A Snake-Like Articulated Robot for Flexible Access Minimally Invasive Surgery - Modelling, Optimisation and Kinematic Control

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Declaration

I herewith certify that all material in this dissertation which is not my own work has been properly acknowledged.

Valentina Vitiello
Abstract

The integration of robotic technologies in surgical instrumentation has contributed to the further development of Minimally Invasive Surgery (MIS) aimed at reducing the patient trauma and hospitalisation costs. Recent advances in imaging and mechatronics promise to enable the execution of more complex interventions through a single incision or natural orifice access. The main requirement for such procedures is the ability to reach the operative target through complex routes and curved anatomical pathways whilst maintaining adequate stability for tissue manipulation. A mechatronically controlled device with a high degree of articulation can potentially fulfil these requirements. However, the incorporation of a high number of Degrees-of-Freedom (DoFs) increases the control complexity of the system.

The purpose of this thesis is to investigate different methods for reducing the control dimensionality of a hyper-redundant snake-like articulated robot for MIS. The design of the robot is based on a modular, flexible access platform featuring serially connected rigid links and a hybrid micromotor-tendon actuation strategy to construct independently addressable universal joints. A path length compensation scheme for reducing the backlash at the joint is presented, together with experimental evaluation of the joint positioning accuracy when using our proposed kinematic control.

The integration of an extra translational DoF along the joint axis allows the performance of a hybrid ‘inchworm-snake’ locomotive scheme for self-propulsion of the device. This ‘front-drive back-following’ approach is implemented by actuating only one module at a time in a serial fashion. Therefore, the operator only needs to steer the distal tip of the device while the body of the robot follows the desired trajectory autonomously. Once the distal tip of the hyper-redundant device has reached the target operative site, the body of the robot has to adapt its shape to the surrounding moving organs while keeping the end-effector stable. A DoF minimisation algorithm is designed to identify the minimum number of joints to be simultaneously actuated to ensure shape conformance whilst simplifying the control complexity of the system.

Finally, optimal kinematic configurations of the platform are derived for performing two specific single incision procedures. The results, based on workspace requirements estimated through pre-operative imaging of the patients, demonstrate the suitability of the system for such procedures. Results from in vivo experiments on porcine models are also provided to show the potential clinical value of the device.
Ai miei genitori e mia sorella
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‘The greatest glory in living lies not in never falling, but in rising every time we fall.’

_Nelson Mandela_
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<tr>
<td>2-D</td>
<td>Two-Dimensional</td>
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<td>3-D</td>
<td>Three-Dimensional</td>
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<tr>
<td>4-D</td>
<td>Four-Dimensional</td>
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<tr>
<td>ACUSITT</td>
<td>Active Cannula UltraSonic Interstitial Thermal Therapy</td>
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<tr>
<td>AESOP</td>
<td>Automated Endoscopic System for Optimal Positioning</td>
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<tr>
<td>ASIS</td>
<td>Anterior Superior Iliac Spine</td>
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<tr>
<td>BSN</td>
<td>Body Sensor Network</td>
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<tr>
<td>CABG</td>
<td>Coronary Artery Bypass Grafting</td>
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<tr>
<td>CAD/CAM</td>
<td>Computer-Assisted Design/Computer-Assisted Machining</td>
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<tr>
<td>CAS</td>
<td>Computer-Aided Surgery</td>
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<tr>
<td>CLIK</td>
<td>Closed-Loop Inverse Kinematics</td>
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<tr>
<td>CoBRASurge</td>
<td>Compact Bevel-geared Robot for Advanced Surgery</td>
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<tr>
<td>cRIO</td>
<td>Compact Reconfigurable Input/Output</td>
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<tr>
<td>CT</td>
<td>Computerised Tomography</td>
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<td>D-H</td>
<td>Denavit-Hartenberg</td>
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<tr>
<td>DC</td>
<td>Direct Current</td>
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<tr>
<td>DDES</td>
<td>Direct Drive Endoscopic System</td>
</tr>
<tr>
<td>DDU</td>
<td>Distal Dexterity Unit</td>
</tr>
<tr>
<td>DoF(s)</td>
<td>Degree(s)-of-Freedom</td>
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<tr>
<td>e-AR</td>
<td>ear-worn Activity Recognition</td>
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<tr>
<td>EM</td>
<td>Electro-Magnetic</td>
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<tr>
<td>EOS</td>
<td>Endosurgical Operating System</td>
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<tr>
<td>Acronym</td>
<td>Full Form</td>
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<tr>
<td>FAS</td>
<td>Flexible Access Surgery</td>
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<td>FDA</td>
<td>Food and Drug Administration</td>
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<tr>
<td>FPGA</td>
<td>Field Programmable Gate Array</td>
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<tr>
<td>FRVF(s)</td>
<td>Forbidden Region Virtual Fixture(s)</td>
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<tr>
<td>GI</td>
<td>Gastro-Intestinal</td>
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<tr>
<td>GPU</td>
<td>Graphics Processing Unit</td>
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<tr>
<td>GUI</td>
<td>Graphical User Interface</td>
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<td>GVF(s)</td>
<td>Guidance Virtual Fixture(s)</td>
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<tr>
<td>HARP</td>
<td>Highly Articulated Robotic Probe</td>
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<tr>
<td>HD</td>
<td>High Definition</td>
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<tr>
<td>HMD</td>
<td>Head Mounted Display</td>
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<tr>
<td>HVSPS</td>
<td>Highly Versatile Single Port System</td>
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<tr>
<td>IR</td>
<td>Infra-Red</td>
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<td>IREP</td>
<td>Insertable Robotic Effectors Platform</td>
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<tr>
<td>LED(s)</td>
<td>Light-Emitting Diode(s)</td>
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<tr>
<td>LER</td>
<td>Light Endoscope Robot</td>
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<tr>
<td>LESS</td>
<td>Laparo-Endoscopic Single Site</td>
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<tr>
<td>MAGS</td>
<td>Magnetic Anchoring and Guidance System</td>
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<td>MASTER</td>
<td>Master And Slave Transluminal Endoscopic Robot</td>
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<td>MIS</td>
<td>Minimally Invasive Surgery</td>
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<tr>
<td>MNS</td>
<td>Magnetic Navigation System</td>
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<tr>
<td>MR</td>
<td>Magnetic Resonance</td>
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<tr>
<td>MRI</td>
<td>Magnetic Resonance Imaging</td>
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<tr>
<td>NOTES</td>
<td>Natural Orifice Transluminal Endoscopic Surgery</td>
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<tr>
<td>OR</td>
<td>Operative Room</td>
</tr>
<tr>
<td>PADyC</td>
<td>Passive Arm with Dynamic Constraints</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>pCLE</td>
<td>probe-based Confocal Laser Endomicroscopy</td>
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<td>PQ(s)</td>
<td>Proximity Query(ies)</td>
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<tr>
<td>PU</td>
<td>Propulsion Unit</td>
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<tr>
<td>RAMS</td>
<td>Robot-Assisted Micro-Surgery</td>
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<tr>
<td>RCM</td>
<td>Remote Centre of Motion</td>
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<tr>
<td>RNS</td>
<td>Robotic Navigation System</td>
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<tr>
<td>SLU</td>
<td>Snake-Like Unit</td>
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<tr>
<td>SMA</td>
<td>Shape Memory Alloy</td>
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<td>SPRINT</td>
<td>Single-Port laparoscopy bimanual robot</td>
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<td>SSPD</td>
<td>Serial Self-Propelling Decoupled</td>
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<tr>
<td>TEC</td>
<td>Tethered Epicardial Crawling</td>
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<tr>
<td>THR</td>
<td>Total Hip Replacement</td>
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<td>TPBVP</td>
<td>Two-Point Boundary Value Problem</td>
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<td>VF(s)</td>
<td>Virtual Fixture(s)</td>
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1 Introduction

In the past few decades, surgical practice has been revolutionised by the introduction of advanced instrumentation enabling a paradigm shift from traditional open surgery to Minimally Invasive Surgery (MIS). The main advantage of MIS is attributed to a reduction in patient trauma, which translates to faster recovery and lower hospitalisation costs. However, the very nature of MIS, laparoscopy for example, which involves the use of long, rigid tools inserted into the patient via small incisions, can introduce a range of ergonomic challenges. The loss of wrist articulation together with the fulcrum effect due to the inversion of motion direction at the trocar, strongly limits the manual dexterity of the surgeon. In addition, the use of a separate display to convey the visual feedback from a laparoscopic camera separates the visuomotor axes, thus affecting the hand-eye coordination of the surgeon.

Improved control and dexterity is one of the main benefits of robotic technologies for MIS. Mechatronically enhanced surgical instrumentation has been designed to compensate for the loss of wrist articulation caused by the traditional approach. Together with the introduction of master-slave control, this has contributed to the safety and consistency of MIS. However, even with the current state-of-the-art robotic surgical systems, such as the 

Improved control and dexterity is one of the main benefits of robotic technologies for MIS. Mechatronically enhanced surgical instrumentation has been designed to compensate for the loss of wrist articulation caused by the traditional approach. Together with the introduction of master-slave control, this has contributed to the safety and consistency of MIS. However, even with the current state-of-the-art robotic surgical systems, such as the da Vinci form Intuitive Surgical Inc, the tools used are still rigid and require careful port placement to ensure the required access and workspace for a given procedure. Safe performance of surgical interventions within the tight confines of the chest or the cluttered peritoneal cavity involving large-scale tissue deformation is a significant challenge.

Whilst the current robotic technologies are being translated into clinical practice, the quest for reduced patient trauma has further pushed the frontiers of MIS towards the execution of ever more complex interventions through a single incision or a natural orifice on the patient body. However, standard flexible endoscopes for these approaches have proven to be too difficult to navigate, especially outside of a lumen. Before such procedures can be applied clinically, it is important to develop specialised instrumentation with enough flexibility, rigidity and stability to reach the operative target through complex anatomical pathways. In order to achieve such adaptability, our research team at the Hamlyn Centre is developing a lightweight universal-joint based articulated flexible access platform. The last prototype [1] features seven independently controllable Degrees-of-Freedom (DoFs) using a modular hybrid micromotor-tendon joint design which allows the integration of multiple internal instrument channels. The device has demonstrated significant clinical potential.
through a series of *in vivo* experiments. The purpose of this thesis is to investigate the modelling, optimisation and kinematic control of the device.

Hitherto, control of robotic surgery tools has mainly focussed on accurately constraining the instrument motion at the entry point and the tip. The rest of the body of the device is considered free to move within the operative workspace, which is basically dictated by the specific procedure and the corresponding port placement. However, when an articulated system is used to navigate along complex trajectories between the access point and the target operative site, it is also necessary to ensure that the body of the instrument accurately follows the desired path, in order to avoid damaging the surrounding tissue or organs. Furthermore, the shape of the organs changes periodically during the procedure due to physiological motion caused by the respiratory and cardiac cycles. This effect, coupled with the limited field-of-view provided by the endoscopic camera, can generate disorientation issues and make the navigation of the device very difficult.

Although the incorporation of a large number of DoFs can enhance the flexibility and dexterity of the robotic platform, the control of such a hyper-redundant structure can become challenging due to the large number of available joint configurations corresponding to a single end-effector task. Most of the traditional approaches to redundancy resolution are based on computing the pseudo-inverse of the Jacobian matrix describing the relationship between the desired velocities in the task space and the angular velocities in the robot joint space. These methods are therefore subject to trajectory reconstruction errors, especially in the vicinity of singular configurations, where the Jacobian is rank deficient and the resulting joint velocities can become very high or even infeasible. Techniques such as the augmented or the extended Jacobian are designed to solve kinematic redundancy by assigning additional tasks together with the end-effector task, so that all the available DoFs become necessary. However, these methods are still subject to algorithmic singularities when the end-effector task conflicts with the supplementary task. In addition, the specification of such a large number of extra constraints can be challenging, especially for implementing path following or shape conformance tasks which are not directly related to the end-effector motion.

The main contribution of this thesis is to investigate the effectiveness and feasibility of different kinematic control strategies in reducing the dimensionality and consequently the control complexity of a hyper-redundant articulated robot for surgery. The specific procedures are addressed using realistic, *in vivo* settings. Detailed simulations and experimental results are provided throughout to demonstrate the practical value of the proposed algorithms.
1.1 Key research challenges and objectives

The development of a flexible access platform designed to address the clinical requirements discussed above presents a number of technical challenges. These can be summarised as:

1. Integration of mechatronic articulation to provide enough flexibility to navigate complex pathways within a constrained workspace;

2. Implementation of an embedded actuation strategy enabling a modular design with a small footprint and the incorporation of internal channels for the passage of endoscopic instrumentation;

3. Miniaturisation of components to achieve trocar port compatibility while ensuring adequate torque and force transmission for stable operation;

4. Introduction of self-propulsion and formulation of an efficient locomotion principle to improve the navigation of the articulated instrument and overcome the disorientation issues caused by the limited field-of-view;

5. Design of an ergonomic user interface and dedicated control strategies to manipulate multiple DoFs;

6. Achievement of adequate bimanual manipulation and triangulation capabilities.

The work presented in this thesis aims to address some of the research issues listed above with particular focus on design optimisation (Challenges 2 and 3) and kinematic control (Challenges 4 and 5). First of all, Chapter 2 presents a detailed review of the relevant robotic systems for surgery, focussing on flexible instrumentation for MIS. Despite the range of research platforms developed in recent years, the review highlights the lack of a versatile flexible access platform for robotic-assisted MIS. Miniaturisation and safe implementation of the available actuation modalities are identified as main technological challenges that still need to be tackled (Challenges 2 and 3 above). In addition, specific solutions have to be designed to address the increased control complexity of the systems incorporating a high number of DoFs. In this case, the design of an ergonomic and intuitive user interface becomes critical to ensure the clinical applicability of the platform (Challenge 5). Current medical robotics research is therefore focussed on the integration of multiple control modalities such as perceptual docking and virtual fixtures together with enhanced visualisation and intra-operative image guidance. Among these, Dynamic Active Constraints are designed to constrain not only the end-effector but also the entire length of the articulated robot. In this chapter, key design issues related to the development of instrumentation for single incision and transluminal surgery are also
highlighted. The main requirement for the safe application of such techniques in clinical practice is the ability to reach different target surgical sites within the patient body through complex access routes. The articulated system currently under development at the Hamlyn Centre has the potential to address such requirement through its novel actuation strategy, therefore an overview of the current prototype is included at the end of this chapter. The modular structure of the articulated section comprises serially connected joint units enabling rotational motion between adjacent links about one or two orthogonal axes. Internal channels for endoscopic cameras and surgical instruments are also provided.

In particular, embedded actuation of the flexible access platform is achieved through a hybrid micromotor-tendon mechanism which transmits the rotational motion about the micromotor axis to the joint plane. This allows miniaturisation of the components while maintaining efficient torque/force transmission. The main contents of Chapter 3 are related to the formulation of a path length compensation scheme for the joint design to ensure accurate articulation and reduce backlash. A geometric model of the joint is derived to quantify the amount of backlash introduced at different angular positions by differences in tendon path length. Optimal design parameters are determined to achieve minimum backlash with adequate force/torque transmission, thus specifically addressing Challenges 2 and 3 listed above. The final joint unit featuring embedded position feedback is also presented, together with experimental evaluation of the joint positioning accuracy when using kinematic control.

For a hyper-redundant robot, as the number of DoFs increases, effective user control becomes a major research issue. For MIS, this is also accompanied with disorientation, as the navigation field-of-view is often limited. To overcome the problem of disorientation, Chapter 4 investigates the benefits of self-propulsion for performing autonomous locomotion along complex pathways. By using a linear actuator to introduce an extra translational DoF along the axis of the joint, it is possible to obtain a 3-DoF Serial Self-Propelling Decoupled (SSPD) joint unit. The connection of multiple SSPD and universal joint units in series results in a hyper-redundant robotic structure able to perform a hybrid ‘inchworm-snake’ locomotion scheme. This ‘front-drive back-following’ approach is implemented by actuating only one module at a time, starting from the distal part of the robot and proceeding proximally in a serial fashion. Therefore, the operator only needs to steer the distal tip of the device on the basis of the visual feedback from the endoscopic camera, while the main body of the robot follows the desired trajectory autonomously. In order to validate the proposed control scheme, detailed simulation studies have been performed by using patient-specific Computerised Tomography (CT) datasets. An inverse kinematic algorithm is designed to determine the variation of the angular joint variables during motion and the associated path following accuracy is assessed by imposing a tubular active constraint on the entire length of the robot.
For the proposed robotic platform, once the distal tip of the hyper-redundant device has reached the desired target, it is necessary to provide enough stability for the operator to perform interventional tasks. In the presence of tissue deformation, the body of the robot has to conform its shape to the surrounding tissue while keeping the end-effector stable. However, as the number of joints to be simultaneously actuated increases, the complexity of the control architecture and the required computational power can become difficult to manage. To address this issue, Chapter 5 introduces a DoF minimisation scheme for simplifying the control of a generic hyper-redundant articulated robot by identifying the minimum number of joints required to perform a specific task without compromising the workspace limits. In particular, a time-varying instrument path is defined for realistic, in vivo settings involving tissue deformation. The minimum number of DoFs is determined by the amount of angular displacement of the joints to ensure shape conformance and seamless trajectory manipulation. Dynamic active constraints are also imposed on the entire length of the flexible robot to ensure the accuracy of DoF minimisation control. Detailed simulation and experimental results are provided to demonstrate the practical value of the proposed framework.

In order to investigate the efficacy of the proposed articulated robot for specific surgical procedures and the required workspace considerations, Chapter 6 presents a feasibility study of the in vivo implementation of the system for two exemplar surgical procedures: transvaginal tubal ligation and single-port diagnostic peritoneoscopy. The corresponding workspace constraints for both applications are estimated from patient CT data. The first optimisation algorithm is designed to demonstrate the ability of the system to achieve complete retroflexion and provide a stable platform for the passage of instrumentation and the execution of simple interventional tasks. For the second procedure, the transvaginal and transumbilical approaches are compared to determine the optimal access route for the robot. The main requirement when performing optical imaging of tissue using probe-based Confocal Laser Endomicroscopy (pCLE) is discussed. This requires the position of the probe to be perpendicular to the tissue surface and maintain a constant contact in the presence of tissue deformation. Therefore, the optimisation algorithm is formulated to determine the proportion of the peritoneal cavity that can be abutted by the probe at 90° when using the transvaginal and transumbilical approach. Results of in vivo experiments carried out on porcine models are presented to demonstrate the capabilities of the device.

Finally, Chapter 7 summarises the technical achievements of this thesis and identifies potential future research directions and technical challenges. It also provides a critical analysis of the potential pitfalls of the modelling, optimisation and kinematic control schemes developed in this thesis.
1.2 Original contributions of the thesis

The original technical contributions of the thesis include:

- Optimisation of a modular mechatronic joint design implementing a hybrid micromotor-tendon actuation scheme to ensure accurate articulation and reduced backlash;
- Experimental evaluation of the joint positioning accuracy when using kinematic control;
- Formulation of a kinematic control algorithm to reduce the dimensionality in controlling a self-propelling hyper-redundant articulated robot for path following applications in MIS;
- Design of a DoF minimisation scheme to reduce the complexity of shape conformance control to a dynamically varying instrument path for the hyper-redundant articulated robot;
- Implementation of the DoF minimisation control using an articulated robot prototype featuring embedded position feedback;
- Evaluation of the feasibility of the in vivo implementation of the articulated robot for two exemplar surgical procedures requiring the ability to achieve complete retroflexion within the pelvis workspace (i.e. transvaginal tubal ligation) and to position an imaging probe perpendicularly to the tissue surface at different locations within the peritoneal cavity (i.e. single-port diagnostic peritoneoscopy).

The work presented in this thesis has resulted in a number of publications in peer reviewed international journals and conference proceedings. The main publications related to this thesis include:


$^1$Joint first authors


2 Articulated tools for enhanced dexterity and navigation in robotic-assisted surgery

2.1 Introduction

In robotic surgery, the development of active tools enhancing the surgeon’s dexterity has evolved in parallel with recent advances in medical imaging and human interfacing techniques. This has improved hand-eye coordination and manual precision down to micron-scales. Historically, most initial research in medical robotics has been directed to overcoming known limitations of industrial robots, particularly in terms of adaptability and autonomy. To help appreciate the perceptual and motor characteristics of human and robot, Table 2.1 summarises some of the main characteristics related to surgery. The main perceptual differences lie in the ability of processing qualitative and quantitative information. Robots can precisely integrate a large amount of quantitative data through different sensors, thus being able to perform and repeat repetitive tasks with good stability and positional accuracy. On the other hand, surgeons are superior in combining diverse sources of qualitative information for making difficult decisions. Such skills are critical to the success of any surgical intervention, yet existing surgical robots are still limited to simple procedures under the direct control of surgeons. Unlike industrial automation, robotic systems for surgery must be considered as “surgeon’s extenders” rather than “surgeon’s replacements” [2, 3].

In this context, one of the key technical challenges in the further development of robotic surgery is to deliver human dexterity and hand-eye coordination with a seamless, intelligent human-robot interface via mechatronically enhanced tools, particularly for applications such as Minimally Invasive Surgery (MIS) [2]. This is because despite many appreciated benefits of minimal access interventions compared to traditional surgery, there are still significant drawbacks associated with conventional MIS instruments including the fulcrum effect, poor ergonomics and a loss of wrist articulation [3]. Much of the current research effort is therefore being directed to the design of small articulated devices that can be controlled intuitively.

It is important to note that robotic-assisted surgery is only one of the different specialties falling under the broader category of Computer-Aided Surgery (CAS).
Table 2.1: Perceptual and motor behaviour of humans and robots.

<table>
<thead>
<tr>
<th></th>
<th>Perceptual capabilities</th>
<th>Motor capabilities</th>
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<tr>
<td><strong>Humans</strong></td>
<td>+ Good task versatility and adaptability</td>
<td>+ Excellent hand-eye coordination</td>
</tr>
<tr>
<td></td>
<td>+ Quick integration of extensive and diverse qualitative data</td>
<td>+ Good dexterity at human scale</td>
</tr>
<tr>
<td></td>
<td>+ Decision making capability</td>
<td>− Subject to tremor and fatigue</td>
</tr>
<tr>
<td></td>
<td>+ Easy interaction with other members of the surgical team</td>
<td>− Limited dexterity at sub-millimeter scale</td>
</tr>
<tr>
<td></td>
<td>− Difficult processing of quantitative data</td>
<td>− Limited geometric precision</td>
</tr>
<tr>
<td><strong>Robots</strong></td>
<td>+ Quick processing of quantitative data from diverse sensors</td>
<td>+ Availability of multi-scale and optimised designs</td>
</tr>
<tr>
<td></td>
<td>+ Ability of multitasking</td>
<td>+ Good stability</td>
</tr>
<tr>
<td></td>
<td>− Lack of flexibility</td>
<td>+ High geometric accuracy</td>
</tr>
<tr>
<td></td>
<td>− Inability to handle qualitative data</td>
<td>− Limited dexterity and force/tactile feedback</td>
</tr>
<tr>
<td></td>
<td>− Poor judgment</td>
<td>− Poor hand-eye coordination</td>
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In this context, the robot represents a single component of a multi-functional system specifically designed to augment the capabilities of surgeons and to improve the overall outcome of surgical procedures. Through a combined use of automated and manually controlled surgical devices, such a system also incorporates pre-operative planning, intra-operative registration, and image-guided navigation and visualisation [4]. In this regard, medical imaging plays a fundamental role in the development of CAS systems and there is a unique opportunity in combining the two. A comprehensive overview of the current issues related to image-guided interventions can be found in [5].

This chapter will discuss some of the key developments in articulated surgical robot from its use in the traditional MIS to the most recent evolution of surgical procedures towards Laparo-Endoscopic Single Site (LESS) Surgery [6] and Natural Orifice Transluminal Endoscopic Surgery (NOTES) [7]. For these procedures, albeit their clinical benefit is still under fervent debate, technologically, they represent an engineering grand challenge that may transform the future of robotically assisted surgical instruments.

One key specification for NOTES instrumentation is an adequate amount of articulation to ensure no tissue damage during insertion and a wide visual exploration angle of the operative site including retroflexion. Once the operative target is reached, the endoscopic tool should become rigid in order to provide a stable platform for
tissue manipulation. For LESS, the introduction of flexible instrumentation could solve the ergonomic issues due to the use of rigid laparoscopic tools, such as restricted hand motion and cluttering of instruments. This level of adaptability can be achieved only with the use of robotic devices incorporating variable levels of flexibility, stiffness and back-drivability [8]. The subsequent sections will describe the technological evolution in recent years towards such an aim.

2.2 Robotic-assisted minimally invasive surgery

2.2.1 Introduction

During MIS, a set of 3 to 5 incisions of about 1 cm length is usually required to introduce at least two long-handled tissue manipulators, such as grippers and retractors, and one video endoscope to visualise the operative site, as shown in Figure 2.1. The main advantages of MIS are related to reduced tissue scar and surgical trauma, less pain and faster recovery [2]. However, the particular configuration of MIS instrumentation also imposes substantial limitations on manual manipulation and hand-eye coordination [3]. The use of rigid, long hand-held tools can result in a loss of surgeon’s wrist articulation, while the fixed access port can constrain the lateral movements of the instrument shaft, acting like a fulcrum or Remote Centre of Motion (RCM). The direction of surgeon’s hand motion is therefore reversed at the instrument tip and motion is scaled depending on the relative position of the tool to the trocar.

In addition to the fulcrum effect, indirect vision of the operative area through a Two-Dimensional (2-D) display, often located at far aside away from the surgeon, presents an unfamiliar relationship between visual and motor coordinates. Furthermore, the field-of-view is often limited by the use of an endoscopic camera, and the view angle can be unnatural due to the constrained position and orientation of the tool. Finally, the perceptual capabilities of the surgeon are also affected by a lack of tactile sensation and force feedback.

2.2.2 Benefits of robotic integration

The application of robotic technologies to MIS is aimed at solving many of these drawbacks [9]. Recent advances in imaging such as Three-Dimensional (3-D) wide-angle endoscopic cameras and high-resolution stereoscopic displays have already been incorporated into the current robotic surgical systems [10]. Structural and functional imaging modalities have been integrated for improved tissue characterisation and additional navigational clues [11]. The articulated tools incorporate additional degree of dexterity to allow for improved flexibility and manual dexterity [11, 12].
Thus far, much effort has been devoted to the development of tele-operated surgical systems based on one or more robotic slave manipulators at the patient side controlled by the surgeon through a master console that can be remotely located [12]. The surgeon can benefit from visual, and sometimes haptic feedback at the master console, and highly dexterous slave manipulators. Hand tremor elimination and motion scaling are provided to obtain accurate movements, as well as improved ergonomics and visuomotor integration. Some robotic systems, such as the da Vinci by Intuitive Surgical Inc [13], can be used for a range of surgical tasks including urology, cardiothoracic and gastrointestinal procedures, whereas others are designed for specific surgical tasks, such as vitreoretinal microsurgery [14] and transurethral prostate resection [15]. There are also systems that exploit the stability and geometric accuracy of robots to perform microscopic surgical procedures [16] or for replacing surgical assistants for tasks such as endoscope positioning [17] and organ retraction [18]. A summary of the drawbacks associated with traditional MIS and the corresponding benefits of robotic integration is presented in Table 2.2.

2.2.3 Representative robotic systems for MIS

In the literature, several authors have attempted to classify surgical robotic systems developed in the last 25 years into specific categories [2–4, 19–21]. According to Taylor [22], these can be based on three main criteria: the interaction mode between the robot and the surgeon, the clinical application, and the role played by the robot during surgical procedures. Systems are defined by the first criterion depending on the level of autonomy of the robot, ranging from autonomous to master-slave systems [19, 21]. Application-based taxonomies focus instead on the clinical area where the robot is used, such as thoracic and orthopaedic surgery [2, 20]. One type of role-based classification divides active and passive robots according to their level of interaction with the patient during the procedure [3]. Due to the current limitations of robotic technology, active robots are generally associated with a low
Table 2.2: Summary of MIS drawbacks and related benefits of robotic integration. Images courtesy of Intuitive Surgical Inc and available at www.intuitivesurgical.com.

<table>
<thead>
<tr>
<th>Traditional MIS</th>
<th>Robotic MIS</th>
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<tr>
<td>• Poor depth perception</td>
<td>• 3-D endoscopic cameras</td>
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<td></td>
<td>• High-resolution stereoscopic displays</td>
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<td></td>
<td>• Immersive visualisation</td>
</tr>
<tr>
<td></td>
<td>• Articulated instruments</td>
</tr>
<tr>
<td></td>
<td>• Articulated instruments</td>
</tr>
<tr>
<td></td>
<td>• Motion scaling</td>
</tr>
<tr>
<td></td>
<td>• Tremor filtering</td>
</tr>
<tr>
<td></td>
<td>• Ergonomic remote surgical console</td>
</tr>
<tr>
<td>• Fulcrum effect</td>
<td>• “Drive-by-wire” instruments</td>
</tr>
<tr>
<td>• Tiredness</td>
<td>• Hands interaction with tissue</td>
</tr>
<tr>
<td>• Physical separation</td>
<td>• “Drive-by-wire” instruments</td>
</tr>
<tr>
<td></td>
<td>• “Drive-by-wire” instruments</td>
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</table>
level of autonomy, being involved in high-risk procedures that require direct supervision of the surgeon. A different role-based categorisation refers to the function of the medical robot within the wider concept of computer-integrated surgical system, distinguishing between surgical Computer-Assisted Design/Computer-Assisted Machining (CAD/CAM) systems and surgical assistants [4].

However, due to the strong interdisciplinary nature of surgical robotics, it is challenging to define a unique taxonomy that incorporates both technical features and clinical applications. Therefore, the most representative systems for robotic-assisted MIS listed in Table 2.3 will be organised in the following sections according to their main role played during the procedures and the corresponding level of autonomy.

Table 2.3: Representative robotic systems for MIS.

<table>
<thead>
<tr>
<th>Application</th>
<th>System</th>
<th>H.U.</th>
<th>University/Company</th>
<th>Ref.</th>
</tr>
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<tbody>
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37
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2.2.3.1 CAD/CAM surgical systems

One of the most immediate applications of surgical robotics is coupled with surgical CAD/CAM systems based on a matching between pre-operative plans and intra-operative execution. This is particularly desirable for orthopaedic surgery or neurosurgery, where the successful outcome of the procedure depends on the surgeon’s ability to follow optimal surgical pathways with extreme precision. The benefits of robotic execution in this context include:

- Reliability and high accuracy in registration to medical images;
- Capability of operating in restrictive environments (e.g. radiation from Computerised Tomography (CT) scanner);
- Ability to precisely and rapidly relocate the surgical tools.

A detailed review of the most relevant CAD/CAM systems for surgery is presented in [4]. Among these, the surgical robot *Minerva* was one of the first robotic systems developed for neurosurgery [40]. It was designed to perform all the stages of a stereotactic brain biopsy completely autonomously inside a CT scanner, so that the surgeon was able to supervise the entire procedure remotely. The robot was mounted on a railed carrier rigidly coupled with the stereotactic frame on the patient’s head. The serial kinematic structure of the mechanism has five Degrees-of-Freedom (DoFs): two linear axes (vertical and lateral), two rotary axes (in a horizontal and a vertical plane) and a linear axis that allows the motion of surgical instruments to and from the patient brain [48]. Although two procedures were successfully executed by the system in 1993 [49], safety issues related with the amount of radiation exposure for the patient within the CT scanner forced the discontinuation of the device. Nonetheless, the concept of precise tool positioning using a 5-DoF robotic arm was then successfully exploited by Benabid *et al* at the Grenoble University Hospital (La Tronche, France), who developed the *NeuroMate* (Figure 2.2(b)), the first robotic device for neurosurgery approved by the US Food and Drug Administration (FDA) [42]. The system has been used in > 1000 clinical cases and features a state-of-the-art navigation and planning system that supports 2-D and 3-D image registration and frame-based or frameless navigation [50]. The technology was first acquired by Integrated Surgical Systems (Sacramento, CA, USA) in 1997 and then recently purchased by Renishaw Plc (Gloucestershire, England, UK).

Together with standard tools, focused delivery of radiation beams can also be used to perform neurosurgical interventions. The *CyberKnife* (Accuray Inc, USA) is a complete robotic radiosurgery system that can be used for both intracranial and spinal applications [39]. It consists of a linear accelerator mounted on a robotic positioning arm. By using feedback mechanisms it can adjust the beam trajectory to correct for patient movement. The flush mounted image detectors capture
Figure 2.2: Commercial CAD/CAM systems for neurosurgery. (a) The CyberKnife robotic radiosurgery system for intracranial and spinal applications [39]; (b) The NeuroMate accurate tool positioning system for stereotactic brain surgery [42]; (c) Mazor’s SpineAssist miniature robot guides a K-wire into a pipe located along the axis of a drilled-hole in a pedicle [43]. The inset shows the actual size of the device.
high-resolution anatomical images throughout the treatment, while the *Synchrony Respiratory Tracking System* continuously synchronises beam delivery to the motion of the tumour, allowing clinicians to significantly reduce margins while eliminating the need for gating or breath-holding techniques. A recent addition to the system is the *RoboCouch Patient Positioning System*, which robotically aligns patients precisely with 6 DoFs, enabling faster patient setup. An overview of all the system components is shown in Figure 2.2(a).

Another surgical robot that was recently awarded FDA approval is the *SpineAssist* robot (Mazor Surgical Technologies, Israel) for spinal surgery [43]. The system features a miniature parallel manipulator designed to attach directly to the patient’s spine and sophisticated software for image-guidance. It can be used as a guide for tool positioning and implant placement and is no larger than a soda can, as shown in Figure 2.2(c). Motion of the robotic arm is defined pre-operatively and is supervised by the surgeon during the procedure.

As previously noticed, CAD/CAM robotic systems are clinically attractive when applied to orthopaedic surgery. The *ROBODOC* (first developed by Integrated Surgical Systems, USA and recently acquired by Curexo Technology Corporation, USA) [46] was one of the first autonomous robots designed for such application. It is an image-guided system that utilises an industrial SCARA robot with 5 DoFs to execute autonomously high-precision bone cutting for implant placement, as shown in Figure 2.3(a). Implant selection, pre-operative planning and registration are performed using the integrated ORTHODOC workstation [51]. The system is used clinically for Total Hip Replacement (THR) since 1992 [52]. Despite the significant precision improvement obtained, the related benefits on patient outcome still have to be demonstrated. Also, the surgical time becomes longer due to learning curves associated with the initial use of the system and the slow error recovery process. Another drawback of the system is the need for an additional surgery before CT scanning to place aluminium pins on the bone for registration. To overcome this problem, a new non-fiducial based surface registration technique (DigiMatch) has recently been integrated in the system [53].

Another system for orthopaedic surgery which is currently undergoing human tests for FDA approval is the *ARTHROBOT* robot for total hip arthroplasty developed by Kwon *et al* [45]. The manipulator has a 4-DoF parallel structure and is mounted directly on the bone using a simplified gauge-based registration technique, as shown in Figure 2.3(b). This reduces the pre-operative set-up time and guarantees over 90% accurate surface conformity with efficient workspace.

Finally, automatic CAD/CAM systems have also been used in urology, particularly for prostate resection. The *Probot* system developed at Imperial College London is especially designed to perform precise cutting of soft tissue within a constrained workspace [15]. In particular, the resectoscope is placed at the tip of a robotic frame which centres its angular motion around a point, thus allowing resection of
Figure 2.3: Example CAD/CAM systems for orthopaedic surgery. (a) The ROBODOC system for orthopaedic surgery [46]; (b) Gauge-based registration of the ARTHROBOT system for total hip arthroplasty and experimental set-up to test bone-mounting feasibility on a pig’s femur [45].
a conical cavity. The dimension of the resected part can be adjusted by translating the centre of rotation, as shown in Figure 2.4(a). The desired prostatectomy area is defined per-operatively through a dedicated surgeon-computer interface featuring both 3-D prostate model construction and on-line imaging capabilities, through which the surgeon can supervise the whole procedure.

In the field of urological interventions, Stoianovici et al at Johns Hopkins University are currently developing a Magnetic Resonance Imaging (MRI) compatible robotic system for fully automated brachytherapy seed placement called MRBot [47]. The robot has five DoFs to control the position and orientation of an end-effector and can be placed directly inside the 50cm bore of a standard closed MRI scanner, as shown in Figure 2.4(b). Four additional DoFs at the end-effector allow to modify the depth of needle insertion and to deploy brachytherapy seeds automatically by manipulating a titanium needle. The entire robot is built of nonmagnetic and dielectric materials and a new type of pneumatic actuator is used to achieve full MRI compatibility.

![Figure 2.4](image)

**Figure 2.4:** Relevant CAD/CAM robotic systems for urology. (a) The Probot system developed at Imperial College London and especially designed to perform precise cutting of soft tissue within a constrained workspace as required for prostatectomy [15]; (b) The MRI compatible robotic system for fully automated brachytherapy seed placement MRBot [47].
2.2.3.2 Endoscopic camera holders

Together with CAD/CAM systems, endoscopic camera holders represent one of the first and most widespread applications of robotics to MIS. Traditionally, an assistant has to understand surgeon’s needs and move the endoscope accordingly. This becomes a demanding task due to the confined manoeuvring space, uncomfortable body position and difficulty in seamless communication in a busy and often stressful operating environment. In this regard, the introduction of a robotic assistant directly under the command of the operating surgeon could improve the ergonomics of the procedure. The main design feature of endoscopic camera holders is the incorporation of a RCM to move the endoscope about the pivoting insertion point on the patient’s skin. While the workspace of the robot must be as large as possible to ensure adequate positional versatility and large field-of-view during surgery, a small footprint is desirable to allow for free motion of the instrument. To achieve these goals, different RCM designs have been proposed.

The AESOP (Automated Endoscopic System for Optimal Positioning) from Computer Motion Inc was the first camera positioning robot to gain FDA approval in 1994 [17]. It uses two revolute joints with intersecting axes to create a passive RCM that constrains the orientation of the instrument inside the patient’s body but not between the access point and the robot (Figure 2.5(a)). This allows for safe endoscope repositioning in case of accidental patient motion. The first generation of the system featured a foot or hand controller to move the endoscope in 6 DoFs (in, out, left, right, up and down), while the second generation robot was voice-controlled [54]. Although more intuitive, the use of voice commands implied long set-up times for calibration and possible positioning errors.

Two generations of endoscopic camera positioning systems based on Infra-Red (IR) sensors and head motion have been developed by Prosurgics (previously Armstrong Healthcare and now Freehand 2010, London, UK). Both feature a five-axis SCARA arm for endoscope positioning. As shown in Figure 2.5(b), the manipulator is mounted on a freestanding, wheeled cart in EndoAssist [31] or directly clamped onto the patient table in FreeHand [32].

In addition to the above commercial systems, one interesting device currently under development is the CoBRASurge (Compact Bevel-gear Robot for Advanced Surgery), which features a bevel-gear wrist with three rotational joints defining a mechanically locked RCM at the intersection of their axes [30]. The compact and lightweight mechanism has an optimised workspace accounting for collision avoidance between the robot’s links and between the patient and the robot, as described in [55]. The system is remotely controlled using a joystick as shown in Figure 2.5(c) and demonstrated good performance as laparoscope holder in recent clinical tests on pigs [56].
Figure 2.5: Commercial and under development endoscopic camera positioning systems. (a) The AESOP voice-controlled camera positioning robot [17]; (b) The EndoAssist [31] and FreeHand [32] robotic camera holders; (c) CAD model and prototype of the cooperative robotic assistant for laparoscopic surgery CoBRASurge (©2009 IEEE) [30].
2.2.3.3 Semi-autonomous robots for soft tissue endoscopy

For MIS, the integration of some degrees of automation in soft tissue endoscopy still remains one of the biggest challenges. The development of tools for endoscopic surgery started 40 years ago with the design of active catheters. These long flexible cables are able to penetrate from the patient’s veins to the most inaccessible areas of the cardiovascular system for performing diagnostic sensing at the tip. In recent years, some therapeutic actions have also been executed using active probes integrating disposable stents to repair aneurysms or super-elastic angioplastic balloons [57]. Although sensorised active catheters possess some degrees of autonomy, they are not considered as real autonomous robots because their advancement is controlled by the surgeon with the aid of external imaging guidance. Also, these probes lack of dexterity at the tip and on-board visualisation. On the other hand, semi-autonomous endoscopes integrate intervention and diagnostic ability of the surgeon through autonomous motion and integrated vision.

As an example, the Tethered Epicardial Crawling (TEC) robot HeartLander by Riviere et al [24] is a miniature mobile robot for cardiac MIS, consisting of two independent components connected by three nitinol wires. Each part can adhere to the epicardium using suction pads, thus enabling forward advancement through inchworm-like locomotion (Figure 2.6(a)). The robot also incorporates an endoscope for visual feedback and an electromagnetic tracking system for real-time 3-D localisation [58]. Recently, a new prototype with miniature on-board motors has been proposed for wireless cardiac MIS procedures [59].

Thus far, most semi-autonomous robots are designed for navigation and examination of the Gastro-Intestinal (GI) tract. This is due to both anatomical and safety reasons, given that the GI tract is naturally not sterile, can be accessed through two natural orifices, and its minimum diameter is about 3cm. Currently, clinically deployable GI robots are limited, apart from endoscopic capsules, which can be considered as passive swallowable imaging tools rather than robotic devices [60].

Different approaches have recently been proposed to provide wireless endoscopic capsules with active locomotion, either through external (e.g. magnetic fields) [63] or on-board actuation [64]. In particular, Dario et al at Instituto Superiore Sant’Anna (ISSA) have used legged locomotion and developed three generations of legged capsular prototypes [28, 61, 65]. One of the prototypes is shown in Figure 2.6(b), for which forward motion is performed by cyclic actuation of two identical sets of 6 legs located respectively at the front and rear of the capsule. Each set of legs is driven by a miniature brushless Direct Current (DC) motor coupled with a slot-follower mechanism. The device has been tested ex vivo using excised porcine colon specimens placed inside a GI phantom model. The average speed was 5cm/min, which would allow the completion of a colonoscopic procedure in less than 30min. The device was powered by wired connection to an external source and wireless power...
Figure 2.6: Different designs of semi-autonomous robots for endoscopic surgery. (a) Heart-Lander miniature mobile robot for cardiac MIS by Riviere et al (©2009 IEEE) [58]; (b) 12-leg robotic capsule for the exploration of the GI tract by Dario et al (©2009 IEEE) [61]; (c) SMA active endoscope by Ikuta et al (courtesy of Prof. Shigeo Hirose, Tokyo Institute of Technology) [29]; (d) Burdick’s inchworm-like robotic endoscope (©1995 IEEE) [26]; (e) Principle of inchworm locomotion and robotic colonoscope by Dario et al [62].
delivery and further size miniaturisation still remain a challenge for future designs.

One of the most challenging tasks in the design of an endoscopic robot is the incorporation of an effective locomotion scheme enabling the advance of the robot through the elastic, slippery, peristaltic and collapsed colon without causing tissue damage. Koji Ikuta [29] was among the firsts to use Shape Memory Alloy (SMA) actuators to drive an automated snake-like endoscopic robot around obstacles. The device consisted of five flexible segments: four bending in the same direction on a plane, and a tip one which could turn orthogonally. It also featured a fibroscope delivering the vision information. The device was able to navigate smoothly through the sigmoid colon (Figure 2.6(c)), but the motion was limited to a two dimensional space. One issue related to the use of SMA tendons is that they require high currents for actuation and forward movement is slow.

Burdick et al [26] designed a robotic endoscope able to perform inchworm-like locomotion in the colon using inflatable balloons and modified bellows as actuators, as shown in Figure 2.6(d). The balloons located at the robot extremities had the function of grasping the colon walls, while the rubber bellows worked as extensors. The system was moderately efficient in vitro, but encountered challenges when tested in vivo, as the balloons tended to slip along the intestinal wall due to insufficient gripping force. Increased dilatation of the colon wall to achieve adequate gripping force carries a risk of producing regional ischemia.

Different generations of semi-autonomous inchworm-like robots for colonoscopy have been developed by Paolo Dario and co-workers [27, 62, 66, 67]. Each of them features a steerable distal tip integrating a visualisation system and a locomotion unit comprising two clamping modules and a pneumatically actuated extension module, which is shown in Figure 2.6(e). Each clamping unit houses several small holes to suck the colon tissue and fix the position of the robotic device relative to the intestinal wall. Inchworm-like locomotion is performed as shown in Figure 2.6(e) by firstly actuating the rear clamper, then extending the central module, and finally closing the frontal clamper while the rear clamper is released. After the central module contracts again, the same steps are repeated. The system demonstrated the capability of smoothly adjust its shape in relation to the intestine during locomotion. However, its major drawback was the so called “accordion effect” which occurs when the colon wall is extending or retracting in accordance with the elongation and contraction phases of locomotion, preventing any advancement of the device.

2.2.3.4 Hand-held mechatronic surgical tools

Although the above systems incorporate a relatively high level of automation, the main goal of robotic surgery is to develop new functional tools enhancing the ability of surgeons. Most medical robots are indeed designed to cooperate with surgeons and assist them during the operation. Among these, robotic hand-held surgical instru-
ments are enhanced mechatronic tools with a certain degree of integrated intelligence and autonomy. They are able to assist the surgeons by adjusting movements and constraining the level of interaction with the operative field.

Manually-driven prototypes are designed to improve the accuracy of tissue manipulation by augmenting a surgeon’s tactile or haptic sensing ability. Dario et al proposed a mechatronic endoscope with a cable-actuated steerable tip for integration in a computer-assisted arthroscopy system [23]. Embedded sensors for detecting the position of the tip and its contact with tissue, as shown in Figure 2.7(a), provide the device with the ability of semiautomatic collision avoidance to prevent the tip from touching critical areas defined before the surgery [68].

The active tremor compensating microsurgical tool for ophthalmology called Micron was developed at Carnegie Mellon University by Riviere et al [14]. Six inertial sensors are integrated to monitor the motion of the tool tip and estimate the physiological error. Tremor is cancelled using piezoelectric actuators to move the tip in the opposite direction using 3 DoFs as shown in Figure 2.7(b). The device has been recently improved by adding visual servoing abilities [69].

![Legend]

1. Central element
2. Strain Gauge sensor
3. Hall Effect sensor
4. Connector
5. Tube
6. Steerable tip

![Figure 2.7:](image)

**Figure 2.7:** Representative robotically enhanced hand-held devices for MIS. (a) Collision-avoidance endoscope for computer-assisted arthroscopy by Dario et al (©2000 IEEE) [23]; (b) Micron hand-held instrument with active motion and tremor removal for vitreoretinal microsurgery (courtesy of Dr Cameron Riviere, Carnegie Mellon University) [14].

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2.2.3.5 Synergistic control systems

To further increase the safety of robotic surgical systems, Rosenberg introduced in 1993 the concept of Virtual Fixtures (VFs) for tele-manipulation [72]. These can be described as perceptual overlays designed to reduce the workload of processing certain sensory modalities while performing a remote manipulation task. Although the implementation of VFs is not limited to haptic interaction, the most common application utilizes computer-generated haptic forces to guide the movement of the operator for improved consistency and accuracy. In practice, two types of VFs can be generated: Forbidden Region VFs (FRVFs) and Guidance VFs (GVFs). FRVFs are used to keep the robot end-effector within a safety region defined pre-operatively by providing a strong reaction force when the operator reaches the surface boundary. GVF$s$ are instead soft attractive forces designed to guide the operator hand motion so that the robot end-effector follows a pre-defined virtual pathway. However, the haptic interface always leaves the operator in full control of the robotic manipulator [73]. Therefore, systems implementing VFs can be described as ‘cooperative’ or ‘synergistic’ control systems.

Although VFs were originally applied to remote manipulation, a number of collaborative systems have been augmented with synergistic control. As an example, the Steady-Hand Eye Robot developed at Johns Hopkins University [16] is a cooperatively-controlled robot assistant designed for retinal microsurgery. Cooperative control allows the surgeon to have full control of the system, with his hand movements dictating exactly the movements of the robot. The robot can also be a valuable assistant during high-risk procedures, by incorporating VFs to help protect the patient, and by eliminating physiological tremor in the surgeon’s hand during surgery. The last prototype of the manipulator [70] consists of four components: 1) XYZ linear stage for translation, 2) rotary stage for rolling, 3) a tilting mechanism with a mechanical RCM, and 4) a tool adapter with a handle force sensor, as shown in Figure 2.8(a).

The concept of VFs in collaborative manipulation has also been refined by Davies et al [44], who introduced the so called “active constraints” by gradually increasing the haptic stiffness when the end-effector approaches the pre-defined forbidden region. The research group at Imperial College London developed the first active constraint robot for orthopaedic surgery known as Acrobot [71]. After the first successful clinical trials [74, 75] the system has been used clinically in a number of robotic-assisted total knee replacement procedures [76]. It was firstly commercialized by the Acrobot Company Ltd and recently re-named ‘Acrobot Sculptor Robotic System’ after acquisition by Stanmore Implants Worldwide in 2010. The system features a back-drivable force-controlled bone-milling instrument, as shown in Figure 2.8(b), which allows “hands-on” sculpting of the bone. The surgeon is in direct control of the milling tool, but his hand motions are constrained to remain within
Figure 2.8: Synergistic control applications in robotic-assisted MIS. (a) Schematic of the Steady-Hand Eye Robot and photo of the system set-up for vitreoretinal surgery (©2010 IEEE) [70]; (b) The Acrobot system for actively constrained orthopaedic surgery [71]; (c) The PADyC robot for cardiac surgery [25].
a permitted region, usually defined pre-operatively. Such a system offers the benefits of a CAD/CAM system with enhanced safety, which makes it clinically more acceptable.

A variation of the same concept has been implemented by Troccaz et al using a 6-DoF passive arm with dynamic constraints (PADyC) shown in Figure 2.8(c) [25]. This system can constrain surgeon’s hand motion inside a predefined region or along a desired trajectory and was developed for application in cardiac surgery (pericardial puncture). The system comprises a three-axis SCARA robot with two additional axes (one for rotation and one for translation) and a modular sixth joint for either translation or rotation. Even though the use of a passive robot ensures increased safety, motion accuracy and stiffness may be compromised.

2.2.3.6 Master-slave surgical systems

Finally, master-slave systems incorporate the lowest level of autonomy since the motion of the surgeon’s hands is replicated by the surgical robot. Because the two parts of the system are physically separated, this control modality is considered as tele-operation and has the potential for treating patients from afar. The most common tele-operated MIS system currently available on the market is the da Vinci surgical system by Intuitive Surgical Inc (Sunnyvale, CA) [13]. Although it was initially developed to perform cardiothoracic surgery, currently its main application is laparoscopic radical prostatectomy. The system consists of a master console and a slave, patient-side cart placed in the same operating room, which houses an endoscopic camera and up to three surgical tools, as shown in Figure 2.9(a).

The most important feature of the da Vinci surgical tools is the EndoWrist with three-axis articulation mimicking the DoFs of the human wrist. Cable drives located in the 10mm shaft of the EndoWrist are used to remotely control the tool through actuators placed at the proximal extremity of the holding module. These cables also drive the grasper oriented by the wrist. Finally, the external positioning mechanism controls the roll axis of the wrist.

The master console of the da Vinci system houses a 3-D display receiving the visual information from the operating field through the stereoscopic cameras at the tip of the endoscope. The surgeon docks the head in the console and places the hands inside the master’s handles, which are registered to the coordinate frame of the 3-D monitor. The reversion of motion direction typical of MIS tools is avoided, tremor is filtered at 6Hz, and motion scaling is applied to ensure the global accuracy of surgeon’s movements. The main benefits of the system are enhanced dexterity and improved ergonomics as compared to conventional laparoscopy. However, limitations of the system include high cost and a lack of haptic and tactile feedback.

The Zeus tele-operated surgical robot [12] was developed by Computer Motion Inc (Goleta, CA) in parallel to the da Vinci system. It also features a patient side
Figure 2.9: Commercial master-slave robotic surgical systems. (a) The da Vinci Si surgical system comprising master console with ergonomic handles (middle insert) and slave manipulators [13]; (b) The Zeus master-slave robot for MIS [12].
slave manipulator with three arms and a master console, as shown in Figure 2.9(b), but the main difference between the two is that the Zeus instruments only have 5 DoFs. Albeit the system was used in the first transatlantic tele-surgery, performed between Manhattan, New York, USA and Strasbourg, France [77], it is no longer in production since its acquisition by Intuitive Surgical Inc in 2003.

Although the da Vinci is currently the only master-slave robotic surgical system commercially available, the NeuroArm, a tele-operated robot for micro and neurosurgery developed by Sutherland et al at the University of Calgary, Canada [37], is currently undergoing clinical tests and will be soon released on the market by IMRIS Inc (Winnipeg, Canada). The design of the MR (Magnetic Resonance) compatible slave manipulator is based on a SCARA configuration and features 7 DoFs plus tool actuation. A 3-DoF optical force sensor to provide haptic feedback is embedded in the end-effector, which can be interfaced with standard neurosurgical tools. The slave part of the system can be mounted on a mobile base for microsurgery or directly clamped onto the patient table for stereotaxis [78]. The master workstation recreates the sound and touch of surgery to enhance the user experience. The user interface comprises four monitors to display visual information from the Operative Room (OR) and the surgical site, as well as the position of the NeuroArm and intra-operative MR images. Binoculars are integrated to convey the images from the surgical microscope and two PHANTOM Omni haptic input devices (SensAble Technologies, Woburn, MA) equipped with a stylus to mimic standard neurosurgical tools are used for manipulation, as shown in Figure 2.10(a). The first phase of clinical testing has been successfully completed by the system [79].

Another promising system already tested on human patients is the NeuRobot tele-controlled system [41] developed by Hongo et al to enable neurosurgery at a microscale. Together with the slave micro-manipulator and the master device, the system comprises a 6-DoF manipulator-supporting device and a stereo display monitor. The slave manipulator features three 1mm forceps and a 3-D 4mm endoscope. The initial position and spatial configuration of the slave arm is defined using the supporting device according to pre-surgical planning. Each micro-manipulator is then remotely controlled during the procedure by three 3-DoF (rotation, swinging, and translation) levers, as shown in Figure 2.10(b). Surgical simulations were firstly performed on a human cadaveric head to validate the system and the NeuRobot was subsequently successfully used to remove a portion of a tumour from a patient with a recurrent, atypical meningioma [80].

In addition to the aforementioned clinically applied robots, a number of tele-operated systems are currently under development. Among these, the one by Berkelman et al [34] has the unique feature of combining simple, modular and light-weight components which can be easily integrated in the operating room. The slave part of the system consists of three manipulators less than 2kg in weight which can be clamped to a rigid frame fixed on the rails on either side of the patient table. Two
Figure 2.10: Clinically tested master-slave robotic surgical systems. (a) The NeuroArm workstation and MR compatible manipulators for micro-neurosurgery [78]; (b) The Neu-Robot tele-operated system for neurosurgery by Hongo et al [41].

of the manipulators are used to position endoscopic instruments while the third one is voice controlled and determines the pose of the endoscope. Also in this case, two PHANTOM Omni haptic devices are used to control the instrument manipulators, but they are customised with a mouse scroll-wheel and encoder to control the gripper opening and closing in a quasi-continuous fashion, as shown in Figure 2.11(a). The design of each slave manipulator is based on the LER (Light Endoscope Robot) [81], which consists of a ring-shaped base to be placed on the patient abdomen at the level of the instrument entry point, a clamp to hold the endoscope trocar and two joints guiding the motion of the endoscope about the incision point. The insertion depth of the endoscope can also be remotely controlled. The instrument manipulators feature an additional DoF to control the rotation of the tool shaft. Hitherto, the system performance has only been assessed in a laboratory environment.

Tadano and Kawashima recently investigated the use of pneumatic actuators to integrate force sensing abilities in a tele-operated surgical system [35]. The slave
manipulator consists of a pneumatically actuated forceps with 4 DoFs arranged as rotation around its axis, two joints and a gripper [82], which is positioned using a 3-DoF supporting manipulator (translation and rotation around the pivot point at the trocar insertion). The master manipulator features a total of 6 DoFs and is constituted by a delta mechanism for 3-DoF translation and a serial gimbal mechanism with three intersecting rotational axes to control the orientation of the forceps tip. Both master and slave manipulators are shown in Figure 2.11(b). Bilateral impedance control is implemented to obtain master-slave tele-operation. In particular, a motion-control type of impedance control is used for the master manipulator, while a force-type impedance control is adopted without a force sensor for the pneumatic slave manipulator. The accuracy of the bilateral control has been evaluated by measuring positions and forces of the manipulators during a suturing task in an in vitro experiment and the results indicated that the force at the slave side is felt by the operator with an uncertainty of about 1.5 N.

The RAMS (Robot-Assisted Micro-Surgery) cable-driven master-and-slave tele-robotic system for eye surgery has been developed at the NASA Jet Propulsion Laboratory (JPL) only for technology test purposes [38]. The system enables enhanced dexterity and accuracy using tremor filters and motion scaling. Force feedback is also delivered to the operator, and the motion of the instrument can be constrained to minimise the negative effect of the surgery on the eye. The tool in the eye is manipulated by a slave robot featuring 6 positioning DoFs with 15-micron accuracy and 6-DoF tip-force sensing. The master manipulator has the same kinematic structure of the slave robot with 6 force-sensed DoFs and 25-micron tip-position measurement accuracy, as shown in Figure 2.11(c). Bimanual operation can also be implemented by combining two systems with a surgical microscope.

The RAVEN robot developed by Hannaford et al at the University of Washington was recently validated for tele-operation of surgical tasks [36]. It consists of a patient side featuring two identical manipulators mounted on the sides of the surgical table and a master side with two input devices, a monitor and a laptop, as shown in Figure 2.11(d). Each 7-DoF cable-actuated surgical manipulator consists of three main parts: a static base which houses all of the motors, a spherical mechanism to position the tool and the tool interface. The spherical 4-DoF mechanism allows rotation of the tool about the pivot point on the patient abdomen while the remaining 3 DoFs at the tool interface control its rotation, grasp and wrist axes. The input devices at the surgeon site are PHANTOM Omni devices, while the monitor displays a video feed of the operative site. A USB foot-pedal is also used to enable and disable the coupling between master and slave manipulators and allow for position indexing.

Finally, the DLR (German Aerospace Center) has recently designed a tele-operated robot for surgical applications called MiroSurge shown in Figure 2.11(e) [33, 83]. The master console features an autostereoscopic display and two haptic input devices with force feedback (Omega 7 by ForceDimension, Lausanne, Switzerland).
Figure 2.11: Promising tele-operated robotic surgical systems currently under development. (a) Manipulators and master console of the tele-operated surgical system by Berkelman et al [34]; (b) Slave and master manipulators of the pneumatically actuated tele-operated system by Tadano and Kawashima [35]; (c) Master and slave manipulators of the RAMS system for eye surgery [38]. Two systems can be used in combination to provide bimanual operation.
The three slave manipulators at the patient side are lightweight MIRO robots [84] with a kinematically redundant structure resembling the one of the human arms. The surgeon controls two of the slave robots equipped with specialised MIS instruments with enhanced articulation and force/torque sensing. The third arm is used to position the endoscopic stereo camera.

2.2.4 Open problems and technical challenges

Although not exhaustive, the above review comprises some of the most successful robotic surgical systems currently available on the market and promising innovative technologies still under research development. In spite of the large number of systems listed in Table 2.3, the review demonstrates how the technology is still in its infancy, especially for application to more complex procedures involving soft tissue manipulation. Indeed, the systems that have been successfully integrated in
the operative theatre and have effectively improved the procedure in terms of ei-
ther surgeon performance or patient outcome, only offer advantages related to the
capabilities of traditional industrial robots, as listed in Table 2.1. Their role is
therefore limited to a minimum number of low-level tasks such as precision cutting
or endoscope holding and positioning. Although some CAD/CAM systems are used
for both pre-operative planning and intra-operative tasks, long pre-operative pro-
duress, high cost and large footprint are major issues, together with the questionable
improvement in patient outcome which is yet to be demonstrated.

Although the integration of autonomous navigation capabilities has the potential
to improve the clinical applicability of a number of devices for soft tissue endoscopy,
current actuation technologies are still too inadequate to allow the implementation
of an efficient locomotion scheme. In fact, the systems reported in Table 2.3 rely on
the tissue to generate the traction force for propulsion. This approach limits their
safety and efficiency since the tissue can be damaged and the propelling force can
result to be insufficient. Similarly, although the introduction of synergistic control
systems can enhance the performance of the surgeon in terms of both accuracy and
safety, their application is limited to specific procedures with highly structured and
static environments due to the challenges of designing an active constraint which
can adapt in real-time to the deforming tissue.

In robotic surgery, the master-slave paradigm has become the preferred control
scheme in many systems, as demonstrated by the significant number of master-slave
robotic systems listed in Table 2.3. This is because the exploitation of an additional
processing level between the surgeon and the robot overcomes many of the issues
related to the traditional MIS approach. The fulcrum effect is eliminated by the
use of ergonomic user interfaces and computerised kinematic mapping. At the same
time, precise motion control of the instrument tip is achieved by tremor removal
and motion scaling. Wrist articulation is introduced by additional flexibility at the
slave level. Recent advances in imaging and computerised vision technologies such
as High Definition (HD) stereoscopic displays with augmented reality have further
enhanced capabilities of the master console.

In spite of the advantages mentioned above, the lack of force control and haptic
feedback still remains the main drawback of current master-slave systems. This is
due to the necessity of embedding multiple miniaturised force sensors in the surgical
instrument, thus requiring practical considerations of biocompatibility and sterili-
sation. For this reason, the current research attention has naturally shifted from
haptic sensing to haptic rendering in tele-operated surgery. However, in order to
provide real-time feedback, the computational cost required for both graphics and
haptic rendering is a major bottleneck. Crucially, the technology has not drastically
improved since the launch of the da Vinci surgical system in 1999. Indeed, the main
innovative features of the last version of the system are related with better visuali-
sation through a 3D HD camera and the integration of a second master console for
collaborative surgery. More importantly, although the adoption of robotic systems in the clinical practice has been significantly promoted by the introduction of the *da Vinci*, its application is still limited to a small range of procedures. While over 2000 units have been installed worldwide and the number of operations performed with the system increases every year, the limited workspace reachable by its long, rigid instruments hinders the execution of procedures involving complex anatomical pathways. In addition to these limitations, the acquisition by many hospitals and healthcare facilities of systems such as the *da Vinci* is prevented by their significant cost and large footprint within the operating theatre. Moreover, long pre-operative set-up times are necessary to adjust the robot configuration according to the specific procedure and any intra-operative modification becomes difficult if not infeasible.

To extend the benefits of improved precision, stability and dexterity to additional procedures will require advances in mechanical design, sensing and control. Further miniaturization of currently available actuation technologies is essential for the development of versatile systems with enhanced flexibility and smaller footprint that can be seamlessly integrated in the operative workflow. However, these are expected to create a number of control and manipulation issues intrinsic to any multi-DoF actuation mechanism. It will consequently be important to provide a single surgeon with the ability to intuitively, effectively and safely take control of the added complexity. In addition, the consolidation of methods for non-rigid registration and tracking of tissue deformation in real-time coupled with advances in 2D and 3D imaging modalities will ensure a better match of pre-operative and intra-operative data and allow the implementation of active constraint control in a dynamic surgical scenario. Recent medical robotics research is already trying to address these issues within the development of articulated robots for laparoscopic and endoscopic surgery, as well as flexible devices for more complex transluminal and single site techniques. The remaining of this chapter will therefore analyse the design, control and ergonomic features of such systems, with the aim of identifying the main research challenges that still have to be tackled to achieve their effective deployment *in vivo*.

### 2.3 Articulated robots for MIS

As explained in the previous section, the use of long and rigid laparoscopic tools inserted through fixed ports on the body limits the surgical workspace and affects the manual dexterity. The integration of articulation at the instrument tip is one of the main benefits of robotic surgery. However, the difficulty of following curved anatomical pathways as required for many cardiac and complex GI procedures remains a major challenge. Hitherto, many research teams have attempted to overcome these limitations by developing robotic devices with a higher degree of articulation. The key attributes of a relevant sample of such systems are presented in Table 2.4. Among
the listed devices are semiautonomous robots for endoscopic surgery [85], master-
slave systems for cardiac [86, 87] or deep area interventions [88–92], a dexterous
instrument for cardiac MIS [93], an articulated robotic probe [11] and a miniature
manipulator for integration in a self-propelling endoscope. The following sections
will discuss the main design and control features of these systems and identify the
technical challenges that still hinder the development of an articulated robotic sys-
tem that can be seamlessly integrated into the surgical workflow.

Table 2.4: Mechanical features of a sampler of articulated robots for MIS.

<table>
<thead>
<tr>
<th>Author/Company</th>
<th>Actuation</th>
<th>Joint DoFs</th>
<th>Joint type &amp; Joint no.</th>
<th>Total DoFs</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degani et al</td>
<td>Tendon</td>
<td>2</td>
<td>Spherical</td>
<td>50, 3</td>
<td>[85]</td>
</tr>
<tr>
<td>Dupont et al</td>
<td>Ni-Ti concentric tubes</td>
<td>2</td>
<td>Continuous bend</td>
<td>- 5</td>
<td>[88]</td>
</tr>
<tr>
<td>Hansen Medical</td>
<td>Tendon</td>
<td>2</td>
<td>Continuous bend</td>
<td>- 6</td>
<td>[86]</td>
</tr>
<tr>
<td>Ikuta et al</td>
<td>Tendon</td>
<td>1/2</td>
<td>Revolute/universal</td>
<td>2+1 7</td>
<td>[89]</td>
</tr>
<tr>
<td>Ikuta et al</td>
<td>Tendon</td>
<td>2</td>
<td>Universal</td>
<td>4 9</td>
<td>[90]</td>
</tr>
<tr>
<td>Noonan et al</td>
<td>Tendon</td>
<td>1</td>
<td>Revolute</td>
<td>3 4</td>
<td>[11]</td>
</tr>
<tr>
<td>Patel et al</td>
<td>SMA wires</td>
<td>2</td>
<td>Continuous bend</td>
<td>- 2</td>
<td>[87]</td>
</tr>
<tr>
<td>Peirs et al</td>
<td>Motor</td>
<td>2</td>
<td>Universal</td>
<td>1 2</td>
<td>[94]</td>
</tr>
<tr>
<td>Salle et al</td>
<td>Motor</td>
<td>1</td>
<td>Revolute</td>
<td>5 5</td>
<td>[93]</td>
</tr>
<tr>
<td>Simaan et al</td>
<td>Super-elastic Ni-Ti tubes</td>
<td>2</td>
<td>Continuous backbone</td>
<td>- 2</td>
<td>[91]</td>
</tr>
<tr>
<td>Webster et al</td>
<td>Ni-Ti concentric tubes</td>
<td>2</td>
<td>Continuous backbone</td>
<td>- 6</td>
<td>[92]</td>
</tr>
</tbody>
</table>

2.3.1 Mechanical designs

Thus far, a number of designs have been proposed for the integration of enhanced
flexibility in robotic surgical tools. Among these, the Highly Articulated Robotic
Probe (HARP) developed by Choset et al [85] and lately named CardioARM [95],
is designed to perform minimally invasive epicardial interventions through a subx-
The flexible part of the device is 300mm long and has a diameter of 10mm, and is able to navigate in confined anatomical regions such as the intrapericardial space with minimal interaction with the environment, as shown in Figure 2.12. The forward motion is performed by alternating the rigidity of two concentric tubes constituting the probe. Both tubes consist of cylindrical links serially connected by spherical joints. The main advantage of this design is the ability of holding an arbitrary 3-D shape or to become completely flexible if necessary. However, the joints can only bend $\pm 10^\circ$ and cannot be actuated independently, thus the radius of curvature is limited and the kinematic redundancy is not fully exploited. Furthermore, the forward speed is low and a large external feeding control mechanism is required.

![CardioArm](image1)

**Figure 2.12:** CardioArm highly articulated robotic probe by Choset *et al* (courtesy of Dr Howie Choset) [85].

The slave part of the system for microsurgery by Ikuta *et al* [89] consists of a guide tube with a 2-DoF decoupled micro-joint at the tip (Figure 2.13(a)) and a 3-DoF micro-manipulator (two 1-DoF revolute joints and a gripper) that can translate and rotate inside the tube (Figure 2.13(b)). The forceps-shaped master mechanism controls grasping, rotation, translation and torsion of the micro-manipulator, and incorporates a gimbal replicating the pitch and yaw of the guide tube micro-joint (Figure 2.13(c)). The system has been validated in animal experiments. However, force feedback is not provided and the basic idea of using multiple micro-manipulators for endoscopic visualisation and triangulation has not been implemented yet.

Also from Ikuta *et al* is the Hyper Finger remote system for MIS [90]. The latest model features identical master and slave with four links connected in series by universal joints and a detachable gripper, giving a total of 9 DoFs. As shown in Figure 2.14, the slave manipulator is mounted on a tripod featuring a system for linear positioning. The system also incorporates a compensation mechanism for the elongation of the driving tendons, which usually occurs due to repeated stress, and
Figure 2.13: Remote robotic system for microsurgery by Ikuta et al [89]: (a) guide tube, (b) slave micro-manipulator, (c) master mechanism.

thus reduces positioning accuracy.

Figure 2.14: Clinical size prototype with 9 DoFs of the Hyper Finger system by Ikuta et al mounted on a camera tripod [90].

Within the Hamlyn Centre, Noonan et al [11] developed a lightweight articulated robotic probe with both augmented white light image feedback for navigation,
and fluorescence visual feedback for in situ tissue characterisation. The integrated dexterity ensures a larger field-of-view than a traditional laparoscope. The design is based on the concept of a “robotic finger” with four links connected in series by three revolute 1-DoF joints. The finger itself is in turn attached to a fourth joint providing axial rotation, which allows the device’s tip to bend in any direction through 90°. As shown in Figure 2.15, the robot is mounted to the Endowrist from Intuitive Surgical Inc [13], featuring a long, rigid shaft connected to a remote actuation unit.

*Figure 2.15: 4-DoF articulated robotic probe by Noonan et al [11]. (a) 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. (b) Image of the actuator pack. The Endowrist™ capstan housing, shaft, servo motors and clamping unit can be clearly identified. Images courtesy of David Noonan.*

The modular instrument for minimally invasive Coronary Artery Bypass Grafting (CABG) by Salle et al [93] comprises 5 position controlled and motor-actuated rotating joints. Each module features one DoF and can be serially connected with any other module, as shown in Figure 2.16. It can also be equipped with a SMA actuated gripper. Optimal design is determined using a generic evolutionary algorithm and is based on simulations and experimental models of the surgical task. In particular, a multi-objective genetic algorithm is used to evaluate each combinations of modules with respect to each task-related objective. A range of optimal solutions is then generated based on a specific combination of objectives. The final optimal design is chosen by the user according to a posteriori criteria. In practice, the surgical tasks is modelled and divided in a number of critical steps. At each step four objectives are considered in the search: capability to perform the task; instrument manipulability in terms of force and speed resolution; maximum joint torque; minimum distance to surrounding organs.

Another system which implements embedded micromotors for actuation is the miniature manipulator for integration in a self-propelling endoscope designed by
Figure 2.16: Optimal 5-DoF dexterous instrument for minimally invasive CABG by Salle et al [93]. It features 5 identical 1-DoF modules that can be connected to form different 2-DoF configurations, also shown.

Peirs et al [94]. As shown in Figure 2.17(a), the design consists of two serial modules driven by electromagnetic motors with worm gear reduction. The resultant two bending degrees of freedom are used to orient camera and tools at the tip of the endoscope. The authors also built a miniature prototype with smaller diameter featuring only one revolute DoF, as shown in Figure 2.17(b). However, the main disadvantage of motor actuation is the need for a worm gear transmission system that significantly reduces the space at the joint, and thus limits its motion speed.

Recently, Simaan et al [91] developed a system for minimally invasive tele-surgery of the upper airway featuring a three-armed slave robot with Distal Dexterity Units (DDU), each comprising a detachable parallel manipulator and a Snake-Like Unit (SLU) with two DoFs. The SLU is different from the systems described above because dexterity is provided by continuous bending of flexible segments rather than articulated connections between rigid links [96]. Four SMA wires are arranged so that three secondary backbones are placed equidistant from one another and from a central primary backbone. The primary backbone is attached to both a base and an end disk, and to several spacer disks featuring holes to allow for sliding and bending of the three secondary backbones attached only to the end disk, as shown in Figure 2.18. The main drawbacks of the system are related to the difficulties in modelling and controlling SMA actuation due to response time, friction and buckling. Also, the incorporation of multiple flexible segments to enhance the robot dexterity would significantly increase its size and control complexity.
A novel approach to performing beating heart intracardiac surgery or other deep area interventions (e.g. percutaneous procedures, endoscopic sinus surgery) is to use concentric-tube robots. Dupont et al [88] are currently investigating different strategies for real-time control of robots constituted by concentrically combined pre-curved elastic tubes. For such continuum robots, the position and orientation of the tip, as well as the overall robot shape, are determined by curvature interactions generated when rotating and translating the tubes with respect to each other. Although the location of the actuators at the proximal end of the tubes can be advantageous for MIS applications, the main limitations of this approach arise from the complexity of the robot kinematic model, which increases with the number of embedded tubes and affects the accuracy of tip positioning, as shown in Figure 2.19(a). Moreover, the implementation of stiffness control, which is critical for tele-manipulation, becomes very challenging due to the coupling between kinematic and force mappings [97].

Webster et al [92] are currently working in parallel with Dupont et al on the clinical application of active cannulas constituted by concentric tubes, as shown in Figure 2.19(b). In addition to robot modelling and control, the authors have recently presented promising results in 3-D shape sensing from stereo camera images by using self-organising maps [98]. Shape reconstruction has also been implemented together with motion planning algorithms for obstacle avoidance and navigation in tubular environments [99] for integration in image-guided procedures [100]. Recently, the
multi-tube steerable Active Cannula (AC) has been integrated with an Ultrasonic Interstitial Thermal Therapy (USITT) ablator to create a steerable percutaneous device that can deliver a spatially and temporally controllable (both mechanically and electronically) thermal dose profile. Initial experiments toward applying the ACUSITT to treat large liver tumours through a single entry point under 3-D Ultrasound image guidance have shown promising results [101].

For cardiac MIS, the Sensei Robotic Navigation System (RNS) for remotely controlled catheter ablation [102] has recently been introduced clinically by Hansen Medical (Mountain View, CA, USA). The slave part of the system consists of a steerable catheter (Artisan) controlled by a remote catheter manipulator fixed at the patient table. The tendon control mechanism is similar to that of the da Vinci system, as illustrated in Figure 2.20. In particular, the Artisan features two flexible guides controlled by separate remotely-located actuation boxes. The combination of outer and inner guide motion allows the catheter to easily conform to any S-shaped curve [86]. Accurate position control is ensured by detailed modelling of the tendons kinematics and real-time vision-based 3-D shape detection and tracking [103].

Finally, also Patel et al are trying to overcome the issues related with percutaneous catheter-based procedures performed under X-ray radiation by developing tele-operated robot-assisted control of an active catheter under image guidance [87]. The distal end of the catheter is instrumented with SMA actuators, a 5-DoF Electro-Magnetic (EM) position/orientation sensor, and a 3-DoF strain gauge-based force sensor. This provides force feedback to a PHANTOM Omni haptic device for
Figure 2.19: Concentric-tube robots for deep area minimally invasive interventions. (a) Concentric-tube robot by Dupont et al comprised of four telescoping sections that can be rotated and translated with respect to each other [88]; (b) A prototype active cannula made of super-elastic nitinol tubes by Webster et al [92]. The inset line drawing indicates the degrees of freedom.
master-slave control of the distal tip of the catheter, as shown in Figure 2.21. A combination of image-based and EM tracking is used for position control. Both unilateral and bilateral tele-operation algorithms are used to control the position of the active catheter using a robotic manipulator. The authors have also developed a force control algorithm to ensure that the contact force on the distal end of the catheter is regulated to enable smooth insertion of the catheter without damaging the artery walls or dislodging plaque [104].
2.3.2 Actuation modalities

As shown in Table 2.4, the choice of an appropriate actuation method is critical when designing an articulated robotic tool for MIS. The criteria for the selection are dependent on the targeted application, which include:

- Actuator arrangement;
- Joint torque and speed;
- Back-drivability;
- Positional accuracy.

The location of the actuator generally affects the design of the device and is mainly dictated by force transmission efficiency, control complexity and size constraints. Most of the devices presented in Table 2.4 feature long transmission elements to connect remotely positioned actuators with the distal links passing through more proximal units. Examples of transmission lines are tendons [11, 85, 86, 89, 90] and SMA wires [87, 88, 91, 92]. This approach is compact and saves space for instrument channels while ensuring high force transmission. However, modelling and control issues due to non-linearities and transmission inefficiencies are major difficulties to deal with. They are introduced by joint coupling, frictional losses, indirect position sensing and path length changes. Also, the total number of DoFs is limited by the available cross-sectional space to accommodate transmission elements. The relative merits of tendons and SMA wires are listed in Table 2.5. Tendons are usually preferred because the actuation of SMA can involve cycles of heating and cooling with large response times and non-linear deformations.

Thus far, a variety of embedded actuators with different features are available for use in robotic surgery. Table 2.5 presents the most common ones being used, although the technology behind artificial muscle is still in its infancy and its application is still limited. Piezoelectric and pneumatic actuators have been mainly used in self-propelling devices such as the epicardial crawling robot by Riviere et al [24] and several semi-automatic colonoscopes [26, 27, 66, 67] because of high force transmission and large linear deformations. However, their use in articulated devices is limited by both integration and miniaturisation issues.

Brushless DC motors have a key advantage of ease of digital control. They are particularly suitable for modular designs such as the one proposed by Salle et al [93]. The main integration challenge arises from the need for miniaturisation, which can significantly decrease the torque of the motor. Therefore, an efficient transmission system must also be implemented to ensure adequate joint motion while occupying the minimum cross-sectional space. Since the motor must be aligned with the central axis of the robot’s link due to the small diameter-length ratio, an immediately obvious solution to transmit the rotation of the motor to the joint is through a
Table 2.5: Comparison of available actuation modalities.

<table>
<thead>
<tr>
<th>Actuator Type</th>
<th>Advantages</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remote</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SMA wires</td>
<td>- Allow miniaturisation</td>
<td>- Cooling required</td>
</tr>
<tr>
<td></td>
<td>- High force transmission</td>
<td>- Modelling and control issues</td>
</tr>
<tr>
<td></td>
<td>- Large motion capacities</td>
<td>- Not back-drivable</td>
</tr>
<tr>
<td></td>
<td>- Simple</td>
<td>- Low backlash and friction</td>
</tr>
<tr>
<td>Tendons</td>
<td>- Allow miniaturisation</td>
<td>- Low backlash and friction</td>
</tr>
<tr>
<td></td>
<td>- High force transmission</td>
<td>- Non-linearities and limited back-drivability over curved path lengths</td>
</tr>
<tr>
<td>Embedded</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Artificial muscle</td>
<td>- Bio-mimetic principle</td>
<td>- Control issues</td>
</tr>
<tr>
<td></td>
<td>- Moderate efficiency</td>
<td>- High activation voltage</td>
</tr>
<tr>
<td></td>
<td>- Sensing ability</td>
<td>- Poor robustness</td>
</tr>
<tr>
<td>Brushless DC motor</td>
<td>- Digitally controlled</td>
<td>- Limited torque</td>
</tr>
<tr>
<td></td>
<td>- Fast response</td>
<td>- Mechanical friction</td>
</tr>
<tr>
<td></td>
<td>- Potentially back-drivable</td>
<td>- Miniaturisation issues</td>
</tr>
<tr>
<td>Piezoelectric</td>
<td>- Good holding force</td>
<td>- High activation voltage</td>
</tr>
<tr>
<td></td>
<td>- High torque at low speed</td>
<td>- Integration issues</td>
</tr>
<tr>
<td></td>
<td>- Large bandwidth</td>
<td>- Not back-drivable</td>
</tr>
<tr>
<td>Pneumatic</td>
<td>- High force transmission</td>
<td>- Lack of accurate control</td>
</tr>
<tr>
<td></td>
<td>- Low cost</td>
<td>- Miniaturisation issues</td>
</tr>
<tr>
<td></td>
<td>- Simple</td>
<td>- Sealing required</td>
</tr>
</tbody>
</table>

worm gear [93, 94, 105]. Although such a system can provide a good additional gearing, the cross-sectional space is significantly reduced. It also has the issue of slow joint speed and a lack of back-drivability.

2.3.3 Human-robot interfaces and control strategies

Together with the robot mechanical design, the choice of a suitable human-robot interface and the application of task-specific control strategies is fundamental to improve the consistency and safety of the operation, especially when the complexity of multi-DoF systems introduces additional ergonomic issues for the surgeon. Although most of the articulated instruments listed in Table 2.4 are controlled in a master-slave fashion [85–91, 93], i.e. the motion of the manipulator inside the pa-
tient’s body replicates the movements of the surgeon’s hands at the master console, different human-robot interfaces and control features have also been implemented depending on specific robot designs and clinical applications. However, these components mainly affect the configuration of the master side of the system, unless additional constraints need to be introduced at the slave level.

The two fundamental components of a master console are a video display for providing the surgeon with visual feedback from the operative site and an input device for sending motion commands to the slave manipulator. The aforementioned systems make use of an additional laparoscope to supply images of the articulated instrument at the surgical site, except for the Sensei RNS [102], which is designed to control a steerable catheter under fluoroscopic guidance. In this case, the surgeon’s workstation features a main display with the fluoroscopic view of the catheter at the surgical site and a 3-D model showing its actual articulation. Local catheter-to-tissue contact information collected using a force sensor at the tip of the catheter is also displayed. Additional screens show intracardiac electrophysiology data and a 3-D reconstruction of the surgical scene, as shown in Figure 2.22.

![Figure 2.22: Sensei® X Robotic Catheter System. The parallel manipulator (b) is a motion input device integrated in the master console (a). The device features tactile vibration feedback corresponding to the contact measure between the tip and the tissue. The motor drive unit (c) is mounted at the patient table for actuation of the Artisan™ Control Catheter [102] (©2011 Hansen Medical Inc).]

The choice of the master input device is mainly dictated by the design of the slave manipulator. Less complex systems use off-the-shelf components such as 3-D
joysticks [85, 102] or Sensable PHANTOM Omni haptic devices [87, 88]. Systems featuring many DoFs, such as the Hyper Finger [90] or the one for microsurgery by Ikuta et al [89], require a dedicated master control mechanism. However, the design of an ergonomic user interface is challenging, especially in presence of redundancy; the use of human hands allows controlling only 3 DoFs at one time, and thus the additional ones have to be controlled independently. One way to achieve seamlessly shared control between the surgeon and the robot is to implement a novel approach to synergistic control called perceptual docking recently proposed by Yang et al [106]. The fundamental idea is to gain knowledge from subject-specific motor and perceptual behaviour through in situ sensing. One example is to integrate eye-tracking as an additional human-robot interface modality and perform gaze-contingent attention selection [107]. Within the gaze-contingent perceptual docking framework, the information derived in situ from the subject eye gaze using binocular eye-tracking has been effectively used to recover 3-D motion and deformation of soft tissue [108, 109]. Consequently, motion compensation and visual stabilisation have been achieved through gaze-contingent robotic control using a beating heart phantom and a Staubli RX60 robotic manipulator [110]. The same idea has been applied to achieve hand-free control of the articulated robotic probe by Noonan et al [111]. In this case, the 3-D fixation points obtained through binocular eye-tracking are used to position the tip of the articulated probe by inverse kinematic control. Based on the perceptual docking framework, Mylonas et al [112] have introduced gaze-contingent haptic constraints. Through the use of motor channelling, real-time binocular eye tracking can be exploited to improve the performance and accuracy of robotic manipulation. This is achieved by generating a haptic force with intensity proportional to the relative separation between the fixation point and the instrument tip. This effectively bridges the visual and motor modalities using a perceptually enabled channel and alleviates the burden of the instrument control as well as the cognitive demand on the surgeon.

As mentioned in the first part of this chapter, the lack of force control and haptic feedback still remains the main drawback of current master-slave systems. The large number of DoFs required for manipulation, together with the friction forces generated at the trocar, can significantly affect the force perceived by the surgeon. In this case, visual cues due to instrument induced tissue deformation can be exploited by the surgeon to infer the amount of force applied. However, haptic feedback becomes critical when performing technically more complex and delicate surgical tasks such as suture manipulation [113]. Specifically, cardiac procedures are particularly challenging to perform due to the large amount of deformation caused by the beating heart. The research team lead by Allison Okamura at Johns Hopkins University has carried out extensive studies to demonstrate the fundamental role of haptic feedback in robotic surgery and have proposed different methods for sensory feedback integration [114]. Besides a number of force and position-based impedance control laws for
bilateral tele-manipulation [115] and the introduction of virtual fixtures for both tool
guidance and navigation within a safety region boundaries [116], they have investi-
gated the use of sensory substitution in the form of visual cues [117], auditory cues,
or both [118] to compensate for the lack in haptic feedback during tele-manipulation
tasks. Although sensory substitution has the advantages over direct haptic feedback
of lower cost and easier integration into existing systems because of the absence
of a haptic master device, it is less effective because human operators must still
“translate” the auditory or visual information into a force estimation. In addition,
conveying the information from a large number of DoFs that would be available
through direct force sensing using sensory substitution remains a major challenge
[119].

As already mentioned, a surgeon’s sensory feedback can also be enhanced by
virtual fixtures or active constraints [72] to guide the surgical tool along specified
3-D trajectories [25] and within safe boundaries [120]. The main limitation of spatial
motion constraints is that they are usually defined based on pre-operative imaging
data or standard anatomical models [121]. During surgery, they must be adapted
to the specific patient model and the surgical environment. To avoid this drawback,
dynamic 3-D virtual fixtures have been proposed to deal with dynamic surgical
scenes such as beating heart procedures. For example, Ren et al [73] combine pre-
operative dynamic MR/CT data with intra-operative ultrasound images to build a
3-D dynamic map of the surgical scenario and integrate the overlaid visual/haptic
model with real-time sensing data. Robust registration of the pre-operative model to
the patient is critical to ensure the effectiveness of the method. However, the validity
of rigid-body registration is strongly compromised in presence of non-periodic tissue
deformation caused by instrument manipulation.

Kwok et al [122] recently defined a scheme for real-time modelling of dynamic
active constraints for an articulated robot that adapt to both cardiac deformation
and local anatomical changes. In contrast to existing methods, the manipulation
boundaries of the forbidden region are defined for the entire length of an articu-
lated surgical tool. Constraining the motion of a single point (e.g. the tip) of the
instrument is not enough, especially when manoeuvring within the tight confines of
chest cavity and pericardium. Moreover, accurate path following is critical for many
procedures, such as epicardial ablation. This procedure currently needs to be per-
formed during open heart surgery or through multiple small incisions on both sides
of the chest to ensure accurate vessel encirclement. In the minimally invasive case,
a catheter is passed along the posterior side of the heart through two narrow spaces
strictly confined by the great vessels and the surrounding pericardium. The lack
of visual feedback strongly affects the hand-eye coordination of the surgeon. The
development of more flexible devices for safe access and navigation, combined with
the application of active constraints, can enhance both the speed and the accuracy
of such procedures.
2.3.4 Current limitations and emerging new directions

Although the enhanced dexterity of the systems in Table 2.4 has the potential to allow performing complex procedures, a number of technical issues still need to be tackled to enable the safe integration of such devices in the operative theatre. Practically, the design of active cannulas and catheters is effective for endovascular procedures where navigation is aided by the vascular walls and only limited interventional capabilities are required at the target operative site. In addition, the lack of embedded visual feedback requires the use of external imaging and/or tracking techniques to provide image-guided navigation. This effectively limits the application of such systems to radiation-based procedures (i.e. CT or fluoroscopy) or requires MRI compatibility.

On the other hand, none of the currently available actuation technologies listed in Table 2.5 allows the construction of a modular and back-drivable articulated system with high force transmission and small footprint. As discussed before, remote actuators such as tendons can provide high force transmission but with limited modularity and a large actuation box. Conversely, embedded actuators such as brushless DC motors allow both modularity and back-drivability but can only generate limited torques when miniaturised and usually require an additional mechanism to efficiently transmit the rotation of the motor to the joint. Therefore, it is envisioned that the design of a novel actuation strategy which incorporates the advantages of both technologies could fulfil the main requirements for MIS applications, specifically in the size constraints due to the diameter of the trocar port (15mm) and the minimum radius of curvature necessary to enable navigation along curved trajectories.

In addition to hardware-related issues, the augmented flexibility of the systems also increases their complexity, especially when dealing with a large number of DoFs to be actuated simultaneously. One way of solving this issue is to couple some of the DoFs as in the case of the CardioARM or the lightweight articulated robotic probe by Noonan *et al.*, thus not fully exploiting the redundancy of the system. Another approach is to design a master device with the same configuration of the slave manipulator so that each joint is directly controlled by the surgeon, as seen in the systems developed by Ikuta *et al.* However, the ergonomics of such input devices is usually very poor, which negatively affects the surgeon’s performance. The implementation of control algorithms specifically designed for the automation of different tasks (e.g. path following, shape conformance, visual servoing) appears therefore critical to reduce the dimensionality of the control and seamlessly interface the system with the operator. Within this framework, the integration of haptic feedback through dynamic active constraints applied on the whole length of the robot body becomes fundamental to ensure safe intra-operative navigation and intervention.

Although in most of the systems listed in Table 2.4 the enhanced dexterity is achieved by introducing mechanically actuated articulated segments in their struc-
ture, a different method for integrating flexibility in MIS instrumentation is based on enhancing the design of standard flexible endoscopes. This approach stems from the recent introduction of transluminal and single site surgical techniques, as described in the next section. It is important to note that the following discussion applies also to endoluminal procedures, since they share the same requirements of transluminal interventions in terms of flexibility and control ergonomics during navigation and could greatly benefit from the integration of additional interventional capabilities in the surgical instrumentation.

2.4 Flexible devices for transluminal and single site surgery

As discussed above, considerable effort has recently focused on pushing the frontiers of MIS towards less invasive procedures, especially for application to GI surgery. Among these, transluminal surgery is introduced as an expansion of the endoluminal operations performed by gastroenterologists using flexible endoscopes. This approach has been called Natural Orifice Transluminal Endoscopic Surgery, which enables the surgeon to perforate the luminal barrier and enter the peritoneal cavity. Endoscopes may be inserted through a single entry point or a combination of transgastric, transrectal, transvaginal, and transcystic accesses. The choice depends on the specific procedure to be performed and potential pitfalls of each access route [123].

There are three main justifications for the development of NOTES: better cosmesis, access easiness and the possibility of further reducing the pain and discomfort associated with traditional surgery with the development of dedicated technologies [124]. From the point of view of the patient, the most important of these advantages is an improved cosmetic result. From the point of view of the practitioner, ease of access gives effective advantages. Regions that are difficult or unsafe to reach passing conventional laparoscopes through the abdominal wall can be reached from the inside with flexible endoscopy. For instance, a safe transgastric approach might offer substantial advantages in accessing the lower esophageal sphincter and the upper stomach during bariatric surgical procedures. In addition to these principal motivations for NOTES, there are several other potential benefits [125]:

- Less physiological and immunological trauma to the body than laparoscopic or traditional surgery;
- The lack of skin and abdominal incisions eliminates the possibility of wound complications (it is currently under discussion if NOTES will produce less intra-abdominal adhesions, and it still has to be proven in large scale investigations);
• Minimal post-operative pain, quicker rehabilitation and shorter hospital stay;

• Since the operations are performed completely endoscopically, it is apparent that a general anaesthesia may not be needed, and that surgical procedures will shift from the OR to the endoscopy unit resulting in further cost savings;

• Certain types of patient who are not suitable for open or laparoscopic surgery (e.g. obese patients) may be better suitable for NOTES and take the most advantage from it.

Although NOTES represents an exciting new technology, current technical hurdles hinder its use in routine clinical practice. This led to the introduction of hybrid laparoscopic procedures performed using rigid instruments and single access route in an attempt to reduce the scars generated by traditional laparoscopy. These interventions can be classified as Laparo-Endoscopic Single Site surgery and are mostly carried out through a single port usually located on the umbilicus. Many authors are showing an increasing interest in LESS as a less invasive approach than conventional key-hole surgery with fewer limitations than NOTES. The basic concept of LESS is to use a single port especially designed for the insertion of up to four laparoscopic instruments or even the surgeon’s hand. The main drawbacks of using a single port are the clutter of hands and instruments externally and the inadequate ability of triangulation. To overcome these issues, flexible instruments with different lengths have been developed. Thus far, dexterity has however been introduced only at the handle or at the tip of the instruments, while the shaft remains rigid [126].

As an example, the VeSPA surgical instruments (Intuitive Surgical Inc, Sunnyvale, CA) are designed for use with the da Vinci robotic system to perform LESS interventions. As shown in Figure 2.23(a), two arms of the da Vinci slave manipulator are equipped with curved cannulae through which flexible instruments can be passed. The cannulae are inserted through a specially designed multi-channel single-port together with a 8.5mm scope in a configuration which allows for triangulation inside the patient body, as shown in Figures 2.23(b)-(c). As reported in [127], single-port kidney surgery using the VeSPA instruments was successfully performed on a porcine model. The particular configuration of the system could provide a wide range of motion and tool stability whilst offering enhanced ergonomics and minimising instrument clashing issues. Albeit these advantages, the lack of articulation at the tip of the instruments is still a major problem that limits the application to more complex tasks such as suturing. The introduction of controlled flexibility at the end-effector is therefore a critical requirement for the widespread application of LESS which many companies and research groups are currently trying to fulfil with the help of robotic technologies, as discussed in the next sections.
Figure 2.23: VeSPA novel robotic instrumentation for LESS using the da Vinci surgical system (Intuitive Surgical, Sunnyvale, CA, USA) [127]. (a) Configuration of the da Vinci robotic manipulators equipped with the VeSPA instruments; (b) Multichannel single port for the insertion of a 8.5mm robotic scope and two curved cannulae through which flexible instruments can be passed; (c) da Vinci system set-up during LESS.

2.4.1 Technical challenges and unmet requirements

Although NOTES promises to be a less invasive surgical approach, available endoscopic instrumentation is generally inadequate for transluminal operations. Flexible endoscopes are too floppy and with small instrument and suction channels, the surgical tools cannot guarantee the required tissue approximation and manipulation abilities. The design of specialised instrumentation is therefore critical for the application of NOTES and is intimately related to the clinical issues introduced by the transluminal approach. In addition to the basic functionalities of standard endoscopic tools such as adequate imaging, insufflation and suction/irrigation capabilities, a designated NOTES instrument needs to fulfil the key clinical requirements of this approach as listed in Table 2.6 [128].

The major technical challenges for effective NOTES instrumentation are related with the integration of flexibility to allow navigation to the operative site through different access routes whilst maintaining adequate stability for safe tissue manipulation, as well as triangulation. The basic idea is to imitate the practice of complex two-handed laparoscopic manipulation, which in turn intends to reproduce the way of operating in open surgery. This is accomplished by elevating the optics above the plane of the operating tools resembling the view given by a laparoscopic device. Other benefits include the capacity to get proper traction and counter-traction and
to keep the visualisation of the operative field without replacing the visual channels when the tools are moved.

Table 2.6: Key clinical requirements and corresponding features of specialised NOTES instrumentation.

<table>
<thead>
<tr>
<th>Clinical requisite</th>
<th>Design feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Access to peritoneal cavity.</td>
<td>Size. The diameter of the shaft should be between 18 and 22mm and include multiple channels of 3 to 6mm size for the camera and at least two instruments.</td>
</tr>
<tr>
<td>Gastric or intestinal closure.</td>
<td>Stability. The device should be completely flexible during insertion and positioning and subsequently become rigid apart from the tip articulation.</td>
</tr>
<tr>
<td>Spatial orientation.</td>
<td>Manoeuvrability. The tip of the device should bend in the vertical, horizontal and lateral plane and 180° retroflexion capability of the shaft is required.</td>
</tr>
<tr>
<td>Development of multifunctional platforms.</td>
<td>Triangulation. The optical view should be elevated from the plane of tissue manipulation, which should in turn be enhanced by effective traction and counter-traction capabilities.</td>
</tr>
</tbody>
</table>

Obviously, the integration of all the features listed in Table 2.6 in one instrument would be optimal but it is not practically possible for all procedures. Simple procedures such as abdominal exploration and organ biopsy do not require high stability and triangulation. In these cases, the diameter of the tool can be reduced, resulting in smaller access holes and more effective viscerotomy closure. On the other hand, the achievement of good stability and adequate tissue manipulation is fundamental for the execution of complex procedures involving tissue excision, organ retraction and/or organ removal. The incorporation of a camera and two instruments that could be controlled independently by the surgeon for triangulation represents a major technical challenge.

Technically, NOTES has raised many challenges, particularly in the development of articulated robotic instruments for MIS. This can potentially have an effect on the future design of MIS instruments and therefore bring improved platforms for general MIS procedures. However, despite the potential advantages of NOTES and
early enthusiasm shown by the MIS community, the technique is not mature and safe enough for clinical adoption in the immediate future. As previously mentioned, LESS is a novel approach halfway between standard laparoscopic surgery and NOTES which could be more easily accepted as a standard practice in a short period since it allows to gain access to the abdominal cavity directly through a pre-existent scar without the need for additional incisions on the patient abdomen [126]. The main advantage of LESS over NOTES is that it does not require viscerotomy closure, which is instead critical for the safe completion of a transluminal procedure. In addition, flexibility is mainly necessary at the tip of the instruments to achieve adequate triangulation while the rest of the device can be rigid, in contrast with the endoluminal access route which requires the whole instrument to be bendable.

2.4.2 NOTES and LESS instrumentation

Novel surgical tools developed for NOTES and LESS include specialised endoscopes, flexible platforms and master-slave flexible systems, as well as bimanual insertable robots with embedded dexterity and intracorporeal mini-robots. Some of the design considerations are listed in Table 2.7. Flexible platforms mainly differ from specialised endoscopes for the use of a more ergonomic user interface, while in master-slave systems the master manipulators are physically separated and remotely located from the slave arms. The design of bimanual insertable robots is different from the one of the other systems as it is not based on a flexible endoscope. Finally, intracorporeal mini-robots are completely deployed inside the patient body and provide a limited set of functions to assist the surgeon during the procedure.

Table 2.7: Proposed designs for specialised NOTES and LESS instrumentation.

<table>
<thead>
<tr>
<th>Design</th>
<th>System/ Author</th>
<th>Company/ Institution</th>
<th>Articulation</th>
<th>Channels</th>
<th>Ref.</th>
</tr>
</thead>
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<td>Specialised endoscopes</td>
<td>Transport</td>
<td>USGI Med.</td>
<td>Tendon</td>
<td>3</td>
<td>[128]</td>
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<td>2</td>
<td>[128]</td>
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<td>R-Scope</td>
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<td>Tendon</td>
<td>2</td>
<td>[129]</td>
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<tr>
<td>NeoGuide</td>
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<td>2</td>
<td>[130]</td>
<td></td>
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<td>Design</td>
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<td>Company/ Institution</td>
<td>Articulation</td>
<td>Channels</td>
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<td><strong>Flexible platforms</strong></td>
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<tr>
<td>EOS</td>
<td>USGI Med.</td>
<td>Tendon</td>
<td>3</td>
<td></td>
<td>[131]</td>
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<tr>
<td>EndoSamurai</td>
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<td>Tendon</td>
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<td>2</td>
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<tr>
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<td>Karl Storz/ IRCAD</td>
<td>Tendon</td>
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<td></td>
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<tr>
<td>Bardou et al</td>
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<td>Tendon</td>
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<td>Kobayashi et al</td>
<td>Waseba Univ.</td>
<td>Spring backbone</td>
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<td><strong>Bimanual insertable robots</strong></td>
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<td>ISSA</td>
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81
Table 2.7: (continued)

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<td>-</td>
<td>-</td>
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<td>MAGS mini-robots</td>
<td>Texas Univ.</td>
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<td>-</td>
<td>-</td>
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<td>Modular mini-robots</td>
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<td>-</td>
<td>-</td>
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</tbody>
</table>

2.4.2.1 Specialised endoscopes

Thus far, a number of specialised NOTES endoscopes are already emerging. The *Transport* by USGI Medical (San Clemente, CA, USA) was created specifically to fulfil some of the design requirements listed in Table 2.6 and utilises the stiffening endoscopic over-tube technology named Shape-lock® [128]. The system also incorporates four large working ports (7, 6, 4 and 4mm), an insufflation channel and four-direction flexibility at the tip, as shown in Figure 2.24(a). A standard flexible endoscope can be passed through the 6mm port, which is also large enough to enable the rotation of the endoscope. Surgical instruments can be inserted through the 7mm and two 4mm ports. The device can be positioned like a standard endoscope, then the Shape-lock® function is activated, locking the device in either endoluminal or intra-abdominal, antegrade or retroflexed position. The scope’s tip can then be manoeuvred by the endoscopist by using the standard controls. The larger size of the tool and the presence of three ports give some ability of triangulation with the working channels parallel to the image. This, in addition to the possibility to advance the internal endoscope enough to be flexed a few degrees, permits more complicated tissue manipulation (*e.g.* grasping, cutting and suturing).

The insertion of *Transport* into the stomach or rectum was performed without
problems in the laboratory setting, as well as the advancement into the abdominal cavity. Its considerable size and large graspers allowed easy manipulation of the bowel or even liver retraction during NOTES cholecystectomy in animal studies. In particular, endoscopic suturing devices can be passed through the 7mm port, enabling enterotomy closure after the scope is retracted back into the stomach or rectum. Even if this advanced endoscopic system has been designed for solving several NOTES issues, some drawbacks are still evident. Triangulation is still poor, although better than a traditional endoscope. Furthermore, the device is quite complex and a significant learning curve is associated with its use. Finally, smooth and precise motion of the tip, and therefore of the surgical tools, is difficult. This caused perforation during dissection in 80% of cholecystectomies done in porcine models.

A prototype device named Cobra has also been developed by USGI in an attempt to solve the problem of triangulation by adding three independent arms to the Shape-lock®-based shaft of the Transport, as shown in Table 2.7 [128]. The Cobra’s visual tool is a conventional 6mm flexible endoscope passed through the central channel of the device. This diminishes the complexity of the Cobra itself making it more cost effective. Currently the controls are tendon-driven and inaccurate, making it difficult to perform fine movements. Another limit is that the device must be removed to exchange instruments and then re-introduced because the tools are fixed. Due to these drawbacks, the execution of complicated tasks such as knotting and suture-tying has been difficult.

In parallel, Olympus (Tokyo, Japan) has adapted a standard dual-channel scope in order to make it functional for advanced endoluminal operation [129]. The device permits secondary curvature so that the primary flexure can be secured leaving independent movement to the tip, shown in Figure 2.24(b). This allows the safe positioning of the tool at the operative area and then gives the surgeon a stable platform for precise retraction, cutting and manipulation of the tissue. The R-scope has an outside diameter of 14.3mm and a length of 103mm, while each instrument channel has a size of 2.8mm and elevators allowing independent motion of tools in perpendicular planes. This permits dynamic retraction and cutting independent of the optical axis. Finally, a larger, separate channel for suction and irrigation is also incorporated. The main drawback of the device is the complexity of the controls involved, also shown in Figure 2.24(b). Nonetheless, laboratory experiments proved that the tool is very useful when performing antegrade intra-abdominal procedures such as biopsies and endoluminal procedures (full thickness colon and gastric excision). One of the problems of the device is disorientation when used in the retroflexed position and its size and flexibility are inadequate to get a proper retraction of tissues for tasks like anastomosis.

The NeoGuide Endoscopy System (NES) (NeoGuide System Inc) consists of a navigation console and a flexible endoscope with an embedded position sensor at the
Figure 2.24: Specialised endoscopes for NOTES and LESS. (a) The *Transport* flexible endoscope with Shape-lock® technology by USGI Medical [128]; (b) Olympus *R-scope* controls and working ports [129]; (c) The *NeoGuide* navigation system (NeoGuide System Inc) for controlling a flexible endoscope made up of steerable articulating segments [130].
tip to measure the endoscopist steering commands and an external position sensor at the base which measures its insertion depth [130]. This allows to automatically control the shape of the several identical electromechanically controlled segments constituting the flexible endoscope in a “front-drive back-following” manner according to the pre-recorded tip movements at each insertion depth, as shown in Figure 2.24(c). Although the system was originally developed to solve the loop forming problem during colonoscopic procedures, it has been recently tested to perform cadaveric NOTES interventions with promising results [146].

2.4.2.2 Flexible platforms

Recently, two of the aforementioned devices have been enhanced to develop flexible multitasking platforms [131]. The design of the Endosurgical Operating System (EOS) by USGI Medical resembles the Transport, but with the integration of an ergonomic user interface to improve bimanual coordination, as shown in Figure 2.25(a). The device can also be mounted on a stand, allowing the simultaneous use of three instruments. Similarly, the design of the EndoSamurai by Olympus is based on the R-scope concept: a standard stereo endoscope’s tip is fitted with two bendable hollow arms, giving two extra DoFs to operate the passive instruments inserted through them. Bimanual coordination is further enhanced by the use of a laparoscopic interface and a third channel is also available, as shown in Figure 2.25(b).

The Direct Drive Endoscopic System (DDES) by Boston Scientific (Natick, MA, USA) has also been evaluated on ex vivo and in vivo animal models [132]. It features a rail platform that can be attached directly to the operating table in an optimal ergonomic configuration and houses two handles to operate specifically designed long flexible instruments with different end-effectors. The instruments are inserted together with a standard endoscope through a flexible guide sheath that can be locked in any articulated configuration, as shown in Table 2.7. This introduces two extra DoFs for proximal positioning of the instruments, giving a total of 7 DoFs. Although the DDES meets many of the criteria listed in Table 2.6, major limitations such as inadequate triangulation and torque for robust manipulation still need to be addressed.

The ANUBISCOPE has been developed by Karl Storz Endoskope in collaboration with IRCAD-Strasbourg within the ANUBIS project [133]. It consists of a multifunctional endoscope with a diameter of 16mm and a tulip-shaped distal tip. When the operative site is reached, the flaps open to reveal two triangulating movable arms with working channels for flexible instrument insertion, as shown in Figure 2.25(c). The system has been implemented clinically to perform a NOTES transvaginal cholecystectomy [147] and a hybrid transgastric cholecystectomy [148].
Figure 2.25: Flexible platforms for NOTES and LESS. (a) The *Endosurgical Operating System* by USGI medical consisting of the *Transport* with modified interface for ergonomic manipulation of additional instruments [131]; (b) *EndoSamurai* advanced endoscope with laparoscopy-like interface by Olympus (©2009 IEEE) [131]; (c) The *ANUBISCOPE* multipurpose platform for endoluminal and transluminal procedures [133].
2.4.2.3 Master-slave systems

The *ViaCath* endoluminal system is the only master-slave system developed by a company, *i.e.* Hansen Medical (Norwood, MA, USA, ex EndoVia Medical), as an expansion of the *Laprotek* tele-operated surgical robot for laparoscopic surgery [149]. The first generation design features a master console with two haptic input devices and external slave drive mechanisms that controls two long-shafted flexible tools running inside a standard endoscope, as shown in Figure 2.26(a). Bimanual tissue manipulation under direct visualisation is permitted by inserting the two instruments further in front of the camera. Each robotic tool is mechanically coupled with a position arm and comprises a flexible shaft and articulated tip with end-effector, giving a total of 7 DoFs [134]. Although the system proved to be functional after validation using phantoms, *ex vivo* tissue samples and *in vivo* animal trials, several limitations were revealed. The two main problems were the insertion and positioning of the instruments at the desired operative site and the insufficient lateral force the tools could exert during tissue manipulation. A second generation system has been designed in order to overcome these problems. A portable cart carrying all the slave components of the system is added for improved positioning of the instruments relative to the surgical table, while a steerable over-tube is specifically designed to allow for proper instrument articulation inside the patient. Finally, the flexible, tendon-actuated sections of the endoluminal tools are replaced by an actuated joint mechanism, replicating the kinematics of the human arm [134].

In addition to the above commercial products, many platforms are also being explored in different research centres. The *Master And Slave Transluminal Endoscopic Robot* (MASTER) by Phee *et al* has been evaluated in both *ex vivo* and *in vivo* animal trials [135]. The system consists of a slave manipulator that can be attached to the tip of a standard dual-channel endoscope and features a translating DoF to slide within its internal channels so that no external overtube is required, as shown in Figure 2.26(b). The two-armed robot has a total of 9 DoFs (4 for each arm plus one gripper), seven of which are remotely controlled using two handles and a foot pedal at the master console, while the translational ones are directly driven by the endoscopist. The mechanical joints are tendon-actuated. Therefore, an actuator housing is also introduced between the slave and master components. Results show a relatively short learning curve and its potential use in NOTES, albeit the remaining issues of sterilisation and gastrotomy closure have yet to be resolved.

Another robotised tele-manipulated system for transluminal surgery has been presented by Bardou *et al* in [136]. The slave part of the system is directly attached to the tip of a standard endoscope using a special cap and it consists of two snake-like hollow arms providing 2 DoFs each to operate the instruments introduced through them. The master console features two Omega7 by ForceDimension (Lausanne, Switzerland) as input devices and two monitors displaying the visual feedback from
Figure 2.26: Master-slave systems for NOTES and LESS. (a) the ViaCath master-slave endoluminal system by Hansen Medical (©2007 IEEE) [134]; (b) Master and slave manipulators of the Master and Slave Transluminal Endoscopic Robot by Phee et al [135]; (c) Master and slave configuration of the tele-manipulated system for transluminal surgery by Bardou et al [136].
Figure 2.26: (Continued.) (d) First application of the *Highly Versatile Single Port System* performing a cholecystectomy using the transanal approach on a NOTES phantom [137]; (e) Master and slave components of the master-slave system for LESS by Kobayashi *et al* [138].
the endoscope. The bending of the endoscope as well as the one of the snake-like arms are motorised and controlled by the master interfaces. The rotation and translation of the passive instruments are decoupled, and thus can be separately controlled. The main drawback of the system is the cumbersome components to be hold in place to control the motorised endoscope and slave arms.

The Highly Versatile Single Port System (HVSPS) by Can et al originally designed for laparoscopic surgery has been recently tested on a NOTES phantom [137]. The two flexible and partially automated manipulators are tele-operated using joysticks and feature 5 DoFs. Triangulation is ensured by the use of a third arm to place a standard endoscope in an S-shape perpendicularly to the plane of the instruments, as shown in Figure 2.26(d). Recently, the first gallbladder was successfully resected in an animal experiment using the HVSPS introduced into the abdominal cavity through a single incision [150]. However, the current configuration needs four operators: one to control the two manipulators, a second one to manually drive the passive instruments, a third one to position the endoscope and a final one for the not motorised DoFs of the flexible arms. Current control is therefore complex and the introduction of a user interface with ergonomic input devices is crucial.

Finally, the most recent master-slave robotic system for LESS has been introduced by Kobayashi et al [138]. It features a slave part comprising a positioning manipulator which pivots a rigid insertable tool around the entry point at the skin incision. The distal end of the insertable tool is flexible and is connected to the rigid part through a 2-DoF snake-like continuum sheath manipulator. A flexible endoscope and two custom-made endoscopic tools are protruding from the distal tip in a configuration allowing triangulation. The control of sheath and tool manipulators is decoupled by switching a food pedal, which in turn determines if the input motion must be read through a joystick or two PHANTOM Omni haptic devices, respectively. The master and slave parts of the system are shown in Figure 2.26(e).

2.4.2.4 Bimanual insertable robots

As previously mentioned, a novel direction in the development of systems for LESS is to use a rigid shaft to deliver both vision feedback and dexterous manipulation to the operative site through a single incision point, usually located at the umbilicus. As an example, Simaan et al are developing an Insertable Robotic Effectors Platform (IREP) with integrated 3-D vision and surgical tools, which can be folded into a 15mm diameter configuration for deployment through a standard trocar port. The device uses 21 actuators to control gross translation movement along the IREP axis, pan, tilt and zoom of the camera (3 DoFs), two 2-DoF five-bar mechanisms to fold, unfold and regulate the distance between the flexible arms, and each dexterous arm featuring 6 DoFs (a 4-DoF continuum snake-like robot, a 1-DoF wrist and a gripper). A prototype of the IREP is shown in Table 2.7 [139]. Similarly, Dario et
al are developing a *Single-Port lapaRoscopy bImaNual roboT* (SPRINT) consisting of two 6-DoF miniature arms that can be passed in turn through a 30mm trocar port at the umbilicus and then unfolded into a configuration similar to the one of the human arms, as shown in Figure 2.27(a). The DoFs are provided by brushless DC motors, four of which are embedded in the distal segments of the arm while the proximal two are actuated externally. A prototype SPRINT arm which has been tested in a laboratory setting with promising results [140] is shown in Figure 2.27(b).

![Prototype SPRINT arm](image)

**Figure 2.27:** The *Single-Port lapaRoscopy bImaNual roboT* by Dario et al [140]. (a) Phases of insertion of the arms; (b) Prototype 6-DoF miniature arm.

### 2.4.2.5 Intracorporeal mini-robots

A different approach in the development of NOTES and LESS instrumentation is to use robotic systems completely inserted in the peritoneal cavity. One example is the insertable surgical imaging device with pan and tilt capability by Fowler et al [141]. The total length of the device is 110mm with a diameter of 11mm, thus it can be inserted into the abdomen through a standard 12mm trocar, as shown in Figure 2.28(a). The device integrates a LED (Light-Emitting Diode) lighting system as part of the camera assembly. A second prototype of the device is also integrated with zoom capabilities. The main advantages of this approach are the improved ergonomics of the control with respect to a standard laparoscope, since a joystick is used to operate the pan and tilt motion of the camera without the restriction of the fulcrum point at the insertion. However, once the camera is inserted into the abdomen the surgeon needs to suture it to the abdominal wall for stable anchoring, thus its position is fixed during the procedure.

In order to provide insertable devices with mobile ability several authors have been investigating the use of a Magnetic Anchoring and Guidance System (MAGS) [151]. Using this approach, Lehman et al have developed both fixed-base camera
robots for providing secondary views of the surgical site, as shown in Figure 2.28(b), and mobile robots for visualisation and task support in laparoscopic procedures, as shown in Figure 2.29(a) [142]. From the same research group is also a dexterous miniature robot with 6 DoFs which has been used to perform a NOTES cholecystectomy [143]. The robot features a central body carrying an on-board camera and magnets for magnetic external navigation, and two foldable arms with cautery and forceps end-effectors to allow for flexible transgastric access and subsequent tissue manipulation, as shown in Figure 2.29(b). A second generation prototype with an additional rotational DoF for each arm has recently been presented and is shown in Table 2.7 [152]. This robot has been tested together with the previously mentioned laparoscopic positioning system CoBRASurge to demonstrate the feasibility of a cooperative LESS procedure in a porcine model [30]. More complex mobile miniature devices have also been developed by Cadeddu et al [144]. Among these are a multiple DoFs camera, a paddle retractor and a robotic manipulator for cautery dissection that can be remotely controlled via a joystick, as shown in Figures 2.30(a)-(c), respectively.

Finally, Dario et al are refining the MAGS approach towards the development of reconfigurable modular robots for endoluminal surgery [145]. In this scenario the patient has to ingest several miniaturised robotic modules that will assemble in the gastric cavity and change configuration according to the surgical task and target location, as shown in Figure 2.31(a). Each 2-DoF prototype module embeds a wireless control system and permanent magnets for self-aligning and docking. The miniaturised reconfigurable robot is controlled in a master-slave fashion using a reconfigurable master device having the same structure of the slave manipulator, as shown in Figure 2.31(b) [153]. Hitherto, a prototype of the complete system has
Figure 2.29: *In vivo* mini-robots for LESS developed by Lehman *et al.* (a) Miniature mobile robot which can be equipped with a camera or biopsy forceps for endoluminal surgery [142]; (b) Miniature bimanual dexterous robot for LESS [143].
Figure 2.30: Intracorporeal MAGS mini-robots for LESS developed by Cadeddu et al [144].
(a) Schematic and intra-abdominally deployed view of intracorporeal MAGS retractor elevating a porcine spleen; (b) Schematic and intra-abdominally deployed view of intracorporeal MAGS multi-DoF camera; (c) Schematic and ex-vivo view of MAGS robotic cautery dissector that can be remotely controlled via a joystick.
Figure 2.31: Modular reconfigurable minirobots for endoluminal surgery by Dario et al. (a) Phases of the surgical procedure using the reconfigurable modules (©2009 IEEE) [145]; (b) Example master-slave topologies [153].
been evaluated using different topologies in order to determine the best configuration in terms of manipulator workspace and master ergonomics. However, *in vivo* application of the device is not envisioned in the immediate future.

### 2.4.3 Future perspectives of NOTES and LESS: towards robotic-assisted flexible access surgery

As clearly explained above, the main requirement for the safe performance of NOTES and LESS procedures is the ability to gain access to different target locations within the patient body from one or more entry points not necessarily optimally positioned for the specific operation. Therefore, the general term Flexible Access Surgery (FAS), coined by Professor Yang at the Hamlyn Centre, will be used to refer to these novel surgical techniques. However, the above discussion highlights how for these 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.

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

**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.

**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.

**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 integrate the functional imaging techniques at the design phase. This combination of access and diagnostic ability offers the possibility of greatly increasing the intra-operative information available to the surgeon.

**Small footprint.** A problem with many of the articulated and flexible robotic designs described above is their large footprint in the operating theatre. An articulated device which aims to facilitate FAS should aim to be small, easy to setup, lightweight and portable.

**Intuitive control.** Any articulated system must have an intuitive control which allows the user to easily control the multiple DoFs. Similarly, many of the
systems described above did not address the issue of how their multiple DoFs are controlled, thus requiring more than one operator.

At the Hamlyn Centre, we are investigating different ways of addressing the above requirements within the development of an articulated device for robotic-assisted FAS [1]. The terms ‘articulated’ and ‘flexible’ are used interchangeably to address this particular platform as flexibility is implemented through mechatronically actuated articulation between rigid links. A detailed description of the system architecture is reported below as the work presented in this thesis is based on its specific design and functionality.

2.5 Articulated robot design for flexible access surgery

As discussed above, in order to ensure seamless integration of a robotic flexible access platform into the surgical workflow, it is necessary to develop a device with a small footprint and which is compatible with existing diagnostic imaging and sensing techniques, as well as simple interventional instrumentation. Controlled articulation is also a fundamental requisite for providing the surgeon with enhanced dexterity and the ability to perform complex surgical tasks involving restricted and cluttered operative workspaces and large tissue deformation. The flexible access platform currently under development at the Hamlyn Centre incorporates all these features, as described below.

2.5.1 System architecture

The key components of the flexible access platform are shown in Figure 2.32. The articulated section of the robot is mounted at the distal end of a rigid shaft and actuated by seven embedded micromotors (Namiki Precision Jewel Co. Ltd.). All the necessary wiring is integrated within a \( \varnothing \) 1.8mm internal channel and connected to an external motor control box through a connection unit at the proximal end of the shaft. The control box contains a Compact Reconfigurable Input/Output (CompactRIO or cRio) Real-Time control unit (National Instruments Corp.) and the necessary drive electronics to actuate the micromotors. Finally, a Graphical User Interface (GUI) displays the system state to the user, who sends input commands through a custom designed hand-held controller linking to the motor control box.

2.5.1.1 Articulated section

The 7-DoF mechatronically actuated flexible section of the platform is shown in Figure 2.33 and features three proximal 1-DoF revolute joints providing yaw rotation and two distal 2-DoF universal joints providing both yaw and pitch rotations between adjacent rigid links. The range of actuation of each DoF is \( \pm 45^\circ \). Since the torque generated by the micromotors is limited, the universal joints are rotated about the
link axis by 45° with respect to the axis of the proximal revolute joints. This ensures that the torque required to lift the distal tip from a horizontal position (i.e. when the axis of rotation of each yaw joint is aligned with the gravity vector so as to eliminate its effect during actuation) is minimised. This configuration effectively maximises the number of DoFs that the system can have given the 5.7mNm torque available from the embedded micromotor.

Figure 2.33 also shows that the length of each module is different as it depends on the number of embedded micromotors and connection points. In this design, the most distal module is 32.5mm long and the shortest as it only carries one motor and it is connected only in one point to the previous joint, while the proximal 1-DoF modules are 34mm in length as they carry one motor but two connection points. Finally, the 2-DoF module is 36mm long as it features two motors actuating two rotatable links orientated perpendicularly at each extremity. Since each of these links is 8mm long, a total length of 186.5mm is obtained for the entire articulated section. The outer diameter of each joint is 12.5mm, allowing the integration of two additional Ø 3mm internal channels for the passage of camera and instrumentation while ensuring compatibility with standard 15mm diameter trocar ports suitable for a range of flexible access interventions (single-port, transluminal and endoluminal procedures).

The enhanced dexterity of the device allows large area exploration (±90° vertically and ±225° horizontally) from a single incision on the patient skin without the limitations of laparoscopic style external manipulation. Since each DoF is independently controllable, the serial structure can be fully exploited by decoupling the proximal modules from the distal universal joints. In particular, the articulation
Figure 2.33: Articulated section of the flexible access platform featuring 7 DoFs arranged as three proximal 1-DoF yaw joints and two distal 2-DoF universal joints (pitch and yaw), an outer diameter of 12.5mm, a 1.8mm internal channel for wiring integration and two 3mm internal channels for instrumentation.

at the proximal joints allows safe manipulation of the distal tip by avoiding obstacles, such as anatomical structures or other instrumentation. When the target site is reached, the surgeon can then benefit from the flexibility of the distal joints to visually explore the area or to carry out minor interventions using the instrument(s) inserted through the additional internal channel.

2.5.1.2 Hand-held controller and graphical user interface

User input commands are sent to the articulated section of the platform through a hand-held controller. The handle has a custom ergonomic design and is decoupled from the robot shaft. The main advantage of this physical separation is that once the robot is positioned according to the needs of the specific surgical procedure, the operator is free to move in the operative theatre and manipulate additional tools while holding the robot controller in a comfortable position, as shown in Figure 2.34. Such adaptability is a useful feature for the seamless integration of the flexible access platform in the existing surgical workflow.

As shown in Figure 2.34, the handle features a thumb-stick with an integrated push switch. The motion along the two axes of the thumb-stick is sensed using two potentiometers, while depressing the push switch allows toggling between the different joints during operation. The potentiometers are arranged orthogonally so that their variation in resistance is directly mapped to the motion about the
corresponding axis of the actuated joint. Relative positioning is achieved by varying the angular displacement of the joint with a velocity proportional to the change in resistance of the potentiometer. This direct ‘joint-by-joint’ control scheme was implemented to make the control of the multi-DoF platform more intuitive for the user. Naturally, due to the input-output asymmetry between the 2-DoF motion of the thumb-stick and the 7-DoF robot, in a direct ‘joint-by-joint’ control mode, the operator needs to switch between joints to actuate one at a time. Toggling is implemented in a sequential manner, starting from the most distal 2-DoF joint and moving proximally along the articulated section of the robot. Depressing the push switch when the most proximal joint is actuated switches the control back to the most distal joint where the toggling sequence starts again.

![Figure 2.34: Photos of the hand-held controller taken during an in vivo pre-clinical trial. The thumb-stick is embedded in the ergonomic design of the handle, which is decoupled from the articulated device to allow remote control. Since only one hand is needed to hold the controller, the articulated device can be used in combination with additional laparoscopic tools.](image)

In order for the user to be aware of which specific joint is actuated at one time, a GUI displaying the state of the system is provided on a portable computer. The GUI is interactive and also allows the user to stop the system actuation in case of emergency.

### 2.5.1.3 Motor control box and embedded controller

The motor control box houses the drive electronics for the 3-phase brushless micromotors, which have to be located remotely due to the size constraints at the joint. However, the box has a reasonably small size and can be located away from the operating table as the system is effectively ‘drive-by-wire’ and the connection to the flexible access platform is via electrical cables. Therefore, the footprint of the articulated robot at the operating table is only slightly increased by the presence of electrical cables connecting the motors to the motor control box through the
The main component of the control box is a CompactRIO (National Instruments Corp.) programmable controller which allows real-time control of the flexible access platform through its associated inputs/outputs. It combines an embedded real-time controller (cRIO-9014) with a Field Programmable Gate Array (FPGA) backplane (cRIO-9113) using a high-speed data bus connection. C-Series modules (National Instruments Corp.) are plugged into the FPGA backplane for signal acquisition and generation so that low-level input/output operations are separated from the real-time processing in the real-time controller. Dedicated control software for the cRIO components is written in the LabVIEW™ development environment using three different programs or ‘Virtual Instruments’ (VIs), specifically one for the real-time controller, one for the FPGA and one for the GUI on the host computer. It is important to note that once the VIs are downloaded to the cRIO it effectively becomes an embedded controller with the ability to control the flexible access platform without requiring a separate laptop, although the GUI would be lost.

In particular, the real-time program implemented in the real-time controller features two deterministic control loops with different priorities so that higher priority is assigned to the essential calculations required for motor control while the less critical control loop addresses lower-priority tasks, such as communication with the GUI or data logging. The VI for the FPGA is also developed in the LabVIEW™ environment based on the desired task and generates a configuration file when compiled which reconfigures the FPGA digital logic accordingly. For the flexible access platform, parallel loops running at 25kHz are used to control the acquisition of all analogue and digital input signals as well as the generation of each output signal. Obviously the acquired signals from the handle are firstly passed to the real-time controller via the high-speed bus for processing and the desired output signals are subsequently passed back to the FPGA to actuate the corresponding 4mm motors via a linear amplifier stage and the Namiki SSD04 3-phase brushless drive electronics. The overall control architecture and corresponding components are shown in Figure 2.35.

2.5.1.4 Additional components

The functionality of the flexible access platform is completed by the introduction of an embedded endoscopic camera with on-board illumination system to avoid the need for an additional laparoscope, an internal sheath to guide the passage of instruments through the device and a protective external sheath. Specifically, one of the \( \varnothing \) 3mm internal channels is used to deploy an IntroSpicio™ 115 Micro CCD video camera (Medigus Ltd, Israel) at the distal tip for visualisation. Two Light-Emitting Diodes (LEDs) (LUXEON® Rebel LXML-PWC1-0120) are mounted on a custom aluminium Printed Circuit Board (PCB) at the distal tip to provide illu-
Figure 2.35: System control architecture. The signal from the thumb-stick in the handle is fed into the motor control box, processed in the embedded controller and output to control the robot accordingly, while the GUI displays the state of the system variables. Image modified from [1].

mination. The PCB has the main purpose of dissipating the heat generated by the LEDs through the aluminium housing of the distal joint unit. The material for the internal sheath is spiral reinforced tubing (OSCO Ltd, UK) and was chosen for its flexibility and strength, as it can follow the bending of the joints while constraining the passage of any instrument through its lumen. The configuration of these components at the distal tip can be seen in Figure 2.36.

Figure 2.36: Configuration of the distal tip of the articulated access device featuring two LEDs providing illumination, an internal sheath for the insertion of third party instrumentation and the Medigus camera for endoscopic visualisation.
Finally, as shown in Figure 2.32 a custom latex sheath is used to cover the articulated section of the device to protect it from contamination during *in vivo* deployment. Bellows are introduced in order to minimise the mechanical impedance of the sheath to the actuation of the joints.

### 2.5.2 System usability and control strategies

To assess the intuitiveness and ergonomics of controlling the flexible access platform using the hand-held controller, system usability trials have been carried out in an abdominal simulator [154] using an early 5-DoF prototype of the system. The articulated section of this device has an identical structure to the 7-DoF robot introduced above, except for the lack of two proximal yaw joints. Particularly, the aim of the study was to determine if the limitations of the direct ‘joint-by-joint’ control paradigm together with the misalignment between the thumb-stick and the distal universal joints axes would prevent novice users from successfully navigating the device. The experimental task was to visualise a number of targets placed at different locations within the abdominal cavity using only the visual feedback from the on-board camera. Since the targets were spread over a large area, all of the available DoFs in the articulated section had to be actuated.

The resulting average and fastest completion times measured for different operators showed that, although the ‘joint-by-joint’ control is suitable for basic navigation of the platform, the lack of position feedback can lead to disorientation due to the uncertainty about the current robot configuration. In fact, the longest completion times were recorded when the operator became disorientated and was unable to visualise the targets until re-orientation was achieved through visual cues. Similar results have been reported for a usability trial performed *in vivo* on a porcine model [155]. Disorientation actually represents a major challenge in FAS, and it is envisioned that as the number of DoFs to control increases, so does the probability to lose spatial orientation and be unable to complete the task. One possible solution offered by the use of controlled actuation is to implement kinematic control to eliminate the misalignment between the thumb-stick and universal joint axes and actuate more than one joint simultaneously to avoid toggling between them.

A different approach to controlling the flexible access platform which uses the eye-gaze of the surgeon has also been proposed [156]. The main advantage of this technique is that the hands of the operator are free to manipulate additional instruments together with the robot. The image feedback from the on-board camera at the tip of the articulated device is used in combination with a commercial eye-tracking unit to detect the fixation point of the eyes on the screen and move the robot joints accordingly. Two different actuation schemes for the joints were investigated. With the first technique, the surgeon switches between the joints using the gaze in a similar fashion to the ‘joint-by-joint’ control implemented by the hand-held controller. The
second method automatically selects the most suitable joint to perform the desired motion on the basis of the current sensed by the micromotors. Therefore, the operator only needs to steer the robot using the gaze without having to toggle between the different joints. Although the ability to manipulate additional instruments while positioning the camera at the tip of the robot using the eyes is beneficial, as it can potentially eliminate the need for surgical assistants, the integration of eye-tracking in the operative theatre is practically challenging. In fact, in a MIS environment the operator might need to move the gaze away from the monitor and visual fatigue can add further difficulties to the already demanding surgical task.

2.6 Discussion and conclusions

Despite the continuous advance of robotic technologies and the growing interest of the robotic research community in surgical applications, it is clear from the review presented in this chapter that challenges as components miniaturisation and seamless human-robot control still represent a major obstacle to the safe integration of robotic systems in MIS. Although the introduction of the master-slave paradigm has effectively enhanced the performance of laparoscopic procedures, the uptake of systems like the da Vinci has been greatly limited by their high cost and large footprint in the operative theatre. The physical and perceptual separation of the surgeon from the operative site also impairs their ability to intervene on tissue due to the lack of tactile and force feedback and affects the ease of communication with other members of the surgical team. In addition, the use of long and rigid laparoscopic tools hinders the execution of procedures involving complex anatomical pathways between the entry point and the target site, such as cardiac or deep area operations. This limitation becomes even more critical in the context of transluminal and single incision surgery, where instrument flexibility is the main requirement.

In particular, the detailed analysis of state-of-the-art articulated systems for MIS and FAS provided in this chapter reveals the lack of a mechatronically enhanced flexible instrument with a small diameter that can be controlled by a single user in an ergonomic manner. Such a device should be port-compatible and allow safe navigation to the operative target even in presence of complex anatomical obstacles. Mechatronic actuation should also ensure the necessary stability for tissue manipulation or deployment of intra-operative imaging probes whilst reducing the control complexity of standard flexible endoscopes currently available. A small footprint incorporating versatile internal channels to pass instruments is also a desirable design feature for the seamless integration of the device into the existing surgical workflow. A flexible access platform which aims to satisfy all of these requirements is currently being developed at the Hamlyn Centre, therefore details of the robot design have also been provided at the end of this chapter.

However, the above discussion about the usability of the flexible access platform
highlights the importance of implementing different control strategies aimed at handling the multiple DoFs of the system according to the surgical requirements and therefore improving its safety and ergonomics. This is part of the motivation for the work presented in this thesis, and we will investigate different algorithms for kinematic control of a snake-like articulated robot featuring a larger number of DoFs than the articulated robot presented above. Particularly, the problem of disorientation arising from the complex kinematic structure of such device, coupled with the limited field-of-view of the endoscopic camera used for visual feedback during navigation, can be alleviated by implementing path following control during autonomous locomotion, as described in Chapter 4. Once the target operative site is reached, the body of the robot has to conform its shape to the surrounding organs, which are deforming under the influence of physiological motion, while providing adequate stability at the tip for tissue manipulation. However, the number of simultaneously actuated DoFs should be minimized to simplify the control complexity of the system, as discussed in Chapter 5. To demonstrate the validity of the proposed algorithm, position feedback has been integrated in the 5-DoF prototype of the flexible access platform used for the usability trials and promising preliminary results of shape conformance control using a minimum number of DoFs are also presented in Chapter 5. Evaluation of the 7-DoF device for in vivo deployment in single-port surgical procedures will also be provided in Chapter 6. However, mechatronically the specific design of the joint module implemented in the flexible access platform suffers from the presence of backlash due to the novel hybrid micromotor-tendon actuation scheme used, as described in the next chapter. This can affect the accuracy of position control, therefore Chapter 3 focuses on the determination of the optimal design parameters to minimise the backlash while maintaining sufficient torque/force transmission for rotating the joint.
3 Design optimisation of a hybrid micromotor-tendon joint unit for a modular snake robot

3.1 Introduction

In the previous chapter, we have discussed the current actuation technologies used for robotically assisted Minimally Invasive Surgery (MIS). Tendons can provide high force transmission while occupying a small space within the joint, but are not suitable for modular designs and usually require a large external actuator pack. On the other hand, embedded micromotors can be digitally controlled and permit modularity in design, but the torque generated is relatively small. In this chapter, a novel hybrid micromotor-tendon joint mechanism offering advantages of both actuation strategies is presented. The joint module has been designed at the Hamlyn Centre offering a modular configuration for a lightweight, articulated flexible access device for MIS, as described in Chapter 2.

The key design optimisation issue to be addressed in this chapter is related to backlash due to the change in tendon path length at different joint orientations. This is an important issue affecting the accuracy of kinematic control, thus the determination of the optimal design parameters to minimise the backlash whilst ensuring adequate torque transmission to the joint is critical for the safe in vivo deployment of the device and its corresponding control algorithms proposed in this thesis. The main focus of this chapter includes the derivation of a general geometric model of the joint unit to characterise the backlash and define a meaningful objective function for the optimisation.

3.2 Hybrid micromotor-tendon actuation scheme

The details of the hybrid micromotor-tendon actuation scheme implemented in the flexible access platform are illustrated in Figure 3.1. The micromotor is coupled

with a pinion which rotates either clockwise or anti-clockwise. The pinion is meshed with a ring gear, so as to transmit the rotary motion in the opposite direction. The tendon is fixed to the ring gear at a fixation point located at the opposite side of the joint with respect to the pinion, so that its total length is maximised. Consequently, a rotation of the ring gear generates a translation movement of the tendon, which is passed around two pulleys to change direction and reach the common member connecting two joint units. The tendon is then terminated at two anchor points located at opposite sides of the common member. As a result, when the gear rotates clockwise, the right end of the tendon in Figure 3.1 is reeled out while the left end is pulled in, so that the common member rotates anti-clockwise about one rotation axis. Similarly, if the gear rotates anti-clockwise the right end of the tendon pulls in while the left reels out and the common member rotates clockwise. The second axis of rotation can also be actuated in a similar fashion at the other side of the common member to form a universal joint unit.

![Figure 3.1: Hybrid micromotor-tendon actuation principle. The tendon is combined with the gear driven by the micromotor to transmit the rotation to the common member connecting two adjacent joint units. Image modified from [157].](image)

The distinctive features of the flexible access platform presented in the previous chapter demonstrate its unique joint design. In particular, the proposed actuation scheme combines the rotary motion generated by the embedded micromotor with the tendon driven mechanism to transmit the rotation without occupying any space at the joint level. This also allows the integration of multiple internal channels for the passage of additional instruments. In addition, the design benefits from the high force/torque transmission characteristics of tendons without the drawback of a large external actuation pack, while at the same time allowing digital control of each DoF.
Finally, since the tendons are only actuated locally within the joint unit, each link can be developed as a standalone 1-DoF or 2-DoF module and combined with other modules to obtain different configurations of the articulated section.

In spite of the benefits of such an actuation scheme, the limited power output of the micromotor prevents the pre-tensioning of the tendon driving the joint, which unfortunately introduces backlash into the joint movement, \( i.e. \) a range of unconstrained rotation in a fixed angular position resulting from the uncompensated path length changes. In particular, the length of the path that the tendon runs from one anchor point, around the pulleys and ring gear, to the other anchor point on the common member, is not constant for all angles of joint rotation. When this path length is shorter than the actual length of the tendon, the tendon is not fully tensioned and therefore unable to drive the joint motion until the length difference is recovered. One approach to backlash compensation is to resiliently secure the tendon at the anchor points on the common member by introducing a compression spring at each end of the tendon, as shown in Figure 3.1. By adjusting the length of the tendon so that the springs are partially compressed when the joint is at the zero angular position, any slack in the tendon as the joint pivots is partially compensated by a decompression of the springs. Consequently, for small path length changes during joint rotation the tendon is maintained under tension and the backlash is reduced.

Although the use of compression springs can moderate the effect of the path length change on the tendon tension, the actual amount of backlash ultimately depends on the geometric configuration of the joint and can be minimised by changing the corresponding design parameters. This backlash compensation technique is described in the following for a more generic joint model, which can be easily adjusted to match the specific configuration illustrated above. In particular, three different joint designs can be derived from the general one described below and their technical details can be found in [157].

### 3.3 Joint model for backlash quantification and force transmission analysis

A schematic representation of a general joint design featuring the hybrid micromotor-tendon actuation principle introduced above is shown in Figure 3.2. In particular, the common member is represented by the red line and has width \( 2r_1 \), while the green line corresponds to the total tendon length connecting the common member to the fixation point on the ring gear (marked with an X). A first set of upper pulleys is positioned at a distance \( h_1 \) below the common member, a width \( 2r_2 \) apart, while a second set of lower pulleys is located at a distance \( h_0 \) below the plane of the upper pulleys, a width \( 2r_3 \) apart. However the value of \( h_0 \) does not affect the tendon path length analysis as it remains constant as the joint pivots. The parameter \( \alpha \)
represents the fraction of the total length $h_1$ determining the distance between the common member and the axis of rotation of the joint. The distance between the axis of rotation of the joint and the line connecting the upper pulleys is therefore given by $h_1(1 - \alpha)$.

With reference to the joint configuration illustrated in Figure 3.1, the model is more generic as the axis of rotation of the joint is not aligned with the anchor points on the common member (i.e. $\alpha \neq 0$) and one extra set of pulleys is introduced (i.e. $h_0 \neq 0$ and $r_2 \neq r_3$). In addition, since in Figure 3.1 the tendon fixation point on the ring gear is in line with the pulleys, the path lengths between the fixation point and a respective pulley on each side of the joint (i.e. $s_1$ and $s_2$ in Figure 3.2) sum to a constant length as the fixation point travels on an arcuate trajectory in a plane containing the pulleys (projected onto a straight line between the pulleys in Figure 3.2). However, the displacement of the fixation point away from the line of the pulleys would introduce a path length difference for the tendon between the pulleys and the fixation point which at least partially compensates for the path lengths difference between the pulleys and the common member, so that tendon slack and backlash can be reduced. Therefore, in Figure 3.2 the fixation point (X) of the tendon on the ring gear is placed at a distance $h_2$ below the plane of the lower pulleys. Different values can be assigned to $r_1$, $r_2$ and $r_3$ and the joint is considered to be at a zero angular position when the common member is aligned with the ring gear, as shown in Figure 3.2(a). Figure 3.2(b) shows the configuration of the joint after a rotation about its axis of an angle $\theta$, corresponding to a displacement $d$ of the attachment point on the circumference of the ring gear, projected on the plane of the pulleys in the figure.

### 3.3.1 Tendon path length variation

The joint model in Figure 3.2 can be used to determine the change in path length of the tendon in terms of the geometric parameters of the joint design. Specifically, the parameters $p_1$ and $p_2$ are defined as:

$$p_1 = \sqrt{(\alpha h_1)^2 + r_1^2} \quad (3.1)$$

and:

$$p_2 = \sqrt{h_1^2(1 - \alpha)^2 + r_2^2} \quad (3.2)$$

so that the angle $\theta_0$ is given by:

$$\theta_0 = \arccos \left( \frac{p_1^2 + p_2^2 - ((r_1 - r_2)^2 + h_1^2)}{2 \cdot p_1 \cdot p_2} \right) \quad (3.3)$$

where in general $p_1 > 0$ and $p_2 > 0$. Using the above definitions, the variation of the
Figure 3.2: Geometry and parameters required to analyse the tendon path length variation and quantify the backlash for a generic joint configuration. The parameter $h_2$ is introduced to partially compensate the backlash in the joint. (a) Joint configuration at the zero angular position. (b) Joint configuration following a rotation of $\theta$. The joint rotation is generated by a rotation through an angle $\gamma$ of the ring gear which results in the displacement $d = \gamma \cdot r_3$. Red line: common member; green line: tendon; X: attachment point of the tendon on the common member or ring gear; ○: pulley; ●: axis of rotation of the joint.
lengths of the tendon connecting the common member to the upper pulleys when the joint rotates clockwise \((\theta > 0)\) can be expressed as:

\[
L_1 = \sqrt{p_1^2 + p_2^2 - 2 \cdot p_1 \cdot p_2 \cdot \cos(\theta_0 + \theta)} \tag{3.4}
\]

and:

\[
L_2 = \sqrt{p_1^2 + p_2^2 - 2 \cdot p_1 \cdot p_2 \cdot \cos(\theta_0 - \theta)} \tag{3.5}
\]

so that the corresponding elongation of the left tendon part is:

\[
\frac{\partial L_1}{\partial \theta} = \frac{p_1 \cdot p_2 \cdot \sin(\theta_0 + \theta)}{\sqrt{p_1^2 + p_2^2 - 2 \cdot p_1 \cdot p_2 \cdot \cos(\theta_0 + \theta)}} \tag{3.6}
\]

and the shortening of the right tendon part is:

\[
\frac{\partial L_2}{\partial \theta} = -\frac{p_1 \cdot p_2 \cdot \sin(\theta_0 - \theta)}{\sqrt{p_1^2 + p_2^2 - 2 \cdot p_1 \cdot p_2 \cdot \cos(\theta_0 - \theta)}}. \tag{3.7}
\]

As shown in Figure 3.2(b), a joint rotation of an angle \(\theta\) is generated by a rotation through an angle \(\gamma\) of the ring gear which results in the displacement \(d = \gamma \cdot r_3\) shown in the figure. In particular, the lengths of the parts of tendon connecting the fixation point on the ring gear with the lower pulleys vary with the rotation of the ring gear according to:

\[
s_1 = \sqrt{\left(\frac{\pi}{2} - \gamma\right)^2 r_3^2 + h_2^2} \tag{3.8}
\]

and:

\[
s_2 = \sqrt{\left(\frac{\pi}{2} + \gamma\right)^2 r_3^2 + h_2^2} \tag{3.9}
\]

where \(h_2\) is defined as a fraction of the height \(h_1\) through the parameter \(\beta\) \((h_2 = \beta h_1)\). Equations (3.8) and (3.9) assume that the diameter of the ring gear corresponds to the distance between the lower pulleys; however this does not affect the generality of the model due to the presence of the upper pulleys which can be placed at a distance \(r_2 \neq r_3\).

When the ring gear rotates, the relationship between \(\theta\) and \(\gamma\) can be defined given the geometry specified in Figure 3.2, noting that the path length for the part of tendon that drives the joint during the rotation does not change since the physical length of the tendon is constant and the driving side of the tendon is under tension. For example, when the joint rotates clockwise the right part of the tendon (length \(L_2 + s_2\)) is driving the joint and the variation of \(L_2\) is, by definition, equal to the variation of \(s_2\) \((i.e. \Delta L_2 + \Delta s_2 = 0)\). Therefore, from Equations (3.5) and (3.9) the variation of the ring gear angle \(\gamma\) corresponding to a clockwise joint rotation \(\theta\) is
given by:

\[
\gamma_{cw} = \sqrt{\left( s_{2,0} + L_{2,0} - L_2 \right)^2 - h_2^2} \frac{r_3}{2} - \frac{\pi}{2}
\]  

(3.10)

where \( L_{2,0} \) and \( s_{2,0} \) are the lengths of \( L_2 \) and \( s_2 \) when \( \theta = 0^\circ \), respectively. A similar expression can be derived for the anti-clockwise rotation case, where the left part of the tendon (length \( L_1 + s_1 \)) drives the joint and remains under tension, so that the variation of \( L_1 \) is, by definition, equal to the variation of \( s_1 \) (i.e. \( \Delta L_1 + \Delta s_1 = 0 \)) and \( \gamma \) is given by:

\[
\gamma_{ccw} = \frac{\pi}{2} - \sqrt{\left( s_{1,0} + L_{1,0} - L_1 \right)^2 - h_2^2} \frac{r_3}{2}
\]  

(3.11)

where \( L_{1,0} \) and \( s_{1,0} \) are the lengths of \( L_1 \) and \( s_1 \) when \( \theta = 0^\circ \), respectively.

It is evident from the above discussion that when the joint changes direction of rotation, the change in path length of the tendon due to the side that was not under tension causes a slackening which needs to be recovered before the rotation of the ring gear can be transmitted to the common member. Therefore, for a certain amount of angular displacement of the ring gear \( \gamma_b \) the value of the joint rotation \( \theta \) remains constant. This angular displacement represents the amount of backlash at the joint and corresponds to the difference between the values of the ring gear angle \( \gamma_{cw} \) and \( \gamma_{ccw} \) when the change in direction of rotation occurs.

### 3.3.2 Analysis of torque/force transmission

The described parameter based model of the joint can also be used to compute the force transmission efficiency between the motor turning the ring gear and the tendon pulling the common member. Figure 3.3 shows the rotated joint configuration with variables relevant to force transmission, where \( F \) is the force exerted on the tendon by applying torque to the ring gear, \( F_{in} \) is the corresponding input force transmitted by the tendon at its anchor point to the common member and \( F_r \) is the resultant force generating the torque \( \tau_r \) about the joint axis of rotation with \( \tau_r = F_r D \), where \( D \) is the distance from the anchor point of the tendon on the common member to the joint axis of rotation, corresponding to \( p_1 \) in Figures 3.2 and 3.3.

According to the diagram in Figure 3.3, the input force on the tendon is:

\[
F_{in} = \frac{F}{\cos(\omega)}
\]  

(3.12)

where:

\[
\omega = \frac{\pi}{2} - \psi
\]  

(3.13)

and \( \psi \) depends on the displacement of the ring gear through:
Figure 3.3: Geometry and parameters required to analyse the torque/force transmission for a generic joint configuration.

\[ \psi = \arctan \left( \frac{\pi/2 \pm \gamma}{r_3} \right) \]  

(3.14)

where the sign and value of \( \gamma \) depend on the direction of rotation, specifically \( +\gamma_{cw} \) during clockwise rotation and \( -\gamma_{ccw} \) during anti-clockwise rotation, which corresponds to the case depicted in Figure 3.3. From these equations it can be seen that \( \cos(\omega) \) decreases as \( h_2 \) increases and, as a result, a smaller force \( F \) generated by a torque on the ring gear is required to provide the same \( F_{in} \). Thus, offsetting the fixation point of the tendon provides increased force transmission.

Finally, the resultant force rotating the joint is related to the force \( F_{in} \) exerted on the common member at the tendon anchor point through the angle \( \rho \):

\[ F_r = F_{in} \cos(\rho) \]  

(3.15)

which in turn depends on the angle:

\[ \delta_{ccw} = \arccos \left( \frac{L_2^2 + p_1^2 - p_2^2}{2 \cdot L_1 \cdot p_1} \right) \]  

(3.16)

during anti-clockwise rotation or:

\[ \delta_{cw} = \arccos \left( \frac{L_2^2 + p_2^2 - p_1^2}{2 \cdot L_2 \cdot p_1} \right) \]  

(3.17)

during clockwise rotation through the relation:
\[ \rho = \left| \frac{\pi}{2} - \delta \right|. \] (3.18)

The above equations are used in the optimisation algorithm described in the next section to ensure adequate force/torque transmission characteristics together with backlash minimisation.

### 3.4 Joint design optimisation for backlash minimisation

As discussed above, when the ring gear drives the joint in a clockwise direction the path length for the right part of the tendon does not change, so the overall change in path length is due to the left part of the tendon. In order to avoid backlash the path length for the left tendon should also remain constant, that is the shortening of \( s_1 \) or \( \Delta s_1 \) should be equal to the lengthening of \( L_1 \) or \( \Delta L_1 \), i.e. \( \Delta L_1 + \Delta s_1 = 0 \). A similar condition needs to be satisfied to reduce backlash when the ring gear drives the joint in an anti-clockwise direction and the left part of the tendon is tensioned driving the joint while the path length of the right part of the tendon changes, that is the shortening of \( s_2 \) or \( \Delta s_2 \) and the lengthening of \( L_2 \) or \( \Delta L_2 \) should be equal \( (\Delta L_2 + \Delta s_2 = 0) \) to avoid backlash. Considering that the length of the right and left parts of the tendon path is the same in an initial configuration when \( \theta = 0^\circ \) (i.e. \( L_{1,0} + s_{1,0} = L_{2,0} + s_{2,0} \)), the path length change may be optimised such that \( s_1 + L_1 \) is as close as possible to \( L_2 + s_2 \) during any rotation (clockwise or anti-clockwise) of the ring gear to minimise backlash. This can be achieved by optimising the design parameters introduced above to minimise an appropriate cost function. Examples of cost functions to be minimised over all rotation angles to reduce backlash are the variance of the total path length \( L_1 + L_2 + s_1 + s_2 \), \( (\Delta L_1 + \Delta s_1)^2 + (\Delta L_2 + \Delta s_2)^2 \), \( (L_1 + s_1 - L_2 - s_2)^2 \), or any other cost function which captures the difference between the total path lengths on each side of the joint, such as the one specified below.

#### 3.4.1 Algorithm design and force optimisation constraints

The cost function chosen for optimisation is the total shortening or elongation of the tendon path length during the joint rotation, which is calculated as:

\[
\frac{\partial L_{tot}}{\partial \theta} = \frac{\partial(L_1 + L_2 + s_1 + s_2)}{\partial \theta} = \frac{\partial L_1}{\partial \theta} + \frac{\partial L_2}{\partial \theta} + \frac{\partial s_1}{\partial \theta} + \frac{\partial s_2}{\partial \theta}. 
\] (3.19)

The main reason for this specific choice is that this function not only captures the difference between the total path lengths on each side of the joint, but also directly correlates the variation of joint rotation angle to the variation in tendon path length. However, in order to compute the shortening or elongation of \( s_1 \) and \( s_2 \) with respect to \( \theta \) it is necessary to determine the relation between the variation of the ring gear angle \( \partial \gamma \) and the corresponding angular displacement of the joint \( \partial \theta \). This can be
derived from Equations (3.10) and (3.11) as:

$$\frac{\partial \gamma_{cw}}{\partial \theta} = -\frac{(s_{2,0} + L_{2,0} - L_2)}{r_3\sqrt{(s_{2,0} + L_{2,0} - L_2)^2 - h_2^2}} \frac{\partial L_2}{\partial \theta}$$  

(3.20)

for a clockwise rotation of the joint and:

$$\frac{\partial \gamma_{ccw}}{\partial \theta} = \frac{(s_{1,0} + L_{1,0} - L_1)}{r_3\sqrt{(s_{1,0} + L_{1,0} - L_1)^2 - h_2^2}} \frac{\partial L_1}{\partial \theta}$$  

(3.21)

for an anti-clockwise rotation.

Consequently, the shortening or elongation of $s_1$ with respect to $\theta$ during rotation is given by:

$$\frac{\partial s_1}{\partial \theta} = \frac{\partial s_1}{\partial \gamma} \frac{\partial \gamma}{\partial \theta}$$  

(3.22)

where $\gamma = \gamma_{cw}$ during clockwise rotation and $\gamma = \gamma_{ccw}$ during anti-clockwise rotation.

In Equation (3.22) the variation of $s_1$ with respect to $\gamma$ can be computed from Equation (3.8) as:

$$\frac{\partial s_1}{\partial \gamma} = -\frac{(\pi/2 - \gamma)r_3^2}{\sqrt{(\pi/2 - \gamma)^2 r_3^2 + h_2^2}}$$  

(3.23)

where $\gamma = \gamma_{cw}$ during clockwise rotation and $\gamma = \gamma_{ccw}$ during anti-clockwise rotation.

Similarly, the shortening or elongation of $s_2$ with respect to $\theta$ during rotation is given by:

$$\frac{\partial s_2}{\partial \theta} = \frac{\partial s_2}{\partial \gamma} \frac{\partial \gamma}{\partial \theta}$$  

(3.24)

where $\gamma = \gamma_{cw}$ during clockwise rotation and $\gamma = \gamma_{ccw}$ during anti-clockwise rotation.

In this case, the variation of $s_2$ with respect to $\gamma$ can be computed from Equation (3.9) as:

$$\frac{\partial s_2}{\partial \gamma} = \frac{(\pi/2 + \gamma)r_3^2}{\sqrt{(\pi/2 + \gamma)^2 r_3^2 + h_2^2}}$$  

(3.25)

where $\gamma = \gamma_{cw}$ during clockwise rotation and $\gamma = \gamma_{ccw}$ during anti-clockwise rotation.

Once Equations (3.6), (3.7), (3.22) and (3.24) are defined, the design parameters to be optimised are collected in the vector:

$$x = [r_1, r_2, r_3, \alpha, \beta, h_1]$$  

(3.26)

and the value of $x$ that minimises the variation of the total shortening or elongation of the tendon path length in the joint rotation range $-30^\circ \leq \theta \leq +30^\circ$ is found. Upper and lower bound values of $x$ are also fixed. The optimisation thus can be
summarised as follows:

$$\min_x \left\{ f(x) = \max \left( \frac{\partial L_{\text{tot}}}{\partial \theta} \right) - \min \left( \frac{\partial L_{\text{tot}}}{\partial \theta} \right) \right\} \text{ with } x_{lb} \leq x \leq x_{ub}$$

where $x_{lb} = [3.5, 3.5, 3.5, 0, 0, 4]$ and $x_{ub} = [5.5, 5.5, 5.5, 1, 1, 6]$ (the values of $r_1$, $r_2$, $r_3$ and $h_1$ are in millimetres). These values are chosen in order to ensure enough space for the integration of biopsy channels within the joint unit whilst keeping its diameter and length to a minimum for improved trocar port compatibility and actuation efficiency.

Furthermore, in order to achieve adequate torque transmission, the following constraints are introduced:

$$\tau_r \geq 4.5\text{mNm for } -30^\circ \leq \theta \leq +30^\circ$$

$$\tau_r(\theta = +30^\circ) = \tau_r(\theta = -30^\circ)$$

where $\tau_r$ is the torque about the axis of rotation of the joint for a force $F = 1\text{N}$ due to a torque applied to the ring gear. The minimum value is chosen so that if each universal joint unit is about 40 mm long and 10 g in weight (as in the case of the flexible access platform described in Chapter 2) the micromotor is able to cantilever lift (i.e. the lift required in the worst loading scenario possible) at least one universal joint. In fact, if $l$ is the length of the joint and $m$ is its mass, the corresponding torque required to lift it is given by:

$$\tau_{uj} = m \times g \times \frac{l}{2} = 1.962\text{mNm}$$

where $g = 9.81\text{m/s}^2$ is the acceleration due to gravity and the centre of mass is placed mid-way through the joint length. Considering that the force applied to the tendon at the attachment point on the ring gear can be easily doubled by minimising the radius of the pinion transmitting the motor rotation to the ring gear (see Figure 3.16(b)), constraint 3.28a effectively ensures that the micromotor can cantilever lift at least two universal joints. Additionally, the constraint 3.28b guarantees that the same amount of torque is available at the extreme values of the range of rotation of the joint. This is desirable because having significantly different levels of torque available at different angular displacements of the joint could result in a device incorporating the actuated joint potentially being unable to perform a cantilever lift at one position but have no problem at another.

In order to ensure the safety of the mechanism, it may be necessary to limit the range of rotation of the ring gear. As is clear from Figure 3.1, the fixation point must not be allowed to travel past $\pm 90^\circ$ to ensure proper tensioning of the tendons. For example, rotation of the ring gear is limited to between $\pm 45^\circ$ while the joint
rotates in the range $\pm 30^\circ$. This constraint is also considered in the optimisation.

### 3.4.2 Optimisation results

The optimisation algorithm presented above corresponds to the minimisation of a constrained non-linear multi-variable cost function which can be implemented within a commercial package for computational analysis. In particular, the results presented below are obtained using the embedded function `fmincon` in the MATLAB® environment. It should be noted that the corresponding joint designs do not necessarily represent global minima of the cost function, so that different optimisation algorithms and different starting conditions can result in different designs. In particular, optimal configurations have been obtained for the most generic design presented in Figure 3.2 and for three other designs which can be obtained by applying further constraints on the parameters $\alpha$, $r_2$ and $r_3$. The initial value of the design parameters is the same for each case, specifically $x = [4.5, 4.5, 4.5, 0.5, 0.5, 5]$.

It is also important to note that while, in accordance with the above description, the free parameters of the design (at least $\beta$ but also one or more of the remaining parameters) may be optimised to get the optimum backlash reduction for a given design, any setting of $\beta > 0$ would provide some degree of path length compensation and hence backlash reduction. Equally, although the design in Figure 3.2 provides the lower pulleys between the tendon fixation point and joint plane, path length compensation could also be achieved by placing the lower pulleys on the opposite side of the fixation point so that this is between the lower pulleys and the joint plane. As long as the plane of movement of the fixation point as the ring gear rotates does not include the line joining the lower pulleys (or, more accurately, the corresponding inflection points of the tendons) some degree of path length compensation may be achieved.

#### 3.4.2.1 Generic joint configuration with $\alpha \neq 0$ and $r_2 \neq r_3$

The design found by the optimisation search for the most generic joint configuration having $\alpha \neq 0$ and $r_2 \neq r_3$ is illustrated graphically in Figure 3.4 and the corresponding design parameters can be readily derived as $x = [3.784, 3.781, 3.88, 0.5, 1, 4]$. Figure 3.4(a) schematically illustrates the movement of the common member and the tendon fixation point on the ring gear for a clockwise rotation of the joint, together with the corresponding tendon path, while Figure 3.4(b) illustrates the movement of the common member for an anti-clockwise rotation of the joint. During the anti-clockwise rotation a small displacement of the ring gear occurs without the joint plane moving, resulting in a relatively small backlash angle as shown in Figure 3.5. This shows the variation in path length of the right and left tendon parts (with the initial path length $L_{1,0} + s_{1,0} = L_{2,0} + s_{2,0}$ at $\theta = 0^\circ$ subtracted) during the overall rotation as a function of the ring gear rotation angle $\gamma$. 

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Figure 3.4: Optimised joint configuration for the generic case $\alpha \neq 0$ and $r_2 \neq r_3$. (a) Joint configuration during clockwise rotation. (b) Joint configuration during backlash recovering and anti-clockwise rotations. Although not clearly visible in the figure due to the relatively small backlash angle, the parts of tendon between the lower pulleys and the fixation point on the ring gear change their length to recover the backlash while the fixation point translates with the ring gear rotation which is not transmitted to the common member.
It is apparent from Figure 3.5 that the path length of the right part of the tendon remains constant during clockwise rotation ($\Delta L_2 + \Delta s_2 = 0$), while the path length of the left part of the tendon varies, causing backlash at the end of the rotation range. When the ring gear rotates anti-clockwise, the backlash has to be recovered before the left tendon becomes tensioned again and can drive the joint rotation. During this time the path length of $s_1$ and $s_2$ changes, while the joint does not rotate so $L_1$ and $L_2$ remain constant. When $\Delta L_1 + \Delta s_1 = 0$ the anti-clockwise rotation of the joint starts and while the path length of the left part of the tendon remains constant the path length of the right tendon changes. The backlash angle therefore corresponds to the amount of ring gear rotation needed to reach $\Delta L_1 + \Delta s_1 = 0$. For comparison, Figure 3.5 also shows the optimised case and the case when $\beta = 0$, which corresponds to positioning the fixation point in a transverse plane comprising the line connecting the lower pulleys. As is apparent, the backlash is reduced by about ten times when the fixation point is displaced.

Figure 3.5: Plot of the variation in path length for the right and left tendon portions during clockwise and anti-clockwise joint rotation with respect to the ring gear angle for the generic case $\alpha \neq 0$ and $r_2 \neq r_3$. The case $\beta = 0$ is shown to demonstrate the efficacy of displacing the fixation point on the ring gear from the line of the pulleys for backlash compensation.

Figure 3.6 shows that, for this arrangement, the resulting torque $\tau_r$ assumes the maximum value at the extreme angle of rotation, although the torque reaches the optimisation constraint at one point over the angular range of movement. The difference in torque transmission between clockwise and anti-clockwise rotation is due to the backlash recovering period, during which the rotation of the ring gear changes the configuration and path lengths of $s_1$ and $s_2$ while the joint does not rotate, thereby affecting the force transmission.
3.4.2.2 Joint configuration with $\alpha = 0$ and $r_2 \neq r_3$

The design found by the optimisation search with the only constraint of $\alpha = 0$ is illustrated graphically in Figure 3.7 and the corresponding design parameters can be readily derived as $x = [5.2, 3.5, 4.56, 0, 1, 4]$. The corresponding results are shown in Figures 3.7-3.9. As compared to the design described above, the backlash angle is slightly increased, while the torque profile shows an improved transmission efficiency.

3.4.2.3 Joint configuration with $\alpha \neq 0$ and $r_2 = r_3$

Optimisation results for a design constrained to have $r_2 = r_3$ with the remaining parameters allowed to vary are reported in Figures 3.10-3.12. The design found by the optimisation search is illustrated graphically in Figure 3.10 and the corresponding design parameters can be readily derived as $x = [3.67, 3.88, 3.88, 0.55, 1, 4]$. As compared with the most generic joint design, the backlash angles are similar and the reduction with respect to the case $\beta = 0$ is again by a factor of about 10. The force transmission efficiency is also similar.

3.4.2.4 Joint configuration with $\alpha = 0$ and $r_2 = r_3$

Finally, by introducing an additional constraint of fixing $\alpha = 0$, a design corresponding to the one illustrated in Figure 3.1 is obtained, with $\alpha = 0$ and $r_2 = r_3$. Although in this case $h_0 \neq 0$, the parts of tendon between the two sets of pulley have constant path length during the rotation of the joint, thus not affecting the final backlash.
Figure 3.7: Optimised joint configuration for the case $\alpha = 0$ and $r_2 \neq r_3$. (a) Joint configuration during clockwise rotation. (b) Joint configuration during backlash recovering and anti-clockwise rotations. Although not clearly visible in the figure due to the relatively small backlash angle, the parts of tendon between the lower pulleys and the fixation point on the ring gear change their length to recover the backlash while the fixation point translates with the ring gear rotation which is not transmitted to the common member.
Figure 3.8: Plot of the variation in path length for the right and left tendon portions during clockwise and anti-clockwise joint rotation with respect to the ring gear angle for the case $\alpha = 0$ and $r_2 \neq r_3$. The case $\beta = 0$ is shown to demonstrate the efficacy of displacing the fixation point on the ring gear from the line of the pulleys for backlash compensation.

Figure 3.9: Plot of the resultant torque applied on the common member during clockwise (upper curve) and anti-clockwise (lower curve) rotations for the joint configuration $\alpha = 0$ and $r_2 \neq r_3$. 
Figure 3.10: Optimised joint configuration for the case $\alpha \neq 0$ and $r_2 = r_3$. (a) Joint configuration during clockwise rotation. (b) Joint configuration during backlash recovering and anti-clockwise rotations. Although not clearly visible in the figure due to the relatively small backlash angle, the parts of tendon between the lower pulleys and the fixation point on the ring gear change their length to recover the backlash while the fixation point translates with the ring gear rotation which is not transmitted to the common member.
Figure 3.11: Plot of the variation in path length for the right and left tendon portions during clockwise and anti-clockwise joint rotation with respect to the ring gear angle for the case $\alpha \neq 0$ and $r_2 = r_3$. The case $\beta = 0$ is shown to demonstrate the efficacy of displacing the fixation point on the ring gear from the line of the pulleys for backlash compensation.

Figure 3.12: Plot of the resultant torque applied on the common member during clockwise (upper curve) and anti-clockwise (lower curve) rotations for the joint configuration $\alpha \neq 0$ and $r_2 = r_3$. 
angle and the force transmission efficiency. The design found by the optimisation search is illustrated graphically in Figure 3.13 and the design parameters can be readily derived as $x = [5.5, 4.4, 0, 0.682, 4]$. Figures 3.13-3.15 show the results for this set of parameters. It is apparent that the backlash angle is somewhat higher than the one obtained in the previous case with $\alpha \neq 0$, but is still significantly reduced in comparison with the case with $\beta = 0$. On the other hand, the force transmission efficiency and resulting torque are increased and the torque $\tau_r$ does not reach the constraint value.

3.5 Optimised joint design and characterisation

Although in the above discussion the backlash compensation is achieved by displacing the fixation point on the ring gear away from the line of the pulleys, such tendon routing is practically challenging to implement in a physical joint unit. Specifically, it would be necessary to increase either the height of the ring gear outside the joint module, or the length of the joint module itself. However, both approaches would also increase the minimum radius of curvature of the articulated section and the weight of the joint unit, thus affecting the robot dexterity and applying an additional load to the limited power of the micromotor. However, the backlash in this case has been minimised by routing the tendon back to the aluminium housing where the ring gear and capstan sit instead of anchoring the tendon at the common member, as shown in Figure 3.16(a). Another advantage of this tendon routing is that the motor torque is transmitted to the common member at two points, thus amplifying the total force generating its rotation, as described in [158].

Furthermore, the initial design illustrated in Figure 3.1 features an external ring gear, which largely increases the diameter of the joint unit. In order to fulfil the requirement of trocar port compatibility, the ring gear in the final joint design is placed internally as shown in Figure 3.16. The tendon is attached to a capstan fixed to the ring gear but with a smaller diameter to further amplify the force transmitted at the fixation point, as described in [158]. As previously explained, the module features three internal channels for the passage of wires and additional instrumentation, arranged as shown in Figure 3.16(b). Finally, in order to satisfy the modularity requirement for the flexible access platform, the common member of Figure 3.1 is split into two parts, which can be connected through a push-and-twist locking mechanism. Each part houses a circular board with spring loaded electrical contact pins (H199MO, Coda Systems Ltd) which allow the transmission of all motor power and signal lines through adjacent modules, as shown in Figure 3.16(a).

In order to assess the accuracy of kinematic control for the particular joint design illustrated in Figure 3.16, a 2-DoF universal joint is constructed by combining two 1-DoF units with orthogonal axes of rotation. Position feedback is provided by two miniature potentiometers (3203X103P, Tyco Electronics) mounted on the joint
Figure 3.13: Optimised joint configuration for the case $\alpha = 0$ and $r_2 = r_3$. (a) Joint configuration during clockwise rotation. (b) Joint configuration during backlash recovering and anti-clockwise rotations. Although not clearly visible in the figure due to the relatively small backlash angle, the parts of tendon between the lower pulleys and the fixation point on the ring gear change their length to recover the backlash while the fixation point translates with the ring gear rotation which is not transmitted to the common member.
**Figure 3.14:** Plot of the variation in path length for the right and left tendon portions during clockwise and anti-clockwise joint rotation with respect to the ring gear angle for the case $\alpha = 0$ and $r_2 = r_3$. The case $\beta = 0$ is shown to demonstrate the efficacy of displacing the fixation point on the ring gear from the line of the pulleys for backlash compensation.

**Figure 3.15:** Plot of the resultant torque applied on the common member during clockwise (upper curve) and anti-clockwise (lower curve) rotations for the joint configuration $\alpha = 0$ and $r_2 = r_3$. 
Figure 3.16: Joint design implemented in the 7-DoF flexible access platform. (a) CAD schematic of the joint module. The joint segment body is removed to identify several of the transmission components. (b) The arrangement of the inner lumen with gearing system and internal channels. Images modified from [158].
axes, as shown in Figure 3.17. This particular configuration is chosen to minimise the effect of the residual backlash when implementing kinematic control. Controlled motion is then obtained by implementing a LabVIEW™ code for closed-loop control in the cRIO real-time controller. In particular, the voltage readings from the potentiometers are mapped to the range of angular motion of each motor so that the joint can be servoed to eight different locations within its workspace.

Figure 3.17: Close-up picture of the 2-DoF universal joint showing one of the potentiometers mounted on its axes for position sensing.

To evaluate the repeatability and accuracy of the control, the position of the distal tip is tracked using an Optotrak Certus optical tracking system (Northern Digital Inc), which allows Three-Dimensional (3-D) position tracking with an accuracy of 0.1mm. The eight locations correspond to the extreme ($\pm 45^\circ$) and mid-range ($\pm 22.5^\circ$) angular positions from the zero on each side on each axis as measured by the two potentiometers. The joint is servoed to each of the eight locations in a random order for three times. Table 3.1 reports the standard deviation values of the 3-D position at each of those locations with respect to the mean of the sampled points as measured by the optical tracking system. The resulting values of mean and standard deviation for the actual angular displacement of each axis at each location are shown in Table 3.2. This was computed on the basis of the measured linear distance travelled by the distal tip of the joint and the known kinematic configuration. The results demonstrate that the system position control is repeatable to within 1mm or $2^\circ$ of angular displacement, which gives adequate accuracy for most kinematic tasks. However, it is envisioned that by optimising the control algorithm and characterising the sensor linearity it will be possible to further reduce any errors in the absolute angular measurements.
Table 3.1: Standard deviations in 3-D position (X,Y,Z) of the distal tip when the joint is servoed to nine different positions, three times each [158].

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>0°</td>
<td>0.82</td>
<td>0.54</td>
<td>0.97</td>
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<tr>
<td>−45°</td>
<td>0°</td>
<td>0.78</td>
<td>0.02</td>
<td>0.4</td>
</tr>
<tr>
<td>45°</td>
<td>0°</td>
<td>0.01</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>−22.5°</td>
<td>0°</td>
<td>0.32</td>
<td>0.94</td>
<td>0.78</td>
</tr>
<tr>
<td>22.5°</td>
<td>0°</td>
<td>0.61</td>
<td>0.16</td>
<td>0.88</td>
</tr>
<tr>
<td>0°</td>
<td>−45°</td>
<td>0.06</td>
<td>0.04</td>
<td>0.01</td>
</tr>
<tr>
<td>0°</td>
<td>45°</td>
<td>0.45</td>
<td>0.12</td>
<td>1.07</td>
</tr>
<tr>
<td>0°</td>
<td>−22.5°</td>
<td>0.20</td>
<td>0.09</td>
<td>0.13</td>
</tr>
<tr>
<td>0°</td>
<td>22.5°</td>
<td>0.15</td>
<td>0.06</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Table 3.2: Mean and standard deviation values of the measured angle on each axis when the joint is servoed to eight different positions, three times each [158].

<table>
<thead>
<tr>
<th>Desired Angle</th>
<th>Mean Measured Angle</th>
<th>Std. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>First Axis</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>−45°</td>
<td>−44.7°</td>
<td>1.0°</td>
</tr>
<tr>
<td>45°</td>
<td>45.6°</td>
<td>0.5°</td>
</tr>
<tr>
<td>−22.5°</td>
<td>−20.6°</td>
<td>2.1°</td>
</tr>
<tr>
<td>22.5°</td>
<td>18.8°</td>
<td>0.1°</td>
</tr>
<tr>
<td><strong>Second Axis</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>−45°</td>
<td>−45.5°</td>
<td>0.0°</td>
</tr>
<tr>
<td>45°</td>
<td>43°</td>
<td>1.6°</td>
</tr>
<tr>
<td>−22.5°</td>
<td>−22.9°</td>
<td>0.3°</td>
</tr>
<tr>
<td>22.5°</td>
<td>19.9°</td>
<td>0.3°</td>
</tr>
</tbody>
</table>
3.6 Discussion and conclusions

In this chapter, the specific design of the basic joint module implemented in the flexible access platform described in Chapter 2 has been presented, with a particular focus on the embedded hybrid micromotor-tendon actuation principle. Although this design benefits from the combination of integrated actuation at the joint level and high force transmission efficiency, thus allowing modularity with a small footprint within the operative theatre, the main drawback has been identified as the presence of backlash. Specifically, the presence of unconstrained motion at the joint due to differences in tendon path lengths during rotation can affect the accuracy of kinematic control. Therefore, an optimisation algorithm for defining the optimal joint design parameters to minimise the backlash while ensuring adequate torque transmission efficiency has been designed.

Although the results obtained from the algorithm have demonstrated the efficacy of the path length compensation technique, the incorporation of the optimal design parameters into a physical joint module has proven to be challenging. Therefore, a joint module with a different design has been developed and tested to experimentally assess the accuracy of position control. The results have demonstrated a repeatability of 2° within the range of angular displacement of each rotational DoF, thus ensuring adequate positional accuracy for the implementation of the algorithms proposed in the following chapters.

As mentioned in Chapter 2, the universal joint based serial-link structure of the articulated section of the flexible access platform will be considered as a kinematic model for the following chapters, which will introduce different algorithms aimed at reducing the high dimensionality of the system control. The results from the usability trials using a 2-DoF hand-held controller have demonstrated the limitations of a direct ‘joint-by-joint’ control paradigm to perform large area exploration within the abdominal cavity. In particular, the problem of spatial disorientation due to the lack of position feedback has been identified as a main challenge in controlling the highly dexterous robotic system. In order to overcome this issue, the next chapter will introduce a ‘front-drive back-following’ approach to kinematically control a self-propelling highly articulated robot to achieve accurate path following for MIS applications.
4 Path following under active constraints

4.1 Introduction

As discussed in Chapter 2, one of the key drawbacks of the current instruments for Minimally Invasive Surgery (MIS) is largely due to their rigidity, which hinders the performance of complex procedures within the cluttered and restricted peritoneal and thoracic cavities. On the other hand, flexible endoscopes are too floppy to provide enough stability for soft tissue manipulation. They are difficult to navigate, especially outside of a lumen as required for transluminal procedures. The integration of mechatronic articulation could therefore improve the performance of such procedures. However, the presence of a high number of Degrees-of-Freedom (DoFs) necessary to achieve the required flexibility also introduces further challenges in handling the complexity of the system.

In this chapter, a ‘front-drive back-following’ approach to robotic navigation is presented. It is designed to reduce the control dimensionality of a self-propelling hyper-redundant robot. The structure of the device is based on the universal joint design introduced in Chapter 3 with which self-propulsion is achieved by the additional integration of linear actuators enabling translation along the joint axis. This design allows the performance of a hybrid ‘inchworm-snake’ locomotive scheme which involves the actuation of only one module at a time. This simplifies the kinematic modelling and control of the robot, as well as the hardware requirements, since the motors only have to generate enough torque and force to actuate a single module.

The main advantage of the ‘front-drive back-following’ locomotion is the ability of the robot to follow complex pathways autonomously while the operator only needs to steer the distal tip. This is critical for improving the quality of MIS procedures which remain highly demanding for the operator due to complex access routes. In addition, the serial rigid-link structure of the device ensures adequate stability at the operative site to perform small interventions such as tissue biopsy or resection. This could enable the performance of more complex procedures through laparoscopic access without a direct line of sight, such as the resection of tissue at the back of the liver surface, for example. Therefore, these MIS applications are simulated in MATLAB® to validate the proposed algorithm on a virtual robot.
4.2 Kinematic modelling of robotic mechanical systems

Kinematics is the field of mechanics for studying the motion of rigid bodies without taking into account their masses or the forces generating the motion. Thus, for the purpose of its displacement analysis, a robotic mechanism can be considered as a kinematic chain, which is a set of rigid links coupled by kinematic pairs or joints. Particularly, a kinematic pair is a connecting unit between two rigid bodies that constrains their relative motion. Two basic types of joints can be distinguished: in a higher kinematic pair the contact between the links takes place along a line or at a point, whereas in lower kinematic pairs the two bodies are connected along a common surface. There are 6 different kinds of lower joints, but they can all be obtained by a combination of two basic pairs: the rotating or revolute joint and the sliding or prismatic joint [159].

Usually in a revolute pair the contact takes place along a circular cylinder, thus the two rigid links can rotate relative to each other about the axis of this common cylinder but are not able to perform relative translations as well as rotations about different axes (Figure 4.1(a)). On the other hand, two rigid bodies coupled by a prismatic joint are connected along a prism of arbitrary cross section that allows only the relative translation along a direction parallel to the axis of the prism (Figure 4.1(b)).

![Figure 4.1: (a) A rotating or revolute joint. (b) A sliding or prismatic joint. Images from MathWorks®.](image)

Each of these basic joints provides the manipulator with a single degree of mobility; their distribution along the mechanical structure of the robot must be designed in order to provide the DoFs necessary to perform a given task. Typically, all the joints are actuated simultaneously. In the most general case, six DoFs are required to arbitrarily position and orient an object in the Three-Dimensional (3-D) space, three for locating a point on the body and three for orienting it with regards to a reference coordinate frame. When the number of available degrees of mobility is higher than the number of DoFs needed to execute the task the robot is kinematically redundant; if the degree of redundancy becomes much larger than the task-space dimension the robot is then considered hyper-redundant, as discussed in detail in
Chapter 5.

On the basis of their mechanical features robotic systems can be classified in two main categories: mobile robots or *locomotors* and robotic arms or *manipulators*. The first class comprises robots that have the capability to move around in their environment and are not fixed to one physical location; usually the mobility is assured using legs or wheels. The mechanical structures belonging to the second class are instead characterised by a fixed base, an arm that guarantees mobility, a wrist that grants dexterity, and an end-effector that actually performs the required task. The flexible access platform introduced in Chapter 2 does not feature embedded propulsion, but the design can be modified to perform a hybrid ‘inchworm-snake’ locomotion as described later in this chapter. However, due to the absence of legs or wheels in its structure, the locomotion can be kinematically analysed using the same methods as applied to manipulators, provided that these are modified accordingly as discussed at the end of this section.

To kinematically analyse a manipulator, it is necessary to define a world coordinate frame and a local coordinate system relative to each link. While the latter moves with the link, the origin of the world frame is usually located at the base of the robot. This can be a Cartesian, cylindrical or spherical coordinate system on the basis of the specific needs. The relative position of each joint can be described in the coordinate frame of the related link and then be expressed in the world frame determining the transformation matrices illustrating the relationship between different coordinate systems. The most commonly used approach for defining the set of reference frames of a serial mechanism is the *Denavit-Hartenberg (D-H)* convention.

### 4.2.1 The Denavit-Hartenberg method

The Denavit-Hartenberg method is a widely used approach for kinematic analysis in robotics. For the sake of completeness, it is briefly summarised here as the notations used in subsequent chapters are based on this framework. Denavit and Hartenberg proposed in [160] a systematic method to define a local coordinate system for each link of a serial manipulator. The D-H representation of the points on the manipulator is then given by the joint variables and the parameters of these coordinate frames. A serial link *N*-joint manipulator possesses *N* + 1 links and one DoF per joint, *i.e.* each joint constraints the relative motion between two contacting links allowing only one rotation about the revolute joint axis or one translation along the direction of the prismatic joint. Since the base of the manipulator is considered as the link 0, the first link is attached to it through the first joint.

The first step of the procedure is the assignment of a right-handed Cartesian coordinate frame to the base of the manipulator. If the first joint attached to the base is a revolute one, then the $z_0$ axis of this system coincides with the rotational axis of the joint; alternatively, if the first joint is prismatic, the $z$ axis of the $(x_0, y_0, z_0)$
frame has the same direction of the axis of translation of the joint and the origin of
the system can be placed arbitrarily in correspondence of the point of intersection
between this axis and the base of the manipulator. For \( i = 1, \ldots, N \), the coordinate
axes of the next link \( i + 1 \) are chosen following a systematic procedure:

1. The direction of the \( z_i \) axis is assigned as the one of the axis of motion of the
link \( i + 1 \). Thus, it corresponds to the rotational axis of a revolute joint or is
aligned with the direction of translation of a prismatic joint. In the first case,
the positive direction of the \( z_i \) axis is chosen to be such that the positive angle
of rotation \( \theta_{i+1} \) is counter-clockwise;

2. If the \( z_i \) axis intersects the \( z_{i-1} \) axis, the direction of the \( x_i \) axis is determined
by the cross-product \( \pm (k_{z_{i-1}} \times k_{z_i}) \), where \( k_{z_{i-1}} \) and \( k_{z_i} \) are the unit vectors
in the positive direction of the \( z_{i-1} \) and \( z_i \) axes respectively. If these two
vectors are parallel, then the \( x_i \) axis has the direction of their common normal.
Particularly, if these vectors together define a plane, then the \( x_i \) axis must
belong to this plane;

3. The \( y_i \) axis must be defined on the basis of the rule of the right-hand in order
to complete the Cartesian coordinate system \((x_i, y_i, z_i)\);

4. Finally, the origin of the \((x_i, y_i, z_i)\) frame must be located in correspondence
of the point of intersection between the \( z_{i-1} \) and \( z_i \) axes, or between the \( z_i \)
axis and the common perpendicular of the \( z_i \) and \( z_{i-1} \) axes;

5. Repeat steps 1-4 for each \( i \).

After assigning the coordinate frames to all the links constituting the manipulator,
it is necessary to define certain parameters for the chosen coordinate systems in
order to compute the transformation matrix relating the expression of a vector in
the \((x_i, y_i, z_i)\) frame to that in the \((x_{i-1}, y_{i-1}, z_{i-1})\) system. These parameters are
called structural kinematic parameters of the manipulator and correspond for the
link \( i \) to: length \( a_i \), twist angle \( \alpha_i \), distance \( d_i \) and angle \( \theta_i \) between the links \( i \) and
\( i + 1 \). For \( i = 1, \ldots, N \) they are defined as follows:

\( a_i \) is the distance between the origin of the \( i \)-th coordinate frame and the point of
intersection of the \( z_{i-1} \) axis with the \( x_i \) axis along the direction of the \( x_i \) axis;
in other words, this parameter is the normal distance between the axes \( z_i \) and
\( z_{i-1} \) and it is generally called the length of the link;

\( \alpha_i \) is the angle of rotation about the \( x_i \) axis measured from the \( z_{i-1} \) axis to the \( z_i \)
axis, where the positive direction is counter-clockwise and it is called the twist
angle of link \( i \);
Figure 4.2: D-H frames and structural kinematic parameters for a general link $i$ (©2006 Kjell Magne Fauske).

$\theta_i$ is the angle of rotation about the $z_{i-1}$ axis measured from the $x_{i-1}$ axis to the $x_i$ axis and it is positive in the counter-clockwise direction;

d_i is the distance between the origin of the $i - 1$ coordinate frame and the point of intersection of the $z_{i-1}$ axis with the $x_i$ axis along the direction of the $z_{i-1}$ axis; if the axes do not intersect, then it is defined as the normal distance between the axes $x_i$ and $x_{i-1}$.

In practice, the angle $\theta_i$ can correspond to the joint variable of a revolute joint and the distance $d_i$ to that of a prismatic joint. In this case, the parameter can assume different values in time when the manipulator is moving. The coordinate frames and structural kinematic parameters determined using the described procedure for a general manipulator are illustrated in Figure 4.2.

The transformation matrix $T_{i-1}^i$ between two adjacent coordinate frames can be computed in terms of the structural parameters defined for each link of the manipulator. Thus, the vector $p_i$ expressed in the $(x_i, y_i, z_i)$ coordinate frame can be written in the $(x_{i-1}, y_{i-1}, z_{i-1})$ coordinate frame as:

$$ p_{i-1} = T_{i-1}^i p_i. \tag{4.1} $$

Particularly, the transformation matrix $T_{i-1}^i$ can be obtained performing subsequent rotations and translations of the axes of the $(x_{i-1}, y_{i-1}, z_{i-1})$ coordinate frame in order to align them with the corresponding axes of the $(x_i, y_i, z_i)$ system. This can
be achieved by multiplying in sequence the related general translation and rotation matrices written in terms of the structural kinematic parameters of the robotic arm. A pure translation matrix is constituted by a rotation sub-matrix corresponding to an identity matrix and a last column specifying the translation vector. Thus, the transformation matrix defining the pure translation of the distances $p_x$, $p_y$ and $p_z$ in the directions $x$, $y$ and $z$ respectively can be written as:

$$
A(p_x, p_y, p_z) = \begin{bmatrix}
1 & 0 & 0 & p_x \\
0 & 1 & 0 & p_y \\
0 & 0 & 1 & p_z \\
0 & 0 & 0 & 1
\end{bmatrix}.
$$

(4.2)

In the 3-D case, it is also possible to perform a rotation of an angle $\theta$ about any of the three axes determining the coordinate system and thus rotate the plane perpendicular to the rotational axis. The three transformation matrices $R_x$, $R_y$ and $R_z$ describing a pure rotation about the $x$ axis, $y$ axis and $z$ axis respectively are given by:

$$
R_x(\theta_x) = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & \cos(\theta_x) & -\sin(\theta_x) & 0 \\
0 & \sin(\theta_x) & \cos(\theta_x) & 0 \\
0 & 0 & 0 & 1
\end{bmatrix},
$$

(4.3)

$$
R_y(\theta_y) = \begin{bmatrix}
\cos(\theta_y) & 0 & \sin(\theta_y) & 0 \\
0 & 1 & 0 & 0 \\
-\sin(\theta_y) & 0 & \cos(\theta_y) & 0 \\
0 & 0 & 0 & 1
\end{bmatrix},
$$

(4.4)

$$
R_z(\theta_z) = \begin{bmatrix}
\cos(\theta_z) & -\sin(\theta_z) & 0 & 0 \\
\sin(\theta_z) & \cos(\theta_z) & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}.
$$

(4.5)

Once these matrices are defined, it is possible to decompose the general transformation matrix $T_{i-1}$ as:

$$
T'_{i-1} = A(0, 0, d_i)R_{z,i-1}(\theta_i)R_{x,i}(\alpha_i)A(a_i, 0, 0) =
\begin{bmatrix}
\cos(\theta_i) & -\cos(\alpha_i) & \sin(\alpha_i) & \sin(\theta_i) & a_i \cos(\theta_i) \\
\sin(\theta_i) & \cos(\alpha_i) & -\sin(\alpha_i) & \cos(\theta_i) & a_i \sin(\theta_i) \\
0 & \sin(\alpha_i) & \cos(\alpha_i) & 0 & d_i \\
0 & 0 & 0 & 1
\end{bmatrix}.
$$

(4.6)

It must be underlined that when a transform is post-multiplied by another transform
the corresponding operation is performed with respect to the coordinate system given by the previous transformation.

After computing the transformation matrices for each link in the manipulator, the global transformation matrix $T^N_0$ is obtained by multiplying them in a successive order:

$$T^N_0 = T^1_0 T^2_1 \cdots T^{i-1}_i \cdots T^N_{N-1} = \prod_{i=1}^{N} T^i_{i-1}. \quad (4.7)$$

This matrix converts the expression of the coordinates of a point $P$ in the coordinate frame of the end-effector ($x_N, y_N, z_N$) in that of the same point in the world frame ($x_0, y_0, z_0$):

$$p_0 = T^N_0 p_N. \quad (4.8)$$

The transformation matrix $T^N_0$ is written in terms of the joint variables and the actual configuration of the robotic arm depends on the values of these variables. When these parameters are measured, for example using sensors attached to the joints, the position of the end-effector of the manipulator is defined and the forward kinematic equations of the robot are finally solved.

### 4.2.2 Inverse kinematics resolution

Usually the end-effector of a robotic manipulator must be controlled in order to execute a given task. This means that it has to follow a desired trajectory which is generally planned in relation with the Cartesian base coordinate frame. Since the control is performed in the joint space, it is necessary to compute the corresponding values of the joint variables of the manipulator. In particular, the determination of the values of the joint variables that result in locating the end-effector in a point specified by its position and orientation in the base coordinate system is the solution of the so called inverse kinematic problem [161]. The inverse kinematic problem is actually much more complex than the forward kinematic problem because:

- Generally the equations to solve are not linear and thus there is no assurance to find a closed form solution;
- It is often possible to find multiple solutions;
- In the case of kinematically redundant manipulators there are infinite solutions;
- Depending on the structure of the manipulator there could be no admissible solution.

Regarding the last point, the existence of solutions is guaranteed if the specified position and orientation of the end-effector belong to the dexterous workspace.
of the robot, i.e. the volume of space that its end-effector can reach with all orientations. The dexterous workspace is a sub-set of the manipulator’s reachable workspace, which corresponds to the set of points in the space that can be reached by its end-effector in at least one orientation [162]. Obviously the shape and the volume of the workspace depend on the structure of the robotic arm as well as on the presence of mechanical constraints on the joints. On the other hand, the existence of multiple solutions is not only related to the number of DoFs of the manipulator, but also to the number of non-zero D-H parameters; in general the number of admissible solutions is directly proportional to the number of non-zero parameters. In such situation it is necessary to apply certain criteria for the choice of the better solution. Also, in the real case the joints are usually mechanically constrained, which decreases the number of admissible solutions [163].

To compute the closed-form solutions of the inverse kinematic problem is therefore needed either algebraic intuition to select the significant equations for determining the unknowns, or geometric perception to choose the significant points in the workspace with respect to which it is convenient to express the position and/or the orientation of the end-effector in order to reduce the number of unknowns. From another standpoint, when closed-form solutions are not admitted or too difficult to find it could be useful to utilise numerical solution techniques, whose main advantage is obviously the applicability to any mechanical structure, but which do not usually permit to compute all the admissible solutions [164–166]. However, rather than using the equations of the forward kinematics, it is also possible to solve the inverse kinematic problem by addressing the relationship between the end-effector velocity and the joint velocities. This is expressed in terms of the so-called Jacobian matrix, which is particularly meaningful when dealing with hyper-redundant systems [167], as will be discussed in detail in Chapter 5.

4.2.3 Specialised methods for snake robots modelling

As previously mentioned, the methods used to kinematically analyse manipulators can still be applied to locomotors that do not rely on additional legs or wheels to propel themselves. The majority of such robotic mechanisms belong to the category of biologically inspired robots as their designs and locomotion strategies are inspired by natural systems. Among these, snakes have been the focus of most bio-inspired robotic research, due to their excellent mobility even on rough terrains. Since Shigeo Hirose firstly built a working serpentine robot prototype in 1972 [168], a variety of snake-like robotic designs have been proposed, together with a number of locomotion techniques [169]. They usually feature a high number of DoFs and a modular structure, which result in increased fault tolerance and flexibility. These characteristics make snake robots suitable for a number of industrial applications, especially those involving the exploration of dangerous structures (e.g. nuclear plants or pipelines).
or inaccessible areas (e.g. rescue missions in earthquake areas).

As discussed in Chapter 2, the enhanced dexterity of serpentine structures has also been exploited in the field of robotic-assisted MIS in an attempt to improve the ergonomics of procedures involving complex anatomical pathways within a constrained workspace, such as cardiac and deep area interventions. However, most of the snake-like robots for MIS are *continuum manipulators*, i.e. they feature a flexible backbone actuated by tendons or super-elastic wires. This design has several disadvantages in comparison to a rigid-link structure since the kinematic redundancy is not fully exploited and modularity is not supported. In addition, continuum robots are both inherently hyper-redundant and under-actuated, which highly increases the complexity of their kinematic analysis [170]. Although specialised methods for modelling continuum backbones have been proposed, they only provide a geometric description of the robot shape and cannot be related to specific actuation modalities. Also, the dynamic behaviour of the robot is not considered, as will be discussed in more details in Chapter 5.

Ultimately, the choice of the optimal technique for modelling the locomotion of a snake-like robot depends on its specific kinematic structure and locomotion scheme [171]. Most of the industrial serpentine robots implement pre-defined gaits by assigning a motion law to the joints and simultaneously actuating all the available DoFs. In the case of robot without wheels, it is necessary to take into account the friction between the robot body and the ground, therefore dynamics must be considered when modelling their locomotion. However, since the hybrid ‘inchworm-snake’ locomotion scheme does not rely on the interaction with tissue to propel, a detailed analysis of these techniques is out of the scope of this chapter. On the other hand, the modular structure of the flexible access platform can be modelled using the modified D-H convention presented in [172]. In particular, the modification allows to determine the pose of the moving module in an inertial frame without traversing through the complete robot body. This is achieved by placing the base coordinate frame in correspondence of the first motionless link at the proximal end of the actuated module. This approach is used to compute the forward and inverse kinematics of the robot during locomotion, as described in the next section.

4.3 Hybrid ‘inchworm-snake’ robot kinematic analysis

The modular structure of the flexible access platform described in Chapter 2 allows to change the kinematic configuration according to the requirements of the specific procedure to be performed. It is also possible to modify the joint design so as to add an additional translational DoF, as shown in Figure 4.3. This 3-DoF unit, combining a universal joint with a linear propulsion mechanism which provides controlled extension of the joint about its central axis, will be addressed as Serial Self-Propelling Decoupled (SSPD) joint. The name refers to the particular
features of the joint, which allows the implementation of a serial control protocol to perform forward locomotion by decoupling the motion between separate modules. Each module comprises one 2-DoF joint as described in Chapter 3 connecting two SSPD units, as shown in Figure 4.3. It is important to note that the universal joint connecting the module with the remaining distal part of the robot also has to adjust its angular values in order to maintain the whole body along the desired trajectory.

Figure 4.3: A schematic diagram of the kinematic structure of each module constituting the hybrid ‘inchworm-snake’ robot comprising two SSPD joints and two universal joints.

As mentioned above, locomotion is performed by each 10-DoF module (two SSPD units and two universal joints) in a ‘front-drive back-following’ manner as illustrated in Figure 4.4, so that the embedded motors only have to develop sufficient torque or force to actuate the individual module. The linear propulsion units are indicated in Figure 4.4 with red circled numbers. During the first step of locomotion the Propulsion Unit (PU) 1 extends of a length $l_1$ while the rest of the body of the robot is rigid (as shown in grey in the picture). In the second step, PU2 extends of the same length $l_1$, simultaneously PU1 retracts of $l_1$ and the joint angles are adjusted based on the previous position to maintain the correct configuration, while the rest of the body of the robot is still rigid. The same process is followed successively by all the other modules, until the end of the probe is reached; here an external robotic feeder mechanism advances the whole robot of a length $l_2 = l_1$, simultaneously PU8 retracts of a length $l_1$ and the joint angles are adjusted, while the remainder of the robot is rigid. At this point, the entire device has advanced of a distance $l_1$ and the locomotion cycle can restart from PU1.

The hybrid ‘inchworm-snake’ locomotive scheme illustrated in Figure 4.4 allows to achieve autonomous self-propulsion in vivo either intra- or trans-luminally. Since each module has the same kinematic structure, the operator only needs to steer the distal module so that the information can be passed to the following modules as the robot advances along the specified trajectory. This decoupling strategy provides
Figure 4.4: A schematic diagram illustrating the ‘front-drive back-following’ locomotive principle of the articulated robot. Image courtesy of David Noonan.

enough flexibility to navigate along complex trajectories while simplifying both the kinematic modelling and control of the hyper-redundant robot. In fact, as mentioned above the simultaneous actuation of a high number of DoFs introduces a number of challenges which will be discussed in detail in Chapter 5. In addition, the manipulation of a high number of DoFs arises a number of ergonomic challenges for the user, especially when the flexibility of the system has to be fully exploited to navigate along complex trajectories between the access point and the target operative site. This effect, coupled with the limited field-of-view provided by the endoscopic camera, can generate disorientation issues and make the navigation of the device very difficult.

As described in Chapter 2, the articulated section of the flexible access platform is mounted on a rigid shaft, which in turn can be attached to the operative table using a mechanical clamp. The integration of a simple linear translation mechanism at the clamp handle, such as rubber wheels, can therefore easily provide the translational motion of the robot base during locomotion, without the need for a large external feeder mechanism which would increase the footprint of the platform. Furthermore, in this configuration, the robot is not designed to support itself along the entire trajectory, but to hold in position the distal module while the body is supported by the surrounding lumen or organs. This gives enough stability and dexterity to the surgeon to explore the area around the distal tip and perform small interventions such as tissue biopsy or resection using the end-effector, while the body of the
Figure 4.5: Schematic of the robot structure showing the parameters used in the kinematic analysis. The variable-length links are represented as yellow cylinders, while the fixed-length links are represented as white cylinders and the orange spheres correspond to universal joints enabling pitch and yaw rotations around orthogonal axes.

The robot can navigate curved pathways within the thoracic or peritoneal cavities (e.g., around the back of the heart or the liver) or intra-luminally along the tortuous colon. These considerations clearly demonstrate how the modular design of the flexible access platform highly improves its versatility, allowing to implement the most advantageous kinematic configuration and control strategy for the specific type of procedure to be performed, either endoluminally or transluminally.

### 4.3.1 Forward kinematics equations

As described above, the proposed device is a series of rigid links connected to each other by universal joints that allow for 3-D movements. The ‘front-drive back-following’ motion is then obtained alternating variable-length links (exploited by linear actuators) with fixed-length ones. Such a structure is hyper-redundant, leading to complex kinematic models and potentially expensive computational costs. In order to simplify the locomotion modelling, a decoupled joint actuation scheme is implemented, so that only a few joints are actuated at one time and the rest of the body of the robot is rigid. Particularly, in order to perform forward motion the moving module must comprise four universal joints connecting two linear actuators with a central fixed-length link and the distal part of the robot, as shown in Figures 4.3 and 4.5. The distal part of the robot is modelled as a fixed-length link connected with the remaining rigid distal joints. This is necessary to determine the D-H parameters for the distal universal joint, which angular values have to be adjusted to keep the distal part of the robot along the desired trajectory.
As seen in Figure 4.4, each SSPD unit must be part of two consecutive moving modules. With this mechanism, the distal one has to extend to a certain length whilst at the same time the proximal one has to contract by the same amount. Since the motion laws of the variable-length links are assigned, the DoFs of each module are the angles of rotation of the universal joints. The D-H convention can be used to compute the joint configuration. As explained above, since the robot is mobile, the method must be modified so that the initial reference frame is placed in correspondence of the last motionless link at the proximal end of the moving module. Referring to Figure 4.5, at each cycle of motion, the reference frame assigned to the first universal joint of the distal module \(k+1\) previously actuated becomes the coordinate system assigned to the third universal joint of the proximal module \(k\) currently actuated. The transformation between the world frame attached to the robot base and the current first joint frame is computed according to the actual configuration of the proximal modules, which are rigid. This modification avoids passing through the whole body of the robot to evaluate positions and orientations in an inertial frame. Obviously, the most distal module only features three universal joints and its last reference frame corresponds to the frame of the end-effector since it is not connected to any other module at its distal end. On the other hand, since the most proximal module is directly connected with the robot base, the transformation between the world frame and the frame assigned to its first universal joint corresponds to the \(4 \times 4\) identity matrix.

Since the motion law of the linear actuators is assigned during locomotion, it is possible to assign a transformation matrix to each universal joint which takes into account both axes of rotation as:

\[
T_j^{j+1}(q_j) = \begin{bmatrix}
    c(q_{j,1})c(q_{j,2}) & -s(q_{j,1}) & -c(q_{j,1})s(q_{j,2}) & c(q_{j,1})c(q_{j,2})a_{j,2} \\
    s(q_{j,1})c(q_{j,2}) & c(q_{j,1}) & -s(q_{j,1})s(q_{j,2}) & s(q_{j,1})c(q_{j,2})a_{j,2} \\
    s(q_{j,2}) & 0 & c(q_{j,2}) & s(q_{j,2})a_{j,2} \\
    0 & 0 & 0 & 1
\end{bmatrix} \quad (4.9)
\]

where \(c(q_{j,i})\) and \(s(q_{j,i})\) with \(i = 1, 2\) represent \(\cos(q_{j,i})\) and \(\sin(q_{j,i})\) respectively, \(j\) indicates the joint number starting from the most proximal part of the robot, \(q_j = [q_{j,1}, q_{j,2}]\) is the vector of the joint variables and \(a_{j,2}\) is the D-H parameter of the second joint variable (i.e. the length of the attached link). In particular, all the rigid links have same base-length \(L\) and the length of the proximal and distal linear actuators, respectively \(L_1\) and \(L_2\), varies between \(L_{\text{min}} = L\) and \(L_{\text{max}} = 2L\). Since each module comprises four universal joints, the forward kinematics of the \(k\)-th module can be written as:

\[
kT_k^5(q_k) = \prod_{j=1}^{4} T_j^{j+1}(q_{j,k}) \quad (4.10)
\]
where \( q_k = [q_{1,k}, \ldots, q_{4,k}] \) is the vector of the joint variables of the \( k \)-th module. Obviously, since the most distal module is not connected with any other module at its distal extremity it only features three universal joints, therefore Equation 4.10 has to be modified as:

\[
mT_1^1(q_m) = \prod_{j=1}^{3} T_{j+1}^{j}(q_{j,m})
\]

where \( m \) is the number of modules and \( q_m = [q_{1,m}, \ldots, q_{3,m}] \) is the vector of the joints variables of the last module. Finally, the forward kinematics of the entire robot when the generic module \( k \) is actuated and the rest of the body is rigid is given by:

\[
T_{N+1}^0 = T_0^1 \prod_{j=1}^{2k-2} T_{j+1}^{j+1} kT_1^5 \prod_{j=2k+3}^{n} T_{j+1}^{j+1}
\]

where \( n \) is the number of universal joints constituting the robot (e.g. \( n = N/2 \)), the frame \((x_{n+1}, y_{n+1}, z_{n+1})\) corresponds to the frame of the end-effector \((x_{N+1}, y_{N+1}, z_{N+1})\) and \( T_0^1 = I^{4 \times 4} \) since the first universal joint is mounted on the external feeder, indicated as link zero. Obviously, Equation (4.12) must be modified when \( k = 1 \) as:

\[
T_{N+1}^0 = T_0^1 \prod_{j=1}^{5} T_{j+1}^{j+1}
\]

and when \( k = m \) as:

\[
T_{N+1}^0 = T_0^1 \prod_{j=1}^{n-3} T_{j+1}^{j+1} mT_1^4.
\]

### 4.3.2 Inverse kinematics resolution

The algorithm used to compute the inverse kinematics of the robotic device during locomotion is divided in two steps: first, an outer cycle in which the external robotic feeder mechanism advances the robot of a length \( \Delta L \) and the distal tip extends for a distance \( \Delta L \). The elongation of the last linear actuator at the tip of the robot (last module, i.e. \( k = m \)) is then given by:

\[
L_{2,m} = L_{\text{min}} + \Delta L
\]

where \( \Delta L \) varies between zero and \( L \). At the same time, the first variable-length link connected to the external feeder at the proximal end of the robot (first module, i.e. \( k = 1 \)) contracts as:
\[ L_{1,1} = L_{\text{max}} - \Delta L. \] (4.16)

The direction of elongation of the last module can either be determined according to a pre-defined trajectory or assigned by the operator navigating the robot on the basis of the visual feedback given by the camera at the distal tip. For the purpose of modelling the locomotion of a virtual robot in a simulation framework, the inverse kinematics is computed to follow a pre-assigned trajectory based on anatomical models derived from pre-operative images of patients, as explained in the last part of this chapter. In particular, the corresponding joint variables are obtained in MATLAB® by minimising an objective function \( F_m(q) \) using the embedded \textit{fmincon} function. In the outer cycle, the cost function takes into account the distance between the last module of the robot and the desired path \( D_m \), together with the overall angular displacement of the universal joints during the motion cycle \( R_m \).

This ensures that the body of the robot follows the desired trajectory continuously avoiding large joint angle differences between consecutive configurations. Therefore, the objective function can be written as:

\[ F_m = k_D \frac{D_m}{D_{\text{max}}} + k_R \frac{R_m}{R_{\text{max}}}, \] (4.17)

where the importance of \( D_m \) and \( R_m \) in the selection of the joint solution is specified by the weights \( k_D \) and \( k_R \), respectively. The two performance criteria are also normalised with respect to their maximum allowable value. In particular, the maximum distance between the robot body and the assigned trajectory \( D_{\text{max}} \) depends on the specific task, while the value of \( R_{\text{max}} \) is related to the physical actuation limits of the micromotors, which allow an angular range of motion between \(-45^\circ\) and \(+45^\circ\) on each joint axis. These values are also set as the boundary limit for the search of the joint variables \([q_{l_b}, q_{u_b}]\).

The distance \( D_m \) between the last module of the robot and the desired trajectory is given by:

\[ D_m = \sum_{j=1}^{3} \left\| \mathbf{x}_{j,m} - \mathbf{x}_{j,m} \right\|. \] (4.18)

where \( \mathbf{x}_{j,m} \) is the desired position of the \( j \)-th universal joint of the last module along the path and \( \mathbf{x}_{j,m} \) is the actual position of the \( j \)-th universal joint of the distal module given by the spatial translation vector of the transformation matrix:

\[ m \mathbf{T}_0^j(q) = m \mathbf{T}_0^j(q_{\text{prox}}) \prod_{i=1}^{j-1} m \mathbf{T}_i^{i+1}(q_{j,m}). \] (4.19)

where \( q \) is the vector of all the joint variables and \( q_{\text{prox}} \) is the vector of the joint variables of the proximal part of the robot. As discussed earlier, the matrix \( m \mathbf{T}_0^j(q_{\text{prox}}) \) allows to compute the inverse kinematics of the last module in an inertial frame since
the proximal part of the robot is rigid during the outer cycle and can be computed as:

\[ m \mathbf{T}_1^0(q_{\text{prox}}) = \mathbf{T}^0_0 \prod_{j=1}^{n-3} \mathbf{T}_j^{j+1}(q_j) \] (4.20)

where \( q_{\text{prox}} = [q_1, \ldots, q_{n-3}] \) and \( \mathbf{T}_0^1 = \mathbf{I}^{4 \times 4} \) since the first joint is directly attached to the external feeder mechanism corresponding to link zero. Finally, the joint angle displacement of the distal module is defined as:

\[ R_m = \sum_{i=1}^{6} |\Delta q_{i,m}| \] (4.21)

where \( \Delta q_{i,m} \) is the change in joint angle \( q_{i,m} \) during the outer motion cycle.

Together with minimising the above cost function, the optimal joint solution needs to satisfy the additional non-linear inequality constraint:

\[ \|\hat{x}_{N+1} - x_{N+1}\| \leq 0.1\text{cm} \] (4.22)

where \( x_{N+1} \) is the desired position of the end-effector on the trajectory and \( \hat{x}_{N+1} \) is the actual position of the end-effector given by the 3-D translation vector of the transformation matrix (4.19). This condition ensures that the end-effector travels within 1mm distance from the desired path independently from the configuration of the rest of the robot body.

Once the joint variables of the distal module are determined and the outer cycle is completed, the algorithm enters an inner cycle during which the rest of the body of the robot advances of the distance \( \Delta L \) using the ‘front-drive back-following’ mechanism discussed in the previous section. Thus, the same procedure, outlined hereafter for the generic \( k \)-th module, can be followed to compute the inverse kinematics of each subsequent moving module starting from the last or most distal one and proceeding proximally until the first one mounted on the external feeder. During the inner cycle the motion law of the linear actuators in each module is assigned as:

\[ L_{1,k} = L_{\text{min}} + \Delta L \] (4.23)

for the proximal one and:

\[ L_{2,k} = L_{\text{max}} - \Delta L \] (4.24)

for the distal one. Similarly to the outer cycle, the inverse kinematics of each module during the inner cycle is determined by minimising the cost function \( F_k \) given by:

\[ F_k = k_D \frac{D_k}{D_{\text{max}}} + k_R \frac{R_k}{R_{\text{max}}} \] (4.25)
where the values of the fixed parameters are the same as in Equation (4.17) and $R_k$ corresponds to:

$$R_k = \sum_{i=1}^{8} |\Delta q_{i,k}|$$  \hspace{1cm} (4.26)

since each module comprises four universal joints, as illustrated in Figure 4.5.

The distance $D_k$ is instead given by:

$$D_k = \sum_{j=2k}^{n} \|\hat{x}_j - x_j\|$$  \hspace{1cm} (4.27)

since the position of the distal rigid part of the robot body is determined by the fourth universal joint of the $k$-th module, which angular values need to be adjusted to ensure that the entire robot always lies on the desired trajectory. In this case, $\hat{x}_j$ represents the actual position while $x_j$ is the desired position of the $j$-th universal joint along the entire robot. In particular, the location of the $j$-th universal joint is computed as the translational vector of the transformation:

$$kT^j_0 = kT^1_0(q^k_{\text{prox}}) \prod_{i=2k-1}^{j-1} T^i_{i+1}(q_i)$$  \hspace{1cm} (4.28)

where in this case $q^k_{\text{prox}} = [q_1, \ldots, q_{2k-2}]$ are the joint variables of the proximal part of the robot which remains rigid and only the joints belonging to the $k$-th module ($i.e.$ $j = 2k-1, \ldots, 2k+2$) are actuated and need to be determined by the algorithm, while the joint values of the distal part of the robot ($i.e.$ $j = 2k + 3, \ldots, n$) are also fixed. The transformation $kT^1_0(q^k_{\text{prox}})$ is therefore given by:

$$kT^k_0(q^k_{\text{prox}}) = T^2k-2_0 \prod_{j=1}^{2k-2} T^{j+1}_{j}(q_j)$$  \hspace{1cm} (4.29)

with $T^0_0 = I_{4\times4}$. Obviously, when $k = 1$ $kT^0_0 = I_{4\times4}$, while when $k = m$ the module is constituted of only three universal joints and the objective function corresponds to $F_m$. Finally, also in the case of the inner cycle, the angular values of the moving module must ensure that the end-effector follows the desired trajectory within 1mm distance, therefore the function $F_k$ is subject to the same constraint assigned by Equation (4.22). In this case however, the actual location of the end-effector is given by the translational vector of the transformation matrix in Equation (4.12), (4.13) or (4.14) according to the value of $k$.

Once the joint variables of module $k$ are computed, the algorithm moves to module $k-1$ and so on until all the joint variables are determined and the entire robot is advanced of a distance $\Delta L$. At that point, a new outer cycle starts and the algorithm repeats the same steps outlined above until the desired trajectory is completed. It is important to note that, since the modules are partially overlapping, it is necessary to
update the corresponding joint variables of the two modules adjacent to the moving one at each step of the inner cycle, i.e.:

\[
q_{1,k+1} = q_{5,k} \quad q_{8,k} = q_{4,k} - 1 = q_{4,k}
\]
\[
q_{2,k+1} = q_{6,k} \quad q_{7,k} = q_{3,k}
\]
\[
q_{3,k+1} = q_{7,k} \quad q_{6,k} = q_{2,k}
\]
\[
q_{4,k+1} = q_{8,k} \quad q_{5,k} = q_{1,k}
\]
\[
L_{1,k+1} = L_{2,k} \quad L_{2,k} = L_{1,k}.
\]

(4.30)

4.4 Path following under active constraints

The proposed ‘front-drive back-following’ locomotion scheme is validated on a snake robot simulator within a simulation framework created in MATLAB® for two surgical applications involving complex instrument paths. In both cases, the length $L = \Delta L$ is assigned as 2cm and the radius of each link is 6.25mm, while the parameters $k_D$ and $k_R$ in Equations (4.17) and (4.25) are set as 1 and 0.5, respectively. The choice of these values was taken considering that the main objective of the cost function is to ensure conformance of the robot body to the path, while the smoothness of the final kinematic configuration is of secondary importance. Realistic in vivo settings are simulated by imposing a tubular active constraint on the whole length of the robot body, which is modelled along anatomical structures according to Computerised Tomography (CT) scans of patients. Although for this application the constraint is kept static, it can dynamically adjust to tissue deformation in real-time, as described in [122] and in more detail in Chapter 5. The value $D_{max}$ in Equations (4.17) and (4.25) is assigned as the maximum radius of the constraint.

The algorithm computing the values of the joint variables implements the inverse kinematic equations described in the previous section. Each joint variable is stored in a matrix where the $k$-th row represents the temporal evolution of the corresponding angle for the $k$-th module. Since the last module only features three universal joints, during the outer cycle and the first inner cycle of locomotion only the variables $q_{m,1},...,q_{m,6}$ are computed, while the $m$-th row of variables $q_7$ and $q_8$ is always set to zero. In the internal cycle, instead, all the joint variables of the current moving module $q_{k,1},...,q_{k,8}$ are evaluated and stored; particularly, since a portion of each module is overlapping with part of the adjacent ones, it is also necessary to update the values of the corresponding joints according to Equation (4.30).

At the end of each computational step, the equations of the forward kinematics (corresponding to Equation (4.12), (4.13) or (4.14) according to the value of $k$) are used to evaluate the actual configuration of the robot with the computed values of the joint variables. The robot is represented as a set of vertices so that Proximity Queries (PQs) can be performed offline as described in [173] to determine the maximum deviation of the robot body into the forbidden region outside the volume defined
by the tubular constraint. This is due to the long computational time needed to perform PQs, however recent work at the Hamlyn Centre has been focussed on adapting their formulation to achieve the online adaptation of the robot kinematics to the active constraint model, as discussed in Chapter 7.

The first simulation investigates the suitability of implementing the hybrid ‘inchworm-snake’ locomotive principle when performing a colonoscopy, as described below.

4.4.1 Colonoscopy

Loop-forming is a major problem of colonoscopic navigation due to the simple actuation scheme adopted by current designs. This can cause discomfort and pain to the patient, as illustrated in Figure 4.6. The ability to perform autonomous locomotion with the forward-driving mechanism has clear advantages.

\begin{enumerate}
\item[(a)]
\begin{figure}
\centering
\includegraphics[width=0.2\textwidth]{figure4.6a}
\caption{A schematic illustration of the common loop-forming problem in conventional endoscopy, where the force applied to advance the tip is instead transmitted to the wall of the colon which distends causing patient pain, and (b) how this can be avoided by aligning the angular position of the distal tip as it navigates and feeding this information to following segments (©Neoguide Systems Inc).}
\end{figure}
\end{enumerate}

As discussed in Chapter 2, most of the proposed locomotion schemes for robotic endoscopes rely on the colon walls to perform the robot’s advancement. For example, inchworm-like locomotion is based on anchoring part of the body of the robot to the colon walls to generate the forward pushing force. This is achieved by stretching the colon walls to their limit [26], sucking them to enclose the robotic device [27, 66] or physically clamping them with mobile jaws [62, 67]. However, due to the presence
of mucus the colon becomes very stretchy and slippery and is particularly hard to anchor it or define the friction in every point. If the supporting area or the traction force applied is ineffective, there would be no forward locomotion. Robotic colonoscopy would therefore greatly benefit from the novel locomotive principle presented above, since it allows the robot’s advancement without using the colon walls and the primary pushing action does not come from the clinician hand.

4.4.1.1 Active constraint model and trajectory definition

The aim of the first numerical simulation is to model the locomotion of the hyper-articulated robot following a linear path along the lumen of the human colon. Figure 4.7 shows a tubular active constraint (red circles) fitted to a model of the large intestine generated from patient CT data. The corresponding linear path (black line in the figure) is generated with MATLAB® using as an input the vector of coordinates \((x_c, y_c, z_c)\) corresponding to the control points along the centreline of the tubular constraint. The subdivision of the lines connecting these points in segments of length \(L\) ensures that when the linear actuators assume their base-length \(L\) the body of the robot can exactly conform to the desired trajectory.

Figure 4.7: Tubular active constraint (red circles) fitted to a 3-D model of the colon obtained from CT images of a patient and corresponding trajectory to be followed by the robot along the constraint centreline (black line). (a) 3-D view. (b) View in the \((x_0, y_0)\) plane.

4.4.1.2 Accuracy assessment of path following control

The images in Figure 4.8 demonstrate the ability of the robot to follow the desired path with a minimal error; they correspond to four outer cycles of locomotion showing the robot navigating the four bends of the colon and reaching the caecum. As seen in Figure 4.5, variable-length links are represented as yellow cylinders while
white cylinders correspond to fixed-length links and the universal joints are illustrated as orange spheres between the links.

![Figure 4.8](image)

**Figure 4.8:** Four images of outer cycles of locomotion showing the robot navigating the four bends of the colon and reaching the caecum. (a) Robot navigating the first bend. (b) Robot approaching the third bend after passing the second bend. (c) Robot approaching the fourth bend after passing the third bend. (d) Robot reaching the caecum.

The pictures in Figure 4.9 show the key phases of a simulated inner cycle of locomotion. It can be seen how the motion of the module is fully decoupled from the rest of the body of the robot that remains rigid. While the linear actuators are respectively contracting and extending, the joint angles are adjusted in order to maintain the correct position along the desired path.

The validity of the proposed inverse kinematics algorithm to perform autonomous locomotion along a pre-defined path is clearly demonstrated by the figures above. In particular, the robot accurately follows the desired path in the straight portions, while a small trajectory error is introduced when negotiating around corners. This imprecision is obviously implied by physical constraints as the links cannot bend and their minimum length is set by hardware limitations (*i.e.* size of the embedded actuators). However, the small error in following the assigned trajectory does not result in a deviation of the robot body outside the constraint for most of the configurations assumed during locomotion. This is shown in Figure 4.10, which reports...
Figure 4.9: Six images of the robot during an inner cycle of locomotion along the colon showing that the robot body conforms to the desired trajectory while the moving module is actuated to navigate a sharp bend. (a) The inner cycle begins with $L_2$ completely extended and $L_1$ completely contracted. (b)-(e) During the inner cycle $L_2$ contracts while $L_1$ extends and the joint angles are adjusted to navigate the bend and keep the distal part of the robot on the desired trajectory. (f) The inner cycle terminates when $L_2$ is completely contracted and $L_1$ is completely extended so that the next module can be actuated.
the values of maximum deviation of the robot body outside the tubular constraint computed at each time-frame of the last cycle of locomotion. Due to the nature of the ‘front-drive back-following’ approach, this cycle effectively incorporates all the previous locomotion cycles and corresponding kinematic configurations of the robot along the entire path. The duration of the cycle is determined by the linear actuator integrated in the joint unit. As an example, the SQL-1.8-RV SQUIGGLE® piezoelectric linear micromotor (New Scale Technologies, Inc., NY, USA) has dimensions 2.8 $\times$ 2.8 $\times$ 6mm and a speed of 10mm/sec, so that if $L = 2$cm each motion cycle would last about 2sec. The graph clearly shows that at the end of each inner cycle of locomotion the robot exactly conforms to the desired trajectory (i.e. the deviation is null), while part of the robot body exceeds the tubular constraint when the actuated module is navigating a sharp bend.

![Graph showing maximum deviation values of the robot body outside the tubular constraint at each time-frame of the last cycle of locomotion along the colon.](image)

**Figure 4.10:** Maximum deviation values of the robot body outside the tubular constraint at each time-frame of the last cycle of locomotion along the colon.

To better visualise the origin of the path following error, Figure 4.11 shows two inner cycles of the last outer cycle of locomotion for which the distal part of the robot body deviates outside the constraint in correspondence of the last bend of the colon. In Figure 4.11(a), the robot exceeds the constraint of 1.7mm while the actuated module is actually navigating the sharp corner. In Figure 4.11(b), the deviation occurs while the actuated module is navigating the second bend of the colon and the adjustment of the joint angles cannot keep the distal rigid part of the robot body along the desired trajectory. In particular, the deviation in this case is 3.7mm, which corresponds to the maximum value computed along the whole path. However, because of the large elasticity of the colon wall and the relatively small force that the distal part of the robot would exert on the tissue due to the actuation of only one module, it is envisioned that such a limited amount of penetration would
not cause any perforation.

Figure 4.11: Two robot configurations exceeding the active constraint in correspondence of the last bend of the colon. (a) The robot deviates from the desired path while the actuated module is navigating the last bend of the colon and exceeds the tubular constraint of 1.7mm. (b) The distal part of the robot body deviates 3.7mm outside the constraint while the actuated module is adjusting to the second bend of the colon.

However, the major drawback of the ‘front-drive back-following’ actuation scheme is the long time needed to complete the colonoscopy and reach the caecum, mainly due to the high number of modules necessary to cover the entire length of the large intestine. For the simulated trajectory, a total of 46 outer cycles of locomotion and 50 links are used, therefore if the linear actuators can extend or contract at a speed of 10mm/sec the total duration of the procedure corresponds to $46 \cdot 26 \cdot 2 = 2392$ sec or about 40min. Considering that experienced endoscopists can execute a colonoscopy in less than 10min, the current completion time should be halved. Possible solutions for this problem will be discussed at the end of this chapter and in more detail in Chapter 7.

4.4.2 Laparoscopic liver biopsy

In spite of the advantages related to the MIS approach, the performance of laparoscopic liver surgery has remained limited due to technical challenges. In particular, the difficulty of manoeuvring the rigid laparoscopic tools to follow accurate resection margins when performing tissue biopsies compromises the safety of the procedure. For tumours located on the right-posterior side of the liver, tool manipulation becomes particularly challenging due to the presence of the diaphragm [174]. The use of a flexible device able to navigate along the surface of the organ could therefore greatly improve the ergonomics and safety of the procedure.
4.4.2.1 Active constraint model and trajectory definition

The aim of the second numerical simulation is to model the locomotion of the hyper-articulated robot following a curved instrument pathway between an incision on the patient body and the back of the liver, as shown in Figure 4.12. Also in this case, the path (black line in the figure) is enclosed in a tubular active constraint (red circles) defined along the surface of a liver model generated by segmentation of patient CT images. The trajectory is created in MATLAB® according to the coordinates of the control points along the centreline of the tubular constraint and divided in linear segments of length \( L \) to ensure the existence of the inverse kinematic solution.

It must be noted that the constraint is generated from the same liver model used in Chapter 5, however in this case it does not dynamically adjust its shape to the deforming organ and the radius is larger to account for physiological motion, since the body of the robot is supported by the liver during locomotion. Obviously, the trajectory to navigate around the back of the liver is much less complex than the one to perform colonoscopic navigation, as shown in Figure 4.12.

![Figure 4.12: Tubular active constraint (red circles) generated along a 3-D model of the liver obtained from CT images of a patient and corresponding trajectory to be followed by the robot along the constraint centreline (black line). (a) 3-D view. (b) View in the \((x_0, y_0)\) plane.](image)

4.4.2.2 Accuracy assessment of path following control

In Figure 4.13, four example images of outer cycles of locomotion showing the robot navigating along a curved path at the back of the liver are provided to demonstrate the ability of the robot to follow the desired trajectory with a minimal error. As in the previous case, variable-length links are illustrated as yellow cylinders while the fixed-length links are represented as white cylinders and the universal joints correspond to orange spheres between the links.
Figures 4.13 and 4.14 demonstrate the adaptability of the proposed inverse kinematics algorithm, which enables autonomous locomotion of the hyper-redundant robot along different pre-defined paths. However, also in this case a small trajectory error is introduced by the rigidity of the links. Nonetheless, Figure 4.15 shows that only during two inner cycles of locomotion the robot body actually exceeds the tubular constraint. In addition, the maximum value of penetration is below 1mm, and the corresponding robot configuration is illustrated in Figure 4.16. Finally, since the instrument path to perform laparoscopic liver biopsy is much shorter than the whole length of the colon, the time needed to reach the back of the liver is only 8min (i.e. 15 outer cycles of locomotion with 8 modules).
Figure 4.14: Four images of the robot during an inner cycle of locomotion along the curved path showing that the robot body conforms to the desired trajectory while the moving module is actuated. (a) The inner cycle begins with $L_2$ completely extended and $L_1$ completely contracted. (b)-(c) During the inner cycle $L_2$ contracts while $L_1$ extends and the joint angles are adjusted to navigate the bend and keep the distal part of the robot on the desired trajectory. (d) The inner cycle terminates when $L_2$ is completely contracted and $L_1$ is completely extended so that the next module can be actuated.
Figure 4.15: Maximum deviation values of the robot body outside the tubular constraint at each time-frame of the last cycle of locomotion around the back of the liver.

Figure 4.16: Robot configuration exceeding of 0.8mm the active constraint imposed on the curved pathway along the surface of the liver.
4.5 Discussion and conclusions

In this chapter, a hybrid ‘inchworm-snake’ hyper-redundant design originating from the modular structure of the flexible access platform introduced in Chapter 2 has been presented. The principle of ‘front-drive back-following’ locomotion has been described in terms of forward and inverse kinematic equations and its practical validity has been demonstrated through detailed simulations. Realistic in vivo settings have been modelled on the basis of pre-operative images of patients for two MIS applications: colonoscopy and laparoscopic liver biopsy. The results have shown the adaptability of the locomotion scheme to different trajectories and the effectiveness of decoupling the motion in different modules. In addition, the accuracy of the path following algorithm has been assessed by imposing a generalised-cylinder active constraint on the entire length of the robot during locomotion. The safety of the self-propelling approach has been demonstrated by the resulting small values of deviation of the robot body outside the tubular constraint.

It should be noted that the main drawback of the ‘front-drive back-following’ motion is the relatively long time needed to navigate the entire path, which is proportional to the number of modules necessary to cover the whole trajectory. This can be reduced by increasing the length of each joint unit; however, this would also affect the accuracy of the path following, especially when navigating around sharp corners. Furthermore, as already discussed in the previous chapters, the torque generated by the micromotors is limited, therefore the size of the joint units should be minimised to ensure adequate actuation force. Another way of increasing the locomotion speed is to actuate more than one module simultaneously. However, this would introduce a number of issues in terms of control complexity and actuation efficiency. Ultimately, the most suitable solution should be implemented according to the specific procedure. For example, in the case of laparoscopic liver resection the path between the entry point and the target operative site is relatively short, but any deviation of the robot body outside the forbidden region defined by the constraint could cause damage to the anatomical structures surrounding the organ. Therefore, the joint dimensions and actuators used in the virtual environment would be ideally suited for the specific procedure. On the other hand, the path along the colon is very long, but the colon walls are very elastic and difficult to perforate even when using a standard flexible endoscope. Therefore, further investigation should be carried out to determine the maximum allowable error in path following accuracy for this case and the corresponding maximum joint length, so as to minimise the number of modules in the robot body.

Finally, further investigation of the robot dynamic behaviour and its interaction with the surrounding tissue is needed to ensure the safety of the ‘front-drive back-following’ control. Although the inverse kinematic algorithm has proven to be effective for the simulated trajectories, during the actual procedure, the direction
of motion of the distal tip of the robot will be assigned by the surgeon according to the visual feedback from the endoscopic camera. Therefore, the path following accuracy \textit{in vivo} could be affected by a number of patient-specific issues, such as the presence of tumoral masses or shape anomalies. Furthermore, the flexibility of the robot could be affected by the passage of endoscopic instrumentation through the internal channels and the force available at the distal tip could be insufficient to perform tissue manipulation. Possible solutions to these issues will be discussed in more detail in Chapter 7.

One obvious limitation of the work presented in this chapter is the lack of experimental validation of the proposed kinematic control algorithm using a hyper-redundant articulated robot prototype. However, hardware limitations such as the limited torque generated by the micromotors and the restricted space at the joint for the passage of sensing and power lines, still hinder the integration of a large number of DoFs in the flexible access platform. Nonetheless, promising preliminary results of kinematic control using a non-redundant articulated robot prototype are presented in the next chapter, where the requirement of providing sufficient stability for tissue manipulation in a deforming environment is addressed under the framework of dynamic active constraints.
5 DoF minimisation for optimised shape control under active constraints

5.1 Introduction

As discussed in Chapter 2, in an attempt to overcome the limitations of the existing robotic surgical platforms, particularly for those related to rigid instrument design, current research is increasingly focused on the development of flexible instruments that enable more complex procedures to be performed. The use of an articulated hyper-redundant robot allows increased flexibility since the body of the robot can follow complex trajectories, as demonstrated in Chapter 4. In addition, serial link mechanisms offer advantages such as the possibility of integrating inner channels to pass through imaging probes, camera and other instruments. They also provide increased design flexibility to facilitate the integration of active constraints and help maintain a desired shape by relying on the stiffness of the unactuated joints.

The problem of kinematic control for redundant manipulators has been extensively studied by the robotics community. In addition to the inverse kinematic method, which aims to find the joint displacements directly, Jacobian-based, gradient projection and task space augmentation approaches can be applied. More recently, several authors have proposed the use of parametric curves to describe the geometric shape of redundant robots. In spite of the theoretical validity of these simulation frameworks, which provide instantaneous solutions allowing for on-line path modifications, significant technical hurdles still prevent their practical application in clinical scenarios. In particular, the simultaneous actuation of a large number of Degrees-of-Freedom (DoFs) significantly increases both hardware and software control complexity. For Minimally Invasive Surgery (MIS) applications, this complexity is further exacerbated if haptic guidance and active constraints are required for safer operation.

In this chapter, a DoF optimisation scheme is proposed to overcome some of these

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difficulties by identifying the minimum number of active joints to be simultaneously actuated for a specific task. It can be used prior to surgery to estimate the desired motion of the joints and then be implemented together with sensing feedback to adapt to intra-operative changes. This simplifies the formulation of the kinematic solution whilst still addressing the motion of each individual joint. Another advantage of the proposed method over the existing algorithms is the use of a volumetric manipulation margin rather than a specific Three-Dimensional (3-D) parametric curve to be followed without any tolerance. This accounts for improved flexibility of manual control and its integration.

With the proposed method, a time-varying instrument path is defined along the surface of a deforming tissue model. The dynamic surgical model can be obtained by pre-operative imaging on a specific patient so that the shape of the instrument path can be registered to the active constraint to be imposed. A generic snake-like articulated robotic instrument is used. The method then utilises an optimisation algorithm to identify the optimum number of active DoFs required to maintain dynamic shape conformance for the given surgical task. The kinematics of the robot can also be easily modified without affecting the algorithm, thus allowing its application to varying robot configurations and surgical tasks. One important feature of the algorithm is that Dynamic Active Constraints are imposed on the entire length of the robot rather than just the end-effector. Detailed simulation results are used to assess the efficacy of the technique and preliminary experimental validation is provided to demonstrate its practical value.

5.2 Kinematics of hyper-redundant robots

As already mentioned in Chapter 4, in robotics the term “redundancy” does not refer to an inherent property of a robotic structure as it can only be defined with respect to a desired task, *i.e.* a manipulator is *kinematically redundant* when possessing more DoFs than required for the execution of a certain task. Nonetheless, manipulators with more than 6 DoFs are usually referred to as “redundant” because they exceed the number of DoFs generally required to achieve any pose in the 3-D space (3 DoFs for positioning and 3 DoFs for orienting the end-effector). The human arm is the most well-known biological example of kinematic redundancy as it features 7 DoFs, three in the shoulder, one in the elbow and three in the wrist. *Hyper-redundancy* can then be obtained when incorporating a large number of joints in a manipulator structure, so that the degree of redundancy becomes much larger than the task-space dimension. The best and most common biological example of hyper-redundancy is the snake, and many types of snake-like robots have been described in the literature, *e.g.* [168, 175].

The interest of industrial robotics research in redundant manipulators has been motivated by advantages such as increased fault tolerance and enhanced dexter-
ity. In particular, the extra DoFs can be exploited to overcome limitations such as singularities, physical joint limits (e.g. actuator torque and acceleration) and the presence of obstacles in the workspace. This avoids forbidden regions in the joint space without the need of a carefully structured and static workspace. The possibility to execute the same task in different joint configurations makes the manipulator more versatile and suitable for application in unstructured and dynamically varying environments [170]. Such versatility is also the main reason that motivates the current research into the use of hyper-redundant robots for minimally invasive surgical tasks.

The human body represents a great example of highly unstructured and dynamically varying environment, due to the presence of elastic organs deforming under the effect of physiological motion (e.g. cardiac and respiratory cycles). The evolution of robotic-assisted surgery towards laparoscopic and endoluminal approaches requires therefore the incorporation of a high degree of flexibility in the surgical instrumentation to ensure safe operation performance, especially for those tasks not under direct control of the surgeon. An example of such task is the ability for the instrument body to conform its shape to a certain path enclosing a dynamically varying forbidden region (e.g. a deforming organ) while the surgeon is operating the end-effector on a site impossible to reach through a direct line-of-sight from the trocar. However, accurate shape control requires the on-line estimation of a large number of joint variables and the simultaneous actuation of the corresponding DoFs, which in turn can result in high computational and control complexities, as described in the following sections.

5.2.1 Task-oriented kinematics resolution using traditional modelling techniques

As already introduced in Chapter 4, the task-space formulation of a manipulator’s kinematics describes the relation between the joint variables determining the configuration of the manipulator and the task variables representing the desired task at the position, velocity or acceleration level. In general, a manipulator is constituted by a number of serially connected rigid links articulated by joints. Therefore, the configuration of an $N$-joint serial-chain robot can be uniquely described by the vector $q = [q_1, \ldots, q_N]^T$, where $q_i$ represents the relative displacement of link $i$ with respect to link $i-1$. This corresponds to either a rotation or a translation according to the type of joint $i$, either being revolute or prismatic. These variables determine the so-called joint-space, while the pose of the manipulator’s end-effector is more conveniently specified in the task-space by a vector $t = [t_1, \ldots, t_M]^T$. Usually $M = 6$ so that the first three components of $t$ describe the position and the last three components the orientation of the end-effector through a minimal representation (e.g. Euler or roll-pitch-yaw angles). In the case of kinematically redundant
robots, $N > M$ strictly and the direct kinematics equation describing the relationship between the joint-space and the task-space variables is given by:

$$\mathbf{t} = \mathbf{k}_t (\mathbf{q})$$  \hspace{1cm} (5.1)

where $\mathbf{k}_t$ is a non-linear vector function [170].

Differentiation with respect to time of Equation (5.1) gives the first-order differential kinematics:

$$\dot{\mathbf{t}} = \mathbf{J}_t (\mathbf{q}) \dot{\mathbf{q}}$$  \hspace{1cm} (5.2)

describing the relation between the task-space velocity vector $\dot{\mathbf{t}}$ and the joint-space velocity vector $\dot{\mathbf{q}}$ through the $M \times N$ task Jacobian matrix $\mathbf{J}_t (\mathbf{q}) = \partial \mathbf{k}_t / \partial \mathbf{q}$. Although in some cases it is possible to solve the inverse kinematics problem (i.e. to determine the joint variables values corresponding to an assigned task) at the position level as described in Chapter 4, redundancy resolution techniques are mainly based on the task Jacobian matrix. This is because the extra available DoFs in the joint-space are usually exploited to execute task-space motions without incurring in singular configurations. These kinematic singularities are undesirable since they cause the Jacobian matrix to be rank-deficient, thus correspond to infeasible end-effector task velocities in certain directions [170].

A number of techniques have been proposed to ensure singularity robustness by exploiting the so called null-space velocities, i.e. the joint-space velocities which yield zero task velocities. These methods are generally not only acting at the singular configuration, but also in its neighbourhood where joint velocities can become really large. Different measures can be used to determine the distance of a certain configuration from a singularity. The manipulability measure [176] represents a generalisation of the determinant of a square Jacobian matrix, which is equal to zero in correspondence of a singularity, and is defined as:

$$\mu = \sqrt{|\mathbf{J}_t \mathbf{J}_t^T|}$$  \hspace{1cm} (5.3)

which in turn is equal to the product of the singular values of $\mathbf{J}_t$, i.e.:

$$\mu = \prod_{i=1}^{M} \sigma_i.$$  \hspace{1cm} (5.4)

Similarly, the condition number indicates the presence of a singularity when its value tends to be infinite, as it is given by:

$$\kappa = \frac{\sigma_1}{\sigma_M}$$  \hspace{1cm} (5.5)

where $\sigma_1 \geq \sigma_2 \geq \cdots \geq \sigma_i \geq \cdots \geq \sigma_M$. Note that when the motion capability of the end-effector is the same in all task space directions all the corresponding singular
values are equal \( i.e. \kappa = 1 \) and the manipulator is at an *isotropic configuration* \([177]\).

Finally, the most direct and most effective measure of distance from singularities is the *smallest singular value* of the Jacobian matrix:

\[
\sigma_{\text{min}} = \sigma_M
\]

which can be estimated using numerical methods or according to the kinematics of the manipulator \([178, 179]\).

### 5.2.1.1 Jacobian-based redundancy resolution

The general inverse kinematics solution for redundant manipulators utilises the pseudo-inverse of the task Jacobian matrix, \(i.e.\) a square, invertible matrix obtained from the task Jacobian matrix, which is rectangular, as:

\[
J_t^\dagger = J_t^T (J_t J_t^T)^{-1}.
\]

This unique matrix satisfies the Moore-Penrose conditions and reduces to the standard inverse matrix when \(J_t\) is square \([180]\). Consequently, the general solution of Equation (5.2) can be expressed as:

\[
\dot{q} = J_t^\dagger \dot{t} + (I - J_t^\dagger J_t) \dot{q}_0
\]

where the term \((I - J_t^\dagger J_t)\) projects the arbitrary joint-space velocity \(\dot{q}_0\) in the null space of \(J_t\), giving a null-space velocity. This solution satisfies the least-squares property for the joint-space velocities, \(i.e.\) it minimises \(||\dot{t} - J_t \dot{q}||\) and therefore improves the accuracy of the end-effector trajectory, while allowing resolution of the redundancy by acting on the null-space velocity vector \([170]\). The minimum-norm solution of Equation (5.2) or standard *pseudo-inverse solution* can be obtained by setting \(\dot{q}_0 = 0\) in Equation (5.8):

\[
\dot{q} = J_t^\dagger \dot{t}.
\]

It is important to note that Equation (5.9) minimises the joint-space velocities only locally when searching for the optimal instantaneous solution; therefore, joint velocities can still become arbitrarily large, being close to singular configurations \([167]\). The robustness to singularity occurrence of the standard pseudo-inverse solution can however be increased by avoiding near-singular configurations on the basis of the measures previously described. This can be achieved by either modifying the planned trajectory or applying regularisation techniques to the Jacobian computation \([170]\). Although the first approach is relatively simple to implement for those singularities naturally characterised in the workspace, it is not suitable for real-time
sensory control applications requiring online task-planning as it may cause large errors in tracking the assigned trajectory [181].

The damped least-squares technique is the most common method of regularisation of the task Jacobian matrix [182, 183] and consists in the introduction of a damping factor $\lambda \in \mathbb{R}$ in the formulation of the direct kinematics:

$$J^T \ddot{t} = (J^T J_t + \lambda^2 I) \dot{q}. \quad (5.10)$$

The solution to Equation (5.10) is given by:

$$\dot{q} = J_t^T (J_t J_t^T + \lambda^2 I)^{-1} \ddot{t} \quad (5.11)$$

and satisfies the condition:

$$\min_q \left( ||\ddot{t} - J_t \dot{q}||^2 + \lambda^2 ||\dot{q}||^2 \right) \quad (5.12)$$

representing a compromise between the least-squares and minimised-norm properties. The choice of the damping factor is therefore critical for obtaining adequate tracking accuracy while ensuring robustness to singularity occurrence. In practice, the use of a configuration-varying damping factor allows to achieve good performance over the entire workspace of the robot by adjusting the value of $\lambda$ according to the distance of the current configuration from a singularity. A formulation based on an estimate of the smallest singular value of the task Jacobian $\hat{\sigma}_M$ which guarantees continuity and smoothness of the joint-space solution is given by:

$$\lambda^2 = \begin{cases} 
0 & \text{when } \hat{\sigma}_M \geq \epsilon \\
\left[ 1 - (\hat{\sigma}_M / \epsilon)^2 \right] \lambda_{\max}^2 & \text{otherwise}
\end{cases} \quad (5.13)$$

where $\epsilon$ determines the size of the singularity neighbourhood for damping and $\lambda_{\max}$ represents the maximum value of the damping factor to be used at the singular configuration [184].

Finally, since the solution derived from inverse kinematics provides the values of joint velocities for the assigned task, it is necessary to use an inverse kinematics algorithm to extrapolate the joint motion profile. Given that the robot control system is usually implemented digitally, a discrete-time numerical approximation of the analytical solution must be derived. In particular, defining the continuous integral of the joint velocities as:

$$q(t) = q(t_0) + \int_{t_0}^t \dot{q}(\tau) \, d\tau \quad (5.14)$$

and a discrete-time sequence of samples of the joint positions $q_k$ and corresponding velocities $\dot{q}_k$ at time instants $t_k$, the first order interpolation of Equation (5.14) gives:
\[ q_k = q_0 + \sum_{h=0}^{k-1} \dot{q}_h \Delta t \]  

(5.15)

or, using the more effective recursive form:

\[ q_k = q_{k-1} + \dot{q}_{k-1} \Delta t. \]  

(5.16)

Higher order interpolation is generally unsuitable for real-time applications, as it generates a large finite-time delay affecting the dynamic performance of motion control. However, the accuracy of Equation (5.16) can be improved by choosing a sufficiently short time step \( \Delta t \). Nonetheless, any approximation of Equation (5.14) can lead to errors accumulating at each time-step which can severely affect the accuracy of the reconstructed trajectory. \textit{Closed-Loop Inverse Kinematics} (CLIK) algorithms are designed to address these issues by including a feedback term accounting for the difference between the desired and actual joint motion, \textit{i.e.}:

\[
\dot{q}_k = J_t^+ (q_k) \left\{ \dot{t}_k + K [t_k - k_t (q_k)] \right\} + \left[ I - J_t^+ (q_k) J_t (q_k) \right] \dot{q}_0. 
\]  

(5.17)

where \( K \) is a constant positive-definite gain matrix [185].

5.2.1.2 Gradient projection approach

As previously highlighted, the most general pseudo-inverse solution (5.8) allows to exploit the redundant DoFs to find the optimal solution. One possibility is to use the redundancy to optimise one or more performance criteria, such as singularity robustness, conformance to physical constraints or obstacle avoidance [186]. An example of cost function that can be minimised to avoid mechanical joint limits is given by:

\[
H(q) = \frac{1}{2} \sum_{i=1}^{N} \left( \frac{q_i - q_{i,mid}}{q_{i,max} - q_{i,min}} \right)^2 
\]  

(5.18)

where \([q_{i,min}, q_{i,max}]\) is the feasible angular motion range of joint \( i \) with midpoint \( q_{i,mid} \) [187].

Optimisation can be performed either locally or globally. One commonly used local optimisation technique resembles the projected gradient approach for constraint minimisation. It consists of minimising a scalar performance criteria depending on the joint configuration \( H(q) \) by assigning the arbitrary velocity vector \( \dot{q}_0 \) in Equation (5.8) in the opposite direction of the gradient of \( H(q) \), \textit{i.e.}:

\[
\dot{q}_0 = -k_H \nabla H(q) 
\]  

(5.19)

where \( k_H \) is a scalar step-size and represents a critical parameter for the perfor-
mance of such redundancy resolution scheme. It can be demonstrated that the corresponding inverse kinematic solution given by:

\[
\dot{q} = J_t^\dagger t - k H \left( I - J_t^\dagger J_t \right) \nabla H (q)
\]

(5.20)

locally minimises the function:

\[
L (q, \dot{q}) = \frac{1}{2} \dot{q}^T \dot{q} + k H \dot{q}^T \nabla H (q)
\]

(5.21)

which represents a compromise between the satisfaction of the minimum-norm joint velocity constraint and the unconstrained local minimisation of \( H (q) \) \[187\].

Although local optimisation cannot guarantee singularity avoidance, it is simple to implement and can be used for real-time applications. On the other hand, global optimisation would ensure singularity robustness but the solution could not exist and generally cannot be expressed in a closed-form.

5.2.1.3 Redundancy resolution via task augmentation

Another approach to solving redundancy involves the use of additional constraints to augment the task so that all the extra DoFs become necessary. These constraints can either enforce the original end-effector task to generate the so-called extended Jacobian or introduce a different set of constraint tasks to form the augmented Jacobian. The first technique \[188, 189\] aims to identify the optimal solution as the one that satisfies a homogeneous constraint in the null-space of the Jacobian matrix, \( i.e. \) in the space spanned by the matrix:

\[
N_{J_t} = I - J_t^\dagger J_t.
\]

(5.22)

In particular, if the objective function \( g (q) \) to be optimised is at an extreme value for a given \( t_0 \) and at a configuration \( q_0 \) for which \( t_0 = k t (q_0) \), the following condition holds:

\[
\left. \frac{\partial g (q)}{\partial q} \right|_{q=q_0} N_{J_t} (q_0) = 0^T
\]

(5.23)

which (when \( J_t \) has full rank \( M \)) corresponds to the set of \( N - M \) independent constraints:

\[
h (q) = \left( \frac{\partial g (q)}{\partial q} [v_{M+1} (q), \ldots, v_N (q)] \right)^T = 0
\]

(5.24)

where \([v_{M+1} (q), \ldots, v_N (q)]\) constitutes a base of \( N_{J_t} \). Equation (5.23) can therefore be incorporated in the direct kinematics of the manipulator to describe any motion starting at initial configuration \( t_0 = k t (q_0) \) and keeping the function \( g (q) \) extremised along trajectory \( t (t) \):
Differentiation with respect to time of Equation (5.25) gives the square extended Jacobian matrix $J_{\text{ext}}$:

\[
\begin{pmatrix}
J_t(q)
\frac{\partial h(q)}{\partial q}
\end{pmatrix} \dot{q} = J_{\text{ext}}(q) \ddot{q} = \begin{pmatrix}
\dot{t}
0
\end{pmatrix} \tag{5.26}
\]

which can be inverted to find the corresponding joint velocities:

\[
\dot{q} = J_{\text{ext}}^{-1}(q) \begin{pmatrix}
\dot{t}
0
\end{pmatrix} \tag{5.27}
\]

In contrast to the extended Jacobian approach, the augmented Jacobian method [190, 191] sets the additional constraints in the task space through the constraint-task vector $t_c = (t_{c,1}, \ldots, t_{c,P})$ with $P \leq N - M$. The relationship between the constraint-task vector and the manipulator configuration can be written as a direct kinematics equation:

\[
t_c = k_c(q) \tag{5.28}
\]

with $k_c$ a non-linear continuous vector function. Differentiation with respect to time of Equation (5.28) gives the mapping between constraint-task velocities $\dot{t}_c$ and joint velocities $\dot{q}$:

\[
\dot{t}_c = J_c(q) \dot{q} \tag{5.29}
\]

where $J_c(q) = \partial k_c(q)/\partial q$ is the $P \times N$ constraint-task Jacobian matrix. Defining the augmented-task vector as:

\[
t_a = \begin{pmatrix}
t \\
t_c
\end{pmatrix} = \begin{pmatrix}
k_t(q) \\
k_c(q)
\end{pmatrix} \tag{5.30}
\]

it is possible to find a configuration $q$ satisfying both end-effector and constraint-task by inverting the differential equation:

\[
\dot{t}_a = J_a(q) \ddot{q} \tag{5.31}
\]

where $J_a$ is the augmented Jacobian matrix given by:

\[
J_a = \begin{pmatrix}
J_t \\
J_c
\end{pmatrix} \tag{5.32}
\]

However, the augmentation of the Jacobian matrix can generate algorithmic sin-
gularities when the constraint task conflicts with the end effector task [188]. To avoid incurring algorithmic singularities, the task priority approach assigns higher priority to a primary task (usually the end-effector task) and satisfies low-priority tasks within the null space of the primary task [192]. This is achieved by loosening the constraint-task velocity condition to minimise the reconstruction error $\dot{t}_c - J_c \dot{q}$ using null-space velocities, i.e. by substituting in Equation (5.8) the expression:

$$\dot{q}_0 = \left[ J_c \left( I - J_t^\dagger J_t \right) \right]^\dagger \left( \dot{t}_c - J_c J_t^\dagger \dot{t} \right).$$  \hspace{1cm} (5.33)

Since the projection of the solution of the low-priority task in the null-space of the primary task $J_c \left( I - J_t^\dagger J_t \right)$ is still subject to algorithmic singularities even when both task and constraint Jacobians are not singular, although correct solutions are still guaranteed for the primary task, large joint velocities may occur in the vicinity of a singularity. One way of decoupling end-effector and constraint solutions is to use only null-space joint velocities to solve the secondary task constraint [193], i.e. by setting:

$$\dot{q}_0 = \left( I - J_t^\dagger J_t \right) J_t^\dagger \dot{t}_c.$$

(5.34)

However, CLIK implementation is usually necessary in order to minimise the error in trajectory reconstruction induced by the secondary-task tracking error in proximity of algorithmic singularities. Specifically, Equation (5.8) becomes:

$$\dot{q} = J_t^\dagger \omega_t + \left( I - J_t^\dagger J_t \right) J_t^\dagger \omega_c.$$

(5.35)

with:

$$\omega_t = \dot{t} + K_t \left( t - k_t (q) \right)$$

$$\omega_c = \dot{t}_c + K_c \left( t_c - k_c (q) \right).$$

(5.36)

It is important to note that one of the major disadvantages of common redundancy resolution schemes is the lack of cyclicity or repeatability, i.e. the final configuration does not correspond to the initial one for periodic task-space trajectories. The cyclicity condition must be addressed on a case-by-case basis, since it depends on both the inverse generalised form used to solve redundancy and the mechanical structure of the manipulator. In practice, the only solution based on differential kinematics which satisfies the repeatability condition is the extended Jacobian approach [170].

### 5.2.1.4 Second-order redundancy resolution

In order to consider the dynamic performance of the manipulator during motion, redundancy must be solved at the acceleration level. The relationship between task-space and joint-space accelerations can be derived from differentiation with respect
to time of Equation (5.2) as:

$$\ddot{\dot{q}} = J_t (q) \ddot{q} + J_t (q, \dot{q}) \dot{q}.$$  
(5.37)

Similarly to the case of joint velocity control, the pseudo-inverse of the task-Jacobian matrix can be used to express the least squares solution of Equation (5.37) in the general form:

$$\ddot{q} = J_t^\dagger (\ddot{t} - J_t \dot{q}) + (I - J_t J_t^\dagger) \ddot{q}_0$$  
(5.38)

where $\ddot{q}_0$ represents an arbitrary joint-space acceleration. The minimum-norm acceleration solution can be obtained by setting $\ddot{q}_0 = 0$ in Equation (5.38) [167]. However, the computational complexity of second-order redundancy resolution schemes does not allow real-time applications. This is due to the need of resolving a Two-Point Boundary Value Problem (TPBVP) to ensure minimisation over the entire trajectory of the norm of the joint velocities, which is guaranteed only locally by using the Jacobian pseudo-inverse solution [194].

Local minimisation of the actuator torque norm can also be achieved by properly assigning the null-space acceleration vector in Equation (5.38) [195]. In particular, if the dynamic model of the manipulator is traditionally expressed as:

$$\tau = M(q) \ddot{q} + c(q, \dot{q}) + \tau_g(q)$$  
(5.39)

where $\tau$ is the vector of the actuator torques, $M$ the inertia matrix of the robot, $c$ the vector of centrifugal and Coriolis terms and $\tau_g$ the gravitational torque vector, the choice:

$$\ddot{q}_0 = - \left[ M \left( I - J_t J_t^\dagger \right) \right] \ddot{t}^\dagger \tilde{\tau}$$  
(5.40)

with:

$$\tilde{\tau} = M J_t^\dagger (\ddot{t} - J_t \dot{q}) + c + \tau_g$$  
(5.41)

ensures the local minimisation of $\tau^T \tau$. Nonetheless, this approach may still lead to instability due to high joint torques over long tasks, therefore the solution of a TPBVP is still required to globally minimise the integral joint torque [196].

Finally, a modified solution of the second-order differential kinematics utilises an inertia-weighted task Jacobian pseudo-inverse $J_{t,M}^\dagger$, given by:

$$J_{t,M}^\dagger = M^{-1} J_t^T \left( J_t M^{-1} J_t^T \right)^{-1}.$$  
(5.42)

In this case, the solution:

$$\ddot{q} = J_{t,M}^\dagger (\ddot{t} - J_t \dot{q}) + \left( I - J_{t,M} J_t \right) M^{-1} c$$  
(5.43)
globally minimises the integral of the manipulator kinetic energy when the correct boundary conditions are used [194].

5.2.2 Continuum kinematics resolution using parametrised backbone curves

The methods described above have the main advantage of being well established in the literature and applicable to any type of redundant rigid-link structure. However, the computational complexity and burden of the Jacobian pseudo-inverse matrix becomes extremely high in the presence of a large number of DoFs. It has been discussed that the extended Jacobian with task priority approach gives the best results in terms of singularity avoidance and repeatability of the joint configuration for periodic task trajectories. Nonetheless, the specification of such a large number of additional constraints can be challenging, especially for implementing shape conformance tasks (e.g. path following, obstacle avoidance) which are not directly focused on the end-effector motion. These considerations have led to the development of specialised techniques for the modelling of hyper-redundant robots which are based on the concept of a “backbone curve” describing their geometric behaviour at a macroscopic level. Chirikjian and Burdick [197] were among the firsts to adopt this approach, which has been further extended by several authors [198–200].

As already introduced in Chapter 4, the backbone curve approach is based on the definition of a piecewise continuous curve to geometrically describe the motion of a hyper-redundant robot and typically coincides with its centreline. The curve is then parametrised using a set of orthonormal frames placed at different locations along its length. The basic concept behind this method is that of a continuum manipulator, which takes hyper-redundancy to the limit by implementing an infinite number of joints with link lengths that tend to zero. Although this design is relatively easy to realise in practice, only a finite number of DoFs can be physically actuated by applying forces/torques to the backbone at fixed and pre-selected locations. Therefore, continuum structures are at the same time hyper-redundant and under-actuated, which causes significant complexity in their modelling and control [170].

Although different authors have proposed alternative methods to parametrise the backbone curve (e.g. [198]), the most common and well established choice is the Serret-Frenet frame, evolving along the backbone according to:

\[
\begin{align*}
\frac{dt}{ds} &= \kappa n, \\
\frac{dn}{ds} &= -\kappa t + \tau b, \\
\frac{db}{ds} &= -\tau n. \tag{5.44}
\end{align*}
\]

In particular, Equations (5.44) describe how the three axes of the orthonormal frame
change with respect to the arc length of the curve $s$ due to its shape, which is in turn defined by the curvature $\kappa$ and torsion $\tau$. The first axis is assigned as the tangent $t$ to the curve at the frame origin $x$ (i.e. $t = \frac{dx}{ds}$), while the other two axes are the normal $n$ (i.e. $t \cdot n = 0$) and the binormal $b = t \times n$. This parametrisation allows to geometrically describe the local motion of the frame in three dimensions, specifically two bending motions corresponding to rotations about the normal and binormal axes and an extension/contraction motion represented by the translation along the tangent axis [201].

5.2.2.1 Rigid-link motion approximation via mode selection and curve fitting

Parametrisation of the set of reference frames along the backbone curve using its arc length allows the computation of the forward kinematics of any hyper-redundant structure in terms of continuum Jacobian matrices. In particular, the inverse kinematics problem in this case is reduced to the determination of a proper time-varying behaviour of the backbone reference set to achieve the desired robot motion [202]. Although this represents a much less demanding computational task than the derivation of joint variables using pseudo-inverse Jacobian approaches, the fundamental drawback of continuum kinematics models is that they have to be constrained to represent physical robotic motions, which can only be controlled in a finite number of ways, as discussed before. This transition from continuum model to discrete hardware implementation can be achieved through either a top-down or a bottom-up approach [170].

The top-down approach for solving the continuum inverse kinematics problem consists of building a general model of the robot motion using a theoretical backbone curve and then adapting it to a discrete specific robot centreline [197, 198, 202]. One way of restricting the number of allowable solutions for shape matching resulting from the infinite redundancy of the continuum model is to use a modal approach. In this case, the set of possible motions is generated as a linear combination of pre-selected modes, corresponding to the basic bending and translation movements [200, 203]. Although this method has proven to be effective, it relies on approximating both the assigned continuum motion and the fitted discrete shape of the real robot, thus introducing a number of intrinsic errors in the accuracy of shape control. In addition, the derivation of a dynamics model by approximation of the continuum backbone curve carries the same computational demand of traditional recursive methods while lacking of intuitiveness in matching the resulting forces and torques to physical actuation strategies [204].

The bottom-up approach to discretisation of continuum kinematics models has been proposed more recently as a dual concept to the one described above [205, 206]. The basic idea behind this method is to use the physical constraints imposed on the
backbone of specific robotic hardware to build continuum kinematics models with adequate accuracy to avoid approximations in the motion planning phase. In practice, the application of a finite number of forces/torques on a stiff continuum backbone generates a final structure comprising a finite number of constant curvature sections, which can therefore be modelled as rigid links using conventional methods. As a result, a series of Jacobians is obtained which describes the continuum kinematics of the robot as a function of locally meaningful variables (e.g. bending angle, curvature, extension) defining the shape of each link or the corresponding type of actuators. Within this framework, the redundancy is finally resolved using the same techniques described for rigid-links redundant manipulators, thus inheriting a similar set of advantages and drawbacks [170].

5.2.2.2 Shape regulation and tracking based on curve parameter estimation

A different approach to modelling the kinematics of hyper-redundant manipulators using a spatial curve was proposed by Mochiyama et al in [199]. The main aim of this method is to accurately track an assigned time-varying shape using the whole body of the robot and not only the end-effector. To this end, the hyper-redundant robot is modelled as a rigid-link structure using traditional Jacobian matrices, while the desired shape is defined as a spatial curve parametrised using a moving Serret-Frenet frame according to Equations (5.44). Similarly to the backbone curve approaches presented above, the continuum inverse kinematics problem is solved by fitting the discrete manipulator model to the continuum curve shape; however, rather than determining the robot configuration that best approximates the assigned trajectory, the method finds the curve which most closely represents the physical characteristics of the robot through curve-parameter estimation. Although this approach simplifies the computation of the joint variables corresponding to the assigned time-varying frames, the estimation of the curve parameters via inverse-dynamics or Lyapunov control cannot be achieved in real-time.

5.3 Shape control under active constraints for a hyper-redundant robot for MIS

The above analysis of traditional and specialised approaches to the kinematic modelling and shape control of hyper-redundant manipulators demonstrates the need for an effective way of handling the high complexity of the problem. For MIS applications, the complexity is further enhanced by the introduction of haptic feedback and active constraints to ensure safe operation. Therefore, the proposed DoF minimisation scheme aims to simplify this problem by identifying the DoFs that need to be simultaneously actuated and constrained to guarantee shape conformance to
a specific time-varying trajectory.

The first step of the algorithm is however to find the optimal hyper-redundant solution to analyse the corresponding motion of each joint. This is achieved by minimising a cost function similar to the one introduced in Chapter 4 describing the distance between the robot body and the centreline of a dynamic active constraint. However, in this case the inverse kinematics of the entire robot is computed at each time-frame. The forward kinematics of the robot is determined using the traditional rigid-link model due to the envisioned physical implementation of the device. This also accounts for increased flexibility of the approach, which aims to achieve shape control within a volumetric margin rather than accurate conformance of the robot body to a 3-D parametric curve. Although the optimal inverse kinematics solution is not computed in real-time, it can be derived pre-operatively on the basis of accurate models of the periodically deforming organs and then updated intra-operatively according to sensing information, as explained in the following sections.

5.3.1 Kinematic structure of the robot

For numerical assessment of the proposed algorithm, a generic 30-DoF snake-like robot is considered. It consists of 15 rigid links of equal length connected by universal joints. Each link is represented as a 20mm long cylinder and each universal joint as a sphere, both 10mm in diameter. Such modular structure simplifies the kinematic formulation for real-time control and practical applications. For kinematic analysis, a local coordinate system is defined for each link with the origin specified at the centre of the sphere representing the actuating universal joint. The origin of the world coordinate frame is instead placed at the origin of the active constraint model. As explained in Chapter 4, according to the standard Denavit-Hartenberg (D-H) convention [160], the transformation between two consecutive link frames \( i \) and \( i + 1 \) can be expressed in terms of the \( i \)th universal joint angles \( q_{i,1}, q_{i,2} \) and the length of the link \( L \) as a 4 \( \times \) 4 matrix \( T_{i}^{i+1} \):

\[
T_{i}^{i+1} = \begin{bmatrix}
c(q_{i,1})c(q_{i,2}) & -s(q_{i,1})c(q_{i,2}) & 0 & c(q_{i,1})c(q_{i,2})L \\
s(q_{i,1})c(q_{i,2}) & c(q_{i,1}) & c(q_{i,1})s(q_{i,2}) & s(q_{i,1})c(q_{i,2})L \\
s(q_{i,2}) & 0 & c(q_{i,2}) & s(q_{i,2})L \\
0 & 0 & 0 & 1
\end{bmatrix}
\]  \( (5.45) \)

where \( c(q_{i,j}) \) and \( s(q_{i,j}) \) with \( j = 1, 2 \) represent \( \cos(q_{i,j}) \) and \( \sin(q_{i,j}) \) respectively. The overall forward kinematic equations describing the position and orientation of the end-effector with respect to the world reference frame are therefore given by:

\[
T_{0}^{n+1}(q) = T_{0}^{1} \prod_{i=1}^{n} T_{i}^{i+1}(q_{i,1}, q_{i,2})
\]  \( (5.46) \)
where \( n \) is the number of links, \( q = (q_{1,1}, q_{1,2}, \ldots, q_{i,1}, q_{i,2}, \ldots, q_{n,1}, q_{n,2}) \) is the vector of the joint variables and \( T_{0}^{1} \) is the matrix defining the pose of the first link with respect to the world reference frame. It is important to note that this study only addresses the shape of the robot’s body while the “head” is free to move outside the active constraint and can be directly controlled by the surgeon. As explained in the next section, the location of the end-effector is fixed since it determines the position of the head, the kinematic chain of which is not considered in the optimisation.

5.3.2 Surgical model

The surgical scenario used for kinematic analysis in this study is laparoscopic liver resection. It is technically complex, involving a high risk of haemorrhage and gas embolism, and is hampered by the limitation of exploring the deeper regions of the organ. According to Couinaud’s classification, only the anterolateral 2 to 6 segments of the liver are considered consistent with the laparoscopic approach, while the upper right part of the organ (segments 7 and 8) is difficult to reach with standard instrumentation (Figure 5.1(a)) [174]. As shown in Figure 5.1(b), laparoscopic resection of lesions in the right side of the liver involves the use of 4 instrument ports on the patient abdomen [207]. In addition, both respiratory and cardiac cycles affect the shape of the liver generating large tissue deformation. The use of an articulated robotic instrument in such a scenario could improve the outcome of the procedure by ensuring safe navigation to the operative site and augmented stability for operation. The complexity of the instrument path together with the high amount of deformation makes this surgical scenario particularly challenging, and thus is ideal for assessing the validity of our method.

For the purpose of this study, a virtual lesion to be excised through a minimally invasive approach is located on the back surface of the liver at the level of segment 7. An example path to be followed by the flexible instrument is defined along the surface of the liver and a dynamic active constraint delimits the safe region of navigation, as shown in Figure 5.2. To be consistent with the laparoscopic configuration, the first point of the path representing the entry point of the instrument on the patient’s body is fixed and located in the lower-left part of the liver (Figure 5.2(a)). The last point is placed in correspondence of the liver lesion behind segment 7 and is kept stationary to ensure adequate stability, since it determines the location of the head of the robot which is free to move for surgical operation and not shown in the model (Figure 5.2(c)).

5.3.3 Definition of the active constraint

Safe manipulation of articulated robotic devices in MIS requires consideration of the allowable workspace coupled with the anatomical structures surrounding the entire body of the device, rather than simply the motion of a single-point end-
Figure 5.1: Anatomical considerations for laparoscopic liver surgery. (a) Couinaud classification of liver’s segments; the anterolateral 2 to 6 segments are considered safe for the laparoscopic approach. (b) Typical port placement for resection of lesions in segments 5 through 8.

effect. Relying on the support of anatomical structures to constrain or guide the device is considered to be unsafe and insufficient for protecting the delicate tissues from being accidentally perforated. A real-time modelling scheme to construct a smooth cylindrical pathway with detailed geometric constraints has been recently proposed at the Hamlyn Centre in order to provide a safety boundary with explicit manipulation margins for the entire articulated device [122]. This follows the concept of dynamic active constraints or virtual fixtures, which can react and adapt to tissue deformation.

Pre-operatively, a surgical planning interface is provided to enable the operator to set a reference pathway defining a volumetric margin for the articulated robot. In order to avoid the defined pathway colliding with the anatomical models and to enable accurate prescription, a haptic device (Omni PHANTOM, Sensable Tech. Inc., USA) is used as a 3-D coordinate input device to indicate contact with the anatomical models during the placement of the control points. The deforming 3-D model of the liver used for this study is reconstructed by segmentation of pre-operative 4-D (Four-Dimensional) CT (Computerised Tomography) scan images of a real patient. The maximum displacement of the diaphragm for this specific case is 16mm. The corresponding peak-to-peak maximum deformation of the constraint adapting to the induced liver deformation is about 14.5mm. As previously explained, this model is used to predict the desired joint motion and has to be integrated with intra-operative data for in vivo applications. As an example, a real-time dynamic shape instantia-
Figure 5.2: Active constraint modeled on the surface of the liver from three different perspectives. The constraint dynamically adjusts its shape according to the liver deformation due to respiratory and cardiac cycles. The corresponding optimal configuration of the hyper-articulated robot inside the active constraint is also shown.
tion method has recently been developed at the Hamlyn Centre to obtain a detailed 3-D deformation model of the liver using imaging data [208]. Proximity query is performed offline to compute the deviation of the robot into the forbidden region defined as outside the volume prescribed by the active constraints as described in [173].

5.3.4 Computation of the optimal hyper-redundant inverse kinematic solution

As previously stated, the head of the snake robot is not considered in the optimisation algorithm since it is usually controlled directly by the surgeon and free to move outside the constraint. The optimal configuration at each time-frame is therefore determined by ensuring that the position of the end-effector remains stationary while the body of the robot conforms to the pre-defined trajectory. This condition can be fulfilled by constraining the motion of each link independently, thus eliminating the need of expressing the inverse kinematics of the end-effector in a closed-form solution.

5.3.4.1 Singularities and local minima

Two singularity conditions must be addressed to ensure the stability of kinematic control methods: position singularities and reduced-rank Jacobian singularities. As already discussed in detail, reduced-rank Jacobian singularities are related to the dexterity of the robot’s head, which is not involved in the optimisation. Nonetheless, singularities can still occur when the trajectory between two consecutive time-frames cannot be followed continuously due to solutions with large joint angle differences. This can be avoided by exploiting the hyper-redundancy so that the motion is equally distributed among different joints. This is ensured by minimising the total joint angle displacement between consecutive time-frames, as explained in the following section. Such constraint is also important for preventing the algorithm from falling into local optima resulting from the multiple inverse kinematics solutions of redundant structures [167].

A position singularity normally occurs when a point of the end-effector trajectory is outside the robot workspace. In our case, the robot body must possess the necessary flexibility to conform to various configurations with adequate accuracy while keeping a fixed end-effector position. This requires the introduction of an additional translational degree of motion at the base of the robot, corresponding to the sliding of the first link inside the trocar port on the patient abdomen. However, this motion is not considered in the optimisation as it is assigned in order to compensate for the difference in path length between time-frames by varying the position of the first robot link.
5.3.4.2 Objective function and optimisation constraints

Since the end-effector is assumed to be target locked, the performance equation for the selection of the optimal inverse kinematics solution does not include a measure of manipulability. The workspace and dexterity of the articulated instrument depend on the head configuration, which is in turn dictated by the type of surgical procedure. On the other hand, the main performance measure is the distance $D$ between the robot’s body and the constraint’s centreline. Also to be minimised is the joint angle displacement between two consecutive configurations $R$, so that the objective function at the $k$-th time-frame is given by:

$$F_k = k_d \frac{D_k}{D_{MAX}} + k_r \frac{R_k}{R_{MAX}}$$

(5.47)

where $k_d$ and $k_r$ are weights determining the importance of each measure in the selection of the optimal solution. Each measure is also normalised with respect to the maximum allowable value.

Particularly, the maximum allowable distance between the robot’s body and the constraint’s centreline $D_{MAX}$ corresponds to the maximum radius of the active constraint, since it defines the safe region of motion. In contrast to [209] where the active constraint is treated as a constraint of the optimisation, this formulation allows the robot to deviate from the pre-set constraint. This increases the flexibility of the proposed algorithm, as it accounts for modifications of the volumetric shape of the constraint according to intra-operative changes. The maximum allowable angle displacement $R_{MAX}$ is instead given by the physical limits of the micromotor used for actuation. The range of motion of each joint is set between $-45^\circ$ and $+45^\circ$. This is also set as the boundary limit for the search of the optimal solution $[q_{lb}, q_{ub}]$. In addition, the physical limit of robotic actuation is also addressed by bounding the joint velocities $\dot{q}$ according to the maximum motor speed in the range $[\dot{q}_{lb}, \dot{q}_{ub}] = [-1, 1] \pi \text{ rad/s}$. Assuming a very short time interval $\Delta t$ between frames, the velocity limit can be converted to an angular displacement range referring to the joint configuration $q_{k-1}$ optimised at the previous frame $k - 1$. Thus, the overall constraint is expressed as:

$$\begin{cases} 
q_{lb} \leq q_k \leq q_{ub} \\
(q_{lb} \Delta t + q_{k-1}) \leq q_k \leq (q_{ub} \Delta t + q_{k-1})
\end{cases}$$

(5.48)

All the values of the constant parameters in Equation (5.47) are reported in Table 5.1, where the time interval between two consecutive time-frames is based on a typical respiration rate of 15 cycles per minute. This is reasonable since most of the liver deformation is generated by respiratory motion.

The distance $D$ between the robot’s body and the constraint’s centreline at the $k$-th time-frame is defined as:
Table 5.1: Values of the parameters in the objective function.

<table>
<thead>
<tr>
<th>$k_d$</th>
<th>$k_r$</th>
<th>$D_{MAX}$</th>
<th>$R_{MAX}$</th>
<th>$k$</th>
<th>$\Delta t$</th>
<th>$n$</th>
<th>$L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5</td>
<td>9.04mm</td>
<td>90°</td>
<td>25</td>
<td>0.16s</td>
<td>15</td>
<td>20mm</td>
</tr>
</tbody>
</table>

\[
D_k = \sum_{i=1}^{n} \| \hat{x}_i - x_{i,k} \| \quad (5.49)
\]

where $x_{i,k}$ is the desired position of the $i$-th universal joint on the constraint’s centreline at the $k$-th time-frame and $\hat{x}_i$ is the actual position of the $i$-th universal joint given by the spatial translation vector of the transformation matrix:

\[
T^i_0(q) = T^1_0 \prod_{j=1}^{i-1} T^{j+1}_j(q_{j,1}, q_{j,2}) \quad (5.50)
\]

which is derived from Equation (5.46). The first universal joint is not considered in the optimisation since it is located outside the active constraint (see Figure 5.2) and its position is pre-defined by the transformation matrix $T^0_1$ according to the desired trajectory using the additional translational degree of freedom.

The joint angle displacement $R$ at the $k$-th time-frame is defined as:

\[
R_k = \sum_{i=1}^{N_{DoF}} |\Delta q_i| \quad (5.51)
\]

where $N_{DoF} = 2n$ is the number of DoFs and $\Delta q_i = q_{i,k} - q_{i,k-1}$ is the change in joint angle $q_i$ with respect to the previous time-frame.

The optimisation algorithm is implemented in MATLAB® using the embedded function `fmincon` to find the inverse kinematic solution $q_k$ within the allowable joint motion range at each time-frame by minimising the value of $F_k$ subject to the non-linear equality constraint:

\[
\| \hat{x}_{n+1} - x_{n+1} \| = 0 \quad (5.52)
\]

where $x_{n+1}$ is the fixed desired position of the end-effector on the constraint’s centreline and $\hat{x}_{n+1}$ is the actual position of the end-effector given by the 3-D translation vector of the transformation matrix (5.46). This condition ensures that the position of the end-effector remains constant at each time-frame.

5.3.4.3 Optimisation results

With the inverse kinematic solution found by the optimisation algorithm, the body of the robot successfully conforms to the deforming active constraint during the whole
Table 5.2: Values of the resulting optimisation parameters.

<table>
<thead>
<tr>
<th>$N_{\text{DoF}}$</th>
<th>$t_{\text{comp}}$ [s]</th>
<th>$\bar{F}$</th>
<th>$F_{\text{max}}$ [rad/s]</th>
<th>$\dot{q}_{\text{max}}$ [rad/s]</th>
<th>$\bar{p}$ [mm]</th>
<th>$p_{\text{max}}$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>336</td>
<td>0.1048</td>
<td>0.3481</td>
<td>1.5018</td>
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<td>1.1452</td>
<td>2.1245</td>
<td>1.4754</td>
<td>0.0422</td>
<td>2.2133</td>
</tr>
<tr>
<td>6</td>
<td>28</td>
<td>1.3947</td>
<td>2.3770</td>
<td>1.4962</td>
<td>0.0534</td>
<td>2.7968</td>
</tr>
<tr>
<td>5</td>
<td>26</td>
<td>1.7564</td>
<td>3.1930</td>
<td>1.4548</td>
<td>0.0665</td>
<td>3.2888</td>
</tr>
<tr>
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<td>14</td>
<td>2.5600</td>
<td>4.6378</td>
<td>1.5439</td>
<td>0.0902</td>
<td>3.6481</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>4.8425</td>
<td>9.2502</td>
<td>1.5439</td>
<td>0.3912</td>
<td>8.3331</td>
</tr>
</tbody>
</table>

respiratory cycle without exceeding the maximum motor speed. All the values of the simulation parameters are reported in Table 5.2. The maximum joint angular velocity $\dot{q}_{\text{max}}$ is found to be 1.5018 rad/s and the computational time $t_{\text{comp}}$ is 336s. This is reported as a measure of complexity to show how it decreases with the number of active DoFs since the method should be used pre-operatively to predict the joint motion and then updated real-time according to intra-operative data, as discussed at the end of this chapter. The minimum value of the objective function is always below 0.3481 and the maximum deviation outside the safety region $p_{\text{max}}$ is 1.4763 mm. This error occurs at the end of the path corresponding to a particularly tortuous and narrow section of the constraint, as visible in Figure 5.2. The use of shorter rigid links would allow for more accurate shape matching in this region; however, the force exerted on the tissue resulting by such a small deviation should not generate safety issues.

5.4 DoF minimisation scheme for optimised shape control during MIS

Once the optimal inverse kinematics solution is found, the amount of angular displacement for each joint among all time-frames is computed. The necessary degrees of freedom are then identified as the ones with a joint motion range higher than 0.2 rad. This value is chosen by comparing the average and maximum angular displacement of each joint among all time-frames. In this specific case, 7 DoFs are needed to ensure shape conformance - a significant improvement over the original 30 DoFs.

Once the active joints are identified, the optimisation algorithm is implemented again to compute the optimal inverse kinematics solution when only the selected joints are free to move and the others remain fixed. The optimal hyper-redundant solution corresponding to the 13-th time-frame is chosen as the initial configuration since it features an average amount of deformation during the respiratory cycle and
the result of the optimisation largely depends on the values of the fixed joints. Once
the minimum DoF configuration is determined, the number of active joints is further
decreased by fixing one at a time the DoF with minimum angular displacement over
the different time-frames. The optimal inverse kinematics solution is determined
in each case by using the proposed optimisation algorithm and the corresponding
results are reported in Table 5.2.

5.4.1 Accuracy assessment of the minimised DoF control

When the number of available degrees of freedom is decreased from 30 to 7, the
computational time is reduced almost 10 times since the kinematics of the robot is
much simpler, while the value of the maximum deviation is still approximately 2mm.
Figure 5.3 shows the comparison of maximum deviation values at each time-frame
between three different cases: a fixed solution corresponding to the initial configura-
tion, the minimised 7-DoF solution and the hyper-redundant solution. The periodic
movement of the active constraint adapting to the liver deformation is clearly shown
on the graph. Figure 5.3 also demonstrates that the maximum deviation is already
more than halved by using only 7 DoFs.

![Figure 5.3: Comparison of maximum deviation values at each time-frame for three different cases: the robot configuration remains constant while the constraint moves (in blue), the robot adapts its configuration according to the constraint motion using all the available DoFs (in red) or only a minimum number of DoFs (in green).](image)

It can be seen from Table 5.2 that the maximum deviation is less than 3mm
when using 6 DoFs and below 4mm when using 5 or 4 DoFs. Higher values of
deviation are encountered when less DoFs are used, which is as expected as the
instrument now becomes more rigid. The maximum joint angular velocity is always
lower than the motor speed limit and the mean value of the deviation $\bar{\rho}$ is much
smaller than the maximum value. These results also suggest that when using a minimum number of DoFs, only a small portion of the robot is beyond the active constraint. This is demonstrated in Figure 5.4, which shows the maximum deviation outside the constraint for each link at each time-frame for both the redundant (a) and the 7-DoF configuration (b). Deviation outside the constraint mainly occurs in correspondence of the distal links.

**Figure 5.4:** Comparison of maximum deviation values at each time-frame for each link for redundant (a) and minimised DoF (b) configurations. Cold colors correspond to lower values of deviation.
5.4.2 Experimental validation of the minimised DoF control

To demonstrate the practical application of the proposed algorithm, controlled laboratory experiments have been performed using an articulated access device for MIS with embedded positional feedback. The robot is an early prototype of the 7-DoF system described in Chapter 2 featuring 5 independently controllable DoFs arranged as two distal universal joints (intersecting pitch and yaw) and one proximal single-DoF joint (yaw only). The angular displacement of each motor is sensed by a potentiometer mounted on the axis of rotation as described in Chapter 3. The anatomical model is obtained by deforming a liver phantom with a custom mechanical device simulating the motion induced by the diaphragm during respiration. Details of the motion model and mechanical device can be found in [210]. Optical markers are attached to the phantom to measure its deformation using an optical tracker (Optotrak Certus, NDI, Canada) and reconstruct the surface to generate the active constraint. Photos of the experimental set-up are shown in Figure 5.5.

![Figure 5.5: Photos of the experimental set-up for validation of the minimised DoF control. (a) Close-up picture of the custom mechanical device used to simulate the motion induced by the diaphragm on the liver during respiration; (b) Photo showing the liver phantom with attached optical markers placed inside the custom mechanical device.](image)

The robot is mounted on an optical table and the active constraint in this case is defined so that the first point and the overall path length are fixed during the motion. Also, due to the limited number of available DoFs, the constraint on the fixed robot tip position is removed from both the active constraint and the optimisation algorithm. The maximum displacement induced by the mechanical device on the liver phantom is 9.5mm and the corresponding peak-to-peak deformation of the constraint is 29mm. This high value is due to the fact that the phantom translation is not constrained in the laboratory environment. Figure 5.6(a) shows the simulated robot and constraint configurations at the two extreme motion positions. The corre-
sponding real robot configurations are depicted in Figures 5.6(b)-(c), where optical tracking of the robot and liver phantom is performed simultaneously to synchronise the motion of the robot to the induced phantom deformation.

To match the kinematic model of the robot with the one in Equation (5.46), an additional constraint is introduced on the pitch axis of the proximal joint to keep its angular displacement equal to zero during the entire motion cycle. The three rigid links have an equal length of 35mm plus 9mm of universal joint unit, giving a total of 44mm, while the diameter of the device is 12.5mm. Each cycle of the periodic motion has duration of 3 sec and is divided in 23 equally spaced time-frames selected from the tracking data. Inverse kinematic control is implemented in the LabVIEW™ software environment as described in Chapter 3 according to the angular values obtained from the optimisation algorithm.

The graphs in Figure 5.7 show the values of the potentiometer readings during one motion cycle with (b) and without (a) DoF minimisation control. Motors are numbered incrementally from the most distal to the most proximal part of the robot. It is clear from the plot in Figure 5.7(a) that motors 2 and 3 have the maximum angular displacement across all time-frames, and therefore compensate for most of the deformation. These observations suggest that the minimum number of DoFs needed to ensure shape conformance in this case is only 2. Figure 5.7(b) demonstrates that in the 2-DoF case the control is able to keep motors 1, 4 and 5 at a fixed angular position within the range of accuracy of the potentiometer readings (about 1 degree).

The potentiometer readings are used in the simulation environment to compute again the forward kinematics of the robot (Equation (5.46)) and determine the maximum deviation outside the active constraint. The plot in Figure 5.8 shows the corresponding value at each time-frame for the 5-DoF and 2-DoF case. It is important to note that the deviation values are much lower with minimised DoF control. This is due to the fact that the simultaneous control and actuation of a higher number of DoFs can be susceptible to trajectory errors accumulating along subsequent joints and jitters introduced by sensing and control inaccuracy. Nonetheless, these results demonstrate the practical application and validity of the proposed algorithm.

5.5 Discussion and conclusions

In this chapter, an effective method for optimising the DoFs of an articulated device for MIS has been proposed. In particular, the minimum number of joints to be simultaneously actuated to perform time-varying shape conformance tasks without entering a pre-defined forbidden region has been determined. Both simulation and laboratory results have demonstrated the practical value of the technique, which greatly reduces the control dimensionality of the system. In addition, by addressing the angular displacement of each joint directly, the algorithm circumvents trajectory
Figure 5.6: (a) Configuration of the simulated robot inside the active constraint at the two extreme positions of full inspiration (blue rings) and full expiration (red rings); Photos showing the articulated robot conforming to the surface of the liver phantom at two extreme configurations corresponding to full inspiration (b) and full expiration (c).
Figure 5.7: (a) Plot of the potentiometer readings for the five simultaneously actuated motors during one cycle of motion; (b) Plot of the potentiometer readings for the five motors during one cycle of motion when only two DoFs are used to ensure shape conformance while the rest are fixed.
reconstruction errors or Jacobian singularities. However, the dynamic behaviour of the robot and its interaction with the tissue must still be analysed in order to prove the safety of the minimum DoF approach, as will be discussed in Chapter 7.

It should be noted that in both the simulated and experimental scenarios the deformation of the liver is perfectly periodic, while during an *in vivo* procedure it can also be affected by tissue-instrument interaction. Therefore, it is expected that the control architecture has to be refined by updating the inverse kinematic solution in real-time on the basis of intra-operative imaging or sensing data. This can be implemented in a number of ways, such as generalised predictive control [211] or Kalman filtering [212].

Moreover, although the smoothness of the inverse kinematics solution is enforced by the minimisation of the total joint angle displacement between consecutive time-frames, the corresponding joint velocities and accelerations are not directly addressed by the proposed optimisation algorithm. This can potentially be the cause of the increased jittering reported in the experimental results when controlling all the available DoFs simultaneously. In addition, the control of the joint’s angular position was based on the voltage readings obtained by the potentiometers without any additional filtering. The accuracy of the kinematic control during the experiment was therefore also affected by the oscillations generated by the combination of the resulting fluctuations of the sensed values with a direct on-off actuation of the motors according to the difference between the desired and the measured voltages. It is envisioned that the use of a more refined control architecture with additional filtering stages and modulated actuation of the motors on the basis of the dynamic response
of the system would highly increase the accuracy of the proposed control algorithm.

The control principle presented in this chapter is particularly relevant to the future implementation of robotic articulated instruments for flexible access surgery, for which path following and dynamic shape conformance are critical to ensure safe operation. This is due to the highly constrained and cluttered workspace of the peritoneal cavity, as well as the unoptimal location of the entry point on the patient body to reach the desired operative target. These issues will be considered in the next chapter, which will investigate the feasibility of \textit{in vivo} deployment of the flexible access platform described in Chapter 2 and the potential advantages of implementing kinematic control as proposed in this thesis.
6 In vivo validation for single-port surgery: a feasibility study based on workspace analysis

6.1 Introduction

As discussed in Chapter 2, transluminal and single-port techniques have been recently introduced to further reduce potential trauma associated with Minimally Invasive Surgery (MIS). The specific requirements for the development of specialised instrumentation that would enable safe performance of such procedures, however, have highlighted a number of technical challenges that have yet to be overcome. Specifically, the integration of enhanced flexibility to reach to the desired operative target through complex access routes, together with adequate stability for the surgeon to perform the required interventions or functional imaging on the tissue are key considerations of any flexible access device. Standard flexible endoscopes are too floppy and therefore difficult to navigate, especially outside of a lumen; furthermore, multiple users are often required to manipulate additional instrumentation.

The flexible access platform described in Chapter 2 has the potential to fulfil the above requirements by implementing mechatronic actuation to achieve fully controlled joint articulation whilst maintaining the required flexibility and stability. In addition, the use of an ergonomic hand-held controller together with the presence of internal channels for the passage of an endoscopic camera and third-party instrumentation allow single-user operation, as seen in Chapter 2. However, before testing the capabilities of the device through in vivo deployment, it is necessary to perform further pre-operative analysis to map out different steps of the robotic-assisted procedure and determine the optimal configuration for the system set-up. As part of this process, the work presented in this chapter is specifically aimed at assessing the feasibility of performing single-port surgery using the articulated access device on the basis of workspace considerations. In particular, two procedures are investigated: transvaginal tubal ligation and single-port diagnostic peritoneoscopy. Optimal joint configurations are determined on the basis of specific workspace requirements, derived from patient anatomical models. Finally, in vivo results from experimental trials carried out on porcine models by surgeons of the Hamlyn Centre are reported to demonstrate the practical capabilities of the system.
6.2 Kinematic model of the flexible access platform

In Chapter 2, the kinematic structure of the articulated section of the flexible access device has been introduced. In particular, the robot features seven rotational Degrees-of-Freedom (DoFs) providing articulation between five rigid links or joint units. The design is modular, so that multiple 1-DoF or 2-DoF units can be connected in different configurations. However, as mentioned in Chapter 2 the particular architecture of the 7-DoF device already incorporates the maximum number of DoFs practically achievable due to the limited torque generated by the embedded micro-motors. Specifically, the three most proximal modules feature a 1-DoF joint allowing yaw rotation in the horizontal plane, while the two distal universal joint units enable yaw and pitch rotation about two orthogonal axes which are orientated at 45° with respect to the gravity vector. The corresponding kinematic model is shown in Figure 6.1, where a unique reference frame is assigned to each DoF according to the Denavit-Hartenberg (D-H) convention, as described in Chapter 4. The $x_i$ axes of frames 1 to 7 are not visible in the figure as they are aligned with the axis of the link and coincide with the $x_8$ axis assigned to the end-effector when all the joints are in the zero angular position. The corresponding D-H parameters are reported in Table 6.1, where $L_1 = 34$mm, $L_2 = 8$mm, $L_3 = 36$mm and $L_4 = 32.5$mm.

![Figure 6.1: Kinematic model of the articulated section of the flexible access platform.](image)

The seven DoFs are organised as three proximal revolute joints (only yaw) represented as blue reference frames and two distal universal joints featuring yaw and pitch rotation axes corresponding to the red and green frames respectively.

The forward kinematic equations describing the pose of the end-effector with respect to the world reference frame can be expressed as:

$$T_{0}^{N_{\text{DoF}}+1}(q) = T_{0}^{1} \prod_{i=1}^{N_{\text{DoF}}} T_{i}^{i+1}(q_{i})$$

(6.1)

where $q = [q_1, \ldots, q_{N_{\text{DoF}}}]$ is the vector of joint variables with $N_{\text{DoF}} = 7$ and $T_{0}^{1}$
Table 6.1: Denavit-Hartenberg parameters for the 7-DoF articulated robot.

<table>
<thead>
<tr>
<th>$\theta$</th>
<th>$d$</th>
<th>$\alpha$</th>
<th>$a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q_1$</td>
<td>0</td>
<td>0</td>
<td>$L_1$</td>
</tr>
<tr>
<td>$q_2$</td>
<td>0</td>
<td>0</td>
<td>$L_1$</td>
</tr>
<tr>
<td>$q_3$</td>
<td>0</td>
<td>$\pi/4$</td>
<td>$L_1$</td>
</tr>
<tr>
<td>$q_4$</td>
<td>0</td>
<td>$-\pi/2$</td>
<td>$L_2$</td>
</tr>
<tr>
<td>$q_5$</td>
<td>0</td>
<td>$\pi/2$</td>
<td>$L_3$</td>
</tr>
<tr>
<td>$q_6$</td>
<td>0</td>
<td>$-\pi/2$</td>
<td>$L_2$</td>
</tr>
<tr>
<td>$q_7$</td>
<td>0</td>
<td>$\pi/4$</td>
<td>$L_4$</td>
</tr>
</tbody>
</table>

is the transformation between the world coordinate system $(x_0, y_0, z_0)$ and the first reference frame $(x_1, y_1, z_1)$. The transformation $T_{i}^{i+1}$ between adjacent reference frames can be computed as:

$$T_{i}^{i+1} = \begin{bmatrix}
\cos(q_i) & -\sin(q_i) \cos(\alpha_i) & \sin(q_i) \sin(\alpha_i) & \cos(q_i) a_i \\
\sin(q_i) & \cos(q_i) \cos(\alpha_i) & -\cos(q_i) \sin(\alpha_i) & \sin(q_i) a_i \\
0 & \sin(\alpha_i) & \cos(\alpha_i) & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}$$

(6.2)

where $\alpha_i$ and $a_i$ are the corresponding D-H parameters according to Table 6.1. By assigning the allowable range of angular displacement to each rotational axis within $\pm 45^\circ$, it is possible to define the kinematic workspace of the robot as the set of locations reachable by the end-effector for a given $T_{0}^{1}$. The coordinates of these points are represented by the Three-Dimensional (3-D) translation vector of the transformation matrix (6.1). Figure 6.2 illustrates different workspaces where $T_{0}^{1} = I_{4x4}$ and the number of actuated DoFs increases from two (i.e. only the distal universal joint moves) to seven (i.e. all the available DoFs are used).

Form Figure 6.2 it is clear that the articulated section of the flexible access platform incorporates enough dexterity to achieve complete retroflexion as well as large area exploration with multiple poses of the end-effector. These features are essential for a number of single-port surgical procedures. In particular, retroflexion is necessary to perform a transvaginal tubal ligation, while single-port diagnostic peritoneoscopy using micro-confocal imaging requires the ability to reach multiple locations within the abdominal cavity, ideally having the optical probe aligned with the normal to the tissue surface. These considerations suggest that the flexible access system would be suitable to carry out such operations and improve the quality of the procedure in terms of better ergonomics for the surgeon and higher accuracy of optical imaging. However, in order to assess the feasibility of the system deployment in vivo it is necessary to consider the actual workspace requirements for each
Figure 6.2: Workspace of the articulated section of the flexible access platform. Different coloured areas corresponding to locations reachable by the robot end-effector are presented to show how the workspace increases when the number of actuated joints increases: blue for the distal universal joint (2 DoFs); orange for both universal joints (4 DoFs); pink for both universal joints and the distal revolute joint (5 DoFs); green for both universal joints and two distal revolute joints (6 DoFs); grey for all joints (7 DoFs).

procedure and determine the corresponding optimal robot configuration to ensure safe operation and successful surgical outcome, as discussed in the next sections.

6.3 Application to transvaginal tubal ligation

Tubal sterilisation or ligation is one of the most commonly performed surgical procedures as it represents one of the most widely used methods of female contraception. In spite of a wide range of highly effective reversible contraceptives currently available, 643,000 operations were carried out in the United States in 2006 [213]. It can be performed by laparotomy, mini-laparotomy, laparoscopy, and more recently hysteroscopy. The latter method corresponds to the transvaginal endoscopic approach, which provides the same results of laparoscopic surgery from a clinical perspective, but with additional benefits for the patient in terms of better cosmesis due to the absence of an abdominal scar and minimal post-operative pain with shorter recovery times. As described in [214], the approach consists in the insertion of a flexible endoscope in the vagina to gain access to the abdominal cavity through an incision on the vaginal wall or colpotomy site, usually about 1.5cm long. Pneumoperitoneum is usually established by insufflation of carbon dioxide in order to create sufficient space for manoeuvring the endoscope to perform a ‘u-turn’ and mobilise the uterus anteriorly using a uterine manipulator. Different techniques can be used to ligate the fallopian tubes, such as electrocauterisation, clipping, or application of silicone
rings. Although suturing and excision of the fallopian tubes are also effective sterilisation methods, the use of a flexible endoscope does not provide sufficient stability and triangulation to perform such operations.

Albeit a number of transvaginal tubal ligations have been successfully performed using standard flexible endoscopes, the control complexity when manoeuvring such instruments outside of a lumen requires extensive surgical training. In addition, operating in a retroflexed configuration can lead the operator to disorientation and make the control of the instruments passed through the endoscope particularly difficult. The use of mechatronic actuation to achieve enhanced flexibility would therefore be extremely beneficial for this specific procedure, as it would ensure adequate dexterity to achieve complete retroflexion while maintaining the stability needed to manipulate endoscopic tools. As discussed above, the 7-DoF articulated device has the potential to address these needs. The following analysis will demonstrate the feasibility of performing a complete retroflexion within the constrained volume of the pelvis using the robot and determine the optimal configuration to ensure successful completion of the tubal ligation procedure.

6.3.1 Workspace requirements

The anatomical configuration of the pelvis is illustrated in Figure 6.3. As can be seen from the figure, the volume enclosing the allowable workspace for manoeuvring the articulated robot can be approximated as a truncated cone with lower base corresponding to the pelvic floor and upper base coinciding with the plane of the Anterior Superior Iliac Spines (ASISs). In particular, the diameter of the pelvic floor is defined as the distance between the pubis symphysis and the sacral promontory (blue line in the figure), while the diameter of the upper base of the cone is given by the distance between left and right ASIS (red line in the figure). The height of the truncated cone therefore corresponds to the distance between the pelvic floor and the line joining the ASISs (black line in the figure). Finally, the fallopian tubes are located below the sacral promontory bilaterally from its mid-point.

In order to reach the fallopian tubes through transvaginal access, the robot must be inserted in the pelvis volume at the level of the pelvic floor and achieve a complete retroflexed configuration within the constraints of the truncated cone described above. In particular, the average values of the parameters defining the pelvis volume have been estimated from eight MRI (Magnetic Resonance Imaging) images of female patients by a surgeon (James Clark) of the Hamlyn Centre and the measurements are reported in Table 6.2.

As shown in Figure 6.4(a), the diameter of the robot in the completely retroflexed position is 89.5mm, which is within the pelvic dimensions specified in Table 6.2. Figure 6.4(b) shows the real robot in the retroflexed configuration to demonstrate the correspondence with the kinematic model. Figure 6.4 provides a preliminary
Figure 6.3: Anatomical considerations to determine the allowable workspace within the pelvis when performing a transvaginal tubal ligation. The parameters defining the truncated cone which approximates the volumetric margins of the pelvis are highlighted using coloured lines: the red line corresponds to the diameter of the upper base, the blue line represents the diameter of the lower base and the black line indicates the height. L-ASIS: Left-Anterior Superior Iliac Spine; R-ASIS: Right-Anterior Superior Iliac Spine. Source of the pelvis model: Marcus Sommer SOMSO Modelle GmbH.

Table 6.2: Anatomical measurements of the pelvis volume estimated from eight MRI images.

<table>
<thead>
<tr>
<th>Anatomical constraint</th>
<th>Measure [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-ASIS to R-ASIS</td>
<td>21.7 ± 0.42</td>
</tr>
<tr>
<td>Pelvic floor diameter</td>
<td>9.86 ± 1.24</td>
</tr>
<tr>
<td>Pelvic volume height</td>
<td>8 ± 1.8</td>
</tr>
</tbody>
</table>

indication that the flexible access platform is suitable to perform a transvaginal tubal ligation. The next section will be focused on determining the optimal robot configuration to carry out the actual procedure.

6.3.2 Optimisation of robot configuration

Once that specific workspace constraints have been identified, it is possible to determine the optimal configuration allowing the robot to retroflex within the pelvis volume, reach the fallopian tubes and still have sufficient dexterity to visualise the whole pelvis. In general, the robot configuration is defined by the seven joint variables and the six parameters (3-D position and orientation in terms of roll, pitch and yaw angles) describing the pose of the first joint with respect to the world coordinate system \( T_0^1 \) in Equation (6.1)). However, the choice of a transvaginal access route introduces further constraints on the pose of the first joint, as the po-
The position of the colpotomy site and the orientation of the robot shaft are dictated by the patient anatomy. In particular, the abdominal cavity is accessed through the rectovaginal pouch, which is located mid-line, one third of a line drawn posterior to anterior at the level of the pelvic floor. In addition, due to the presence of the sacral promontory, when the patient is on the operative table in the supine position the robot shaft is inserted with an elevation from the horizontal plane of about $10^\circ$. Therefore, the only free parameters that can be optimised apart from the seven joint variables are the translation of the shaft inside the abdominal cavity and the roll rotation about the shaft axis.

The optimal robot configuration is computed by implementing the kinematic model of the robot in MATLAB® together with all the constraints discussed above. The origin of the world coordinate frame is positioned at the centre of the lower base of the truncated cone representing the pelvis volume, so that the $x_0$ axis is aligned with the height of the cone, the $y_0$ axis is orientated as the line connecting the ASISs with the positive direction towards the right ASIS, and the $z_0$ axis lies in the plane of the pelvic floor, with positive direction towards the pubis symphysis. This choice is justified by considering that during the surgical procedure the patient is lying on the operative table in the supine position. Since from Table 6.2 the pelvic floor diameter can be approximated as 98mm, the colpotomy site is located along the $z_0$ axis 15mm below the origin according to the position of the rectovaginal pouch defined above. Each fallopian tube is represented as a parallelepiped having a width of 3cm, a height of 1cm and a depth of 1cm and located as shown in Figure 6.5.

From Figure 6.5 it is clear that part of the articulated section of the robot will be located in the abdominal cavity during the procedure. However, retroflexion must be achieved within the margins of the upper base of the pelvis cone in order for the tip of the endoscopic instrument to reach the fallopian tube. In particular, the
Figure 6.5: Geometrical model of the pelvis workspace illustrating the position of the fallopian tubes and the robot initial configuration. The grey truncated cone represents the volume of the pelvis and the pink parallelepipeds correspond to the fallopian tubes. The robot enters the pelvic floor at the level of the rectovaginal pouch with a 10° inclination with respect to the horizontal plane to avoid the sacral promontory. Views from four different perspectives are shown, specifically: (a) 3-D view; (b) view in the ($x_0, y_0$) plane; (c) view in the ($y_0, z_0$) plane; (d) view in the ($x_0, z_0$) plane.
optimal configuration is computed as the one giving the maximum overlap between the instrument tip and the volume of the fallopian tube. The algorithm is designed to optimise the ligation of the right fallopian tube, however the corresponding configuration for the left tube is symmetrical with respect to the \((x_0, z_0)\) plane. Upper and lower bounds are assigned to the joint variables according to the range of motion of each actuator as \(q_{lb} = -45^\circ\) and \(q_{ub} = 45^\circ\) and the roll rotation about the robot shaft \(\theta_x\) is limited between \(45^\circ\) and \(90^\circ\) so that the fallopian tube can be visualised from above. The maximum allowable translation of the shaft within the abdominal cavity \(d_x\) is set to 15cm, while the endoscopic instrument can be pushed outside the distal tip of the robot for a maximum length of 60mm.

The optimisation algorithm can be summarised by the following steps:

1. Set the values of roll rotation and translation along the robot axis;
2. Find the values of the joint variables giving the smallest distance between the distal tip of the robot and the right fallopian tube while ensuring that the robot body is within the pelvis workspace;
3. Actuate the two distal universal joints to span the allowable angular range of motion without exceeding the pelvis workspace;
4. Compute the total volume overlap between the tip of the endoscopic tool and the fallopian tube;
5. If all the possible combinations of values of roll and translation along the robot shaft have been considered exit the algorithm, otherwise go back to step 1.

Specifically, the smallest distance between the distal tip of the robot and the right fallopian tube is computed as the minimum of the distances between the 3-D translational vector of the transformation matrix (6.1) \((\mathbf{x})\) and the \(n\) points constituting the outer surface of the parallelepiped representing the fallopian tube \((\mathbf{x})\), \(i.e.\):

\[
\min_{j=1,\ldots,n} \{ |\mathbf{x}(\mathbf{q}) - \mathbf{x}_j| \} \tag{6.3}
\]

where \(\mathbf{q}\) is the current robot configuration and the transformation matrix describing the pose of the first joint with respect to the world coordinate system in (6.1) is given by:

\[
T^1_0 = \begin{bmatrix} R^1_0 & x_0 \\ 0 & 1 \end{bmatrix} \tag{6.4}
\]

with:

\[
R^1_0 = R_z(0^\circ)R_y(-10^\circ)R_x(\hat{\theta}_x) \tag{6.5}
\]

and:
where \( \hat{\theta}_x \) and \( \hat{d}_x \) are the current values of roll angle of rotation and translation along the robot shaft respectively.

A 3-D Delaunay triangulation of the truncated cone was computed using the embedded MATLAB® function `delaunayn` and a 3-D closest simplex search was performed for each vertex constituting the robot using the embedded function `tsearchn` to determine if the robot body was within the pelvis workspace. The same procedure was applied to identify the points spanned by the tool tip which lie within the volume of the fallopian tube. The total volume overlap between the endoscopic instrument tip and the fallopian tube was then computed by increasing the length of the tool of 1mm at each iteration and summing up the surface areas described by the tool tip within the fallopian tube volume. Each surface area was computed by determining the 3-D convex hull of the constituting points using the embedded function `convhulln` and summing up the area of each triangle-shaped facet of the convex hull. The values of roll rotation were varied at angular intervals of 5°, while the translation values were taken every 1mm within the allowable range. Once the algorithm was run for each set of values of roll and translation along the robot shaft, the optimal configuration was chosen as the one giving the maximum total overlapping volume. The result of the optimisation is reported in Table 6.3, while Figure 6.6 shows the optimal configuration of the robot within the pelvis workspace. The corresponding total volume overlap is 99.7%.

Table 6.3: Optimal values of the parameters defining the robot configuration for performing a transvaginal tubal ligation.

<table>
<thead>
<tr>
<th>( q_1 )</th>
<th>( q_2 )</th>
<th>( q_3 )</th>
<th>( q_4 )</th>
<th>( q_5 )</th>
<th>( q_6 )</th>
<th>( q_7 )</th>
<th>( \theta_x )</th>
<th>( d_x )</th>
</tr>
</thead>
<tbody>
<tr>
<td>45°</td>
<td>45°</td>
<td>45°</td>
<td>45°</td>
<td>45°</td>
<td>[0, 45°]</td>
<td>[−45°, 45°]</td>
<td>70°</td>
<td>12.4cm</td>
</tr>
</tbody>
</table>

As can be seen from Table 6.3, in order for the robot not to exceed the pelvis workspace the five most proximal DoFs have to maintain the retroflexed position, while the distal universal joint can be actuated to carry out the procedure. From Figure 6.6 it is also clear that by moving the distal joint it is possible to visualise the whole pelvis from the optimal configuration. Furthermore, it is not necessary to deploy the endoscopic instrument more than 4cm outside of the robot tip, which makes the manipulation less complex.

It is important to note that if the robot is retroflexed by simultaneously actuating all the joints the trajectory of the distal tip traces an arc with a radius of 143mm, as shown in Figure 6.7(a). Since this value exceeds the pelvis workspace, the robot should be further inserted in the abdominal cavity to achieve the retroflexed
Figure 6.6: Optimal robot configuration giving the maximum overlap between the tip of the endoscopic instrument and the volume of the right fallopian tube. The corresponding optimal configuration for the left fallopian tube is symmetrical with respect to the \((x_0, z_0)\) plane. Only the most distal universal joint is actuated to manipulate the endoscopic instrument during the tubal ligation procedure, while the other joints maintain a retroflexed position. Views from four different perspectives are provided, specifically: (a) 3-D view; (b) view in the \((x_0, y_0)\) plane; (c) view in the \((y_0, z_0)\) plane; (d) view in the \((x_0, z_0)\) plane.

Figure 6.7: Position and orientation of each link of the articulated robot during retroflexion, projected on the \((x_0, y_0)\) plane for clarity. (a) Retroflexion is achieved by actuating all the joint variables simultaneously. (b) Retroflexion is achieved in two steps: first the distal universal joints are simultaneously actuated, then the three proximal yaw joints.
position and then repositioned within the pelvis volume. To avoid this problem, a two-step retroflexion should be performed, where the distal universal joints are retroflexed before the three proximal revolute joints. In this case the maximum radius of retroflexion is reduced to 112mm, as shown in Figure 6.7(b).

The above analysis demonstrates the feasibility of a transvaginal tubal ligation procedure using the articulated robot. Although position feedback is not embedded in the current prototype of the flexible access platform, as discussed in Chapter 5 promising preliminary results of kinematic control were already obtained using a 5-DoF prototype articulated robot. A simple algorithm to achieve the automatic straightening and retroflexion of all the joints simultaneously by pressing only one button on the GUI has also been tested on this device, as shown in Figure 6.8.

![Figure 6.8: Demonstration of the automatic retroflexion manoeuvre. In these images the retroflexion is achieved by simultaneously actuating all five DoFs.](image)

Future work will include the application of kinematic control to the 7-DoF robot to achieve automatic positioning according to the optimal configuration parameters presented above. However, in vivo validation of these results using manual control has already been carried out on a porcine model and will be described in the last part of this chapter. The next section will further analyse the suitability of the flexible system to perform a single-port diagnostic peritoneoscopy.

6.4 Application to single-port diagnostic peritoneoscopy

Diagnostic peritoneoscopy [215, 216] was one of the first intraperitoneal applications of flexible access surgery, together with tumour staging [217] and minor interventions such as liver biopsy [218]. This is due to the common characteristics of these procedures, which require a high degree of flexibility for the exploration of the abdominal cavity, but do not involve extensive interaction with the tissue. In addition, the main purpose of such exploratory surgeries is to investigate the extent of disease progression so that the best therapeutic solution can be applied. Early diagnosis frequently helps to avoid unnecessary surgical operations and the potential related complications. Therefore, any reduction in invasiveness and increase in accuracy would make these procedures more easily acceptable by patients and improve the efficacy of disease screening. Together with the evolution of single-port and transluminal surgical
techniques, numerous intra-operative laparoscopic/ endoscopic probe based imaging devices have also been developed with the aim of further decreasing the invasiveness of diagnostic procedures. These techniques allow real-time ‘optical biopsy’ of tissue, offering near histopathological grade information for intra-operative diagnosis without the risks and discomfort caused by standard tissue biopsy. Near infrared fluorescence [219], optical coherence tomography [220] and probe-based Confocal Laser Endomicroscopy (pCLE) [221, 222] are amongst the most promising optical imaging methods. In particular, pCLE is performed by deploying the optical probe through the operational channel of a standard endoscope to acquire \textit{in vivo} images of up to 1.5$\mu$m resolution by fluorescing intravenous fluorescein. By sliding the probe over tissue, it is also possible to create larger field-of-view mosaics of a few millimetres by stitching together consecutive images after compensation of motion-induced distortions [223].

However, significant ergonomic challenges currently affect the accuracy of intra-operative diagnosis using optical imaging in combination with a flexible endoscope. The problems of instability, counter-intuitive movements and disorientation arising from the extraluminal manoeuvring of the endoscope, are further complicated by the additional requirements of precise targeting and gentle and steady perpendicular probe contact to acquire meaningful images. The ability to perform slow and controlled motion over a few millimetres using the complex controls of the endoscope is also desirable for the generation of accurate mosaics. In fact, even hand-held manipulation of a confocal probe during open surgery cannot guarantee maintaining steady probe apposition with consistent pressure on tissue due to the high deformation induced by bowel flaccidity, peristalsis and cardiorespiratory motion. The potential benefits of coupling robotic actuation with optical biopsy probes are therefore manifold, since it could allow the execution of precise and controlled motions at the sub-millimetre scale while automatically compensating tissue deformation and maintaining a constant contact force between the probe and the tissue.

The above considerations clearly identify the flexible access platform as a potential solution for the efficient deployment of optical imaging during single-port surgery. The enhanced dexterity of the articulated section allows performing large area exploration with a desired end-effector pose with respect to the tissue surface. Furthermore, the integration of kinematic control would ensure precise and steady targeting as well as automatic execution of desired patterns for real-time image mosaicking. The following analysis is therefore aimed to assess the potential for clinical translation of the system for single-port diagnostic peritoneoscopy on the basis of workspace constraints derived by patient anatomical models.
6.4.1 Workspace requirements

The main difficulty of modelling the available workspace within the abdominal cavity during a single-port intervention is the presence of pneumoperitoneum. Imaging techniques like Computerised Tomography (CT) or MRI can only be used preoperatively and in absence of pneumoperitoneum, therefore the extra space created by the insufflated carbon dioxide can only be estimated. Only limited information is available about the effect of pneumoperitoneum on the shape of the abdomen, particularly that the diaphragm is raised 2-3cm caudally [224] and that the umbilicus is lifted of approximately 8cm by external elevation of the abdominal wall fascia prior to insufflation [225]. Recent approaches to intra-operative imaging during endoscopic procedures are based on modelling the shape deformation according to the elasticity of tissue [226]. Although this method is very effective, it is patient-specific and cannot be used to define a generic pneumoperitoneum model.

Therefore, in this study the workspace was obtained from the CT scan of a male patient with a pneumoperitoneum secondary to a perforated colon. The 3-D mesh shape provided by the extraluminal air was then smoothed across the deep surface in collaboration with Su-lin Lee at the Hamlyn Centre. The 3-D mesh was then modified in order to match the size of a female abdomen on the basis of the average length and width dimensions obtained from ten abdominopelvic CT scans of female patients. All the CT scans were taken and analysed by a surgeon (Richard Newton) of the Hamlyn Centre and the corresponding measurements are reported in Table 6.4. In particular, the length was measured from the most cranial part of the diaphragm to the parietal peritoneum at the level of the pubic symphysis; however, in the simulated workspace 25mm were added to this value to consider the insufflatory diaphragmatic elevation [224]. The width was calculated across the peritoneal cavity at the widest part of the iliac crests. Table 6.4 also reports the measurements from the inferior tip of the pneumoperitoneum of the location of the entry point for both the transvaginal and the transumbilical approach.

Table 6.4: Average and standard deviation values (mm) of abdomen length and width and position of the entry point from the inferior tip of the pneumoperitoneum for the transvaginal and the transumbilical approach obtained from ten CT scans of female patients.

<table>
<thead>
<tr>
<th>Length</th>
<th>Width</th>
<th>Colpotomy Site</th>
<th>Umbilicus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>Std. Dev.</td>
<td>Mean</td>
<td>Std. Dev.</td>
</tr>
<tr>
<td>319.5</td>
<td>±21.3</td>
<td>235</td>
<td>±22.3</td>
</tr>
</tbody>
</table>

*aAnteroposteriorly
*bCaudocranially

The final 3-D mesh used as a model of the peritoneal workspace is illustrated in Figure 6.9 from three different perspectives, e.g. lateral view (Figure 6.9(a)), view
of the parietal pneumoperitoneum from above ((Figure 6.9(b))) and view of the visceral surface from below (Figure 6.9(c)). After shrinking the 3-D male mesh to the dimensions listed in Table 6.4 a pneumoperitoneum depth of 90mm was obtained, as shown in Figure 6.9(a).

![Figure 6.9: Three-dimensional mesh representing the allowable workspace in the abdominal cavity of a female patient after the establishment of pneumoperitoneum. (a) Lateral view of the 3-D mesh illustrating the location of key anatomical features and showing the pneumoperitoneum depth. (b) View of the 3-D mesh from above showing the surface of the parietal peritoneum. (c) View of the 3-D mesh from below showing the surface of the viscera.](image)

As discussed earlier, the key requirement for performing an accurate diagnostic peritoneoscopy using optical imaging is the ability to explore the large area of the abdominal cavity while maintaining precise and steady targeting of the probe, ideally
with an orientation perpendicular to the tissue. Therefore, in order to assess the suitability of the flexible access platform for this surgical task, it is necessary to determine the percentage of the above estimated workspace that can be reached by the probe protruding at the distal tip of the robot with an orientation close to the tissue normal. This is achieved by implementing the optimisation algorithm described below in MATLAB\textsuperscript{\textregistered} using two different single-port approaches, so that the optimal access route for the system deployment is also determined.

6.4.2 Optimisation of robot configuration

As shown in Figure 6.9, for the implementation of the robot kinematics in MATLAB\textsuperscript{\textregistered} the origin of the world coordinate system is located in correspondence of the inferior tip of the pneumoperitoneum at the level of the pubic symphysis, half-way between the iliac crests. As for the tubal ligation case, the $x_0$ axis is oriented caudocranially along the length of the abdominal cavity, the $y_0$ axis is parallel to the line connecting the iliac crests, with positive direction towards the right one, and the $z_0$ axis is perpendicular to the coronal plane in posteroanterior direction. The algorithm is designed to optimise a total of eleven configuration parameters. These correspond to the seven DoFs of the articulated section ($\mathbf{q}$), the roll rotation about the axis of the robot ($\theta_x$), the pitch ($\theta_y$) and yaw ($\theta_z$) rotations of the rigid shaft about the entry point and the translation of the rigid shaft within the abdominal cavity ($d_x$). As a result, only the position of the entry point ($\tilde{x}$, $\tilde{y}$, $\tilde{z}$) is fixed as it is dictated by the patient anatomy. However, the range of pitch and yaw rotation is limited to 30\textdegree due to the small diameter of the trocar port (about 15mm). The translation of the rigid shaft within the abdominal cavity is also limited to 100mm in order to not exceed the allowable workspace. The actuation limit for the rotational joints is again set between $q_{lb} = -45^\circ$ and $q_{ub} = 45^\circ$ while the roll angle can vary in the range $[0^\circ; 360^\circ]$.

In order to determine the percentage of the peritoneal cavity reachable by the probe protruding at the distal tip of the robot with an orientation close to the normal to the tissue surface, it is necessary to determine the corresponding optimal robot configuration for all the 3-D points constituting the mesh illustrated in Figure 6.9. It is assumed that the probe lies along the axis of the distal joint and protrudes from the tip for a length of 10mm. In particular, optimisation is performed using the embedded MATLAB\textsuperscript{\textregistered} function \textit{fmincon} to minimise the angular disparity between the direction of the axis of the distal joint and the normal to the tissue surface, with the constraint that the distance between the tip of the confocal probe and the target point is within 1mm. The orientation of the distal joint for a given set of configuration parameters $[\hat{d}_x, \hat{\theta}_x, \hat{\theta}_y, \hat{\theta}_z, \hat{\mathbf{q}}]$ is given by the rotation matrix $\mathbf{R}_0^{N_0-\text{DoF}+1}$ in the transformation $\mathbf{T}_0^{N_0-\text{DoF}+1}$ computed according to Equation (6.1), where the transformation matrix between the world coordinate frame and the first joint frame
\( T_0^1 \) has the same structure of Equation (6.4) with:

\[
R_0^1 = R_z(\hat{\theta}_z) R_y(\hat{\theta}_y) R_x(\hat{\theta}_x) \tag{6.7}
\]

and:

\[
x_0 = R_0^1[\hat{d}_x, 0, 0]^T + [\tilde{x}, \tilde{y}, \tilde{z}]^T. \tag{6.8}
\]

It is important to note that the initial value of \( \theta_y \) is different for the transvaginal and the transumbilical approach and is assigned as \(-70^\circ \) and \(50^\circ \) or \(130^\circ \) respectively, considering two symmetrical entry configurations at the umbilicus. The location of the entry point also depends on the access route and corresponds to the colpotomy site \((\tilde{x} = 20\text{mm}, \tilde{y} = 0\text{mm}, \tilde{z} = -58\text{mm} \) from Table 6.4) for the transvaginal approach and to the umbilicus \((\tilde{x} = 158\text{mm}, \tilde{y} = 0\text{mm}, \tilde{z} = 90\text{mm} \) from Table 6.4) for the transumbilical approach. The initial value of \( \theta_z \) is assigned as \(0^\circ \) in any case. The direction of the axis of the distal joint can then be computed as:

\[
\hat{d}_f = R_{N}^{DoF+1}[1, 0, 0]^T \tag{6.9}
\]

so that the angular disparity with the normal to the tissue surface \( d_n \) at the target point \( x_n \) is given by:

\[
F_n = \cos^{-1}\left( \frac{\hat{d}_f \cdot d_n}{||d_n||} \right) / \pi. \tag{6.10}
\]

Finally, the position of the tip of the confocal probe is computed as:

\[
\hat{x}_p = \hat{x} + R_0^{N}\hat{x} \tag{6.11}
\]

where \( \hat{x} \) is the 3-D translation vector of matrix (6.1) corresponding to the current robot configuration. The optimal set of configurations for all the target points constituting the 3-D mesh \( \Omega \) can therefore be expressed as:

\[
[d_n^x, \theta_x^n, \theta_y^n, \theta_z^n, q^n] = \min_{[d_x, \theta_x, \theta_y, \theta_z, q]} \{ F_n \}
\]

s.t. \( |\hat{x}_p - x_n| < 1\text{mm} \) \( \forall n \in \Omega \). \tag{6.12}

In addition to the above requirements, the optimal configuration should also ensure that the body of the robot does not exceed the margins of the peritoneal wall. However, due to the large number of points and high complexity of the 3-D mesh, the search for the closest simplex for each vertex constituting the robot body is highly computational demanding and requires a long time to be completed. Therefore, the search is not included as a constraint of the optimisation algorithm. Nonetheless,
the set of optimal configurations resulting from Equation (6.12) is checked off-line to determine what percentage exceeds the volumetric margins of the 3-D mesh. This information is useful for evaluating the performance of the robot when using different access routes. The results of the optimisation for both transvaginal and transumbilical approaches are discussed in details in the next section.

6.4.3 Comparison of transvaginal and transumbilical approaches

As described in the previous section, Equation (6.12) is used to find the set of optimal robot configurations for two different access routes corresponding to the transvaginal and the transumbilical approaches. The resulting values in terms of percentage of reachable points on the 3-D mesh surface are reported in Table 6.5 according to the corresponding orientation of the confocal probe with respect to the tissue surface. In particular, the results indicate that the enhanced dexterity of the robot allows to reach almost the entire peritoneal surface and about half of the points with the confocal probe oriented perpendicular to the tissue.

Although the values in Table 6.5 are comparable for the two approaches, the areas of the workspace reachable by the confocal probe at various orientations are different for the two access routes. This is clearly visible in Figures 6.10 and 6.11 showing the heat maps of the peritoneal workspace for the transvaginal and transumbilical approach, respectively. Cold colours correspond to areas that can be abutted by the probe at an orientation close to 90°, while warm colours represent unreachable points or areas that can be abutted with an orientation < 45°. From the figures it is clear that due to the kinematic structure of the robot and the resulting minimum radius of curvature, the areas surrounding the crossing point between the robot shaft and the 3-D mesh cannot be reached by the distal tip. An example of this situation is illustrated in Figure 6.12 for both the transvaginal (Figure 6.12(a)) and the transumbilical (Figure 6.12(b)) approach.

<table>
<thead>
<tr>
<th>Contact angle</th>
<th>Transvaginal approach</th>
<th>Transumbilical approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 90°</td>
<td>88%</td>
<td>91%</td>
</tr>
<tr>
<td>≥ 45°</td>
<td>83%</td>
<td>82%</td>
</tr>
<tr>
<td>≥ 60°</td>
<td>78%</td>
<td>76%</td>
</tr>
<tr>
<td>≥ 70°</td>
<td>70%</td>
<td>70%</td>
</tr>
<tr>
<td>≥ 80°</td>
<td>61%</td>
<td>59%</td>
</tr>
<tr>
<td>90°</td>
<td>53%</td>
<td>50%</td>
</tr>
</tbody>
</table>

Table 6.5: Proportion of reachable points on the 3-D mesh surface for different orientations of the confocal probe with respect to the tissue resulting from the set of optimal configurations obtained for the transvaginal and the transumbilical approach.
Figure 6.10: Heat maps illustrating the areas of the peritoneal workspace that could be pCLE biopsied at particular angles from a transvaginal approach according to the optimisation algorithm. Cold colours correspond to areas that can be abutted by the probe at an orientation close to 90°, while warm colours represent unreachable points or areas that can be abutted with an orientation < 45°. (a) Lateral view of the 3-D mesh. (b) View of the 3-D mesh from above showing the surface of the parietal peritoneum. (c) View of the 3-D mesh from below showing the surface of the viscera.
Figure 6.11: Heat maps illustrating the areas of the peritoneal workspace that could be pCLE biopsied at particular angles from a transumbilical approach according to the optimisation algorithm. Cold colours correspond to areas that can be abutted by the probe at an orientation close to 90°, while warm colours represent unreachable points or areas that can be abutted with an orientation < 45°. (a) Lateral view of the 3-D mesh. (b) View of the 3-D mesh from above showing the surface of the parietal peritoneum. (c) View of the 3-D mesh from below showing the surface of the viscera.
Figure 6.12: Robot configurations for the (a) transvaginal and (b) transumbilical approach corresponding to points on the workspace surface that cannot be reached by the pCLE probe due to the kinematic structure and minimum radius of curvature of the robot.

However, most of the unreachable areas for the transvaginal approach are within the workspace pelvis, especially on the deep visceral surface. Here, the robot is retroflexed, rendering its transvaginal forward translation unhelpful for closing in on the probe’s target. From Figure 6.10 it is also evident that the recesses of the workspace and some areas of the irregularly shaped visceral surface can only be reached at angles shallower than 90°. Figure 6.13 shows three exemplar robot configurations for the transvaginal approach corresponding to an unreachable target in the pelvis area, a target abutted at 90° on the parietal surface and a target abutted at a shallower angle on the visceral surface.

On the other hand, most of the unreachable areas for the transumbilical approach are located on the parietal surface around the umbilicus and on the visceral surface opposite to the entry point. This is due to the length of the articulated section of the robot, which exceeds the depth of the pneumoperitoneum. Therefore, it is necessary to reduce the number of joint modules or to keep part of the articulated section outside the patient abdomen to abut the probe at 90° orientation with respect to the tissue on the areas of the visceral surface opposite to the umbilicus. It is also important to note that the heat maps in Figure 6.11 are generated by the combination of two entry configurations with symmetrical orientation at the umbilicus, as shown in Figure 6.14. From the figure it is clear that one configuration allows to reach the pelvic surface while the other permits to span most of the upper part of
Figure 6.13: Three robot configurations for the transvaginal approach corresponding to an unreachable target in the pelvis area, a target abutted at 90° on the parietal wall and a target abutted at a shallower angle on the visceral surface.

the peritoneal workspace.

Figure 6.14: Three robot configurations for the transumbilical approach corresponding to an unreachable target on the visceral surface opposite to the umbilicus and two targets abutted at 90° in the pelvis area and on the liver surface.

Although the results of the optimisation are similar for the transvaginal and transumbilical approaches, it is necessary to determine the number of optimal configurations causing the robot body to exceed the volumetric margins of the peritoneal workspace to identify the optimal access route. As discussed in the previous section, the search for the closest simplex within the convex hull described by the 3-D mesh is performed for each vertex of the robot body at each optimal configuration. As a result, none of the configurations obtained for the transvaginal approach is found to be outside the allowable workspace, while about 7% of the configurations computed for
the transumbilical approach cause the robot body to exceed the 3-D mesh volume. This is due to the restricted manoeuvring space within the pneumoperitoneum, as clearly illustrated in Figure 6.15.

![Figure 6.15: Example of optimal configuration causing the body of the robot to exceed the peritoneal workspace when using the transumbilical approach.](image)

The above discussion clearly identifies the transvaginal approach as the optimal access route for performing a diagnostic peritoneoscopy in vivo using the current prototype of the flexible access platform to deploy the pCLE probe. Although Figure 6.10 shows that the pelvis area cannot be reached by the probe when it protrudes of 10mm from the distal tip of the robot, Figure 6.13 suggests that if the optimisation algorithm is adjusted to permit longer deployment of the probe, much of the unreachable pelvic region could probably be contacted. In addition, although perpendicular probe abutment is preferable for consistent images, deformable soft tissues tend to pucker, enabling shallower angles to often achieve adequate results. Therefore, using the transvaginal access route it could be possible to pCLE biopsy almost the entire peritoneal cavity, while the kinematic structure of the current robot articulated section hinders any probe abutment on the areas of the workspace surrounding the umbilicus on the parietal wall and on most of the visceral surface when using the transumbilical approach. To demonstrate the validity of these results, an in vivo transvaginal diagnostic peritoneoscopy has been carried out using the flexible access platform on a porcine model and the results are presented in the next section.

### 6.5 In vivo validation of the flexible access platform

As mentioned in the previous sections, the flexible access platform was tested in vivo on a porcine model to demonstrate the feasibility of specific surgical applications which could benefit from its articulated design. In particular, the results
of the analysis reported above identified transvaginal unilateral tubal ligation and transvaginal diagnostic peritoneoscopy as two suitable procedures. Although the optimal configurations resulting from the study could not be implemented during the *in vivo* trials because of the lack of position feedback from the joints and the difficulties in estimating the allowable workspace *in situ*, the results are reported in the following as a preliminary validation of the enhanced dexterity of the robot using manual control.

The procedures were non-survival and the followed protocol was approved by the home office under the Home Office Animals for Scientific Procedure Act 1986 (number 80/2297). An adult large white landrace crossbread female pig (70kg) was chosen in both cases in order to simulate the conditions of a human procedure as accurately as possible. Anaesthetisation was obtained by intramuscular ketamine 5mg/kg and xylazine 1mg/kg and maintained with oxygen, nitrous oxide and isofluorane, while sodium pentobarbitone (Lethobarb) was used to euthanise the pig at the end of the procedure. An additional 10mm umbilical port was applied to create pneumoperitoneum and insert a laparoscope used to visualise the robot during the surgery. Due to the large size of the pig, a standard 15mm port valve was attached on a bespoke 30cm long trocar through which the robot was inserted transvaginally and the peritoneal cavity was finally accessed through a posterior colpotomy. The following sections will describe the key steps and results for each procedure.

### 6.5.1 Transvaginal tubal ligation

The unilateral transvaginal tubal ligation was performed by a surgeon (James Clark) of the Hamlyn Centre using the flexible access platform in the following key steps:

1. Introduction of the robot through the transvaginal port within the peritoneal cavity;

2. Retroflexion of the articulated section in the horizontal plane;

3. Rotation about the robot shaft to visualise the uterine horn (used as a model of the fallopian tube in the pig);

4. Insertion and application of the first resolution clip;

5. Insertion and application of the second resolution clip;

6. Insertion of a rat-toothed grasper to verify the clip application;

7. Insertion of a needle-knife diathermy unit;

8. Ligation of uterine horn;

9. Straightening and extraction of the system.
Steps 3, 5, 6 and 8 listed above are illustrated in Figure 6.16, which reports still frames of the footage recorded by the laparoscope during the procedure. Figure 6.16(a) clearly shows that the final configuration adopted to carry out the procedure was very close to the optimal configuration obtained by the optimisation algorithm as shown in Figure 6.6. In addition, all the manoeuvres needed to complete the tubal ligation were carried out using only the distal joint as envisioned by the algorithm (see Table 6.3). The total time for the completion of the procedure was 47 minutes.

![Snapshots of the video recorded by the additional laparoscope identifying the key steps of the transvaginal unilateral tubal ligation procedure carried out on a porcine model by a surgeon (James Clark) of the Hamlyn Centre.](image1)

(a) Configuration of the robot completely retroflexed after rotation about the rigid shaft. (b) Application of the second resolution clip. (c) Lifting of the uterine horn using a rat-toothed grasper to inspect the correct application of the clips. (d) Application of the needle knife diathermy between the two clips and completion of the tubal ligation.

Although the feasibility of performing a transvaginal tubal ligation using the flexible access platform was clearly demonstrated in vivo, a number of issues have to be tackled in order to improve the safety and ergonomics of the procedure. First of all, retroflexion in Figure 6.16(a) is achieved by controlling one joint at a time using the hand-held controller as described in Chapter 2. This process is time consuming and the operator can get disoriented if the view from the additional laparoscope is not available to see the current robot configuration. The integration of embedded position feedback would allow the application of kinematic control to achieve auto-
matic straightening and retroflexion of the robot as discussed earlier in this chapter. In addition, the information about the position of the joints during manual control could be used in Equation (6.1) to determine the current configuration and display it on a screen using a virtual model of the robot, thus avoiding the need for the additional laparoscope. Kinematic control could also be applied to compensate for the $45^\circ$ disparity between the axes of the universal joints and the motion of the thumb-stick on the hand-held controller to improve the control ergonomics.

6.5.2 Transvaginal diagnostic peritoneoscopy

The transvaginal diagnostic peritoneoscopy was performed by a surgeon (Richard Newton) of the Hamlyn Centre by deploying a standard 2.5mm diameter pCLE probe (Cellvizio Gastroflex ‘Z-probe’, Mauna Kea Technologies, Paris, France) through the internal channel of the flexible access platform. Fluorescein sodium 10% (Martin-dale’s, UK) (0.05ml/kg body weight) was injected intravenously as a contrast agent to enhance the visualisation of tissue structure during optical biopsy, together with a saline flush, 5 minutes before pCLE imaging. A linear translation mechanism, utilised in [227] to perform force adaptive imaging with the robot, was attached to the proximal end of the rigid shaft to maintain effective contact between the probe and the tissue even in presence of tissue deformation. The translation was also controlled using the hand-held controller introduced in Chapter 2, so that the operator could manoeuvre the robot and deploy the pCLE probe using only one hand.

Optical biopsies were taken at pre-defined locations in the peritoneal cavity, specifically of stomach, liver, spleen and parietal peritoneum at the anterior abdominal wall, as shown in Figure 6.17. The robot was navigated to each of these locations using only the visual feedback from the on-board camera in less than three minutes. When the distal tip was close enough to the target, the probe was abutted on the tissue using the linear translation mechanism and controlled motion of the distal joint was performed to slide the probe on the tissue and create mosaics of up to 2mm in length to augment the field-of-view of the image without artefacts. The total time for the biopsy was about 1-2 minutes at each target location. Tissue deformation frequently enabled imaging at shallower angles than $90^\circ$. Although recognisable features could not be found in the images from the stomach surface, meaningful images and mosaics were obtained at the other biopsy targets, as shown in Figure 6.18. The figures also show the position of the pig during the procedure and the robot configurations adopted at each target.

The above results clearly demonstrate that the flexible access platform represents an ergonomic and efficient solution for the deployment of a pCLE probe to perform a diagnostic peritoneoscopy in vivo. The enhanced dexterity of the articulated section coupled with the mechatronically controlled motion allows the exploration of the entire abdominal cavity and ensures accurate targeting of the biopsy site. How-
ever, the execution of slow movements to generate mosaics is challenging due to the limited accuracy of the thumb-stick control. The integration of position feedback would be particularly beneficial in this case, as the distal tip of the robot could be kinematically controlled to follow specific trajectories with a pre-defined speed. Automatic pattern execution could allow the generation of detailed mosaics covering large areas of tissue. In addition, kinematic control could be applied on the body of the robot to compensate for periodic respiratory motion causing the tissue to deform and resulting in unwanted artefacts in the optical images.

6.6 Discussion and conclusions

In this chapter, the feasibility of performing single-port interventions using the flexible access platform has been investigated. In particular, two potential clinical applications have been identified on the basis of the specific capabilities of the device: transvaginal tubal ligation and single-port diagnostic peritoneoscopy. The first procedure requires complete retroflexion of the device within the constrained volume of the pelvis and sufficient stability to deploy and manipulate endoscopic instrumentation. In order to assess the suitability of the system for this application, accurate workspace margins have been defined on the basis of MRI images of female patients and the region of the pelvis around the fallopian tube, where most of the procedure takes place, has been identified. An optimisation algorithm has been designed to determine the optimal robot configuration which ensures the maximum overlap between the endoscopic instrument protruding at the distal tip of the robot and the fallopian tube volume when only the distal joint is actuated while the other joints maintain the retroflexed position. Results from an in vivo transvaginal tubal ligation on a porcine model performed using the flexible access platform have been presented.
Figure 6.18: pCLE optical biopsies of (a) peritoneal wall, (b) liver and (c) spleen acquired in vivo using the flexible access platform. The slow and controlled movements of the distal joint allowed to use mosaicking software to expand the field-of-view by up to 4 times (approximately 2mm) to create more representative and interpretable optical biopsies (A, D and H show the expansion). Images courtesy of Richard Newton.
to demonstrate the validity of the algorithm even when using manual control.

Diagnostic peritoneoscopy requires high dexterity for large area exploration together with accurate motion control for positioning the optical probe on the target. Ideally, the probe should be abutted with a 90° orientation with respect to the tissue in order to acquire meaningful images. In order to investigate the suitability of the flexible access platform for this application, a model of pneumoperitoneum workspace has been defined on the basis of patient CT data. An optimisation algorithm has been designed to determine the set of optimal configurations ensuring positioning of the pCLE probe within 1mm from each target point within the abdominal cavity with an orientation close to the normal to the tissue surface. The optimisation has been applied using both the transvaginal and the transumbilical approach in order to determine the optimal access route for the robot deployment. The results have shown that when the system is inserted transvaginally 88% of the abdominal cavity can be pCLE biopsed and more than half of the workspace can be abutted by the probe at 90° with respect to the tissue. Results from a transvaginal diagnostic peritoneoscopy performed on a porcine model using the flexible access platform have also been reported to demonstrate the capabilities of the robot in vivo.
7 Conclusions and future work

7.1 Summary of thesis achievements

Recent advances in medical robotics have the potential to revolutionise current surgical practice. Since the introduction of Minimally Invasive Surgery (MIS), the robotic community has shown a growing interest in developing new technologies aimed at overcoming the ergonomic and safety issues of the MIS approach. Poor manual dexterity and visuomotor coordination, caused by the rigid instruments used and the fulcrum effect, have been enhanced by micro-processor controlled mechanical wrists, allowing for motion scaling and improved accuracy. However, as the technology advances, the clinical limits are further pushed towards new frontiers. This introduces a new set of technical challenges. The quest for reduced patient trauma has recently led to the development of natural orifice or single incision laparoscopic surgery. Before these techniques can be used in routine surgery, it is important to develop specialised instrumentation to provide enhanced flexibility and stability to reach to the operative target. The work presented in this thesis addresses some of the technical issues related to the development of such a flexible access platform, with a particular focus on its design optimisation and kinematic control.

Technically, the key achievements of the thesis include:

- Determination of optimal joint design parameters for reducing the backlash and improving the positioning accuracy of a hybrid ‘micromotor-tendon’ actuation mechanism;

- Derivation of a ‘front-drive back-following’ control scheme for reducing the complexity and increasing the accuracy of path following navigation using a virtual self-propelling hyper-redundant robot;

- Design of a Degree-of-Freedom (DoF) minimisation scheme for optimised shape control of the hyper-redundant robot under dynamic active constraints;

- Application of the minimised DoF control to the flexible access platform;

- Demonstration of the ability of the flexible access platform to achieve complete retroflexion within the pelvis workspace and provide a stable platform for performing a transvaginal tubal ligation in vivo;
Demonstration of the ability of the flexible access platform to accurately position an imaging probe perpendicularly to the tissue surface at multiple locations within the peritoneal cavity for performing a single-port diagnostic peritoneoscopy in vivo.

The technical chapters of the thesis address some of the unmet clinical challenges outlined in the introduction of this thesis. It is recognised that none of the currently available actuation technologies can meet the key requirements for integration in an articulated robot for MIS. Specifically, the size constraints due to the diameter of the trocar port (15mm) and the minimum radius of curvature necessary to enable navigation along curved trajectories require further miniaturisation of the actuators. A small footprint in the operative theatre is also critical to ensure seamless integration of the system within the surgical workflow. At the same time, adequate force/torque transmission is needed to provide sufficient stability at the distal tip of the device to perform functional imaging or minor interventions on tissue. Modularity is also desirable to simplify both the control and the maintenance of the robot by addressing each joint unit independently. The flexible access platform currently under development at the Hamlyn Centre and described in detail in Chapter 2 solves some of these issues through its novel joint mechanism specifically designed for MIS applications. The optimisation of the design parameters to obtain minimum backlash and adequate torque transmission tackled in Chapter 3 has been the main contribution of this study to the development of the universal joint unit design.

In this thesis, a major part of the work has been focussed on reducing the complexity of manipulating a higher-dimensionality dexterous system with structure and functionalities based on the flexible access platform by applying kinematic control. Chapter 4 has introduced a ‘front-drive back-following’ approach for controlling the locomotion of a hyper-redundant self-propelling robot which specifically addressed Challenge 4 as outlined in Chapter 1. The effectiveness of the method for path following applications in MIS has been demonstrated through detailed simulation for realistic, in vivo settings. Active constraints have also been imposed on the whole length of the robot body to assess the accuracy of the proposed control algorithm.

In Chapter 5 we have proposed a DoF minimisation algorithm to identify the necessary joints to be simultaneously actuated in order to ensure shape conformance of a hyper-redundant articulated device to a time-varying instrument path. The algorithm was designed to address Challenge 5 as outlined in Chapter 1 and improve the control ergonomics by reducing the dimensionality of the multiple DoF system. Dynamic active constraints have been imposed on the whole length of the robot to ensure the safety of the minimum DoF approach in a realistic simulation framework. Experimental results using a 5-DoF version of the flexible access platform with embedded position sensing have also been presented to demonstrate the practical value of the minimised DoF control.
Finally, the kinematic model and workspace of the flexible access platform have been introduced in Chapter 6 to investigate the potential of the system in addressing Challenges 1 to 3 as outlined in Chapter 1. In particular, detailed simulations have been provided to demonstrate the feasibility of performing two exemplar single-port interventions using the robot: transvaginal tubal ligation and single-port diagnostic peritoneoscopy using micro-confocal imaging. Results from in vivo validation carried out by surgeons of the Hamlyn Centre on a porcine model have also been presented to demonstrate the practical capabilities of the device.

7.2 Ongoing work and future research directions

One obvious direct expansion of the work presented in this thesis is the implementation of the proposed kinematic control algorithms using a hyper-redundant articulated robot prototype. Our team at the Hamlyn Centre is already working on improving the capabilities of the flexible access platform by further reducing the size of the modules and integrating position sensing within the joint units. However, hardware limitations such as the limited torque generated by the micromotors and the restricted space at the joint for the passage of sensing and power lines, still hinder the integration of a large number of DoFs. Nonetheless, the effectiveness of the minimised DoF control has already been demonstrated for a non-redundant articulated robot. Further validation of the method in vivo requires the integration of pre-operative imaging and intra-operative sensing to generate the active constraint model and update it in real-time during the procedure. Kinematic control should also be refined to account for intra-operative changes by implementing generalised predictive control or Kalman filtering, as already discussed in Chapter 5. Since optical tracking cannot be used in vivo, a suitable technique must also be implemented to ensure accurate co-registration of the robot and the model.

It is important to note that the dynamic active constraint model is used in the proposed kinematic control algorithms only for the definition of the desired instrument path, while Proximity Queries (PQs) are performed offline to assess the accuracy of the control. This is due to the long computational time needed to calculate the deviation of the robot body outside the safety region prescribed by the constraint. However, recent work at the Hamlyn Centre has been focussed on adapting the formulation of the PQs into a GPU (Graphics Processing Unit) platform to achieve a fast update for haptic rendering at higher rate than 1kHz. The method is highly flexible as it can be applied to any robot shape represented as vertices, but not restricted to a convex polygon or other continuity properties. This can potentially allow the online adaptation of the robot kinematics to the dynamically varying active constraint model in order to keep the robot body within the safety region.

As already mentioned in Chapter 4, the main pitfall of the ‘front-drive back following’ approach is the relatively slow speed to advance the robot when using a
large number of modules. One possible solution is to increase the length of the links so that a smaller number of modules is needed to cover the entire path; however, this would increase the error in following the prescribed trajectory, therefore further investigation would be necessary to assess the safety of the specific procedure. Another possible solution is to implement a control algorithm that actuates multiple modules simultaneously rather than only one at each cycle of locomotion. However, this actuation scheme would greatly increase the control complexity of the system. It is also important to note that the surgical models considered in this thesis only represent testing trajectories to validate the proposed locomotion principle. In the real case, the trajectory points would be defined by the endoscopist himself who would drive the device on the basis of the visual feedback given by the camera at its tip. In the case of colonoscopy, the surgeon may have to face different challenges when dealing with a diseased colon, such as the presence of a tumour mass obstructing the lumen or shape anomalies. If a tumour is found during the procedure, the decision on how to operate should be taken by the specialist performing the colonoscopy; one possibility would be to take a biopsy of the cancerous tissue and retract the robot. Nevertheless, other possible physiological constraints and solutions have to be investigated with the aid of a specialised team of physicians. In addition, pre-operative imaging data could be obtained to give a better insight of the patient-specific surgical scenario before performing the procedure.

Although the results presented in Chapter 6 clearly demonstrate the potential of the in vivo implementation of the flexible access platform, the lack of effective position feedback hinders the application of kinematic control, which would effectively improve the ergonomics and safety of the procedures. Disorientation issues caused by the direct ‘joint-by-joint’ control paradigm coupled with the misalignment between the axes of the hand-held controller and the distal universal joints are major issues that need to be addressed. One solution is to simultaneously actuate multiple DoFs to perform large area exploration by controlling only two DoFs using the hand-held input device. By exploiting the kinematic mapping between the pose of the universal joints and the direction of motion of the thumb-stick, it would also be possible to compensate for the misalignment and reduce the spatial disorientation. The information from the embedded position sensing could also be used to provide the surgeon with an interactive graphical representation of the flexible access platform illustrating the actual configuration of the joints.

It is evident from the results presented in this thesis that a simple kinematic control algorithm which would be particularly beneficial for the performance of a transvaginal tubal ligation is the execution of automatic straightening and retroflexion movements. However, due to the limited workspace within the pelvis, the motion should be performed in two different steps, as discussed in Chapter 6. For the case of transvaginal diagnostic peritoneoscopy, the automatic execution of pre-defined distal tip trajectories while keeping steady contact between the tissue and the op-
tical imaging probe offers the potential to generate intra-operative high-resolution functional tissue maps. This could be achieved by combining kinematic control with force adaptive imaging techniques, such as the linear translation mechanism under development at the Hamlyn Centre. This has been already successfully tested with the flexible access platform both \textit{ex vivo} [227] and \textit{in vivo}, as described in Chapter 6. Undesired artefacts in the optical images due to periodic tissue deformation could also be eliminated by compensating the physiological motion using kinematic control. Motion tracking control under dynamic active constraints has already been implemented within a realistic simulation framework to ensure stable visualisation of deforming tissue during manipulation tasks [173]. Ongoing work will need to focus on the application of visual servoing control on the flexible access platform with embedded position sensing.

To summarise the shortcomings identified above, Table 7.1 lists all the assumptions made in this thesis, together with possible modifications for a more realistic future implementation of the proposed algorithms.

\textbf{Table 7.1:} Summary of the simplifications made in this thesis and possible improvements to the proposed algorithms.

<table>
<thead>
<tr>
<th>Assumptions</th>
<th>Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic response of the system is negligible</td>
<td>Introduction of a dynamic model of the system</td>
</tr>
<tr>
<td>Robotic prototype can incorporate any number of joints</td>
<td>Consideration of hardware limitations</td>
</tr>
<tr>
<td>Offline performance of PQs</td>
<td>Improvement of PQs formulation for fast haptic rendering</td>
</tr>
<tr>
<td>Perfect matching of pre-operative data to intra-operative scenario</td>
<td>Kinematic control update according to intra-operative imaging and sensing data</td>
</tr>
<tr>
<td>Lack of position feedback</td>
<td>Introduction of embedded sensors</td>
</tr>
</tbody>
</table>

Finally, ongoing work at the Hamlyn Centre is currently focussing on the integration of bimanual manipulation capabilities in the flexible access platform to address Challenge 6 as outlined in Chapter 1. This would allow the execution of surgical tasks involving large amount of tissue manipulation such as suturing. In addition, by elevating the endoscopic camera from the plane of the instruments it would be possible to obtain sufficient triangulation for tissue dissection and retraction. As already discussed in Chapter 2, fervent interest has recently been shown by the robotics community in the development of a flexible platform incorporating bimanual manipulation capabilities, however none of the proposed systems has yet demonstrated the clinical efficacy necessary for translation into clinical practice. One of the main drawbacks of these systems is their poor ergonomics, since they currently require the
collaboration of multiple operators to manipulate the endoscopic tools and control the camera pose accordingly. Current work is therefore focussed on the exploitation of additional control modalities to allow single-user operation of the multiple DoFs integrated in the bimanual flexible access platform. One possibility is to combine eye-tracking with kinematic control to allow the simultaneous actuation of multiple DoFs and position the endoscopic camera according to the direction of the surgeon’s gaze. Another possibility is to couple the positioning of the endoscopic camera with the operator’s body motion using wearable sensors, as described in Appendix A.

The work presented in this thesis has clearly demonstrated the great potential of integrating kinematic control within the development of a novel flexible access platform for MIS. It is hoped that future research will succeed in improving the ergonomics and safety of surgical robotic systems to ensure their seamless integration into the surgical workflow for providing enhanced vision and dexterity, as well as to ensure the positive outcome of minimally invasive procedures.
Appendices

Appendix A  Control of an articulated endoscopic camera by using an ear-worn activity recognition sensor

A.1 Introduction
As discussed in Chapter 2, Minimally Invasive Surgery (MIS) is constantly evolving to allow for safer interventions and shorter recovery. With the integration of robotic technologies, further improvements are made towards flexible access surgical platforms [228] such as the one presented in Chapter 2. These can provide navigation along curved anatomical pathways and deliver bimanual dexterity to the operative site through a single port access. Nonetheless, the complexity of the current instruments requires multiple operators to work together. Furthermore, limited field-of-view coupled with misaligned visual-motor axes can cause significant problems due to disorientation. These necessitate the integration of mechatronic articulation in the endoscopic camera, which can be controlled in an ergonomic and intuitive way. Recently, Gaze-Contingent control has been proven to be effective for robotic interface [156]. Head motion control has also been proposed in [229] to position the tip of a motorised endoscope during thoracic surgery. The main drawback of the technique is the need to wear a specialised motion sensor using a headband and a Head Mounted Display (HMD) to ensure that the image is co-registered. The use of such devices can make the surgeons feel restricted and separated from their environment. In this work, a lightweight ear-worn sensor [230] is used to detect the orientation of the surgeon’s head and directly control the motion of an articulated endoscopic snake robot.

A.2 System components and their interaction
As shown in Figure A.1, the system consists of four main components: the ear-worn sensor, a local processing unit, a laptop and the flexible surgical platform.

This work can be found in: Vitiello V, Lo B, Yang G-Z (2011) Control of an articulated endoscopic camera by head motion using the ear-worn activity recognition sensor. In: Yang GZ, Darzi A (Eds.) Proceedings of The 4th Hamlyn Symposium on Medical Robotics, 81-82.
The platform comprises two flexible arms and a three degrees-of-freedom (DoFs) articulated endoscope. The design of the articulated endoscope is based on the flexible access platform design presented in Chapter 2, with the DoFs arranged as one proximal revolute joint (yaw rotation) and one distal universal joint (intersecting pitch and yaw axis). However, since the motion of the head can only be detected in one plane with this sensor, only the proximal yaw and distal pitch rotations are used to position the endoscopic camera.

![Diagram of system components](image)

**Figure A.1:** System components for head motion control.

The ear-worn Activity Recognition (e-AR) sensor features a BSN (Body Sensor Network) node [231], a built-in battery and a 3-axis accelerometer. The measured angular accelerations are digitalised by the BSN node into three signals in the range of 0-3.5V, where higher outputs correspond to higher accelerations. As shown in Figure A.2, each signal represents the head motion in a different direction, namely right/left (blue line), forward/backward (green line) and up/down (red line). The BSN node also provides a wireless link to send the data to a local processing unit where the signal is processed. Figure A.2 shows the output of the e-AR sensor before (a) and after (b) the application of a median filter with a moving window of size 10 samples. Once the noise is filtered out, the orientation of the head is determined by comparing the signals along the different directions to their baseline values, which are obtained when the head is at rest in the position shown in Figure A.4(a).

The information about the head direction of motion is then sent through a USB connection from the local processing unit to the serial port of the laptop using 5 letters: C (Centre), U (Up), D (Down), R (Right), L (Left). The desired motion of the articulated endoscope is finally realised by reading the serial port and actuating the corresponding motors via a linear amplifier stage and the Namiki SSD04 3-phase brushless drive electronics.
Figure A.2: Signal extracted from the e-AR sensor accelerometer before (a) and after (b) median filtering. Head displacement is detected along right/left (blue line), forward/backward (green line) and up/down (red line) directions.
Table A.1: Mean and standard deviation values of completion time and distance from the desired path over 5 subjects for three increasingly complex paths.

<table>
<thead>
<tr>
<th></th>
<th>Time [sec]</th>
<th>Distance [degrees]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Std Dev</td>
<td>Mean Std Dev</td>
</tr>
<tr>
<td>1st Path</td>
<td>62.7 10.6</td>
<td>0.0782 0.0587</td>
</tr>
<tr>
<td>2nd Path</td>
<td>91 22.5</td>
<td>0.0813 0.0346</td>
</tr>
<tr>
<td>3rd Path</td>
<td>39.7 13</td>
<td>0.3280 0.0602</td>
</tr>
</tbody>
</table>

A.3 Experimental task and results

An experimental task was designed to assess the intuitiveness and precision of the proposed control. Five subjects were asked to follow increasingly complex paths on a screen by moving a cursor using head movements. Two parameters were measured during the experiment: completion time and distance between the desired path and the actual cursor position in terms of visual angles. The resulting mean and standard deviation values for each path over the five subjects are reported in Table A.1.

Figure A.3 shows the trend of mean and standard deviation values of the distance between the desired path and actual cursor position computed over the five subjects along each of the three paths. The path increasing complexity is clearly reflected in both the graphs and the values in Table A.1, where path following accuracy is significantly worse for the third path than for the first two. However, the completion time is longer for the second path because it is constituted by a higher number of points, as shown in Figure A.3.

Figure A.4 shows four snapshots from a video recorded during a subject test in a laboratory setting when the articulated endoscope was positioned at extreme workspace positions and the corresponding head orientation. The range of motion of the first DoF is between $-45^\circ$ and $+45^\circ$ along the right/left direction, while the second spans from $0^\circ$ to $90^\circ$ downwards. A flexible neck connects the articulated endoscope to a rigid shaft so that it can be elevated from the plane of motion of the flexible arms once it is passed through the trocar port and the operative site is reached.

The above results demonstrate the ergonomics and efficacy of the e-AR sensor control. Moreover, although positioning accuracy is affected by the complexity of the followed trajectory, a maximum distance of less than 1.5 degrees of visual angle can be considered adequate for the specific application.

A.4 Discussion and conclusions

In this work, we have proposed an intuitive and ergonomic control modality to position an articulated endoscope using head movements. The e-AR sensor used to
Figure A.3: Plot of the mean and standard deviation values of the distance between the desired path and the actual cursor position in terms of visual angles computed over the five subjects for each point of the three paths.
Figure A.4: Snapshots of four extreme positions reachable by the articulated endoscopic camera and corresponding head orientations: (a) centre, (b) down, (c) right, (d) left.

detect the orientation of the head is lightweight and wearable, and can seamlessly integrate into the surgical workflow with a very small footprint. The overall set-up time of the system is minimal as the calibration of the sensor only requires a short pause at baseline position. In contrast to [229], there is no need for the surgeon to wear a HMD as the endoscopic image remains in the field-of-view of the user when the head is tilted (see Figure A.4(b)–(d)). The use of a serial-link mechanism to position the camera also eliminates kinematic errors and disorientation issues associated with the unknown tip orientation of standard flexible endoscopes.
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