the probe is in free space.

Synchronised images captured using the onboard camera can be seen in Figure 6.11 - Figure 6.14. These images clearly show that as the setpoint of the force controller is increased, the probe is indenting further into the tissue surface and causing local deformation.

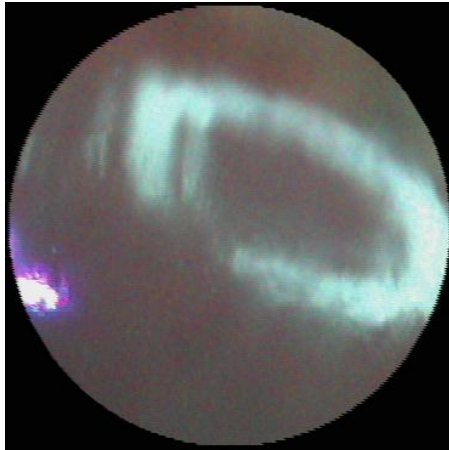


Figure 6.11: Onboard camera view when the probe is not in contact with the tissue. The fluorescence light from the illumination fibre can be seen reflecting off the tissue surface on the left of the image.

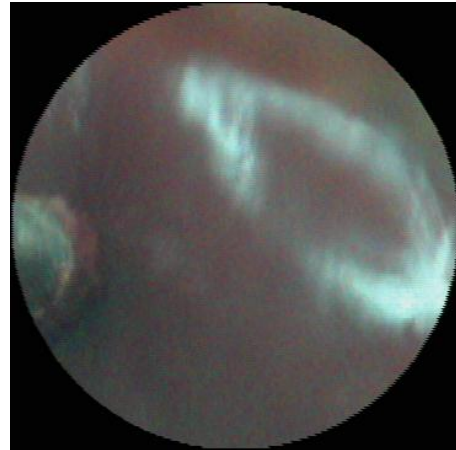


Figure 6.12: Onboard camera view when the probe is contacting the tissue with a 40mN contact force. The probe tip can be seen on the left of the image.

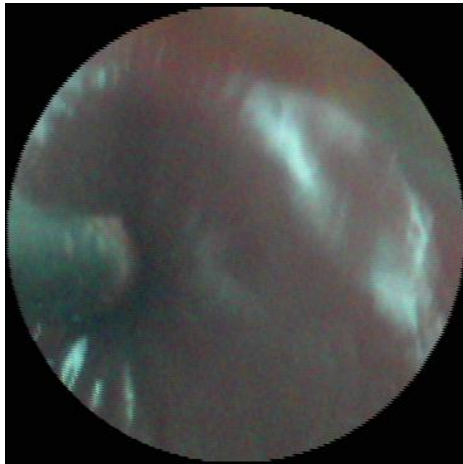


Figure 6.13: Onboard camera view when the probe is contacting the tissue with a 90mN contact force. More of the probe tip is now visible and the tissue deformation can be seen.



Figure 6.14: Onboard camera view when the probe is contacting the tissue with a force of 150mN. The probe can now be clearly seen deforming the tissue as it is advanced by the force adaptive linear servoing mechanism.

These results show that while the magnitude of the tissue autofluorescence remains constant for all contact forces, the effect of the ambient light on the spectral trace decreases in proportion to increasing force. This trace from the ambient light can be seen for all force values even as they become quite high, although there is a significant attenuation in the intensity of the peak as the probe engages the tissue. The fact that this trace is present even when the probe is in full contact with the tissue is due to the diffusion of the ambient light through the tissue to the detection fibres. However, at each of these contact forces, the spectra show that the primary autofluorescence peak at 510nm does not vary, even with the large tissue deformation which

can be seen with the 150mN contact force (Figure 6.14). This implies that there is no advantage in applying large contact forces to the tissue in order to improve the signal to noise ratio. Indeed, translating the probe tip when engaged with such a contact force could potentially damage the tissue surface.

These results indicate that in order to obtain consistent imaging results with the fluorescence spectroscopy probe without damaging the underlying tissue, the key requirement is to maintain a low force contact with the tissue at all times during image acquisition (between approximately 40mN and 60mN). This contact force should be sufficiently large enough to stop any ambient illumination from interfering with the autofluorescence measurements, but not too large so as to cause any tissue damage. Achieving this during static ex-vivo experiments is straightforward; however, the unique challenges of the in-vivo environment could potentially make this difficult for an operator to achieve. In particular if the operator wishes to translate the probe over the surface of the tissue in order to generate a functional map of the underlying tissue response, issues such as tissue deformation, non-planar surface profiles, and motion artefacts due to cardiac and respiratory cycles, could result in the probe easily becoming disengaged from the tissue surface or damaging the tissue if the contact force inadvertently became too high. In these situations, the force adaptive linear servoing mechanism could be used to ensure that such problems do not occur by automatically advancing or retracting the probe as the surface profile changes.

6.5.2 Force Characterisation

The purpose of the force characterisation experiments was to identify the required force setpoint to advance the probe within the internal channel for different deflections of the distal tip. Only small deflections of the distal tip were used during these tests to ensure that the force transmission from the probe tip is not adversely affected by changes in the flexible access platform configuration. To find the minimum setpoint required to advance the probe for different deflections, the distal tip was servoed to five different positions using the handheld controller. The coordinates of these positions are listed in Table 6.1 and represent the straight configuration and positions in each of the four quadrants of the Cartesian coordinate system. These four tip positions indicate the extreme deflections that will be used during this study. The resulting workspace of the distal tip is approximately a square with an area of 216mm^2 . At each position, the setpoint of the controller was increased from 0mN in increments of 10mN until the probe was advanced and made contact with a silicone phantom located approximately 15mm

from the distal face of the flexible access platform. The results showing the minimum force required to advance the probe for each distal tip position are shown in Table 6.1.

The data shows that larger forces are required to advance the probe when the tip is deflected than when it is straight. This is due to the increase in frictional interference effects between the imaging probe and the internal channel as the distal tip deflects. Consequently, for the remainder of the experiment a minimum setpoint of 40mN was employed during all tests.

Table 6.1: The minimum setpoint required to advance the imaging probe for different deflections of the distal tip

Tip Location (mm)	Minimum Force (mN)
(0,0)	20
(-7.1, 7.1)	30
(8.3, 8.3)	40
(-6.6,-6.6)	40
(7.3, -7.3)	40

It should be noted that for the purposes of this feasibility study, only the two distal degrees of freedom of the flexible access platform were used. Actuation of all degrees of freedom is possible; however, for any large displacement of the joint angles, additional work would be required to reduce the friction co-efficient between the internal channel and the imaging probe. Additionally, the interaction of the imaging probe and the internal channel would need to be adequately modelled in order to ensure accurate operation of the force controller.

6.5.3 Phantom Validation

A double fluorescence stained silicone phantom was developed to demonstrate the ability of the system to trace a trajectory over a surface and to accurately reconstruct the underlying multi-spectral response. The phantom features four horizontal lines of alternating yellow and green fluorescent dye mounted on a flat surface. This surface is parallel to the distal face of the flexible access platform when it is in the ‘straight’ position. A gap of approximately 1.5mm separates the individual lines, and each line is approximately 1.5mm thick. As was described in Section 6.3.1, each of the separate components of platform control, force adaptive linear servoing mechanism control, onboard camera acquisition and autofluorescence image

acquisition were synchronised and the distal tip was servoed along a 2D scan pattern using the handheld controller. An additional camera was setup to record the position of the probe tip during the experiments.

As the probe is servoed along the 2D scan trajectory, the distal tip moves in an arc due to the actuation characteristics of the universal joint. In order to maintain a consistent contact force between the probe and the phantom, the force adaptive linear servoing must constantly adjust the probe position. This is similar to the situation that would arise when imaging biological soft tissue, as the surface profile of the tissue would typically be different from the arc traced by the distal tip. Analysis of the spectral response and the external camera (used for validation purposes only) confirms that the probe did not lose contact with the phantom at any point along the trajectory.

An additional advantage of the force adaptive linear servoing mechanism is that the synchronised data streams allow for the spectral information at each acquisition point to be localised along the tip trajectory using the estimation of tip position from the motor pulses. This feature addresses *Challenge 3* as outlined in Chapter 1 by effectively increasing the information provided to the operator, and allowing for seamless comparison of the white light tissue images and the autofluorescence intensity signal. This has the potential to not only improve real-time, in-vivo diagnosis but to also provide the operator with a synchronised dataset which can be further analysed offline after a procedure has taken place. The presence of this dataset for subsequent analysis or comparison is significant since, unlike traditional biopsies, optical biopsies do not leave a scar. In the absence of a scar, can be difficult for a clinician to return to a previously biopsied location for comparison purposes [164]. To demonstrate the usefulness of this approach, all relevant data streams have been combined and visualised in Figure 6.15. This figure contains a schematic representation of the fluorescent dye pattern with the robot tip trajectory projected onto its surface (parallel to the distal face when the platform is straight). Using the synchronisation between the tip trajectory and the image acquisition streams, three ‘data points’ have been extracted and are displayed. Each of these ‘data points’ contains the spectra as recorded by the six fibres of the imaging probe (*bottom*) and the image as captured by the onboard camera (*top, right*) at that location on the tip trajectory. An additional image from the external camera (*top, left*) is also shown to confirm that the imaging probe is engaged with the phantom at all times and that the fluorescence intensities identified on the spectral traces correspond with the dye that the probe is touching.

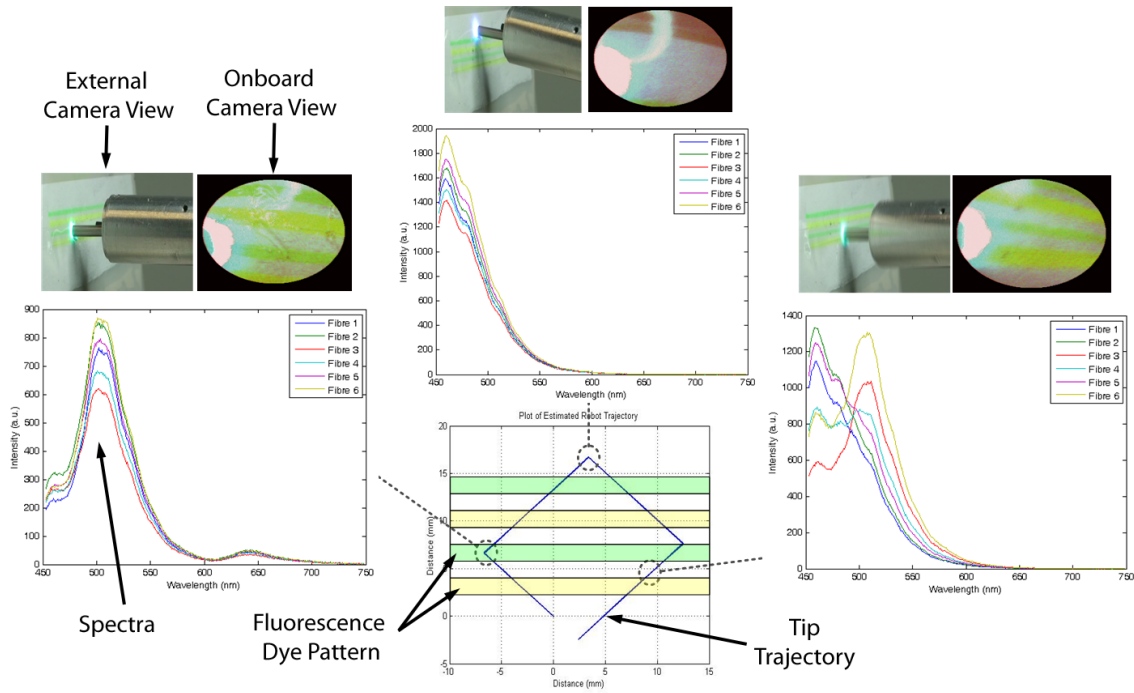


Figure 6.15: Plot of the trajectory of the robot tip as it passes over the green and yellow fluorescence dye. Three results sequences displaying the spectral information (*bottom*) the onboard camera view (*top-right*) and an external camera for visual confirmation of the spectral result (*top-left*) are also shown.

The spectral traces clearly show intensity peaks at four different wavelengths. These match precisely with locations of the three ground truth excitation wavelengths known to be on the phantom. These are yellow dye with a peak at 515nm, green dye with peaks at 505 and 640nm and the background paper with a peak at 460nm. These results clearly demonstrate the ability of the system to differentiate between the different wavelengths as recorded at the different locations. The results illustrated in the right hand spectra in Figure 6.15 are of particular note as the different fibres of the imaging probe display different wavelength peak intensities (i.e. four of the fibres show a peak at 460nm and the other two display a peak at 515nm). The reason for this can be identified by looking at the image feed from the onboard and external cameras – at this particular point on the tip trajectory, the imaging probe is located between the yellow fluorescent dye and the paper. As a result, different fibres within the probe display different excitation wavelengths. This information can be interpreted to increase the effective resolution of the multi-spectral probe by incorporating the relevant spatial distribution of the fibres.

6.5.4. Ex-vivo Liver Tissue Validation

The final experiment carried out with the force adaptive linear servoing mechanism was performed on an ex-vivo sample of fowl liver. The purpose of this experiment was to

demonstrate the ability of the system to servo the imaging probe across the surface of a biological tissue sample, while ensuring full contact with a consistent contact force, and simultaneously recording synchronised images and tip trajectory information. The orientation of the tissue sample with respect to the probe was chosen to represent a more challenging scenario than the orthogonal placement of the fluorescent phantom in the previous experiments. In this case, the tissue was arranged to slope away from the distal face of the flexible access platform at a shallow angle. This orientation results in a significant change in the profile of the tissue as the imaging probe moves across its surface, and necessitates both advancement and retraction of the probe to stay in consistent contact. The results from this experiment are visualised in Figure 6.16. The information presented in this image is similar to that displayed in Figure 6.15 with the tip trajectory projected onto a 2D plane and information regarding five 'data points' along the trajectory embedded within the figure. In this case just the autofluorescence spectra and the onboard camera image are displayed.

The magnitude of the primary autofluorescence peak (approximately 510nm) in the spectra remains consistent at all points along the trajectory of the probe. This indicates that good contact was maintained with the tissue throughout the experiment and that the region of the tissue sample probed was homogenous. In the images recorded from the onboard camera, the probe can be clearly seen to advance and retract as it moves across the surface profile. This movement can be further examined by looking at the profile of the force as measured by the 'Proximally Mounted' F/T sensor and synchronised *xy* position of the distal tip (Figure 6.17). The plot in this figure shows how the controller is attempting to maintain a consistent contact force at the setpoint of 40mN. Significant deviations from this value occur after approximately 43 and 66 samples. Matching these timeframes to the images from the onboard camera shows that at these times, the profile of the tissue changes significantly. When the force drops suddenly after 43 samples, the probe almost loses contact with the tissue sample but the force adaptive linear servoing mechanism advances it in order to maintain contact. Conversely, after 66 samples the trajectory brings the probe into a tissue region close to the flexible access platform which results in the probe becoming embedded deeper in the tissue. This can be seen in the sharp increase in the force measured by the F/T sensor. In the onboard camera footage the probe can be seen to retract in order to reduce the force exerted on the tissue.

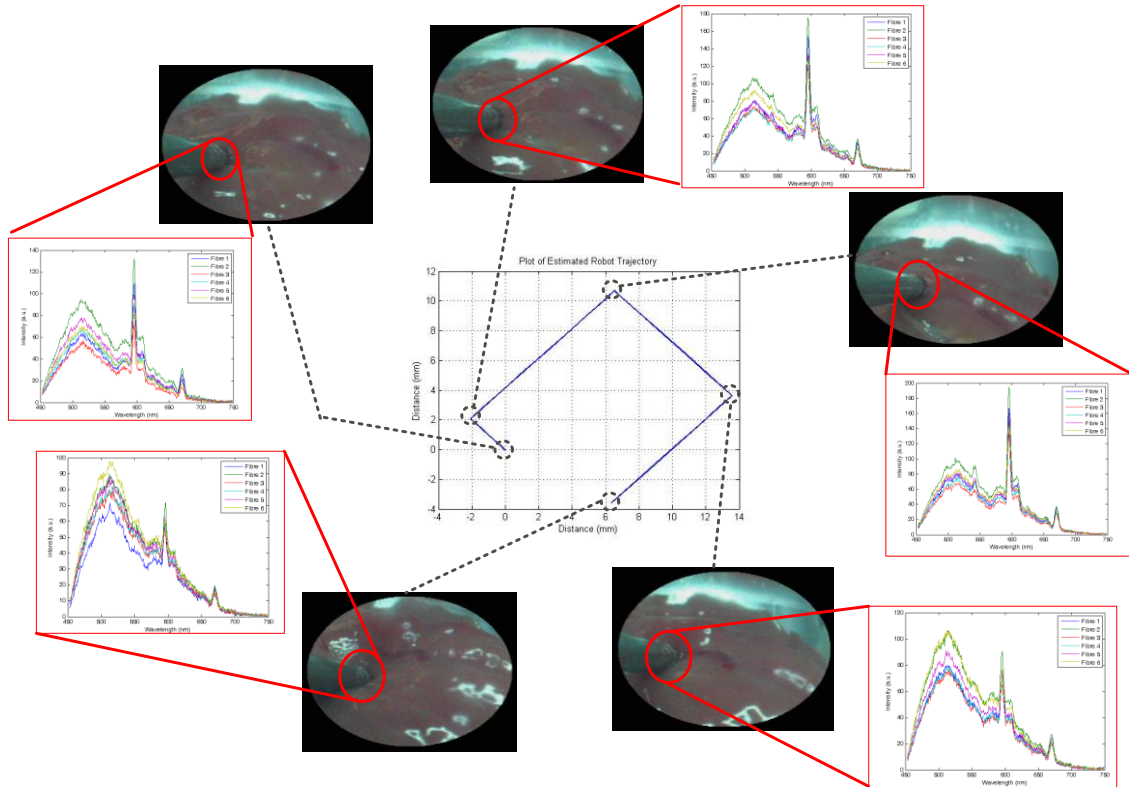


Figure 6.16: (middle) 2D plot of the trajectory of the probe tip with five results sets indicated. Each results set displays the spectral information and the synchronised onboard camera image. An aluminium tray used to hold the liver sample can be identified in the top portion of the onboard camera images as well as the orientation of the tissue sloping away from the distal face of the flexible access platform.

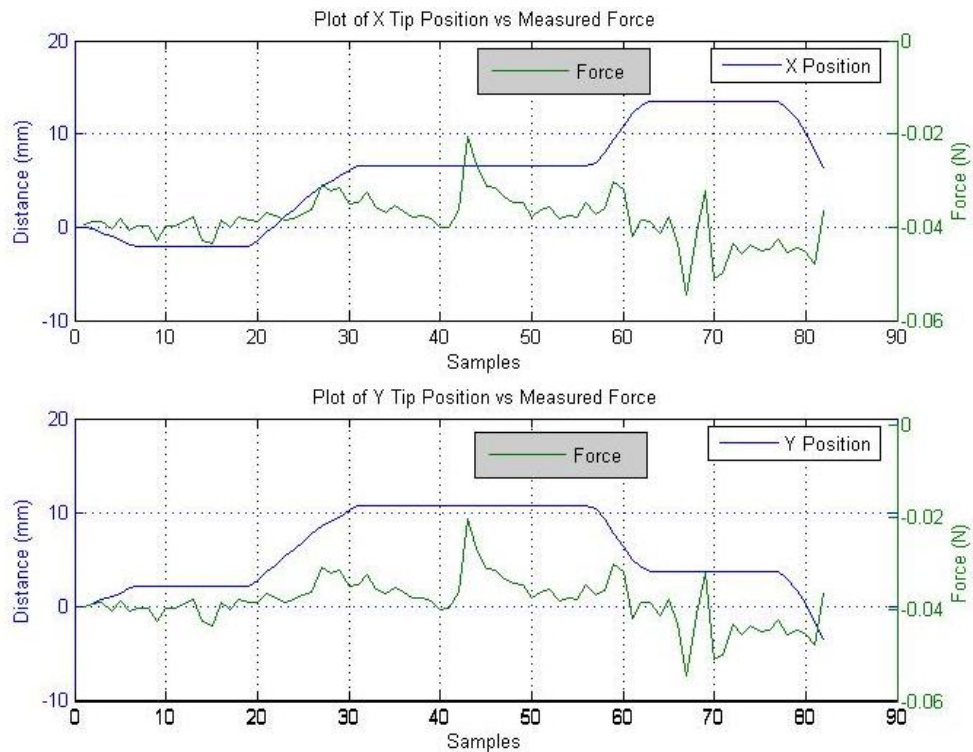


Figure 6.17: Plot of the X (top) and Y (bottom) coordinates of the probe tip (green) versus the force measured by the F/T sensor (blue). The controller is attempting to maintain the contact force at the setpoint of 40mN.

6.6 Discussion and Conclusion

The experimental results demonstrate that the combination of the flexible access platform and the force adaptive linear servoing mechanism address several core challenges outlined in Chapter 1 of this thesis. These achievements include:

1. Improvements in the ergonomics of deploying and targeting probe-based optical imaging techniques through the combination of the dexterity of the flexible access platform and the hands-free probe advancement capabilities provided by the linear servoing mechanism;
2. Improvements in the accuracy and repeatability of probe-based optical imaging through the use of force controlled probe advancement which aims to ensure a consistent contact force across all tissue profiles;
3. Improvements in the intraoperative information flow provided to surgeons through the synchronised acquisition of onboard camera images and fluorescence intensity spectra, and the subsequent localisation of these images on the trajectory traced by the distal tip.

The results presented here represent the first step towards the development of a clinically deployable force adaptive linear to servo the probe using all of the degrees of freedom of the flexible access platform for large area surveillance. This will require focusing on reducing the friction between the probe and the internal channel and modelling of probe-channel interaction for different deflections of the platform's joints. Such deflections would result in a different minimum force setpoint for each configuration of the platform. For example, the 40mN setpoint (as shown in Table 6.1) required to advance the probe for small deflections of the tip would significantly increase if the platform was fully retroflexed. Modelling and predicting the required setpoint would rely on knowledge of the angular displacement of each of the degrees of freedom. A practical demonstration of this limitation can be seen in Chapter 7 where the force adaptive linear servoing mechanism is employed during an in-vivo study solely to advance and retract the probe, but not to maintain a consistent contact force. During that study the configuration of the platform's joint units was unknown and so it was not possible to predict the minimum setpoint that would be required to advance the probe at any point in time. Consequently the setpoint of the controller was incrementally increased by the operator until the probe was seen to advance. Without knowledge of this setpoint and a model of the interaction of the probe within the channel of the platform, it is impossible measure the resulting contact force between the tissue and the probe and to ensure this force remains consistent as the probe is servoed over the surface of the tissue. This problem can potentially be addressed through the

use of accurate modelling of the probe – channel interaction or alternatively by measuring the interaction force directly at the distal tip. This would involve moving the F/T sensor from its proximal mounting location to the distal tip of the probe itself. The size restrictions of minimally invasive surgery and current force sensing technology make this a significant challenge, however, with advances in fibre optical force sensing technology such as is displayed in [165] [166] and [73], imaging probes may become integrated with force sensing capabilities to make this a reality.

A second limitation of the system as presented here, is the use of motor pulses to estimate the joint position employed with *Version_3* of the flexible access platform. Although acceptable for estimating the position of the tip, this technique is prone to drift and erroneous readings due to the fact that the motor can output extra pulses when stalled or when changing direction. As a result, it is not suitable for commanding the distal tip to trace specific trajectories. At the time that this work was carried out, the potentiometer-based position feedback developed for *Version_5* of the flexible access platform was not yet available. However, kinematic control is possible with this latest version and it is anticipated that when the force adaptive linear servoing mechanism is deployed with *Version_5*, the ability to servo the probe over specific trajectories will allow for clinically relevant functional tissue maps (in the case of the fluorescence spectroscopy probe) or large area mosaics (in the case of the pCLE probe) of specific regions to be generated. Finally, the potential also exists to combine the system described here with the experimental gaze contingent control strategies described in Chapter 5. If deployed simultaneously, such a system would offer a clinician the ability to use the dexterity of the flexible access platform to target the probe along curved pathways and perform force adaptive optical imaging in a completely ‘hands-free’ manner.

The next chapter will take the flexible access platform and its sub-systems out of the laboratory setting and present results from two case studies performed during in-vivo pre-clinical trials. These case studies show the translational nature of the work presented in this thesis and demonstrate how the system can be used as a research test-bed to investigate the potential applications of robotic assisted flexible access surgery.

Chapter 7:

In-Vivo Surgical Intervention using the Flexible Access Platform

In Chapter 1, several challenges facing the adoption of flexible access surgery were outlined. These included the ability to provide controlled flexibility and stability along curved instrument pathways (*Challenge 1*), to reduce the system footprint within the operating theatre (*Challenge 1*), to provide an ergonomic platform to target minor interventional instrumentation and imaging probes (*Challenge 2* and *Challenge 4*) and to improve the intraoperative information flow to a clinician through the integration of advanced imaging techniques (*Challenge 3*). The systems which have been described over the preceding four chapters incorporate features which aim to address each of these challenges. In this chapter, potential clinical applications of the flexible access platform will be introduced. The feasibility of performing two focused applications will be demonstrated with case studies carried out during pre-clinical trials in live porcine models. The procedures performed were a unilateral transvaginal tubal ligation and a transvaginal diagnostic peritoneoscopy using optical biopsy techniques. The former procedure demonstrates the ability of the platform to achieve complete retroflexion within the constraints of the pelvis

and to provide a stable platform for the successful deployment of multiple interventional instruments. The latter procedure highlights the suitability of the device for performing large area visualisation in conjunction with probe-based optical imaging. Each of the case studies will be preceded by a laboratory based workspace assessment to demonstrate the suitability of the platform for performing the specific procedure. In the case of the tubal ligation, an analysis of the retroflexion capabilities of the platform will be theoretically demonstrated, while in the case of the diagnostic peritoneoscopy, a peritoneal exploration was performed in a simulated environment. The key contribution of this chapter is the demonstration of the translational nature of the work described in this thesis and the suitability of the flexible access platform for exploring the challenges of flexible access surgery.

7.1 Surgical Evolution - Minimising Invasiveness

The ongoing drive to minimise the invasiveness of surgical procedures has, wherever possible, led to a reduction in the size and number of incisions being made during surgery. As can be seen in Figure 7.1, the trend over the last 25 years has evolved from open surgery to minimally invasive surgery (MIS) and now to the emerging experimental fields of single incision laparoscopic surgery (SILS) and natural orifice transluminal endoscopic surgery (NOTES).

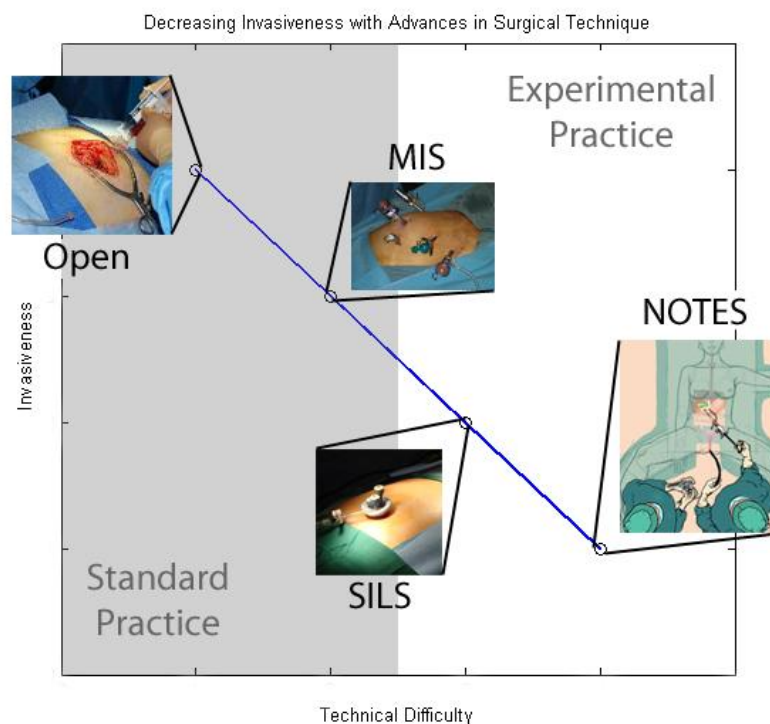


Figure 7.1: Surgical technique with respect to technical difficulty/complexity and invasiveness.

However, as the techniques become less invasive, the technical difficulties facing clinicians when performing the procedures are increasing [167] [168]. One specific challenge is the fact that the incision points are no longer solely dictated by the procedure to be carried out. Instead, the incisions are being moved to locations which, although might be sub-optimal for the procedure, have other significant advantages for the patient [169]. These advantages can be in the form of clinical benefits, such as reduced post-operative pain, intraoperative blood loss and complications, or other benefits, such as reduced scarring and improved cosmesis. Naturally, the importance of these factors will vary from patient to patient. However, at this stage in the evolution of surgery, the instruments do not exist to provide a surgeon with the option of carrying out a given procedure from any incision point. This is due to the fact that positioning incisions away from the current ‘optimum’ incision point, has negative consequences for the dexterity and workspace available to laparoscopic instrumentation, which traditionally feature a rigid shaft with little or no flexibility. An example of this is shown in Figure 7.2, where the approximate workspace available to a rigid instrument within the peritoneal cavity from a transvaginal incision is shown. Clearly, removing a gall-bladder [82], performing a nephrectomy [170] or ligating the fallopian tubes [138] from this route with existing instruments, presents significant challenges which ultimately will preclude its uptake as standard surgical practice.

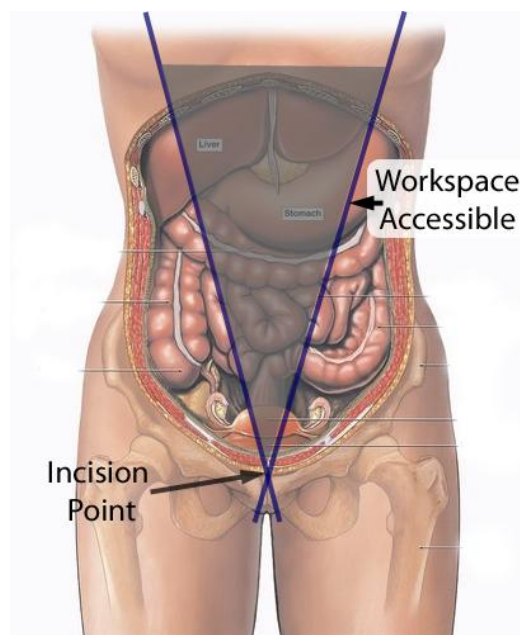


Figure 7.2: Schematic illustrating the approximate accessible workspace for a rigid instrument if inserted through a transvaginal incision. Image source (original illustration of female anatomy): [171]

Therefore, in order for flexible access surgery to become a reality - and for surgeons to be able to make an incision at any location and yet operate safely and comfortably at the desired anatomical location – a requirement exists for the development of new instruments capable of operating along curved pathways and navigating safely inside the body. A preliminary step towards such a system is the flexible access platform described in this thesis. With this platform, the operator is no longer restricted to only intervening at locations within direct reach of the incision, but rather can chose the most appropriate incision point for the given patient and subsequently use the capabilities of the device to carry out the procedure.

Given the current capabilities of the platform, a series of clinically relevant procedures were identified within the gynaecological and upper gastrointestinal specialties. All procedures are to be carried out from a single incision. These are outlined in Table 7.1 and are split into two broad categories – Access/Diagnostic and Tissue destruction/ablation.

Table 7.1: Potential clinical applications for the flexible access platform

	Access / Diagnostic	Tissue destruction / ablation
Gynaecological	Pelvic exploration	Tubal ligation / sterilisation
	Ovarian cyst drainage	Endometrial ablation
	Diagnostic peritoneoscopy	
Gastrointestinal	Optical biopsy mapping	Tissue biopsy

Each of these procedures can potentially be carried out using the flexible access platform if compatible third-party instruments are used. For example, the controlled focused energy delivery for endometrial ablation could be provided by a CO₂ or Argon laser via a flexible probe, cyst drainage via a flexible suctioning probe and tubal ligation via flexible clips and/or electrocautery instruments. To demonstrate the feasibility of the system for performing these procedures, two case studies carried out during live porcine experiments will be described. These include a tubal ligation procedure and a diagnostic peritoneoscopy with the approach from a transvaginal incision – a location which would traditionally be considered suboptimal for the given procedures but which offers several potential advantages owing to the natural orifice

approach [172]. As a consequence of the limited direct access available from the incision point to the target anatomy, the full dexterity of the flexible access platform must be employed in order to perform these flexible access procedures.

7.2 System Overview: In-vivo Deployment

Each of the five versions of the platform developed as part of this project were deployed during live porcine experiments in order to test, evaluate and refine the overall system design. Details of these in-vivo trials can be found in Appendix II. However, for the purposes of the case studies to be described in this chapter, the 7-DoF *Version_5* and the ‘decoupled-handheld’ controller were used. Specific details of these two systems have already been described in Chapters 4 and 5 respectively. The key components of flexible access platform that are required in theatre can be seen in Figure 7.3.

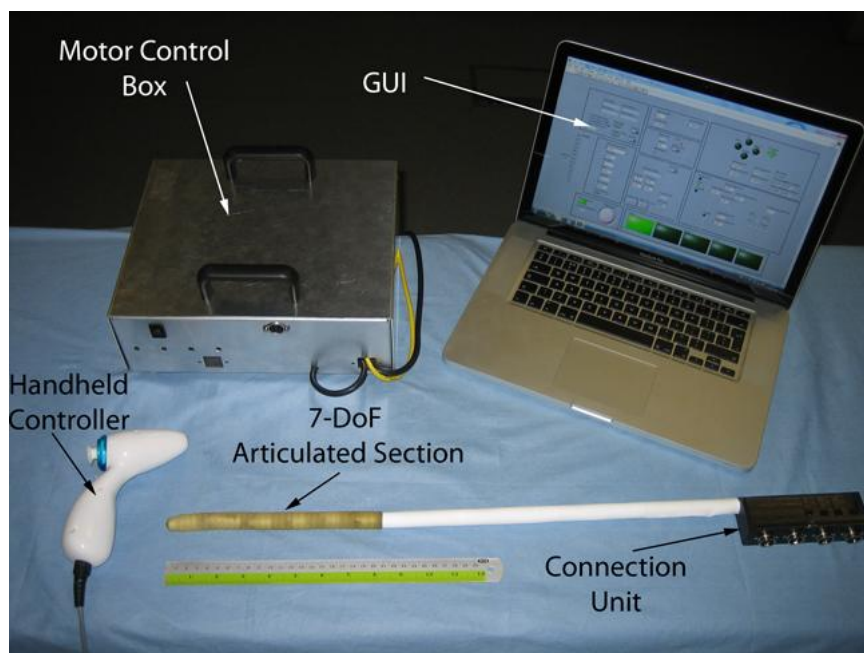


Figure 7.3: Key components required for in-vivo deployment. In practice, the Motor Control Box is connected to the flexible access platform via four 8-way DIN cables (not shown) and the Connection Unit at the proximal end of the rigid shaft. The laptop only displays the graphical user interface (GUI) and does not control the flexible access platform.

As can be seen in Figure 7.3, the footprint of the mechatronic elements required in-theatre is minimal and the use of three metre cables to connect the motor control box and the connection unit means that the control does not need to be placed in the direct vicinity of the operating table. In practice, three additional commercially available components were deployed during the in-vivo trials alongside those shown above. These are listed in Table 7.2. Naturally, for the

specific clinical tasks to be described, additional commercially available equipment was also required. Such equipment includes endoscopic instrumentation for the tubal ligation procedure and the Cellvizio pCLE imaging system for the diagnostic peritoneoscopy. Full details of this additional equipment will be provided in the relevant sections.

Table 7.2: List of additional equipment used during in-vivo deployment of the flexible access platform

Component	Manufacturer	Function
Laparoscopic Arm	Limbs & Things Ltd Part No: 50147	To clamp the flexible access platform into place and thus free the operator from holding it
Camera Control Unit	Medigus Ltd Part No: CAMCCU115	To control the 1.8mm camera in the tip of the flexible access platform
HDV Portable Recorder	Sony Part No: GV-HD700E	To record the video stream from the 1.8mm camera

7.3 Case Study 1: Transvaginal Tubal Ligation

The first exemplar procedure to be described is a transvaginal tubal ligation in a porcine model, similar to that described in [173], where access to the fallopian tubes can be achieved by establishing pneumoperitoneum, putting the endoscope in a ‘u-turn’ and mobilising the uterus anteriorly using a uterine manipulator. In that case study, the authors report that transvaginal tubal ligation using a flexible endoscope is possible and offers the patient several benefits in the form of no abdominal scar, minimal postoperative pain, rapid convalescence and minimal morbidity. From a clinical perspective, it was found to provide the same results as laparoscopic surgery and allows the visualisation of the entire pelvic anatomy. However, the surgical team did experience difficulties during the procedure regarding control of the flexible endoscope. Specifically, the flexible nature of the endoscope makes controlling the instruments passed through the device difficult, and when operating in a retroflexed configuration the image is upside down or sometimes lateral. Each of these problems can be addressed by the flexible access platform since they can be solved by the unique capabilities of the system. Solutions include the ability to perform a tight retroflexion in the pelvis to provide an overhead visualisation of the uterine horn (used as a model for the fallopian tube in a porcine model), and the provision of a stable platform for the passage of interventional instrumentation for tissue interaction under mechatronic control. The system also only requires a single operator to both

actuate the platform and pass the interventional instrumentation through the biopsy channel. Finally, the multiple, independently addressable degrees of freedom can be used for more detailed examination of the pelvic region if required. An analysis of the workspace of the device will be presented along with a description of the endoscopic instruments required to perform the procedure. Finally, the procedure itself will be described in a step-by-step manner.

7.3.1 Workspace Analysis of the Flexible Access Platform Capabilities for Performing a Transvaginal Tubal Ligation

The purpose of carrying out a workspace analysis of the 7-DoF flexible access platform was twofold:

1. To ensure that the system can perform a full retroflexion within the confines of the peritoneal cavity. This retroflexion is necessary due to the location of the incision with respect to the target anatomy.
2. To ensure that once in the retroflexed position, the system has sufficient dexterity to enable visualisation of the uterine horn.

The first step of the workspace analysis is to define a series of local coordinate frames on each of the axes of rotation of the platform. The frames are defined such that rotation occurs along the z -axis of each frame, as can be seen in Figure 7.4. Transformation matrices which describe the rotations and translations between adjacent local coordinate systems are used to compute the position and orientation of each coordinate frame relative to the world coordinate frame (defined as co-incident with the frame of the first axis of rotation). These transformation matrices were calculated using the two step process proposed by Denavit-Hartenberg (D-H), which decomposes the manipulator into a series of local coordinate systems, joint variables and link parameters as described in [174]. In the case of the flexible access platform, these variables are the angular displacements of each joint unit (i.e. $\theta_1, \theta_2, \theta_3, \theta_4, \theta_5, \theta_6, \theta_7$) and the link constants marked in Figure 7.4.

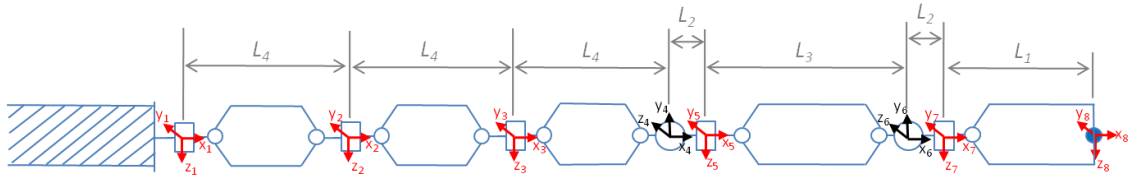


Figure 7.4: Schematic representation of the coordinate systems of the 7-DoF flexible access platform. The three proximal yaw joints are parallel while the distal two universal joints are offset by 45° with respect to the yaw joints. Note: For clarity, the 45° offset is not indicated in the coordinate frames 4, 5, 6, 7 and 8 in this figure, it is however, represented in the D-H parameters.

The use of the D-H notation links the adjacent coordinate systems via the equation:

$${}^{n-1}_nT = Trans_{z_{n-1}}(d_n) \cdot Rot_{z_{n-1}}(\theta_n) \cdot Trans_{x_n}(r_n) \cdot Rot_{x_n}(\alpha_n)$$

Where $Trans()$ and $Rot()$ are matrices representing translations and rotations about the z and x axes and n represents the current frame. Full details of these matrices can be found in Appendix IV. The D-H parameters for the 7-DoF flexible access platform are given in Table 7.3 while the link constants are given in Table 7.4.

Table 7.3: D-H parameters for the 7-DoF flexible access platform to be used during in-vivo pre-clinical trials

${}^{n-1}_nT$	$Trans_{z_{n-1}}(d_n)$	$Rot_{z_{n-1}}(\theta_n)$	$Trans_{x_n}(r_n)$	$Rot_{x_n}(\alpha_n)$
1_2T	0	θ_1	l_4	0°
2_3T	0	θ_2	l_4	0°
3_4T	0	θ_3	l_4	-45°
4_5T	0	θ_4	l_2	90°
5_6T	0	θ_5	l_3	-90°
6_7T	0	θ_6	l_2	90°
7_8T	0	θ_7	l_1	0°

Table 7.4: Link parameters for the 7-DoF flexible access platform deployed during the pre-clinical in-vivo trials

Link constant	Measurement (mm)
l_1	32.5
l_2	8
l_3	35
l_4	34

The resulting individual transformations are given in Table 7.5 below.

Table 7.5: Transformation matrices for the local coordinate systems on the 7-DoF flexible access platform

${}^1_2T = \begin{bmatrix} C_1 & -S_1 & 0 & l_4C_1 \\ S_1 & C_1 & 0 & l_4S_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$	${}^2_3T = \begin{bmatrix} C_2 & -S_2 & 0 & l_4C_2 \\ S_2 & C_2 & 0 & l_4S_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$	${}^3_4T = \begin{bmatrix} C_3 & \frac{-S_3}{\sqrt{2}} & \frac{-S_3}{\sqrt{2}} & l_4C_3 \\ S_3 & \frac{C_3}{\sqrt{2}} & \frac{C_3}{\sqrt{2}} & l_4S_3 \\ 0 & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$
${}^4_5T = \begin{bmatrix} C_4 & 0 & S_4 & l_2C_4 \\ S_4 & 0 & -C_4 & l_2S_4 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$	${}^5_6T = \begin{bmatrix} C_5 & 0 & -S_5 & l_3C_5 \\ S_5 & 0 & C_5 & l_3S_5 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$	${}^6_7T = \begin{bmatrix} C_6 & 0 & S_6 & l_2C_6 \\ S_6 & 0 & -C_6 & l_2S_6 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$
${}^7_8T = \begin{bmatrix} C_7 & -S_7 & 0 & l_1C_7 \\ S_7 & C_7 & 0 & l_1S_7 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$		

In order to compute the position of each link with respect to the world coordinate system the relative sub-system transformations are multiplied. Thus the final transformation is given by:

$${}^1_8T = {}^1_2T {}^2_3T {}^3_4T {}^4_5T {}^5_6T {}^6_7T {}^7_8T$$

The Matlab code used to generate this transformation matrix can be found in Appendix IV. This matrix was computed for each coordinate frame and allows the position and orientation of each link to be identified for any given joint displacement. To demonstrate, Figure 7.5 illustrates the position and orientation of the flexible access platform shaft (black) and each of the seven link units as each joint unit is servoed from 0° to 45° simultaneously. For clarity, the configuration is only plotted every 5°. Each link unit is plotted using a different colour so that individual links can be identified. The plot shows the flexible access platform in the *xy-plane*, which is the horizontal plane with respect to the world coordinate system of the platform. Three specific configurations *One*, *Two* and *Three* are marked and represent the flexible access platform configuration when all joint variables, θ_n , are set at 0°, 25° and 45° respectively. The first clearly shows the platform in the straight configuration while the third shows the configuration with each joint at the maximum possible displacement. The colours of the links from proximal

to distal are marked blue, red, cyan, blue and green respectively, while frames of the proximal and distal universal joints are marked in black and red respectively.

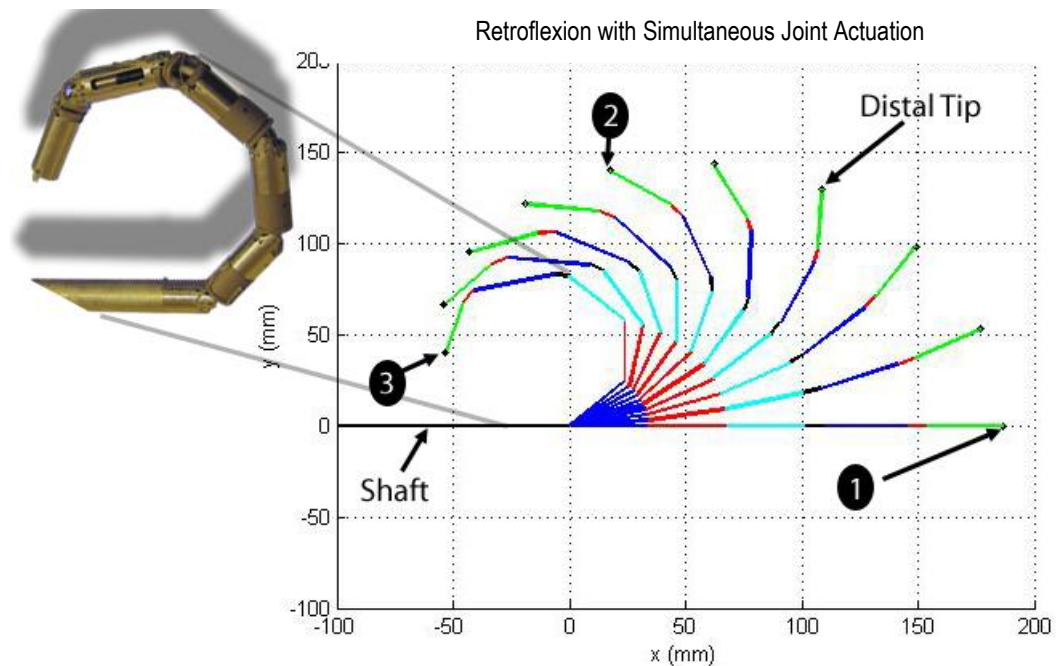


Figure 7.5: Position and orientation of each link as the joint variables transition from 0° to 45° simultaneously as seen looking down on the horizontal (XY) plane. The straight configuration with all joints set to 0° is marked *One*, the approximate mid-point of the retroflexion with all joints set to 25° is marked *Two* and the maximum retroflexion configuration with all joints set to 45° is marked *Three*. The plot also shows the real 7-DoF flexible access platform when in this retroflexed position.

This plot demonstrates that when at the maximum range of all seven joints, the flexible access platform is capable of pointing its distal tip past the 180° position and back towards its rigid shaft. It also shows that when retroflexed, the radius of retroflexion is 89.5mm (assuming that the links above are plotted along the centreline of the physical joint units which have a radius of 6.25mm). This is within the pelvic dimensions specified in Chapter 4 and provides a preliminary indication that the flexible access platform is suitable for the tubal-ligation procedure.

However, the plot also indicates that in order to obtain that configuration while simultaneously actuating all joint units, the trajectory of the distal tip traces an arc with a radius of 143mm. The platform would not be capable of retroflexing within the volumetric constraints of the pelvis. Instead, retroflexion would need to take place in the larger volume of the insufflated abdomen. This is not desirable and so it is necessary to reduce this retroflexion radius where possible. Such a reduction can be achieved by actuating the joint units in a ‘two step’ rather than

simultaneous manner. The first step of this process involves only the two universal joints being actuated (simultaneously) to their maximum angular displacements while the proximal joints remain at 0° . Once the universal joints have reached their limits, the proximal joints then actuate simultaneously. The resulting trajectory plot for this ‘two step’ retroflexion can be seen in Figure 7.6. From the figure it is clear that the maximum radius of retroflexion has been reduced to 112mm. It is also important to note that although the majority of actuation takes place in the XY plane, there is a small movement in the XZ plane which cannot be visualised in this plot (a maximum displacement of 13mm occurs at the distal tip).

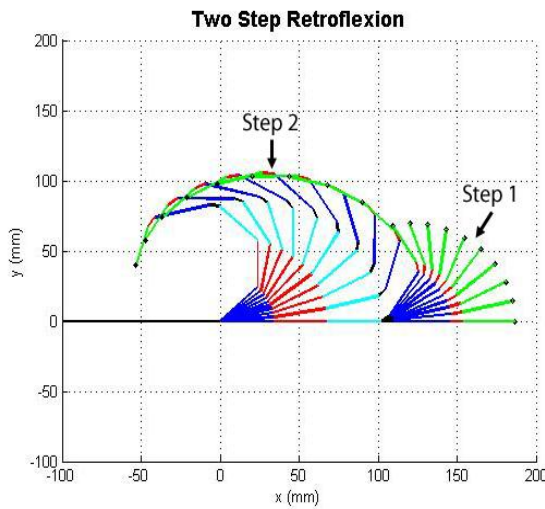


Figure 7.6: Position and orientation of each link as the flexible access platform retroflexes with simultaneous joint actuation during two distinct phases. The view point is looking from above, down on the XY plane of the platform.

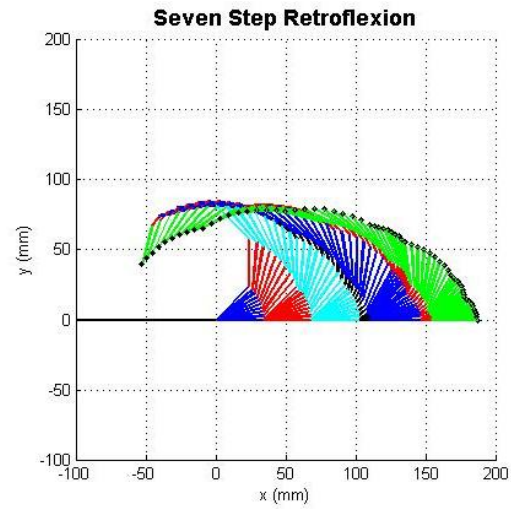


Figure 7.7: Position and orientation of each link as the flexible access platform retroflexes in seven distinct phases. Each joint is independently actuated to the limit of its travel.

Given the lack of position control on this version of the flexible access platform and the ‘joint to joint’ control methodology introduced in Chapter 4, the actual retroflexion technique to be employed during the in-vivo trials involves servoing each joint to the limit of its actuation in turn, beginning with the most distal joint. This will obviously be slower than simultaneously actuating each joint; however the resulting maximum radius of retroflexion, as can be seen in Figure 7.7, is only 91mm. This is within the volumetric constraints of the pelvis as identified in Chapter 4. However, a disadvantage of this retroflexion technique is that there is more motion in the XZ plane than with the previous techniques (maximum *z-plane* displacement of the distal tip is 25mm). This means that the flexible access platform must be positioned more than 25mm above the tissue bed before attempting retroflexion to avoid system or tissue damage.

The final simulations were carried out to demonstrate the distal dexterity provided by the final two degrees of freedom of the platform when the proximal five degrees of freedom are fixed in the retroflexed position. This can be seen in Figure 7.8 - Figure 7.11 where the reachable workspace of the distal tip is marked in red and the reachable workspace of an instrument extended 30mm from the distal face of the platform is marked in magenta. Figure 7.8 shows the 3D view of the flexible access platform retroflexed in the horizontal plane, while the views in the XY, XZ and YZ planes are shown in Figure 7.9, Figure 7.10 and Figure 7.11 respectively. This demonstrates the large area which can be accessed behind the platform when in the retroflexed position.

These results indicate that *Version_5* of the flexible access platform has the dimensions and degrees of freedom necessary to position and orientate its distal tip at locations suitable for pelvic exploration and the tubal ligation procedure from a transvaginal incision. It is important to note that these plots display the flexible access platform when retroflexed in the horizontal plane. In Chapter 4, it was stated that the desired approach for the tubal ligation procedure involved visualising the uterine horn from above. In order to achieve this positioning, the platform should be rotated through approximately 60° along the axis of its rigid shaft (if the system was retroflexed in the opposite direction then a rotation of approximately -60° would be necessary). This degree of freedom is not currently actuated and so must be carried out manually. The system can then be clamped into position and the distal dexterity used for any further instrument manipulation. The following section will now describe the actual transvaginal tubal ligation procedure was carried out with the flexible access platform.

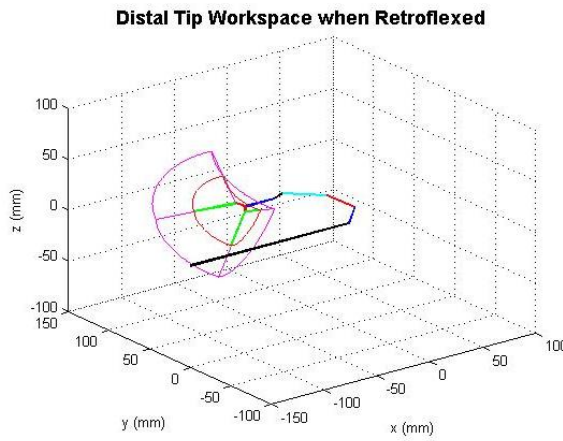


Figure 7.8: 3D view illustrating the workspace of the distal tip (red) and an instrument extended 30mm from the tip (magenta) when the five proximal joints are at their maximum displacements.

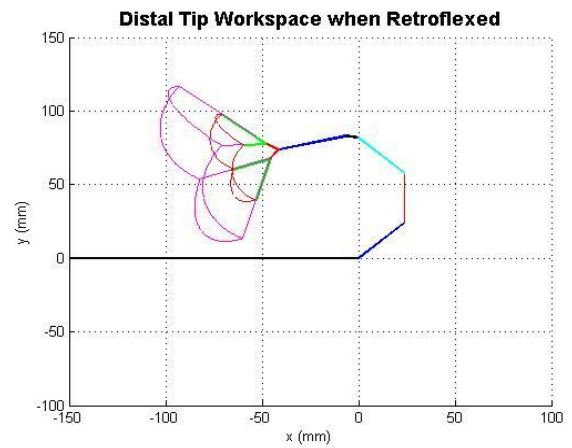


Figure 7.9: View in the *XY-plane* of the workspace of the distal tip (red) and an instrument extended 30mm from the tip (magenta) when the five proximal joints are at their maximum displacements.

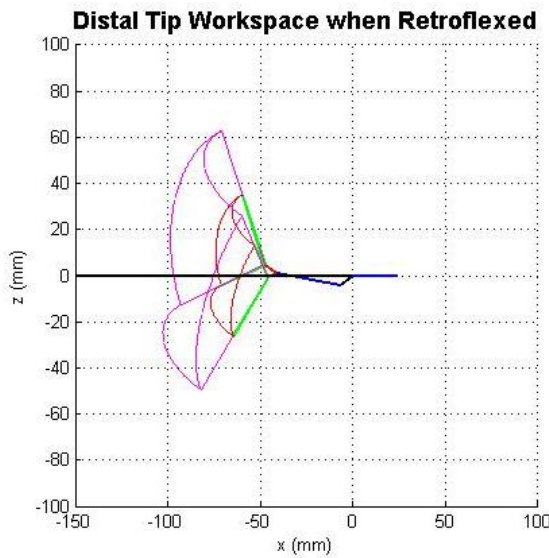


Figure 7.10: View in the *XZ-plane* illustrating the workspace of the distal tip (red) and an instrument extended 30mm from the tip (magenta) when the five proximal joints are at their maximum displacements.

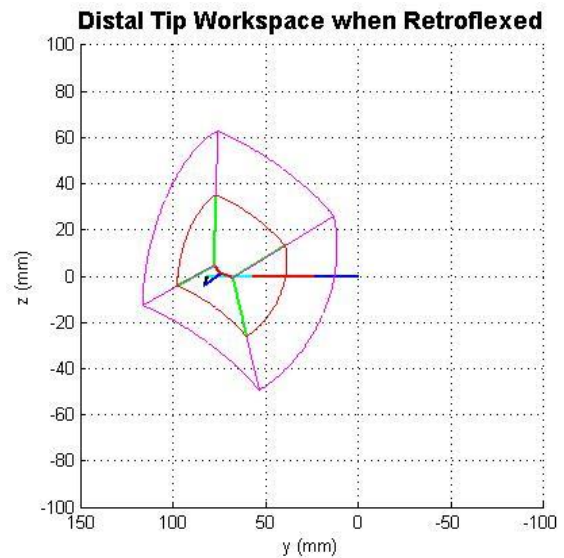


Figure 7.11: View in the *YZ-plane* illustrating the workspace of the distal tip (red) and an instrument extended 30mm from the tip (magenta) when the five proximal joints are at their maximum displacements.

7.3.2 Transvaginal Tubal Ligation Steps

The unilateral transvaginal tubal ligation was performed during a non-survival porcine study. Prior to introduction of the flexible access platform, an adult, white landrace crossbred female pig (70kg) was anaesthetised with intramuscular ketamine (5mg/kg) and xylazine (1mg/kg). After endotracheal intubation, it was ventilated with oxygen, nitrous oxide and isoflurane. At the conclusion of the procedure, the animal was euthanised with anaesthetic overdose using

sodium pentobarbitone (Lethobarb). The experimental protocol was approved by the Home Office under the Animals (Scientific Procedure) Act (ASPA) 1986, (PPL 80/2297). The pneumoperitoneum was created, and a laparoscope inserted, through a 10mm umbilical port. This laparoscope was utilised to provide visualisation of the flexible access platform when inserted. Transvaginal access was via a bespoke 15mm diameter trocar port (Applied Medical Resources Corp., USA) which was extended to 30cm in length and inserted through a posterior colpotomy.

The key steps of the procedure involving the flexible access platform were as follows:

1. Introduction of the platform
2. Retroflexion on the horizontal plane
3. Rotation about the axis of the flexible access platform shaft to visualise the uterine horn
4. Passage and application of first Boston Scientific resolution clip
5. Passage and application of second Boston Scientific resolution clip
6. Passage of rat-toothed grasper to examine clip application
7. Passage of needle-knife diathermy unit
8. Complete ligation of uterine horn using needle-knife
9. Straightening and removal of platform

Each of these steps will now be discussed in greater detail along with images of the flexible access platform performing the intervention. The instruments required to carry out the procedure are shown in Table 7.6.

Table 7.6: Instruments required to perform the transvaginal tubal ligation procedure

Instrument	Image	Required channel	Purpose
Resolution clip		2.8mm	To block the uterine horn in two locations prior to applying endoscopic diathermy in between the clipped locations
Rat-toothed grasper		2.6mm	To grasp the uterine horn in order to examine the applied clips
Needle-knife		2.8mm	To provide diathermy coagulation between the two applied clips. Current was supplied by a ValleyLab Force FX diathermy unit.

7.3.2.1 Insertion of the Flexible Access Platform

The robot was inserted through the bespoke trocar port. It features a 30cm long tube onto which a standard Applied Medical 15mm diameter port valve (Kii Optical Access System 150mm, C0R39) was attached. This allows insufflation to be achieved via the valve and pneumoperitoneum to be maintained while the flexible access platform is inserted. The external view of this setup can be seen in Figure 7.12 while in Figure 7.13 the robot can be seen emerging from the trocar port within the pelvis.



Figure 7.12: An assistant is holding the Applied Medical 15mm trocar port as the flexible access platform is inserted.

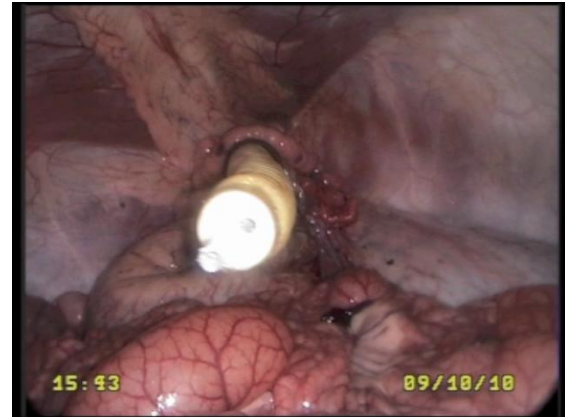


Figure 7.13: The view from the additional laparoscope as the flexible access platform is introduced into the peritoneal cavity.

7.3.2.2 Retroflexion to identify the uterine horn

The flexible access platform was rapidly retroflexed (approximately 40 seconds) on the horizontal plane by an experienced operator. This retroflexion can be seen in Figure 7.14 and was achieved by actuating each joint independently as simulated in Figure 7.7. Once fully retroflexed, the rigid shaft of the platform was rotated through approximately 60° such that the camera in the distal tip was looking down on the target area, as can be seen in Figure 7.15. It should be noted at this point, that due to variations in porcine anatomy from humans, assistance from a 5mm laparoscopic grasper was required in order to retract the bowel away from the posterior vagina so that the uterine horn could be revealed. However, as is noted in [173], such laparoscopic intervention would not be required in humans.



Figure 7.14: The flexible access platform in 180° of retroflexion on the horizontal plane (the distal tip is facing away from the laparoscope).



Figure 7.15: The flexible access platform in full retroflexion with the distal tip and onboard camera pointing at the uterine horn.

7.3.2.3 Passage and application of two Boston Scientific Resolution Clips

Two separate Boston Scientific Resolution Clips were deployed through the platform and applied to the uterine horn. Application of the first clip can be seen in Figure 7.16 (laparoscope view) and Figure 7.17 (onboard camera view). The second clip was applied in a similar manner at a location approximately 7mm from the first clip and can be seen in Figure 7.18 and Figure 7.19.

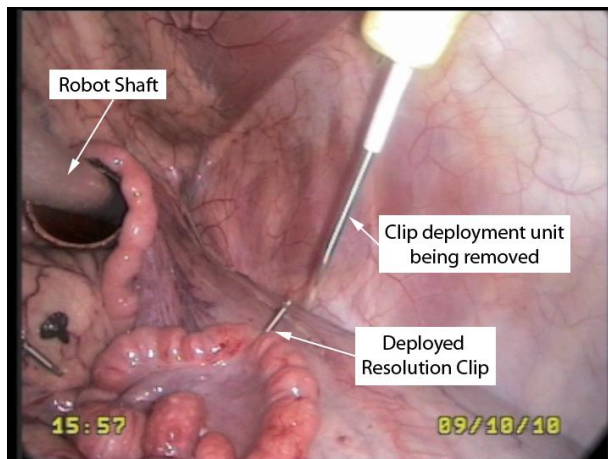


Figure 7.16: The first resolution clip immediately following application as viewed from the external laparoscope. The uterine horn, robot shaft and distal tip can also be clearly identified.

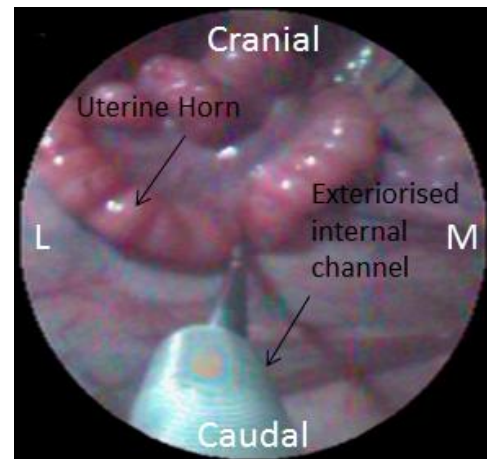


Figure 7.17: The view from the onboard camera of the application of the first resolution clip. The uterine horn can be clearly identified. The internal channel can be seen protruding from the distal tip.

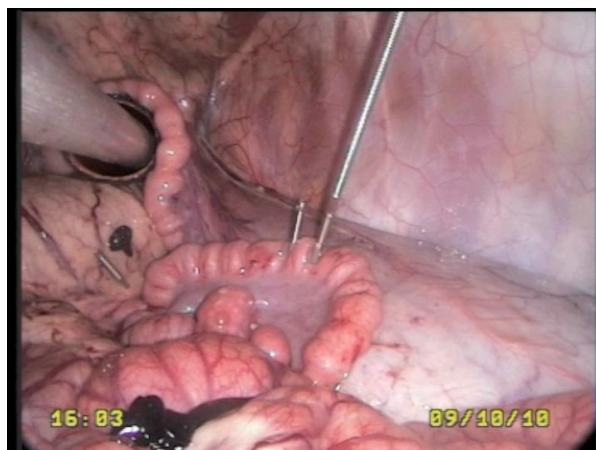


Figure 7.18: The second resolution clip is applied to the uterine horn beside the first clip.

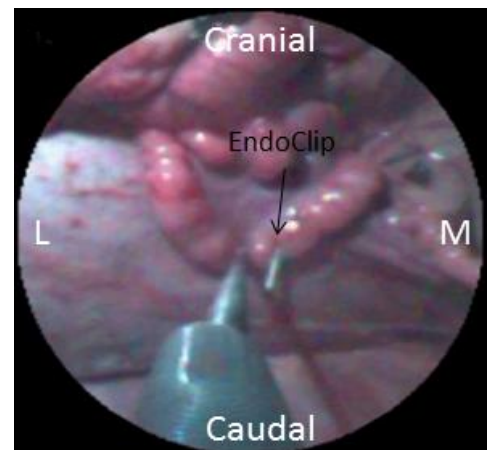


Figure 7.19: The view from the onboard camera as the second clip is applied. The location of the first clip can be clearly seen in the image.

7.3.2.4 Passage of the rat-toothed grasper to examine the clip application

A key advantage of the flexible access platform is its ability to provide a stable platform for the passage of multiple instruments. This is clearly demonstrated by the next stage of the procedure, when a rat-toothed grasper was passed down the internal channel and used to pick up the uterine

horn for the purposes of inspecting the clip application. This can clearly be seen in Figure 7.20 and Figure 7.21 below:

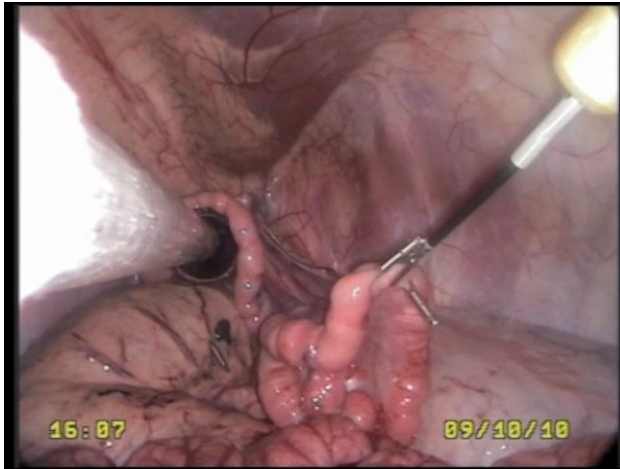


Figure 7.20: The rat-toothed grasper can be clearly seen lifting the uterine horn up for inspection. The two applied resolution clips can also be identified.

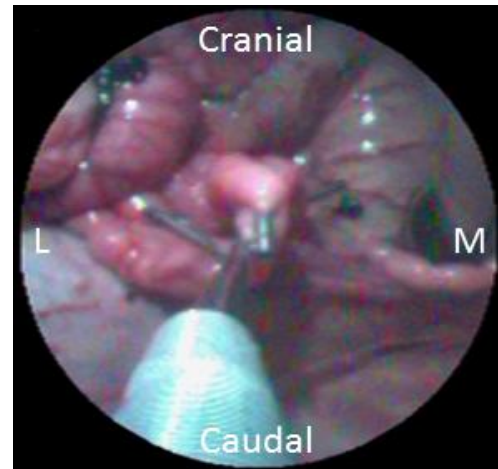


Figure 7.21: The view from the onboard camera as the rat-toothed grasper is deployed to visualise the two resolution clips applied to the uterine horn.

7.3.2.5 Passage of the needle-knife electrocautery unit

In order to fully perform the tubal ligation procedure, the needle-knife electrocautery unit was then passed through the platform. Precise mechatronic control was employed in order to cauterise directly between the two applied resolution clips. The small contact area of the needle-knife combined with the robotic control, allowed for accurate dissection with no electrocautery applied outside of the clip boundaries, as can be seen in Figure 7.22 and Figure 7.23 below. Achieving such accurate control would be a significant challenge using a standard flexible endoscope.

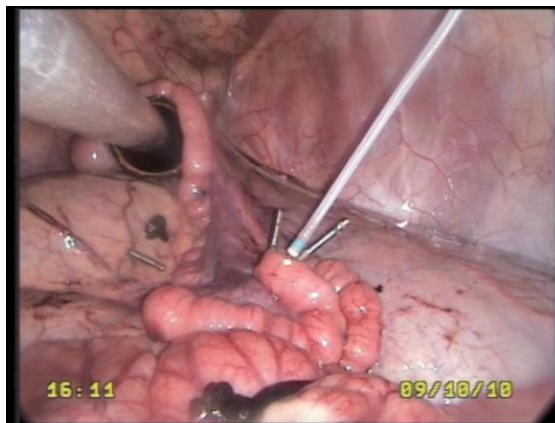


Figure 7.22: First application of the needle knife diathermy between the two resolution clips.

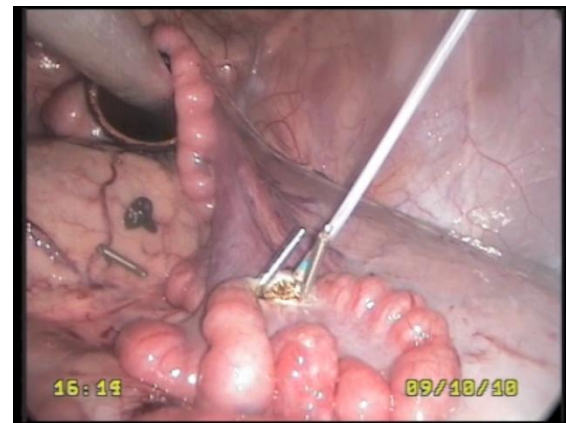


Figure 7.23: Midway through the diathermy procedure with the clear dissection between the two clips.

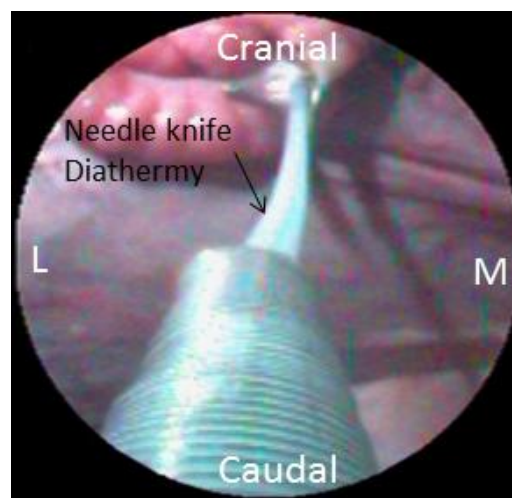


Figure 7.24: View from the onboard camera during the diathermy procedure.

7.3.2.6 Inspection of the ligation and flexible access platform removal

Once it had been ensured that the uterine horn was completely ligated the robot was straightened and removed from the peritoneal cavity. The entire procedure took 47 minutes.

7.3.3 Case Study 1: Conclusion

The flexible access platform clearly demonstrated its ability to perform a transvaginal tubal ligation. However, in order to make the procedure faster and safer, several areas must be addressed as part of future work. These include:

- Camera: The current camera in the system (1.8mm Medigus IntroSpico™) is inadequate for the task at hand. An improved camera is required in order to provide a clinically useful view of the target anatomy. The Medigus camera was originally designed for integration within an endoscope for intra-luminal visualisations and consequently is not

optimised for wide area visualisations within spatial environments such as the peritoneal cavity. Several customised solutions are currently being evaluated to resolve this issue.

- Automatic manoeuvres: It would be very useful for the platform to have the ability to automatically retroflex or straighten within the pelvis. This would eliminate the requirement for an operator to manually perform these tasks.
- Disorientation: In order to minimise operator disorientation, it would be helpful to rotate both the camera image and the robot coordinate frames of reference to a fixed, intuitive orientation when the system is retroflexed. It is envisaged that this will also simplify the operation of the robot and the overall procedure.
- Graphical representation: A graphical rendering of the configuration of the flexible access platform would be a significant aid when navigating to visualise the target. In this case study the operator was able to confirm the position and orientation of each joint using the laparoscope, however, this view would not be available during a true flexible access procedure.

Each of these points is already being addressed as part of the ongoing development of the flexible access platform and will be further discussed in Chapter 8.

7.4 Case Study 2: Transvaginal Diagnostic Peritoneoscopy

The second case study performed using the flexible access platform was a diagnostic peritoneoscopy. The purpose of this procedure was to evaluate the efficacy of the system for deploying a multi-modal imaging solution in a clinically relevant in-vivo setting. Diagnostic peritoneoscopy, or staging laparoscopy, is typically performed in order to accurately define the extent of disease progression so that appropriate therapy can be applied, and also to avoid unnecessary intervention and the resulting complications it could incur [175]. Advances in pre-operative imaging techniques such as CT, MRI and Positron Emission Tomography (PET), are improving the detection and diagnosis of primary tumours and metastases for gastrointestinal malignancies. However, small metastases and metastatic disease of the peritoneal surface are still frequently missed [176] [177]. This can result in their discovery at the time of a laparotomy and can lead to cancellation of the procedure, unnecessary trauma and a delay in appropriate treatment for the patient. However, the staging laparoscopy still represents an additional procedure, and consequently, any reduction in its invasiveness and increase in its efficacy is desirable. The use of flexible endoscopy has been proposed as a potential method by which the invasiveness can be reduced by obviating the need for more than one incision. However, as has

been mentioned previously in this thesis, the inherent flexibility of endoscopic devices can make them challenging to navigate outside of a lumen [18]. The flexible access platform offers controlled dexterity, a stable platform and more degrees of freedom than are available with traditional endoscopes. Additionally, the integration of probe-based in-vivo imaging offers the potential to increase the diagnostic abilities of the procedure. These advantages in dexterity, combined with the intraoperative optical imaging techniques described in Chapter 6, point towards a potential clinical application for the flexible access platform in the area of diagnostic peritoneoscopy via a single incision.

The goal of this case study is to demonstrate that the system can successfully obtain multiple optical biopsy samples from the liver, spleen, stomach and parietal peritoneum in a simulated diagnostic peritoneoscopy. The force adaptive linear servoing mechanism was also employed during this experiment to hold, advance and retract the probe as required. These controls were activated via a 3-way switch on the handheld controller. This effectively makes performing the peritoneoscopy a single handed procedure and thus improves the ergonomics while also reducing the technical complexity for the operator. As with the tubal ligation procedure, the incision was made transvaginally to fully demonstrate the ability of the flexible access platform to operate along curved instrument pathways from a single incision point.

7.4.1 Workspace Analysis of the Flexible Access Platform Capabilities for Performing a Transvaginal Diagnostic Peritoneoscopy

The transformations computed in the previous workspace analysis section (Section 7.3.1) indicate that the platform has sufficient degrees of freedom to easily access the volume of the peritoneal cavity. By entering the cavity with the horizontal plane of the platform (i.e. the XY plane as defined by the world coordinate system in Figure 7.4) parallel to the coronal plane of the animal as it lies on its back, each of the degrees of freedom can be actuated for exploration within the volume. Additionally, the two un-actuated degrees-of-freedom (translation along, and rotation about, the primary axis of the rigid shaft) can also be manually manipulated if required. However, to demonstrate the flexibility of the system for performing the peritoneoscopy without requiring translation or rotation about this axis, a simulated procedure was performed in an abdominal simulator [148]. The purpose of this simulated procedure was to demonstrate that the flexible access platform is capable of placing its distal tip in multiple positions and orientations within a volume representative of an abdomen from a single incision. Nine example

images of the system performing the exploration using only the mechatronically controlled seven degrees of freedom can be seen in Figure 7.25.

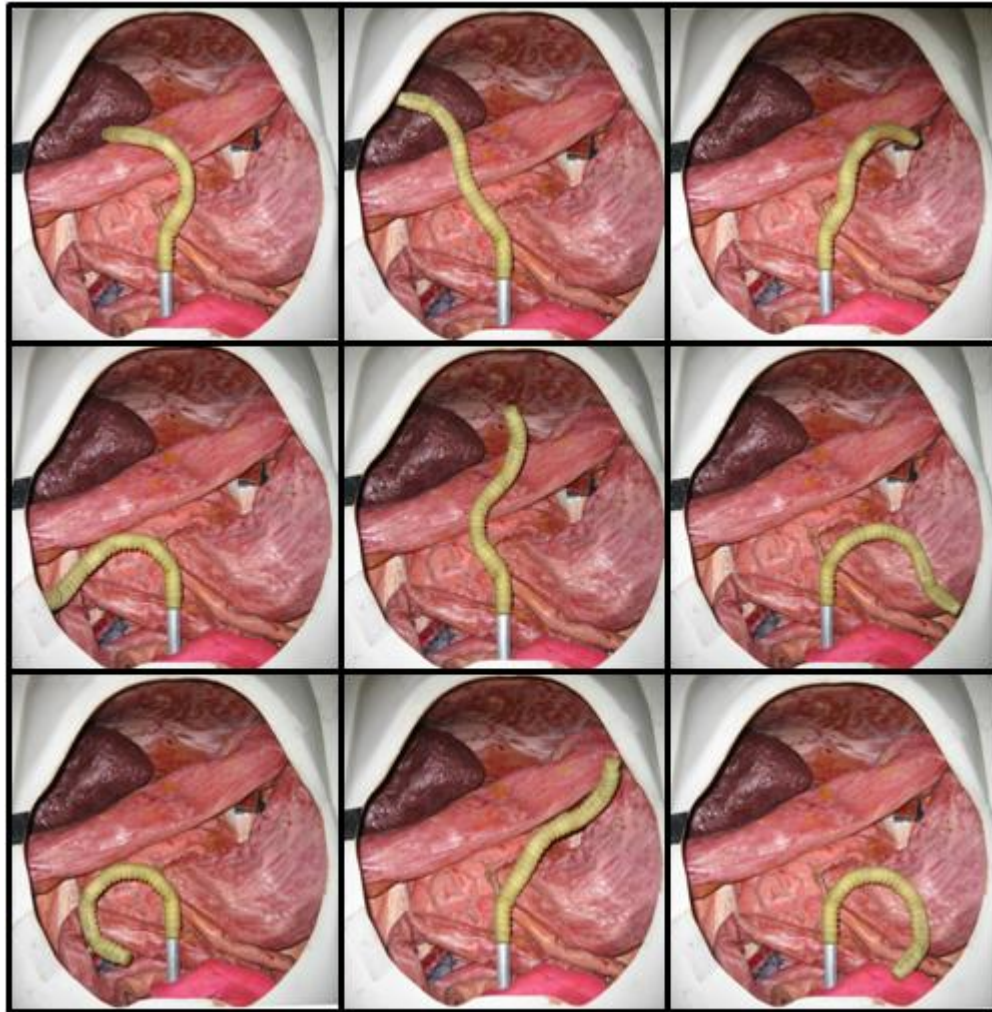


Figure 7.25: Nine example images taken during a simulated diagnostic peritoneoscopy in a simulated environment. The images are taken from above the simulator and demonstrate the ability of the flexible access platform for large area visualisation within a spatial cavity. All actuation was achieved using only the 7-DoF of the platform.

These images were all acquired without external translation or rotation of the shaft of the platform, and clearly demonstrate the flexibility and dexterity of the system and its suitability for performing a peritoneoscopy. The following section will describe the steps carried out during the in-vivo peritoneoscopy.

7.4.2 Transvaginal Diagnostic Peritoneoscopy Steps

The diagnostic peritoneoscopy was performed during a non-survival porcine experiment. The details of the pig breed, size, anaesthetic and euthanasia techniques were all identical to those

described in Section 7.3.2. In order to enhance the visualisation of the tissue structures, a medical contrast medium was used. Fluorescein sodium 10% (Martindale's, UK) was introduced intravenously (0.05ml/kg of body weight [178]) with a saline flush five minutes prior to the initial acquisition of the optical biopsy images [179]. As is also described in Section 7.3.2, access to the peritoneal cavity was achieved after first establishing pneumoperitoneum through a 10mm umbilical port. A 10mm laparoscope was passed through this port to visualise the pelvic region as the posterior colpotomy was created. The customised 15mm trocar port (Applied Medical, Kii Optical Access System 150mm, C0R39) was then inserted through the colpotomy. Once the transvaginal access point was established, the flexible access platform was introduced into the peritoneal cavity in a manner similar to that shown in Figure 7.12 and Figure 7.13, and clamped into position using the laparoscopic clamp listed in Table 7.2.

The key steps of the procedure involving the platform and the force adaptive linear servoing mechanism were as follows:

1. Introduction of the platform
2. Peritoneal navigation using the handheld controller to identify the stomach
3. Introduction of the optical imaging probe via actuation of the force adaptive linear servoing mechanism and acquisition of optical biopsy images
4. Navigation to identify the liver
5. As per '3' above
6. Navigation to the parietal peritoneum on left and right sides of the cavity
7. As per '3' above
8. Navigation to identify the spleen
9. As per '3' above

Each of these steps will now be described in greater detail along with images of the flexible access platform performing the intervention. The imaging probe used during the experiment was a Cellvizio Gastroflex™ 'Z-probe' (Mauna Kea Technologies, Paris, France) as described in Section 6.3.2. Synchronised image sequences from the onboard camera, external laparoscope and optical imaging probe were acquired from multiple locations on each of the targets listed above.

7.4.2.1 Stomach Optical Biopsy

The first optical biopsy site targeted was the stomach, as can be seen from the laparoscope view in Figure 7.26. The view from the onboard camera can be seen in Figure 7.27 while a representative optical biopsy image can be seen in Figure 7.28.

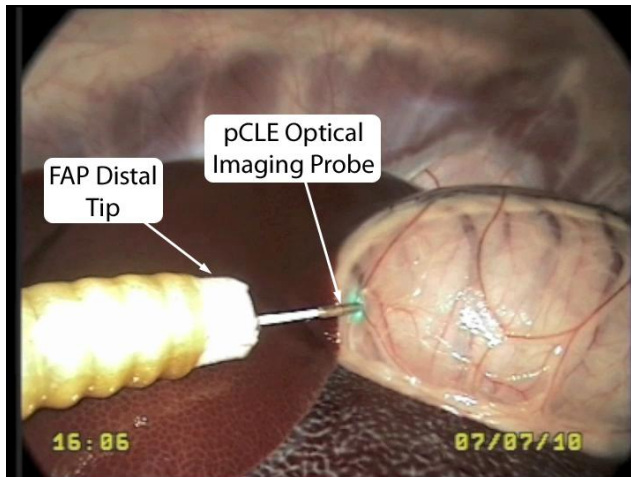


Figure 7.26: The view from the laparoscope of the flexible access platform and force adaptive linear servoing mechanism being used to acquire probe-based confocal laser endomicroscopy (pCLE) images from the stomach.

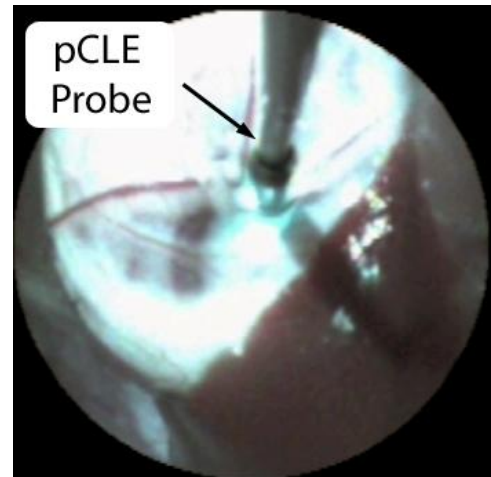


Figure 7.27: The view from the onboard camera as the pCLE images are acquired of the liver.

Once at the correct location, the proximal joints of the platform were locked into position and the distal tip was actuated to obtain multiple optical biopsy samples from the surface of the stomach. It was found that the system was straightforward to operate, although clearly the image feedback from the onboard camera is poor in comparison to the laparoscope. This issue will be further discussed in the conclusion of this chapter.

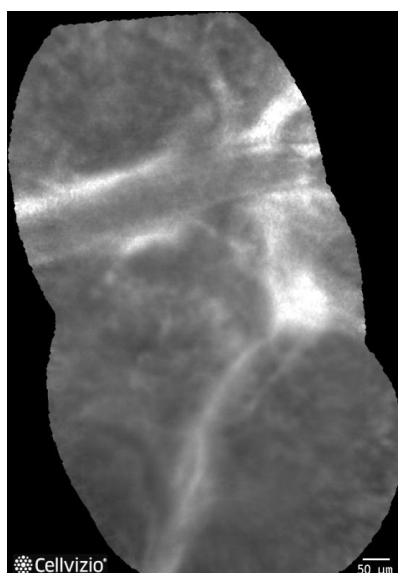


Figure 7.28: pCLE images taken of the stomach.

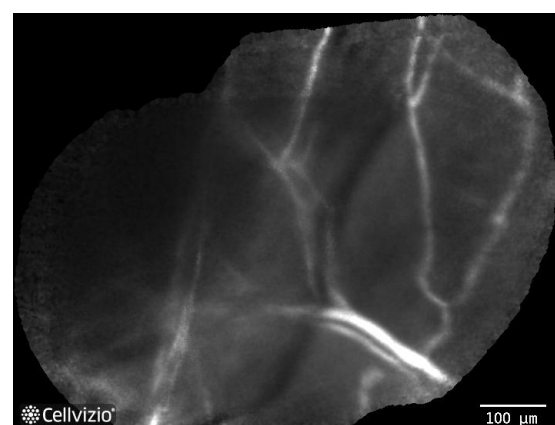


Figure 7.29: pCLE image sample from the liver.

7.4.2.2 Liver Biopsy

The second optical biopsy to be obtained was from the liver, as can be seen in Figure 7.30 and Figure 7.31 below. A sample optical biopsy is shown in Figure 7.29.



Figure 7.30: The view from the laparoscope of the flexible access platform and force adaptive linear servoing mechanism being used to acquire probe-based confocal laser endomicroscopy images from the liver.

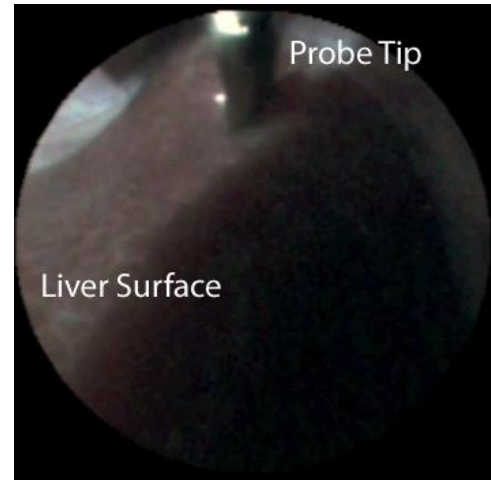


Figure 7.31: The view from the onboard camera as the pCLE images are acquired of the liver.

Navigation of the flexible access platform from the stomach to target the liver was not difficult to achieve. Similarly, activation of the force adaptive linear servoing mechanism to bring the pCLE probe into contact with the tissue was straightforward. Optical biopsy samples were obtained from multiple locations on the surface of the liver for a duration of approximately 5 minutes. It was noted that clear optical biopsy video sequences could be obtained by locking the flexible access platform into position and allowing the natural respiratory motion from the diaphragm to translate the surface of the tissue over the distal face of the probe. At locations where this translating effect was attenuated or insignificant, it was possible to use the distal dexterity of the platform to servo the probe over the surface of the tissue. However, the video sequence quality obtained during these experiments was limited due to the fast motion of the distal tip. Given the small field of view of the pCLE probe, only slow translation of the probe over the tissue should be used to avoid blurring of the resulting image. Consequently, in these circumstances, the flexible access platform was primarily used to obtain point-based optical biopsy images and not video sequences.

7.4.2.3 Optical Biopsy of the Parietal Peritoneum

The third set of example images are provided from the parietal peritoneum and are shown in Figure 7.32 and Figure 7.33. A sample pCLE image can be seen in Figure 7.34.



Figure 7.32: View from the laparoscope of the flexible access platform and force adaptive linear servoing mechanism acquiring pCLE images from the parietal peritoneum to the left of the centreline of the platform.

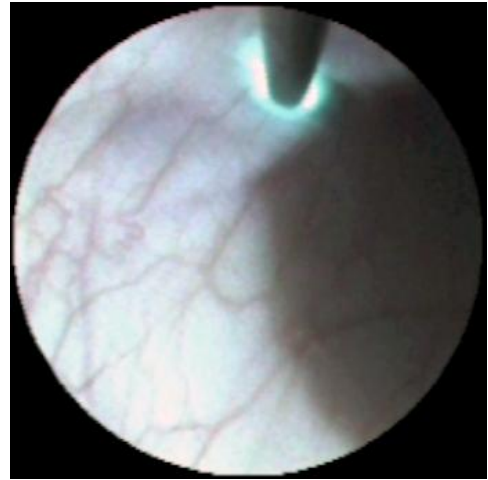


Figure 7.33: View from the onboard camera as the pCLE images are acquired from the parietal peritoneum.

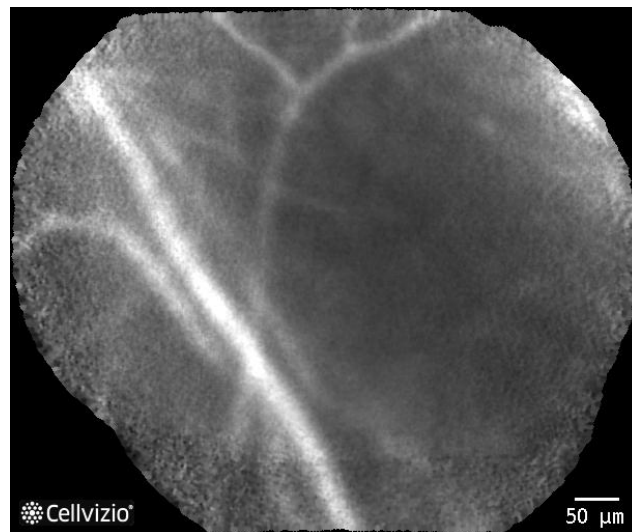


Figure 7.34: pCLE images taken of the parietal peritoneum.

7.4.2.4 Optical Biopsy of Spleen

The final set of results sequences were obtained from the spleen, as can be seen in Figure 7.35 and Figure 7.36. A mosaicked video sequence acquired from the spleen is shown in Figure 7.37.



Figure 7.35: View from the laparoscope as optical biopsy images are acquired from the spleen.



Figure 7.36: View from the onboard camera just prior to acquisition of images using the optical imaging probe of the spleen

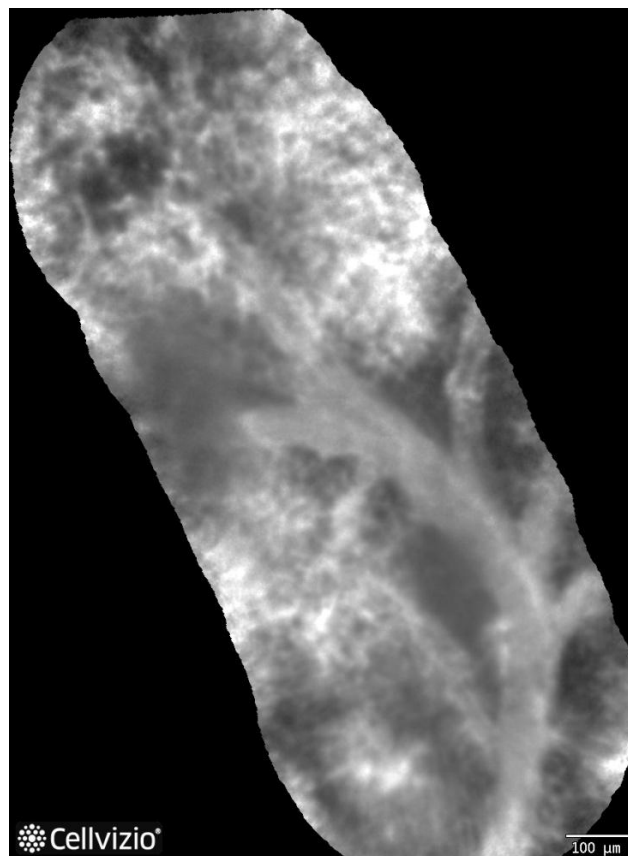


Figure 7.37: pCLE images taken of the spleen

7.4.3 Case Study 2: Conclusion

The results presented above demonstrate that the flexible access platform is capable of using its large number of degrees of freedom to successfully target the optical imaging probe within the peritoneal cavity. It offers an operator a stable platform from which to deploy the probe in an ergonomic and easy to control manner, thus simplifying the procedure and providing more time to interpret both the white light and confocal endomicroscopy images. However, the experiment also highlighted several areas which if developed would improve the overall performance of the system. These are detailed below:

- As was identified during case study 1, the image quality, resolution and field of view of the camera must be improved in order to provide the operator with a clinically useful view of the target anatomy.
- The current control architecture which delivers power to the motors proportional to the displacement of the thumb-stick can make slow movements difficult to implement. However, by utilising the position feedback provided by the joint mounted potentiometers, described in Chapter 4 and Appendix III, it is possible to implement specific trajectories for the distal tip to trace and specific speeds at which to move along these trajectories. This can potentially be implemented as a series of automatic functions which can be selected by the operator and should allow for detailed mosaics and video sequences to be acquired over large areas of the organs. It is anticipated that this feature will greatly improve the quality and length of the resulting video sequences.
- In the above experiments the force adaptive linear servoing mechanism was only used to advance and retract the probe under operator control to improve the overall ergonomics of the procedure. However, by expanding on the results presented in Chapter 6, the mechanism could be used to improve the consistency of images acquired with the flexible access platform. In particular, if used in conjunction with automatic trajectory tracking using the distal tip, it should be possible to obtain detailed, consistent, high quality video sequences which will provide significantly enhanced information to the operator.

Each of these points is similar to the findings of case study 1 and will be further discussed as part of the future work in Chapter 8.

7.5 Discussion and Conclusion

Building on the concepts of flexible access surgery introduced in Chapter 1, the results presented in this chapter clearly demonstrate the potential for deploying the platform as a ‘focused’ robotic device whose unique capabilities can be used by a surgeon when required during a given procedure. In the case of the flexible access platform, these unique capabilities are centred on the high level of distal dexterity provided to the clinician, coupled with the minimal footprint within the operating theatre. By also ensuring seamless integration with third party probe-based optical imaging techniques, the platform potentially offers a surgeon a very useful diagnostic tool which can be deployed with a minimum of trauma to the patient. Additionally, during the case studies described in this chapter the platform operated continuously for up to five hours in-vivo demonstrating that even at this early prototype stage the hybrid micromotor-tendon drive mechanism is suitable for prolonged deployment.

The specific results presented in this chapter demonstrate that from a mechatronic perspective, the platform has the necessary degrees of freedom required to explore the peritoneal cavity and to facilitate the passage of instrumentation through its internal channels. However, it is also obvious that in its current configuration, limitations still exist. Looking firstly at the onboard camera, it is clear from the results presented that the image quality and field of view need to be improved before any clinical deployment can be considered. Identification of a more suitable camera is beyond the scope of this thesis, but several systems are under consideration. Secondly, in its current guise, the flexible access platform is a ‘mechatronic’ rather than a ‘robotic’ device and so does not maximise its potential. Consequently, the major focus for future applications will involve using the joint position sensors to develop many new robotic control algorithms which will serve to both simplify operation and provide new advanced capabilities to the surgeon. Examples of such algorithms which have already been developed, but are outside the scope of this thesis, include the automatic rotation of the camera image based on a tip-mounted inertial sensor [180], and automatic servoing of all joints simultaneously to maintain shape conformance under dynamic active constraints [142]. This future work will be further described in Chapter 8 and represents many exciting potential applications for the system.

Chapter 8:

Conclusions and Future Work

8.1 Contribution of this Thesis

The evolution of surgery over the last 25 years has been driven by the desire to reduce the invasiveness of surgical procedures. This has been achieved through development of new technologies which allow procedures to be carried out through smaller and smaller incisions. As these incisions shrink in size, and the procedures being undertaken become more complex, technology again has a role to play to ensure that the trend continues. In this arena, the emerging field of medical robotics offers unique possibilities for combining the ingenuity of a surgeon with the dexterity of miniature mechatronically controlled tools. The challenge facing the next generation of medical robotic devices is not just how to deal with increasingly complex access routes and procedures, but also how to leverage the advantages in pre- and intraoperative

imaging techniques to improve the intraoperative information flow and provide new methods for diagnostic and therapeutic decision making.

The work presented in this thesis represents the first steps towards the development of a new type of ‘focused’ robotic device that features unique capabilities which can enhance a surgeon’s ability to access, diagnose and intervene inside the body. The key purpose of this device is to provide the flexibility required to navigate along curved pathways and to provide channels through which a surgeon can interact with target anatomy. The device is not intended to be used throughout the entire procedure, but rather to be used at the times when its capabilities can be of benefit. These capabilities may be as simple as providing an alternative visualisation of an organ or as critical as identifying accurate tumour margins in conjunction with optical biopsy techniques. Developing such a device is challenging on many fronts and the work presented in this thesis makes the following key technical and clinical contributions:

- A dual-modality imaging instrument that provides a surgeon with the ability to perform large area robotically-controlled scans using synchronised white light and tunable fluorescence light;
- A modular mechatronic joint design that can be used to create novel multiple degree-of-freedom flexible access instruments;
- A gaze contingent control strategy suitable for controlling multiple degree-of-freedom robotic devices in a hands-free manner;
- A system for providing consistent probe based multi-spectral imaging in an ergonomic fashion and the ability to provide a surgeon with co-registered white light and multi-spectral image information;
- A demonstration of the ability of the flexible access platform to perform a minor interventional procedure within the pelvic cavity from a transvaginal incision and to provide a stable platform for the deployment of interventional instrumentation;

- A demonstration of the ability of the flexible access platform for targeting optical imaging probes at multiple locations within the peritoneal cavity from a single incision.

Table 8.1: How the individual chapters relate to the challenges outlined in Chapter 1

No.	Challenge(s) Addressed	Key Contribution
Chapter 3	1,3	Controlled articulation and integrated multi-spectral imaging
Chapter 4	1,4	Modular joint design and 7-DoF flexible access platform
Chapter 5	2	Ergonomic handheld controller and gaze continent control framework
Chapter 6	2,3	Ergonomic, consistent probe-based optical imaging
Chapter 7	1,3	Controlled flexibility and targeting of instruments in-vivo

Each of the chapters in this thesis presented solutions to the first four unmet clinical challenges outlined in Chapter 1. Chapter 3 presented a preliminary solution to both *Challenge 1* and *Challenge 3* through the development of an **articulated multi-spectral imaging robot**. This system offers a surgeon the ability to perform robotically-assisted imaging scans using both white light and fluorescence illumination. The use of fibre optic technologies for transmission of the image from the distal tip to external acquisition hardware and a tunable supercontinuum laser source allowed all structural, actuation and imaging components to be integrated within a diameter compatible with existing trocar ports for minimally invasive surgery. It was demonstrated that by using the robotic capabilities of the device, synchronised tip trajectories can be traced and co-registered functional panoramas can be generated. The use of such scanning techniques coupled with the dexterity of a flexible robotic device offers the potential for the generation of functional tissue maps intraoperatively. Such information could potentially be used by surgeons to improve the diagnosis and treatment of disease.

In Chapter 4 a **modular mechatronic joint design** incorporating a hybrid micromotor-tendon actuation scheme is presented. Multiple joint modules were combined to construct a platform which is capable of providing self supporting, controlled flexibility along curved pathways. As outlined in *Challenge 1* and *Challenge 4*, the purpose of having such flexibility is driven by the clinical demand to reduce invasiveness and to allow surgeons to intervene at locations not in a

direct line of sight from the incision point. The flexible access platform described in this chapter facilitates such interventions by providing seven serially connected degrees of freedom which can be used to explore all quadrants of the peritoneal cavity from a single incision. Once the system reaches the desired location in-vivo, the provision of a hollow central core allows for the passage of imaging probes or interventional instrumentation. The use of embedded joint actuation results in a significantly reduced footprint within the operating theatre – a feature which allows the device to be rapidly deployed without disturbing the existing surgical workflow. The result is a research test-bed suitable for investigating the concepts of flexible access surgery, and the application of robotic control algorithms for improving the usability of flexible robotic devices in surgery.

Crucial to the usability of any mechatronic device deployed in a clinical environment is the control interface. As outlined in *Challenge 2*, given the high-stress, dynamic environment of a modern operating theatre, any ‘focussed’ robotic device is required to have a control interface that is easy to use, presents a minimum footprint in-theatre and is capable of rapidly adapting to changing scenarios. The ‘**decoupled handheld controller**’ introduced in Chapter 5 meets each of these criteria. In a small package it provides an intuitive method to control all seven degrees of freedom and does not hinder a surgeon’s movement around the operating table. Although limitations in the overall interface exist, and will be discussed in the next section, this handheld controller has successfully been deployed during multiple laboratory and in-vivo studies. However, while it represents a practical engineering solution to the issue of how to control the flexible access platform, Chapter 5 also introduces an experimental control interface developed to investigate the feasibility of controlling a multiple degree-of-freedom device in a hands-free manner through the eyes of the surgeon. Two different **gaze contingent control strategies** were developed to control the flexible access platform. The first provided the operator with direct control over each joint unit while the second abstracted the complexity of the system using an algorithm to select the joint unit to be actuated automatically. This concept of ‘hands-free’ control directly addresses *Challenge 2* and offers the potential for reducing the number of operators required during complex procedures in-vivo.

Chapter 6 addresses *Challenge 3* by describing the integration of probe-based multi-spectral imaging techniques within the flexible access platform. The purpose of combining the platform and such imaging probes is to increase the ability of a surgeon to make diagnostic decisions intraoperatively. A **force adaptive linear servoing mechanism**, which is capable of clamping

an imaging probe into place and adjusting its insertion depth within the internal channel, is described. The force adaptive linear servoing mechanism can be operated in two modes – the first of which aims to improve the ergonomics of manipulating optical imaging probes by allowing the operator to advance and retract the probe via the handheld controller. This reduces the operator workload as they no longer need to hold and translate the probe within the internal channel. The second operating mode further simplifies the ergonomics by automatically adjusting the insertion depth of the probe within the channel based on the relative changes in the measured contact force between the soft tissue and the probe tip. Preliminary studies to demonstrate the importance of measuring and controlling this probe-tissue interaction force are described and an ex-vivo practical demonstration of the technique is also presented. A further advantage of this integrated approach is that it is possible to localise the information provided by the multi-spectral imaging probe within the field of view of the camera and the tip trajectory. The practical benefits of the force adaptive linear servoing mechanism combined with the flexible access platform offer surgeons a feasible solution to address the current difficulties of deploying probe-based optical imaging techniques in real-world environments.

In Chapter 7 the practical deployability of the flexible access platform and its sub-systems are demonstrated through the description of **two case studies performed in-vivo during live porcine experiments**. Bridging the gap between the laboratory and a real clinical scenario is a challenging engineering endeavour; the fact that the flexible access platform was successfully deployed during multiple such trials is demonstrative of the success of the initial design process and the refinements made following each trial. The first case study described in this Chapter demonstrates the ability of the flexible access platform to enter the peritoneal cavity via a single incision, use its flexibility to locate the uterine horn within the pelvis and deploy multiple interventional instruments at the target site. This one case study addresses *Challenges 1, 2 and 4* and demonstrates that the platform can be used as a research platform to investigate the concepts of flexible access surgery. The second case study described addresses each of *Challenges 1- 4* as outlined in Chapter 1 by performing a diagnostic peritoneoscopy using both the platform and the force adaptive linear servoing mechanism. In this study, the dexterity of the flexible access platform is used to target multiple organs within the peritoneal cavity while the force adaptive linear servoing mechanism is used to advance and retract a pCLE imaging probe through the hand-held controller. Optical biopsy samples were obtained from the stomach, the spleen, parietal peritoneum and the liver, all from a single incision and in an ergonomic, controllable manner. These two case studies demonstrate that even in its current limited form,

the flexible access platform is suitable for deployment in pre-clinical trials and provides a test-bed for exploring the potential applications of flexible access surgery.

8.2 Future Research Directions

A key achievement of the work presented in this thesis is the development of a platform which can be used as a test-bed to investigate both the concepts of flexible access surgery and the application of robotic control algorithms to improve the usability and efficacy of flexible robotic devices in surgery. Looking initially at the future direct expansion of the work presented in this thesis, the possibility of combining the gaze contingent control framework with the force adaptive linear servoing mechanism is obvious. This would result in an entirely ‘hands-free’ method by which optical biopsy images could be obtained over a wide area from a single incision. A potential clinical scenario where such a system would have significant impact is that of a laparoscopic tumour resection. In this case, the lead surgeon would be able to use traditional rigid laparoscopic instruments to manipulate tissue to expose the tumour region and simultaneously use gaze contingent control to command an optical biopsy probe to scan the surrounding tissue to identify the tumour margins. Such a system would truly be a demonstration of the potential of flexible access surgery and the importance of bringing optical diagnostic techniques into an intraoperative setting. However, as was indicated in the conclusions to Chapter 5 and 6, before such a device could become a reality, further development work is necessary. In the case of the gaze contingent control interface, a full evaluation of fatigue introduced by the system would need to be performed. Such fatigue may be introduced by the increase in cognitive workload when attempting to simultaneously control three instruments, for example. Additionally, from a practical perspective, the commercial eye tracking unit used to extract the operator fixations in the study presented here, would struggle to function accurately within the dynamic environment of an operating theatre. The use of a wearable eye tracking unit which is capable of tracking the surgeons gaze fixation with respect to a monitor displaying the onboard camera feed would be of particular benefit. Looking at the force adaptive linear servoing mechanism, a future task is to model and characterise the interaction between the probe and the internal channel of the flexible access platform in order to predict the effects of the frictional interaction between the two as the distal articulated segments of the flexible access platform actuate. An alternative solution, as was discussed in Chapter 6, is to investigate the possibility of integrating tip mounted force sensing capabilities into optical imaging probes. Advances in fibre optic based miniature force sensors offers significant potential for this application.

It is also anticipated that the clinical applicability of the flexible access platform will increase with improvements in both endoscopic instrumentation and optical imaging probes, and the contrast agents used to visualise disease markers in-vivo. Looking firstly at endoscopic instrumentation, in the case studies described in Chapter 7 only a limited subset of existing instrumentation was used. Other instruments not described include lasers for tissue ablation or photodynamic therapy. CO₂ or Argon lasers are capable of being passed through the flexible access platform and precisely targeted at any location inside the peritoneal cavity. A limitation of the flexible access platform is the lack of additional torque available at the joints for direct tissue dissection; however using a laser system for tissue ablation would not require additional torque and so is ideally suited to applications with the platform. Similarly, much research effort is being applied in the area of lasers for tissue fusion, as an alternative to staples and suturing [181]. Such technology is again perfectly suited for deployment with the flexible access platform as it would allow the system to perform tissue reconstruction without the need for traditional suturing or clipping equipment. The system also has significant potential application for use with emerging optical contrast agents and imaging probes. As new markers become more prevalent and safe to apply in humans, the requirement for a flexible device capable of exploring large areas to visualise the response will arise and the flexible access platform is ideally suited to this task.

The deployment of robotic control algorithms with the platform offers many exciting possibilities in the areas of closed loop trajectory definition using optical imaging probes and operator disorientation reduction during procedures. As was mentioned in the main text of this document, the ability to define specific trajectories for the distal tip to trace when manipulating an optical imaging probe offers the potential to generate high-resolution functional tissue maps which can be used by surgeons to make more informed diagnostic decisions. Furthermore, the potential exists to automate large parts of the acquisition procedure by allowing the flexible access platform to systematically probe a region which is defined by the surgeon on an organ's surface. Robotic control algorithms can also be used to mitigate the disorientation effects of flexible access surgery. The simplest possible disorientation reduction strategy would be to provide the operator with an interactive graphical representation of the flexible access platform which illustrates the system configuration at any point in time. An expansion on this concept is to actively track each degree of freedom (including the external translation and rotation of the rigid shaft) so that both the camera image and the joint coordinate frames of reference remain

mapped to a fixed reference frame, even as the device is rotated about the axis of the shaft. Such techniques potentially offer solutions to *Challenge 6* as identified in Chapter 1.

Another area of research which is expected to impact significantly on the field of medical robotics is that of Image Guided Intervention (IGI). Currently, high resolution imaging systems such as MRI and CT scanners are installed in dedicated imaging suites. However, in a few centres around the world, these imaging technologies are co-located with operating theatres so that the imaging systems can be used to guide surgeons intraoperatively. Examples of clinical areas where such procedures are currently being performed include the use of MRI images to guide neurosurgery [182] [183], the use of CT images to guide pedicle placement for spine surgery [184] and CT imaging for head and neck surgery [185]. The current state-of-the-art Integrated Operating Theatres [186] include the systems which feature intraoperative MRI, CT, 3D Angio and Ultrasound. These theatres can be further expanded to include image guided surgery platforms which also incorporate optical tracking systems to track surgical tools during procedures. Significant potential exists for combining the precise localisation of anatomical targets provided by such intraoperative imaging suites, with the dexterity and reduction in patient trauma offered by robotic devices operating inside the body.

If, for example, the flexible access platform was used in conjunction with a high-resolution imaging system it would potentially be possible for the robotic device to know its exact location with respect to the surrounding soft tissue. This knowledge, coupled with input from the surgeon, would allow advanced safety features and augmented visualisations to be introduced. These enhanced features offer the potential to reduce errors and improve the diagnostic and interventional decision making by the surgeon. Examples include the provision of Dynamic Active Constraints [187, 188] which would prohibit the flexible access platform from cauterising or ablating in regions which are critical for patient survival or quality of life – such as the nerves close to the dissection site in prostate resection. The use augmented reality (AR) visualisations, such as Inverse Realism [189], have the potential to provide surgeons with intraoperative visualisation of structures beneath the tissue surface. This in turn will allow for incisions to be made in optimum locations. Another area in which the fusion of intraoperative imaging and robotics presents possibilities is that of haptic interaction. Currently, systems such as the daVinci lack the ability to provide any sense of touch back to the surgeon. Consequently surgeons use the immersive 3D environment to infer how much force is being applied onto tissue by the system's manipulators. Sensorising the manipulators to provide haptic feedback is

challenging due to the degrees of freedom requiring sensors and the size constraints of minimally invasive surgery [190] . However, image based sensing of the tissue deformation and how the flexible access platform is interacting with the tissue could potentially allow for haptic feedback to be applied. Haptic feedback could also be employed with the force adaptive linear servoing to give the operator kinaesthetic information regarding the amount of pressure the probe is applying onto the tissue surface.

Finally, the flexible access platform presented in this thesis is only capable of a sub-set of procedures which would be considered flexible access surgery as outlined in Chapter 1. Effectively, these are any procedures which do not require large amounts of physical tissue manipulation since the flexible access platform is not equipped for such tasks. Performing the whole range of flexible access surgery will require the remaining three challenges identified in Chapter 1 to be solved. Of these the most challenging is that of providing the bimanual tissue manipulation capabilities used currently during laparoscopic surgery to achieve triangulation for tissue dissection and reconstruction. Several platforms, both robotic [40] [38] and otherwise [191] [192], are under development to provide such capabilities however none have yet demonstrated the clinical efficacy necessary to disrupt current clinical practice. Nonetheless, it is hoped that by building on the lessons learnt and challenges solved with the development of the flexible access platform described in this thesis, such surgical devices are one step closer to reality.

Appendices

Appendix I: Multi-Spectral Imaging Robot

A. Construction Technique



Figure A.1: Six images showing several of the steps required to wire and pretension the articulated segment of the robotic probe. (1,1) The base joint showing the connection to the rigid shaft and the first link. The legs of the torsion spring, the axle and the tendon are also visible. (1,2) shows two joints with three links connected. The effect of embedding the torsion spring with 120° between the legs is evident as the joint assumes an inverted orientation since there is no tension in the tendons to act against the springs. (1,3) shows the tendons running out of the articulated segment with the brass rods clearly visible. (2,1) The brass rods running into the rigid shaft can be clearly seen as well as a hollow rubber tube used to protect the fibre bundle. (2,2) The capstan configuration can be seen here, with the front left capstan unwired and the front right capstan wired. (2,3) the final tensioned configuration. The protective tubing for the fibre bundle can also be clearly seen exiting the shaft

B. Fibre Image Guide Data Sheet



Image & Bundle Products

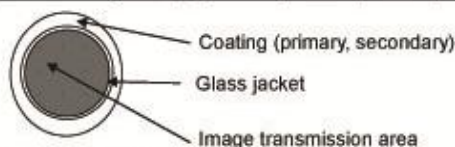
Image guide (IGN series)

General

Image guide, which consists of thousands to tens of fiber elements arranged coherently, enables to transmit any picture image directly to a remote end. SEI's image guides, which are made of synthetic quartz and fabricated by drawing multi-core glass elements, provide excellent transparency at visible ray band and ultra-fine resolution. SEI's image guides have been contributing to application areas that need imaged data as diagnosis and inspections.

Physical characteristics (typical value)

	IGN-02/03	IGN-035/05	IGN-037/10	IGN-05/10	IGN-08/30	IGN-15/30	IGN-20/50
Number of picture elements	3000	6000	10000	10000	30000	30000	50000
Numerical aperture	0.35(nom.)					0.3(nom.)	
Diameter of fiber(glass dia.) (mm)	0.2	0.35	0.37	0.5	0.8	1.5	2
Diameter of image transmission area (mm)	0.18	0.315	0.333	0.45	0.72	1.35	1.8
Distance between neighboring cores (um)	app.4					8-9	
Diameter of primary coating (mm)	0.25	0.42	0.45	0.59	0.96	1.9	2.4
Diameter of secondary coating (mm)	-					2.5	3
Core material	GeO ₂ Containing Silica						
Cladding material	F Containing Silica					Pure Silica	
Lattice defect(black dots)	< 0.1%					< 0.05%	
Allowable bending radius (mm)	10	15	20	25	40	75	100



[Cross sectional view]

Safety instructions

- This Product is designed for industrial purpose. If this Product is used of medical care or applied to medical equipment, it is the Purchaser's responsibility to ensure the Product meets all applicable safety, reliability or other standards or requirements.
- Product should not be used as the delivered condition itself without additional protection (additional protection is like an outer protection tube and / or catheter into which the Product is inserted). This is for preventing any hazards that might be occurred by small fine glass in the Product.

Contact informations

Tokyo : Sumitomo Electric Industries, Ltd.

(phone)+81-3-3423-5889 / (fax)+81-3-3423-5099

US : Sumitomo Electric U.S.A., Inc.

(phone)+1-310-782-0227 / (fax)+1-310-782-0211

Europe : Sumitomo Electric Europe Ltd.

(phone)+44-208-953-8118 / (fax)+44-208-207-5960

catalog
Jan. 09, 2001

Sumitomo Electric Industries, Ltd.
1 Taya-cho, Sakae-ku, Yokohama 244-8588 Japan
(phone)+81-45-853-7143 / (fax) +81-45-851-1265

C. Mechatronic Features

C.1. Actuation Component Selection

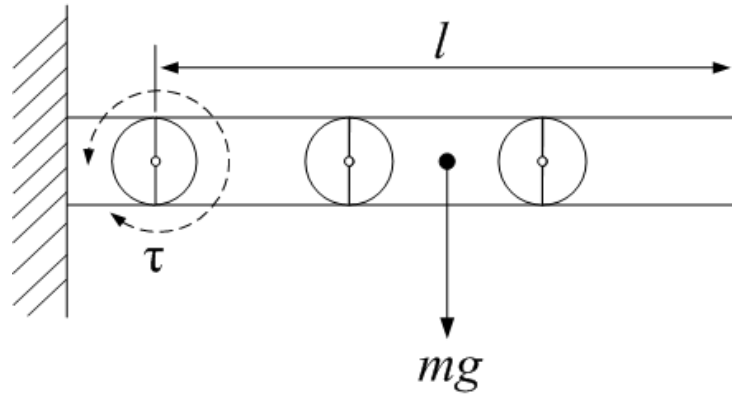


Figure C.1: Free body diagram showing the torque required by the torsion spring in order to rotate the three joints into position.

The torque, τ , required to cantilever the robot from the proximal joint is $1.58mNm$. This is obtained from:

$$\tau = F * d \quad (I - 1)$$

Where:

$$F = (n * m) * 9.81 \quad (I - 2)$$

$$d = \frac{(n * l)}{2} \quad (I - 3)$$

The parameters used to calculate this value were a link mass, m , of $1.2g$ (including bearings, washers, axles), a link length, l , of $30mm$ and the number of links, n , of 3 . A torsion spring providing a torque of $13mNm$ was selected. This is a small enough size to fit within the structure of the joint and is capable of producing sufficient torque to rotate each link when the tendon is slack. The springs used are capable of 180° deflection and produce zero torque when the angle between the legs is 180° . To ensure that the springs are always in a configuration to provide a restoring torque, they are embedded into the link units with an angle of 120° between the legs. A Futaba S3001 DC motor was selected for actuation of the joint as it provides $294mNm$ of torque. This is significantly more torque than is required to change the tendon length against the torsion spring.

C.2. Actuation Pack

To maximise the repeatability of the device, each tendon was wired directly to a split capstan and pre-tensioned such that when each link is in a 0° position, both the tendon and the torsion spring are under tension. Each capstan is mounted on the output shaft of a servo in the actuator pack, as can be seen in Figure 2.C.

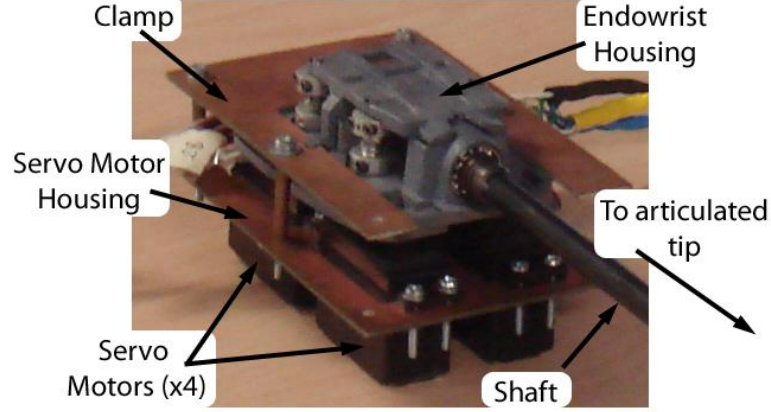


Figure C.2: Image of the actuator pack. The Endowrist™ capstan housing, shaft, servo motors and clamping unit can be clearly identified.

Each tendon is also encased in a 0.8mm brass tube for the linear section of the transmission (i.e. within the rigid shaft) to minimise the effects of friction and torsion between the tendons as the device is actuating. These steps serve to maximise the repeatability of the device so that any movement of the capstan results in a proportional movement of the joint. This repeatability will be discussed in greater detail in Section 3.3. The steps performed to wire the device in this configuration are shown in Appendix I.

The tendon lengths (and thus angular displacement of their respective joints) are controlled by the rotation of the capstans which are driven by the servo motors in the actuator pack. The actuator pack was adapted from the EndoWrist™ design from Intuitive Surgical [24]. Each servo horn was customised to mate with the existing interface plate on the EndoWrist™ and the servos were clamped into place using a custom housing, as can be seen Figure C.2. The relationship between motor angular position, θ_{motor} , tendon linear displacement, δ_{x_0} , and the angle of link $n + 1$ relative to link n , θ_{tip} , is shown in Figure C.3 and given by:

$$r_{pulley}\theta_{motor} = \delta_{x_0} \quad (I - 4)$$

$$\delta_{x_0} = x_0 - \sqrt{(a^2 + b^2 - 2ab \cos(\theta_0 - \theta_c - \theta_{tip}))} \quad (I - 5)$$

where variables a, b, x_0, θ_c , and θ_{tip} are defined in Figure C.3.

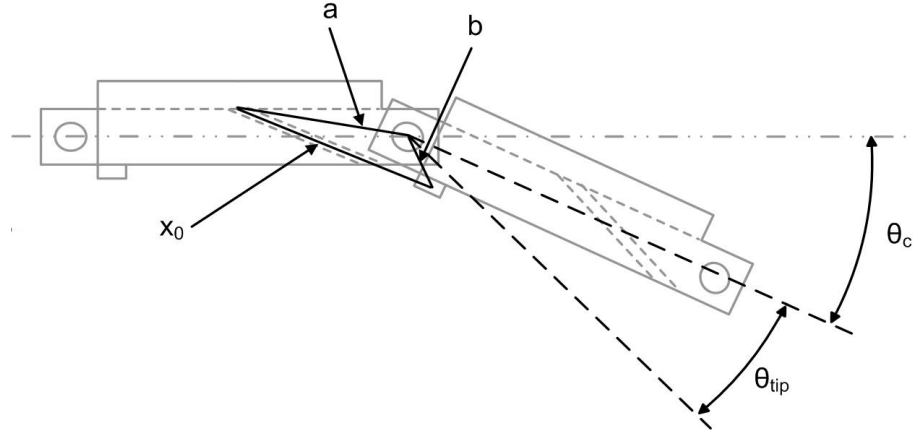


Figure C.3: Schematic illustration of the proposed robotic joint, where a and b are 18mm and 5mm respectively, θ_c is the current tip orientation angle of link $n + 1$ relative to the preceding link n , and θ_{tip} is the desired orientation relative to θ_c . When θ_c is 0° , x_0 is 22mm and θ_0 (angle between a and b when the link is in a horizontal position) is 2.41rad.

For this design, r_{pulley} is 2.5mm, a and b are 17mm and 5mm respectively, x_0 is 22mm when the two links are in a horizontal position, θ_c is the current tip orientation angle relative to the preceding link and θ_{tip} is the desired tip orientation relative to the preceding link. In Equation (3-5), θ_0 , which represents the angle between a and b , is 3.1 radians when the two links are in a horizontal position.

The range of motion for each joint is approximately $+85^\circ$ to -30° , although for the dual mode imaging experiments, these values were software limited so as not to exceed the minimum bending radius of the fibre image guide (25mm). The fourth degree of freedom, J_4 , is also controlled by a Futaba S3001 located in the actuator pack. It was necessary to modify this servo to increase its rotation range from $0-180^\circ$ to continuous. This was achieved by disengaging the internal potentiometer, which provides position feedback for the output shaft, and removing the mechanical block on the output shaft. This servo is also clamped into position and rotation of its output shaft is coupled to the main shaft of the multi-spectral imaging robot via the pre-existing EndoWristTM capstan drive. This capstan is only capable of $0-540^\circ$ of rotation, which must be taken into account when programming the servo motion.

This four motor actuation scheme allows the multi-spectral imaging robot to perform large area scans, where the tip traces overlapping circular trajectories at different overall tip defections. Alternatively, the redundancy in the joints can be exploited and the device can be set to image behind structures by fixing the proximal link(s) to a set angular displacement and scanning with the distal link alone.

D. Repeatability Analysis

Each of the servo motors acts as a closed loop positioning system via an embedded rotary potentiometer coupled to the output shaft. Based on the assumption that the motor rotates to the position commanded by the PIC, the angular positions of J_1 , J_2 and J_3 can be estimated. However, the lack of a dedicated position-sensing element on the joint represents a limitation of the system and limits its accuracy. Consequently, a series of repeatability tests were carried out to demonstrate its suitability for performing large area imaging scans. Specifically, two separate tests were carried out on the device:

- To assess the repeatability of the in-plane articulation when moving to different preset angular displacements of J_1 , J_2 , J_3
- To assess the system repeatability when simulating a large area imaging scan with all four degrees of freedom

Validation was performed using optical tracking markers and an Optotrak Certus system (Northern Digital Inc, Ontario, Canada). The core components of this system are three IR sensitive cameras and active IR tracking markers which allow 3D position tracking with an accuracy of 0.1mm.

D.1. Position Repeatability During In-plane Actuation of J_1 , J_2 , J_3

For assessing position repeatability of the device, four markers were attached to the robotic probe – one at the end of the hollow shaft, one on the medial link and at two positions (proximal and distal) on the distal link. The optical tracking unit was placed so that the four tracking markers lie on a plane that is parallel to the plane formed by the three tracking cameras. Consequently, the results can be visualised on an xy plot. Five different distal tip positions were programmed into the software and the robot was actuated to each position in turn. The xy position of each marker was recorded at each position. This was repeated three times and the variation in marker position was calculated. The robot was returned to a default horizontal position between tests, the significance of which will be discussed later. The results of these tests are displayed in Figure D.1. The variation in marker position was calculated using the standard deviation from the mean marker position and is shown in Table D.1.

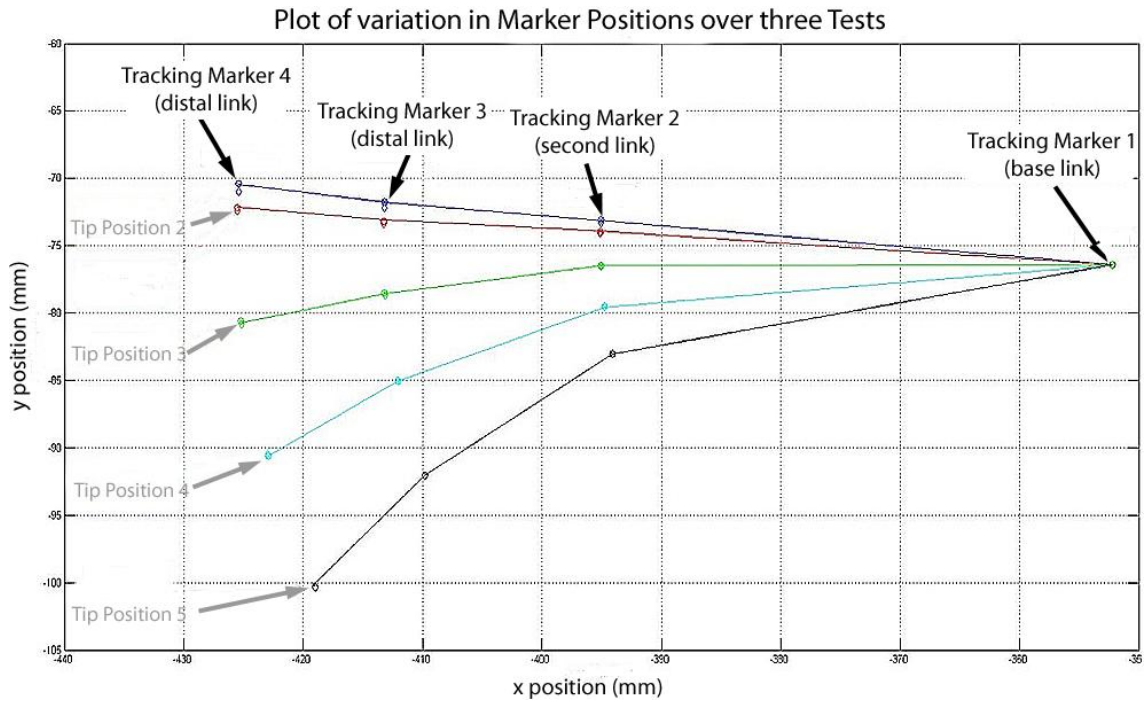


Figure D.1: Location of the four optical tracking markers as recorded during three separate experiments where the distal tip of the multi-spectral imaging robot was servoed from a horizontal position to four different angular displacements. The position of the markers is indicated during each test and demonstrates that the actuation is repeatable when moving to preset positions of angular displacement.

Table D.1: Position repeatability statistics for in-plane actuation tests

Position	σ in x direction (mm)	σ in y direction (mm)
1	0.017	0.304
2	0.003	0.159
3	0.014	0.125
4	0.003	0.150
5	0.061	0.123

Given the small standard deviation, σ , in the x and y directions, the results indicate that the device is capable of repeatable actuation when moving to preset positions of angular displacement. The standard deviation in the x -direction is much smaller than that in the y -direction. This can be explained by the smaller range of motion that the distal tip undergoes in the x -direction. However, the tests also identified that in order to obtain such repeatable results, it is necessary to always start from a default position such that when the device actuates, it works against the torsion springs. When actuating in the opposite direction (i.e. relying on the torsion springs to rotate the links to place the tendons in tension) the errors in position are more pronounced. This is primarily due to changes in friction along the tendon paths when the probe

is in different configurations. If the friction is particularly high (if, for example, two tendons interfere with one another within the central channel) then the torsion spring does not return the link to the exact position from which it started. These errors could be reduced by removing the torsion spring and employing an antagonistic tendon transmission scheme with individual tendon channels. However, this would have a correspondingly negative effect on the cross sectional space taken up by the transmission elements within the device. Additionally, as was discussed in Section 2.3, any tensioned tendon transmission system will ultimately suffer from control difficulties due to the inherent limitations of attempting to transmit precise movements over long transmission path lengths. Consequently, to minimise positional errors it was ensured that when performing synchronised fluorescence and white light imaging scans, the device was always actuated from a default position against the torsion springs.

D.2. Positional Repeatability During Large Area Imaging Scans

Following on from the results shown in Figure D.1, a second set of repeatability tests were performed. The purpose of these tests was to simulate a large area imaging scan where the probe traces several concentric circle trajectories to image a large field of view. As discussed above, to ensure maximum repeatability, the device is always returned to a default position between tests. The position of the distal tip was tracked as it rotated through 360° at six different angular displacements. This was repeated three times at each angular displacement and the trajectories of the distal tip are shown in Figure D.2. The trajectory for each of the three tests is shown in a different colour (blue, green and red). Positional errors in x , y and z axes are shown Table D.2.

Table D.2: Position Error Analysis

Rotation Number	Radius (x,y) Error (mm)		Z Error (mm)	
	Mean	σ	Mean	σ
1	0	0	0.12	0.05
2	0.79	0.055	0.48	0.02
3	0.55	0.31	0.58	0.13
4	0.71	0.16	0.60	0.13
5	0.89	0.05	1.19	0.09
6	0.8	0.2	1.20	0.085

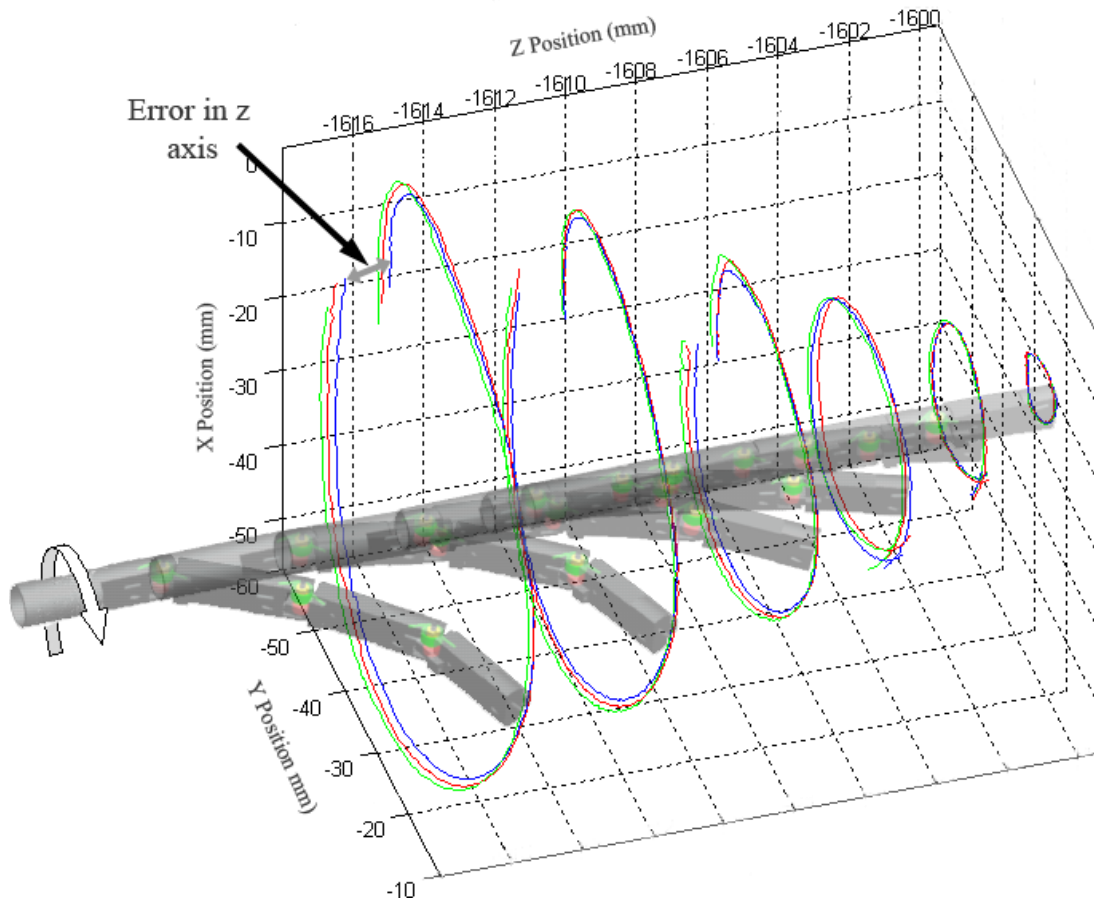


Figure D.2: Evaluation of the device repeatability during six different angular displacements using optical tracking technology. The trajectory traced by the tip during each test is shown in a different colour. The first test is shown in blue, the second in red and the third in green.

As before, the results indicate that the motion is repeatable and synchronised data acquisition during the dual mode imaging tests is possible. However, it is worth noting that while the radius of the circle remains consistent for all trajectories, an error is introduced along the z -axis. This error increases as the radius of the circle increases. An example is marked in Figure D.2 where a separation exists between the beginning and end of the trajectories. This is also represented by the mean z error in Table D.2. This error can be accounted for by the fact that the rotation of the shaft causes an increase in tension on the tendons and hence small shifts in joint position. This occurs even though the tendon lengths are not being changed as the device rotates. However, analysis of the standard deviation in the z -axis clearly shows that this positional error is repeatable. Therefore, it will not affect the consistency of the synchronisation between the white light and fluorescence imaging scans if they are performed successively.

E. Image Mosaicing Steps

The Autostitch mosaicing program takes place in four steps:

1. Feature tracking: The software uses the Scale Invariant Feature Transform (SIFT) [193] to extract and match features between all images. The location, orientation and a characteristic scale of each feature is computed and used to make measurements between different features. Once all features have been extracted from the image set, each one is matched to its k nearest neighbours in feature space.
2. Image matching: The purpose of this stage is to identify overlapping images which will be used to generate the panorama. It is performed using the Random Sample Consensus (RANSAC) robust estimator [194]. This takes a set of sample images (identified based on the number of feature correspondences matching the current image) and then finding geometrically consistent feature matches between the samples and the current image. The veracity of the image matches are then checked using a probabilistic model.
3. Bundle adjustment [195]: This step is used to solve for the camera parameters of geometrically consistent images one-by-one. The ‘best’ image, or image which has the maximum number of matches, is added to the bundle and initialised with the same rotation and focal length as the image it matches.
4. Image rendering: The final stage of the panorama generation is to adjust the gain of the individual images to ensure a consistent intensity in the final image. Multi-band blending is also performed between images to smooth out edges in the final panorama.

Appendix II: System Design and Evolution of the Flexible Access Platform

The purpose of this Appendix is to provide a systems level overview of the five iterations of the flexible access program that have been developed over the duration of this PhD project. Each iteration of the design – from *Version_1* to *Version_5* – adheres to the original modular joint design principals outlined in Chapter 4. Naturally, improvements in all aspects of its mechatronic design take place over the course of the design evolution, however, the overall principals of the design have remained constant. In the following chapter, each element of the systems will be described. These elements include:

- Joint Design
- User Interface
- Motor Control Box and Software
- Visualisation and internal channel configuration
- In-vivo Testing
- Advantages and Disadvantages

A: Flexible Access Platform Version_1

This system was the first device constructed. To maximize the potential of the embedded micro-motor actuation scheme, the device was designed as a multi-degree of freedom handheld stereo-laparoscope.

A.1: Joint Design

Version_1 featured five controllable degrees of freedom arranged into three serially connected link segments and attached to a 300mm rigid aluminum shaft. The degrees of freedom are arranged into two universal joints (intersecting pitch and yaw) at the distal and medial joints and a single yaw DoF at the proximal joint. Each DoF is capable of actuating approx. $\pm 30^\circ$. More actuation capability was desired but not possible with the design due to the frame impinging on the joint body when at the extremities of its range of travel. To minimize the torque required from each actuator when in the worst loading scenario (i.e. when performing a cantilever lift from a horizontal position), the universal joints are rotated through 45° with respect to the gravity vector. The device is capable of servoing its tip over a large area ($\pm 60^\circ$ vertically and

$\pm 90^\circ$ horizontally). As discussed in Chapter 4, an advantage of the serially connected joint architecture is that since each joint can be actuated separately the proximal/medial joint(s) can be used to avoid obstacles, such as anatomical structures or other instrumentation, to safely position the distal joint at a more advantageous position. The distal joint alone can then continue scanning and providing visual feedback to the operator from a location not possible with a traditional laparoscope.

As can be seen in Figure A.1, the diameter of the shaft and articulated segments is 11mm so as to be compatible with existing 12mm trocar ports. Each DoF is actuated by an embedded 4mm diameter Brushless DC micromotor (Namiki Precision Jewel Ltd, SLB04-0829) with a 337:1 planetary gearbox. The rotary motion of the motor is converted to joint rotation the “ring-gear” mechanism described in Chapter 4. Ball bearings and miniature pulleys were used to reduce friction between the ring gear and the joint body and along the tendon transmission path respectively. Since the Namiki motors terminate with a 40mm long Flat Printed Circuit (FPC) flexible cable, it was not possible to pass the motor power and control wires inside the robot. Instead, 300mm long custom FPC cables were developed and passed along the outside of the device. The length of the proximal and medial segments is 44mm while the distal segment is 36mm long. This results in an overall device length of 424mm where the distal 124mm is actuated. The device also features an internal channel of diameter 2.5mm.

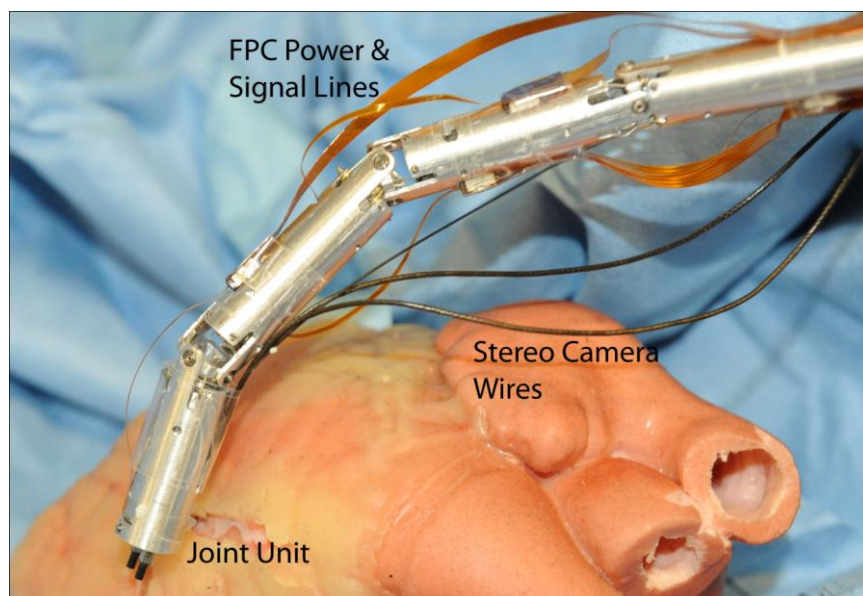


Figure A.1 *Version_1* Joint Units. The external wiring of the FPC's and stereo camera control wires can also be identified.

A.2: User Interface

In order to adhere to the design goal of a handheld instrument, a custom “pistol grip” style handle unit was attached at the proximal end of the rigid aluminum shaft (at the opposite end to the articulated units as can be seen in the schematic illustration in Figure A.2). The handle features an embedded two-axes potentiometer based thumb-stick located in line with the robot shaft. This also has an integrated push switch which activates when the thumb-stick is depressed. The five-DoF are controlled using relative positioning where joint angles are moved incrementally with a fixed velocity based on user commands from either the embedded thumb-stick. Under this direct “joint to joint” control paradigm, a movement along one axis of the input device results in a corresponding movement along one of the five joint axes. Naturally an input-output asymmetry exists and so the operator must switch between the distal, medial and proximal joints sequentially to fully actuate the device. This toggling function is activated via the integrated “push-switch” housed within the thumb-stick.

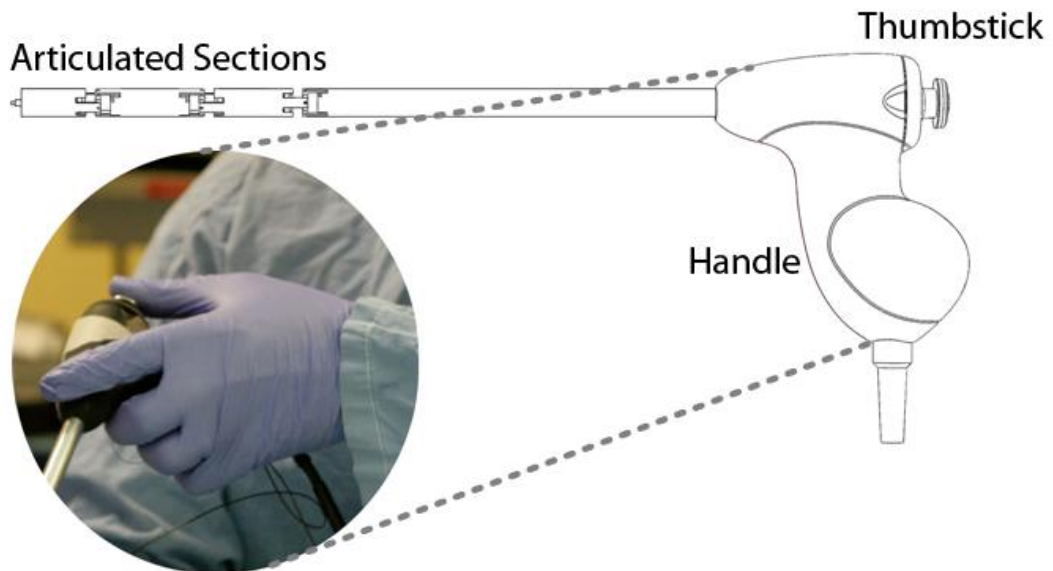


Figure A.2: Schematic of the handheld multi-DoF stereo-laparoscope showing the articulated distal tip, rigid shaft and handle with integrated thumb-stick for user control. A picture of the actual handle in use is also shown.

A.3: Motor Control Box and Control Software

Controlled actuation of each of the five embedded brushless DC motors is achieved via the motor control box, three-phase drive electronics units and the user interface described in Section A.2 above. The interfacing between the motors and the laptop is performed using the microcontrollers within five USB DAQ (Data Acquisition) cards (National Instruments USB-6009) which are housed within the Motor Control Box. As can be seen in Figure A.3, from

the motor control box two 8-way wires carry the motor power and signal lines to a set of five drive electronic circuits which are embedded in the handle. A 5-way wire carries the power and signal lines to the joystick and a single USB line connects the box to the laptop. External power for the system is provided through two power supply units which plug directly into the box. The box itself is manufactured from sheet aluminium and features necessary connectors to physically connect each of the power and signal lines. The entire system is expandable, portable and modular to allow for easy replacement should breakdown occur.

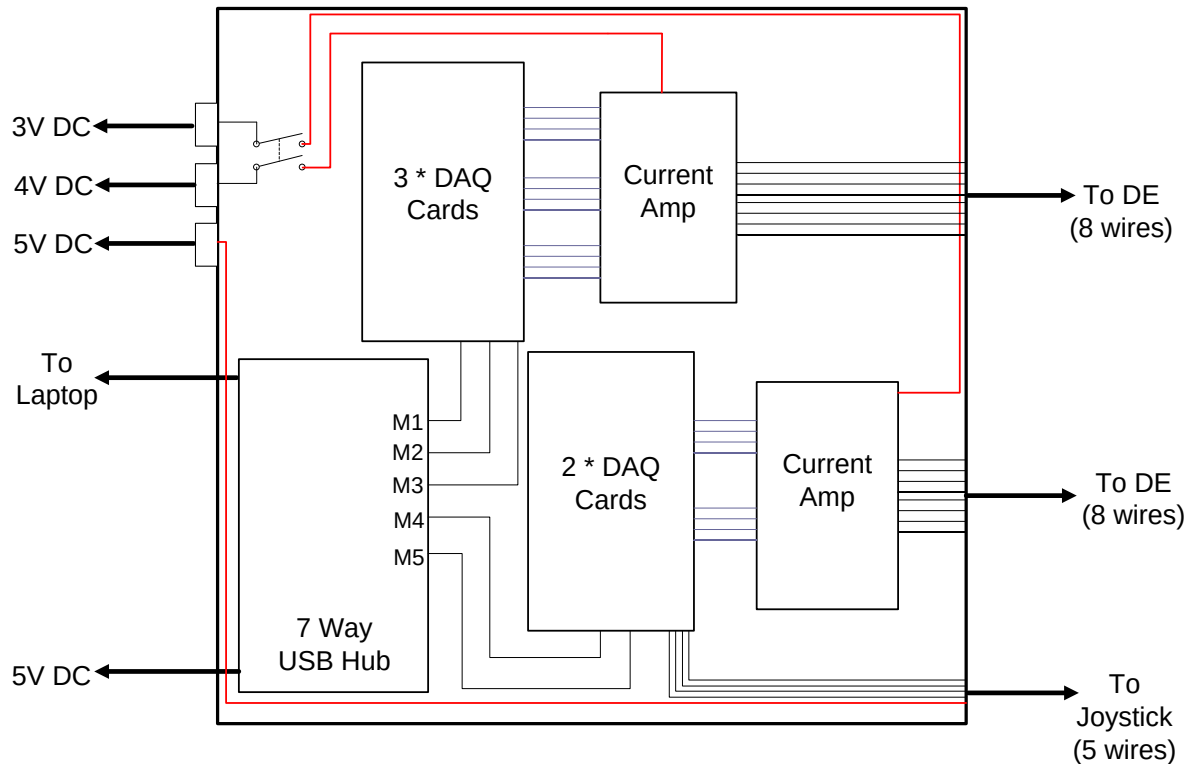


Figure A.3: Schematic illustrating the wiring and components within the Motor Control Box. Key components include a 7-way USB hub, five DAQ boards and two Current Amplifier Boards. Three power rails provide power to the two amplifiers and the joystick. The box features six sockets (3*stereo phono, 2*DIN connector, 1*USB) which allows all peripherals to be easily connected and disconnected

Motor actuation is achieved in the following manner:

- The resistance of two potentiometers within the thumbstick detect the desired motion direction along orthogonal axes. This resistance change is measured using a custom program written in the G programming language (LabView software from National Instruments) on the laptop.

- The control logic identifies which motor should be switched on, in which direction it should rotate (Clockwise/Counter-clockwise) and outputs an analog voltage along the correct circuit.
- Due to the low output current available from the DAQ cards ($\approx 5\text{mA}$), it is necessary to amplify the current in order to get maximum output torque from the motors (current draw at stall $\approx 80\text{mA}$). Consequently, the analog output from each DAQ card is wired to a current amplifier circuit. Each motor requires two amplifier circuits, one for the CW rotation circuit and one for the CCW rotation circuit. These 10 amplifier circuits are split between two amplifier boards so that all components can fit within the motor controller box.
- As shown in Figure A.4, each amplifier circuit features a PNP transistor, a resistor and a low impedance power rail. The analog output from the DAQ is wired across the base-emitter junction of the transistor and when the voltage drops below 0.7V the transistor switches on. This allows the current from the low impedance source to power the selected drive electronic circuit and thus rotate the motor.

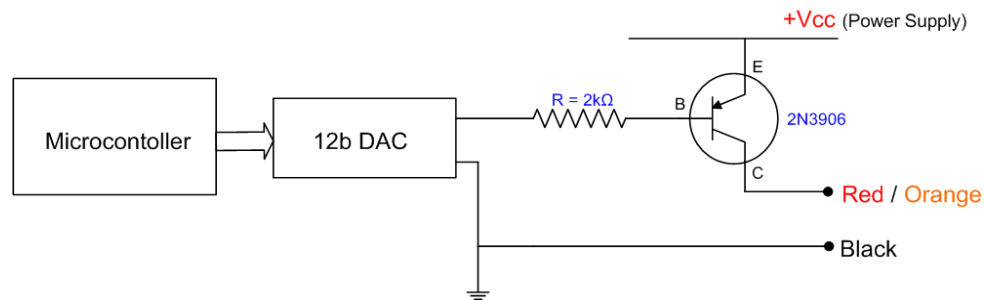


Figure A.4: Schematic of the amplifier circuit for the Version_1

- To switch the motor off, the analog output voltage from the DAQ card is set to greater than 0.7V thus switching off the transistor and power to the drive circuit.

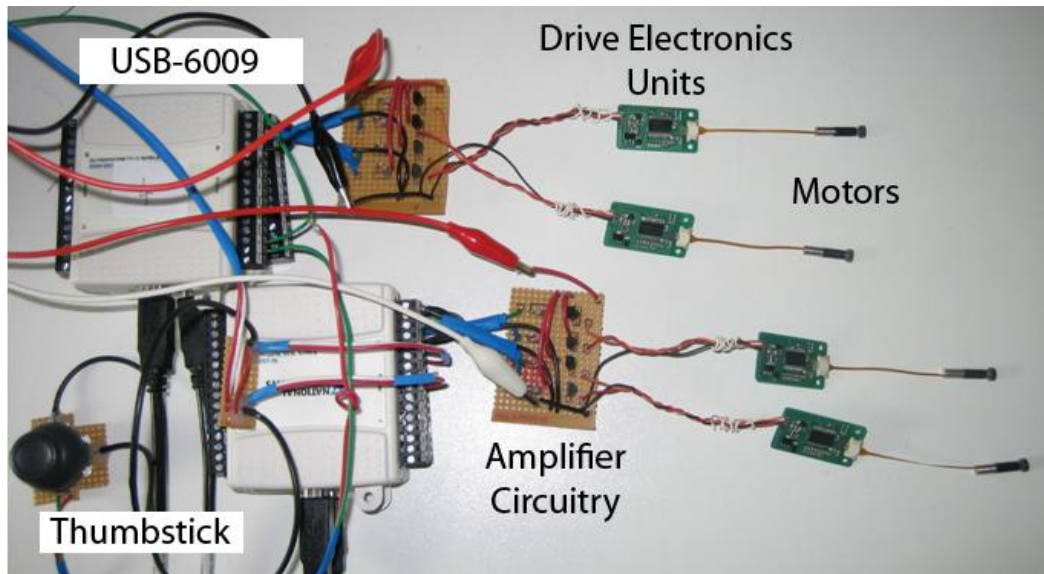


Figure A.5: Image illustrating the relationship between the thumb-stick, the USB-6009 micro-controllers, the amplifier circuitry, the drive electronics units and the motors. To control the 5-DoF of the *Version_1*, three additional USB-6009 were required, along with an additional amplifier board, drive electronics unit and motor. All of these components were housed within the aluminium motor control box.

The control software used to achieve the above results was developed using the *National Instruments LabView* programming environment. The program ran on the laptop with communication to the five USB-6009 units through the USB hub located in the Motor Control Box. Consequently, the control loop iterated at approx. 66Hz. A Graphical User Interface (GUI) was also developed in order to display key system parameters to the operator. These parameters included:

- Position of the thumb-stick
- Active joint segment
- Output voltages

The GUI can be seen in Figure A.6 below:

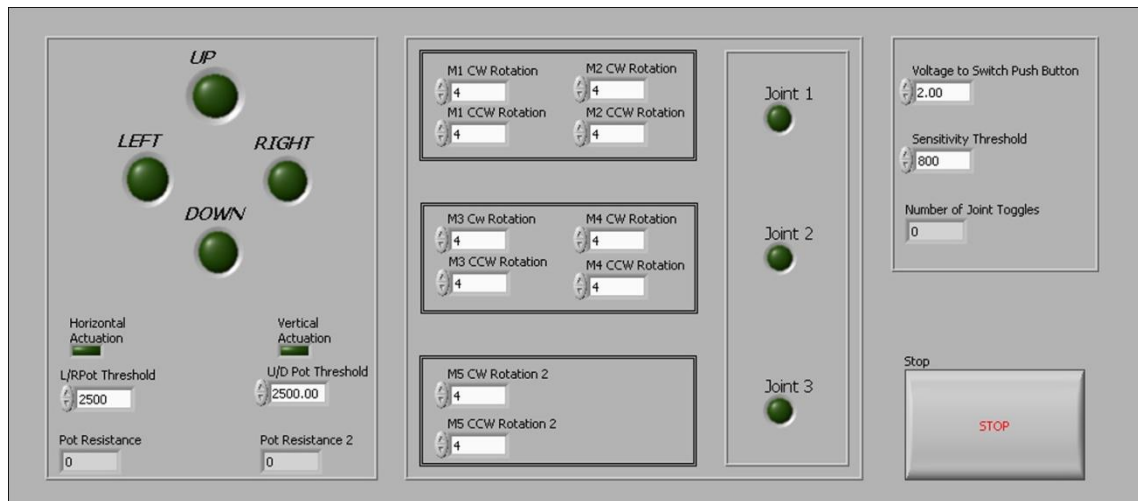


Figure A.6: Graphical User Interface developed for the Version_1. Information regarding the position of the thumbstick, the motor voltages to be output to the motors and the current active joint unit are all provided

A.4: Visualization and Internal Channel Configuration

In theory any instrumentation compatible with the 2.5mm channel can be passed through the device (camera, biopsy forceps, etc). However, in reality the channel was too small in diameter to be of any practical use. The distal tip of the device features a pair of IntroSpicio™ 115 Micro CCD video cameras from Medigus Ltd (Omer, Israel). These cameras are clamped within an aluminum housing and are arranged with a baseline of 5mm and a vergence of 0.5° (Figure A.7). Illumination is provided by a 1.2mm diameter MicroWhite (Nichia Corp.) blue laser diode which converts the blue to white light through a tip mounted phosphor. During the studies described in this paper cables for both stereo cameras and the illumination source were coiled around the external surface of the robot. This increased the effective diameter to 12mm. It is also possible to pass instrumentation, such as an endoscopic biopsy forceps, through the central channel as shown in Figure A.8 below. This system has been tested actuating in all of the 5-DoF's with travel ranges of 30° per joint (limited by hardware). The system was demonstrated during the animal trial with a biopsy forceps passed through the central channel. However, the with the forceps in place the travel range for each joint was reduced due to the stiffness of the instrument.



Figure A.7: The twin Medigus IntroSpico™ cameras can be clearly seen protruding from the tip of the robot. The cameras have a baseline of 5mm and a vergence of 0.5°. The light source can also be seen between the two cameras



Figure A.8: The internal channel can also be used to pass endoscopic instrumentation, such as a biopsy forceps

A.5: In-vivo deployment

In order to assess the feasibility of deploying the *Version_1* in an in-vivo setting, the system was trialed in a live porcine model. The goal of the procedure was to introduce the *Version_1* and to perform a peritoneoscopy. Due to the fact that the system was unable to fit down a standard trocar port (since the FPC wiring would be damaged by the trocar valve) a custom Introducer Port was developed. This port consisted of a 15mm in diameter aluminum tube that passed through the incision and a rubber seal designed to fit within the inner diameter of the tube, as can be seen in Figure A.9. The seal was located on the rigid shaft of the *Version_1* and the system was free to translate axially through both the seal and the port. Thus to establish pneumoperitoneum the port was passed through the incision and the robot inserted until the seal reached the mouth of the port. The practical deployment of this system was problematic as it was necessary to fully insert the robot prior to the establishment of pneumoperitoneum. Consequently there was a significant risk of damage to the system during the insertion phase. However, it was possible to establish pneumoperitoneum and a limited peritoneoscopy was performed using the system. However specific concerns raised include

- The loss of the pneumoperitoneum during insertion of the instrument transabdominally - a redesign of the instrument enabled integration of the motor power cables inside the robot reducing the overall diameter. This enabled us to use a standard 15mm bariatric trocar 150mm length (Applied Medical) to access the peritoneum and insufflate before insertion.
- The leverage caused by the surgeon manipulating the instrument externally, affecting the functional segments of the robot - the development of a remotely operated control handle has proved to be highly effective both in terms of eliminating surgeon damage

caused by manual manipulation as-well as providing a means to monitor and record usability in a reliable and repeatable manner. Furthermore, positioning of the port became less of an issue when using a standard trocar. Angling the trocar for optimum instrument insertion was removed from the surgeon through a method of clamping the robot in position by the drive shaft enabling complete hands free control.

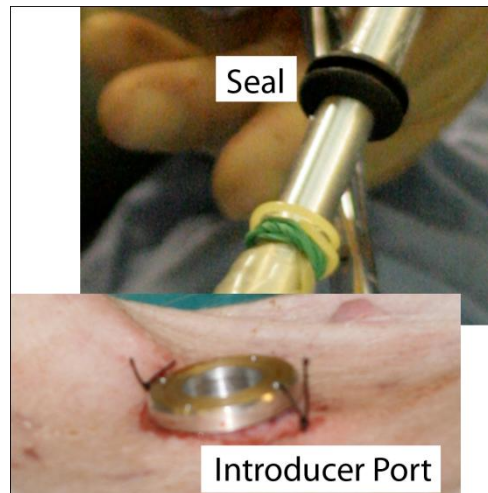


Figure A.9: Images of the trocar system used with the *Version_1*. The black seal located on the robot shaft (top) was required to sit into the aluminium port (bottom) before pneumoperitoneum could be established



Figure A.10: In-vivo deployment of the *Version_1* inside the peritoneal cavity under insufflation as seen from an additional laparoscope. The FPC wiring, ultrasound probe cover and illumination from the Nicha pulsed laser diode can be seen



Figure A.11: Image highlighting the challenges of maintaining a constant pneumoperitoneum without a standard trocar port. Here the *Version_1* is being damaged as the abdominal wall collapses on it

A.6: Advantages and Disadvantages

Engineering and deployment of the *Version_1* led to many solutions critical to the overall flexible access platform development cycle. Most notably advantages include:

- The system provided a practical demonstration that the joint design mechanism was capable of actuating a multi-degree of freedom articulated robotic system
- the achievements in joint manufacture and assembly
- the modular control architecture
- ability to pass internal instrumentation internally.

However, for practical purposes the system was unusable. The reasons for this were as follows:

- The motor power and signal lines ran outside the robot body. This resulted in a significant risk of damage during any operation during which the robot may come into contact with foreign bodies
- The internal channel diameter of 2.5mm was too small to realistically pass endoscopic instrumentation. Additionally, the system lacked an internal sheath to guide any instrumentation passed down this internal channel meaning that any instrument passed through the device was not interchangeable during a procedure
- The control software turned the motors ON/OFF in a binary fashion. Consequently subtle or small movements of the distal tip were difficult to achieve
- When an instrument is inside the channel, the range of motion of the device was significantly reduced due to the lack of available torque.
- The handheld nature of the device is desirable, however, usability trials indicated that in its current prototype configuration, this approach can lead to operator damage. Additionally, in certain circumstances operators would rather have the ability to tele-operate the robot and not only use it as a handheld device

Each of these challenges was taken into account with the development of the *Version_2*, which will be described in the next section, Appendix II-B.

B: Flexible Access Platform Version_2

This iteration of the robot design built on the experiences obtained with *Version_1* and featured two key differences. These were the integration of the motor wiring inside the robot and the decoupling of the thumb-stick from the robot to a separate joystick.

B.1: Joint Design

The *Version_2* had the same joint design and configuration (5-DoF, 11mm outer diameter, 2.5mm internal channel, 124mm articulated length) as the *Version_1*. However, a customization of the 4mm Namiki motor allowed for integration of the motor control wires inside the design. The standard 4mm Namiki motor (SBL04-08) features a 53mm long Flexible Printed Circuit (FPC) flat cable which terminates with a 4-track ZIF connector. Following discussion with

Namiki, this FPC was replaced with a 0.5mm diameter 4-core wire, 2 meters in length. This allowed all wiring to be integrated within the robot itself. However, since the internal channel remained at 2.5mm, it was still not possible to integrate the camera control wires inside the system, as can be seen in Figure B.1.

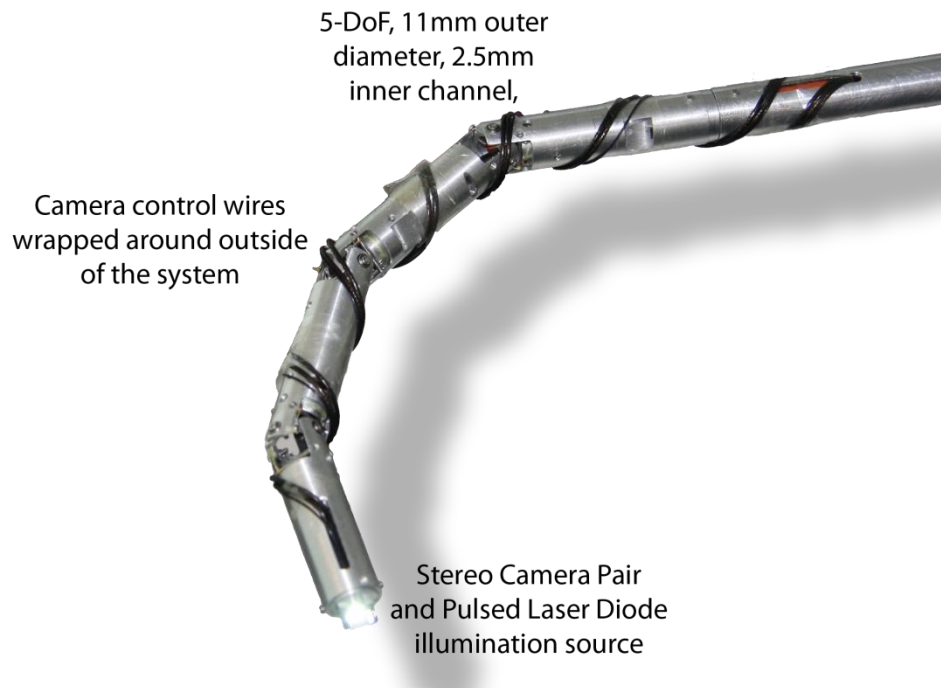


Figure B.1: : Version_2 Joint Units. The joint units are very similar to the Version_1, with the exception of integrated motor power and signal lines. The external wiring of the stereo cameras can also be clearly identified

B.2: User Interface

Based on the experiences with the handheld *Version_1*, and specifically feedback from the clinical team regarding a desire to have the ability to clamp the system to the operating table, a decoupled joystick user interface was developed. This allowed the operator to be physically dislocated from the robot during operation in a manner similar to the tele-operation achieved with systems such as the daVinci Surgical System. This was achieved using the same two axes potentiometer utilized for the user interface for the *Version_1*, however this time the output shaft of the potentiometers was coupled to a custom handle unit which allowed the joystick base to be clamped to a rigid body. Subsequent manipulation of the handle would result in rotation about the axes of the potentiometers. In order to maintain a similar control methodology as the *Version_1*, the push switch (previously integrated on the thumb-stick) was replaced by a “trigger style” push switch on the handle. Additionally, the handle featured a short aluminum shaft protruding from its distal tip to facilitate easy clamping (and thus mechanical grounding)

of the unit. All other elements of the user interface architecture operated in a similar manner to those described in previously.

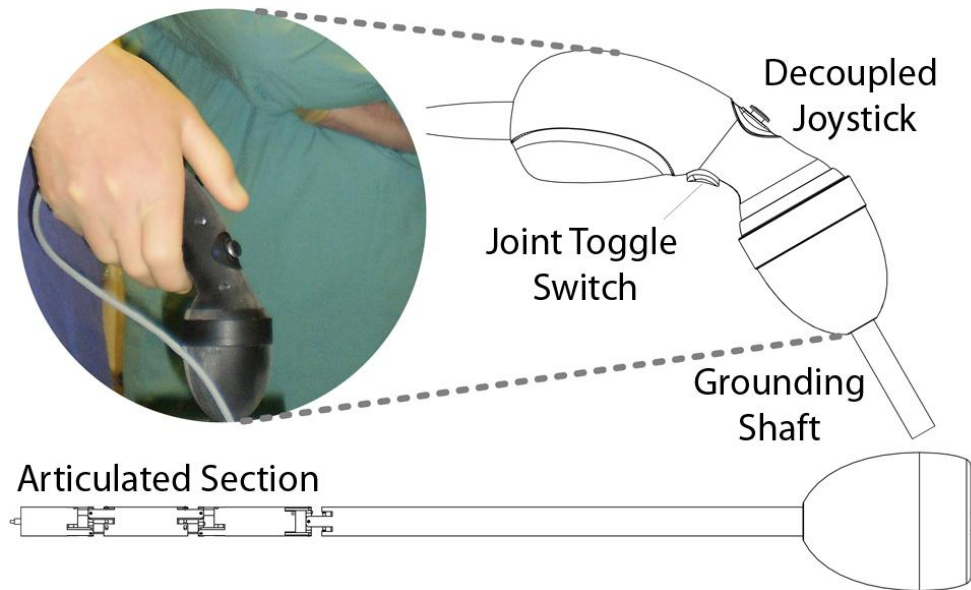


Figure B.2: Schematic of the decoupled multi-DoF stereo laparoscope showing the articulated segment, rigid shaft, interface unit and “master” handle. A picture of the actual handle in use is also shown

B.3: Motor Control Box and Software

In order to reduce the number of components within the Motor Control Box the five USB-6009 units were replaced with a National Instruments CompactDAQ unit and a two National Instruments C-Series modules. The cDAQ unit provides a modular platform for mixed signal data acquisition and the C-Series modules are self-contained measurement modules which plug into the cDAQ. The MCB_V2 features a cDAQ-9172 8-slot chassis, a NI-9264 16-channel analog output module and a NI-9205 32 channel analog input module. The high channel count on both analog input and output modules obviates the need for the five USB-6009 units and the USB hub. Specifically, ten AO lines are used to control the five motors and five AI lines are used to interface to the joystick. An additional advantage of this new architecture is that the system can be easily expanded to include additional motor control elements. The overall software architecture of the system remained similar to that detailed above.

An additional feature incorporated into the MCB and the control software at this stage was a pulse counting circuit designed to estimate the joint position. The purpose to this pulse counting circuit was to count the single pulse output from the motor drive electronics for every full 360° of the motor. By counting this pulse (1 pulse $\approx 0.41^\circ$, based on a the 337:1 of the Namiki gearbox and the 2.6:1 ring gear reduction) it would theoretically be possible to obtain an

estimation of the current ring gear angular position (assuming a calibration procedure was performed). Pulse counting was achieved using a NI-9401 digital I/O C-Series module and additional software within the *LabView* program. However, in practice the signal output from the drive electronics system frequently counted more pulses than actually occurred, thus causing inaccuracies in the estimated joint position. To filter out the high frequency components of the signal, a passive Resistor-Capacitor low pass filter with a cut-off frequency of 220Hz was designed.

The system was deployed on two joints, however it was ultimately not deemed suitable for kinematic control due to errors introduced by drift over time, and more problematically, over-counting of the pulses when the joint motor stalled. This situation frequently occurred when the system was actuating and the joint reached the limit of its travel. At this point, the joint (and hence the ring gear and the motor) were no longer moving however the drive electronics circuitry still output a pulse which was counted by the Pulse Count Circuit. This counting of a pulse while the joint was not moving thus presented an erroneous joint position value.

B.4: Visualization and Internal Channel Configuration

The *Version_2* had an identical stereo camera configuration and illumination source as the *Version_1*. The internal channel (2.5mm diameter) was also identical between systems. An example image from the stereo camera pair is shown in Figure B.3 below. This image was captured during in-vivo trials of the *Version_2* and show a view of the gallbladder and liver.

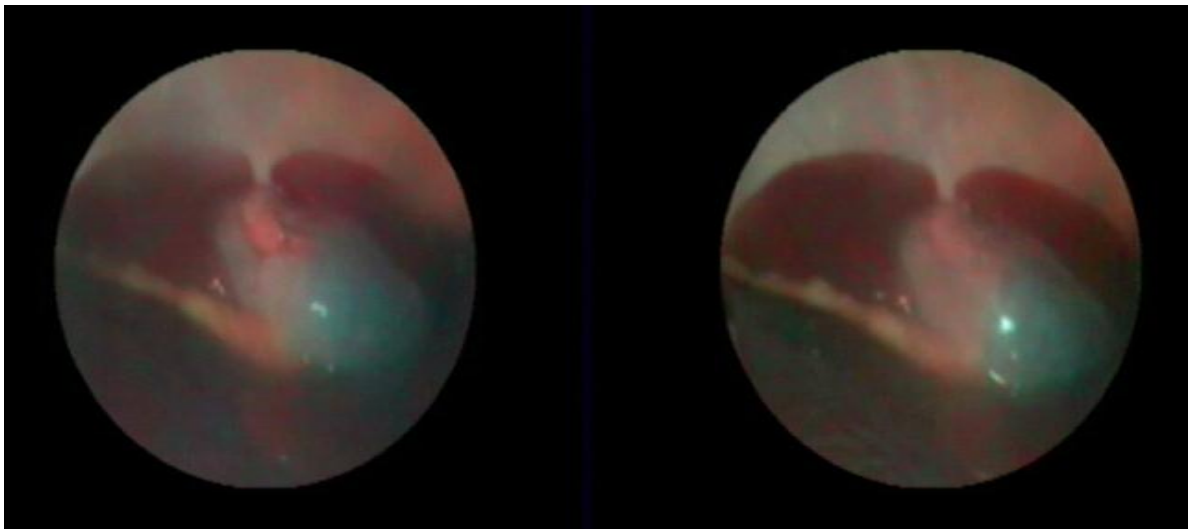


Figure B.3: Images from the onboard stereo cameras of the gallbladder during in-vivo trials of the *Version_2*

B.5: In-vivo Deployment

Following the challenges with simply inserting the *Version_1* and maintaining pneumoperitoneum, the primary focus of the *Version_2* development was to ensure safe and repeatable access through a standard trocar port. As is described above, the integration of the motor wiring inside the joint units allowed this to be successfully achieved. Consequently, the focus of the in-vivo trials with the *Version_2* focused on device usability in-vivo – particularly with regard to the ability of a clinician to switch between joint units control the robot during a large area exploration task.

The task undertaken was to perform multiple users trials navigating the device between defined targets within the abdominal cavity. The device was inserted through a standard 15mm trocar port (Applied Medical Resources Corp.) and pneumoperitoneum maintained throughout. The device was covered with an ultrasound probe cover during the procedure to avoid contamination of the joint mechanisms. A similar trial to that performed in the abdominal simulator - and described in Chapter 5 - was carried out. In this case the targets to be visualized, in the correct order, were: Left Trocar Port (T1) – Clip on Abdominal Wall (T2) – Gall Bladder (T3) – Right Trocar Port (T4) – Left Trocar Port (T1). These targets are shown in Figure B.4. Visualising T1 could be achieved using the distal joint alone, T1 – T3 required the distal and medial joints and T4 required all three joints. Four novice users with a surgical background operated the device 10 times each navigating the robot between each of the targets. The average and fastest times for each user is shown in Figure. B.5.

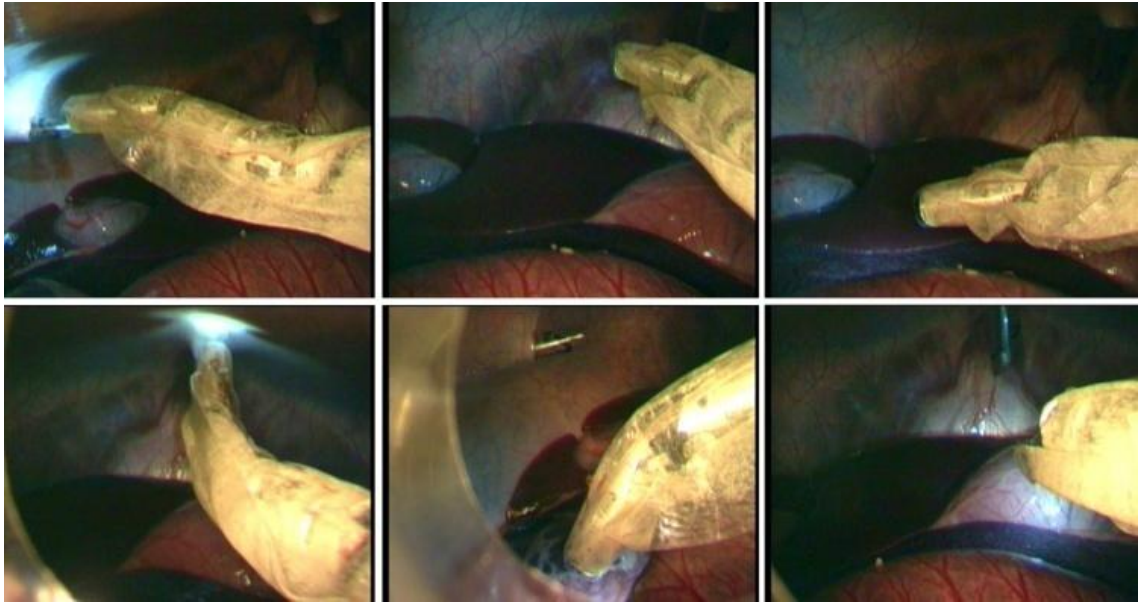


Figure B.4: . Images of the robot during the in-vivo trial. Clockwise from top left: Robot imaging T1, T2, T3, image of a disorientated user lost to the right of T4, image of a disorientated user to the left of T1, robot image T4. Note: The point of view of the laparoscope used to capture these images was constantly changing as the robot actuated around the abdominal cavity

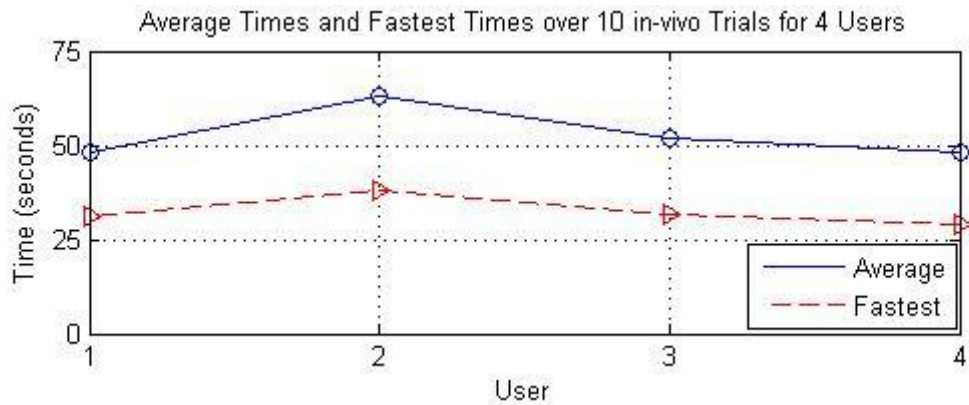


Figure B.5: Plot of the average (blue) and fastest (red) times for four users performing ten trials each

The device successfully performed multiple abdominal explorations with multiple users clearly demonstrating its ability to provide a surgeon with large area visualization without requiring external manipulation of the laparoscope in a clinical setting. However, both simulator and clinical trials show the large difference between the average and fastest times of the operators. This indicates that during certain trial runs (i.e. when the operator does not get disorientated) the input strategy does allow for the robot to be successfully and quickly navigated around the abdomen. However the lack of positional information provided to the user can result in disorientation which subsequently makes the task difficult to complete. The conclusion to this issue is that significant improvements could be obtained by implementing two additional

features: a graphical display of the robot pose presented to the operator and kinematic control of the joints which would eliminate the need for direct joint control (except where desired by the operator). This would also eliminate the misalignment between the joystick axes and the axes of the universal joints. It is anticipated that incorporation of these features would significantly reduce the disorientation experienced by the operators

B.6: Advantages and Disadvantages

The key improvement of the *Version_2* over the *Version_1* was that the integration of the motor power and signal wiring inside the robot. Specifically this allowed the system to be realistically passed through a standard trocar port in a safe and repeatable manner. Additionally, it significantly increased the robustness and reliability of the system as failure of the FPC's no longer occurred. The introduction of the "Decoupled Handle" user interface also provided a new and potentially useful manner in which the system could be deployed in-vivo. Feedback from the clinical team on the decoupled handle indicated that they value the ability to have the system clamped into place and such that the articulated distal tip can be maneuvered in-vivo while the operator simultaneously manipulates tissue with a separate instrument from a different physical location within the operating theatre.

However, several vital disadvantages present in the *Version_1* were not addressed by the *Version_2*. Most notable among this is the issue of the internal channel being too small to realistically pass any instrumentation. Consequently, this issue was addressed in the design of the *Version_3*.

C: Flexible Access Platform Version_3

The *Version_3* featured two key differences over the previous iteration:

1. An increase in outer diameter from 11mm to 12.5mm. This allowed the incorporation of all wiring inside the joint units and integration of a dedicated internal channel for instrument passage
2. The evolution of the decoupled joystick design from a grounded joystick to a handheld "thumbs-stick" style controller.
3. The development of a linear amplifier stage within the Motor Control Box
4. The development of a linear feed mechanism to translate the robot along the axis of the rigid shaft

Each of these improvements will now be discussed in further detail.

C.1: Joint Design

The *Version_3* featured a further evolution of the “ring-gear” based joint design. A specific requirement of the design was to incorporate a dedicated internal channel of diameter 3mm for the passage of additional instrumentation. To achieve this, the outer diameter of the joint was increased to 12.5mm. This allowed three internal channels to be included inside the joint. These included two channels of 3mm in diameter and one channel of 1.8mm, as can be seen in Figure C.1). In this configuration it was intended that the two 3mm diameter channels would be used for a camera (and light source) and an empty channel respectively. As with the *Version_1* and *Version_2*, the device features five degrees of freedom arranged as two universal joints and one yaw joint. The distal two universal joints were arranged at 45° to the plane of gravity in order to minimize the effect on joint loading when lifting in the cantilever position.

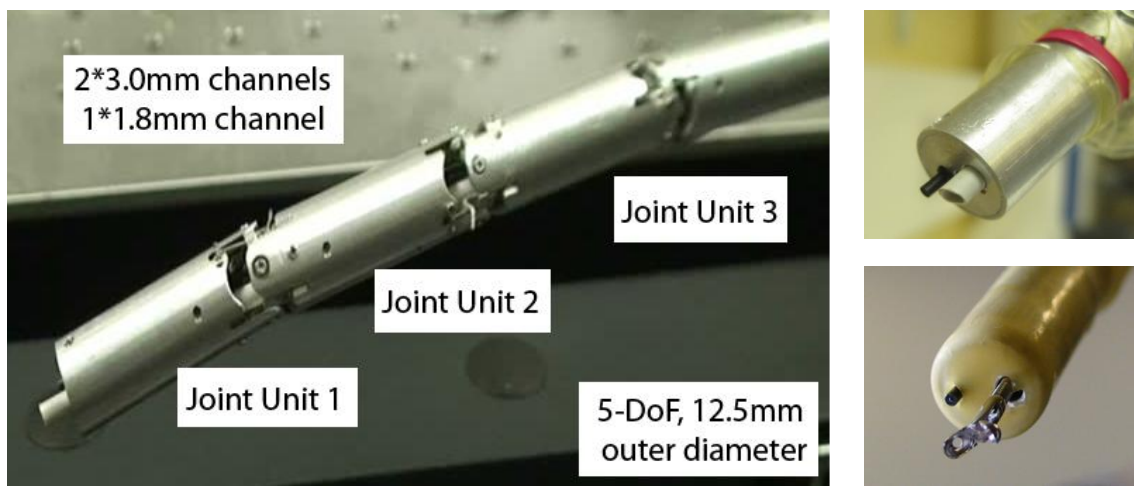


Figure C.1: The *Version_3* featured a larger outer diameter of 12.5mm and incorporated three channels. Two 3mm channels were used for a camera and light source while a single 1.8mm channel was used for motor power and signal lines. The ability of the device to pass a biopsy grasper is illustrated on the lower right.

C.2: User Interface

The new user interface developed for *Version_3* was conceived based on feedback from the clinical team associated with the project. As such, the advantages of both the “thumb-stick” design and the “decoupled joystick” were combined to make a “Decoupled Thumb-Stick”. This interface allowed the operator to easily control the joint motions however the unit was not constrained to being clamped/grounded at any location around the operating table. This provides the operator with the flexibility to stand in as ergonomic and suitable a location as possible. Figure C.2 shows a schematic of the new design. The thumb-stick unit remains unchanged from previous designs, with switching between adjacent joint units still being achieved via depressing an integrated push switch. This new interface does however also feature an additional 3-way

switch. This switch is used to activate the linear translation mechanism which will be discussed in Section 5.3.2.

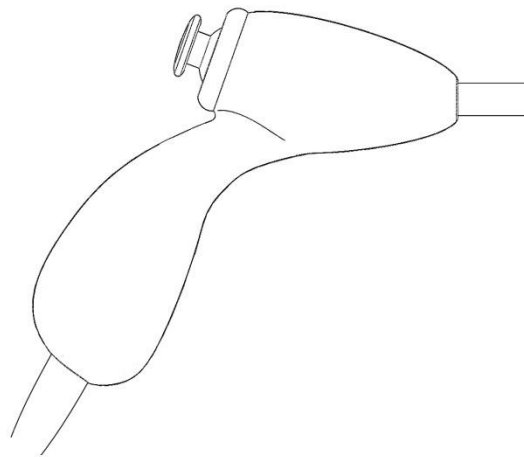


Figure C.2: The User Interface for Version_3 - a decoupled thumb-stick. This allows the operator to be located in any comfortable position around the operating table and operate the system single-handedly

C.3: Motor Control Box and Software

The majority of the components in the Motor Control Box were identical to those contained within the MCB for *Version_2*. However, the motor current amplifier units were improved to allow more accurate control over the joint movements. In the previous robot iterations, movement of the joints was achieved in a binary ON/OFF manner where the voltage applied to each joint was fixed (and thus the joints always moved with a fixed velocity). This resulted in a system whereby small, subtle motions were difficult to achieve. To overcome the problem, the transistor based amplifier circuits were replaced with a linear amplifier unit which consisted of a op-amp in a voltage follower configuration. Using this new amplifier circuit, it was possible to scale the output voltage transmitted to the drive electronics units in proportion the distance the thumb-stick was moved. For example, if the thumb-stick was only moved a minute amount outside the resistance threshold then the program only output 3V to the drive electronics. However, if the thumb-stick was moved to its full range of travel then the program output 5V to the drive electronics. This has the effect of scaling the motor power and the velocity of joint rotation to the thumb-stick location.

C.4: Visualisation and Channel Configuration

As can be seen in Figure C.1, the system features a single 1.8mm Medigus camera, a Nichia pulsed laser diode and a 3mm internal channel. In order to successfully pass any instrument when the robot is in an articulated configuration it is necessary to also pass an inner sheath through this internal channel. The purpose of this sheath is to guide any instrument around the

articulations at the joint units. A PTFE sheath with suitable dimensions was used for this purpose. However, due to a wall thickness of this sheath being 0.3mm, the overall cross-sectional area available for passing instrumentation was reduced to 2.4mm.

C.5: In-vivo Deployment

The purpose of the deployment of the *Version_3* was to access its ability to access the peritoneal cavity, either through a standard laparoscopic approach or through a trans-vaginal approach, perform a peritoneoscopy and obtain biopsy samples via the internal channel. The challenges of establishing and maintaining pneumoperitoneum both during insertion and robot operation had been solved with the *Version_3*. The system was successfully deployed and multiple liver biopsies were obtained (see Figure C.3). However, the system did not function as well as anticipated and the reasons for this will be discussed below.



Figure C.3: (left) *Version_3* obtaining a liver biopsy form a trans-abdominal insertion point. (top, right) the *Version_3* performing a peritoneoscopy from a transvaginal incision and (bottom, right) three of the liver biopsy samples obtained through the internal channel of the *Version_3*.

C.6: Advantages and Disadvantages

Although the *Version_3* represented the first true manifestation of the flexible access concept (through the first successful deployment of an interventional instrument through the internal channel of the device), it still had several drawbacks. Most notably was the lack of torque available to actuate the device, particularly when the biopsy grasper was inside the device. Additionally, the system still only features five degrees of freedom – which at a range of motion of approx. 35° per joint is significantly short of the design goal of Retroflexion. However, to summarize the advantages of the *Version_3* include:

- An internal channel to pass instrumentation
- Dedicated channels for camera, light source and motor power lines
- Ability to achieve finer control movements due to proportional scaling of motor velocity based on thumb-stick motion
- A decoupled-thumbstick for enhanced flexibility in the operating theatre

However, on the negative side, the disadvantages of the system include:

- Lack of suitable range of motion and number of degrees of freedom to achieve Retroflexion
- Small internal channel diameter when compared to existing endoscopic instrumentation (typically instruments require a 2.8mm channel).

D: Flexible Access Platform Version_4

The *Version_4* represented a significant step towards the development of the flexible access platform. This system maintained a diameter of 12.5mm and featured two 3.0mm and one 1.8mm internal channels. However, a new mechanical configuration at the joint resulted in an increase in the range of motion to $\pm 45^\circ$ per joint and amplified the available motor output torque by a factor of two (this was the theoretical amplification – the real-world amplification was closer to 1.7:1 once frictional losses were taken into account). This increase in torque also facilitated the addition of another yaw joint unit, thus bringing the total number of degrees of freedom of the system to 6 and its retroflexion ability to 180° .

D.1: Joint Design

The joint design for the *Version_4* is identical to that presented in Chapter 4. The key improvements of the system over the previous joint designs include the re-routing of the tendon pathways such that the tendon termination point is no longer located on the joint body. Instead the tendon passes through a hole in the frame, along a groove in the side of the frame and then down to the joint body on the other side. The result of this is that as a joint actuates, two tendons applying the same force onto the frame and causing it to rotate. In this configuration the effective force available to rotate the joint is doubled. This latest joint design also allows the joint to rotate $\pm 45^\circ$ at each joint unit, thus significantly increasing its range of motion and becoming more suitable for use as a flexible access platform.

Two further improvements over previous designs include that of the modular interconnect capability, also described in Chapter 4, and the addition of a sixth degree of freedom. The former feature offers the capability of assembling different joint units in different configurations in a straightforward manner while the latter allows the system to fully actuate its tip through 180° degrees, as can be seen in Figure D.1 (top).

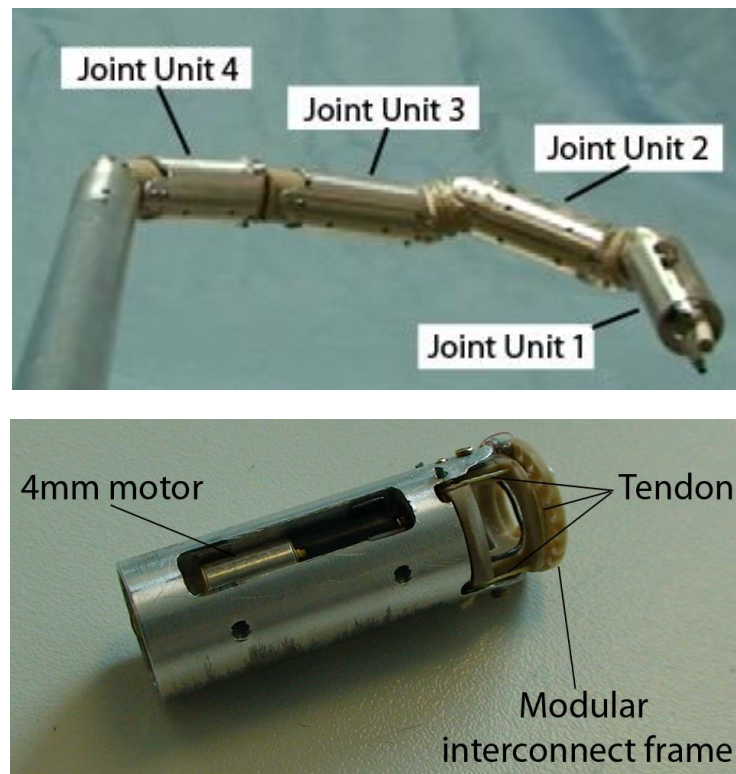


Figure D.1: (top) Version_4 in fully retroflexed position. The range of motion of the joints can be clearly seen and (bottom) the distal modular unit of the Version_4. The two tendon torque amplification is marked

D.2: User Interface

The User Interface for the Version_4 is identical to that developed for the Version_3– the decoupled thumb-stick. As before the thumb-stick is used to control the a single joint unit at a time and switching between joint units is achieved via depressing the thumb-stick.

D.3: Motor Control Box and Software

Until the Version_4 the system was controlled via a USB connection between either multiple USB-6009 units or a CompactDAQ unit. A severe limitation of this system was the speed at which information could be transmitted over the USB connection. This was compounded by the fact that the computation was being performed on a standard laptop and thus was not optimized. To overcome these issues and to allow for Real-Time embedded control over the robot and its associated I/O a new Motor Control Box with an embedded CompactRIO was developed. The cRIO consists of two core modules: the Real-Time controller (cRIO-9014) and a FPGA

backplane (cRIO-9113). The Real-Time controller carries out processing based on software deployed to the cRIO while the FPGA backplane performs low-level logic operations on the Input/Output lines. The C-Series modules previously used with the cDAQ system are also hot-swappable within the cRIO chassis. Using the National Instruments Scan Engine new software was developed which yielded an immediate increase in the loop processing time to 1kHz. Additionally, in order to reduce the footprint of the system in the operating theatre, this version of the MCB only requires a single external power supply (Agilent E3648A). Power from this PSU is run to a bank of three voltage regulators which step the input voltage of 17V down to 12V, 8V and 6V to provide the correct voltage levels to the thumb-stick, push-switch and amplifiers respectively. The cRIO runs from the 17V rail.

D.4: Visualisation and Channel Configuration

The *Version_4* contains a single 1.8mm Medigus camera running through one of the 3mm channels and a single internal instrument channel passing down the other 3mm channel. The instrument channel still features a PTFE sheath which reduces its effective diameter to 2.4mm.

D.5: In-vivo Deployment

The goal of the in-vivo trial with *Version_4* was to achieve trans-vaginal access, to perform a large area exploration of the peritoneal cavity from that location and to demonstrate retroflexion capabilities to visualize the uterine horn (used as a model of the fallopian tube in porcine models). The system was successfully deployed in this manner, however it was found that the 180° of retroflexion was insufficient to visualize the uterine horn. The problem was identified as two-fold – there exists a requirement for both more degrees of freedom and shorter joint segments so as to achieve a tighter radius of retroflexion.

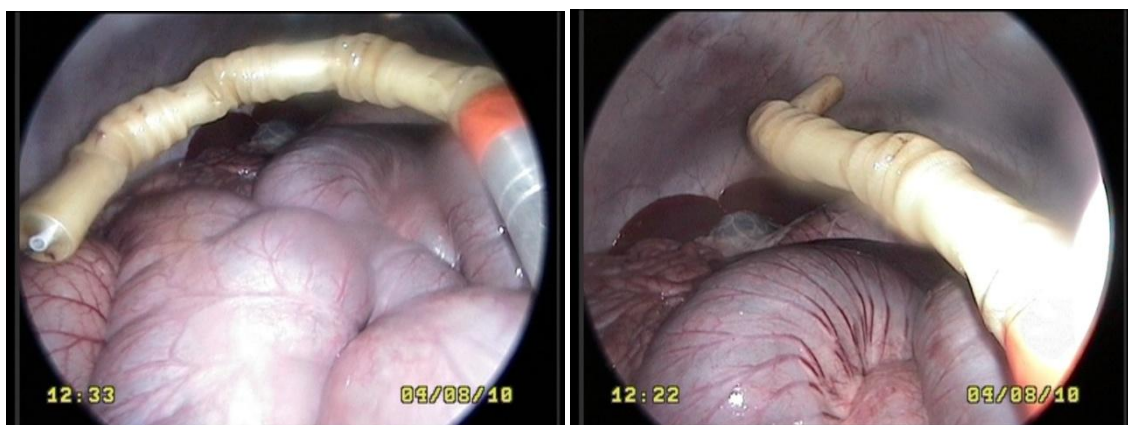


Figure D.3: View from an additional laparoscope of the *Version_4* during in-vivo trials. The images demonstrate trans-vaginal access, peritoneal exploration (right) and 180° retroflexion in the pelvis (left)

D.6: Advantages and Disadvantages

The *Version_4* contained many of the features outlined in the design brief of the flexible access platform. Specific advantages of this design include:

- Amplification of the torque available at each joint unit
- Two dedicated 3mm channels for camera(s), imaging probes and interventional instrumentation
- Multiple degrees of freedom capable of 180° of retroflexion
- Ability to perform large area exploration from a single incision
- A modular and expandable real-time control architecture

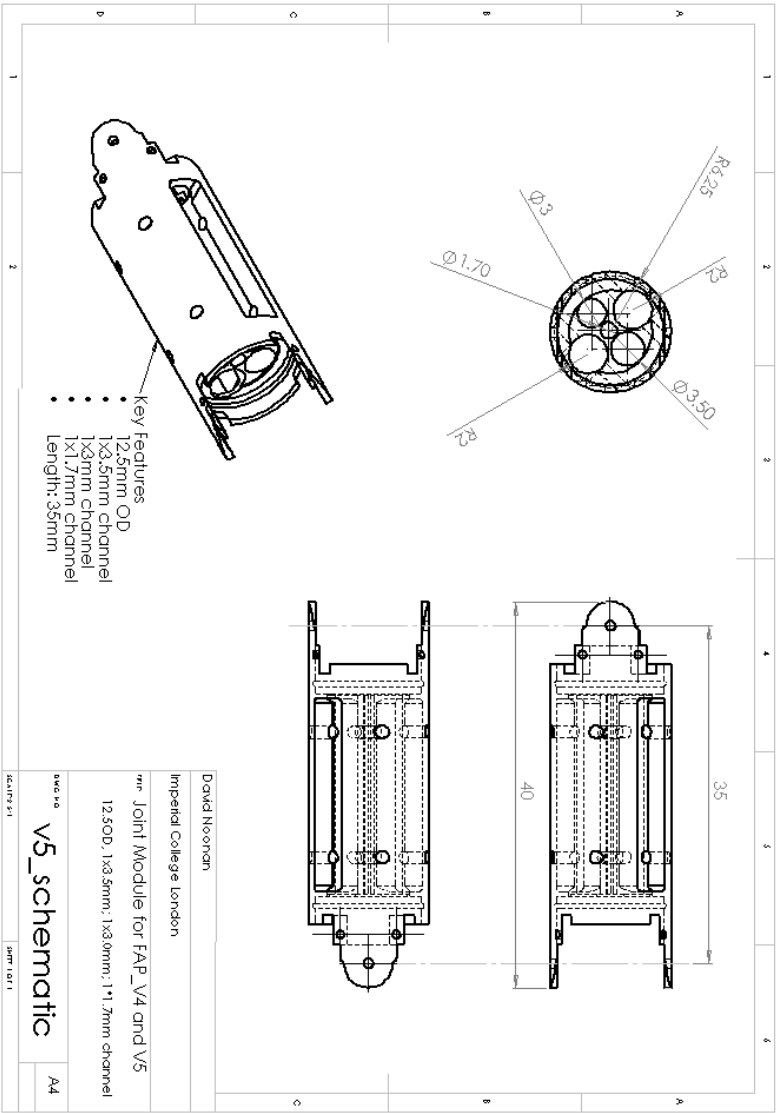
However, while the system does have the above advantages, several problems still exist. These include:

- Insufficient range of motion/degrees of freedom to visualize the uterine horn in a porcine model
- The operational amplifiers used in the amplifier circuits have a current limit of 80mA per amplifier. Due to the power losses experienced over the 2m of 4-core wire (between the amplifiers and the motors) it is sometimes necessary to provide power to the motors of greater than 80mA, however, this is not possible due to the limitation on the op-amps. Under these conditions, the performance of the robot is not optimum
- The 3.0mm channel is only available when an internal sheath is not used. If the sheath is not used then it is very difficult to use interchangeable instruments/probes without removing the robot, straightening and re-threading the instrument/probe through the channel
- Difficulty passing instrumentation through the channels due to the lack of a suitable internal sheath and the reduction in the available cross-sectional area when the sheath is in place

E: Flexible Access Platform Version_5

This version of the flexible access platform has been described in the main thesis.

F: CAD Schematic



Appendix III: Joint Position Repeatability

In order to test the joint module design and to analyse the performance of the joint position sensors, a 2-DoF universal joint based module was constructed. This universal joint consisted of two 1-DoF units joined together with orthogonal axes of rotation. To obtain controlled motion on both axes and to test the repeatability of the feedback from the joint mounted potentiometers, a closed-loop position feedback controller was implemented using a National Instruments cRIO-9014 Real-Time controller and a cRIO-9113 4-slot FPGA chassis. In this implementation the voltage readings from two potentiometers were used as the input to a position control loop which actuated the 4mm motors via a linear amplifier stage and the Namiki SSD04 3-phase brushless drive electronics.

A: Joint Position Repeatability

To assess the mechanical repeatability and accuracy of the universal joint, the position of the distal tip was tracked as it was servoed to nine different locations within the joint workspace. Tracking was performed using an Optotrak Certus optical tracking system (Northern Digital Inc). This allowed 3D position tracking with an accuracy of 0.1mm. The nine locations correspond to: the 0° position on each axis, the extreme positions (i.e. $\pm 45^\circ$) on each axis and mid-way between the zero position and the extreme position on each axis as measured by the two potentiometers. The joint was servoed to each of the nine locations in a random order and the 3D position of the distal tip was recorded. This was repeated three times at each location. The results of the experiment are illustrated in Figure A.1. Table A.1 shows the standard deviations of the (x,y,z) position at each of those locations with respect to the mean of the sampled points. Table A.2 shows the actual angular displacement of each axis at each location. This value was calculated using the linear distance travelled by the distal tip of the joint and the known kinematic configuration. The results indicate that the system position control is repeatable to within 1mm or 2° of angular displacement. It is anticipated that errors in the absolute angular measurements will be reduced following an optimization of the control algorithm and characterization of the sensor linearity.

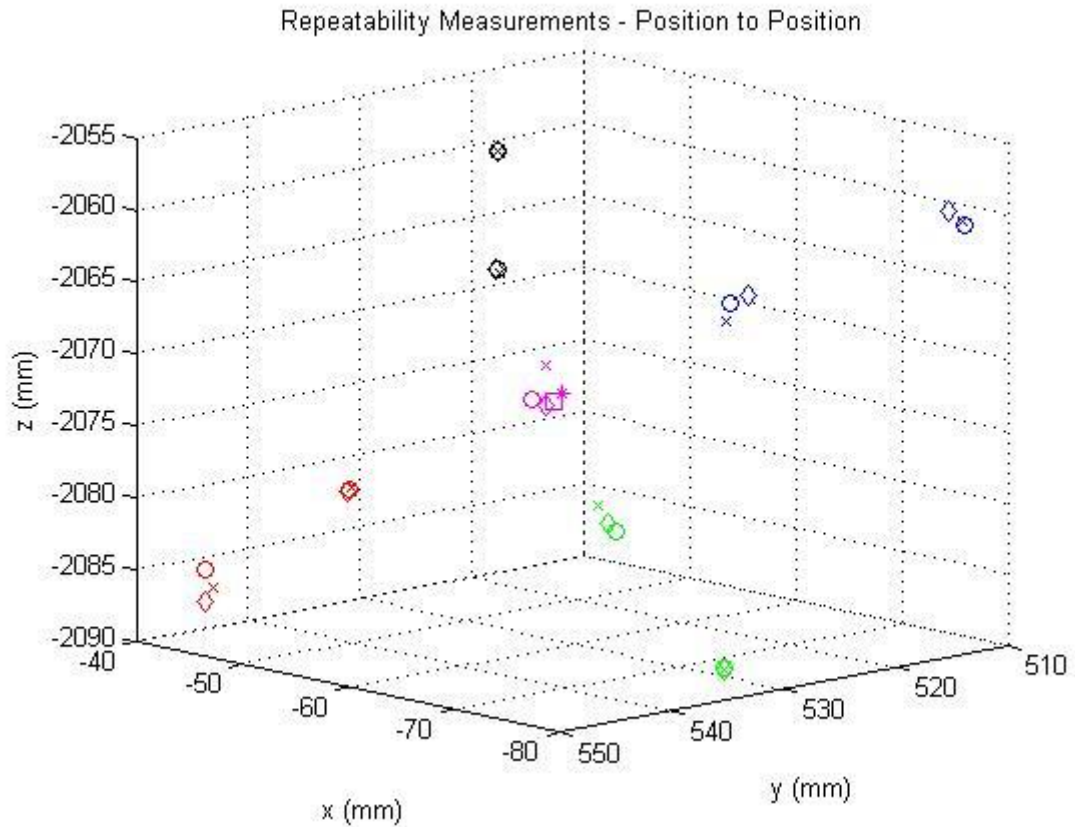


Figure A.1: Position repeatability of the distal tip when servoing the two degrees of freedom to nine random points within the joint workspace. The tip was driven to each point three times and the position to position repeatability was assessed.

Table A.1. Repeatability Analysis. Standard deviations in 3D position (X,Y,Z) of the distal tip when the joint is servoed to nine different positions, three times each

Position	Position	Std. Dev.	Std. Dev.	Std. Dev.
Joint 1	Joint 2	X (mm)	Y (mm)	Z (mm)
0°	0°	0.82	0.54	0.97
-45°	0°	0.78	0.02	0.4
45°	0°	0.01	0.03	0.01
0°	-45°	0.06	0.04	0.01
0°	45°	0.45	0.12	1.07
-22.5°	0°	0.32	0.94	0.78
22.5°	0°	0.61	0.16	0.88
0°	-22.5°	0.20	0.09	0.13
0°	22.5°	0.15	0.06	0.13

Table A.2. Repeatability Analysis. Mean measured angle and standard deviation for each axis when the joint is servoed to nine different positions three times each

Desired Angle		Mean Measured Angle		Std. Dev.	
<i>Axis 1</i>	<i>Axis 2</i>	<i>Axis 1</i>	<i>Axis 2</i>	<i>Axis 1</i>	<i>Axis 2</i>
-45°	0°	-44.7°	0°	1.0°	0°
45°	0°	45.6°	0°	0.5°	0°
-22.5°	0°	-20.6°	0°	2.1°	0°
22.5°	0°	18.8°	0°	0.1°	0°
0°	-45°	0°	-45.5°	0°	0.0°
0°	45°	0°	43.0°	0°	1.6°
0°	-22.5°	0°	-22.9°	0°	0.3°
0°	22.5°	0°	19.9°	0°	0.3°

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