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A Spring-like Continuum Joint for Endoluminal Surgery

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Submitted in part fulfilment of the requirements for
the degree of Doctor of Philosophy in Computing
at Imperial College London, March 2023

Statement of Originality

This is to certify that this thesis embodies the results of my own course of study and research. All else from other published or unpublished work is appropriately referenced.

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Abstract

In endoluminal surgery, the endoscope is essential and it needs to be highly accurate and flexible to access the curved lumens. To improve its performance and functionality, a novel design of a metal-printed continuum joint is proposed, with the work mainly focusing on three topics: design, modeling, and insertion.

In this thesis, I will first introduce a novel continuum joint design that takes advantage of the spring-like structure, where the 1-DoF motion can be achieved by adding a series of circular contacts along the coils. Then, a snake-like flexible endoscope design are presented that consists of an active snake robot and a passive flexible body.

To facilitate the insertion of the endoscope, a novel endoscope design has an outer tube covered by a rotating screw-like sheath. The entire shaft of the endoscope can be actively rotated, providing crawling ability from the attached spiral sheath. Redundant control over the spring-like continuum joint allows the bending tip to maintain its orientation, assisting in endoscope navigation.

Taking into account the challenges identified in the previous robot designs, a new joint design inspired by the structure of DNA is introduced. It is acknowledged that compliant mechanisms using additive manufacturing are often affected by residual stress, resulting in defects like wrapping, twisting, and deformation. Several solutions are proposed to prevent these problems during the design stage.

Apart from optimising the additive manufacturing process, a new variable pitch design is investigated for the continuum joint. By incorporating this design into the spring-like structure, position errors accumulated at the distal tip of the joint can be reduced, especially at large bending angles.

The works presented in this thesis aim to solve the challenges encountered in robotic surgery. By exploring and refining the spring-like structure, various solutions have been investigated to improve the design and control of such flexible

robots. The promising results make this structure a viable option for the next generation of surgical robots in endoluminal surgery.

Acknowledgements

Firstly, I would like to thank Prof. Guang-Zhong Yang, who led me into this challenging but exciting area. His expertise, enthusiasm, and mentorship have been invaluable in shaping my career path.

My most profound appreciation goes to my supervisor Dr. Benny Lo for his valuable feedback, suggestions, and support during the course of my research.

I would also like to thank my fellow colleagues Dr. Yang Hu, Dr. Lin Zhang, Dr. Dan-Dan Zhang, Mr. Xiao Gu, Dr. Mohamed E.M.K Abdelaziz, Dr. Ya-Yen Tsai, Dr. Bo Xiao, Dr. Khushi Vyas, Dr. Pierre Berthet-Rayne, Dr. Francesco Corsi and Dr. Shen Treratanakulchai for their friendship and valuable suggestions. Their presence has made my time in the Hamlyn Centre a pleasant and enriching experience.

Finally, I would like to express my sincere gratitude to my parents and girlfriend, Yining Li, whose unwavering support, encouragement, and love have been my anchor throughout my academic journey. My friends and family have encouraged and motivated me through their sacrifices, understanding, and belief in me.

Abbreviations

APC	Argon Plasma Coagulation
CLE	Confocal Laser Endomicroscopy
DLR	German Aerospace Centre
DMI	Depth of Maximal Insertion
DNA	Deoxyribonucleic Acid
DoF(s)	Degree of Freedom(s)
EDM	Electrical Discharge Machining
EGC	Early Gastric Cancer
EGD	Esophagogastroduodenoscopy
EM	Electro Magnetic
EMR	Endoscopic Mucosal Resection
ESD	Endoscopic Submucosal Dissection
EUS	Endoscopic Ultrasound
FBG	Fiber Bragg Grating
FDA	Food and Drug Administration
FEA	Finite Element Analysis
GI	Gastrointestinal
IMU	Inertial Measurement Unit
MIS	Minimally Invasive Surgery
MRI	Magnetic Resonance Imaging
Ni-Ti	Nitinol
NOES	Natural Orifice Endoscopic Surgery
PSE	Power Spiral Enteroscopy
R-LESS	Robotic-assisted Laparoendoscopic Single-Site Surgery
SLM	Selective Laser Melting
SMA	Shape Memory Alloy
WHO	World Health Organization

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Chapter 1

Introduction

1.1 Background

Based on the data from WHO, cancer is the second most common cause of death globally, with an estimated 9.6 million deaths in 2018, representing roughly one in six of the total deaths. Colorectal cancer is one of the major types of cancer among both men and women. In the U.K., according to the cancer statistic between 2016 and 2018, colorectal cancer is the fourth most common cancer, accounting for eleven of the newly registered cases [26]. At the same time, the report also shows that the survival rate for colorectal cancer has doubled in the last decade. Similar positive trends can be found in most countries, and the likely reason can be contributed to better awareness and greater uptake of early screening and improved treatment. There are several screening modalities used for the early detection of colorectal cancer, such as colonoscopy and fecal occult blood testing (Stool tests). While blood testing is an inexpensive and noninvasive way for early detection, it is not a specific test for identifying polyps, which can lead to false-positive results [27]. Currently, colonoscopy is the gold standard for colorec-

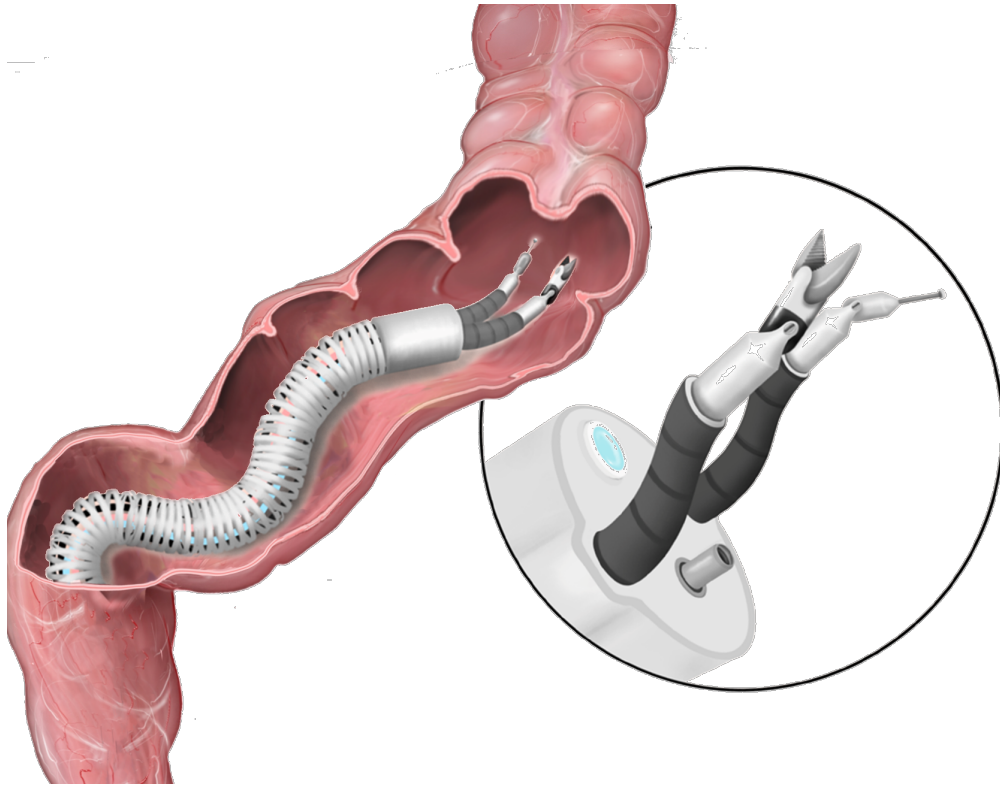


Figure 1.1: The concept of robotic endoluminal surgery (ESD surgery in the colon).

tal cancer screening, associated with diagnostic approaches, such as biopsy, narrow band imaging, endoscopic ultrasound imaging, and confocal endomicroscopy, suspicious areas can be identified and evaluated. Early intervention can be introduced to remove colorectal lesions before they develop into more serious conditions.

Following this principle, endoscopy has transitioned from purely screening and biopsies to surgical procedures, evolving from a diagnostic to a therapeutic procedure. Standard polypectomy is improved to Endoscopic Mucosal Resection (EMR) and Endoscopic Submucosal Dissection (ESD) to remove mucosal lesions, significantly reducing the risk of damage to the submucosal and layers underneath [28]. The procedure involves the use of a long, flexible endoscope that is inserted through a natural orifice to the target of interest. Both techniques require the use of specialised needles which can inject fluid into the submucosal tissue layer and lift the lesion off the muscular layers. Snares or energy delivery knives are used for

cutting the lesions away from the underlying layers. From the meta-analysis result, ESD has shown a higher complete resection rate and lower local recurrence rate, without an increase in procedure-related complications. This technique is not only performed in the colon, but its feasibility has also been investigated in the esophagus, as reported in [29,30].

From a broader view, the therapeutic endoscopic procedure or the endoluminal surgery is a rapidly emerging field; however, the procedure is still encountering some key challenges that limit its widespread use. The limited dexterity and mobility of standard endoscopes, as well as their limited compliance with accessory instruments, hinder the performance of advanced endoscopic procedures and lead to challenges in operations. Firstly, the efficacy of advanced treatment is associated with technical complications, such as the risk of bleeding and perforation. Compared with EMR, ESD surgery is considered to be more time-consuming in dealing with bleeding and more costly. Operating such procedures in a confined space is very demanding for surgeons, which requires extensive training to master the control of the elongated flexible endoscope and miniaturised instruments. It also has been reported that the non-intuitive steering control might reduce the efficiency of endoscopic interventions [31]. On the other hand, there is a growing need for both screening and therapeutic colonoscopies, the lack of skilled endoscopists is a major problem for healthcare providers and has further exacerbated the burden on the surgeons.

Although there is much advancement in technology, the endoscope design still remained fairly similar and more improvement is needed to ease the operation. The ideal features for the endoscopic platforms can be glanced through the summary of the 2006 NOSCART meeting [32]. Apart from the standard requirements on the camera and suction/irrigation channels, a flexible and steerable overtube is also mentioned, with a compact size less than 20 mm in diameter, as well as at

least three ports for interchangeable instruments. The progress of development can be traced from manually controlled platforms, such as EndoSAMURAI and Anubiscope, to the latest robotic endoscopic systems, such as the K-Flex system, the Cyclops and the EndoQuest system.

The technological advancements, such as additive manufacturing and deep learning, have also boosted the development of surgical system in design, control and image analysis. While these advancements have also brought new demands to next generation endoscopic systems. Specifically, the requirements for three key components can be identified:

- “Eyes”: the stereo camera at the tip of endoscope should provide a wider view of the operative field and enable depth perception. Also, the suspicious areas should be thoroughly examined using image-enhanced methods such as narrow-band imaging, Endoscopic Ultrasonography (EUS) and Confocal Endomicroscopy (CLE). Moreover, the integration of deep learning approaches has been reported to be highly beneficial for lesion detection, classification, and characterisation [33].
- “Hand”: the upgrade to dual-arm and tele-operated instruments aim to optimise manipulation, thereby enhancing the precision of the procedure. And the triangulation arrangement is aimed at enhancing the ergonomics of the system. However, ensuring sufficient force output and maintaining the shape under external load is still a challenge. Depending on the specific requirements and surgical needs, a variety of instruments, such as surgical graspers, scissors, energy delivery tools (CO₂ laser and electrocautery etc.) etc., should be interchangeable for tissue manipulation and ablation.
- “Body”: the robotic endoscope body should have multi-DoF, which provides flexibility and a sufficient workspace for the operations. The endo-

scope should offer improved manoeuvrability during procedures, allowing for steering, advancing, rotating, and shape maintaining. In addition, the design of endoscope should be focused on miniaturisation to reduce invasiveness, and the incorporation of dual working channels allowing for the use of robotic instruments for both diagnosis and treatment purposes. To ensure the safety of the system, force feedback should be built on the robotic body with sensors.

The main objective of this thesis is to address some of these challenges through the use of a novel spring-like continuum joint. Much effort was focused on the part of "body" design or endoscope design. To begin, the key characteristics of the spring-like structure is evaluated, and the extension to a multi-segment design is assessed. Then, a practical solution for improving the insertion is proposed which is based on a spiral propel technique. Based on the problem exposed by these two design, a novel 2-DoF joint design will be introduced and the defects from fabrication process will be investigated. Furthermore, the position accuracy will be improved by modifying the design with a static modelling approach.

The first step involves evaluating the key characteristics of the spring-like structure, followed by its extension to a multi-segment design. Then, a practical solution aimed at enhancing the insertion process is proposed, based on a spiral propel technique. Building upon the issues identified through these two designs, a novel 2-DoF joint design will be introduced, and an investigation into the defects arising from the fabrication process will be conducted. Furthermore, the variable pitch will be assessed with static modeling and implemented to the design.

1.2 Thesis Structure

A summary of the main chapters in this thesis is structured as follows:

Chapter 2 provides an overview of endoscopy and the development of therapeutic endoscopic surgery. The challenges that occurred in the current procedures inspired the emerging of robotic platforms. Next, the current robotic platforms, including those with commercial potential are discussed and compared. In addition to the endoscopic platforms, the well-known multi-port platforms and single-port platforms are also discussed. These platforms have shared knowledge and faced similar problems, which also serve as indicators of the trends and phases in the development of Minimally Invasive Surgery (MIS). The following sections give an overview of the technical challenges involved in developing a flexible robotic platform, which can be organised by the broad themes of design structure, modeling, and endoscope insertion.

Chapter 3 introduces a novel design of a continuum joint fabricated by Selective Laser Melting (SLM). It presents a design of a flexible endoscope with a snake-like body, which includes an active snake robot and a passive flexible body. The active section is composed of the 1-DoF joint. To maintain the internal space, the actuation tendons are arranged in a novel strategy. To evaluate the performance and clinical viability of the proposed flexible robot, several tests were conducted, including Finite Element Analysis, workspace analysis, path following accuracy, and force testing. The results indicated that the robot could reach a minimum retro-flex bending radius of 23 mm and the distance errors of each joint when advancing along a simulated colon path are analysed.

Chapter 4 describes a novel robotic endoscope which is covered by a rotating screw-like sheath and uses a spiral insertion technique to generate "pulling" forces at the distal tip of the endoscope to facilitate insertion. The whole shaft of the en-

doscope can be actively rotated, providing the crawling ability from the attached spiral sheath. With the redundant control on a spring-like continuum joint, the bending tip is capable of maintaining its orientation to assist endoscope navigation. To test its functions and feasibility in addressing the looping problem, three experiments were carried out. Results show the effectiveness of the spiral technique and verify its potential for clinical application.

Chapter 5 proposes a modified design further improved to 2-DoF capability, incorporating with helical routing to reduce the cross-talk. In addition, the effects of residual stress during the fabrication are investigated. An additional support structure was introduced and an extensive experiment was conducted to access the effect of the variables on the design (pitch, thickness, width and the number of coils), with the aim of determining optimal parameters for reducing discrepancy caused by manufacturing variations.

Chapter 6 shows a modified design of the continuum joint, which aims to improve the problem of position accuracy described in previous chapters. By incorporating a variable pitch feature into the spring-like structure, the design can reduce the position errors accumulated on the distal tip of the joint, especially at large bending angles. The specification of variable pitch is investigated and determined with a friction model. A multi-segment prototype was developed to verify its effectiveness for potential surgical applications.

Chapter 7 concludes the works presented in this thesis, and the future working direction is described.

The key contributions of this thesis include:

- Introduced a spring-like continuum joint design fabricated by metal printing; the tests and simulation were conducted on a preliminary design of a multi-segment snake-like design with a 15 mm outer diameter and 7 DoFs.

- Proposed a robotic endoscope design that can improve the performance during insertion. By adopting a spiral technique, a "pull force" can be generated at the tip of the endoscope to aid insertion. An additional axial redundancy feature is incorporated to maintain the orientation of the tip.
- Investigated the defects generated during the metal printing process. The twist induced during the process were measured on the spring-like structures with different configurations (pitch, thickness, width and number of coils), and the results are used for compensation.
- Modified the spring-like structure with a variable pitch based on the friction model and the constant curvature model. Thus the position errors can be significantly reduced.

Validation of the proposed structure demonstrates its potential use for designing a robotic endoscope for ESD and other types of endoluminal surgeries.

1.3 Publications Arising from this Thesis

W. Li, D. Zhang, G.Z. Yang, B. Lo, "Design and Modeling of A Spring-Like Continuum Joint with Variable Pitch for Endoluminal Surgery", In 2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Kyoto Japan, Oct 23-27, 2022

W. Li, M. Shen, A. Gao, G.Z. Yang and B. Lo, "Towards a Snake-Like Flexible Robot for Endoscopic Submucosal Dissection", IEEE Transactions on Medical Robotics and Bionics, vol.3, no.1, pp.257-260, 2020.

W. Li, Y.Y. Tsai, G.Z. Yang and B. Lo, "A Novel Endoscope Design Using Spiral

Technique for Robotic-Assisted Endoscopy Insertion”, 2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), pp.3119-3124, 2020.

Y. Hu*, **W. Li***, L. Zhang and G.Z. Yang, “Designing, Prototyping, and Testing a Flexible Suturing Robot for Transanal Endoscopic Microsurgery”, IEEE Robotics and Automation Letters, vol.4, no.2, pp.1669-1675, 2019.

Y. Hu, L. Zhang, **W. Li** and G.Z. Yang, “Design and Fabrication of a 3-D Printed Metallic Flexible Joint for Snake-Like Surgical Robot”, IEEE Robotics and Automation Letters, vol.4, no.2, pp.1557-1563, 2019.

* indicates equal contribution.

Chapter 2

Literature Review

2.1 From Endoscopy to Endoluminal Surgery

Over the course of the last three centuries, the techniques and approaches related to endoscopy have undergone significant and continuous development. The first endoscopy was conducted in 1806 when a German urologist constructed a device named as ‘Lichtleiter’ (Fig. 2.1(a)) that allowed candle light to be reflected into the esophagus, bladder and rectum [1]. In the following century, the clarity of endoscopic view had improved with the use of an inner light source and optimised optical systems. However, the depth of examination in a curved lumen is restricted by the rigid design of the endoscope. Hopkins invented a rod-lens optical system in 1954, which initially introduced fiber optics for light transmission [34]. As shown in Fig. 2.1(b), Basil Hirschowitz further developed this novel technology into a flexible design, which was the cornerstone of the development of modern endoscopy [2].

Since then, the field of flexible endoscopy has undergone constant evolution, and substantial improvements including adjustable tip design and external cold light

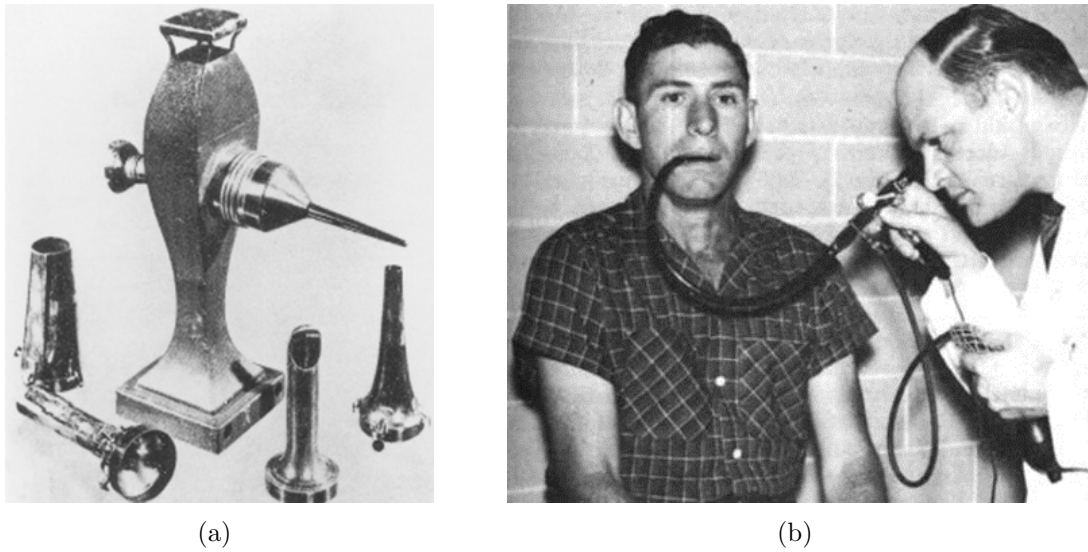


Figure 2.1: The development of endoscope. (a) The first endoscope is intended for urological examination (©2019, Elsevier. Reprint with permission from [1]). (b) Basil Hirschowitz demonstrates the first flexible fiberscope for gastroscopy on a patient (©2006, Springer Nature. Reprint with permission from [2]).

source were introduced to increase the range and resolution of the views. Flexible endoscopy has become a common procedure used for diagnosis and intervention, and the advanced surgical approaches make therapeutic endoscopy possible allowing minimally invasive operations to be conducted in the bronchus, urethra, uterus, *etc.*. In this section, I will focus more on the development from endoscopy to endoluminal surgery or from conventional to therapeutic endoscopy in the GI tract.

2.1.1 Conventional Endoscopy

A conventional endoscopy or diagnostic endoscopy in the GI tract mainly consists of the insertion of an endoscope equipped with examination tools and a camera through a natural orifice into the patient's body, which allows an endoscopist to view the mucosal lining along the lumen. The test is also called an esophagogastroduodenoscopy (EGD) in the upper GI tract or a colonoscopy in the lower GI

tract. Traditionally, direct inspection is an easy method to examine the interior tissues, while the whole screening process can be challenging especially as lesions can be subtle and inconspicuous. Also, it has been described that lesions may be easily overlooked, as they may locate behind folds and inner curves of flexures, which are very difficult to be spotted by the forward viewing camera of the endoscope [35, 36]. The average misdiagnosis rate of 11.3% for upper gastrointestinal cancers from [37] compared with that of 4% for colorectal cancers from [38]. To detect those hidden lesions, endoscopists mainly rely on the retroflexion ability of the endoscope. Retroflexion describes a function that the endoscope can show a backward view to examine the tissue, which relies on the large bending angle ($>180^\circ$) of the flexible joints, and lesions can be spotted which are often missed with only the forward view.

To evaluate the suspicious areas, the diagnosis is sometimes combined with other procedures, such as biopsy. A previous study has shown that clinicians with less experience are more likely to perform unnecessary biopsies [39]. Taken biopsy samplings randomly may miss relevant lesions, and the extra samplings pose a burden to both endoscopists, pathologists and patients, in terms of workload and the risk of post-operative complications respectively. Chromoendoscopy can help locate and identify suspicious lesions for biopsies by applying the dye or stain on to the mucosa, however, the lack of standardised methods and analysis may lead to uncertain results [40].

With technological advances, image-enhanced endoscopy has much improved the endoscopic diagnosis. The differences in the mucosal microstructure and microvascular features with normal tissues can be clearly observed using magnifying endoscopy and narrow-band imaging [40]. Endoscopic Ultrasonography (EUS) offers another dimension in imaging. Its ability to penetrate deep into the tissue allows the GI wall to be differentiated in a series of tissue layers, and the surrounding

tissues and lymph nodes can be inspected to assess the stage of cancer [41].

Recently, a new imaging technique called Confocal endomicroscopy (CLE) has been proposed, which can provide real-time, high resolution and high magnification images. It allows the surgeons to view the cellular structure of mucosa. It has been reported that CLE has the potential to reduce the number of biopsy specimens taken due to its comparable results to histology [42]. In some cases, CLE can guide the biopsy process ensuring that tissue samples are taken precisely in the suspicious areas and the margin of lesions could be confirmed.

2.1.2 Therapeutic Endoscopy

Technological improvements along with the development of novel surgical approaches have much improved the precision of surgical operations, and enabled the performance of complex operations. Thus, the role of a flexible endoscope has evolved from a diagnostic tool to a surgical tool.

Currently, the Early Gastric Cancer (EGC) can be treated with different techniques, such as mucosal ablation with chemical (photodynamic therapy [43]) or thermal (argon plasma coagulation [44]) techniques, and dissection methods (standard polypectomy, Endoscopic Mucosal Resection (EMR) and Endoscopic Submucosal Dissection (ESD) [45]). In particular, a typical polypectomy involves utilising cold snares or cold biopsy forceps for small lesions. In the process of cauterising the tissue, the potential risks are deep thermal injury and perforation [28, 46]. EMR is an extension of polypectomy, which is commonly used to treat small-size (less than 20 mm) polyps with a prior injection of fluid into the submucosa. By injecting the fluid underneath the lesion, the lesion will be lifted and further away from the muscle layer, and the lesion can then be removed by anchoring the tip of the snare. The high recurrence rate around 10% to 30% is the main disadvantage of

EMR [47]. Argon Plasma Coagulation (APC) is a non-contact electro-coagulation procedure used to treat patients with lesions that are impossible to be resected completely [44]. It is easy to use and has a short operation time; however, the depth of coagulation is difficult to be predicted. The latest studies have shown that the recurrence rate can be prospectively reduced with hybrid APC assisted EMR [47, 48].

Compared with piecemeal resection from EMR, ESD offers the flexibility of performing *en bloc* resection* and R0 resection† of larger lesions (greater than 20 mm) than EMR in both upper and lower GI tracts. The lesions should be removed in a few pieces, preserving histological features and enabling more accurate assessment [50]. The meta-analysis studies also demonstrate a consistently high resection rate and low recurrence rate [45, 51]. During the procedure, the circumference of the tumor is marked with cautery. A specialised needle is then inserted to inject the lifting solution such as, saline and sodium hyaluronate to create separation between the lesions and the underlying muscular layers. Subsequently, an endoscopic electric knife is used to remove the lesions. Due to the size of the channel, these tasks can be performed with combined and multi-function tools, such as DualKnife (Olympus, Japan) and HybridKnife® (Erbe Elektromedizin GmbH, German). Performing the ESD procedure requires a highly skilled and experienced from the surgeon, sustainable and long-term training is necessary to maneuver the instruments efficiently and precisely. Inadequate training with the current surgical setup can lead to human errors, and which could cause bleeding, perforation and incomplete resection [45, 52]. The complexity of performing the ESD procedure and the associated risks have hindered its wider adoption in practice.

**En bloc* resection refers to the complete removal of a lesion in one piece without any partial resection.

†R0 resection refers to a microscopically margin-negative resection, indicating that there is no residual tumor remaining in the primary tumor bed. [49]

2.2 Surgical Robots Toward Commercialisation

In recent years, surgical robots have much improved and have gradually replaced traditional MIS tools to become the preferred choice of devices for surgical operations. Enhanced functions such as ergonomics design, visualisation and manipulation are being continuously explored and developed. Starting with the success of the da Vinci robotic platform, novel design and surgical robot technologies have been introduced by companies as well as the research community. As the advanced technologies have widespread benefits across various aspects of the field of MIS, the review in this section will extend beyond the scope of endoscopic systems. By exploring those robotic platform with commercial potential, they can be categorised as multi-port platforms, single-port platforms and endoscopic platforms. These categories also reflect the trends and phases in the evolution of MIS.

2.2.1 Multi-Port Platform

The da Vinci[®] robot system received the clearance from Food and Drug Administration (FDA) in 2000. Designed as a master-slave system, the da Vinci consists of two main components: the master console which provides stereoscopic vision and control interface, and the surgeon can control the instruments mounted on the slave robotic arms remotely via the master console. It was not the first surgical robot for clinical use, but a game changer on the market. The innovations of this system have deeply influenced the later products. One of the unique features of the da Vinci robot is its EndoWrist[™] technology. This technology is designed to provide a greater range of motion for surgeons, where the tip of the instruments has 3-DoF which models the natural movement of a human wrist. Another unique feature of the system is its 3D immersive vision, the 3D vision allows the operator to perceive the depth of the scene, and increases gesture precision and

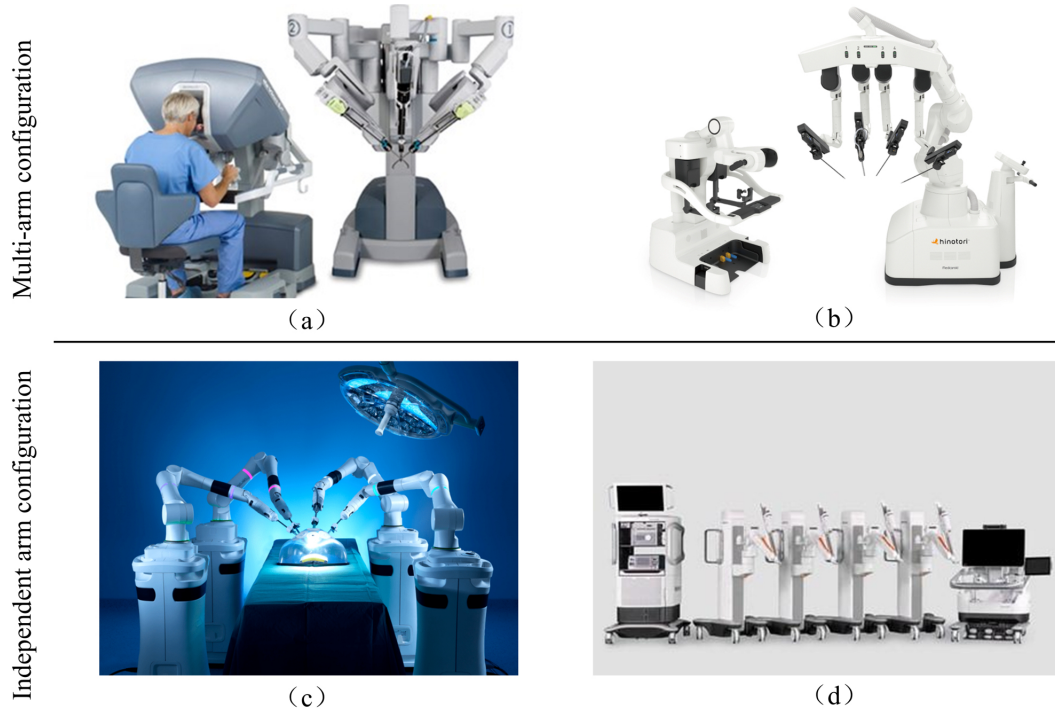


Figure 2.2: The current multi-port platforms with two types of arm configurations. (a) The da Vinci[®] robot system (image courtesy of Intuitive Surgical). (b) The hinotori[™] Surgical Robot System (image courtesy of Tezuka Productions). (c) The Versius[®] Surgical Robotic System (image courtesy of CMR Surgical Ltd.). (d) The Hugo[™] RAS system (image courtesy of Medtronic).

safety in surgical tasks. In the latest version of da Vinci Xi, these functions have been enhanced with upgraded visualisation functions, an easier docking design and reduced arms sizes.

The Senhance system from Transenterix Surgical Inc. was unveiled in 2017. It has several unique features making it competitive to the da Vinci system. To enhance the tactile sensitivity, the pressure that comes from the target tissue is detected and fed back through built-in sensors on the proximal end of the instruments. Instead of changing the camera view by hand or joystick, Senhance comes with a gaze control function which allows the camera to move following the surgeon's eye movements.

Different from the multi-arm configuration as per the da Vinci system, independent-

arm design is tended to make arm positioning and instrument exchanges easier and faster, differences between these two types of configurations can be viewed in Fig. 2.2. One example of such independent arm design is the Versius[®] from CMR Surgical Ltd.. The Versius[®] has a relatively small footprint of 38 cm x 38 cm which eases its accessibility around the operating tables. A similar concept can be found in other systems, such as the Hugo[™] system developed by Medtronic which incorporates the technological principles of the DLR MiroSurge system (German Aerospace Center). It utilises lightweight, torque-controlled, and multi-sensor robotic arms inherited from the DLR MiroSurge system to ensure precise motions in either manual or tele-operated mode. Another feature of these independent-arm designs is to increase the overall cost-effectiveness associated with robotic laparoscopic surgeries. It has been supported by [53] that the charge is largely attributed to the instruments, and both Versius and Hugo systems have extended the number of uses of their instruments to lower the overall operating cost.

With the wider adoption of robotic assisted laparoscopic surgery, a number of companies and institutes are following the design of the da Vinci platform in designing their own systems, such as, the Hinotori[™] system developed by Medicaoid Cooperation (Kobe, Japan), recently approved by Japanese authorities in 2020; Micro hand S system developed by Tianjin University, and Revo-i developed by Meere-company Inc. (Korea). While maintaining the fundamental multi-arm structure, these systems prioritise the development of their functional capabilities.

2.2.2 Single-Port Platform

Since Haber *et al.* [54] first reported the laboratory experience with Robotic-assisted Laparoendoscopic Single-Site Surgery (R-LESS) in 2008, R-LESS techniques have rapidly developed. Some studies have supported that robotic surgery



Figure 2.3: Two of the representative single-port robotic platforms, both of them share similar configurations of vision unit and manipulation arms. (a) The da Vinci SP surgical system (image courtesy of Intuitive Surgical). (b) SPORT (image courtesy of Titan Medical Inc.).

has not shown superior long-term outcomes compared with conventional laparoscopic surgery [55, 56]. However, its perioperative performance cannot be ignored. To further shorten the recovery period, reduce pain and blood loss, and minimise the risk of postoperative complications, one essential concept is to limit the number of incisions used in the procedures. With the enhanced assistance from the robotic system, the robotic single-port surgery is being well-developed.

The single-port surgical robotic system has the ability to enter the body through a single and relatively small incision. Different from multi-port surgery, the rigid shaft and paralleled arrangement of instruments make it challenging to create enough workspace for manipulation and operate the instruments in reverse position. Therefore, the system requires a higher dexterity and ergonomic design. By incorporating a section of flexible or articulated joints design at the distal tip, the robotic arms can branch-out and create triangulation around the target anatomy, mimicking the natural pose of the surgeons and enabling the surgeon to perform complex tasks.

Intuitive Surgical Inc. recently released its new iteration of the da Vinci robot

called the SP (Single Port) system (Fig. 2.3(a)). The main design of the SP system shares multiple functions with the prior multi-port version, such as the surgeon console, stereo vision and tremor reduction, which can help to shorten the learning curve for experienced surgeons. Compared to the previous version, most technical advancements can be found in the patient side. A flexible endoscope is integrated which can be lifted up to provide a wider field of view. Similarly, the rigid rod near the proximal end is replaced with a section of flexible joints which provide necessary triangulation for complex surgical tasks. During the operations, three instruments and an endoscope can be passed through a 25mm cannula and be re-oriented to view around the anatomy. The efficacy of the SP system has been investigated for several urological and transoral procedures [57].

As shown in Fig. 2.3(b), the SPORT™ (Single Port Orifice Robotic Technology) Surgical System manufactured by Titan Medical Inc. (rebranded to Enos surgical system in 2020) is reported to be a potential device for R-LESS [58]. It is developed based on the IREP system [59, 60] that has a 3D stereo camera and two multi-DoF continuum arms. Each manipulation arm has 6 mm in diameter which is relatively larger than its competitors. However, a fair payload capacity above 3.25 N can be achieved. The system can pass through a 25 mm port and covers a large workspace of 64 mm x 103 mm. Titan has recently revealed the next-generation of the single-port system, a third-arm is integrated with the design.

Micro-IGES (Precision Robotics Ltd., U.K.) is a single-port platform for transanal endoscopic microsurgery [61]. The main advantages of the robot are its light-weight and small footprint in the operating room. As shown in Fig. 2.4(a), a passive robotic arm mounted on the operation table can lift up and hold the slave robot in position for the operation. There are two actuation modules on the slave robot to control the multi-DoF flexible surgical instruments. The tendon-driven instruments typically have nine segments and can present 7-DoF, by using

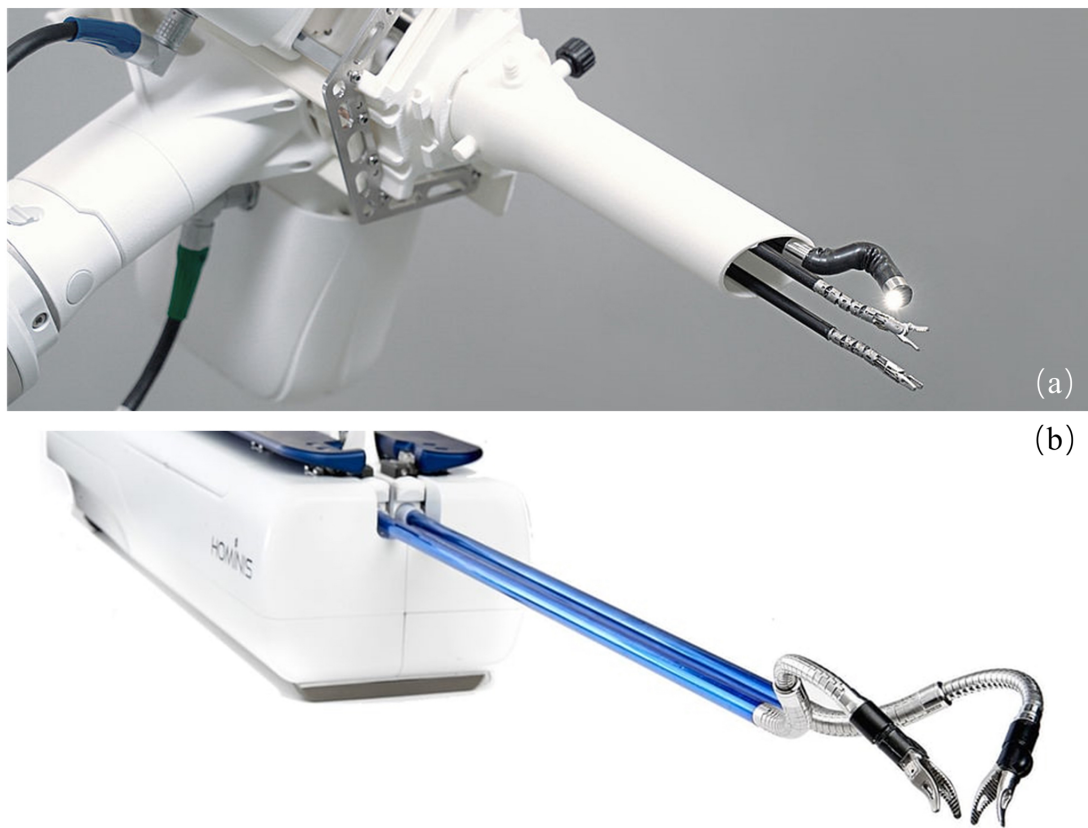


Figure 2.4: The single-port design with the ideas of reduced size and less footprint. (a) Micro-IGES (image courtesy of Precision Robotics Ltd.). (b) The Anovo[™] Surgical System (image courtesy of Momentis Surgical[™]).

which, the surgeons can perform complex procedures in a more ergonomic way. The platform has been tested in pre-clinical trials and is in the process of being commercialised.

Though Micro-IGES is still facing challenges before getting through the regulatory requirements and clinical validations, its concept and configurations have been recognised on other platforms. The Anovo[™] Surgical System (Fig. 2.4(b)) developed by Israeli company Momentis Surgical[™] Ltd. (rebranded from The Hominis surgical robotics platform and Memic Innovative Surgery) has become the first robotic device for transvaginal procedures and received the clearance from FDA. The instruments of Hominis can be retroflexed towards the point of entry.

This enables the surgeons to carry out the procedure with a laparoscopic point of view and reach various structures in the pelvic cavity, in a manner not possible with traditional manual vaginal tools.

MIRA introduced by Virtual Incision provides another solution for single-port surgery. It is a portable platform and only weighs 2 lbs. The fittings with a removable camera and interchangeable instrument tips make it easier to be sterilised and relocated between the theatres [62]. Unlike others that use disposable instruments with a continuum shape, it has two articulated arms fixed on the platform and can achieve 6-DoF each. The company is currently focusing on the MIS in the Lower GI tract and the first right hemicolectomy procedure has been reported as completed in the U.S.

Vicarious Surgical, which is making an effort on launching disposable instruments requiring a 15 mm incision and bringing virtual-reality technology with its advanced camera [63]. The research group in Shanghai Jiaotong University has introduced the SJTU unfoldable robotic system (SURS) [64]. The required size of the incision could be further reduced to 12 mm in the folded status and reach 50 mm x 50 mm x 50 mm workspace after deployment.

2.2.3 Endoscopic Platform

As the trend in MIS moves toward less invasive procedures, there has been an increased number of endoscopic surgery performed through the natural orifice without any external incisions, also known as Natural Orifice Endoscopic Surgery (NOES). From a clinical aspect, this transformation from extraluminal to transluminal and endoluminal surgery has further reduced the patients' trauma and hospitalisation time. Endoscopic procedures can be performed in the long and thin lumens such as the oesophagus, colon, bronchi and *etc.*. Instead of using a

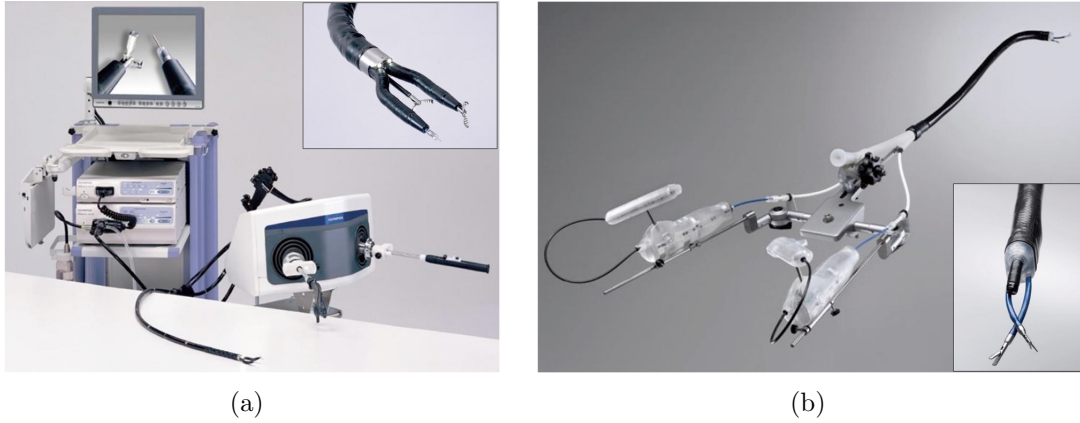


Figure 2.5: The multi-tasking flexible endoscopic platforms. (a) EndoSAMURAI (image courtesy of Olympus). (b) DDES (image courtesy of Boston Scientific).

rigid cannula, the flexible body of the endoscope can be led deep into the target sites, which is the main difference between an endoscopic platform and a single-port system introduced in the previous section. This change in the robot structure causes problems in manipulability, dexterity, visualisation, and instrumentation, and some of the research outcomes will be discussed later in this section.

The endeavours were firstly made on developing a mechanism with bi-manually controlled instruments, also known as multi-tasking flexible endoscopic platforms (Fig. 2.5). After the attempt on R-scope, Olympus Medical Systems (Tokyo, Japan) developed the EndoSAMURAI. The tip of EndoSAMURAI has two articulated arms with five DoFs in each. The flexible endoscope has 15 mm in diameter and is controlled via an 18 mm steerable overtube. Besides, it comes with a conventional working channel of 2.8 mm in diameter. Similar configurations can be viewed from other conventional endoscope manufacturers, such as the Direct Drive Endoscopic System (DDES) (Boston Scientific, Natick, Mass), Incisionless Operating Platform[™] (IOP) from USGI Medical and Anubiscope from Karl-Storz. Although the study has demonstrated the feasibility of manually driven endoscopic platforms in the cases of transgastric, small bowel resection and anastomosis, the limited maneuverability of the flexible endoscopes with a lack of platform stability



Figure 2.6: The Flex[®] robotic system consists of two main units: The patient's cart and the console. The details of the robot can be viewed that the body is connected by a series of spherical joints and with function channels on the side (top right). The robot can demonstrate the follow-the-leader manner (bottom right). (Image courtesy of Medrobotics).

has been mentioned as the critical issues [65]. The long length and parallel orientation issues of the instruments are noted [66]. Also, these endoscopes generally require two endoscopists for the manipulation, one manages the scope and the other one controls the two instruments at the command console. One simple solution to build a teleoperated system is to upgrade the existing manual controlled platform. Then, STRAS, a motorised version of Anubiscope was proposed [67,68]. The original handles for controlling the endoscope and instruments are replaced by the motor-tendon architecture, and the system can obtain 12-DoF in total. After several improvements, preclinical experiments (ESD) have been successfully performed on a porcine model [69]. Compared with the Anubiscope platform, the dissection speeds are significantly improved.

The limited capacity for navigation and visualisation of a traditional endoscope can be improved with a robotic flexible endoscope design. The Flex[®] robotic system (Medrobotic Inc, Rayham, MA) shown in Fig. 2.6, is a snake-like device developed based on the Highly Articulated Robotic Probe (HARP). It received the approval for transoral and colorectal surgeries before the company went out of business. Each tube on the robot consists of a concentric tube connected by spherical joints with three tendons running through the outer tube and controlling the bending, and the other one pass through the centre of the inner tube. The Flex system is controlled through a propelling sequence, with the outer and inner snakes switching their stiffness between rigid and limp states. The outer tube acts as a guide wire while the other is propelled forward, and at least one tube must remain rigid to keep the generated path intact. Further aiding in shape reconstruction, a 5-DoF EM sensor is mounted on the tip of the body. To compensate for the principal drawback of the limited space for interior channels and instruments, two functional channels and the camera cables are located externally to the outer tube, inevitably increasing the overall size.

The NeoGuide Endoscopy System is a fully-articulated robotic endoscope intended for use in lower GI endoscopy and interventions with enhanced access and visualisation. It is composed of 16 independent elements, with a total length of 173 cm. The orientation and position of the endoscope can be monitored by the sensors located at its tip and insertion mechanism. The information gathered from these sensors can be used to estimate the shape and path of the colon. Different from the Flex system, the robot can be guided and avoid looping by actively controlling all the joints. The feasibility of the platform has recently been tested with diagnostic and screening colonoscopy [70].

Unlike the Flex and NeoGuide systems equipped with a full-body active segment, most of the other systems choose the strategy that has a short active segment



Figure 2.7: The robotic-assisted platforms for bronchoscopy. (a) The Ion endoluminal system (image courtesy of Intuitive Surgical). (b) The Monarch platform (image courtesy of Johnson & Johnson MedTech).

followed by a passive segment. The research team in KAIST proposed a flexible robotic platform, K-FLEX. It consists of two robotically controlled instrument modules, an overtube and a master console [71, 72]. The proposed robot has a 17 mm in outer diameter for the applications in GI tract. The overtube is versatile with flexibility and enhanced payload capability; the two sections of the flexible body have 4-DoF in total and are capable of handling a load of 300 g.

The robotic bronchoscope is a challenging area, which has higher requirements on scope size and navigation ability in the branching airways. To date, there are only two commercially available products (Fig. 2.7), the Monarch system from Ethicon Medtech (Johnson & Johnson, NJ, U.S.A. acquired from Auris Health) and the Ion system from Intuitive Surgical, both systems obtained FDA clearance for bronchoscopy in 2018 and 2019 respectively [73]. Their technical approaches are very different. Monarch followed a more common solution by using outer and inner scope designs, which have 6 mm and 4.4 mm in diameter respectively. With the support of the outer sheath, the endoscope can reach a deeper location and

resist the looping problem. During the procedures, the camera provides visual information for navigation and the insertion is controlled via two 7-DoF robotic arms. Ion chooses a single catheter design, leading to a 3.5 mm outer diameter with a 2 mm instrument channel. However, the endoscopic camera is compromised and replaced with the shape sensing technique, Fibre Bragg Gratings (FBG), providing precise location and shape information throughout navigation and biopsy [74]. Although an additional vision probe can be inserted through the channel for the intervention, Ion is incapable of receiving visual information and using instruments simultaneously. This limitation restricts the use of the Ion system in other areas. In contrast, Monarch has proposed its clinical application in urology in May 2022. The study results demonstrated high nodules diagnostic yield, and safety with a favorable complication profile for Monarch [75, 76] and Ion [77, 78].

2.2.4 Instruments for Endoscopic Platform

Besides the attempts in robot-assisted maneuvering, other efforts have been made to enhance the therapeutic functions of endoscopes by adding operating arms at the tip of the endoscope, as shown in Fig. 2.8. To merge into the current surgical flow, most of the designs keep the size of the instruments below 4 mm. Compared with the instruments used in multi-port and single-port platforms, where the flexible arm at the tip is connected to a rigid shaft, the flexible body of an endoscopic instrument is unable to provide a steady position, which can affect control accuracy and force transmission.

As shown in Fig. 2.8(a), the ViaCath system is a medical device intended for large mucosal resection in NOTES. It consists of a mechanical connector to the positioning arm, articulating tip with an end-effector, and long-shafted flexible instruments that run alongside a standard gastroscope or colonoscope [3]. In its early genera-

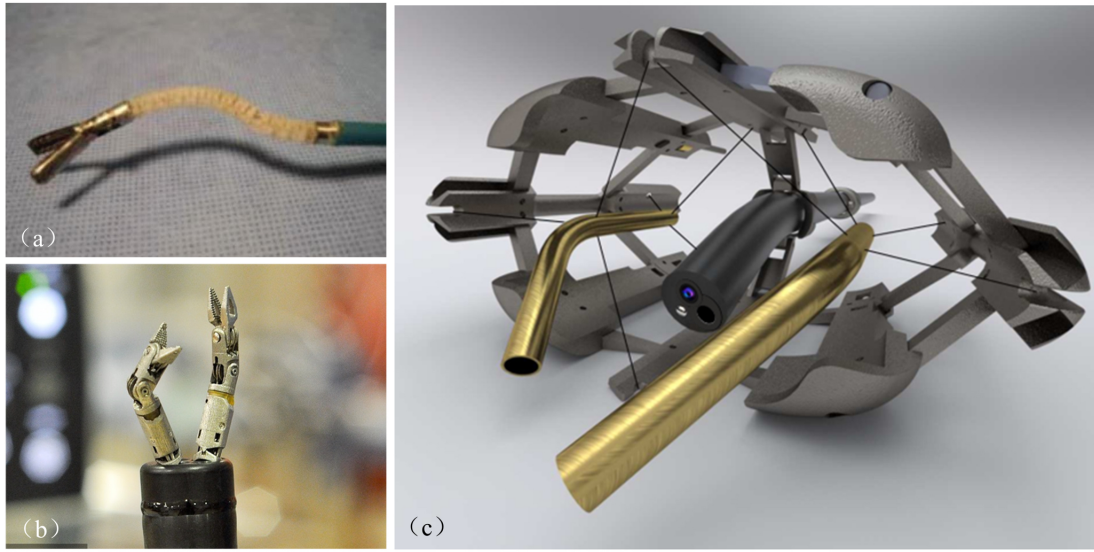


Figure 2.8: Three typical robotic instruments used in endoscopic surgery. (a) The ViaCath instrument uses a two flexible section design. (©2007, IEEE. Reprint with permission from [3]). (b) The EndoMaster EASE System improved from the MASTER system (image courtesy of EndoMaster Pte Ltd.). (c) A graphic of the CYCLOPS system at the deployed state (©2018, IEEE. Reprint with permission from [4]).

tion, the system has a diameter of 4.5 mm with a 90 cm long shaft, providing a total of 7-DoF within the visual field of the scope. However, some problems have been exposed in the design. The main issue with the ViaCath system is the long passive shaft, which has uncontrollable sections that frequently catch on tissues, making it challenging to insert and position the instrument. Another limitation of the system is that the instruments can only produce 0.5 N of lateral force, which is insufficient for manipulating tissues during the intended procedures. This is primarily due to the inherent compliant behavior of the continuum joint design, as the joint body deforms due to external forces.

Endomaster EASE, the latest version of MASTER system was developed by the Nanyang Technological University and EndoMaster Pte Ltd. As shown in Fig. 2.4(b), the system is equipped with an independently designed endoscope [79]. The endoscope features with three working channels (two for robotic arms and one for accessories). The two robotic arms which contain a needle-like electrocautery

knife and a grasper can be extruded out through the channels. The Endomaster allows 9-DoF movement, seven of which control the slave arms. An additional endoscopist is required to manually control the positioning and orientation of the endoscope (2-DoF in total). The main drawback of this system is that the instruments cannot be changed during the procedures. A preclinical study has been conducted on human cadavers and shows promising potential for transoral surgery [80]. Another study on a porcine model demonstrated its feasibility and effectiveness on ESD [81]. The recent results have revealed that a clinical trial was conducted by the Chinese University of Hong Kong, in which 18 patients were treated for colorectal ESD with this system [82, 83].

The concept of the CYCLOPS (Fig. 2.8(c)) was introduced as a portable attachment design which can be easily merged into the current endoscopy workflow and turned the conventional endoscope into a surgical robot [4, 84]. The CYCLOPS incorporates a deployable mechanism and dual instruments manipulators. A collapsible scaffold allows the insertion of the endoscope and subsequent deployment of the system when the point of therapy is reached. It contains two 4 mm tubes, connected by the tendons and performs as tendon-driven parallel manipulators when they are controlled in pairs. The manipulation force of 46 N is much higher compared with other platforms. Although the scaffold can be folded before reaching the target area, it still has a size of 30 mm in width and 72.9 mm in length at unexpanded status, which is relatively large and might cause difficulties in inserting and steering in the rectum.

Table 2.1: The list of flexible robotic systems for endoscopic surgery

System Name	Developer	ToTal DoFs	System Diametre (mm)	Number of Internal Channels	Internal Channel Diameters (mm)	Actuation	Main Body Type
HARP [85,86]/ The Flex system	Carnegie Mellon University/ Medrobotics	4	12/~18	2	4.2	Tendon driven	Discrete joints
iSnake [87]	The Hamlyn Centre, Imperial College London	7	12.5	2	3	Embedded Motors	Discrete joints
i ² Snake [88]	The Hamlyn Centre, Imperial College London	8 (snake-like robot) 7 (KUKA robot)	16	4	4	Tendon driven	Discrete joints
K-FLEX [72]	KAIST	4	17	2	-	Tendon driven	Two continuum joints
K-COLON [24]	KAIST	3	15.9	1	-	Tendon driven/ Pneumatic actuator	One continuum joints
Wire-driven flexible manipulator [89]	DGIST	2	10	1	4	Tendon driven	One Continuum joint
Neoguide [70,90]	Intuitive Surgical	3	14	1	3.2	Tendon driven	Continuum joints
Ion [91]	Intuitive Surgical	3	3.5	1	2	Tendon driven	-
Mornach [92]	Eithcon Medtech (Johnson & Johnson)	2 x 7 + 7(feeding arms) 3 (sheath) 3 (scope) 6 (overtube)	6.0 (sheath) 4.4 (Scope)	1	2.1	Tendon driven	-
SAIT robot [93]	SAIT, Samsung Electronics	2 x 7 (instruments) 3 (camera) 5 (slave arm)	30	2	-	Tendon driven	Discrete joints
A soft robot [94]	The Hamlyn Centre, Imperial College London	6	11.75	-	-	Pneumatic actuator	Three continuum joints
Cyclops [4]	HARMS Lab, Imperial College London	5	Width:30/66 Height:18/39.6 (Undeployed/Deployed)	2	-	Tendon driven	-

2.2.5 Towards the next generation endoscopic system

The surgeons have pushed the boundaries with the aim of offering better patient outcomes, and which has increased the operation difficulty. The use of robotic system can provide smoother and more precise manipulation that conventional equipment cannot achieve. In particular focusing on the robotic endoscope design, several designs, have been introduced and implemented on robotic surgical platforms, as indicated in Table 2.1. These works have explored the endoscope design in different sizes, control modalities and joint configurations.

However, despite the endeavours from both academy and industry, certain challenges remain unsolved and which include:

- The primary challenge is to design a robot with multiple degree of freedoms (Multi-DoF) which consist of flexible joints. The joints should perform large bending angles for wide range inspection and flexibility to lead the robot in curved pathway.
- In practice, the factors such as, manufacturing errors and friction can have impact on the accuracy of the robotic system. Modifications are always necessary to reduce the errors by introducing new control methods, sensors or refining the fabrication process.
- The rigidity of the endoscope is important. The bending section should be flexible enough to navigate the rest of body. While the robot should be stabilised during the operations that its shape can be maintained even against external load.
- Another fundamental challenge is the loop formation that occurs at the stage of endoscope insertion, making it difficult to pass through the tight turns in the lumen. Despite the gentle push and pull technique employed by surgeons to minimise the formation of loops, the pressure exerted on the lumen wall can still cause discomfort and pain for the patient.

To understand and solve the challenges mentioned above, further investigation will be given in the subsequent sections, which are design structure, modeling, and insertion techniques. It is worth noting that while different surgical systems are designed for specific surgical applications, but they share common underlying technologies. For instance, both multi- and single- post system have begun using the instruments with flexible section as "wrist". Recently developed endoscopic system (Ion, Mornach and EndoQuest) are still adhere to the master-slave configurations. Therefore, this investigation will not limit to the endoscopic system, and instead it will provide the inspiration for the new possibilities in robotic endoscope design.

2.3 Design Structures

To achieve flexible motion on the body of an endoscope, the design can be classified in terms of their mechanism and actuation modalities. Considering the number of combinations in structure and actuation, a suitable modeling that accounts for kinematics, static assumption and sensing can have an impact on the control accuracy and computation costs. In addition, the realisation of variable stiffness function will be discussed in this section, which can significantly improve the position accuracy of the flexible robot under external load. At the end, the challenges in the insertion of an endoscope will be described and two types of solutions will be given.

2.3.1 Discrete and Continuum joint

To be more specific, the typical structure design for a flexible robot can be categorised into two groups: discrete joint and continuum joint. The first category is the discrete joint design (Fig. 2.9) which is usually composed of a series of rigid links and has been widely used due to its structure and control simplicity. A ba-

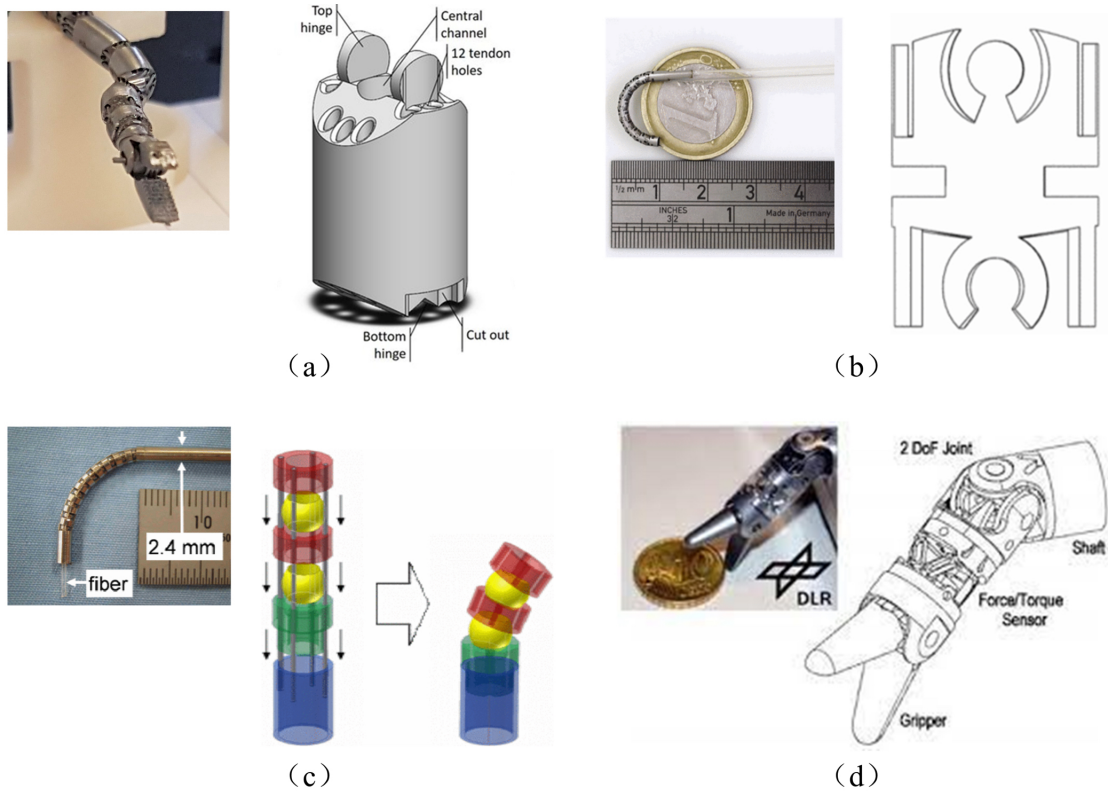


Figure 2.9: Four types of discrete joint design used in surgical robots. (a) The rolling joint design (©2019, IEEE. Reprint with permission from [5]). (b) The inter-lockable revolute joint design (©2018 IEEE, Reprint with permission from [6]). (c) The design is composed of a series of spherical joints (©2007, IEEE. Reprint with permission from [7]). (d) The flexible instrument with universal joints (image courtesy of DLR).

One idea to construct a flexible robot comes with serially stacking the 'Hinge-like' revolute joints and using a pin-pivot structure. To get spatial motion, the use of other types of design, such as universal joints [87, 95], spherical joint [7, 89] and orientated preserving joint [96] have also been reported in the previous studies. For the instruments used in surgical applications that have limited size and tight volume, the solution are more straight-forward as illustrated in the da Vinci surgical instruments and the related works [5, 61], where the size can be minimised to 5.4 mm, 5 mm and 4 mm respectively.

A similar design can be found on the endoscopic robot, i-Snake², which is a full-body flexible robot designed for ear, nose and throat (ENT) surgery. This robot uses a bio-inspired rolling joint design and the overall size is finalised at 16 mm in

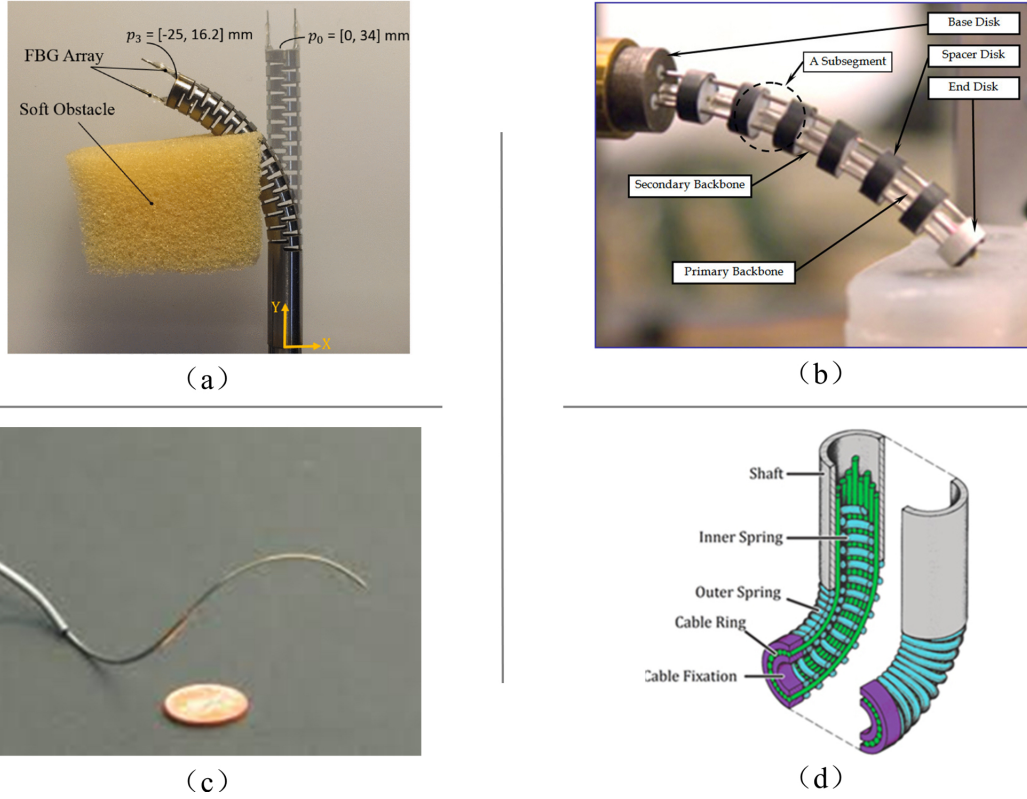


Figure 2.10: Four types of continuum joint design used in surgical robots. (a) The design with notches on a Ni-Ti tube (©2018, IEEE. Reprint with permission from [8]). (b) A continuum joint with multi-backbone structure (image courtesy of Rii™ Lab, SJTU). (c) The concentric tube design with pre-curved superelastic tubes (©2009, Springer Nature. Reprint with permission from [9]). (d) HelixFlex with spring-like structure (©2015, IOP Publishing, Reprint with permission from [10]).

diameter. Each pair of joints can roll against each other along the geared surfaces to avoid undesired slippery. The robot is composed of 12 joints orthogonally, which allows 8-DoF to be independently controlled [97]. Moreover, the combination with the KUKA robot arm provides the insertion motion with the desired orientation, while the function of virtual remote centre motion can be achieved [88]. Another advantage of the discrete design is that the large channels can be maintained, and for the i-Snake², four channels with 4 mm in diameter each reserve enough space for the cameras and robotic controlled instruments.

As shown in Fig. 2.10, another category is the continuum joint in terms of its continuously deformed shape taking the advantage of the material elasticity. A

typical design uses a central backbone made of Ni-Ti or plastic wires, with additional spaces required to accommodate the actuation cables. The stiffness of the structure is primarily determined by the size of the backbone, with a thin wire resulting in a floppy structure when subjected to an external force. To increase the stiffness of the design, Simaan [98] introduced a multiple backbones design. Instead of using pulling tendons, the Ni-Ti wires are employed and referred as the secondary backbone. Because the Ni-Ti wire has a relatively higher stiffness, it can be actuated by the pull-push concept, the forces applied on the tip can be transferred and sensed away from the joint [99]. Also, the design featuring a multi-backbone can be operated as a parallel mechanism with compliant legs. The result indicates that this kind of architecture can provide high payload capacity and a larger workspace. The compliance of design gives great potential for miniaturisation and safe interaction in medical applications [100]. The concentric-tube robot has a unique design composed of multiple pre-curved Ni-Ti tubes that are concentrically inserted inside each other [101, 102]. The base of each tube can be axially translated and rotated, and their common axes conform to a mutual curvature. Compared with other designs, the concentric tube can easily achieve a smaller size.

The flexibility of continuum robots can be also achieved through the use of a compliant mechanism. The leaf-type designs are commonly used as the compliant rotation pairs [103], but considering the miniaturisation and fabrication for medical use, the bending of this mechanism often depends on the laser cut notches or a spring-like structure. The shape of notches can be variant and demonstrated as rectangular shape notches [104, 105], T-shape notches [106, 107], triangular shape notches [108, 109] and hollow spiral structures [110]. A mechanical model is constructed for any of the notched designs, predicting the intrinsic deformation, tendon force, friction force, as well as considering the presence of external force on the tip of joint [111].

Continuum joints with a helical spring structure can achieve bending motion easily, but the actuation force also generates undesired axial compression (the DoF with

translation) resulting in a loss of control accuracy. To address this issue, a novel design was introduced in [112], in which a slender shaft is added to the double helix structure to eliminate compression. The bending stiffness and torsion resistance are improved by attaching reinforced rings on the spring coils and can be derived by a static model. The mechanical properties of the spring-like structure are an important factor in the design of a continuum robot. The features of the structure such as materials, pitch and shape of cross-section determine the stiffness and bending capability. In the work [113], a test was performed to reveal the bending behavior of flexible joints with different preset stiffness. To meet the requirements of different operations, the joints can be 3D printed using various materials to achieve preset stiffness and dexterity. Song *et al.* proposed a design with multiple helical segments and an optimised version was developed with refined structural parameters to get higher loading capacity [114]. Apart from modifying the flexure design, another study has investigated that the overall stiffness of the structure can be significantly improved by changing the routing paths of actuation tendons when they are placed inline to the neutral axis of a joint segment [115].

The discrete joint design is often affected by the friction generated between the joint body and actuating tendons, making it difficult to reach equal bending angles at each subsection and recover a straight shape. On the other hand, the maximum bending angles for a continuum joint are limited by stress concentration near the bending flexures, and its life cycle may be affected by fatigue in the elastic materials. A hybrid design aims to compensate for the shortcomings of both types of structures. Li [116] presented a hybrid design, the commonly used flat spacers are replaced with spherical links, which enables the 2-DoF bending in a smoother shape. Liu, on the other hand, presented a laser-profiled continuum manipulator [6]. The contact aided and interlocked joint features can be directly fabricated on a 2.2 mm tube. With a thermal drawn polymer tube inserted, both inner channels and the stiffness are guaranteed.

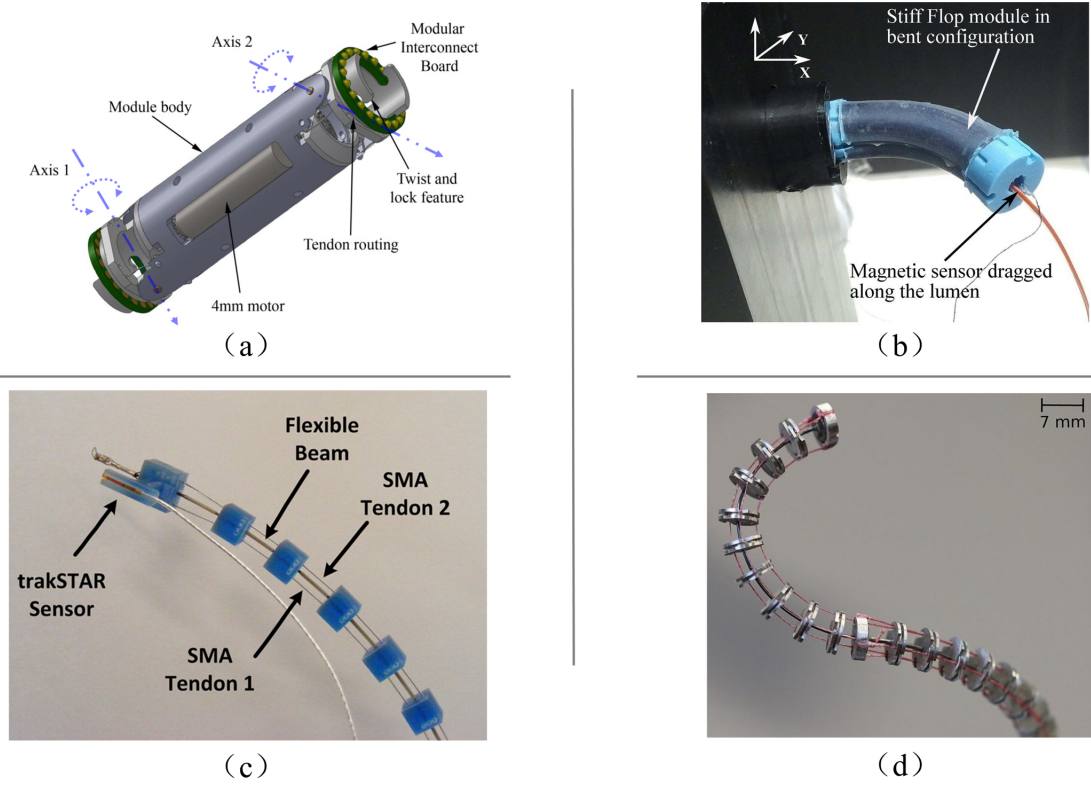


Figure 2.11: The commonly used actuation modalities for actuating a flexible robot. (a) Actuation with intrinsic micro-motors. (©2011, Imperial College London. Reprint with permission from [11]). (b) Stiff-Flop controlled by pneumatic actuators (©2018, John Wiley and Sons. Reprint with permission from [12]). (c) Continuum joint controlled by SMA tendons (©2012, SAGE. Reprint with permission from [13]). (d) The robot with tendon-driven strategy (©2021 SAGE, Reprint with permission from [14]).

2.3.2 Actuation Modalities

Tendons driving mechanism is the most widely used actuation method for flexible robots in multi-scale, from the centimeter-sized endoscope to millimeter-sized endovascular robots [117]. The selection of materials for tendons can be variant: such as metals (e.g. stainless steel, Ni-Ti), polymers (e.g. Kevlar) or fibreoptics [118]. Tendons can be routed through holes on the joints created using manufacturing techniques such as drilling and Electrical Discharge Machining (EDM), or by directly fabricating them using 3D printing. Furthermore, mechanisms that incorporate additional insertions are described in [6]. A cable-ring mechanism is described in [10], in which a ring of cables are enclosed by two springs. Cross-talk

in a tendon-driven multi-segment robot refers to the phenomenon where the motion of one segment affects that of others, resulting in undesired or unexpected movements. The options to mitigate the cross-talk include: optimising the tendon routing with helical routing or Bowden cables, or coordinating the motion of the segments with decoupled control.

A soft actuator is defined by the material used for the structures. Instead of using rigid materials, elastomeric materials such as silicon and rubbers are used to create hollow channels for actuation. The actuator can be operated pneumatically [12, 119–121] or hydraulically [122–124] to inflate the channels to a desired shape. An in-extensive tube is placed at the central to prevent axial movement and enable the bending motion. A thread or braided mesh can be wound around the outer surface to constrain the radial expansion. Molding is the most popular method for manufacturing a soft robot and other methods such as shape deposition and soft lithography have been reviewed in [125, 126]. Recent progress has been enabled by utilising 3D printing techniques, and molds with more complex structures can be printed. Treratanakulchai [94] proposed a 6-DoF soft robotic manipulator fabricated by lost wax silicone casting, each segment has three independent chambers that are primarily constructed with 3D printed wax molding. The tip position and orientation can be monitored through feedback with stretchable sensors attached on the surface. Alternatively, the final soft structure can be printed directly using soft materials [127]. The main concerns of using soft actuators are fluid leakage and the bulky size of the compressor.

Shape memory alloys (SMAs) have the unique property of undergoing large deformations and generating high forces, which makes them suitable for actuation in flexible robots. A micro manipulator was demonstrated in [128] where the outer diameter is 970 μm while the 850 μm inner channel can be kept. SMA can be used in a manner similar to tendon-driven architectures in soft robots, but with the actuation power being intrinsic to the SMA material itself [13]. The use of SMAs also offers the added benefit of being MRI compatible, and several prototypes have been introduced [129, 130]. However, the use of a tendon-driven strategy in

conjunction with SMA needs to keep away from the patient, thus minimising any potential noise in the MR images.

Most of the actuation methods are encountering a barrier of scalability. The length of a snake-like robot cannot be formed by the infinite number of sections due to the intrinsic limitation of the actuation mechanism. This situation could be worse when each segment is independently controlled and has a 2-DoF bending capability, the internal space for instrumentation will be occupied.

The “iSnake” is a modular robotic system developed for laparoscopic surgery [87]. It employs a combined tendon-micromotor strategy in each module, with the motion being transmitted via short pre-tensioned tendons. The actuation mechanism is independent in each module, and the conventional hard wiring is replaced by the electrical contact pins, allowing for customisation of the robot’s length from a single to a large number of joints. However, the stability and controllability are determined by the output torques from embedded motors, the current design has been tested with seven sections. Moreover, the long rigid bodies due to the size of the motors result in a large bending radius when performing retroflexion.

2.3.3 Variable Stiffness

The high slenderness ratio of the body significantly impacts the payload capacity of a flexible robot, and the shape can be difficult to maintain under external forces. To this end, the function of variable stiffness has been explored for the implementation of adjustable compliance. With the capability of switching between rigid and compliant modes, robots can adapt to a wider range of tasks and environments. This allows for the precise handling of high payloads while also providing the necessary softness to interact with a patient’s body.

Compliant actuators can be employed to achieve variable stiffness in multi-segment continuum robots. These types of actuators can control the robot’s shape and

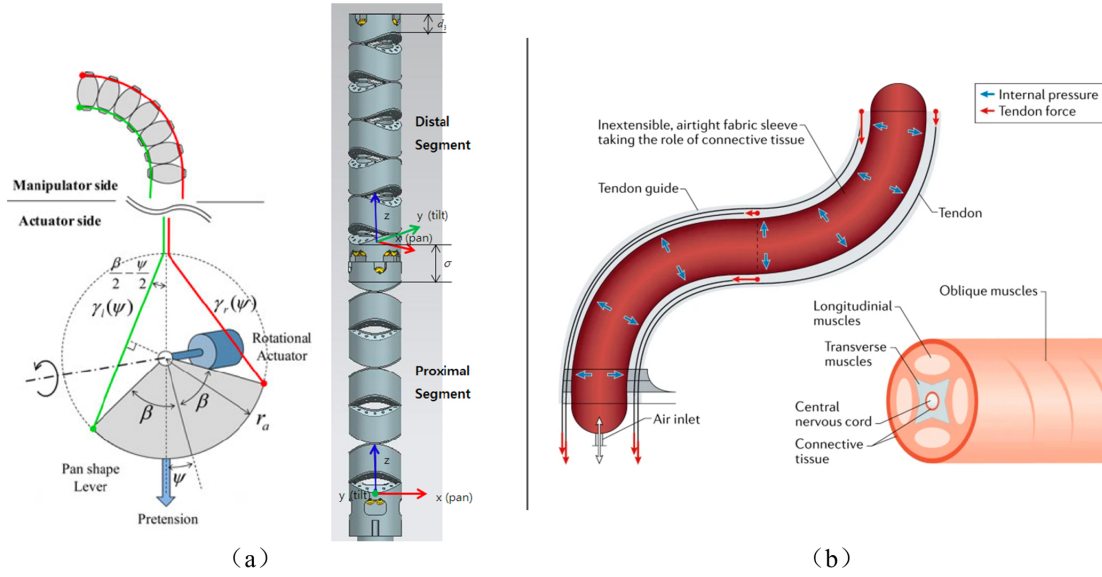


Figure 2.12: Two methods to achieve the variable stiffness on a flexible robot. (a) Compliant actuator by adjusting tensions on actuating cables (©2013 IEEE, Reprint with permission from [15]). (b) The antagonistic method is based on a hybrid principle with tendon and pneumatic control (©2018 Macmillan Publishers Ltd., Reprint with permission from [16]).

provide additional stiffness without the need for other mechanisms. Samsung has introduced a 6-DoF flexible-access robot composed of two serially attached segments, each comprising six stacked arc-shape contacts that form a variable neural-line design [15]. As demonstrated in Fig. 2.12(a), by adjusting the tension on the actuation cables, the robot can maintain precise positioning with high stiffness and ensure movement with low stiffness.

The antagonistic method is bio-inspired by the muscular structure of the octopus tentacle. A pair of muscles move in an opposite direction, thus capable of varying the stiffness over a wide range. This method can be inherently transferred to the soft robot design. A mechanism has been reported in [131], which consists of a central contracting McKibben actuator enclosed by five extending actuators. A similar design can be found in [132], featuring a central extensor actuator and a parallel array of six contractors. The contractors are divided into two groups, and by adjusting the inflation between them, it is possible to decouple the end-effector positioning from the stiffness control. The antagonistic effect can be also generated based on a hybrid principle (Fig. 2.12(b)) that combines pneumatic

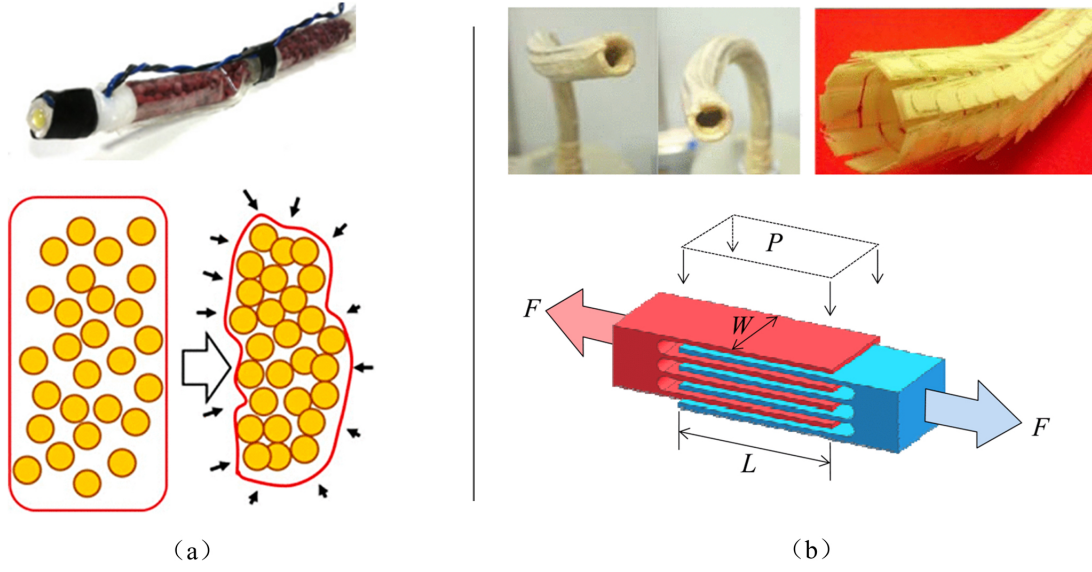


Figure 2.13: The principles and examples to realise the granular jamming and layer jamming methods. (a) The granular jamming-based robot with hydraulic control (©2013 ASME, Reprint with permission from [17]); and the sketch of the granular jamming phenomenon (©2016 IEEE, Reprint with permission from [18]). (b) The concept and prototype of a layer jamming element (©2013 IEEE, Reprint with permission from [19]).

and tendon-driven actuation mechanisms [16, 133]. By simultaneously inflating the extending actuator and increasing the cable tension, the antagonistic effect can be produced to enable rigidity control.

Moreover, structure-based strategies have been exploited. By adding additional mechanisms on the joint body to acquire the function of variable stiffness. The stiffness can be controlled by smart materials, including thermoplastic polymers [134,135], magneto-rheological fluid [136] and Low Melting Point Alloy [137]. They can be directly used as a backbone or as a damper on the discrete joint. When activated by heat or a magnetic field, the rigidity of these materials can be transmitted between soft and hard states and affect the stiffness of the whole structure.

Another technique that allows obtaining variable compliance in a soft robot structure is taking inspiration from the phenomenon of granular jamming (Fig. 2.13(a)). The effectiveness of this strategy has been already investigated in [138]. An obvious difference can be viewed between jammed and unjammed states, and also

depends on the particle size of granular media. Stiff-Flop is one of the designs using such strategy [119, 139], fine powder and latex was used as granular material and containing membrane respectively. When the vacuum is applied to the stiffening chambers, the density of the granular material contained within can be increased, causing a transition to jamming. The level of stiffness can be adjusted by varying the vacuum level. [140] has introduced a chain-like granular mechanism, the jamming is activated by pulling the thread and no vacuum is needed.

In cases where the size of a manipulator is limited, a layer jamming-based design can be a suitable option. Layer jamming can be achieved through the use of flexible fibres [141] or overlapped flaps [19, 142] (Fig. 2.13(b)) that experience frictional interactions due to the application of a vacuum. A similar design can be achieved on mechanical locking devices, a "dragon-skin" shape locking mechanism where the flaps are connected by teeth to resist the deformation [143]. They usually have thin-walled tubular shapes which make it possible to be an overtube and outer sheath for flexible robots.

2.4 Modeling

The basic framework for modeling a robot with discrete links is Denavit- Hartenberg (D-H) parameter tables. In this approach, a series of rigid links connected by conventional mechanisms (revolute, universal, prismatic, *etc.*) can be described using a series of homogeneous transformations generated from the D-H tables [144]. The constant curvature model is widely used as the kinematic model of a continuum joint due to its simplicity [145]. It can be considered as a desirable description for modeling the continuum robots, however, some research has investigated that the constant curvature theory is not sufficient for accurate control of continuum robots [146].

Some more complex frameworks can be derived from mechanic behaviours of the continuum body. The Bernoulli-Euler beam theory has been widely used for long

slender subjects, such as the concentric tube design [147]. For a more general case, where the transverse shear and strain from elongation cannot be ignored, such as those soft robotics and bending under nonlinear conditions (e.g. large deflection), the Cosserat rod theory can give a better result. The benefits of using different modeling frameworks have been investigated on continuum actuator in [111, 148], and the comparison results illustrated that the constant curvature related methods show the advantages on design optimisation and path planning, but less accurate on control than the mechanic-based methods, accompanied with increasing computation and sensing cost.

As outlined in Section 2.3.3, the shape of the continuum robot can be affected by its passive compliance property following an inevitable collision with the lumen in the endoscopic operation. Several approaches have been suggested for estimating and predicting the motion of a robot. One method involves taking into account the internal friction in a lumped parameter model, as proposed by Jung *et al.* [149]. Alternatively, the shape of the robot can be monitored through the use of sensor-based methods. It is challenging to track the motion of continuum robots with external sensors (e.g. visual-based tracking) in surgical applications, as the robots are inserted into the human body cavity during operations. Furthermore, the limited internal space of the robot restricts the available sensor options, with FBG and Electromagnetic (EM) sensors being the most commonly used for sensor-based shape estimation.

In the study proposed by Gao *et al.* [118], FBG sensors were employed to replace the actuation tendons, the restored and external force can be directly and accurately measured. By incorporating calibrated variables into the model framework, the shape of the continuum joint can be estimated. Additionally, the FBG sensors can be also used directly for shape sensing. Xu *et al.* [150] used helical wrapped FBG design for measuring force, torsion and curvature, and Kim *et al.* [151] presented a framework for optimising the number and location of sensors along the robot body to minimise errors. Since FBG is a non-magnetic sensor, it is also possible to be used in the MRI guided intervention [152, 153]. Song *et*

al. [154] proposed a general shape sensing method for multi-segment continuum robots; however, multi-EM trackers should be attached around the robot body, which is not suitable for the miniaturised robots. Tully *et al.* [155] presented a filtering method that with the measurements from a EM sensor, the shape of a highly redundant robot (HARP) can be estimated. It should be noted that EM sensors have a major disadvantage in that they are sensitive to the surrounding environment. Magnetic objects such as operating tables and instruments within the magnetic field can affect the measuring accuracy.

2.5 Endoscope Insertion

The function of variable stiffness aims to help the endoscope maintain its shape after reaching the target location. However, another challenge should be solved at the insertion stage. In this section, two types of strategies will be investigated that rely on the hyperredundancy of the robot and a 'pull force' concept, respectively.

2.5.1 Challenges for Endoscope Insertion

Conventional flexible endoscopes often have limited forward progression ability and Depth of Maximum Insertion (DMI) because the endoscopes are inserted passively into the GI tract. Looping often occurs when the distal tip of the endoscope cannot pass beyond the colon region where there is a large curvature or folding. When this happens, the endoscopist would apply counter pressure, move the patient's body or even attempt re-insertion. This may expose the patient to higher levels of anaesthesia due to longer procedures and may cause discomfort, internal bleeding or even perforation of the GI tract. Recent research has indicated that colorectal cancer is ranked as the fourth of the most common cancers and the fifth in cancer-related deaths [156]. Due to its leading cause of morbidity and mortality, there is an increasing demand for endoscopic diagnosis of colorectal cancer which

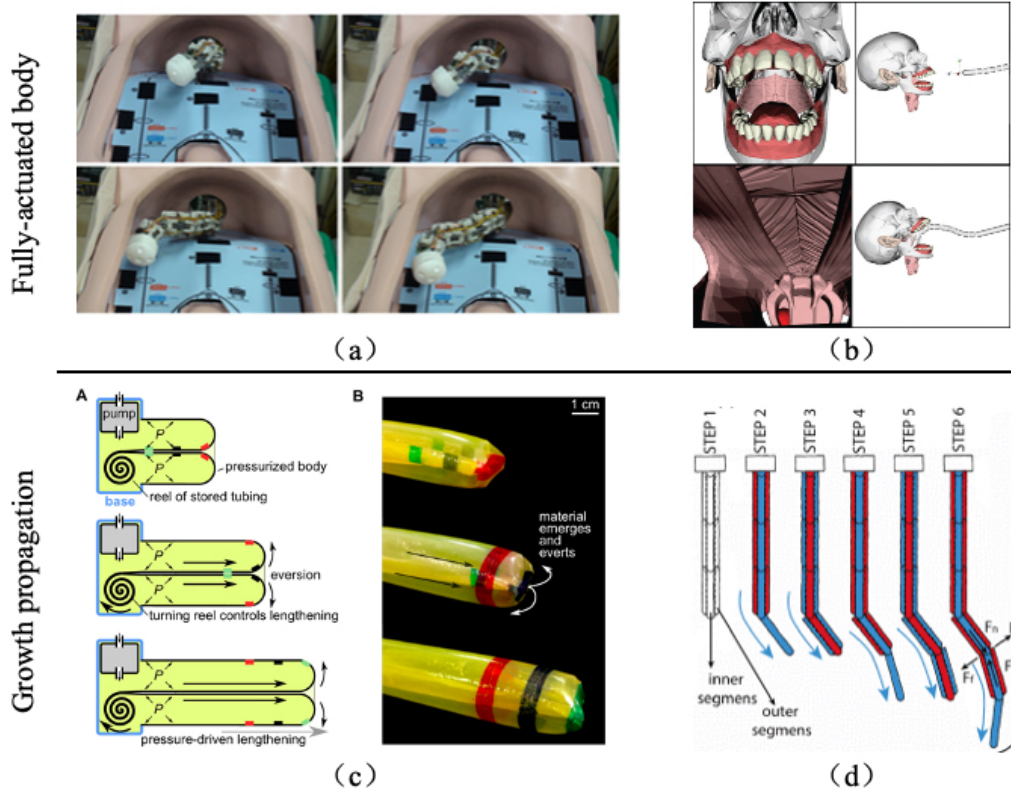


Figure 2.14: Two types of design implementing follow-the-leader with fully-actuated body or growth propagation. (a) The motion test of a snake-like robot that each segment can be independently controlled (©2017, John Wiley and Sons. Reprint with permission from [20]). (b) Two screen-shots of the simulator demonstrate that the iSnake² moves towards the surgical site (©2018 IEEE. Reprint with permission from [21]). (c) The principle of actuating a soft robot that the body lengthens as pressurised air pushing the material everts at the tip (©2017, AAAS. Reprint with permission from [22]). (d) The graphic demonstrates the propagation of the HARP and the FLEX robotic system (©2021, IEEE. Reprint with permission from [23]).

involves colon biopsies at deep colon locations, such as ascending colon, cecum, *etc.*. As such, in the last decades, these have driven the rapid development of novel endoscopic devices with advanced manoeuvrability. Particularly, there has been a growing interest in developing snake-like or flexible robotic endoscopes whose shape can adapt to anatomical structures to avoid collisions to the inner colon wall and resolve looping problems [23, 157].

2.5.2 Follow-The-Leader Manner

A definition is provided by Burgner-Kahrs *et al.* in [144], stating that the devices with the follow-the-leader manner should conform to the path taken by their end-effector without relying on anatomical interaction forces. Based on this principle, a variety of research and commercial robotic systems have been developed for endoscopic interventions and can be broadly divided into two main streams (Fig. 2.14). One type of endoscope is the snake-like robot composed of multiple segment structures and hence possesses multiple degrees of freedom (DoFs) to perform a follow-the-leader manner. Examples to such design include the modular robot iSnake [87], snake-like tendon-driven robots i-Snake² [88] and [15, 20], multi-segment continuum robots in [158, 159], extensible continuum robots [14, 160] *etc.*.

The other group consists of devices that propagate by advancing the relative distal segments of the shaft while the relative proximal segments of the device remain stationary. This function has been achieved on the devices such as the concentric tube, and the Flex featured with the design of multi-mechanical and concentric linkages. It is worth highlighting a novel concept originally developed for search and rescue operations, known as a soft robot with growth navigation [22]. The device moves forward in a deploying manner with the aid of air pressure. The steering is achieved by controlling a series of latches using a side pump, which releases the latches to allow the device to lengthen on one side and steer in that direction.

Relying on the hyper-redundancy mechanisms and the follow-the-leader manner, a snake-like endoscope can be manoeuvred and pushed towards the target location while avoiding any injuries due to collisions. The snake-like robots often take the advantage of incorporating multiple joints to increase their flexibility and thus, improve the insertion smoothness and alleviate the potential tearing or scratching of the colon wall. However, many of these designs require a rigid passive arm or the actuation unit behind which may limit the DMI for the robots due to the early formation of looping and in addition, by including more joints to the device can

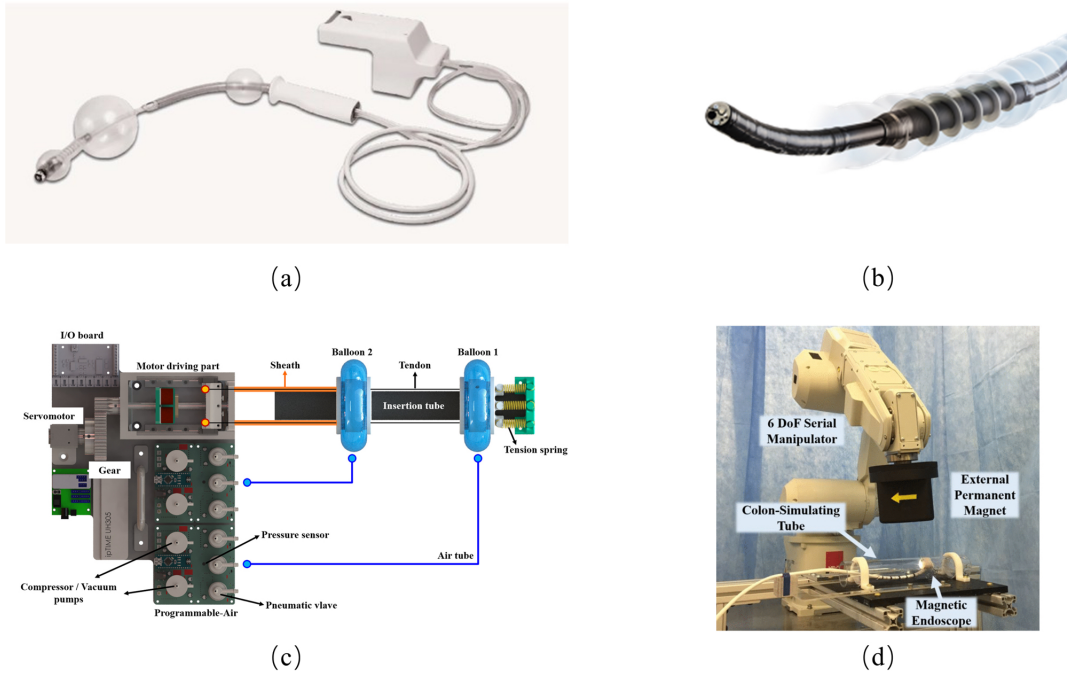


Figure 2.15: The endoscope design with the concept of pulling force. (a) Aer-O-Scope colonoscope (Image courtesy of GView Ltd.). (b) PowerSpiral Enteroscope (PSE; image courtesy of Olympus). (c) The system architecture for controlling the K-COLON (©2022. Springer Nature. Reprint with permission from [24]). (d) The system of a magnetically actuated endoscope (©2017 IEEE. Reprint with permission from [25]).

significantly increase the complexity of the physical design and the control of the system.

2.5.3 Generating Pulling Forces

Instead of employing the feeding mechanisms from the handle to advance the endoscope, enteroscopes [157] were specifically designed to generate propelling forces at the scope tip to prevent looping formation in small-bowel procedures. For this purpose, a few designs have been developed including K-COLON [24], the Single-Balloon Enteroscope (SBE; Olympus Co., Tokyo, Japan) and Double-Balloon Enteroscope (DBE; Fujifilm Optical, Saitama, Japan). All systems have an overtube that can grip and hold to the intestine wall by inflating the enclosed balloons. Spiral Enteroscope (SE; Spirus Medical, MA, USA), on the other hand,

equipped with a spiral-shaped overtube was developed for deep insertion into the small intestine. These systems have been evaluated in a number of treatments and results highlighted their diagnostic and therapeutic performance. However, the study has also suggested that the procedures with those enteroscopes are both labour intensive and time consuming during the manual insertion process [161, 162].

Some novel designs have emerged in recent research, as shown in Figure 2.15. Unlike the conventional double-balloon colonoscopy realises the insertion of the endoscope by sequentially inflating the two balloons, Aero-O-Scope (GI View Ltd., Ramat Gan, Israel) controls the forward and backward motion using pneumatic force generated in the space sealed by the inflated balloons and the bowel wall. However, the pressure should not exceed 60 mbar to protect the colon [163]. Consis Medical (Beer'Sheva, Israel) has proposed a self-propelled endoscope with a similar concept, where the water is pressurised in a disposable sleeve to push the tip camera. The steering of both products is controlled by the flexible tip joints.

To further simplify and expedite the insertion process, a more advanced and reliable system was proposed recently, called PowerSpiral Enteroscope (PSE; Olympus Co., Tokyo, Japan) [162]. A motorised spiral segment is attached on the shaft to pleat the small bowel onto the enteroscope. Forward or backward rotation of the spiral segment is converted into linear translation for insertion or withdrawal of the endoscope. The smoother and faster rotation movement substantially reduces the procedure time. Nevertheless, the high cost and complications in sterilisation hinder it from wide adoption in clinical use. Apart from these two insertion mechanisms, there is also another very different approach which is the wireless capsule endoscopy known for small-bowel endoscopic evaluation [164]. However, the lack of manoeuvrability to drive towards the desired anatomical sites and functionality to take biopsy specimens are the main drawbacks of this type of system [165]. A magnetic controlled flexible endoscope has been introduced in [25, 166]. Based on the visual information, the endoscope inside the patient's body can be manipulated by an external magnet mounted on the robotic arm.

2.6 Summary

In summary, endoscopy has evolved from a diagnostic to a therapeutic procedure with the development of advanced surgical techniques such as EMR and ESD, becoming less invasive and more precise. While these techniques have posed significant challenges to the standard endoscopes which have limited dexterity and mobility, and lack of accessory instruments. In recent years, there has been a technical transition from bulky robotic laparoscopy systems to lightweight robotic endoscopic systems. With further advancements, the outcomes such as the Flex and the EndoMaster system has shown promising results in clinical applications.

However, challenges remain in the design, stiffness control, and insertion of these systems. To this end, various types of flexible robots and state-of-art research are explored in this section and classified according to their structure, actuation and functions. This overview has provided enough background knowledge for the design of an endoscopic robot with a spring-like mechanism.

Chapter 3

Design of a Multi-segment Flexible Robot[†]

3.1 Introduction

As described in the previous chapter, the joint design is a critical factor in determining the performance of a flexible robot. There are many approaches to achieve the flexible or bending motion on a joint, and the spring-like structure has received considerable attention due to its structural simplicity and reliability. In comparison to other continuum joint designs that employ laser-cut notches [104–109] and central backbones [98, 116, 147], the spring structure exhibits less stress concentration on the bending flexure. In addition, the main structure can be printed and manufactured in a single piece without the need for additional components or post-assembly works.

To access deep lesions within the human body through natural orifices using a robotic system, an endoscope with multiple robotic joints is often necessary. The

[†]The content of this chapter was published on: W. Li, M. Shen, A. Gao, G.Z. Yang and B. Lo, “Towards a Snake-Like Flexible Robot for Endoscopic Submucosal Dissection”, IEEE Transactions on Medical Robotics and Bionics, vol.3, no.1, pp.257-260, 2020.

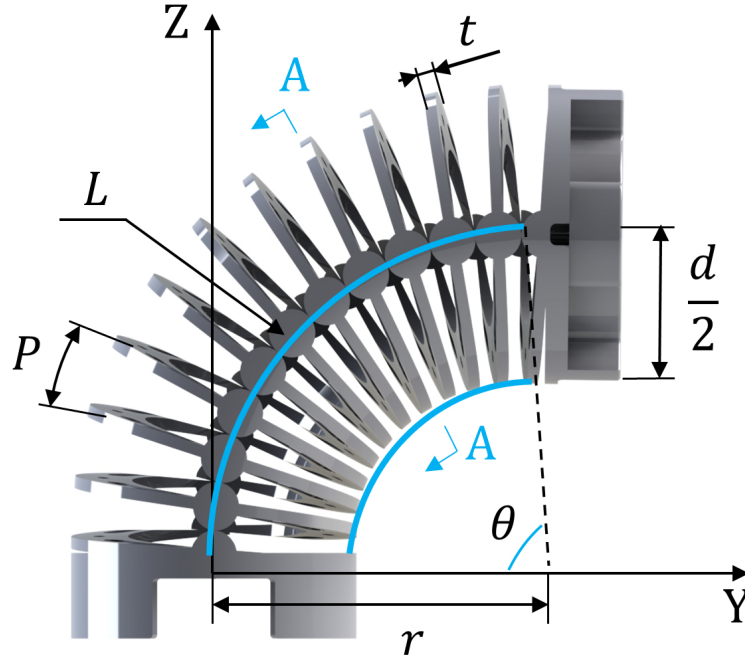


Figure 3.1: The CAD model of a flexible joint in the bending status. The cross-section view illustrates the detailed design of four pilot lumens for tendon routing.

main idea involves sequentially and orthogonally connecting a multi-joint structure, allowing the robot to bend and follow a curved pathway. However, an increment in the number of joints brings about several problems. It not only significantly complicates the structure of the robot, but also restricts the space available for instruments to pass through and weakens the transmission of manipulation force at the proximal end. iSnake² robot described in [21] is equipped with 12 discrete joints. To minimise the number of actuation motors required, the joints, except for the two joints at the tip, are grouped into three sections. The use of continuum joint aims to address this problem. The length of a continuum joint can be adjusted in the design process, which can reduce the total number of sections and provide smoother shape at bending.

This chapter will first introduce a novel continuum joint design that takes advantage of the spring-like structure. During the design process, the adjustable features from rectangular coils and effective length provide a number of combinations. This allows the characteristics, such as bending angle and stiffness, of the joint can be accommodated to different surgical requirements, while the bending

capability will not be affected. The mechanism will be verified with Finite Element Analysis (FEA) when subjected to bending conditions.

Then, a snake-like endoscope designed will be presented, which consists of an active snake robot and a passive flexible body. The preliminary design of the active snake robot features a redundant body with 7-DoF composed of 1-DoF spring-like continuum joints. By utilising a novel arrangement of tendons and Bowden cables, the cross-talk can be avoided and a relatively large internal channel can be maintained. Also, the kinematic control of this snake-like robot will be presented. To analyse the performance and clinical feasibility of the proposed flexible robot, workspace analysis, path following accuracy, and force testing will be shown.

3.2 Design of a Spring-Like Continuum Joint

3.2.1 Design Overview

In the proposed design, a spring-like structure serves as both the main supporting body and elastic backbone. A spring mechanism that is fixed at one end and applied a torque at the other free end can function as a flexible joint. This type of joint can move freely with 3-DoF, including two lateral bending motions and one axial translation. Since the actuation torque is generated by controlling antagonised tendons, the tension accompanied by the joint may trigger axial translation, which can result in undesired motion and reduce the structural stiffness and bending accuracy. To prevent the axial compression on the spring-like structure, one simple solution is to insert a series of circular contacts along the coils, the rolling motion constraints the linear movement and enables planar bending with one DoF.

This design offers a key advantage in that the specifications of the joint can be adjusted to meet the desired bending angle and structural stiffness of the entire robot, thereby providing flexibility in tailoring the design to specific requirements. However, the modifications on any parameter of the spring structure lead to a

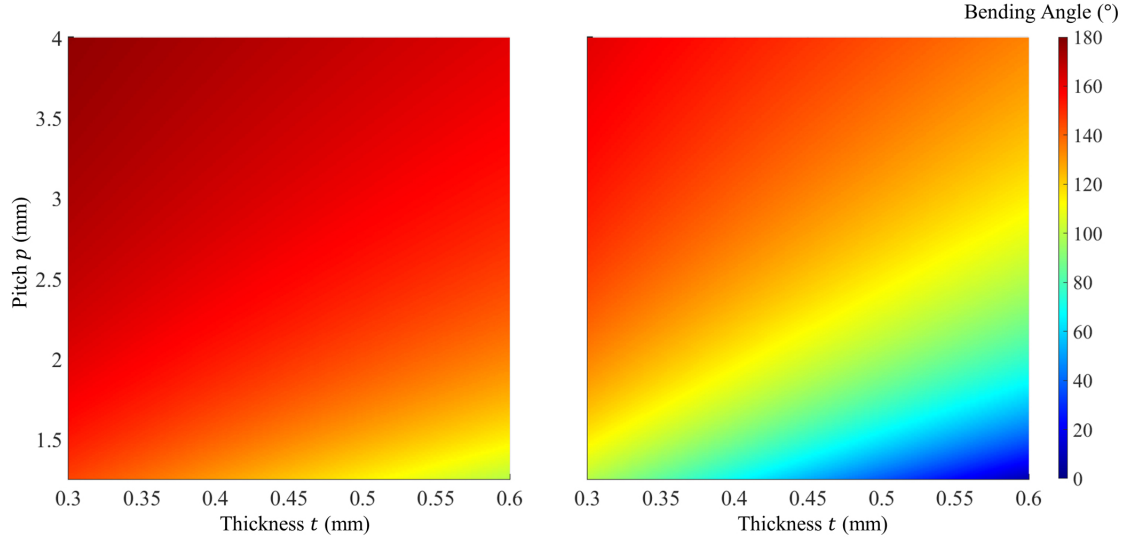


Figure 3.2: The maximum bending angle analysis with the specifications of pitch and thickness of coil at a given length of 25mm. (a) single thread helix. (b) Double thread helix.

change in the maximum bending angle. Before deriving the bending ability of the proposed design, it is important to introduce a model that describes the shape of a continuum joint in a bending status. Given that the total length of the joint is fixed with rolling contacts, the constant curvature framework can be employed and written in the following Eq. (3.1),

$$r = \frac{L}{\theta} \quad (3.1)$$

where L is the arc length or the effective length of the flexible joint, r is the bending radius, and θ represents the complementary angle of the bending angle. From the geometric relationship shown in Fig. 3.1, the maximum bending angle occurs when the outer side of coils come into contact with each other, and can be expressed by

$$\theta_{max} = \frac{2(np - mt(n+1))}{d} \quad (3.2)$$

where d is the outer diameter of the flexible joint, n is the number of revolutions for

the coil, m is the thread number of the coil, t is the thickness of the coil and p is the pitch length. To reduce the variables taken into account, the relationship $L = np$ is introduced. The bending angle analysis based on the geometry of a deflected spring can be viewed from Fig. 3.2, where the total length L is fixed at 25 mm, with the value t and p in the range of 0.3 mm to 0.6 mm and 1.25 mm to 4 mm respectively. According to the results, the increase in the number of coils and the reduction in the pitch of the coil can shorten the operating distance between coils, and reduce the maximum bending angle. Using a single helix design, the joint can achieve a maximum bending angle exceeding 90° easily, with the possibility of reaching 180° . In contrast, the design with a double helix presents a limited choice of specifications. In this case, the length of the joint is being a primary factor that affects bending performance; the requirement of a large maximum bending angle inevitably leads to an increase in the length of the joint.

The spring constant is a measure of deformation under external stretch or compression. In the context of this continuum joint design, the spring constant is directly linked to bending stiffness and is mainly affected by the shape of the cross section. Rectangular and circular are the two most commonly used shapes in the design and the spring constant κ_r and κ_c can be calculated by

$$\kappa_r = \frac{F}{\delta} = \frac{Gw^2t^2}{\nu nd'^3} \propto w^2t^2 \quad (3.3)$$

and

$$\kappa_c = \frac{F}{\delta} = \frac{Gt^4}{\nu nd'^3} \propto t^4 \quad (3.4)$$

where F is the force applied on the spring and δ is the distance of travel. G and ν refer to the shear modulus and Poisson's ratio of material respectively. w represents the width of the coil and d' refers to the mean diameter of the spring. It has been shown in the equations that the spring constant is proportional to the square of the cross-sectional area. Although the stress distribution around the rectangular cross section may not be as uniform as that of the round wire section,

spring structures with rectangular coils can still store more energy than those with round-shaped coils with the same maximum bending angle configuration (p and t), because the width of the coil can be extended towards the inside of the spring, thereby incorporating more material into the bending behavior. Also, increasing the width of the coil w that in a direction perpendicular to the central axis can enhance the torsional resistance.

3.3 Design of a Multi-Segment Flexible Robot

3.3.1 Concept Design

Based on the review of current research and commercialized systems described in the previous chapter, it is clear that an overall size ranging from 12.8 mm to 18 mm is acceptable for the robotic endoscope design. Taking into account the required strength and stiffness of the spring-like structure mentioned in Section 3.2.1, the proposed design in this work adopts an outer diameter of 15 mm and has a large central channel of 9 mm. The section view of the design is shown in Figure 3.3. It is possible to separate the space into multiple channels to accommodate various accessory devices and facilitate the passage of robotic instruments. In order to align with the clinical requirements in ESD surgeries, the essential components include endoscopic cameras, irrigation channels, suction channels and instrument channels with at least 3.2 mm in diameter. Also, the presence of a large circular central channel at this size allows the flexible robot to perform as an overtube. Another advantage of this design is that the length of the joint is adjustable to satisfy the desired bending ability of the whole robot.

It is also important to form the retro-flex shape at a small bending radius to follow the anatomical structure. To enhance the steering ability of the robot, the long-short arrangement is used in the design where the joints bending at the horizontal plane have a longer length than those at the vertical plane.

3.3.2 Kinematics

When the constant curvature model serves as the kinematic framework, the calculation of the varying length of actuated tendons at each segment in the configuration space with respect to the joint space can be written as:

$$L_i' = L + d'\theta_i \quad (i = 1 \cdots n) \quad (3.5)$$

where d' is defined as the moment arm of actuation tendons applied on the joint. The bending angle at i th joint is θ_i . Recalling the constant curvature model, the position matrix in local coordinate can be written based on the bending relationship given in Eq.3.1

$$\mathbf{P}_i = \begin{bmatrix} 0 \\ \frac{L(1-\cos\theta_i)}{\theta_i} \\ \frac{L\sin\theta_i}{\theta_i} \end{bmatrix} \quad (3.6)$$

when the bending angles of joints approach zero, the function in Eq. 3.6 will be unsolvable, thus they can be expanded with the Taylor series

$$\frac{\sin(\theta)}{\theta} \approx 1 - \frac{\theta^2}{3!} + \frac{\theta^4}{5!} - \frac{\theta^6}{7!} \quad (3.7)$$

$$\frac{1 - \cos(\theta)}{\theta} \approx \frac{\theta}{2!} - \frac{\theta^3}{4!} + \frac{\theta^5}{6!} - \frac{\theta^7}{8!} \quad (3.8)$$

When both rotation and translation behaviours are accounted for, the forward transformation matrix from the $(i-1)$ th frame to the i th frame can be expressed as

$${}_{i-1}^i\mathbf{T} = \begin{bmatrix} \mathbf{R}_x(\theta_i) & \mathbf{P}_i \\ 0 & 1 \end{bmatrix} \quad (3.9)$$

and the full transformation from base to the end-effector can be found by multiplying all of the individual transformation matrices

$${}^0_N\mathbf{T} = {}^0_t\mathbf{T} {}^t_r\mathbf{T} \mathbf{T}_{\text{Assem}} {}^r_1\mathbf{T} \mathbf{T}_{\text{Assem}} {}^1_2\mathbf{T} \cdots \mathbf{T}_{\text{Assem}} {}^{n-1}_n\mathbf{T} \quad (3.10)$$

where $\mathbf{R}_x$ is rotation matrix about X axis. $\mathbf{T}_{\text{Assem}}$ is an assembling matrix which makes sure the joints follow the orthogonal arrangement and can keep each segment operated in the same local bending plane. By using the rotation matrix $\mathbf{R}_z$, the matrix can be given by

$$\mathbf{T}_{\text{Assem}} = \begin{bmatrix} \mathbf{R}_z(\frac{\pi}{2}) & 0 \\ 0 & 1 \end{bmatrix} \quad OR \quad \begin{bmatrix} \mathbf{R}_z(\frac{3\pi}{2}) & 0 \\ 0 & 1 \end{bmatrix} \quad (3.11)$$

The pose of the robot can be described by a vector in joint space defined as,

$$\mathbf{q} = \begin{bmatrix} t \\ \theta_r \\ \theta_1 \\ \vdots \\ \theta_i \end{bmatrix} \quad (i = 1 \cdots n) \quad (3.12)$$

where the axial translation and axial rotation on base are t and θ_r respectively. The relationship of velocity between joint space and task space can be written as

$$\dot{\mathbf{P}} = \mathbf{J}\dot{\mathbf{q}} \quad (3.13)$$

where $\mathbf{J}$ is Jacobian matrix. When both the position and orientation of the end-effector are considered, the Jacobian matrix can be expanded as

$$\mathbf{J} = \begin{bmatrix} \mathbf{J}_{\mathbf{P}} \\ \mathbf{J}_{\mathbf{O}} \end{bmatrix} \quad (3.14)$$

where $\mathbf{J}_{\mathbf{P}}$ and $\mathbf{J}_{\mathbf{O}}$ relates to position and orientation on the tip respectively. They can be calculated as

$$\mathbf{J}_{\mathbf{P}i} = \frac{\mathbf{P}(q_i + \Delta h) - \mathbf{P}(q_i - \Delta h)}{2\Delta h} \quad (3.15)$$

where Δh is a small value, $\mathbf{J}_{\mathbf{P}i}$ is a vector element at the k th column of Jacobian matrix $\mathbf{J}_{\mathbf{P}}$. And

$$\mathbf{Q}^+ = \mathbf{Q}(i + \Delta h) = \{\eta^+, \epsilon^+\} \quad (3.16)$$

$$\mathbf{Q}^- = \mathbf{Q}(i - \Delta h) = \{\eta^-, \epsilon^-\} \quad (3.17)$$

$$\mathbf{J}_{\mathbf{O}i} = \frac{\eta^- \epsilon^+ - \eta^+ \epsilon^- - \mathbf{S}(\epsilon^+) \epsilon^-}{2\Delta h} \quad (3.18)$$

where $\mathbf{J}_{\mathbf{O}i}$ is a vector element at the k th column of Jacobian matrix $\mathbf{J}_{\mathbf{O}}$, $\mathbf{S}$ is screw operator. In the situation when the Jacobian matrix is not uniform, the pseudo-inverse matrix $\mathbf{J}^\dagger$ can be defined as

$$\mathbf{J}^\dagger = (\mathbf{J}\mathbf{J}^T)^{-1} \mathbf{J}^T \quad (3.19)$$

3.3.3 Path Following

To avoid collision with patients' intestinal walls, the snake-like robot should be ideally positioned close to the centreline of the intestine. The path that the whole robot body shall conform to is either a predefined path or a generated path using the real-time recorded trace of the tip. The latter approach is known as the follow-

the-leader manner [144]. To keep all the joints following a predefined spline curve, a joint-to-joint approach was adopted instead of the end-to-end inverse kinematics. First, assuming that the desired position of each joint tip $\tilde{P}$ is on the predefined path, the distance between the adjacent joint tips should satisfy the condition

$$|\tilde{\mathbf{P}}_i - \tilde{\mathbf{P}}_{i-1}| = L \quad (i = 2, 3 \cdots n) \quad (3.20)$$

where L is the joint length. To minimise the distance between each joint and its corresponding reference point, the full body inverse method is implemented. The full body Jacobian matrix $\mathbf{J}_f$ can be expressed as

$$\mathbf{J}_f = \begin{bmatrix} \frac{\partial \mathbf{P}_1}{\partial \theta_1} & \frac{\partial \mathbf{P}_1}{\partial \theta_2} & \cdots & \frac{\partial \mathbf{P}_1}{\partial \theta_n} \\ \frac{\partial \mathbf{P}_2}{\partial \theta_1} & \frac{\partial \mathbf{P}_2}{\partial \theta_2} & \cdots & \frac{\partial \mathbf{P}_2}{\partial \theta_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial \mathbf{P}_n}{\partial \theta_1} & \frac{\partial \mathbf{P}_n}{\partial \theta_2} & \cdots & \frac{\partial \mathbf{P}_n}{\partial \theta_n} \\ \frac{\partial \mathbf{O}_n}{\partial \theta_1} & \frac{\partial \mathbf{O}_n}{\partial \theta_2} & \cdots & \frac{\partial \mathbf{O}_n}{\partial \theta_n} \end{bmatrix} \quad (3.21)$$

where $\mathbf{P}_i$ is the pose matrix for joint i ($i = 1, \dots, n$) and $\mathbf{O}_n$ is the orientation matrix for the tip joint n , which can be estimated via the constant curvature model [167]. Each element in the equation is a 3×1 matrix and the orientation on the tip should keep forward. By substituting the equation into the pseudo inverse method given by Eq. 3.19, the joint configuration can be calculated.

3.3.4 Arrangement of Tendons

One of the key characteristics that should be considered when designing a tendon-driven snake-like robot is how to arrange the tendons inside the robot effectively. The common method is to let all the tendons pass through the centre of each robot joint to avoid cross-talk between joint sections. However, this solution occupies too

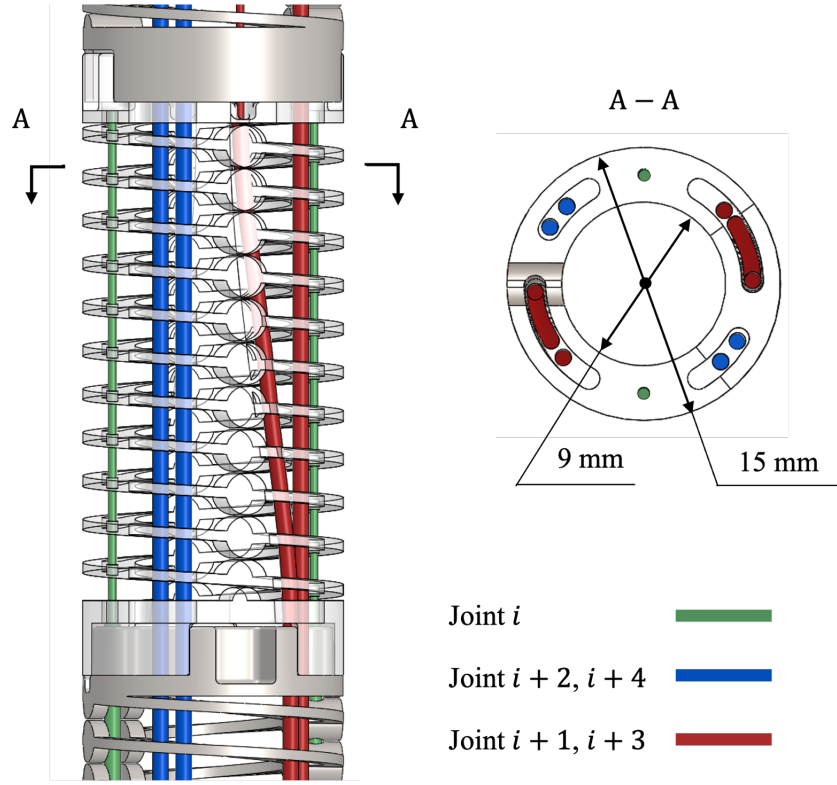


Figure 3.3: The arrangement of tendons and Bowden cables inside the pilot lumens. For better visualisation, the tendons and Bowden cables on the back are hidden in this view.

much space along the neural line of the robot, compromising the available space left for the instrument channels. An alternative method is to evenly distribute all the tendons on the outer wall of joints. In this design, the cross section in the helical spring is modified to a rectangular shape with a large aspect ratio (5:1), therefore, the features such as guiding channels for tendons can be created on the coil and the contact areas between rolling contacts can be increased to prevent undesired slipping. To eliminate the cross-talk between the serially connected joints, a bunch of Bowden cables are well arranged inside the robot by passing through four pilot lumens that are evenly distributed around the body. As shown in Fig. 3.3, the tendons for the upper section pass through the pilot lumens with the helical shape at the lower section, allowing a sequential arrangement of the Bowden cables, thus avoiding the problem of winding.

The proposed design not only preserves an intact and large central channel, but

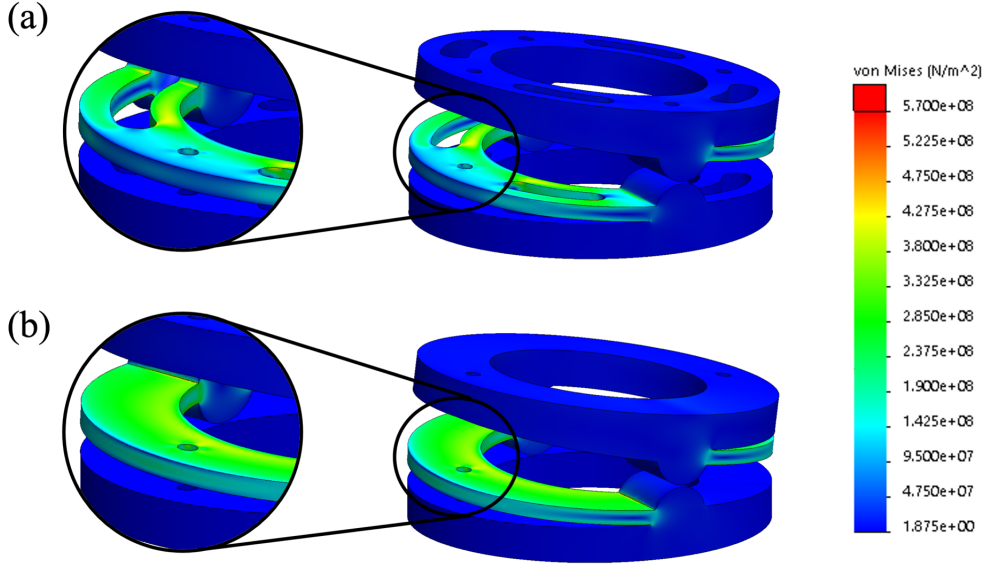


Figure 3.4: FEA results of von Mises stress for the design with (a) pilot lumens (b) the solid coil.

also optimises the usage of the space in the wall of coils. Besides, the structure with pilot lumens is capable of maintaining structural strength compared with the solid coil design. As shown in Fig. 3.4, when the torque is applied to the simplified model, resulting in the bending angle at 8.16° . Therefore, the overall stress on the design with the pilot lumens has no significant difference compared with that with solid coils, while the stress on both structures is less than the ultimate yield strength (470 MPa).

With the advance of SLM, the proposed joint design that contains hollowing features with a large slenderness ratio along the axial direction is self-supported and manufactured using austenitic stainless steel (CL20ES) in a laser metal 3D printer (Concept Laser MLab Cusing, GE Additive, U.S.).

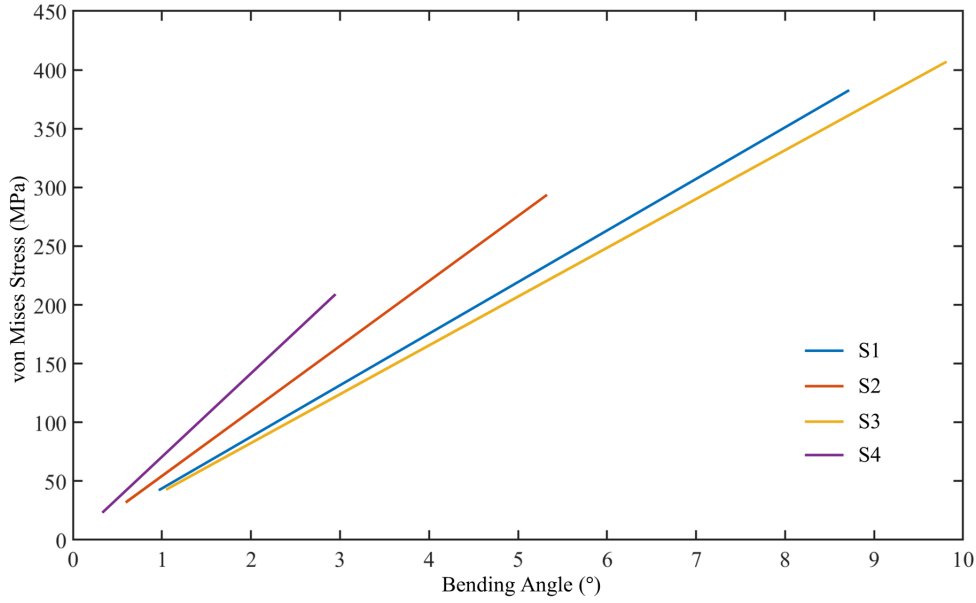


Figure 3.5: The relationship between the bending angles and maximum von Mises stress obtained from FEA results.

3.4 Results and Discussion

3.4.1 FEA: 1-DoF Design Validation

It should be noted that the geometric analysis alone is not sufficient for determining the specifications of a spring structure. There are certain constraints posed by the material and mechanical properties must also be taken into account.

The analysis was proceeded in the Workbench (ANSYS Inc.) static structural simulation. Recall the description in Section 3.2.1; the critical parameters of a spring mechanism including pitch, thickness and width of the coil are investigated. Since the helix of spring is a repetitive structure, the analysis with a single coil

Table 3.1: Specifications of the multi-segment designs

	S1	S2	S3	S4
Pitch, p (mm)	2	2	3	2
Thickness, t (mm)	2.5	3.5	2.5	2.5
Width, w (mm)	0.5	0.5	0.5	0.7

model can present the motion of an actual structure, while finer mesh can be used on the models for more accurate and more computationally efficient solutions.

Four models are used to validate the motion of joints in FEA. To simulate the bending motion of joints, the force generated by pulling the tendons is converted to an external tip moment. As shown in Fig. 3.5, the results demonstrate the relationship between the bending angles and maximum von Mises stress on the models. Due to the combination of bending and torsional load applied on the coil structure, high stress occurred close to the inner side of the coil. Comparing the results between all the models, the variation of the pitch has no obvious effect on the stress; however, at the same bending angle, higher stress can be observed with the increase of width and thickness on a cross section of the coil, capable of restoring more energy than other models. but less maximum bending angle can be expected, since the structure will reach the ultimate stress earlier. The ultimate yield strength of the CL20 material is 470 MPa. Although the experimental results from printed parts may have slight differences due to the friction generated between guiding channels and tendons, and the printing qualities (manufacturing errors and defects) and the pattern will remain the same.

3.4.2 Experiment Setup for the Multi-Segment Robot

As shown in Fig. 3.6, a prototype of the snake-like flexible endoscope has six joints orthogonally arranged and a feeding mechanism providing one DoF translation. To be specific, the front section of 175 mm is an active robot configured with two types of joints with 10 and 6 active coils respectively. The active robot and the actuation unit are connected by a passive body, giving a total length of 675 mm for the entire robot. For the actuation pack, six brushless DC motors (Faulhaber Minimotors, Switzerland) are used for actuating the tendons that pass through a series of pulleys. A linear DC servomotor directly actuates the translation motion with a stroke length of 220 mm. The following experiments and simulations are configured and proceeded with these given specifications.

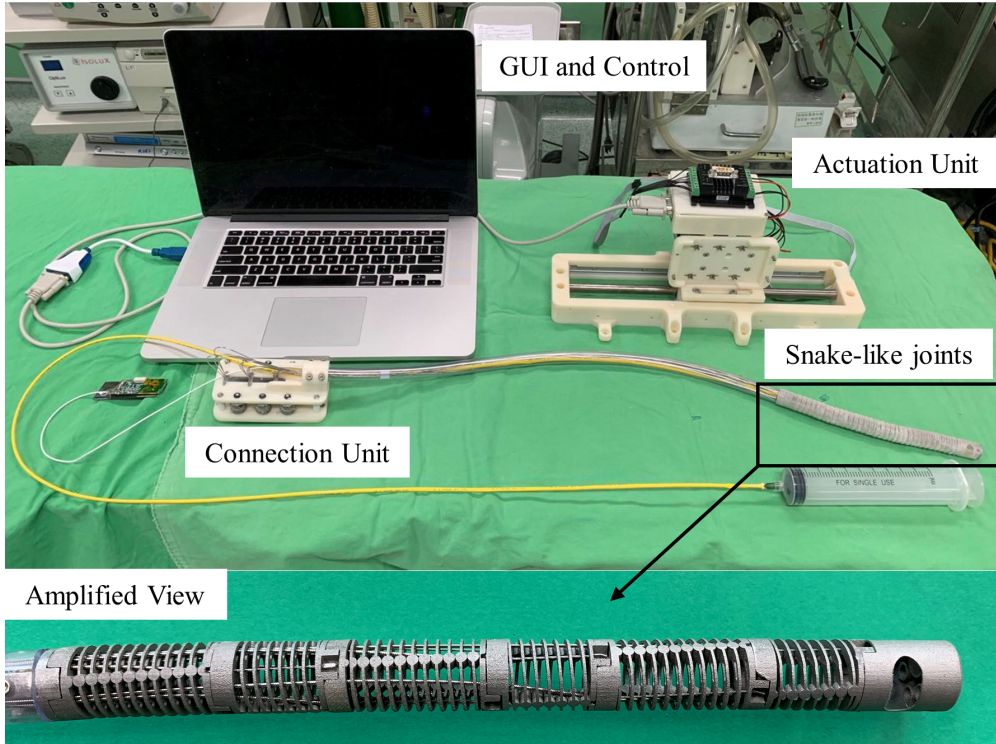


Figure 3.6: The overview of the system that consists of six 1-DoF continuum sections, a passive body and an actuation unit with one DoF translation.

3.4.3 Path Following Simulation

The performance of the path following strategy introduced in Section 3.3.3 is validated using a simulated colon path illustrated as the blue curve in Fig. 3.7(a). The shape of the flexible robot is continuously estimated using the curve fitting method while advancing along the path. Two example states which represent the flexible robot in different bending shapes are displayed in red. The distance errors of the robot joints to the desired reference points on the simulated path over time are plotted in Fig. 3.7(b). The results show that the joint distance errors significantly increase at those three turns with high curvature. Both the qualitative and quantitative results demonstrate that the proposed robotic endoscope can continuously follow the desired surgical path with good accuracy.

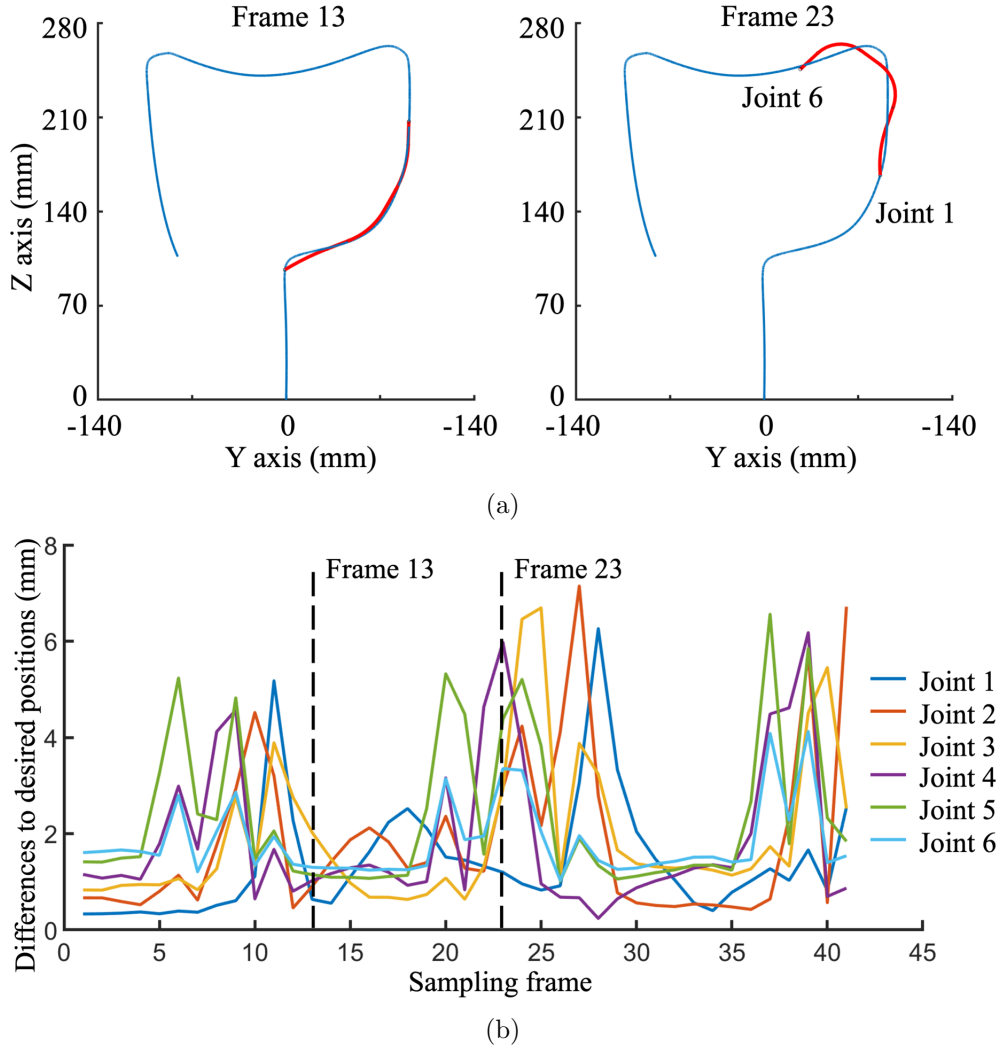


Figure 3.7: (a) The robot shapes (red line) at two different timestamps when following a simulated colon path (blue line). (b) The distance errors of each joint over time when advancing along the path.

3.4.4 Workspace Analysis

The workspace of the proposed robot is analysed and shown in Fig. 3.8. Because of the alternating arrangement of the long and short segments, the robot can reach a greater area in the horizontal plane (XOZ) than the vertical plane (YOZ). Although manipulability measurements [168] are usually used to evaluate the dexterity of a robot design, the bending radius is considered as a vital characteristic specifically for manoeuvring through natural pathways during endoscopic surgeries. With the proposed joint arrangement, the adjacent joints bend

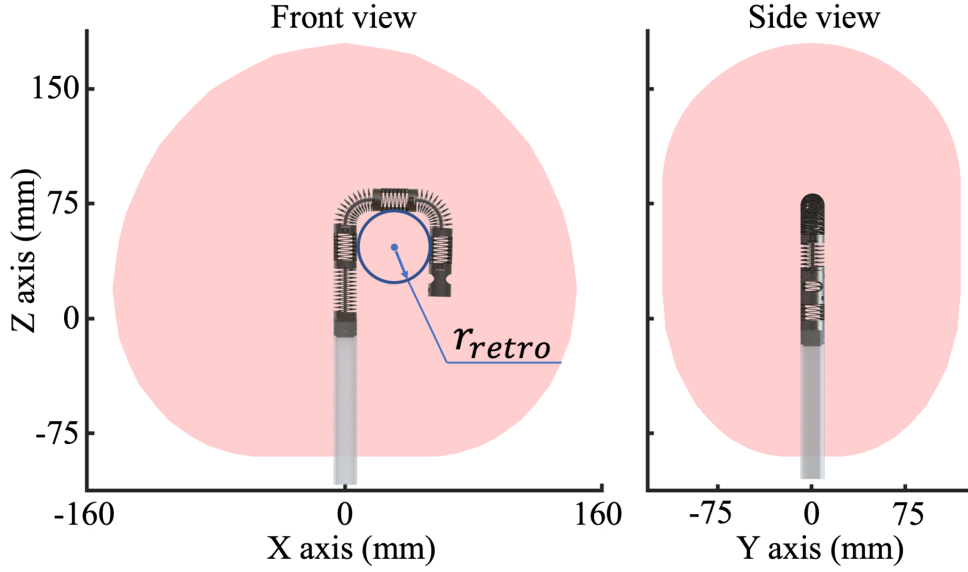


Figure 3.8: The workspace of the proposed design in two views. r_{retro} represents the bending radius in the retro-flex shape

in orthogonal directions. If the robot needs to bend in the horizontal direction following the shape of the colon, all the segments responsible for bending in the vertical direction will act as solid bodies. Therefore, the bending radius in the horizontal direction increases. However, by using shorter segments for the bending in the vertical direction in the proposed design, the bending radius in the horizontal direction can be reduced without compromising the horizontal bending angle. As shown in Fig. 3.8, the bending radius in the retro-flex shape is 23 mm.

3.4.5 Force Test

The manoeuvrability of a snake-like robot is often evaluated by measuring the output forces from the joints. An adequate amount of force is necessary to bend the joint while resisting the lateral force caused by any contact with the tissue. The force test is performed by mimicking a scenario when the robot needs to bend on the horizontal plane to pass a curved colon section. The state when the robot is fully stretched is selected to result in torque with the maximal lever length at the proximal end. As shown in Fig. 3.9, the output forces at the proximal end and the tip on the horizontal plane are measured with a force gauge (SAUTER FK

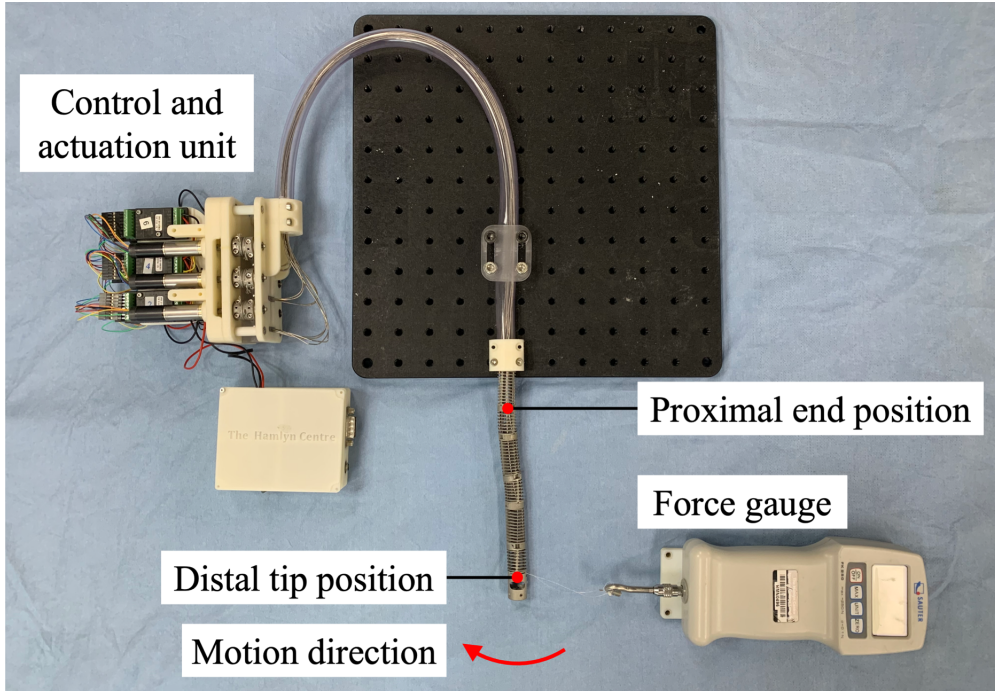


Figure 3.9: Experiment setup for the force test on the proposed design.

250 Force Gauge, 250 N x 0.1 N). The force gauge used in this experiment has a maximum force range of 250 N with a resolution of 0.1 N. The forces measured at the proximal end and the tip is 2.6 N and 0.9 N, respectively. The output forces from the joints at those two key positions are limited due to the friction between the tendons and the Bowden cables, even though the Bowden cables can avoid cross-talk. Additionally, the insufficient force output from the actuation unit also restricts the performance. In comparison with the state-of-the-art *i*²Snake [88] and K-Flex [72] which can achieve higher tip payload capability of 5.58 N and 3 N, respectively, the output forces of the proposed design need to be improved while maintaining the advantageous minimum outer diameter tailored for lower GI insertion.

There are two potential solutions for improving the output forces from the joints. One is to increase the force output from the actuation unit, such as using more powerful motors or reducing the diameter of capstans. While reducing the diameter of capstans makes it challenging for tendons to wind, resulting in the potential loss of overall control accuracy. The other solution is to reduce the length of the

lever arm by optimising the length of the robot. Parameter analysis can be performed to find the optimal number of joints and joint lengths that allow the robot to pass through a curved colon section smoothly and achieve a retro-flex shape.

3.5 Summary

In this chapter, I have presented the design of a flexible joint with a spring-like structure. Based on the constant curvature assumption, an investigation into the maximum bending capability has been conducted. This estimation serves as an initial guide for selecting design parameters suitable for required surgical applications. The FEA results on a series of 1-DoF models have been given for understanding the characteristics of the flexible joint.

Furthermore, a preliminary design of a snake-like flexible endoscope with 7 DoFs is also presented. Referring to current research, the joint has 15 mm in diameter. Upon metal printing, the design showcases a compact form, effectively accommodating the necessary internal channel. A novel design for tendons arrangement is proposed and validated through FEA. Kinematic control is calculated by the full body inverse method. To ensure suitability for the application of ESD surgery, the accuracy is tested in a simulated colon model. Finally, the manipulation of the snake-like robot is tested in a force test, resulting in 2.6 N at the tip. And a comparison between different platforms is given.

Although the results demonstrate that the proposed robot has the potential to be used as an endoscope in ESD surgeries, certain issues have been identified related to manufacturing defects and positioning accuracy. The forthcoming chapters, Chapter 5 and Chapter 6.1, will investigate the optimized manufacturing process and modeling methodology, respectively.

Chapter 4

Endoscope Insertion Using Spiral Technique[†]

4.1 Introduction

It has been highlighted in Section 2.5.1 that the insertion of endoscope remains a challenge for both diagnostic and therapeutic procedures. To address this issue, the solutions in developing snake-like or flexible robotic endoscope with advanced ability can be divided into two mainstreams. Relying on the hyper-redundancy mechanisms and follow-the-leader manner, a snake-like endoscope with multi-segment configuration can be controlled to conform with the natural paths. Examples to such design include the modular robot iSnake [87], the i²Snake system [88] which used multiple tendon-driven articulated joints design; and the snake-like robot, which is based on variable neutral-line mechanism to continuously adjust the stiffness of the continuum joints by varying tensions, proposed by Kim et al. [15]. It should be noted that many of these designs incorporate a rigid pas-

[†]The content of this chapter was presented as: W. Li, Y.Y. Tsai, G.Z. Yang and B. Lo, “A Novel Endoscope Design Using Spiral Technique for Robotic-Assisted Endoscopy Insertion”, 2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) , pp.3119-3124, 2020.

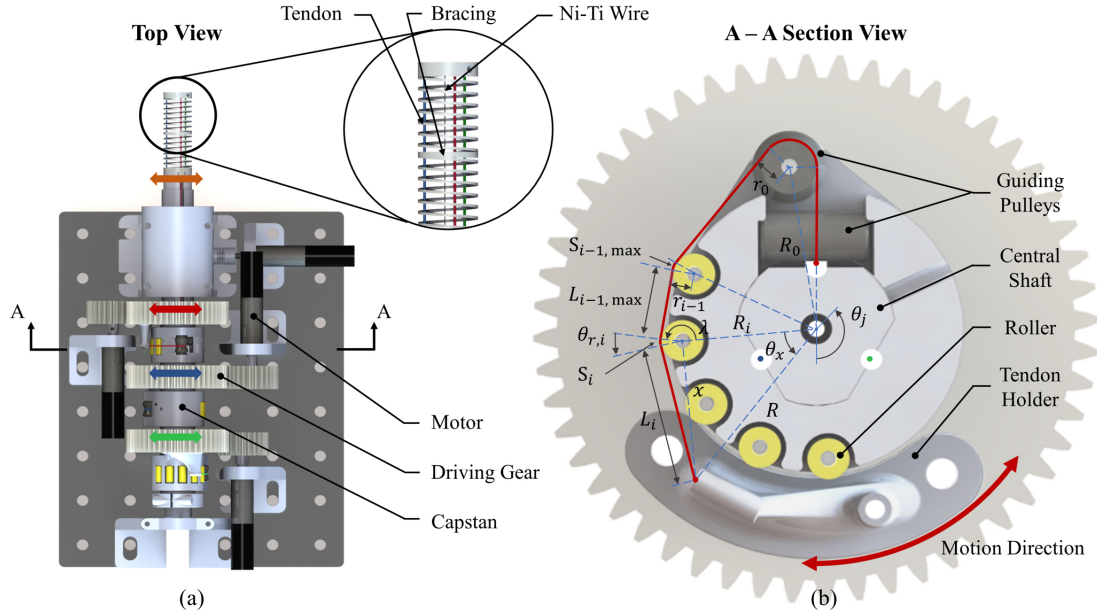


Figure 4.1: Conceptual design of the spiral endoscope without flexible body and the main components are labelled. (a) Top CAD view and magnified view of the continuum joint. (b) Section view of a capstan that shows the mechanical play of one tendon. In the sketch, the red line represents the tendon and the blue dot lines show the geometric relationship.

sive arm after the snake-like robot, which can limit the DMI. However, adding more joints to the device can significantly increase the structural complexity and difficulty in control of the system.

Another concept was proposed to generate propelling forces at the scope tip to prevent looping formation during the procedures. This is achieved through techniques such as employing balloons in the endoscope design and utilising a spiral technique. While the performance of using single balloon and double design has been evaluated, it has also suggested that the procedures with those enteroscopes are both labour intensive and time consuming during the manual insertion process [161,162]. Also, PowerSpiral (PSE) shows promise with its advanced features, however, its high cost and complex structure could pose challenges in sterilisation and hinder its wide adoption.

In the last chapter, the option with multi-segment design has been tested and validated. In this chapter, I will propose a robotic endoscope design that makes

use of a spiral insertion technique. Compared with the PSE technique mentioned previously, which uses an individual rotate spiral sheath, the proposed design incorporates active rotation of the entire shaft of the endoscope during insertion. This design provides crawling ability through the attached spiral sheath while maintaining the orientation of the distal tip, facilitating easier navigation during the procedure. Compared with prior works, the proposed scope design has a more compact and simple structure, which is easier for sterilisation and disposable use. The rest of this chapter is organised as follows: In Section 4.2, we present the design and the prototype of the proposed device. Section 4.3 shows the system kinematic, and the control and the manipulation via the tendons. Section 4.4 covers the three experiments and the results followed by the discussion and the conclusion in Section 4.5.

4.2 Design and Prototyping of an Endoscope Using Spiral Technique

4.2.1 Concept and Methodology

Given the characteristics and limitations of the current enteroscope designs, the spiral design is favoured due to its higher mobility and less structure complexity. Unlike the PSE, which has an independent rotating spiral overtube driven by a torque wire, the proposed robotic endoscope has a fully rotatable body and a novel design of actuation mechanism. It can simultaneously control the bending angle while maintaining the orientation of its tip.

The proposed design concept is inspired by an actuation approach that drives a continuum joint with three tendons to achieve 2 DoFs bending capabilities and 1 DoF rotation around the central axis. To further improve the rotation ability and manoeuvrability of the joint, an alternative solution is to provide one redundant

DoF around the central axis, known as in-plane rolling motion. This property is an important feature for robotic instruments, usually achieved by either transmitting the motion to tip [5] or rotating the shaft, such as the da Vinci surgical instruments and Micro-IGES [61]. Due to different application requirements, most existing designs only have a maximum of $\pm 90^\circ$ in the rolling motion for instrument operation, limited either by the structural design or by the winding pattern of the tendons. Hence, a novel design of actuation mechanism is developed to enhance the shaft rotation capability. The detailed design of the actuation mechanism is presented next in Section 4.2.2, followed by the design and fabrication of the continuum joint in Section 4.2.3.

4.2.2 Design of the Actuation Mechanism

As shown in Fig. 4.1(a), the actuation mechanism proposed for this endoscope has a rotatable shaft, where the joint is fixed on one side, and the driving gears and capstans are sequentially arranged along the axial direction on the other side. In the circumferential direction, three fixed capstans are equally distributed and the driving gears can revolve freely under the control of the three motors respectively.

The three tendons that control the continuum end-effector are routed through the lumens of the central shaft to the driving unit. Each tendon goes through a pair of pulleys and terminates at the corresponding holder on the driving gears. The tendons are guided with either Bowden cables or grooved pulleys with a bending radius larger than 4 mm to minimise the occurrence of kicking and permanent deformation. By synchronising the motion between driving gears and the central shaft, the rotation differences applied on the tendons can be used to actuate the bending movement of the continuum joint. Detailed control for the actuation mechanism is discussed in Section 4.3.

4.2.3 Design and Fabrication of the Continuum Joint

The continuum joint design is modified from work presented in Chapter 3 and previous works, where the design specifications and the strength of the metal printed spring-like joint have been validated through fatigue experiments and Finite Element Analysis (FEA). To tailor the joint design to achieve multiple DoFs movements while keeping a steady orientation of the camera mounted on the tip, the circular rolling contact is replaced by a central Ni-Ti backbone wire. The selected Ni-Ti wire should be strong enough to resist compression while flexible enough to closely follow the shape of the central axis during bending. It is also important to avoid eccentric rotation at bending poses due to the different stiffness between the spring-like structure and the Ni-Ti wire. Hence, a thin layer of bracing is added in the middle of the spring structure. The applied mid-bracing also helps to prevent buckling of the Ni-Ti wire due to its high slenderness ratio.

A summary of the design specifications of the proposed spring-like continuum joint is listed in Table 4.1. The Ni-Ti wire used for the backbone has a diameter of 0.7 mm and the tendons used for driving the joint are made of 316 stainless steel, with 0.45 mm in diameter and 7x19 strand (ASAHI INTECC CO., Seto, Japan). With the outlined design specifications, the estimated maximum bending angle can reach up to 90°.

Table 4.1: The specifications of the metal printed continuum joint

Specifications	Values
Number of coil	14
The thickness of coil (mm)	0.6
Maximum Bending angle (°)	180
Diameter (mm)	15
Pitch (mm)	2.8

4.3 Control and Manipulation

4.3.1 Mechanical Play of the Tendons

As mentioned in Section 4.2.2, when the tendon holders have relative motion around the capstans, the lengths of the tendons will change and thus tendons will attach on the rollers. The correspondence between the rotation angle θ_j and the tendon length $L(\theta_j, j)$ at j^{th} tendon can be calculated based on the CAD model. According to the geometric relationship shown in Fig. 4.1(b), the length variation of each tendon on the actuation capstans can be described as:

$$L(\theta_j, j) = \begin{cases} \sum_{m=0}^{i-1} (L_{m,\max} + S_{m,\max}) + L_i + S_i, & i = n \\ L_i + S_i, & i = 0 \end{cases}. \quad (4.1)$$

where n is the index of the last roller in contact with the tendon which can vary from 1 to 5. L_i and S_i represents the euclidean distance and arc length at the i th roller respectively. The values of L_i and S_i can be solved by defining an auxiliary line x ,

$$x = \sqrt{R^2 + R_i^2 - 2RR_i \cos \theta_x} \quad (4.2)$$

where θ_x is related to θ_j and substitute x into the following equations,

$$S_i = r_i [2\pi - \lambda - \arccos(\frac{x^2 + R_i^2 - R^2}{2xR_i}) + \arctan(\frac{L_i}{r_i})] \quad (4.3)$$

$$L_i = \sqrt{x^2 - r_i^2}, \quad i = 0, 1 \dots n \quad (4.4)$$

where λ is a fixed value calculated from the geometric relationship of rollers. The

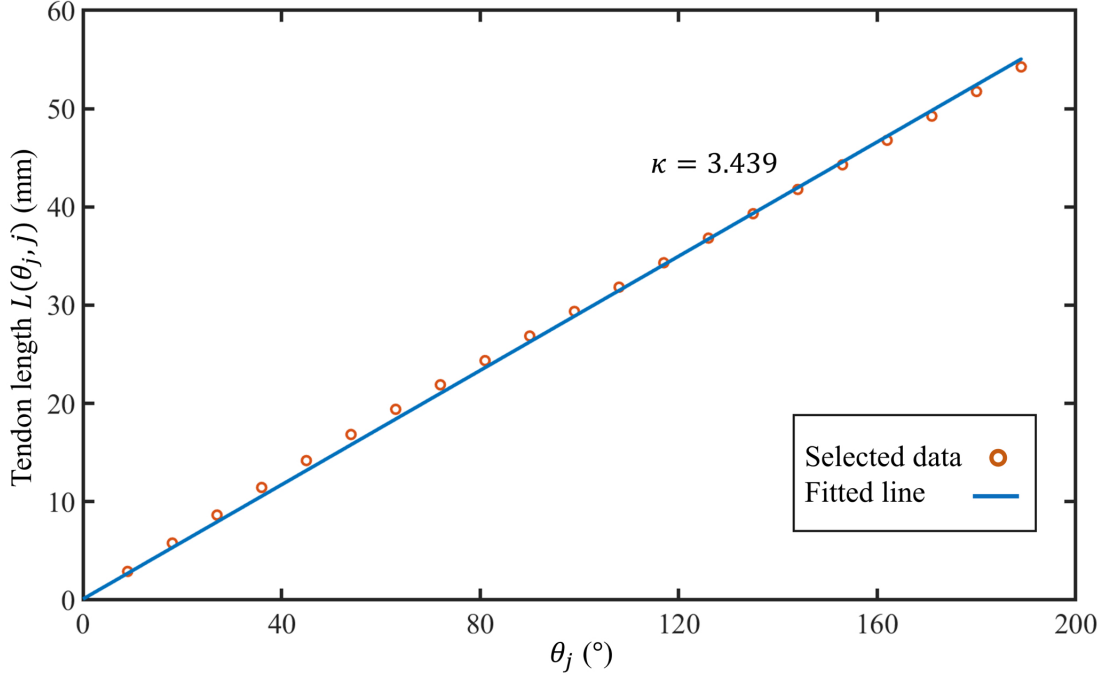


Figure 4.2: The estimated linear relationship between the rotating angle θ_j and the total tendon length on the capstan based on the sampled tendon lengths at different rotating angles. Orange circles are the sampling data and the blue line is the fitted linear regression line.

next stage $(i+1)$ will begin when the tendon L_i becomes tangential to the $(i+1)$ th roller, while the tendon length in current stage will become fixed values, written as $L_{i,\max}$ and $S_{i,\max}$. By substituting the values of rotation angles from zero to π , the variation of tendon lengths can be illustrated in Fig. 4.2. The relationship between θ_j and $L(\theta_j, j)$ can be approximated as linear by fitting a straight line to the sample points. The approximated linear relationship is used to not only simplify the kinematic model but also to reduce the complexity of joint assembling and initial tendon calibration. The neutral position of tendons is set in a range near the bending angle $\frac{\theta_{j,\max}}{2}$, providing a suitable pre-tension force. As a result, Eq. (4.1) can be written as

$$L(\theta_j, j) = \kappa \theta_j \quad (4.5)$$

where κ is the gradient of fitted line labelled in Fig. 4.2 and the value is 3.439.

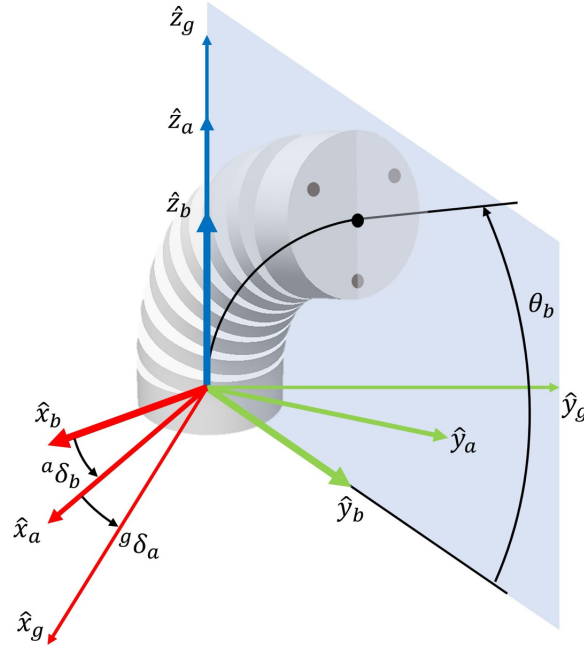


Figure 4.3: The kinematic model of a single-segment continuum joint. The origins of the three coordinate systems are at the base of the bending section.

4.3.2 System Kinematics

To derive the pose and orientation of the single joint system, the constant curvature-based method [167, 169] is implemented as the modeling framework. Fig. 4.3 illustrates the kinematic model in three coordinate systems including global frame $\{g\}$, rotation frame $\{a\}$ and joint frame $\{b\}$. The forward kinematics of the single-joint design can be transformed from the joint frame to the global frame with the position matrix given by

$${}^g\mathbf{R}_b = \frac{L}{\theta_b - \frac{\pi}{2}} \begin{bmatrix} \cos({}^a\delta_b + {}^g\delta_a)(1 - \cos(\theta_b - \frac{\pi}{2})) \\ -\sin({}^a\delta_b + {}^g\delta_a)(1 - \cos(\theta_b - \frac{\pi}{2})) \\ \sin(\theta_b - \frac{\pi}{2}) \end{bmatrix} \quad (4.6)$$

where L and θ_b define the length and bending angle of the joint respectively. The corresponding orientation transformation can be expressed by

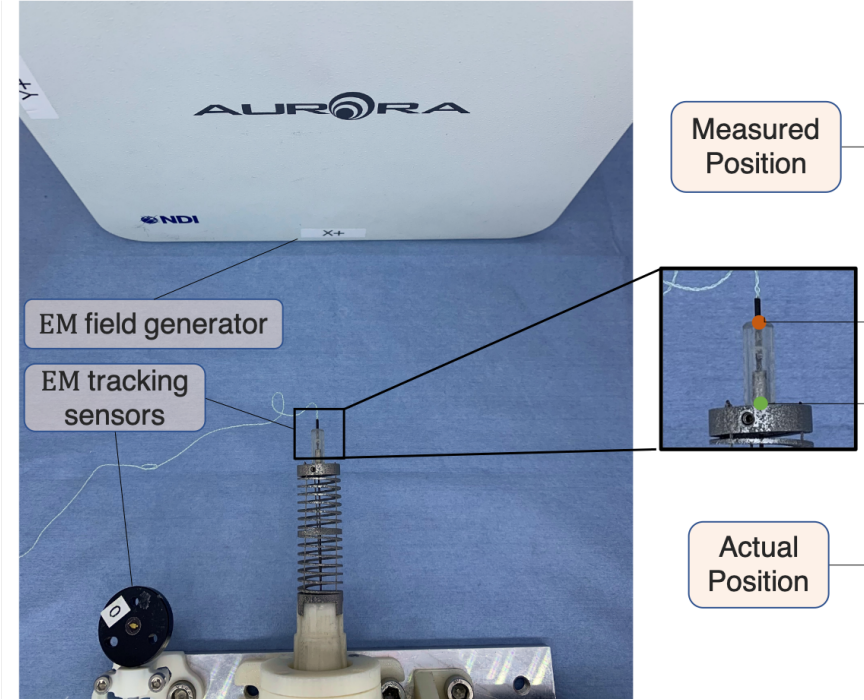


Figure 4.4: The experimental setup for the rolling motion validation using an EM tracking system. The disc EM sensor is used as the reference point to keep the sampling data in the same coordinate system. The location measured by the micro EM sensor is marked in red and the actual tip position is marked in green.

$$\begin{aligned}
 {}^g\mathbf{R}_b &= {}^g\mathbf{R}_a \cdot {}^a\mathbf{R}_b \cdot {}^b\mathbf{R} \\
 &= \mathbf{R}_{\hat{x}\hat{o}\hat{y}}({}^a\delta_b + {}^g\delta_a) \cdot \mathbf{R}_{\hat{y}\hat{o}\hat{z}}(\theta_b - \frac{\pi}{2})
 \end{aligned} \tag{4.7}$$

where ${}^g\mathbf{R}_b \in \text{SO}(3)$ is the orientation matrix. As described in Section 4.2.1, to maintain the position and orientation at determined angles corresponding to ω and Θ , when the central shaft is rotating, the redundant solution can be written as

$$\begin{cases} \omega = {}^a\delta_b + {}^g\delta_a \\ \Theta = \theta_b - \frac{\pi}{2} \end{cases} \quad \text{or} \quad \begin{cases} \omega = {}^a\delta_b + {}^g\delta_a + \pi \\ \Theta = \frac{\pi}{2} - \theta_b \end{cases} \tag{4.8}$$

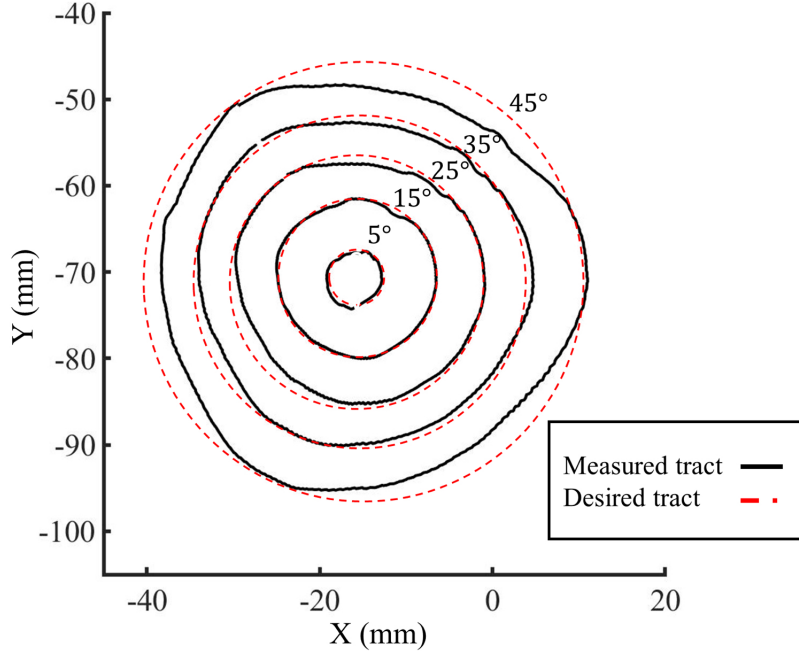


Figure 4.5: The comparison between the measured tip trajectories and the desired circular trajectories at several fixed bending angles.

where $\omega, \Theta \in (0, 2\pi)$. In order to enforce constraint direction and motion consistency, the second solution is neglected. The configuration vector $\Phi \in \mathbb{R}^3$ can be given by

$$\Phi = \begin{bmatrix} \omega & {}^g\delta_a & \Theta \end{bmatrix}^T \quad (4.9)$$

By using the assumption of constant curvature, the inverse kinematic from an array of configuration variables to tendons length can be produced as

$$L(\theta_j, j) = r_b \Theta \cos[(\omega - {}^g\delta_a) + (j - 1)\gamma], \quad j = 1, 2, 3 \quad (4.10)$$

where γ is the angle between equally separated tendons and r_b is the radius from central backbone. Recall Eq. (4.5), the values of θ_j for actuators can be solved.

4.4 Experiments

To evaluate the functionalities of the endoscope with a rolling tip presented in this chapter, three experiments have been conducted. The characteristics of the kinematic motion of the joint were tested in the first two experiments. The performance of an assembled spiral endoscope prototype was validated using an intestine phantom in the last experiment.

Table 4.2: The statistic results of the radius at different bending angles.

Bending Angles ($^{\circ}$)	Test No.	Mean (mm)	Std. (mm)
5	1	3.17	0.21
	2	3.18	0.21
	3	3.19	0.21
15	1	9.03	0.51
	2	9.02	0.52
	3	9.00	0.53
25	1	14.10	0.91
	2	14.07	0.91
	3	14.08	0.92
35	1	18.95	1.16
	2	18.91	1.15
	3	18.94	1.16
45	1	23.91	1.61
	2	23.61	1.46
	3	23.53	1.47

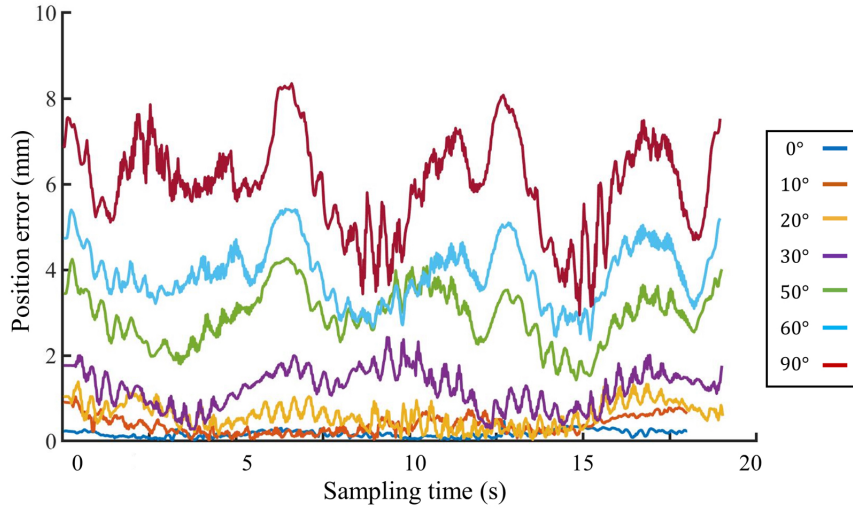


Figure 4.6: Position errors at different bending angles when performing the rolling motion at the joint tip for a full circle. The sampling rate is 40Hz.

4.4.1 Position Error Analysis

To conduct the first and second experiments, a test rig was set up as shown in Fig. 4.4, which consisted of an Aurora Electromagnetic (EM) Tracking System (Northern Digital Inc, Canada), two EM sensors (one Aurora Micro 6 DoF 0.8 mm x 9 mm Sensor and one Aurora 6 DoF Reference, 25 mm Disc, Standard sensor). The micro EM sensor was mounted at the tip of the joint to track the position. As illustrated in Fig. 4.4, there was a small displacement between the sensed location and the actual device tip. The recorded position data was therefore adjusted to reflect such translation.

In the first experiment, the device was set to follow different circular tracks. This was done by bending the device tip at different angles and rotating it about the $\hat{Z}_g$ axis. In this test, the three tendons would have to alternatively change their lengths to keep the tip following the circular path. We have tested a total of 5 different angles at 5°, 15°, 25°, 35° and 45°. With the simple open-loop control, the device was able to follow closely to the desired tracks up to 15°. Then, it started to deviate from the desired tracks as the angles increased. Table 4.2 presents the statistical results for the three tests, where the corresponding radius and standard deviation are calculated. For better visualisation, one set of the measured and

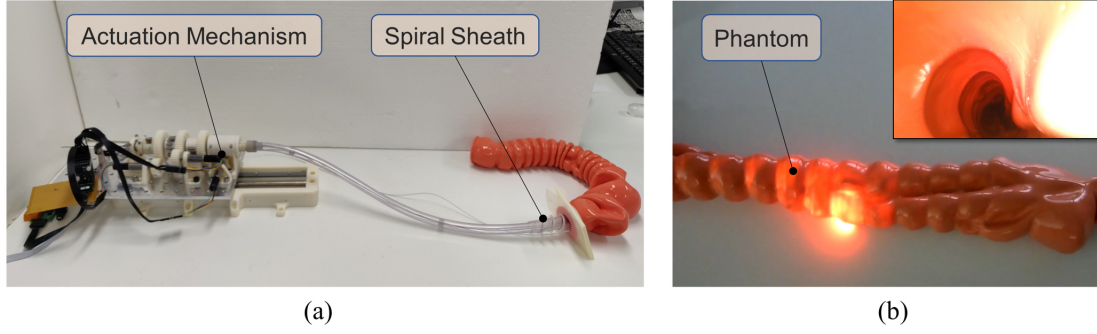


Figure 4.7: (a) The experimental setup for validation on a section of the intestine phantom. (b) An enlarged view of the endoscope inside the intestine phantom and the video output.

desired tracks were illustrated in Fig. 4.5.

In the second experiment, the device was validated to see if the proposed design can maintain a fixed joint tip orientation during spiral insertion. We, again, bent the device at different angles by pulling the three tendons at different lengths. Different from the first experiment, the redundant motion on the shaft will be involved, hence, the joint will keep relatively static about the $\hat{Z}_g$ axis. We have tested different bending angles from the home position, i.e. 0° to 90° with an increment of 10° . We recorded the position error information of the micro EM sensor in relation to the disc EM sensor for a full cycle of axial rotation. Again, with the simple open-loop control, as the bending angles increased, the position error increased. The position error result is shown in Fig. 4.6. It is worth noting that the position error for each bending angle appears to have 3 clear cycles. This indicates that the tool tip was drawing a small circle at its tip.

4.4.2 Phantom Experiment

The phantom experiment was conducted to test for potential looping problems with the proposed design. In this experiment, we tested our device on a section of the intestine phantom which has a diameter of 60 mm to mimic the curvature and the folding of the real intestine. The actuation unit and continuum joint was connected via a flexible tube. The tube has a length of 600 mm and its distal side

was covered by a spiral sheath printed using the Elastic 50A resin (Formlabs Inc., USA). The selected material is considered soft enough not to damage the tissue. In addition, an endoscopic camera was attached to the tip of a joint to provide visual information.

During the insertion, the endoscope rotated about its axis, while the continuum joint can guide the advance direction and manoeuvre the camera inside the intestine phantom. The advanced motion was done by pleating the phantom wall, where the rotation of the spiral sheath is transmitted to linear movement. We tested the insertion and the retrieval by rotating the continuum joint at different directions. From the visual inspection, there was no sign of loop formation during the procedure.

4.5 Discussion and Summary

For the first experiment as illustrated in Fig. 4.5, the deviation increased as the bending angle increased. The same conclusion can also be drawn in the second experiment. Additionally, according to Fig. 4.6, there were clear periodic changes to the position error over the course of full axial rotation. One possible reason could come from the kinematic model that the constant curvature assumption cannot accurately represent the motion of the joint used in this design. It has been investigated that the constant curvature model led to significant errors at large bending angles [6]. Another source of error might be from the overstrained Ni-Ti backbone at a large bending radius, which can be solved by reducing the diameter of the backbone. However, in this case, the performance of resisting external axial force would be affected.

In the phantom experiment, the spiral sheath can easily facilitate the advancement of the endoscope during insertion. Although there was no sign of potential looping, the result has shown that the performance was directly affected by the material of the passive tube. Furthermore, due to the weak torsional resistance of the passive

tube, the torque cannot be fully transmitted from the actuation unit to the joint, resulting in an offset error in the desired orientation and the limited insertion depth. In summary, I proposed a 4 DoFs (2 DoFs bending, 1 DoF rotation, and 1 DoF axial redundancy) robotic endoscope design by adopting a spiral insertion technique. A novel actuation mechanism is proposed to simultaneously rotate the endoscope shaft and control the bending angle of the joint. The kinematic model is constructed based on constant curvature assumption; however, the position errors show increasing deviation at large bending angles. The proposed design was tested on a section of the intestine phantom, and the result showed moving ability using the spiral technique, and the potential of clinical feasibility and usability.

It is worth noting that the observed errors could be attributed to mismatched design and modeling method. Another factor to consider is the interference between the elastic Ni-Ti wire and the spring structure in the proposed design. In the upcoming two chapters, the modified design and fabrication process will be investigated, aiming to mitigate these errors.

Chapter 5

Design and Fabrication of a Two-DoF continuum joint

5.1 Introduction

In Chapter 3, a design is proposed for a spring-like continuum joint that allows 1-DoF bending motion by adding circular rolling contacts on the coils. To create a snake-like robot, a serial and cross configuration can be employed. However, it can be observed from the experiments and simulation results that utilizing 1-DoF joints has an impact on the performance of the robot, leading to a significant increase in both bending radius and overall length of the robot.

Also, a robotic endoscope should have the flexibility to be controlled to obtain a wider view. One potential solution involves enhancing the design by transitioning from 1-DoF to 2-DoF bending motion while constraining linear compression. The proposed design in [112] achieves 2-DoF motion by inserting a slender shaft in the middle of the spring-like joint. However, adding another elastic material would be redundant when the spring mechanism is already capable of achieving the compliant motion.

The main contributions in this chapter focus on enhancing the flexibility of the spring-like continuum joint and modifying the fabrication process. Firstly, taking inspiration from the DNA chain structure, the joint design is further improved to a double helix structure that incorporates ball-shaped contacts on the central supporting beams, allowing the joint to have 2-DoF bending capacity. Except for the solution provided in Section 3.3.4, a new concept to avoid cross-talk on actuating tendons will be introduced, alongside an investigation into errors arising from helical routing.

while aiming to improve the flexibility of joint, it is also important to consider the potential impact of the fabrication process on its quality. In the case of using the Selective Laser Melting (SLM) technique, the defects can occur on the compliant mechanism or bending flexure due to residual stress, resulting in issues such as wrap, twist and deformation. To eliminate the twist of the joint induced during the metal printing process, empirical measurements were conducted on sets of samples with different configurations of the spring-like structure (pitch, thickness, width, and number of coils). Furthermore, an additional support is designed to prevent the permanent deformation generated during the printing process.

5.2 Design of a 2-DoF Continuum Joint

5.2.1 Concept Design

To address the problem, a novel design inspired by the structure of the DNA chain is shown in Fig. 5.1. This 2-DoF continuum joint design can be divided into two main parts, a helical-spring structure and supporting structures. The spring structure is designed with a double helix that provides higher bending stiffness. To prevent undesired axial compression, ball contacts are added along the central axis and connected to the spring structure with supporting beams. The ends of the beams are connected to different threads of coils, allowing the bending of the

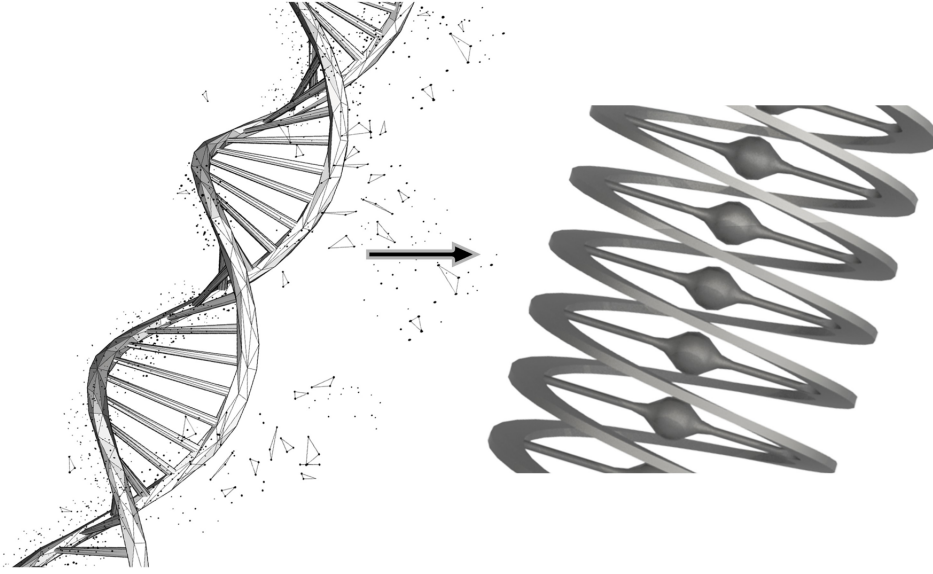


Figure 5.1: Introduction to the 2-DoF design bio-inspired by DNA chain. The sugar-phosphate backbones are replaced with double helix wires. The base pairs are replaced with supporting beams that have ball-shaped contacts.

spring to remain unaffected by the supporting structures. To resist the axial force generated by pulling tendons or payload, the top and bottom supporting beams have been designed with increased thicknesses. The beams in the middle have the same size as the thickness of the coil.

5.2.2 Helical Routing

Cross-talk is a common problem in designing a multi-segment robot with tendon-driven modality. Tendons controlling the joints at the front need to be routed in a designated path passing through other joints behind. The cross-talk happens when the motion of one segment lead to unintended movements on others or interference with their intended motion. To improve the control accuracy, it is important to avoid cross-talk and ensure each segment moves independently.

For the flexible robot composed of the 1-DoF joint, a method was introduced by Hu et al. [170], the tendons for the upper section pass through the neutral plane

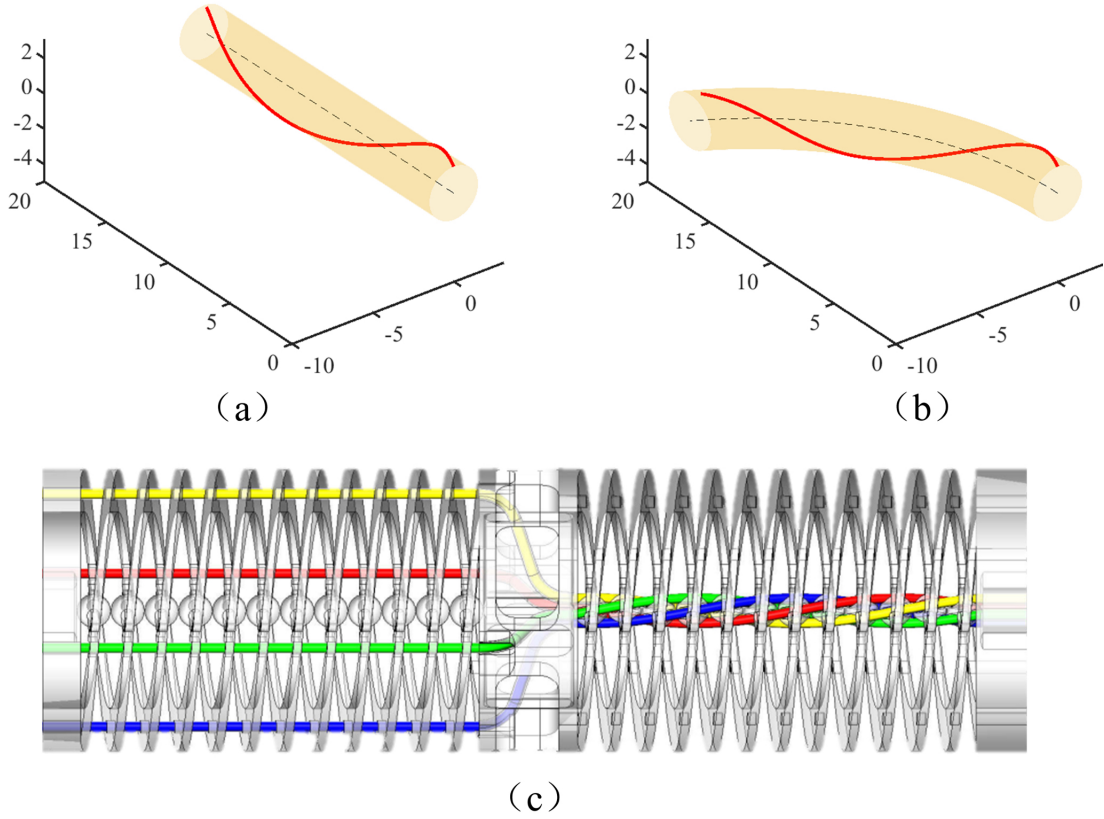


Figure 5.2: The concept of helical routing for preventing cross-talk. The helical channel is represented by the red lines at (a) $\phi = 0^\circ$ and (b) $\phi = 30^\circ$, where both channels have the same total length. An application of helical tendon routing in a two-segment design, where a pair of actuating tendons are represented by yellow and blue lines, and another pair of tendons are represented by red and green lines.

of the lower section and follow a spiral route with 90° rotations in between. For a multi-segment or 2-DoF joint design which only possesses a neural axis, iSnake² uses a strategy that keeps the tendons close to its axis to minimise the effect of cross-talk; however, the Bowden cables are still required. The strategy of using non-straight tendons routing that wraps around the central backbone can offer a lot of potentials. It has been proposed in [171,172], a helical routed tendon enables rotation of its backbone can greatly benefit for advanced control of a continuum joint. Improved motion capabilities are reported in the results, as evidenced by a wider workspace and position redundancy.

Instead of using helical routing to control a joint, a novel concept is introduced here to avoid the problem of cross-talk. For a 2-segment design, the path generated

along a helix at the root joint will perform as a guiding channel for the tip joint. The helix has one complete revolution and the pitch is equal to the effective length of the coil. Regarding the constant curvature framework, the parametric equations describing a helical channel can be given by

$$\begin{cases} x_h = r_h(r/r_h + \sin(2\pi t'/\phi)) \cos(t') - r \\ y_h = r_h(r/r_h + \sin(2\pi t'/\phi)) \sin(t') \\ z_h = r_h \cos(2\pi t'/\phi) \end{cases} \quad (0 < t' \leq \phi) \quad (5.1)$$

and

$$L_h(t') = \int_0^{2\pi} \sqrt{x_h^2 + y_h^2 + z_h^2} dt \quad (5.2)$$

where r and ϕ represent the bending radius and bending angle of the flexible joint respectively. r_h refers to the radius of the helix. t' is the parameter that denotes the points (x_h, y_h, z_h) on the helix in Cartesian coordinates. Therefore, the total length of the path $L_h(t')$ can be calculated. Based on Eq. 5.2, the helical channel can vary its shape with a bending joint but the total length keeps a constant value, because the displacement (lengthen/shorten) at t' will be compensated at $(t' + \pi/2)$. It also can be imagined that the coil length of a spring mechanism will remain constant regardless of the conditions of bending, stretch and compression. As shown in Fig. 5.2, an example of helical routing in a two-segment design has been given. Since the 2-DoF bending can be controlled by two pairs of tendons, 4 intertwined tendons run parallel and equally distributed to one another. Another advantage of implementing helical routing is the strength of supporting beams can be enhanced to resist the load from a transverse direction. At the top of the helical channels, additional curved channels in the connection area will guide the tendons to the side of the joint.

Despite the potential benefits of using helical routing, errors can occur in practical implementations. The guiding channels are expected to bend smoothly and follow the desired helix; however, the channels have fixed shapes in the ball-shaped con-

tacts while the tendon is directly connected between the neighbouring contacts. Since the value of pitch and number of revolutions has been determined, this error can be minimised by optimising either the size of ball contacts or the radius of the helix for the channels.

5.3 Fabrication of the Spring-like Continuum Joint

5.3.1 Manufacturing

The spring structures with the rectangular coil is generally more costly and has higher manufacturing difficulty than that with the circular coil. It has been highlighted in Tsubouchi et al. [173] that the fabrication of spring structure with a high aspect ratio w/h is difficult to be achieved using conventional manufacturing methods. The implementation of additive manufacturing is an attractive solution considering both cost-effective and printing availability. In this project, the spring-like continuum joint is fabricated using the Concept Laser Mlab machine based on the Selective Laser Melting (SLM) technique, and stainless steel (CL20ES) was used for prototyping. The continuum joints printed with metal are more compact in size than those printed with resin and plastic. Therefore, the structure can contain a relatively larger internal space while maintaining high stiffness and long fatigue life. Also, features such as connectors, rolling contacts, ball-shaped contacts and guiding channels can be printed directly on the joint body.

As this technique is a form of 3D printing, it shares some similarities with other additive manufacturing methods. Additive manufacturing techniques can result in features that fuse together when they are in close proximity. Due to the fine raw materials and the precision laser used in the process, this issue can be significantly reduced. To prevent the fusion of neighbouring circular or ball-shaped contacts in

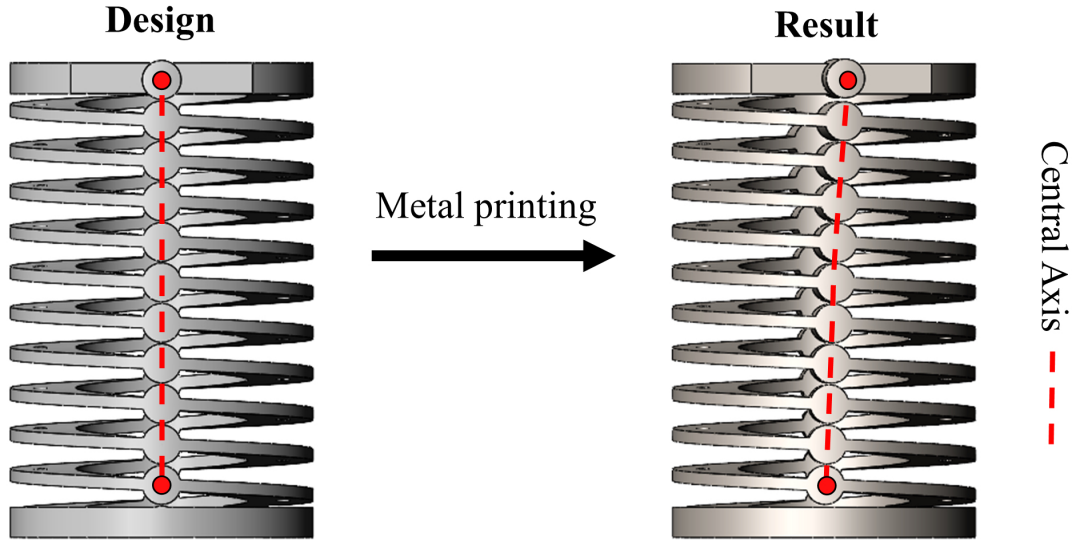


Figure 5.3: The sketch shows the distortion of the structure after printing. The central axis of the rolling contacts is labelled to illustrate the distortion.

the proposed joint design, a tolerance of 0.05 mm was set. To print a part with hanging or hollow structures, a support structure is necessary to hold the hanging surface in place during printing. The support structure can only overhang at an angle of less than 45 degrees without requiring additional supporting structures. In contrast to techniques such as FDM which use dissolvable support material and other resin-based printing methods, the mono-metallic material used in SLM has a stronger bond strength on the supports that requires careful treatment, particularly when dealing with helical structures. In addition, supports in hard-to-reach cavities can be challenging to remove during post-processing.

It is also crucial to setup a proper orientation for printing the compliant structure. Studies have shown that parts printed vertically have significantly lower yield and fatigue strength than those printed horizontally [174,175]. Furthermore, the printing process generates a high-temperature gradient from the scanning surface to the base due to the localised heat source. Consequently, high thermal stress accumulated between layers may lead to undesirable distortions and cracks. For the compliant mechanism with a high requirement on flexibility and elasticity, distortion usually occurs on the thin-wall structure. Three types of distortion can be observed in the spring-like continuum joint design: twist, wrap, and deformation,

where the first one needs the data to be collected from experiments and the rest two can be improved in the pre-processing step.

5.3.2 Defect: Twist Study[†]

The first defect is the distortion that occurs along the wire of the coil, resulting in a twist around the central axis of the joint. As illustrated in Fig. 5.3, the distortion of the joint can be observed with the left-hand helix. In this study, an experimental approach will be used to explore the distortion patterns and measure the magnitude of twists in the proposed continuum joints. The data obtained will be used to pre-compensate the geometry of the joint. The effectiveness of compensating for distortion experimentally has been demonstrated in various studies [176, 177], where the distortion of turbine blades can be either computed by a simulation tool or measured from an optical 3D scan. The data of displacement are inverted and added to the model, and the results have shown that distortion can be corrected.

Based on the structure of the helical spring, four variables are considered in studying the distortion effect, including the number of coils, pitch, thickness and width of the joint. The range of variables should not cause compliance to be excessively strong or flexible. Otherwise, it will result in structural fracture or a reduction in

Table 5.1: The range of four parameters for the twist study

	Min value	Max value
Number of coils n	5	15
Pitch p (mm)	1.5	4
Thickness of coils t (mm)	0.5	1.2
Width of coils w (mm)	2	6

[†]The content of this section was presented as: W. Li, D. Zhang, G.Z. Yang, B. Lo, “Design and Modeling of A Spring-Like Continuum Joint with Variable Pitch for Endoluminal Surgery”, In 2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Kyoto Japan, Oct 23-27, 2022

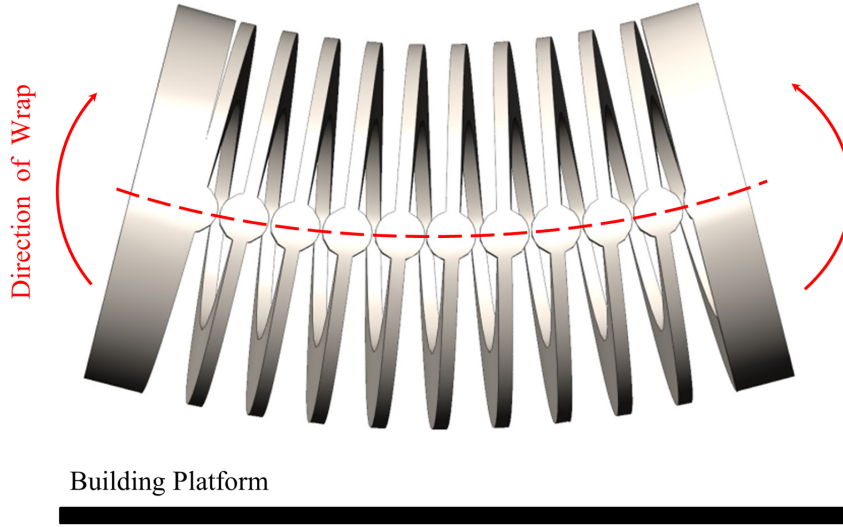


Figure 5.4: The sketch shows the wrap of the structure after printing. A curved bending plane is labelled.

the maximum bending angle of the spring. The range of the parameters for the test is listed in Table 5.1, predicated on the design specifications from the previous section 3.2.1.

5.3.3 Defect: Wrap

The wrap is another primary defect caused by residual stress and has been investigated in several research works [178]. The effect on the proposed joint can be viewed from Fig. 5.4. The geometry experiences a distortion pattern that both far ends tilt up along the building direction, characterised by the compression strain accumulated layer by layer. This issue can be addressed by choosing an appropriate supporting direction, such that the bending plane is placed parallel to the printing surface. And the stress is intended to be relieved after a few working cycles.

In addition, the residual stress restored in the proposed spring-like design can be mitigated through post heat treatment. As demonstrated in [179, 180], a stress

relieving method at a temperature of 900°C for 2 hours can not only effectively remove residual stress but also increase fatigue strength. Heat treatment should be conducted prior to removing the supporting structures, since the restored energy of residual stress in the geometry will be released after changing the constrained conditions. An alternative solution is to design with simulation tools. The mathematical model constructed using the finite element method allows the parts to be qualified and compensated before printing. An artificial intelligence-based algorithm based on a data-driven statistics approach has been proposed and validated to mitigate thermal distortion [181]. However, these methods will significantly increase the time required for either pre-process or post-process sections.

5.3.4 Defect: Deformation

When designing coils with low pitch and thin thickness, a Z-shaped discontinuous structure can be observed near the top surface of the structure. As shown in Fig. 5.5(a), this discontinuity is located tangent to the upper side of the internal channel, and it affects the self-supporting structure above the defect, leading to cracks and reducing fatigue life. The main reason is still attributed to residual stress. During the printing of the bottom structure, some residual stress is released, causing deformation in the direction of the falling pitch. Unlike the defects mentioned in the last two sections, this deformation cannot be resolved through post-processing, as the residual stress permanently alters the structure of printed parts.

To enhance printing quality, additional supports can be added prior to the printing process. The support structures is usually added to prevent vertical failure, and the prevention of deformation along the horizontal direction is not considered. Also, it should be strong enough to stand against the residual stress while be easily removed and not damaging the flexure of the spring mechanism. The design of horizontal supports comes with a tear strip shape can be viewed from Fig. 5.5(b). An example of the specifications can be given as

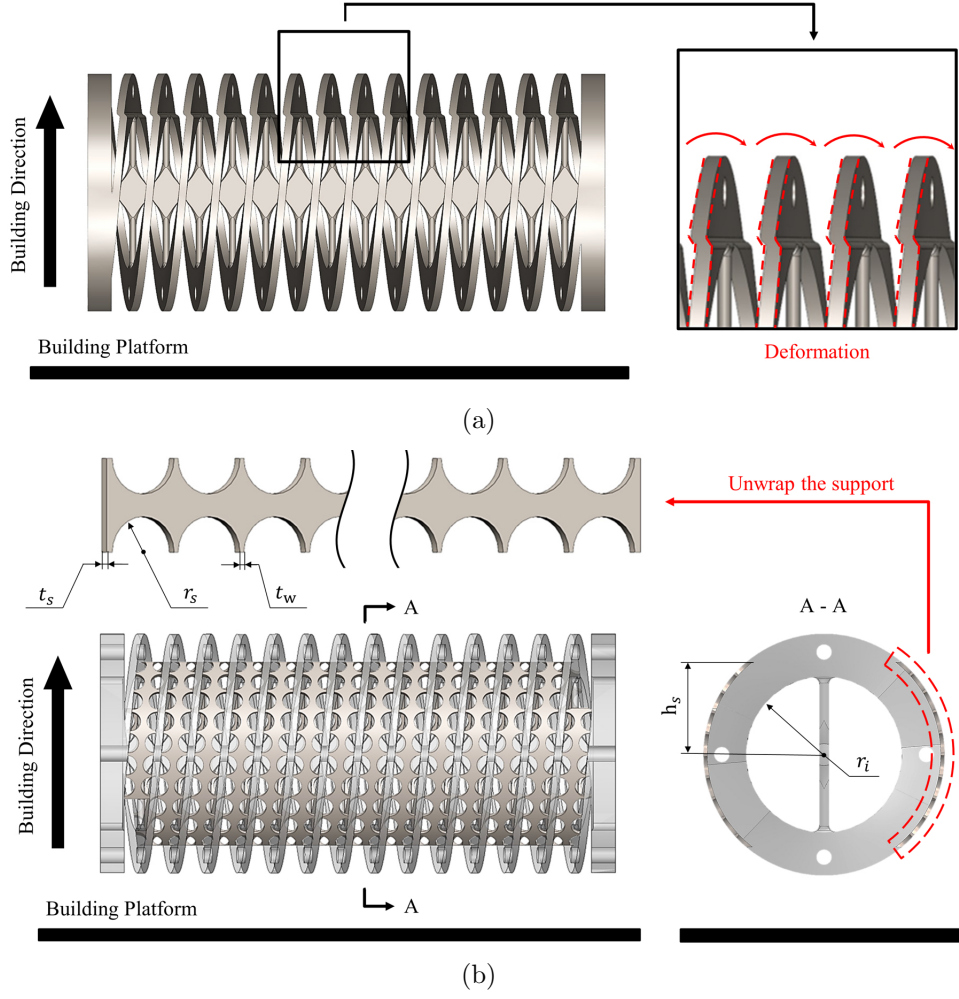


Figure 5.5: The sketch shows the deformation generated during the printing process. (a) The defects occur on the upper side of the joint. (b) The solution for preventing deformation with additional supports.

$$t_s = 0.15 \text{ mm} \quad (5.3)$$

$$t_w = 0.07 \text{ mm} \quad (5.4)$$

$$r_s = 0.54 \text{ mm} \quad (5.5)$$

$$h_s - r_i > t_w + 2r_s \quad (5.6)$$

where t_s and t_w are the thickness and width of the supports respectively. The protection by this supporting structure can also be viewed after the printing process;

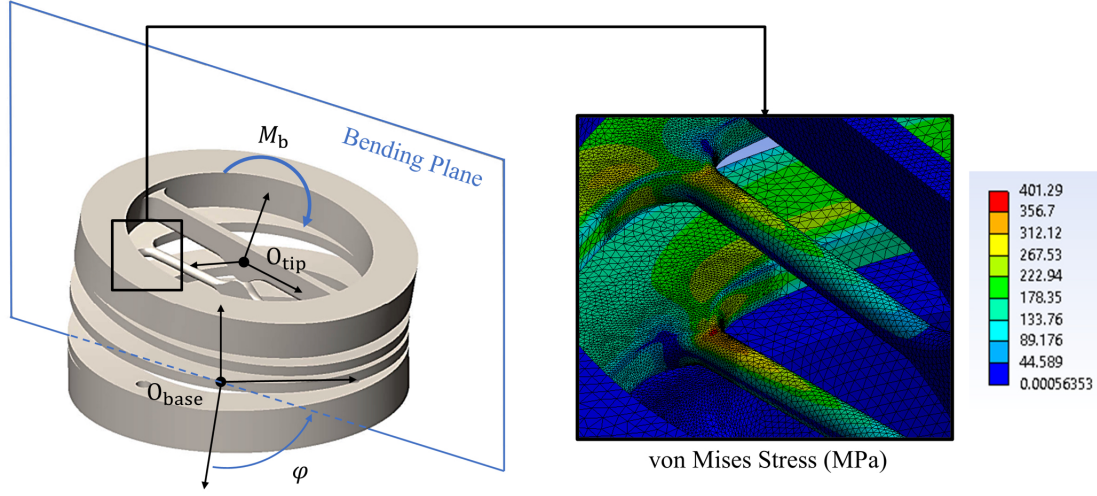


Figure 5.6: The sketch for heterogeneous bending test with $\varphi = 90^\circ$. The zoomed view shows the place with maximum stress.

when the joint is removed from the building platform, the joint can be kept away from the damage of the torsional force and peeled off afterwards.

5.4 Results and Discussion

5.4.1 FEA: Heterogeneous Bending

With the introduction of support beams and ball-shaped contacts in the design, two independent helix springs are connected as one part attributing to the bending motion. The structure shows a non-symmetric geometry to the bending planes, except for two orthogonal planes that coincide with the neural axis. This characteristic will lead to asymmetric bending stiffness around the central axis, resulting in heterogeneous bending performance. The analysis is performed with a single coil model as shown in Fig. 5.6. The contour plots present the results of bending angles and Maximum von Mises stress under a series of tip moments on a sample with a single revolution. The radial axis indicates the magnitude of the moment M_b , ranging from 0 to 36 N·mm, and the angular axis represents the angle of moment applied around the central axis φ , increasing from 0 to 360° .

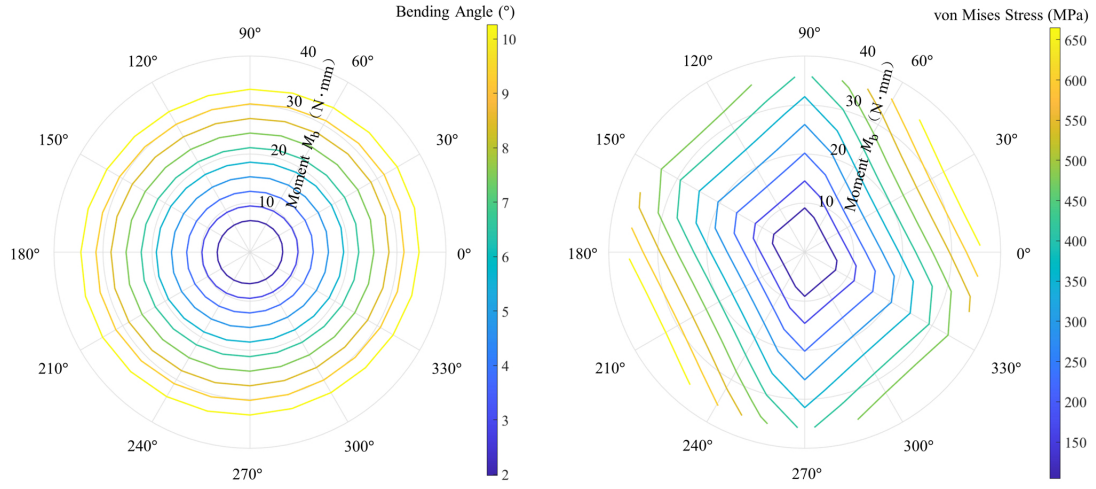


Figure 5.7: The contour plots of a bending joint around the z-axis. (a) Deformation (b) Maximum von Mises Stress

As shown in Fig. 5.7, the results of the bending angle show an elliptical shape, with the major and minor axes occurring around 15° and 135° respectively. In contrast, the results from stress analysis are not continuous and significantly fluctuated, the highest and lowest value locate at 45° and 105° respectively. To be more specific, with the maximum input moment, the difference in bending angle is only 0.55° ; however, a difference of 326.15 MPa in stress can be observed. The main reason can be concluded as the maximum stress concentrated at two ends of the supporting beam rather than the coils of spring. This heterogeneous performance has no significant effect to the kinematic control framework; however, this should be considered when the shape is estimated based on a mechanic framework. In most situations, the joint can reach 11 degrees bending angle without exceeding the ultimate stress value, which means at least 8 revolutions of coils are needed to reach the required 90° bending capability in each segment. The high stress on the supporting beams is mainly caused by the bending behaviour. Although the values exceed the ultimate value, it might not lead to the break of structure since only occurs at the top and bottom surfaces. In future work, the cross section of the supporting beam can be optimised to minimise the stress concentration.

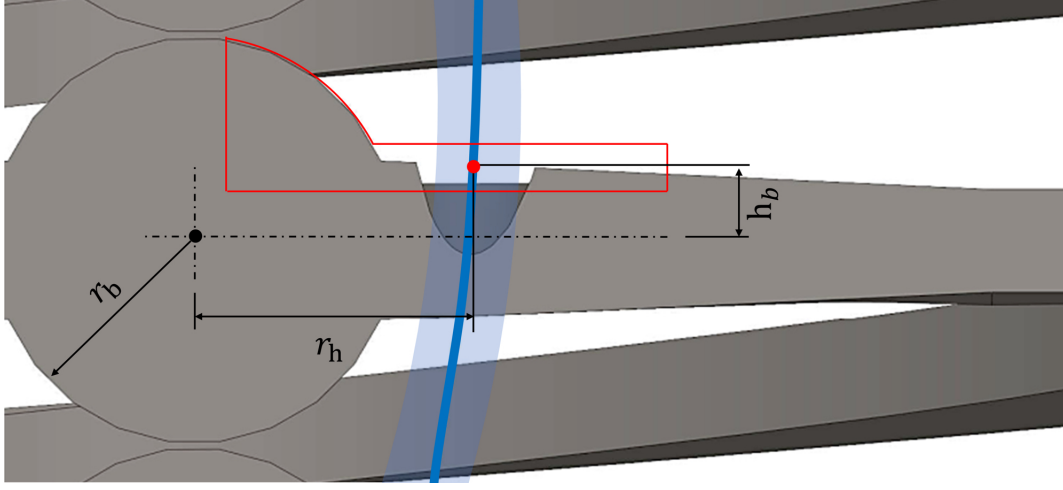


Figure 5.8: The sketch for the simulation of helical routing. The possible design combined with crucial parameters is studied, and the tip of a channel (red dot) can be located in the marked area.

5.4.2 Helical Routing Simulation

To investigate the variation of tendon length in the proposed helical channel design, a model is constructed based on the geometric relationship of ball contacts as shown in Fig. 5.8. The helical channels can pass through the side of ball-shape contacts or locate on the supporting beams with a bore structure. Also, a pure rolling motion is assumed between each neighbouring contact. Based on the structure of double helix coils, the radius of ball contacts can be three options: $p/4$, $3p/8$ and $p/2$, with a given value of pitch $p = 3.6$ mm, the values are 0.9 mm, 1.35 mm and 1.8 mm respectively. When $r_b = 1.35$ mm, the supporting beams should be crossly arranged. When the number of revolutions is chosen as $n = 9$ and with the maximum bending angle around 90° , the results of tendon variation passing through the helical channel in one segment can be shown in Fig. 5.9.

The findings of the empirical study reveal that the height of the guiding channel, h_b , is a crucial factor in the accuracy of the ball shape contact system, with a higher value of h_b resulting in a significant increase in errors. Conversely, the radius of the helix for the guiding channels, r_h , has a positive correlation with accuracy, as a larger radius leads to less error; however, it may also lead to an increased torsional load and transmission loss simultaneously. Furthermore, the

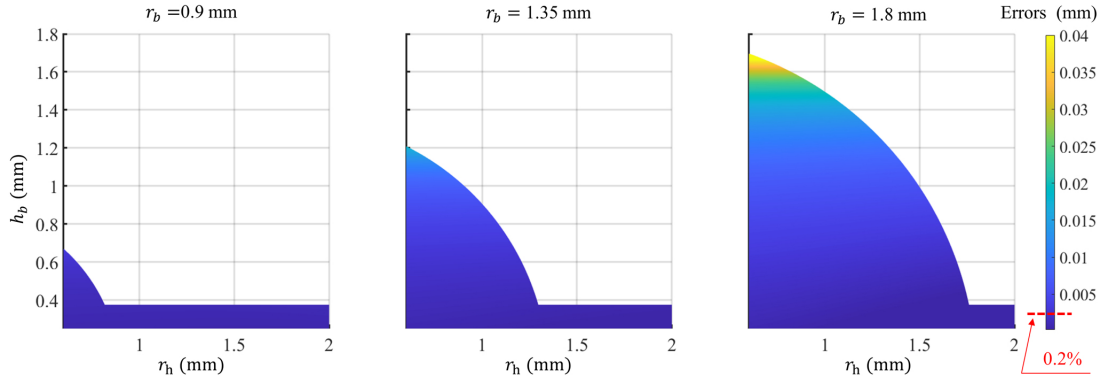


Figure 5.9: The variation of tendon length with different specifications of helical channels. (a) $r_b = 0.9$ mm (b) $r_b = 1.35$ mm (c) $r_b = 1.8$ mm.

radius of the ball, r_b , has a detrimental effect on the accuracy of the system, with higher values of r_b taking over more internal space for instruments and resulting in increased errors. The overall results show that the total length of helical channels will be slightly longer, except for a few results at the bottom right with $r_b = 1.35$ mm and 1.8 mm. This change in length can be compensated with elasticity from the tendon itself. However, the amount of tension should be kept less than the value of 0.2% to prevent permanent plastic strain occurs on the tendons. This simulation emphasizes the importance of balancing the design parameters such as h_b , r_h , and r_b in order to achieve optimal accuracy and performance by merging helical routing into ball shape contacts design.

5.4.3 Twist Compensation Result[†]

To measure the twist angle of the proposed continuum joint with different configurations, the number of coils, pitch, thickness and width of the coils are used as the independent variables in the experiments. During all the experiments, the outer diameter of the joint is fixed to 15 mm. The twist angles of the joints are measured from the top view of the joints, where the bottom is fixed on a calibrated reference

[†]The content of this section was presented as: W. Li, D. Zhang, G.Z. Yang, B. Lo, “Design and Modeling of A Spring-Like Continuum Joint with Variable Pitch for Endoluminal Surgery”, In 2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Kyoto Japan, Oct 23-27, 2022

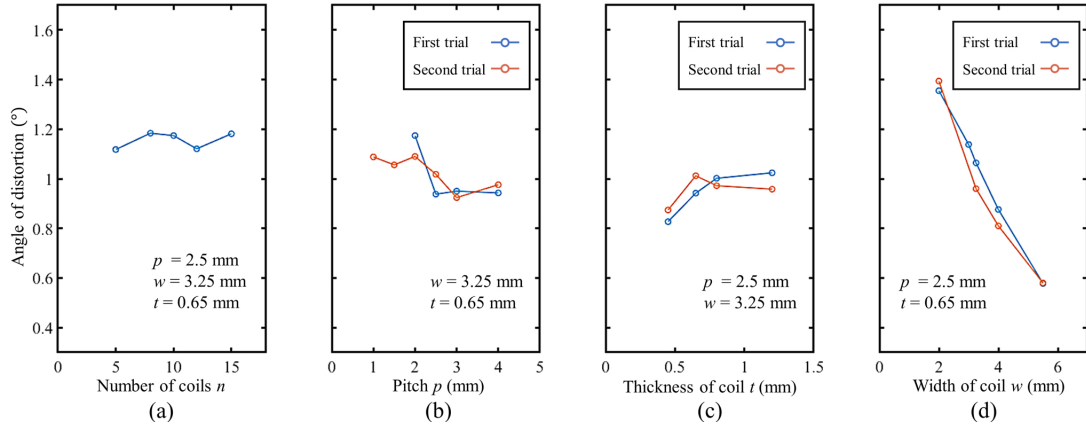


Figure 5.10: Distortion measurements on the samples with different configurations. (a) The number of coils. (b) Pitch. (c) The thickness of the coils. (d) Width of the coils. The first and second trials were finished with the different numbers of coils ($n = 10$ and 5 respectively.)

plane; thus, the differences between the tip and bottom can be calculated.

As shown in Fig. 5.10, the change in width significantly influences the distortion. When the width of the coils increases from 2 mm to 5 mm, the angles of distortion drop from 1.355° to 0.578° . The angles of distortion slightly increase when the thickness of the coil is decreased from 1.2 mm to 0.4 mm. A similar result can be seen in Fig. 5.10(b), where the angles of distortion improve by 0.1° when the pitch is increased from 1 mm to 4 mm.

Since the number of coils has no contribution to the distortion, the twist angle is determined solely by the specifications that affect its stiffness. As illustrated in Fig. 5.10, the higher stiffness of a spring mechanism usually incorporates a stronger structure, such as a thicker and wider cross-section shape of the coil, thus, the smaller effect caused by the residual stress can be observed after printing. Additionally, the structure with high stiffness also mitigates the effect of deflection under external load. Nevertheless, higher stiffness results in greater stress on the inside of the coil, which increases the risk of structural failure and reduces the fatigue life of the joint. Although the measured data shows consistency, it cannot be overlooked that some of the results fluctuated in different trials. The possible reason might be that the excessive forces applied to the structures lead

to deformation, when the structures were removed from the building platform, particularly for the spring mechanisms with less stiffness. To address this issue, wire-EDM processing can be considered as an alternative solution to remove the supporting structures.

5.5 Summary

In summary, a design variation is introduced to improve the flexibility of the bending joint. By positioning the ball-shaped contacts at the central axis, the motion of the joint can be increased to 2-DoF. The bending performance, which exhibits heterogeneity due to the asymmetric structure around the central axis, has been extensively studied through FEA. Notably, a single subsection of the joint can reach up to 11° without exceeding the ultimate stress. To resolve the issue of cross-talk in a design involving multiple actuating tendons, a proposed solution is to implement the helical routing method near the central axis. The possibility of this method has been validated with a simulated model. It is important to select key parameters to ensure that tendon length variation remains below its elastic limit of 0.2%.

Apart from using the traditional heat treatment in post-processing, some solutions are given to overcome the defects caused by residual stress. The wrap on the ends of the printed parts is the most common issue that can be solved by adjusting the orientation during the printing process. The bending plane of a 1-DoF joint should be aligned parallel to the building platform. Moreover, an experimental method is employed to eliminate the twist generated during the fabrication process; the results can help the correlation and compensation of design. Finally, the preparation of additional supporting structures can prevent the occurrence of deformations and ensure better structural integrity.

Chapter 6

Modification with Variable Pitch Design[†]

6.1 Introduction

As described in the previous chapter, several technical challenges remain unsolved for flexible robots with continuum joints. For example, the controllability and predictability of the joints shall be improved, since any errors on the root will be accumulated and amplified at the distal end, especially for a serially connected multi-segment robot. Although integrating advanced control algorithms can actively enhance the control of the continuum robots, it is more effective to solve the fundamental issues by improving the mechanical design, after which the inaccurate motion can be compensated. No sensor will be needed for shape estimation while the control algorithm can be simplified.

The work in this chapter focuses on optimising the design of a continuum joint with a helical spring structure, where the flexibility and scalability of this metal

[†]The content of this chapter was presented as: W. Li, D. Zhang, G.Z. Yang, B. Lo, “Design and Modeling of A Spring-Like Continuum Joint with Variable Pitch for Endoluminal Surgery”, In 2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Kyoto Japan, Oct 23-27, 2022

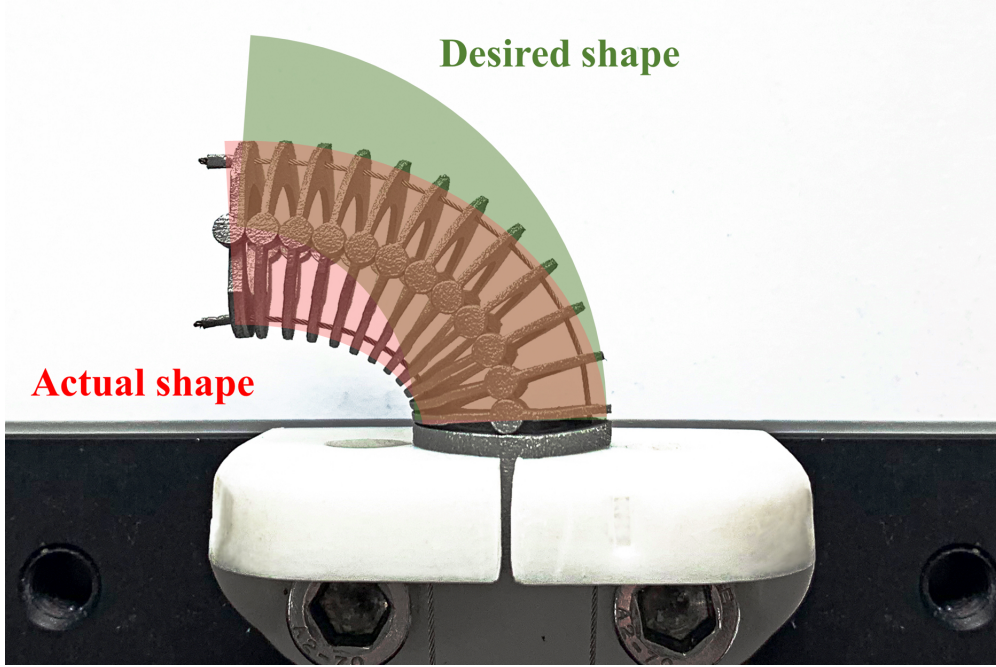


Figure 6.1: Discrepancy due to manufacturing variation. The difference between the actual bending shape of the joint and the desired shape is estimated from the constant curvature model.

printed continuum design have been validated with diameters in 7 mm [182], 9 mm [170] and 15 mm (Chapter 3). Spring-like continuum joints have attracted much attention recently. A novel helix-based structure has been proposed while a mathematical model has been developed to estimate the stiffness in [112]. Song *et al.* proposed a design with multiple helical segments and an optimised version was developed with refined structural parameters to get higher loading capacity [114]. However, the issue on how to reduce the position errors at large bending angles has not been addressed. Therefore, we aim to construct a kinematic framework that considers the friction between the guiding channels and tendons. The model will be used to inform the hardware design, which can be used to rectify the motion and fit the constant curvature model. Incorporating with the results from the last chapter, the undesired out-of-plane motion from manufacturing can be eliminated and the variable pitch design improves the in-plane position accuracy, especially for the continuum joint at large bending angles.

The main contributions of this chapter can be concluded as, based on the friction

model, a novel continuum joint design with variable pitch is proposed, thus the position errors in bending can be reduced with respect to a constant curvature model. The remainder of the chapter is organised as follows. In Section 6.2, I will present the design, modeling, kinematic, and control of the continuum joint with the variable pitch structure. Section 6.3 shows the experimental design and result analysis, followed by the discussion and the conclusion.

6.2 Problem Overview and Modeling

6.2.1 Problem Overview

Recall the constant curvature model presented in Eq. (3.1), the behaviour of a continuum joint can be described as follows: for a given bending angle, the curvature remains constant with respect to the arc length [144].

$$\frac{1}{\rho_\theta} = r(\theta, L) \quad (6.1)$$

where L is the effective length of the joint, θ represents the total bending angle of the joint, ρ_θ is the curvature at the given bending angle.

However, this kinematic model is insufficient to describe the behavior of a continuum joint in practical use without the improvement of the control algorithm. Previous research has indicated significant errors at large bending angles of the continuum joint when the constant curvature model is used [6]. The desired and actual bending shape for a spring-like continuum design is marked with red and green respectively as shown in Fig. 6.1. Compared with the desired shape from the constant curvature model, the non-uniform bending curvature has a much larger radius at the distal tip than that at the proximal end. The transmission loss along the joint body can be attributed to the friction between pulling tendons

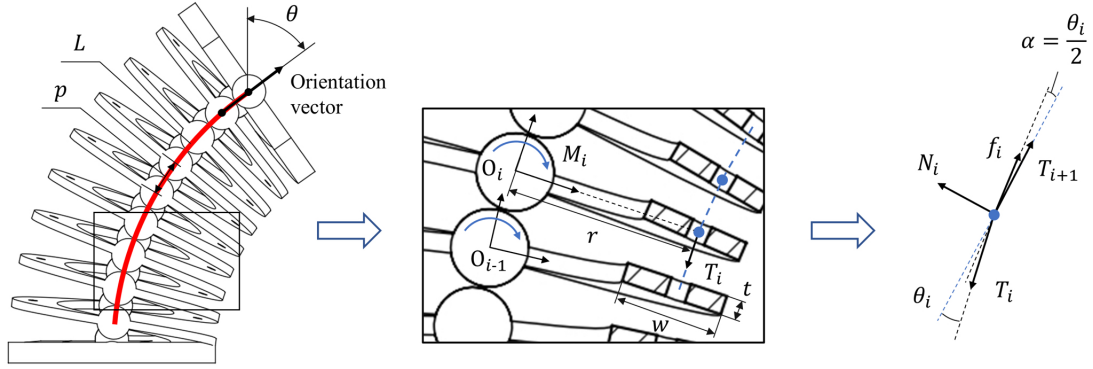


Figure 6.2: The sketch of a continuum joint under a bending condition. Left: the bending status of the joint. Middle: the free body diagram in a magnified view. Right: the diagram of cable at coordinate O_i . L is the effective length of the joint, θ represents the total bending angle of the joint, p is the pitch of the helical structure. T_i is the articulated tensions on tendons and r is the distance from the guiding channels to the central axis. M_i is the bending moment of the i th subsection of the continuum joint.

and guiding channels, which inspired the idea of this work that the non-uniform stiffness on the spring structure might cancel out the effect of friction.

6.2.2 Kinematics and Modeling

Based on the geometric relationship shown in Fig. 6.2, a static model is developed for the continuum joint, where the joint is discrete to a number of subsections with respect to the total number of coils n . By employing the constant curvature assumption, the bending angles between adjacent subsections can be assumed to be equal. Therefore, the relationship between θ and α can be obtained as follows

$$\theta = n\theta_i = 2n\alpha \quad (6.2)$$

Suppose that the bending moment of the i th subsection of the continuum joint is M_i . T_i is the articulated tensions on the tendons, and r is the distance from the

guiding channels to the central axis. M_i can be calculated as follows.

$$M_i = T_i r \cos \theta_i \quad (6.3)$$

The propagation of tensions can be determined by Eq. (6.4) and Eq. (6.5).

$$T_{i+1} \cdot \sin \alpha_i + T_i \cdot \sin \alpha_i = N_i \quad (6.4)$$

$$T_{i+1} \cdot \cos \alpha_i + f_i = T_i \cdot \cos \alpha_i \quad (6.5)$$

where N_i indicates the normal force generated at the middle of the guiding channel, f_i is the steady-state friction force generated between the guiding channels and tendons, as illustrated in Fig. 6.2. The relationship of f_i and N_i can be expressed by Eq. (6.6).

$$f_i = N_i \cdot \mu \quad (6.6)$$

where μ is the equivalent friction coefficient, the value of μ can be determined through calibration. Combining the Eq. (6.4)- Eq. (6.6), the relationship between T_{i+1} and T_i can be obtained as follows:

$$T_{i+1} = T_i \frac{\cos \alpha_i - \mu \sin \alpha_i}{\cos \alpha_i + \mu \sin \alpha_i} \quad (6.7)$$

The deflection of a spring-like structure under axial loading can be identical to a cantilever beam model (the wire of spring) under bending and torsion, and the angular deflection can be calculated by

$$\theta = \pi M r_m \left(\frac{1}{EI} + \frac{1}{GJ} \right) \quad (6.8)$$

where r_m is the mean coil radius and M is the bending moment applied on the tip. EI and GJ are two constants that denote the flexural and the torsional rigidities respectively related to the cross section of the coil. Considering the curvature in

bending status, the equation can be formulated as

$$\frac{1}{\rho} = \frac{\theta}{p} = \frac{\pi M r_m}{p} \left(\frac{1}{EI} + \frac{1}{GJ} \right) \quad (6.9)$$

where p is the pitch of the helix structure. According to Eq. (6.7), the tension decreases when it propagates from the proximal end to the distal tip of the joint, thus, causing the reduction of bending moment M_i .

To maintain the constant curvature, the bending stiffness of the joint should be proportional to the bending moment. This can be achieved through modifying the shape of cross section or pitch. The variation of the pitch in each subsection is more straightforward and the value at the joint tip after passing through i th subsections can be calculated by Eq. (6.10).

$$p_i = p_1 \left(\frac{\cos \alpha_i - \mu \sin \alpha_i}{\cos \alpha_i + \mu \sin \alpha_i} \right)^i, \quad i = 2, 3, \dots, n \quad (6.10)$$

As we can see from the equation, μ and α_i cannot be determined during the design process, where μ should have a constant value and can be calibrated by experiments. For the bending angle related variable α_i , an assumption can be made that the improvement made at large bending angles would benefit the bending behaviour at smaller bending angles, therefore, a constant value $\alpha_i = \theta_{max}/2n$ is used. Finally, the variation of the p_i at each subsection can be given, where the length of pitch and size of the rolling contacts will gradually decrease from the end to the distal tip of the joint.

6.3 Experiments and Results

Two experiments were conducted to investigate the accuracy in the proposed variable pitch design, and a prototype with a multi-segment design was fabricated to evaluate the effectiveness of the proposed model and design.

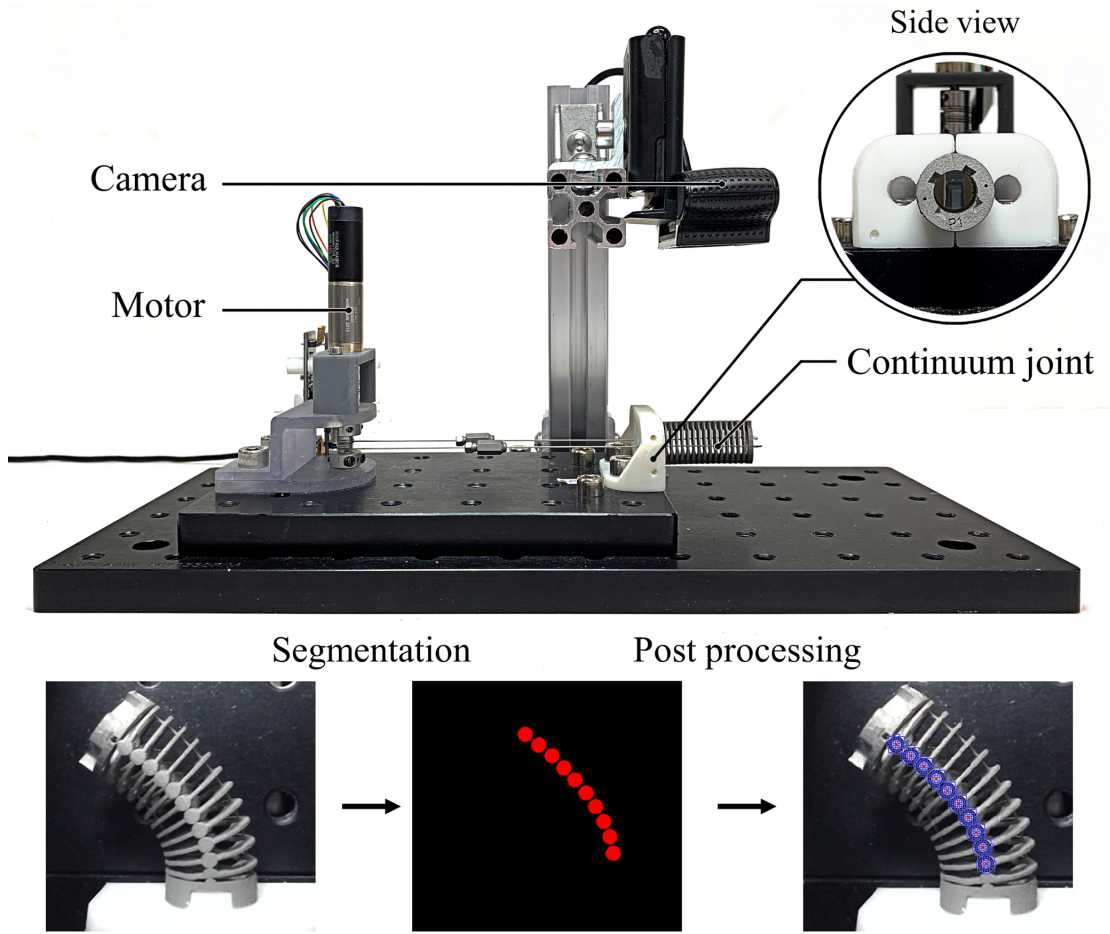


Figure 6.3: Experimental setup. The bending motion will be recorded from the top view. The vision-based method is illustrated at the bottom.

6.3.1 Experimental Setup

The experimental setup is shown in Fig. 6.3, which is used to record the bending motion of the joints. The continuum joints are connected through the tendon-capstan mechanism and actuated by a brushless DC motor (Faulhaber), while the bending angle is captured by a webcam (Logitech c920). The webcam was set up such that the image plane is paralleled to the bending plane. Since we only analyse the one DoF motion in the horizontal plane, we assume that gravity along the Z-axis is not a factor that may influence the kinematic results.

6.3.2 Vision-based Tracking

To compare the differences between the constant curvature model and the motion of the proposed design, it does not only require the tip position, but also its pose information along the joint body; therefore, the sensor-based methods are too complex for the task. With a vision-based method called U-net, the circular features can be extracted from the structures of rolling contacts on the continuum joint. U-Net is a convolutional neural network that has been used for image segmentation, which stems from a fully convolutional network [183]. It has a U-shaped architecture, formed by a contracting path and an expansive path. The spatial information is reduced while feature information is increased in the contracting path. After contraction, a sequence of up-convolutions and concatenations are used to combine the feature and spatial information in the expansive pathway.

The side view of the joints can be captured by the RGB camera in the test rig, while U-Net can be employed to segment the continuum joint in the image frames. Following that, the centres of the circular rolling contacts can be identified and extracted with Matlab using the Hough transform, and the shape of the continuum joint can be estimated. As the last half revolution of the coil is not actively contributed to the bending of the joint, the orientation of the joint can be determined using the top two rolling contacts. By connecting the centre of circles, the direction vector can be found and is shown in Fig. 6.2.

6.3.3 Variable Pitch Design Based on a Friction Model

To analyse the bending motion of the original design and the proposed design with variable pitch, this experiment was conducted with three designs where $\theta_{max} = 90^\circ$, $p_1 = 3$ mm, and $\mu = 0, 0.2$ and 0.3 respectively. The design is shown in Fig. 6.4, which highlights the differences reflected in the sizes of the rolling contacts. The in-plane motions of the joints are obtained using the vision-based tracking approach described in section 6.3.2 for results analysis. The tip errors between the

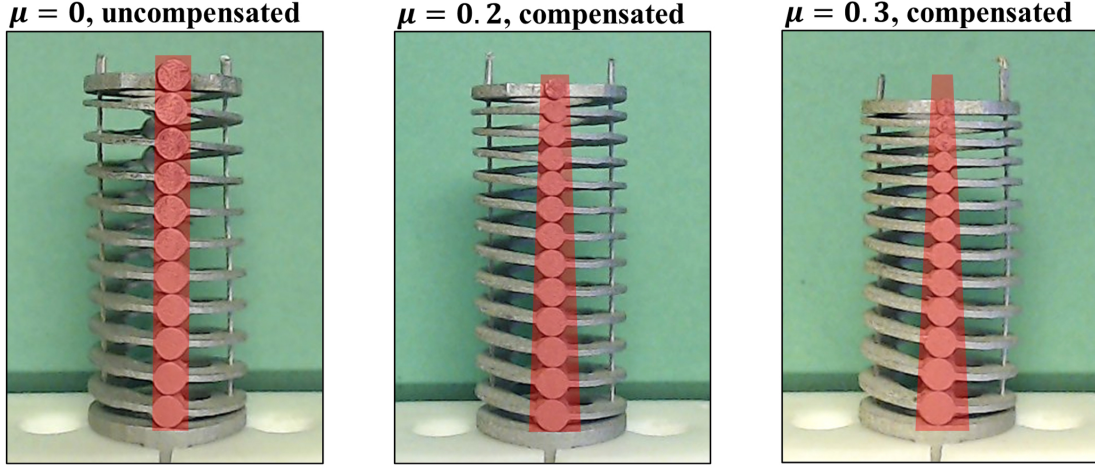
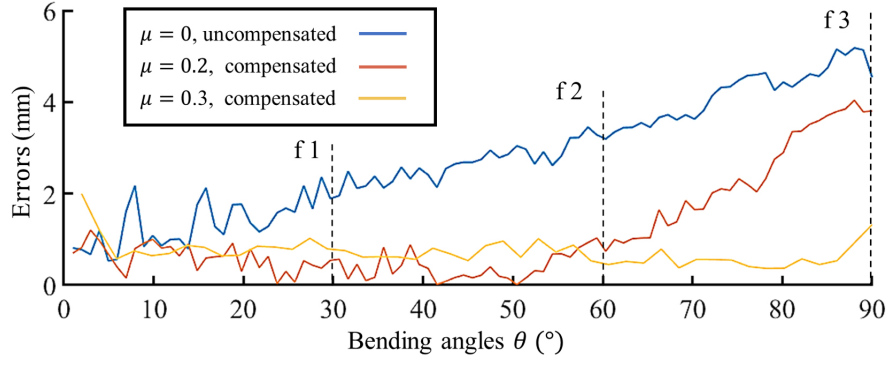


Figure 6.4: Test samples. Three samples were used in the test where the left one has a constant pitch and the others have variable pitch design.

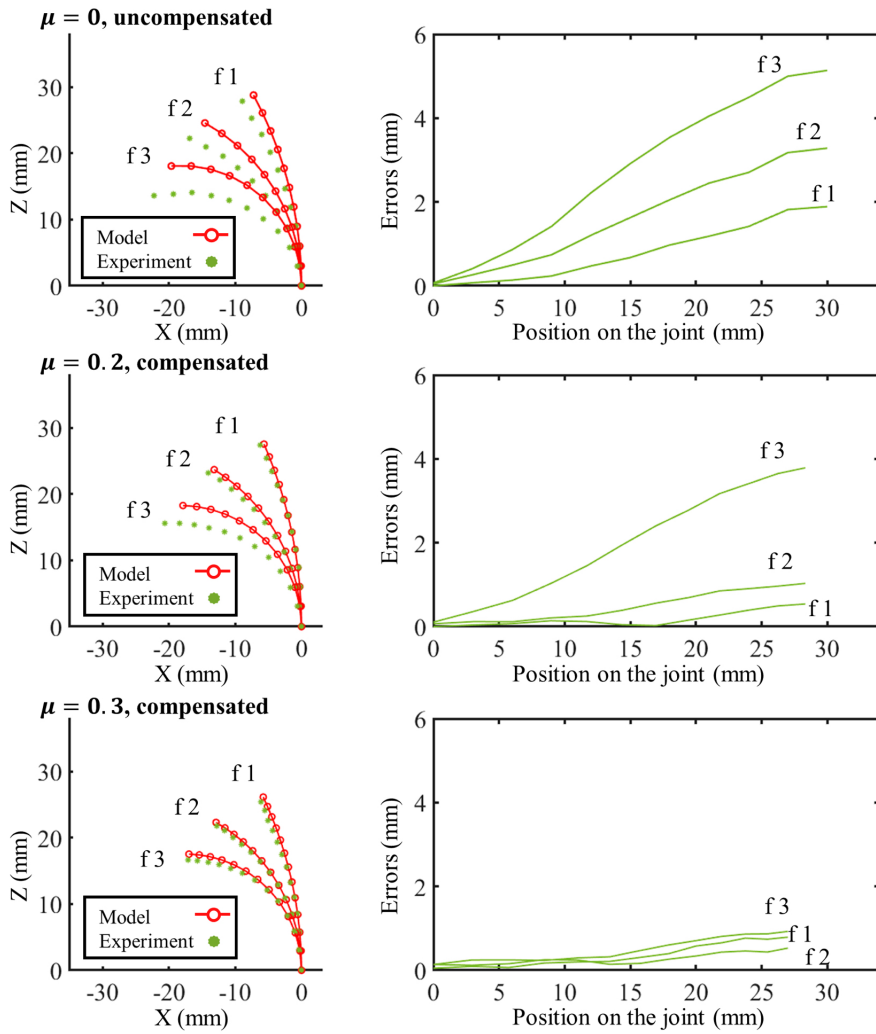
experimental data and the mathematical model are shown in Fig. 6.5(a). More significant errors can be observed as the bending angle increases from 0° to 90° . To be specific, the motion at three frames with bending angles 30° , 60° and 90° are plotted in Fig. 6.5(b). The errors corresponding to the rolling contacts increase from the bottom to the tip of the joint, and grow with a higher gradient near the middle of the joints. The error of the original design with constant pitch reaches the peak of 5.13 mm, representing 18.10% of its effective length. By contrast, the errors are significantly reduced when variable pitch design is used. When $\mu = 0.3$ is used for the design, the errors keep at small values at all the bending angles, the value of which is 1.32 mm at 90° , representing 4.63% of its effective length.

6.3.4 Accuracy Test

In this experiment, a prototype was developed by serially connecting two continuum joints. The two-segment robot was set to follow different circular tracks with different radii to verify its effectiveness for potential applications in GI surgery. Because the robot will not only move in the plane, the spatial information of the rolling contacts is hard to be tracked via the vision-based method. A micro Electro-Magnetic sensor (Aurora 6-DoF sensor) was used for position tracking,



(a)



(b)

Figure 6.5: Comparison results between the simulation and experiments, where $p_1 = 3$ mm. Top: the errors between recorded data and the constant curvature model. More details for three frames (f1 - f3) are shown in (b), where the motion of joints (left) and errors from the proximal end to the distal tip (right) can be viewed.

where the sensor was mounted with a plastic adaptor on the top of the joint. Hence, the errors caused by metallic materials from the printed joint can be minimised. The comparison will be given between two types of joints, the original design with constant pitch and the proposed design with variable pitch respectively (Fig. 6.6), following the specifications summarised in Table 6.1. Because of the modified design features with variable pitch design, a different number of coils are selected to maintain similar free lengths at the spring section, minimising the influence of cumulative errors along the length. Based on the result from the previous section, the friction coefficient can be identified as 0.3.

In the experiments, the radius of the circular tracks ranged from 13 mm to 25 mm and three tests was performed for each radius. Fig. 6.7(a) shows an example of the comparison between the desired circular trajectories and the measured tool tip trajectories obtained in one of the experiments. Also, the mean errors and standard deviations for each test are calculated and shown in Fig. 6.7(b) and Table 6.2. Better results can be observed in the modified design, where the mean value is close to the desired radius and the standard deviations are half about the values of the original design.

Table 6.1: Specifications of the multi-segment designs

	Original design	Modified design
Pitch p_1 (mm)	3	3 to 1.625
Outer diameter (mm)	15	15
Thickness t (mm)	0.65	0.65
Width w (mm)	3.25	3.25
Friction coefficient μ	0	0.3
Number of coils n	10	12
Total length (mm)	69.5	69
Twist compensation	No	Yes

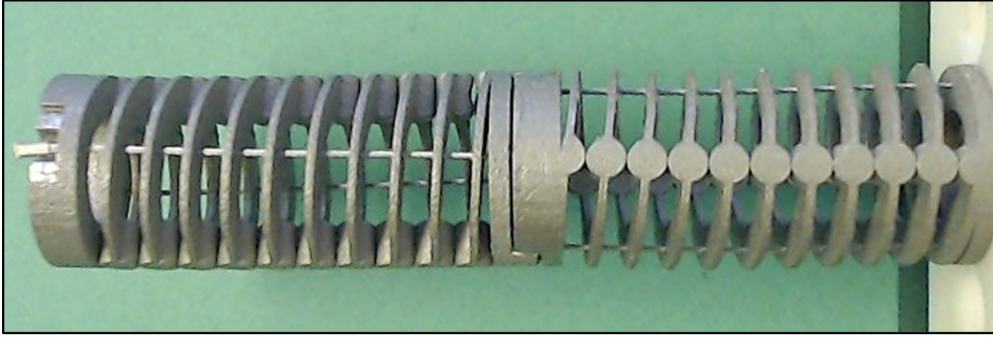
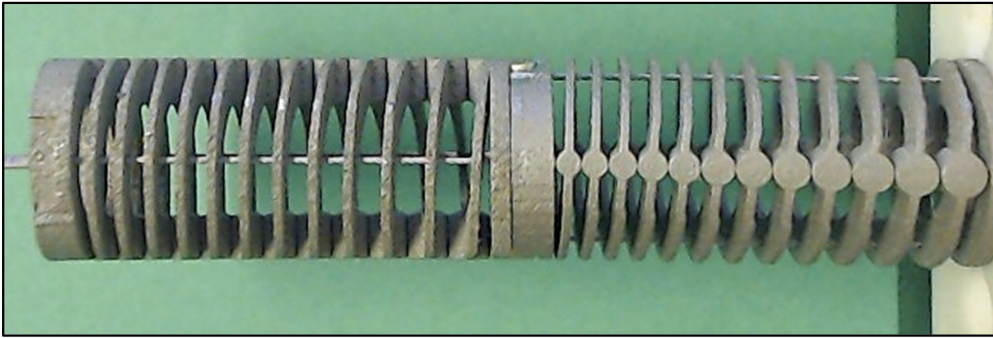
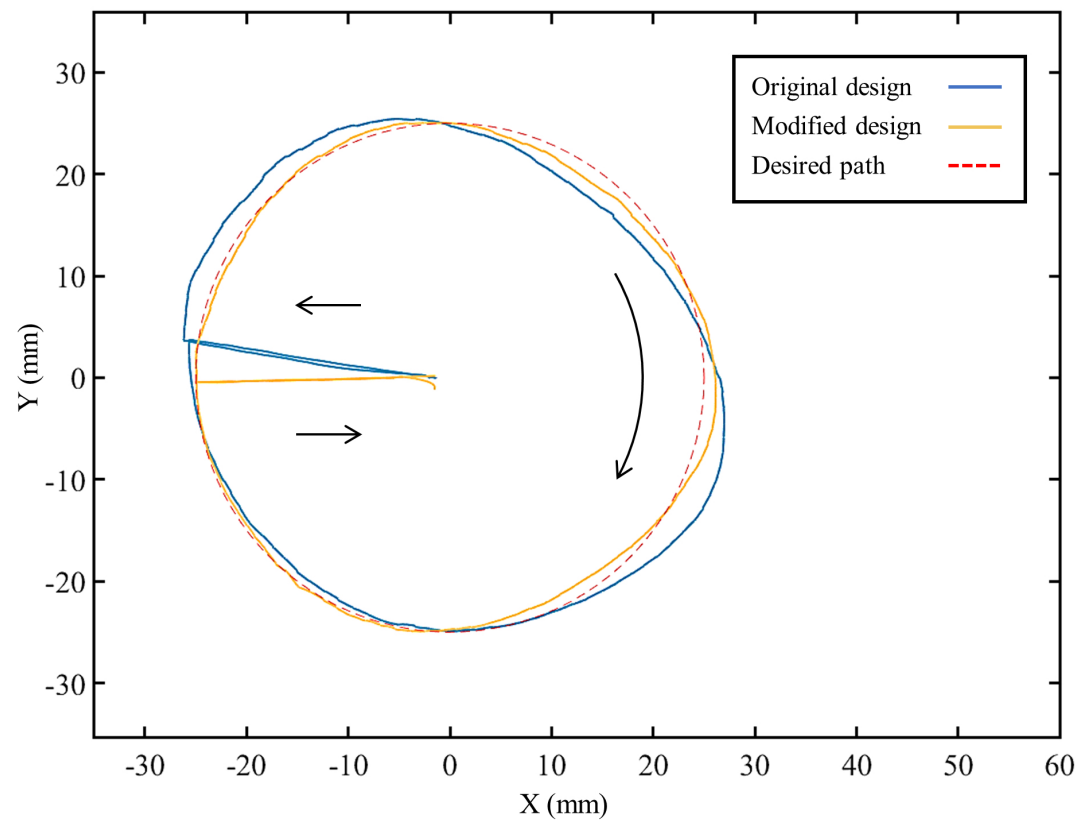
Original design**Modified design**

Figure 6.6: The original and modified designs were used in the accuracy test, and both of them have two segments connected orthogonally.

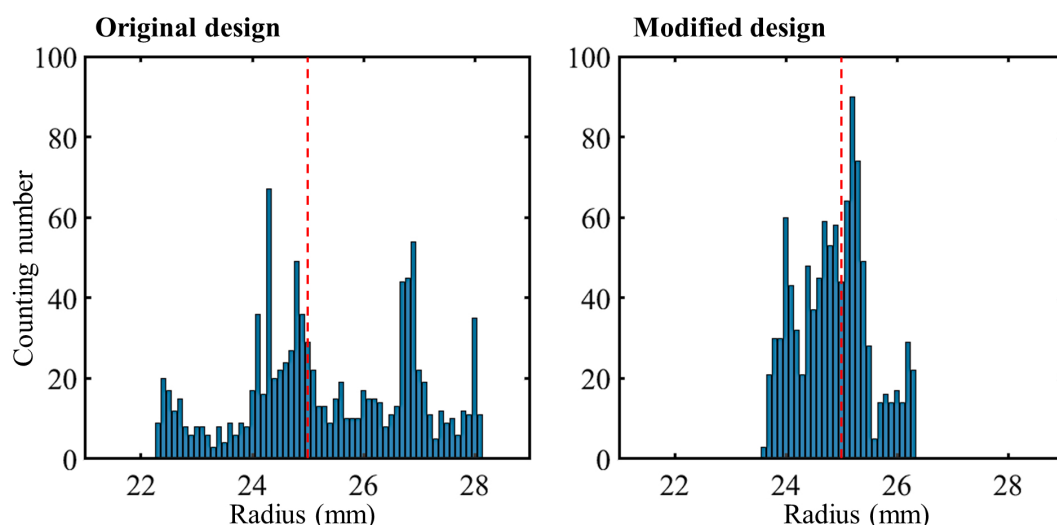
6.3.5 Repeatability Test

To further assess the performance and reliability of the proposed design, a repeatability test was conducted on the two-segment robots for the original and modified designs. During this test, both robots were subjected to following a circular track multiple times, with a radius of 25 mm.

The results of the repeatability test are shown in Fig. 6.8. The comparison between the two designs is evident, with the modified design demonstrating superior performance. Consistent with the results from the previous accuracy test, the peak values of averaged errors on the modified design are only half of those observed on the original design (± 1 mm vs. ± 2 mm). These errors occur between $1/2\pi$ to π and π to $3/2\pi$ of the process. Although the mean position errors fluctuate during the test, the deviation between the two groups exhibits consistency and remains at low values along the track (indicated by the red areas). The maximum values



(a)



(b)

Figure 6.7: Experimental results for the accuracy test. (a) The projected trajectories on X-Y plane. The desired radius is 25 mm. (b) The distributions of the radius for the path.

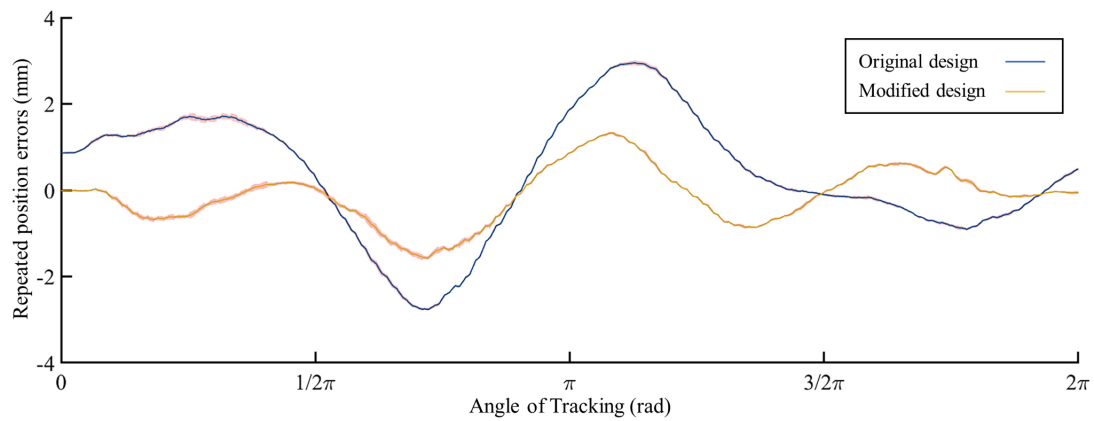


Figure 6.8: The repeatability errors follow the circular track with 25 mm radius.

recorded for original and modified design are 0.09 mm and 0.10 mm, respectively.

Table 6.2: The statistic results with different radius.

Desired radius (mm)	Test number	Original design		Modified design	
		Mean	Std.	Mean	Std.
25	1	25.37	1.46	24.86	0.72
	2	25.40	1.46	24.87	0.74
	3	25.33	1.39	24.90	0.73
	Aver.	25.37	1.47	24.88	0.73
21	1	21.95	1.19	21.63	0.60
	2	21.95	1.19	21.66	0.56
	3	21.94	1.18	21.68	0.57
	Aver.	21.95	1.19	21.66	0.58
17	1	17.44	0.83	17.28	0.42
	2	17.43	0.83	17.29	0.44
	3	17.43	0.83	17.29	0.44
	Aver.	17.43	0.83	17.29	0.43
13	1	12.99	0.59	12.95	0.42
	2	13.00	0.60	12.94	0.43
	3	13.00	0.61	12.94	0.43
	Aver.	13.00	0.60	12.94	0.43

6.3.6 Discussion

When determining the specifications of the variable pitch design, an assumption was made that the improvement made at large bending angles would also benefit its bending behaviour at relatively smaller bending angles. Therefore, a constant value $\pi/2$ was chosen for the bending angle related variable α_i . As shown in Fig. 6.5(a), the tip errors are hardly identified below 20° and show a significant upward trend as the bending angle increases. With the modification of the variable pitch design, the tip errors become much smaller at large bending angles. The improvement can also be viewed in the multi-segment tests, where a reduction in the radius of the circular trajectory leads to reduced errors. Both test results demonstrate that the proposed method for the selection of α_i can improve the bending performance at all bending angles.

For a conventional spring-like continuum joint shown in Fig. 6.5(b), the subsections near the end of the joint tend to bend more than those near the tip of the joint. This is due to the fact that the variation of the tendon length has not been uniformly distributed to the subsections, resulting from friction between the guiding channels and the pulling tendons. However, the implementation of a variable pitch on the spring-like structure, with larger pitch values near the proximal end and gradually decreasing to smaller pitch values near the distal tip, results in a joint with a progressively reduced structural stiffness along its body. This design balances the bending angle at each subsection, minimising the errors accumulated from the end to the tip.

The accumulated errors are still present when the number of joints increases. As shown in Fig. 6.8, the peak errors on the original design are significantly larger than those on the modified design. These errors are primarily generated by the segment near the proximal end of the robot and are sequentially accumulated and magnified by the subsequent segments. It is worth noting that the original design cannot perform an enclosed circular path during the tests, possibly due to the hysteresis effect. This effect, which has been discussed in several works

[106, 184, 185], is considered to be another problem generated by friction between the joint body and tendons. However, no obvious hysteresis effect can be observed from the modified design when the friction model is implemented.

6.4 Summary

In summary, I proposed the design of a spring-like continuum joint with a variable pitch structure. The main target of the work was to reduce the bending errors when using the constant curvature model for control. Extensive experiments were conducted to compare the proposed design with the conventional spring-like continuum joints. Results indicated that the deviation of position errors at relatively large bending angles could be reduced from 5.13 mm to 1.32 mm with our proposed design, accounting for 18.10% and 4.63% of the effective length of the joint respectively. To further demonstrate its potential in surgical applications, a multi-segment prototype was developed, and the effectiveness and repeatability of the modified design was assessed in the circular tracks following task.

Chapter 7

Conclusion

7.1 Summary of Thesis Achievements

This thesis presented the works of designing a continuum joint with a spring-like structure for use in surgical applications, specifically in endoluminal surgery.

Firstly, the structure design of the flexible joint was investigated. Based on the constant curvature assumption, a geometric relationship between the bending angle and helix structure was constructed, which can serve as an initial estimation for selecting design parameters for different applications. To maintain the bending motion while eliminating undesired linear motion of the spring-like structure, a series of circular contacts can be used between the coils. The characteristics of the bending motion was further studied with FEA, conducting on the samples with single coil and different specifications. Aiming at the endoluminal surgery deep inside the patient's body, a preliminary design of a flexible robot was developed with a snake-like body. The robot has a 6-DoF motion to conform to the natural path and a large central lumen can be maintained for passing endoscopic instruments. The manipulation of the snake-like robot was tested in a force test and a comparison between different platforms was given.

It can be viewed from the results that the insertion of such flexible robots into the lumen has difficulties. Although the active snake-like body can keep reducing excessive contact forces, the looping at the passive tube still causes discomfort to patients and reduce the control accuracy of the robot. To overcome this issue, I proposed a robotic endoscope design by adopting a spiral insertion technique. A novel actuation mechanism that can simultaneously rotate the endoscope shaft and control the bending angle of the joint. The proposed design was tested on a section of the intestine phantom, and the result showed its ability pulling itself into the phantom model, and the potential of clinical feasibility in a robotic endoscope design.

However, based on the findings from the previous chapter, it can be observed that the current design exhibits limited performance, particularly in terms of bending capability and accuracy. To address the first issue, a bio-inspired design based on the structure of DNA was proposed, which can achieve 2-DoF bending. To further investigate the issue of cross-talk in the multi-segment design, a method of helical routing near the central axis was introduced. This method was validated with a simulated model. Compared with theoretical values, the length of helical channels will be slightly lengthened; however, it should work properly when the elongated percentage is lower than 0.2% which is the elastic limit of the tendons' material. Furthermore, several solutions are proposed to overcome the defects caused by residual stress including wrap, twist and deformation. An additional supporting structure ensures better structural integrity during the printing process. And an experimental method was employed to eliminate the distortion generated during the fabrication process. The results can be used in the correlation and compensation of the design.

A modified design was proposed to improve the accuracy of the joint design. The tip position and orientation of the continuum joint cannot be kept as same as the model, the errors can be significant when using the constant curvature model solely. The main reason can be contributed by the friction generated between the tendons and guiding channels, therefore, a solution was proposed by modifying

the spring-like structure with a variable pitch design. Extensive experiments were conducted to compare our proposed design with the conventional spring-like continuum joints. Results indicated that the deviation of position errors at relatively large bending angles could be reduced significantly with the proposed design.

7.2 Future Work

Although the use of spring-like continuum joints has shown great potential in endoluminal surgery, there are still many challenges that need to be solved in future research.

For the design of the proposed joint, optimisation on the cross section of the coil needs to be investigated. A previous study in [186] has shown that the T-shape springs have greater torsional rigidity compared to the rectangular cross section. It also can be expected that the bending rigidity can be increased; thus, the joint may obtain the same mechanical properties with an increased proportion of channel area to the overall area. In addition, the joint design can be extended and tested on multi-segment prototypes with diameters ranging from 5 mm to 9 mm, which are the common sizes of endoscopic surgical instruments.

As described in the review section of this thesis, a continuum joint is characterised by infinite DoFs and a number of joints. The shape of the joint may not be well maintained under transverse loading when the bending plane or axis paralleled the tendons. It has validated in [115] that non-parallel tendon routing (or converging configuration) can significantly increase the stiffness along the entire length of a continuum joint. This solution can be considered as an option to constraint redundant flexibility, however, the antagonised tendon-driven configuration should be replaced by three tendon-controlled design.

To achieve more precise control of such a continuum joint, further investigation into modeling and control methods is necessary. In this work, only the static

model was investigated. However, in surgical applications, the control accuracy may be influenced by the contact between the surgical tools and the surrounding tissues in the lumen. Therefore, closed-loop and feedback control with real-time tip position tracking should be explored, especially when dealing with significant contact forces. This can be accomplished by applying multi sensors into the system. The shape of the endoscope can be monitored during the operation by using IMU, FBG or EM sensors. And the pressure sensors and force sensors can be enclosed externally on the endoscope to measure the contact forces.

Based on the research outcomes, it is evident that the development of a robotic endoscopic system requires the collaboration and efforts from different disciplines, such as mechanical design, automatic control, sensing, and image processing. The works presented in this thesis are expected to provide some ideas in designing a robotic endoscope and inspire the researchers to address the challenges faced by the current system.

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