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Huang, Yanpei

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DEVELOPMENT OF AN INTUITIVE FOOT-MACHINE INTERFACE FOR ROBOTIC SURGERY

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SCHOOL OF MECHANICAL AND AEROSPACE

ENGINEERING

2020

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SCHOOL OF MECHANICAL AND AEROSPACE ENGINEERING

A thesis submitted to the Nanyang Technological University in partial fulfilment of the
requirements for the degree of Doctor of Philosophy

2020

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution.

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I have reviewed the content and presentation style of this thesis and declare it is free of plagiarism and of sufficient grammatical clarity to be examined. To the best of my knowledge, the research and writing are those of the candidate except as acknowledged in the Author Attribution Statement. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

.....14 July 2020.....
Date

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Prof. Phee Soo Jay, Louis

Authorship Attribution Statement

This thesis material has been published in five peer-reviewed journal papers.

The content of Chapters 3 and 4 corresponds to the publication, Y. Huang, E. Burdet, L. Cao, P. T. Phan, A. M. H. Tiong and S. J. Phee. Subject-specific four-degree-of-freedom foot interface to control a surgical robot. *IEEE/ASME Transactions on Mechatronics* **25(2)**, 951-963 (2020). DOI: 10.1109/TMECH.2020.2964295.

The contributions of the co-authors are as follows:

- I designed the foot interface and performed the experiments, analysed the results and wrote the manuscript drafts.
- Prof. Phee and Prof. Burdet guided the project direction, provided the supervision and edited the manuscript drafts.
- The manuscript was revised by Dr Lin Cao.
- Phuoc Thien Phan, Anthony Meng Huat Tiong helped fabricating the experiment platform.

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The contributions of the co-authors are as follows:

- I prepared the experiment platform, designed and performed the experiments, analysed the results and wrote the manuscript.
- Prof. Phee and Prof. Burdet guided the project direction, provided the supervision and edited the manuscript drafts.
- The manuscript was revised by Dr Lin Cao and Dr. Pai Zheng.
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- I developed the robotic system and performed the experiment, analysed the results and wrote the manuscript drafts.

- Wenjie Lai and Lin Cao helped on fabricating the experiment platform.
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- I prepared the experiment platform, designed and performed the experiments, analysed the results and wrote the manuscript.
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- I developed the integrated robotic system and performed the experiments, analysed the results and wrote the manuscript.
- W. Lai, L. Cao, J. Liu and X. Li developed part of the robotic system and helped on fabricating the experiment platform.
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Abstract

In robotic surgery, the surgeon controls the surgical robot through human-machine interfaces. The most common interfaces are for hands so that the surgeon can only control at most two robotic instruments at one time while three or more instruments may be needed at the same time in some procedures, e.g., robotic endoscopic/laparoscopic surgery. Current practices to these cases, i.e., having one assistant control the additional instrument, is not ideal because fine collaboration between the surgeon and the assistant is required, and delayed actions and even safety issues due to communication errors may occur. These limitations can be avoided if the surgeon could control all the tools on his/her own simultaneously. This thesis work developed a novel foot-controlled human-machine interface, enabling the surgeon to control the additional robotic surgical tool using the foot, together with the two tools that are controlled by the hands.

This foot-controlled interface controls a robotic surgical instrument in continuous direction and speed based on the motion of the foot in four degrees of freedom (DoFs), i.e., foot left/right translation, forward/backward translation, lateral/medial rotation, and toe-up/down rotation. The foot force/position signals are collected through eight feedback-sensing modules of the interface surrounding the foot. Each feedback-sensing module consists of a spring and a load cell. The foot's position can be determined by the deformation of the springs which is calculated based on the forces measured by the load cells. The whole foot operation is separated into elastic and isometric modes. In the elastic mode, the springs are not fully compressed and thus the foot can move freely with reaction forces from the springs (i.e., passive force feedback); in the isometric mode, the foot's motion is limited by the boundary (some springs are fully compressed) but its force is not limited and thus can still be used for output commands. The seamless transition between the two modes provides the user with rich proprioceptive information and meanwhile enlarges input ranges that are limited only by his/her strength. The interface also features a singularity-free workspace with a neutral central home position. The weight of the foot is well supported, and the friction of the interface is minimized to limit operation fatigue.

An analytical model based on the kinematics and statics of the foot interface was derived for output command calculation; however, this model does not consider the distinct motion behaviors of different users. Therefore, a data-driven mapping approach using independent component analysis was proposed to adapt the interface to the specific user's motion pattern, which effectively reduces the deviation between users.

Three studies were conducted on the developed interface: (1) Controlling of an industrial robotic arm for path-tracking and button-pressing tasks and comparison to a foot button interface. The proposed interface was about 30% faster and 60% smoother than a conventional foot button interface. (2) Three-hand manipulation using the proposed foot interface and two commercial hand interfaces for virtual reality tasks. The subjects were able to reliably control three virtual tools to perform independent and coordinated tasks. (3) A three-limb robotic flexible endoscopic system using the foot interface. The system enables the surgeon to simultaneously control an endoscope and two surgical instruments by the foot and hands, respectively. The feasibility of this concept was confirmed through an ex-vivo trial on a porcine stomach. In addition, the three-limb teleoperation with hands and one foot was 43.7% faster in contrast to a clutch-based hand control scheme.

The developed four-DoF foot interface enables one user to simultaneously control three robotic arms which otherwise require two operators, and it facilitates efficient and intuitive robot control. The interface may find wide applications in both surgical and industrial robotic systems, leading to reduced manpower, less communication errors, and improved efficiency.

Keywords: Human-machine interaction, foot control, three-tools operation, teleoperation, robot-assisted surgery.

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List of Acronyms

2T1R Two planar Translation DoFs and one Rotation DoF in the horizontal plane

2h Two-hand

3h Three-hand

AESOP Automated Endoscopic System for Optimal Positioning

ANOVA Analysis of Variance

AR Augmented Reality

B Backward

BM Bending Module

BMI Brain-Machine Interface

BTD Backward & Toe Down

BTU Backward & Toe Up

CoM Center of Mass

CoP Center of Pressure

DoF Degree of freedom

EEG Electroencephalography

EGM External Guided Motion mode of ABB robot

EMG Electromyography

EMR Endoscopic Mucosal Resection

EOR Endoscopic Operation Robot

ESD Endoscopic Submucosal Dissection

F Forward

FREEDOM Foot-controlled Robot-Enable Endoscope Manipulator

FSR Force Sensitive Resistor

FTD Forward & Toe Down

FTU Forward & Toe Up

HCI Human Computer Interaction

HMI Human-Machine Interaction

ICA Independent Component Analysis

IMU Inertial Measurement Unit
IQR Interquartile Range
kNN k-Nearest Neighbors algorithm
L Left
LapMan Laparoscope Manipulator
LB Left & Backward
LER Light Endoscope Robot
LF Left & Forward
LL Left lateral rotation
LODEM Mobile Locally Operated Detachable End-effector Manipulator
LTD Left & Toe Down
LTU Left & Toe Up
MF Mobile Frame
MIS Minimally Invasive Surgery
NASA-TLX Nasa Task Load Index
NL Natural Limb
NOTES Natural Orifice Transluminal Endoscopic Surgery
OR Operation Room
R Right
RAFE Robotic-Assisted Flexible Endoscope
RB Right & Backward
RF Right & Forward
RL Right lateral rotation
RM Rotation Module
RTD Right & Toe Down
RTU Right & Toe Up
SRL Supernumerary Robotic Limb
TCP Transmission Control Protocol
TD Toe Down rotation
TM Translation Module
TU Toe Up rotation
UDP User Datagram Protocol
VH Virtual Hand
VR Virtual Reality

Chapter 1 Introduction

1.1 Background and motivation

Compared to conventional open surgery, minimally invasive surgery (MIS) offers many benefits to the patient, such as reduced trauma, less blood loss and fast recovery [1]. In the conventional laparoscopic procedure of MIS, the surgeon makes several small incisions of 0.5 to 1cm in the patient's abdominal or chest wall. The rigid long-shaft instruments then access the surgical area of the patient's body through the incisions. Manipulating the laparoscopic instruments is complex and skill-demanding, requiring the surgeon to overcome many difficulties, such as the fulcrum effect, loss of haptic feedback and hand tremor [2]. In addition, due to the small incision, the surgical operation in patient's abdominal cavity is indirectly viewed through the laparoscopic camera by the surgeon. As the surgeon's both hands are already occupied by the laparoscopic instruments, an assistant is needed to adjust the camera assisting the operation of the primary surgeon. This indirect observation breaks the natural coordination of the surgeon's hands and eye. The need for collaborative assistance can be a source of errors and inefficiency due to miscommunication [3].

The newer MIS procedure of natural orifice transluminal endoscopic surgery (NOTES) [4] using flexible endoscopic instruments, encounters the same issues as described above for laparoscopic surgery. Complex endoscopic surgical procedures, such as Endoscopic Mucosal Resection (EMR) or Endoscopic Submucosal Dissection (ESD), require at least two skilled persons' cooperation, where the surgeon manipulates the bi-manual instruments whilst an endoscopist controls the endoscope. The operation

of the endoscope is tiring as the operator needs to use one hand to hold and maneuver the endoscope through dials with fingers, and another hand to hold the flexible body performing insertion and exertion [5]. Furthermore, the communication and collaborations between the primary surgeon and assistant may be problematic, especially for novice assistant or new team [6].

In addition, in endoscopic surgery, the endoscopic tools access to the region of operation through the channels inside the endoscope. The endoscope is a carrier with a camera, both providing view and transportation. This forms a dependent tree-shaped structure of endoscope and instruments, which means the motion of the endoscope and motion of the instruments are coupled [7]. The small movement of the endoscope will cause a significant deviation of the instruments. This makes the cooperation between the surgeon and endoscopist even more difficult. The endoscopist not only requires adjusting the camera view but also holding the endoscope and synchronizing the movement with the instruments. Moreover, the space to be shared by the two persons four hands is limited, resulting in uncomfortable and tiring positions.

Robotic systems with teleoperation mechanisms have made the surgical operation easier [8]. The surgeon can now sit behind the master console with hand controllers and high-resolution camera view, telemanipulates slave robot arms with surgical tools inserted into patient's body. Robotic systems such as Da Vinci [9] can provide four robotic arms for robotic treatment with versatility. The operation is performed by a primary surgeon through hand controllers and one assistant specially controlling the laparoscopic camera [10]. While the space issue is solved with this robotic solution, the assistance procedure still requires the cooperation of at least two skilled persons. Good coordination between the two operators is mandatory as they interact to perform the surgical procedure. Another example is in endoscopic robotic surgery, as shown in Fig. 1-1, where systems such as MASTER [11], ViaCath [12], enable intuitive bi-manual teleoperation of the instruments but still require another trained endoscopist

to assist the surgeon by directly holding and manipulating the endoscope at the patient side [13].

Figure 1-1: Robotic endoscopic surgery [13], [14].

Beyond the control of the laparoscopic camera or endoscope in the mentioned minimally invasive surgery, many surgical procedures require three or four surgical tools operation together, such as holding or exposing the tissue while the primary surgeon performs the suturing, suction the blood while performing the cutting, etc. The surgical team's communication is critically important and will directly determine the operational efficiency of the surgery and ultimately affect the patient's health. My thesis project is motivated by this collaboration issue in the surgical team and aims at developing a proper method to enable one surgeon to control three tools without loss of efficiency.

1.2 Objective and scope

Robot-assisted surgery allows a surgeon to perform the complex operation with more dexterity, precision and control. It also gives an opportunity to augment the surgeon operation capabilities by controlling multiple robotic arms all by themselves. If a

surgeon can complete the whole surgical operation without assistance, it avoids the potential for errors due to human-human miscommunication.

Previous studies reported in the literature proposed “third hand” control strategies such as using hand-free interfaces operated by the head, foot, finger, voice and eye gaze. However, the proposed control modalities all have inherent limitations. Thus, it is still an open question on how to develop an intuitive and efficient way to control three robotic arms by one person with little mental and physical efforts. This thesis will address the related issues through the following objectives:

- The first objective is to provide an intuitive and efficient control strategy for the operator to teleoperate a robotic arm with a hand-independent input source. Achieving this objective requires: (1) Designing a hands-free interface that could control a surgical robot in multiple DoFs. This interface should *i*) capture and identify human control intention; *ii*) provide intuitive mapping; *iii*) enable ergonomic and comfortable operation. (2) Study the human-machine interaction with the novel interface and compare it with a conventional interface.
- The second objective is to develop a robotic surgical system integrating the proposed foot interface to control a surgical instrument and validate the system through a comparison study with existing control schemes.
- The third objective is to investigate the human capability on “three hand” control. The interface can facilitate the operation, but the concept implementation in practical surgery will ultimately depend on how the operator can use the system. Therefore experiments will be conducted to study the effect of the “third hand” control on the natural hands’ operation and investigate learning and manipulation capability of three-limb control in tasks requiring different levels of coordination and cognition.

- The last objective is validate the concept of the three-hand surgery with foot control in a surgical task and three-tool teleoperated surgical system. The experiment will demonstrate the concept that one operator effectively controls three surgical tools performing a surgical operation.

1.3 Impact and innovation

The Ph.D. project has the following potential **impacts**:

- It will provide a feasible and intuitive method with an input interface and a three-limb teleoperated system to achieve solo surgery, which can improve the operation's efficiency and potentially reduce manpower and cost. Critically, the developed system would avoid communication errors between the surgeon and assistants and may improve the surgical outcome.
- Results of supernumerary robotic arm control and trimanipulation will provide valuable human behavior data to further explore the augmentation of human capability in three-handed operation.
- The proposed interface and control schemes are not limited to be applied in robotic surgery, and can be directly applied to other teleoperation systems or virtual reality as a master controller.

The principal **innovation** of the project is a novel interface that can control a surgical robot in four DoFs and free hands to perform the main operation. This includes the design of the mechanical structure, sensing and feedback modules and built-in software that extract operator's specific commands. User studies on the performance evaluation of using the additional input source to control a robotic arm and three-limb teleoperation by one operator in both general and surgical tasks are further novelties. Finally, a novel three-limb teleoperated robotic system for flexible endoscopic surgery

is introduced and validated in experiments, enabling one surgeon to control three robotic arms simultaneously without additional assistants.

1.4 Thesis outline

This thesis is composed of eight chapters organized in the following manner. **Chapter 1** introduces the background and motivation of the Ph.D. work. The objective and approach as well as the significance and novelty of this work are also outlined. **Chapter 2** presents a literature review of related approaches and components. It constitutes four main sections: a review on the “third hand” control strategies in current robotic surgical systems, existing foot interfaces in robotic surgery, characteristics of user and foot-based interaction. **Chapter 3** describes the design process for the proposed foot interface used to control the third surgical tool, including its working principle, mechanical structure, sensing, feedback and friction reduction. **Chapter 4** presents the command computation methods of the proposed interface. An experimental study on interaction with the proposed interface is conducted whose results are used to develop an intuitive data-driven mapping from the operator specific movement patterns to the interface inputs. **Chapter 5** describes an experimental validation of the proposed interface and compares the resulting performance with an existing interface for teleoperating a robotic arm. **Chapter 6** presents a novel foot-controlled teleoperated robotic endoscope system using a foot interface to control a flexible endoscope. **Chapter 7** shows an experimental study on the operator’s ability for trimanipulation in virtual reality tasks. The result shows the feasibility of the proposed interface and control scheme in three-handed teleoperation and provides evidence for further study in surgical applications. **Chapter 8** presents a three-limb teleoperated surgical system integrating the foot-controlled robotized endoscope and two-hand controlled instruments. The proposed system is validated in an ex-vivo surgical test experiment on a porcine stomach. **Chapter 9** then summarizes the contributions and proposes future research directions.

Chapter 2 Literature Review

This chapter presents a literature review for the Ph.D. work. It is divided into five sections. In Section 2.1, the control strategies on controlling the third tool in robotic surgery are presented, i.e., hand sequential and hand-independent controls. Comparison and analysis of these control strategies led to the choice of foot control. In Section 2.2, existing foot interfaces in robotic surgery to control the third tool (usually a laparoscopic camera) are reviewed. The objectives and scope of the proposed foot interface are then determined from the limitations of state-of-the-art interfaces. The biomechanics of human foot and existing foot-based interaction techniques are reviewed in Section 2.3 in order to design an intuitive and user-friendly human-machine interface. Section 2.4 then showed recent studies about human multi-tasking capability using body interfaces, especially foot interfaces. The last sections of this chapter discusses and summarises the outcome from the literature review.

2.1 “Third hand” control in robotic surgery

Human interfaces (HMI) are important components of teleoperation systems. Some commercial hand-controlled HMIs, such as the Phantom (3D Systems, US) and Omega/Sigma haptic devices (Force Dimension, Switzerland), can be used as master devices to telemanipulate remote robotic arms. For example, the RAVEN robotic system [15] includes the Phantom Omni hand interface for teleoperation and haptic feedback; the MiroSurge [16] uses the Sigma 7; the Da Vinci system [9] is equipped

with a built-in master console through which the surgeon can telemanipulate and switch instruments.

These HMIs provide sufficient manipulation control with two hands; however, many surgical operations require three or more instruments simultaneously. Traditionally, a human assistant controls the additional instruments in coordination with the surgeon. For instance, an assistant can adjust the camera's field of view during laparoscopic surgery; in a robotic flexible endoscopic surgery, the robotic arms controlled by the surgeon can only work in a small workspace and thus an endoscopist is needed to move the endoscope which is carrying the robotic arms to adjust the working area **caolin2019**, [17]. The necessity to collaborate with an assistant may create issues, as surgical performance and efficiency are often limited by the communication delays and errors between the surgeon and the assistant [3].

A solution to address this issue is to let the surgeon control the additional instruments all by themselves [10], [18]. To enable surgeon control multiple instruments, robotic technology has been integrated with surgery. The third tool can be controlled in an autonomous way. Current procedure for the autonomous positioning of the endoscope [19]–[21] are based on visual servoing control, i.e. guide the endoscope using visual feedback from the camera. Regardless of technical and practical issues such as image blur due to fast motion of the instrument or blood in surgical cutting, the auto-tracking scheme may not provide the optimal view match surgeon's intention [21] and cause safety issue [20]. There is still a long way to achieve full and smart automation in robotic surgery. Most of the current systems are therefore using hand or hand-free interfaces to control the "Third hand".

2.1.1 Control strategies

Hand control is the most common way to tele-operate robotic endoscope systems [22]–[24]. Flexible endoscopic robotic systems such as MASTER [25] and ViaCath [12] enable intuitive bi-manual teleoperation of the flexible endoscopic instruments. However, the endoscope operation is complex and skill-demanding [26], and these systems typically require an endoscopist assisting the surgeon by directly holding and manipulating the endoscope at the patient side [13]. Robotized endoscopic systems such as Endoscopic Operation Robot (EOR) [23], Robotic-assisted flexible endoscope (RAFE) [24], motorized endoscope [27], and i^2 snake robot [28] facilitate the endoscope operation through teleoperation with one or two hands interfaces. These platforms also require the surgeon to cooperate with an assistant in order to control the two surgical instruments and the endoscope, which may cause miscommunication and errors [3].

There are few complete robotic systems in flexible endoscopy which include three or more robotic arms controlled by one surgeon. The representatives systems [22]–[24], [29]–[31] including robotic endoscope control mechanism are listed in Table 2-1. Among them, the FLEX [22], EOR [23] and RAFE [24] systems remained in manual control on the instruments. In general, three approaches have been put forward to help a surgeon control both endoscope and instruments:

- *Separate interface hand control*. For example, in the Medrobotics Flex system [22] (Fig. 2-1b), the operator firstly navigates the endoscope to the target area using a joystick and then switch to the two manual instruments. Some passive camera positioners [32]–[34] allow the surgeon manually adjust the position of the laparoscopic camera by one or two hands.
- *Clutch-based hand control*, with clutch buttons or pedals in the master console to activate the swapping to the third tool. For systems such as K-Flex [31],

the operator uses the same hand interface to control a surgical tool or flexible overtube, swapped by a foot clutch. Similarly, The Da Vinci system [9] is equipped with a built-in master console with hand controllers and footswitches. The footswitch located on the left wall is used for arm swapping (Fig. 2-1a).

- *Hand-independent interface control*, using the other body parts like the head, foot, finger or voice to command the surgical tool. For example, the latest version of the STRAS system [30] includes two small four-way finger joysticks on the hand controllers to operate the endoscope using two thumbs of both hands. Each joystick can control the two-DoF motion of the endoscope. The detail of this control strategy is shown in the next subsection.

Table 2-1: Robotic systems for flexible endoscopic surgery

System	Endoscope control	Tools control	Endoscope DoF	System DoF	Application
RAFE[24]	Hand, Handle	Manual	4	-	gastrointestinal tract surgery
STRAS [30]	Thumbs, Two four-way switches	Robotic	4	11	gastrointestinal tract surgery
K-FLEX [31]	Hand, Handle (swap by foot clutch)	Robotic	4	14	gastrointestinal tract surgery
FLEX[22]	Hand, Joystick-like controller	Manual	-	-	ENT surgery
EOR [23]	Hand, Handle and mini-joystick	N/A	4	-	gastrointestinal tract surgery
Proposed system	Foot, Foot interface	Robotic	4	13	gastrointestinal tract surgery

Using a separate hand interface or a hand clutch require sequential control, which may not be intuitive or efficient. For instance, when adjusting the camera view with some camera positioners [10], the surgeon needs to release the current instruments, disengage the locking mechanism, operate the third instrument, reengage the locking mechanism, pick up previous instruments, and resume the procedure. Some studies [20], [35] also reported that in the Da Vinci surgical system the swapping procedure using pedal clutching may disrupt the surgical flow and lead to errors or extended operation. In contrast, using the foot to operate a third tool does not disrupt the hands

operation. The behaviour study in [36] also suggests that three-handed simultaneous positioning is preferred to - and more efficient than - bimanual operation. Using hand-independent interface provide a solution to simultaneous control three surgical tools by one surgeon. This method is discuss in the following subsection.

Figure 2-1: (a) Master console of Da Vinci Si Surgical System (Intuitive Surgical, Inc, USA). (b) Flex robotic system (Medrobotics, USA)

2.1.2 Hand-independent control

Various hand-free robotic assisted camera systems have been developed for laparoscopic or otolaryngological surgery. The hand-free input source can be head movements, voice control, finger and eye gaze, as described below:

- **Head control**, Fig. 2-2a, [35], [37], [41]–[43]: In the systems, such as EndoAssist [41] and Freehand [42], four-DoF head movements (3 rotations and forward/backward translation) are detected using an infrared transmitter attached to the surgeon's head and a receiver installed on the monitor, which are used to control the endoscope holder robots.
- **Voice control**, Fig. 2-2b, [38], [44], [45]: The surgeon is typically using a headset with microphone to communicate commands using simple words like “up”, “down”, “right”, “left”, “in”, “out”, which are subsequently repeated it

Figure 2-2: Hand-free control strategies. (a) Head control [37]; (b) Voice control [38]; (c) Eye gaze control [39]; (d) Finger control [40]

the headphones for checking that the proper command was identified by the system. The systems AESOP (Automated Endoscopic System for Optimal Positioning) 2000 [44] and VIKY [38] robots are using such voice control.

- **Eye gaze control**, Fig. 2-2c, [39], [46]–[48]: Interfaces have been developed using eye gaze to detect the intention of the operator. In this system, an eye tracker device is needed to infer where the surgeon is looking at by monitoring his/her eye movements. The camera could be controlled by following the user's gaze position. For example, Staub et al. [47] have proposed a system to control a laparoscope through surgeon's gaze with a pedal to activate the robot.
- **Hand/Finger control**, Fig. 2-2d, [40], [49]–[51]: Interfaces such as a finger-controlled joystick or switches are directly attached to the manual surgical instrument. For example, the Lapman [40], [51] robot has a joystick clipped on the instrument under the surgeon's index finger that can be controlled using one

finger without affecting the hand operation. The FIPS endoarm [49] equipped a finger-ring joystick which makes the endoscope tip movement corresponding to the fingertip movement. The latest version of the STRAS system [30] includes two small four-way finger joysticks on the hand controllers that can be used to operate the endoscope using two thumbs of both hands. Each joystick can control the two-DoF motion of the endoscope.

While these control strategies could be used to free the surgeon's hands throughout the operation, all suffer from limitations in specific applications. Voice recognition may fail due to environmental noise or other surgeons nearby, and yields so far only a limited vocabulary of commands. Moreover, voice control cannot be used simultaneously to speaking. Controlling head movement may distract the surgeon's attention, who should be able to use natural eye gazing and head to coordinate whole-body movements [52]. Inadvertent negligence may cause security issues, thereby, some head/eye control systems would still need additional activation buttons or pedals to distinguish control from casual movements. Fingers can provide independent motion when hands are conducting the operation, but the finger control may be affected by the hands operation. Accidental activation was reported with the Naviot [53] system which has buttons on the hand controller to operate the endoscope: The operator sometimes pushes the button accidentally when the hand controller rotates.

2.1.3 Foot control

Compared to other hand-free control sources, foot controlled movements are easy to learn [54] and can be used in conjunction with hand movements without interference. We have selected foot control for the following reasons:

1. First, foot control could provide independent and simultaneous input without coupling to other necessary actions. In robotic surgery, the surgeon can sit comfortably at the master console, the lower limb with foot are free to conduct any movement. In contrast, rather than augmenting human capability, coupled input channels will affect the original hands' operation. For example, in normal operation, an operator requires the coordination of eye and hands and probably needs to communicate with other persons. The head motion will interrupt the hands operation' as the view has been shifted from the interested field. Similarly, voice control will affect communication with the team members.
2. Secondly, foot control can provide simple, clear and efficient input commands to achieve desired motion. In comparison, the head control systems of EndoAssist [41] and FreeHand [42] requires a simple foot switch to prevent unintended movements: movement is enabled only when the pedal is in pressing state. Similarly, the eye-trackers may have difficulties to recognize whether a user found an interest target or it is just simple gazing [55].
3. Thirdly, foot position/force signals are easily detectable and robust to environmental disturbances. Unlike voice control, foot motion is not affected by the noisy environment of the operation room.
4. Lastly, foot motion enables the operator to simultaneously work with the hands using little mental effort. The input source may be already naturally used in combination with the hands, e.g., when manipulating objects during walking, driving vehicles, playing instruments such as church organ or drums, and in activities of daily living.

2.2 Foot interfaces in robotic surgery

This section introduces state-of-art foot interfaces in surgical robotic systems to control the multi-DoF movement of the third tool. This includes the robotic systems of AESOP [44], [56], VIKY [57]–[61], RoboLens [62], [63] and HWIN, which are using button-based foot interfaces with several buttons. Normally, one button is represented as one direction. When pressing down/touching the button, there will be a constant speed for the slave tool. The speed may have several levels that can be selected beforehand. On the other hand, the FREEDOM robot [62], [63] and Abdi et al's interfaces [64]–[66] use foot position signal to control the slave robot.

AESOP system

The surgical robot AESOP 1000 [56] (Fig. 2-3a) uses a pressure-sensitive foot interface, where the velocity increases linearly with force exerted by the foot. It has two switches with six transducers to control the endoscope movements (Fig. 2-3b) in order to move the endoscope in, out, left, right, up or down by applying pressure to the corresponding buttons. In the system of AESOP 2000 [44], the foot controller shown in Fig. 2-3c acts as an alternative approach to the voice interface. Compared to previous foot controllers, the in/out buttons are placed on the two sides of multiple directions buttons which can be controlled in a flexible way using both feet.

VIKY system

The endoscope holder system VIKY (Fig. 2-4a) by the Endocontrol Medical Company [57]–[61] has two control options of voice control and footswitch control. The foot controller uses multidirectional footswitch to control three DoFs of the robot. The endoscope movement in directions right/left, up/down or in/out can be controlled

Figure 2-3: (a) AESOP robotic system [67] and foot interface of (b) AESOP 1000 foot controller [56] (c) AESOP 2000 foot controller [67]

using the corresponding foot button (Fig. 2-4b). Clinical evaluation and validation of solo operation were conducted as described in [60].

Figure 2-4: (a) VIKY robotic system [57] and its (b) foot interface [61]

Figure 2-5: (a) RoboLens robotic system and its two foot interfaces V2.2 (Courtesy of Robotic Surgery Lab., RCBTR) of (a) Foot switch [68] and (b) wearable shoe [68]

RoboLens system

The RoboLens [62], [63] endoscope holder robot (Fig. 2-5a) uses two kinds of foot interfaces. Firstly, it is equipped with a six-button footswitch which consists of two pedals (Fig. 2-5b). The right pedal is used to control the lateral movement of the camera (up, down, left and right) and the left pedal to zoom in and out. In addition, a pair of wearable shoes (Fig. 2-5c) with optical sensors is used to collect the feet movements. The right foot determines the movements in left, right, forward and backward. The left foot control in forward and backward directions.

FREEDOM system

Figure 2-6: (a) FREEDOM robotic system [69], and its (b) active joints [70], (c) foot IMU controller [70] and (d) operation foot gestures[69].

The Foot-controlled Robot-Enable EnDoscope Manipulator (FREEDOM, Fig. 2-6a,b) is a surgical robotic system designed for endoscopic sinus surgery [69], [70]. The system has a wearable foot interface (Fig. 2-6c) with IMU (inertial measurement unit) modules recording the three-DoF rotation angles of the foot. The four foot rotation gestures (Fig. 2-6d) control the three active joints (Fig. 2-6c) of the slave robot. Joint 1-3 drive the three DoFs of the left/right, up/down and forward/backward of the rigid endoscope. The foot gesture I, shown in Fig. 2-6d upper left panel, enable/disable the foot control; foot gesture II (Fig. 2-6d right upper panel), foot eversion/inversion,

control the switching to previous/next joint; foot gesture III+IV (Fig. 2-6d lower panel) map the movement of the joint. The continuous position information of foot is collected and used only for “position switch”. For example, once the foot rotation angle beyond a threshold value, one joint is activated. Each joint requires to be activated separately and cannot be combined. Moreover, activating a joint movement requires the combination of multiple foot gestures. For example, a sequence of foot gestures I, II, III and IV can move the joint 2.

MTGH100 system

Figure 2-7: (a) MTGH100 endoscope holder [71] and its (b) foot interface [71].

Another commercial robotic system is the MTGH100 endoscope holder [71] (Fig. 2-7a) from HIWIN Technologies Corp, Taiwan. Surgeons can move the endoscope in six directions in, out, up, down, left, right via a six-direction foot pedal shown in Fig. 2-7b. The pedal is arranged in a compact way with a central position. All six buttons can be accessed from this central position, which provides a position reference for the surgeon.

Abdi et al. foot interfaces

Abdi et al. [64]–[66] have developed an elastic-isometric foot interface to control a robotic endoscope holder shown in Fig. 2-8a. This interface enables control of three DoFs through pressing six pistons, and a fourth DoF is provided by foot rotation around the vertical axis. However, the movements those interfaces could control are still limited to discrete directions, as it is not possible to command two or more DoFs simultaneously. Furthermore, the use of Hall effect proximity sensors to detect the spring force limits the control range thus for forces above 3N the slave robot could only move at a constant speed.

Figure 2-8: Abdi et al. s' (a) isometric interface and (b) isotonic interface [64].

In the isotonic foot interface of Fig. 2-8b), a structure with two linear guides and two rotational joints are serially connected from the base to the pedal. The selected serial structure increases the total height of the foot interface and may cause the coupling of foot motions. For example, the forward motion of foot may cause both movements of the interface in the directions of forward and pitch rotation. Each joint collects one-DoF foot position information. Specifically, the translational movement of the interface is measured by magnetic membrane potentiometers and rotational movements by optical encoders. These signals are mapped to control the robot position, with the drawback of limited workspace. Additionally, the motion accuracy of the slave device may suffer from foot motion error.

Table 2-2 summarizes the representative foot interfaces described in Section 2.2 based on the following characteristics:

- **Degree of freedom (DoF)** The number of DoF that the foot interface can control.
- **Input mode** What input signal the foot interface capture.
- **Control mode** How the foot interface output commands control the robot. Whether the interface can control the movements of the robot in combined continuous direction or single (Cartesian) axes “forward”, “backward”, “left”, “right”, etc.
- **Positioning and resting:** Whether the device has a positioning assistance design to help the operator activate the right control commands without using vision. And whether the device provides a resting place which is convenient to start operation without re-position their foot.
- **Haptic feedback:** Whether the device could provide the surgeon with haptic (e.g., force and touch) feedback to enable rich robot control.
- **Individual Foot adaptation:** Whether the device can identify operator-specific commands from the motion patterns of the foot.

Table 2-2: Characteristics of foot interfaces for robotic surgery.

Denomination	DoF	Input mode	Control mode	Positioning & resting	Force feedback	Individual adaptation
AESOP [56]	3	binary	single axis, pressure proportional speed	✗	✗	✗
VIKY [57], [59]	3	binary	single axis, constant speed	✗	✗	✗
RoboLens [62], [63]	3	binary	single axis, constant speed	✗	✗	✗
FREEDOM [69], [70]	3	binary	Single axis, constant speed	✓	✗	✗
HIWIN [71]	3	binary	single axis, constant speed	✓	✗	✗
Elastic-isometric interface [64]	4	continuous, force	single axis, constant speed	✓	✓	✗
Isotonic interface [64], [66]	4	continuous, position	combined in four DoF, position	✓	✗	✗
Proposed interface	4	continuous position and force	combined in four DoF, pressure proportional speed	✓	✓	✓

✓ / ✗ means that a device has / does not have a corresponding feature ; Binary input is either 0 or 1.

2.3 Foot-based interaction technique

To design an intuitive human machine interface, the user's characteristics and the interaction between user and the interface system are key issues that need to be analyzed. This section analyses the biomechanical aspects of the human foot and leg, identifies the foot control input, sensing and feedback that the foot interface's design should consider.

2.3.1 Lower limb biomechanics

Three main poses for human are sitting, standing and walking/running. The proposed foot interface is used for the surgeon to perform teleoperation in robotic surgery; thus, the situation of walking/running and standing would not be considered, and the foot gestures analysis is thus based on the sitting posture. The leg's anatomical analysis considers the thigh (the upper leg), the leg (the lower leg) and the foot. It can be modeled as an open mechanical chain with the foot as end-effector considering the hip, knee and ankle joints.

Hip joint

The hip joint can be modeled as a "ball and socket" joint that allows three-DoF rotations of flexion/ extension, abduction/adduction and outward/inward rotation. Flexion and extension motion are limited to the range shown in Fig. 2-9b in a sitting position; Abduction and adduction (Fig. 2-9c) represent sideways movement of the leg from the midline of the body or inward movement toward the midline of the body. The outward/inward rotation of hip leads to shank rotation around the thigh (Fig. 2-9d). The movement of the hip joint leads to the motion of the whole leg which introduces more fatigue.

Figure 2-9: (a) Sitting posture and lower limb's joints. Motion of the hip joint in (b) flexion and extension; (c) abduction and adduction; and (d) outward rotation and inward rotation. (e) Motion of the knee joint.

Knee joint

The knee can be modeled as a hinge joint enabling relative movement between upper and lower leg. It provides one DoF in flexion and extension motion in sagittal plane (Fig. 2-9e). Knee flexion is the movement that decreases the angle between the leg and the ankle whereas knee extension is the movement that decreases the angle between the leg and ankle. The flexion can reach about 140°, and the extension's limit is 0°. As a gesture, these movements combine into a “kick” [72].

Ankle joint complex

The foot has a complex structure with 26 bones, 2 sesamoid bones, 33 joints, 19 muscles and 107 ligaments. It is a highly dexterous system involving multiple joints (Fig. 2-10). Each joint provides multiple movements with varying ranges. The commonly called ankle joint is not one joint but can be considered as composed of three separate

Figure 2-10: The structure of the foot in (a) perspective view and (b) back view (heel).

articulations which are subtalar (talocalcaneal) joint, ankle (tibiotalar) joint and talonavicular joint enabling three rotations [73]. The subtalar joint (Fig. 2-10) consists of three articulations between talus and calcaneus [74], yielding three-dimensional motions of supination and pronation, and allowing the inversion and eversion of the ankle [75]. The tibiotalar joint which is the true ankle joint is like a hinge joint, mainly contributing to the plantar-and dorsiflexion motion of the foot.

Figure 2-11: Motion of the ankle in (a) dorsi/planar flexion; (b) abduction and adduction; (c) eversion and inversion; and (d) supination and pronation (demonstrated with right foot). (e-g) Rotation axes of ankle joint complex.

The foot can conduct three-DoF rotations with the ankle joint complex (Fig. 2-11a-d, Table 2-3):

- *Abduction and adduction* (Fig. 2-11a) is the movement of the foot away/towards the centerline of the body (moving outwards/inwards), yielding heel rotation when pivoting around the heel or as toe rotation if pivoting around the toe [76]. In the interface of Foot Menu [77], the user was using abduction and adduction around the heel to control the horizontal movement of the cursor.
- *Dorsiflexion and plantarflexion* (Fig. 2-11b) is the movement of foot away/close from the leg, commonly used to operate a pedal. The pedal can be toe or heel activated depending on where is the foot anchored [76].
- A foot twist outwards (*Eversion*) and twist inwards (*Inversion*) (Fig. 2-11c). The range of motion for along this axis is very limited. Those movements are often combined with the other rotations into supination and pronation which are introduced below.
- *Pronation and Supination* (Fig. 2-11d) are tri-planar movements that combine these movements. Pronation is the upward and outward movement of the foot involving dorsiflexion, abduction and eversion. Supination is a downward and inward movement of the foot involving plantarflexion, adduction and inversion. They are typically used to move foot joysticks [78].

Table 2-3: Range of motion of the human ankle [79]

Motion	Roation Axes	Motion plane	Range (deg)	Mean (deg)	Standard deviation(deg)
Dorsiflexion	Medial-lateral/oblique	Sagittal plane	20.3-29.8	24.7	3.3
Planarflexion	Medial-lateral/oblique	Sagittal plane	37.6-45.7	40.9	4.3
Inversion	Anterior-posterior	Frontal plane	14.5-22	16.3	3.9
Eversion	Anterior-posterior	Frontal plane	10.0-17.0	15.9	4.5
Adduction	Vertical	Transverse plane	22.0-36.0	29.8	7.6
Abduction	Vertical	Transverse plane	15.4-25.9	22.0	6.0

Axis of rotation of the ankle

It should be noted that there is relatively high variability on the anatomical parameters (Table 2-3), especially for the subtalar and talocrural joint orientation in the horizontal plane. The rotation axes of ankle joint are not orthogonal axes but oblique (Fig. 2-11e,f) which means that the foot joints are not simple hinge joints and the rotations are not simple single stable rotation. In addition to motion in the plantar-dorsiflexion axis, slight abduction-adduction or rotation is present [74]. The rotation axis of the subtalar joint is shown in Fig. 2-11g. In the sagittal plane, the subtalar axis lies at an average angle of about 41° from the medial-lateral axis, and deviates about 23° from the anterior-posterior axis. There are considerable anatomic variations for the tilt angles of the axis [74]. Furthermore, the motions of the ankle and subtalar joints are coupled.

2.3.2 Foot input and sensing

Except for above foot interfaces in robotic surgery, foot interface can be used in multiple situations, for human-computer interaction (HCI), virtual reality (VR), rehabilitation, prosthesis control, etc. Based on the input foot gestures and sensing, foot interfaces can be classified into *force/pressure based* foot interface and *position tracking based* foot interface.

Force/pressure-based foot interface

The foot force/pressure information is an important source to monitor the gait state for detecting lower limb issues [81], injury prevention [82], etc. It can also be used to control a device. Carrozza et al. [80], [83] designed a wearable foot interface with pressure sensors to control a prosthetic hand as shown in Fig. 2-12. The four pressure

Figure 2-12: (a) ACHILLE interface and (b) the location of its sensitive areas [80]

sensors are imbedded in the wearable insole as binary footswitches. The force signals will activate the switch once override the threshold (69N with toe switch, 79N with heel switch, 112N with lateral internal switch and 96N with lateral external switch). Using the pressure sensors, potentially allowing fine control over a large workspace without visible foot motion [84]. However, it may be non-intuitive to use the force for controlling movement [85].

Position tracking-based foot interface

Figure 2-13: Mapping of the MetaArms robotic system [86]

Using foot motion is more intuitive, but may require large movements of the leg and may cause fatigue. As shown in Fig. 2-13, the impressive MetaArms system [86] uses all six-DoF foot motions and one-DoF toe motion to control a supernumerary robotic limb. It is found that the perceived physical fatigue was increased with trials and may affect the operator's performance. In this system, the foot and toe position information are collected through HTC VIVE optical-based tracking system

and resistance-based bending sensors. Similarly, the interaction shoe designed by Ambreen Zaman et al. [87] also uses optical sensors to record the foot position for interaction with 2D image data.

2.3.3 Feedback to foot

Figure 2-14: Haptic foot interfaces from (a) Inaki Díaz et al. [88], (b) Jacob Hernandez et al. [89], and (c) Daniel Horodniczy et al. [90], [91]

Haptic feedback can improve the surgeon's performance during intervention [92]. Haptic feedback can be active or passive haptic feedback. Active haptic feedback is provided by actuators, while passive (or pseudo-) haptic feedback is produced indirectly by the operator using appropriate visual feedback.

The foot pedal, shown in Fig. 2-14a, can control one DoF of the drilling tool's speed with active haptic feedback provided by a vibration motor [88]. The authors have proved that providing haptic feedback to the foot can reduce the surgeon's response time to a warning signal. Another foot interface [89] shown in Fig. 2-14b can control the robotic arm with haptic feedback to perceive contact and change in load. Meanwhile, the foot interface of [91] provides variable friction force to the foot using passive mechanism and could improve performance on a pointing task relative to a regular foot mouse [90].

Active haptic feedback offers the advantage to enable flexible adjustment of the resistance force/torque. And it provides a bi-lateral interaction (separate from the motion control)

with the target environment. However, the active haptic feedback normally requires an expensive and complicated system, and the bilateral communication may cause the oscillation and instability of the teleoperation system [93]. In comparison, passive haptic feedback has less flexibility to adjust but it is easy to achieve using elastic elements or physical objects. It has been shown that the passive elastic haptic feedback can improve the performance and perception [94]–[96], and can yield similar performance compared to active feedback [97]. Moreover, some studies [98], [99] have shown improvement in performance and learning enabled by using compliant interfaces providing the operator both force and position feedback. Experimental study [64] found that the elastic-isometric interface was preferred by operators than the isotonic interface, as the former one requires less effort and provides accurate control with passive elastic feedback.

Similar to other gestural interactions, foot movements may be less accurate when there is no visibility of the limbs. However, the lack of visibility of the feet can be compensated by relying on the user's proprioception. Overall, a compliant interface with elastic elements [100], [101] can give rich displacement and force feedback that may give the operator more accurate perception of their control actions, thus enabling them more skillful operation even there is no assistance of visual. Therefore, even though users cannot see their feet they still know where they are in relation to their bodies.

2.4 Tri-manipulation with body interface

Supernumerary robotic arms can be controlled through hand-free body interfaces and cooperate together with natural hands to perform multi-tasks. However, it is still unclear now whether human can deal with the complexity to control extra arm(s)

and benefit from it. Human machine interfaces for controlling additional degrees of freedom in coordination with the natural limbs (NLs) have not been studied systematically.

It was found in [102] that polydactyly individuals with more than five fingers by hand were able to control the additional degrees of freedoms and yield superior manipulation abilities without motor deficits or impairments. Although supernumerary robotic limbs (SRL) are different from body parts and need to be controlled through external interfaces, human may have the capability to build a representation for the SRL and perform augmented manipulation with their NLs.

Ali Shafti et al. [103] used foot rotation gestures to control wearable robotic 6th finger and perform a piano playing task. They found that human can learn to play piano with six fingers after a short training. Paulina Kieliba et al. [104] also use feet (big toes) to control two DoFs of a supernumerary robotic Thumb (SRT) to conduct tasks requiring hand-Thumb coordination. The embodiment and motor control of the SRT were improved through five days' usage. And it was speculated that the integration of human and robotic finger may modify the body representation and motor control on some aspect. Similar to the control of SRT, there is a gap in understanding how the human motor adopts and learns to control the SRL and multi-tasking. For example, it is unknown whether and how the addition of the SRL affects the representation and performance of the NLs, how to effectively improve the performance of tri-manipulation and achieve human body augmentation, etc.

There are some works that examined the simultaneous operation of foot and hands including [105], who studied the re-sizing, with one or two feet, of a 2D square positioned with the dominant hand. It was observed that two-feet gestures are faster than one-foot on re-sizing. Additionally, the works [36], [106] demonstrated how a virtual "third hand" could be controlled by the foot continuously and simultaneously with the natural hands to reach towards objects, and found that the use of three hands was more efficient than two. [89] exhibits a single subject carrying out bipedal

telemanipulation of two robotic arms in tasks of lifting, grasping or holding along with the operation of hands. The MetaArms [86] system has proved the feasibility of controlling two wearable robotic arm cooperation with natural hands. These studies considering the simultaneous operation of a SRL are currently in a preliminary stage in which the action is highly restricted to fixed tasks, or the control is only one DoF. The use of foot interfaces for controlling supernumerary robotic arms in coordination with the natural limbs has not been studied systematically.

In addition, tri-manual motion control include many different operation scenarios. It is out the scope of this thesis to study all trimanipulation cases. Based upon existing taxonomies for bimanual manipulation [107], [108], a tri-manipulation taxonomy can be defined considering *i)* the physical *couplings* between the limbs, and *ii)* whether the limbs are conducting a common task or *independent* task. For example, in laparoscopic surgery, the three tools may conduct independent movement to reach the operation area; or perform two-handed coupled operation when using grasper and knife cutting the tissue, the third hand control the suction tool or endoscope to do independent motion to suction the blood or navigate the direction.

2.5 Discussion and conclusion

Multiple hand-free interfaces enable one surgeon perform complete surgical operations without breaking the coordination of hands and eye [18]. The “third hand” can be controlled by head movement, voice commands, finger, tongue, eye gaze and foot. Among all these input sources, we have selected foot control based on three considerations: First, foot control is an independent and simultaneous input without influencing the main operation of hands, eye view and team communication. From this point of view, it is superior to control strategies using finger, eye gaze and voice commands. Secondly, foot control is easy to learn and can clearly and naturally

express the human motion intention. Thirdly, foot position and/or force can be easily detected by the interface with less environmental noise.

Table 2-2 suggests that current foot interfaces used in robotic surgery are not sufficient and intuitive to control a robotic arm efficiently and in conjunction with the (natural) hands. Commercially available foot interfaces [56], [57], [62], [71] mainly consist of switches and buttons closely placed on a planar base to command the surgical tool at constant speeds in various single-axis directions. Such an interface is simple to control but may not be suitable for complicated manipulation motions (especially with more than three DoFs). Furthermore, the need to lift the leg up and down can cause fatigue during long operations. Most of these interfaces provide neither positioning assistance nor force feedback, thus may require the operator to visually check the foot posture frequently. Abdi et al.[64], [65] developed two foot interfaces to manipulate a laparoscopic camera in four DoFs with the foot at rest. Interestingly, the passive isometric interface was preferred by operators to the robotic interface providing active force feedback, perhaps as it is lighter and simpler to use. However, the passive interface offered feedback of the contact, but no haptic feedback monotonically increasing with the force level, and it could only be used to command one direction at a time.

The proposed foot interface should solve the limitations of those existing interfaces providing intuitive and efficient control. When selecting the foot gestures used to output control commands, the human fatigue, gesture repeatability and intuitiveness of mapping should be taken into consideration. The float-in-air gesture of the foot causes significant fatigue. The dragging foot gestures can be used when the friction force is extenuated. Proper sensing mechanism should be developed based on the selected natural foot motions. The foot movement can be used to generate the command to the interface and also receive haptic information.

In addition, the foot interface was designed to let the surgeon control three or four surgical tools simultaneously and intuitively. The use of this interface should be

tested in tri-manipulation scenarios with both natural hands and foot-controlled third hand. The modular master foot interface will be integrated into a robotic surgical system to verify the three-hand surgery concept. We will developed a three-limbed teleoperated system allowing one operator to control three tools. Compared to the sequential operation of multiple tools, the surgeon could potentially control the three instruments simultaneously.

Chapter 3 Foot Interface Design

3.1 Summary

The state-of-art in foot interfaces in robotic surgery have been analysed in Chapter 2, where it was found that existing foot interfaces may not be intuitive enough to control the four-DoF motion of a robotic arm. Most of these interfaces only allow single axis control without providing neither positioning assistance nor force feedback, thus may require the operator to visually check the foot posture. This chapter presents the design of a novel foot interface overcoming the limitations of the existing foot interfaces in robotic surgery. The novel four-DoF passive interface enables an operator to control a slave robotic arm with continuously changing directions and speeds. The parallel-serial hybrid mechanism of this interface is conceived to pick up natural foot movements and integrates a ground support that reduces fatigue. Specially designed modules provide simultaneous force and position sensing and feedback for skillful control with an unlimited force range in a small foot movement range (less fatigue).

The chapter presents the design of a passive four-DoF foot interface to control the third surgical robotic tool. Section 3.2 presents the design requirement and specifications. Section 3.3 describes the design concept and working principle of the proposed foot interface. Then, Section 3.4 shows the detailed design of the structure. Section 3.5 summarises the novelties of the proposed interface.

3.2 Design objective and specifications

3.2.1 Design objective

Based on the literature survey and discussion in the last Chapter, we can found that there are challenges in applying the foot to control a robot.

Firstly, lower limbs account for more than 30% of the human body weight. Moving the whole leg for long surgical operations will cause much fatigue. According to an examination of the human factors of foot operation and the consideration of the application in the surgical operation room, we set some constraints to minimize the fatigue: 1) One-foot operation is selected rather than two feet, as moving two feet was more tiring than moving just one, and to enable the other foot to be used for other functions, e.g., foot pedal of diathermy; 2) The mid-air gesture of lifting foot and stepping should be avoided. All selected foot motions should be kept in a small range within the allowed motion range of foot biomechanics; 3) Friction force of foot sliding on the ground may become the main source of the physical fatigue and thus should be reduced.

Secondly, control command repeatability is an essential factor, and even more important than accuracy. Considerable anatomic variations are found in human, based on the complex foot anatomy and diverse biomechanics. It can be foreseen that, the range of foot motion and force will exert a large diversity between users. Thus it may be necessary to introduce a subject-specific control strategy to fit different users' foot motion characteristics in the developed foot interface.

Thirdly, as studied in the literature, the haptic feedback may improve foot performance. It will be beneficial if the proposed interface provides positioning assistance and haptic feedback. The passive elastic element can provide sufficient proprioception

feedback with low cost and simple structure. This inspired us to design a special feedback-sensing module.

Therefore, the proposed foot interface should enable four-DoF control with one foot; provide foot support during foot movement with friction reduction mechanism. The small range of foot input should not lead to the ceiling effect of sensing, the position-force combined sensing is considered to endow intuitive motion mapping with unlimited input depending only on the human capability. Haptic feedback and individual adaption will assist the user in improving the performance of foot control. The foot interface will work together with two hand controllers (e.g. Force dimension hand controllers) to control three robotic arms in both virtual reality and real surgical scenarios.

3.2.2 Design specifications

From the overall project objectives described in Chapter 1, and the reviews on critical biomechanical aspects of human foot and state-of-art foot interfaces in Chapter 2, the proposed foot interface considers the following design requirements:

1. Interface functionality:

- The interface should enable to control of at least four-DoF movements of a slave robot; the multi-DoF foot information should be collected without coupling.
- The motion it controls should not be limited to single Cartesian directions, but supports any free spatial movements.
- The foot interface should have a modular design so that it can be easily integrated into a medical system or a robotic system as a master controller.

2. Assistance to operation:

- The interface should not require the hand operation.
- It should provide haptic feedback to facilitate operation control without visual check of the foot.

- The interface should not induce much physical fatigue during long time operation.
- The interface should be ergonomic, intuitive and easy to learn, with minimal learning time and mental effort required from the operator.

3. Safety:

- The risk of accidental activation should be avoided, e.g., “riding the pedal” [109].
- The interface should have a compact structure. As the space in the operation room is limited [110].
- The chance of losing contact with the foot pedal must be minimal [2].

4. Individual adaption:

- The interface should be usable with each foot. It should be easy and quick to adjust to different anthropomorphical characteristics.
- It should consider the individual anatomical and behavioural characteristics.

3.3 Working principle

3.3.1 Foot gestures selection

Based on the lower limb's biomechanics, the foot can output up to seven-DoF foot motions (including the toes). When using those gestures to control a device, we should consider three points: Firstly, the selected gestures should be comfortable and should not cause excessive fatigue to the operator; Secondly, the input gesture should have high repeatability to ensure stable control. Thirdly, the mapping between the foot gestures and the slave robot should be intuitive and easy to learn without introducing mental effort. The following strategies are applied to satisfy the requirements, and to select appropriate foot input gestures.

Minimum energy consumption

The entire human lower extremity weighs on average approximately 31.2% of our body mass, of which 19.4% is from the thighs, 9.0% from the legs, and 2.8% from our feet [76]. Because the lower limbs weigh a lot more than the upper limbs, their movement tends to be more tiring than arms and hands. This fatigue stems mainly from: (1) the body weights need to be moved and the (2) friction with the environment. While it is difficult to model the energy required to move the body accurately, it can approximately be estimated as:

$$E = GH + F_f S,$$

$$G \leq (m_{foot} + m_{shank} + m_{thigh})g = \alpha\%W_b, \quad (3.1)$$

$$\min(E) \rightarrow \min(G) \& \min(F_f)$$

where H and S are effective motion distance for gravity and friction force, m_{foot} , m_{shank} , m_{thigh} are the masses of the respective limbs, and F_f the friction force, and W_b is the whole body mass. Accordingly, the effort needed to perform a foot gesture is estimated and listed in Table 3-1.

Table 3-1: Limbs involved in movements to different directions.

	% of W_b	z_f	x_f	y_f	r_x	r_y	r_z
F_f	-		×	×			×
Foot	1.4	×	×	×	×	×	×
Shank	4.5	×	×	×			
Leg	9.7	×					
E	-	15.6% W_b	5.9% $W_b + F_f$	5.9% $W_b + F_f$	1.4% W_b	1.4% W_b	1.4% $W_b + F_f$

× indicates that there is friction or that the respective body part is moved in this motion.

We see in this table that the foot translation in z_f direction requires a significant effort as the whole leg has to be lifted up. Using foot support dragging on the ground can reduce the effort against gravity but will introduce friction, which should be minimised through the interface design.

Repeatability and accuracy

Table 3-1 suggests that foot rotations require less effort than translations. However, the complex anatomy and large diversity of the ankle joint may prevent stable and consistent control commands, especially when three-DoF foot rotations are all included. To avoid coupling different foot gestures, some foot interface [70] set relatively large thresholds for foot rotations, and perform gestures one by one in a sequential manner. Amongst the three-DoFs of foot rotations, the dorsi/planarflexion and abd-/add-uction are commonly used in vehicle control and human computer interaction (HCI), as these DoFs have a relatively large motion range and little deviation. In comparison, the foot inversion and eversion have a smaller motion range, which may confuse with the foot pronation and supination.

Compared to the hand, the foot motion is less accurate and slower [111]. The feet move 1.6 to 2 times slower than the hands, but this difference can be reduced with practice [112]. T. Han et al. [113] have investigated the foot kick gestures and how well users were able to control the direction of their kicks. They found that users have a best performance when the movement range is divided into segments of at least 24° . Additionally, the users have difficulty in controlling the velocity of the kick, but can remember two broad ranges of velocity. Because of the limitation of accuracy of foot, Raisamo and Pakkanen suggest that the feet should be limited to low fidelity tasks, in which accuracy is not crucial [111], such as menu selection, non-accurate spatial tasks. However, D. Podbielski et al. [114] have compared the hand- and foot-activated surgical tools in ophthalmic surgery and found hand and feet have similar performance.

Considering the factors of human effort, ergonomics and intuitive mapping, four-DoF foot motions are selected. They are foot lateral/medial rotation (shank roll), the two-DoF foot translations in the horizontal plane (shank yaw and pitch) and the foot

dorsiflexion and planarflexion (foot pitch). The foot eversion/inversion DoF is not used in the proposed design due to the poor control capability and relatively small motion range. The mid-air gesture of foot translation in the vertical axis is also not involved.

Figure 3-1: (a) Four-DoF foot movements and (b) Placement of the feedback-sensing modules.

3.3.2 Motion mapping between foot and surgical tool

The novel foot interface is designed to map the natural foot gestures as directly as possible to the surgical instruments, e.g., rigid laparoscopic tool in laparoscopic surgery or flexible endoscope in endoscopic surgery.

Mappings

The foot gestures should be collected and mapped effectively to the control commands. Based on the selection of the input foot gestures to control the slave robot's multiple-DoF movements, we could discriminate three mappings: 1) one-to-many: The number of foot gestures selected is less than the DoF needs to be controlled; so one gesture is used repeatedly on two or more DoFs. For example, the planar button-based foot

interface [56], [59] is using lifting up the foot and stepping to activate multiple DoFs by pressing different buttons. 2) many-to-one: multiple foot gestures activate one DoF movement of the robot. For example, when using wearable Inertial Measurement Unit (IMU) foot interface in [69], [70], move each joint of the robot require the operator heel off the ground to start the robot, foot inversion or eversion to change joints, then using foot left/right movement to control a particular joints. Both one-to-many and many-to-one mapping can provide stable operation and multiple-DoF motion control. However, these mappings may be not intuitive and user-friendly, especially when controlling more than three DoFs movements without visual assistance. The operator either need to frequently lift up their leg and find correct button or memorize a serial of control commands. Which may introduce complex planning and may lead to ineffective operation [115]. In addition, these two mappings do not allow simultaneous control of the multiple DoFs and also difficult to perform tri-manual operation cooperating with natural hands. 2) One-to-one: using continuous foot gestures as the output command directly control the multiple DoFs of the slave robot. This mapping could take advantage of the natural control mechanism fully optimized in humans [116].

Figure 3-2: Mapping natural foot motions to control the four DoF movements of (a) laparoscopic instrument and (b) flexible endoscope.

Foot movements to control a laparoscopic tool

The conventional laparoscopic tool, e.g., a laparoscopic camera, use four-DoF positioning (Fig. 3-2a upper panel): in/out translation, two rotations around the trocar at the incision of the abdominal wall, and rotation around the longitudinal axis of the tool. The three rotations can be conducted in a curved plane around the pivot point, and the in/out translation can be controlled separately. Correspondingly, humans can rotate the shank around the knee, leading to foot translations and rotation in the horizontal plane. Four-DoF specific foot motions (Fig. 3-2a lower panel) were selected to provide an intuitive mapping to control the laparoscopic tool: *i*) foot forward/backward movements control the pitch of the tool, *ii*) foot lateral movements control the yaw of the tool, *iii*) foot lateral/medial axial rotation maps to the roll of the tool, *iv*) the dorsi/planta-flexion of the ankle controls the in/out translation of the tool.

A relatively small workspace has been set to avoid uncomfortable operation and human fatigue. Specifically motions *i*) and *ii*) are limited to 2cm; *iii*) is maintained within 12.5° and *iv*) within 10°. Further, fatigue can be minimized by letting the foot be supported by the interface.

Foot movements to control a flexible endoscope

The flexible endoscope has a long flexible shaft with a bending tip. It can move in four DoFs (Fig. 3-2b zoomed view): two-DoF bendings of the tip and, translation and rotation DoFs along the longitudinal axis. Similarly, the four DoFs of the endoscope can be controlled by foot motions (Fig. 3-2b): *i*) The foot pitch DoF control U/D bending of the endoscope distal tip; *ii*) The foot yaw DoF map to L/R bending of the endoscope distal tip; *iii*) Foot forward/backward motion control endoscope in/out motion; *iv*) The endoscope rotates along with itself when the foot and shank conduct

lateral rotations around the thigh, reflected as foot left/right translations. The detailed information of the foot-controlled flexible endoscope can be found in Chapter 7.

3.3.3 Feedback-sensing modules

The feedback-sensing modules are designed and located around the foot to sense and assist the foot motions. They entail four main characteristics for the foot interface system: *i)* enable recording both position and force inputs in a small workspace with force that is limited only by the operator's abilities; *ii)* facilitate accurate and comfortable foot motion through a compliant interaction; *iii)* provide automatic homing assistance without singularities in the workspace; *iv)* yield dynamic position/force feedback to enable accurate control.

Figure 3-3: Feedback-sensing module in elastic mode (a) and in isometric modes (b,c). v : velocity, F_e : force exerted by the foot, F_s : elastic force, F_r : reaction force.

There are eight feedback-sensing modules placed around the foot (Fig. 3-1b) to collect the above mentioned foot motions and provide feedback. Each feedback-sensing module consists of an elastic element set against a force sensor [101] as illustrated in Fig. 3-3. The mobile part is activated by foot movements whilst the elastic element is deformed under the force of the foot motion/force detected by the force sensor. The measured forces can then be used to calculate the deformations of the elastic module which are used to calculate the position and orientation of the mobile part through its kinematics. The whole foot operation is separated into an elastic mode (Fig. 3-3a) and an isometric mode (Fig. 3-3b,c). Within the elastic element's motion range, the foot

is free to move (with reaction forces from the springs), and the position/force of the foot can be used as the output of the interface to control a robotic arm; this yields the *elastic control mode*. Once the elastic element reaches the elastic limit (e.g., the fully compressed compression spring in Fig. 3-3b) or mechanical constraint (Fig. 3-3c), the foot cannot move beyond the boundary. However, the force can still be increased by the user. This force signal yields the *isometric control mode*. The continuous transition of the elastic and isometric modes creates an interaction providing rich proprioceptive information to the operator with a force range limited only by their strength.

3.3.4 Interface structure selection

When determining the foot interface structure, we consider three aspects that the foot interface should 1) not affect foot natural motion; 2) assist the foot to move accurately or decouple noisy foot motion; 3) fit the application scenario;

Figure 3-4: Interaction between foot motion and foot interface.

Foot motions will bring dynamic interaction between the foot and the foot interface. The foot interface should accurately record the foot motion and let the operator focus on their own motion. However, unlike hand which can perform grasping gesture and move the grasping point, one DoF foot motion may bring coupling of multiple DoFs

in the foot interface. For example, when the foot is moving forward, as seen in Fig. 3-4, there will be a torque M on the pedal:

$$M = (F_{foot} + F_{friction}) \frac{H_{pedal}}{2} \quad (3.2)$$

where H_{pedal} is the height of the pedal, F_{foot} and $F_{friction}$ are foot driving force and friction force between pedal and the base. This torque M will also rotate the pedal so that the pedal cannot support the foot well and introduces coupling in forward-backward translation DoF and pitch rotation DoF. This issue can be addressed by 1) reducing the pedal height H_{pedal} , 2) providing a contra-directional torque and 3) minimizing the friction force.

Furthermore, the planar foot motion may bring foot pressure in vertical directions. We have performed a small test (described in Appendix A.1) by placing six FSR sensors at the bottom of an insole and monitoring the trajectory of foot center of pressure (CoP). The results confirmed that foot planar movement also introduce pressure vibration which need to be considered in the foot interface design. This is the reason why we designed DoF redundancy in vertical axis and chose relatively larger stiffness of the torsion spring and located feedback and sensing module out of the vibration area for pitch rotation DoF. For the other three planar DoFs we used six compression spring feedback and sensing modules located around the pedal. The redundancies could help to enlarge the motion workspace and guarantee a more accurate signal [117], [118].

In addition, the interface was designed to control a surgical tool. It could be easily integrated with a robotic surgical system, e.g. Da Vinci robotic system, to control a third surgical instrument. The space limitation of the operation room (OR) determines the general dimensions of the foot interface. For example, the Carl Zeiss Surgical Wireless Footswitch to control the microscope has dimensions of $415 \times 245 \times 110mm^3$ (Length $\times$ Width $\times$ Height). The foot pedal of the Da Vinci Classical system is about $540 \times 480 \times 110mm^3$ in dimension and the height of hand controllers to the ground is

about 740 mm. If the foot interface is too high, the legs in sitting posture may affect the operation of hand controllers. Thus, in general, the cross section of the developed foot interface is better within $540 \times 480\text{mm}^2$ (the foot pedal space of the Da Vinci master console) and the height of the foot interface is better below 150 mm.

The interface could be designed with a i) serial structure, e.g. Phantom omni hand interface (Sensable Technologies Inc.); ii) a parallel structure, e.g. Steward robot, Delta robot; iii) a parallel-serial structure, e.g. Force Dimension Omega/sigma hand interfaces. We have designed a serial structure (See appendix A.2) but found it is difficult to achieve the dimension requirement. In addition, a serial structure may lead to large error due to the error accumulation of serial joints. We selected a parallel-serial mechanism with a planar parallel structure and a serial embedded pedal. This structure effectively reduces the height of the pedal to only 102 mm, which is similar with the height of the common foot interface in OR.

3.3.5 Home position with the minimum of global elastic energy

The two structure diagrams of the foot interface can be illustrated in Fig. 3-5a and e. The foot is support by a mobile pedal and can drive the pedal to move in four DoFs with respect to the fixing base. The six feedback sensing modules with elastic elements are placed around the foot connecting the pedal and the base forming a parallel structure.

Instead of using the design that feedback-sensing module is locating between the pedal and the base (Fig. 3-5a), we finally select to place six compression springs outside the base (Fig. 3-5e). When there is no force on the pedal, it remains horizontally; Six compression springs are equally compressed with pre-tension forces, keeping the pedal in the middle of the base. This position is defined as the home position. This former design (Fig. 3-5a) has a poor self-center mechanism. The compression spring

Figure 3-5: (a) A naive design (not selected in this study) with springs between the base and MF (b,c) exhibiting two singular postures and (d) elastic energy changing curve with yaw rotation angle. (e) Improved design with (f,d,g) global energy minimum.

system will only stable in the position with minimum global elastic energy. The resultant torque making the pedal rotates is much bigger than the torque helping it go back to the home position. The extreme rotation positions, shown in Fig. 3-5b and c, have the smallest spring potential energy (Fig. 3-5d) which cause singularities in the workspace. Thus, after the external force is removed, the pedal assembly tends to stay in the extreme rotation positions rather than go back to the home position. In comparison, putting the compression springs outside the base defines a well homing mechanism (Fig. 3-5e). The compressing forces (from the compression springs) to the pedal transmit to pulling forces. The resultant force and torque are zero and a minimum of global elastic energy for the whole system is achieved at the home position. Once the operator releases the pedal, the interface will return to that home position automatically, providing a chance for the operator to rest his or her foot.

3.4 Mechanical design

3.4.1 Design overview

The interface is designed as a parallel-serial hybrid mechanism controlled by foot interacting with a pedal. Foot motions drive the pedal and mobile frame (MF) resulting in sliding in the horizontal plane in two translations x, y and one rotation ϕ (2T1R) in a parallel structure with six feedback-sensing modules integrating a compression spring and a load cell (Fig. 3-6a). The pitch rotation θ of the pedal is activated by foot dorsi-/plantar-flexion, which is decoupled from the horizontal movements through an extended serial structure with two feedback-sensing modules integrating torsion springs (Fig. 3-6b). The parallel mechanism provides a simple and compact structure with low inertia and high accuracy through closed-loop kinematics. The serially connected pedal provides a relatively large space for the foot to control the in/out translation of the laparoscopic tool.

Figure 3-6: Passive four-DoF foot interface. The schematic diagram in (a) top view and (b) side view at home position (dotted lines show a random position of the pedal). (c) Zoomed view of torsion spring feedback-sensing module.

The elastic mode of the system is achieved through the elastic network with eight springs providing dynamic real-time passive force and position feedback. The usage of force sensors instead of position sensors collects force information of the operator's foot within and even beyond the geometric workspace, enabling transition between the elastic and isometric modes. The isometric mode can be activated either by the fully compressed compression spring (Fig. 3-6a) or by mechanical constraint (e.g., in Fig. 3-6b, θ reach the largest value when the moving block hits the fixing block).

Figure 3-7: 3D structure of the foot interface. Perspective view (a) and mobile frame and pedals' side view (b). Explosive views of compression spring feedback-sensing module (c) and torsion spring feedback-sensing module (d).

The 3D model of the foot interface is presented in Fig. 3-7. The interface includes a base which is fixed on the ground, a mobile frame (MF), a pedal with an adjustable foot fixture and the feedback-sensing module with the spring and force sensor. The base and the MF are assembled in a parallel structure, connected with six guides and pivot joints (Fig. 3-7a). The corresponding feedback-sensing modules are assembled on the guides (Fig. 3-7c). The MF and the pedals' structure is shown in Fig. 3-7b.

The pedal plate for the foot is serially mounted on the mobile frame with a pivot shaft and two vertically placed feedback-sensing modules (Fig. 3-7d), acting as an input component for pitch rotation θ . An adjustable foot fixture mechanism (Fig. 3-7a,b) attached to the pedal enables an operator specific adjustment to the foot size yielding comfortable but rigid fixation. This fixture is composed of four foot-shaped guides connected to eight guide screws to achieve flexible adjustments in length and width by easily twisting the handle. The foot-shaped guides (fabricated using 3D printing) can fit well different human foot anthropometry from foot size sizes from 35 to 46 in the European standard [119].

3.4.2 Elastic elements

The six compression springs and a pair of torsion springs form a spring network with four DoFs:

Compression spring

Springs of different stiffness $\{0.01, 0.02, 0.03, 0.05, 0.1\}$ N/cm were tested, and the 0.02 N/cm compression spring was selected as it was not too hard to press while providing sufficient haptic feedback. Compression rather than extension springs were used, which yield force measurement even when fully compressed and are simple to assemble.

Torsion spring

A pair of torsion springs with 46.3 Ncm/ $^{\circ}$ stiffness was selected for the pitch rotation DoF in order to provide an elastic force with the pedal motion. The torsion springs are mounted symmetrically but in the reverse direction around the pivot rotation shaft which supports the pedal plate. The lower fixed arm is horizontally placed as a reference arm. The torsion springs do not directly contact the shaft leaving a

rotation margin as the inner diameter of the torsion spring changes a little during operation (Fig. 3-7d). The v-shape lock and the slot on the load cell tray are designed to fix and avoid noisy shaking of the torsion spring's upper limb in radial and axial translation. The maximum twisting angle of the pedal plate (from the initial position) was mechanically limited to $\pm 10^\circ$. This can be reached once the stopper (moved with the pedal plate) is touching the vertical plane of the pivot shaft seat (Fig. 3-7d).

3.4.3 Feedback and sensing

The eight springs form a compliant system providing haptic feedback of force and distance via the interaction of the operator's foot and the pedal. In the foot interface, the haptic feedback is provided in a dynamic and real-time way in accordance with the operator's foot motions. The three DoFs in two translations and one rotation inside the base horizontal plane will lead to movements of six spring guides. The movement of each guide is coupled with the varying force of the responding compression spring. Different pedal movements will bring different compressing states for the springs' system. The combined motions of any single directions will bring combined haptic feedback. For instance, the operator will receive diagonal displacement and force feedback when they conduct diagonal movement.

The forces applied by the operator are translated into electrical signals through eight force sensors (LW1025-25 from Interface, Inc., USA). To ensure that the springs can effectively transmit forces to the loadcells in any poses of the pedal, a 5.6N pre-compression and a 57N pre-tension force are applied for each compression spring and torsion spring respectively at home position. While the pedal's movement is limited by the deflection range of the compression spring (for DoFs in 2T1R) and mechanical constraint (for DoF in pitch rotation), the force detection range is not restrained, i.e., once a compression spring is fully compressed, or the pitch rotation reaches the limit

angle, the isometric force continues to build up and is therefore still measured by the loadcell.

3.4.4 Friction reduction

Three DoFs of foot motions in the horizontal plane are selected as the input to the proposed system. Those gestures require the foot driving the pedal to move on the surface of the base. The friction of dragging will introduce fatigue and affect the performance of the user.

Figure 3-8: Design solutions to minimise friction.

In the design, we have implemented a series of measures to keep friction low (Fig. 3-8). This includes: *i*) Four ball bearing universal wheels mounted on the bottom of the mobile plate to avoid sliding friction; *ii*) In each module the linear bearing is mounted on the spring guide rod to minimise the sliding friction between the guide rod and the O-shaft; *iii*) Two radial bearing are mounted between the base bracket and the O-shaft in order to reduce the friction of the hinge joint. *iv*) Furthermore, considering the parallel structure of the foot's planar movements, the dynamically changing pressure accompanying the foot movement causes small vertical fluctuations that may lead to

radial forces and resistance in the axial motion. Ball joint rod end bearings (connecting each guide rods with the mobile plate) and radial spherical plane bearings (assembled in the O-shaft around linear bearing) allow vertical movement and avoid resistance due to vertical fluctuations.

Figure 3-9: Friction estimation. (a) Principle of estimation experiment. (b) Experimental setup.

We have carried out a simple test to estimate the friction. We see in Fig.3-9a that friction can be described through:

$$N = G \cos \alpha, \quad f = G \sin \alpha, \quad f = \mu N, \quad \mu = \tan \alpha \quad (3.3)$$

where α is the slope angle, G the gravitational force on the object and N the support force normal to the slope and f the friction force along the slope. When the slope angle α is small, the object remains static. We record the angle α at which the object just starts to move, and the friction coefficient is equal to the tangent of this angle.

After taking out the six compression springs and conforming the platform's levelness using gradienter, one end of the base plate of the foot interface system was slowly lifted using a simple lever mechanism with an adjustable clamp (Fig. 3-9b). We recorded the lift height of the base when the mobile plate was just starting to move. The procedure was repeated five times. The resulting friction coefficient was about

0.018 to 0.026 and the friction force about 0.81N to 1.17N for the foot interface system.

3.5 Discussion and conclusion

Compared to existing foot interfaces for robotic surgery [56], [57], [63], [64], [71], the interface presented in this chapter provides a natural motion mapping from the foot to the robot. This enables users to continuously adjust the movement directions and flexibly vary its speeds. The parallel-serial hybrid mechanism of this interface is conceived to pick up four-DoF foot movements. Specially designed feedback-sensing modules provide simultaneous force and position sensing and feedback for skillful control. This facilitates efficient foot positioning without requiring any visual check of the foot (especially useful for novice users). The dedicated sensing of the proposed foot interface provides users with a large force range while requiring only small movements and providing a resting place with automatic homing. In addition, the motion friction is effectively reduced to enable long time operation without much effort. However, some limitations should be noted. First, the interface is designed to control maximally four DoFs. It cannot control six-DoF spatial motion and grasping. Second, the proposed foot control is suggested to control assistive surgical tools, such as laparoscopic camera, flexible endoscope or suction tool etc, which perform discrete spatial navigation without direct contact with tissue. It is not recommended to control electric knife or monopolar hook which requires continuous fine movement and perform the main cutting procedure.

In summary, the proposed interface has following features:

1. The developed interface uses a parallel-serial hybrid structure with four-DoF control without the coupling of motion in a compact structure. Also, the movement is not limited to a single discrete direction but, in contrast, can yield any combination

of directions in four DoFs. For instance, the robotic arm can be controlled by the foot to move in diagonal directions (e.g., both forward and right) and modify the direction continuously.

2. The mechanism provides feedback in force and position via the elastic interaction between the interface and the operator's foot. The movement distance of the pedal assembly is increasing monotonically with the imposed force, through which the surgeon can sense the pedal's position and thus receive real-time dynamic haptic feedback. This allows the surgeon to control various conditions without having to control the foot position using vision, thus improving efficiency and reactivity.
3. The interface has an automatic positioning mechanism comprising multiple springs yielding a single minimum of elastic energy. This can bring the system to home in the posture corresponding to this global minimum when the foot is relaxing, which is the position of the interface with pedal assembly located in the center of the base space. Once the surgeon finishes operation movements and releases the pedal, the interface will automatically go back to this neutral position, thus providing a resting position for the operator's foot.
4. The system uses elastic-isometric elements. The interaction information between the foot and the interface is collected through force sensors. The operators can perform natural motions and continue to increase the force when they reach the workspace boundary of the foot interface. The operation does not require moving over a large area; thus the interface can be compact. Besides, this design avoids the ceiling effect of the input signal. The input signal can be set individually based on specific requirements.
5. The interface software has a built-in technique and algorithm to extract individual operator commands based on natural foot movement patterns thus yielding

intuitive and efficient control of a slave mechanism e.g., a robot arm equipped with surgical tools, as will be described in Chapter 4.

Chapter 4 Computation of Motor Commands

4.1 Summary

In those teleoperation systems, operators remotely control the slave robot through the master interface. The master interface is supposed to be intuitive to use and easy to learn when the personalized control pattern of users [120] is integrated into the control strategies with data-driven methods [121]. As we have studied in section 2.3, the users differ in their biomechanical parameters and movements. The unpredictability of joint axis location and body segment sizes may deteriorate the operation performance. If the system could identify the specific characteristics of an operator, this may give them relatively stable control commands by diverse from the other operators.

This chapter first derived kinematic and statics models of the novel interface, which can be used convert foot motion/force signals to four-DoF external control commands in elastic or isometric states. Then a data-driven technique is developed which can adapt the interface to the specific user's motion patterns. In the experiment section, a pilot test with ten subjects was conducted to study the foot motions interacting with the foot interface. The variability of foot motion in multiple directions inter and between subjects were studied. Given the variable motion behaviour of each subject, the data-driven methods reflects individual motion characteristics and reduces the deviation than the analytical method. Another teleoperation test was also conducted to verify the system and modeling methods. In general, Section 4.2.1 presents how to

map the foot force to control commands using analytical and data-driven mappings. Section 4.3 describes two experiments to test the mapping methods and validate how the interface can be used to teleoperate a robot in the typical tasks of surgical training. Section 4.5 analyzed the result and presents the conclusion.

4.2 Computation of motor commands

4.2.1 Analytical modeling

In this section, a kinematic model of the novel interface is first derived in Section 4.2.1. This direct kinematic model can be used to compute how the foot movements can be translated to external commands in elastic mode. A static model is then derived in Section 4.2.1, which can be used to compute the motor command from the applied forces in isometric mode. Alternatively to this analytical model, it is possible to identify a mapping from the eight force sensors to the intended motor command directly from the data of a specific operator. Such a data-driven approach using Independent Component Analysis (ICA) is developed in section 4.2.2.

Kinematics

The kinematics of the three DoFs of 2T1R can be simplified as planar movements within a 6-RPR planar parallel mechanism as shown in Fig. 4-1a in which the pedal is constrained and connected to the base with six guides with hinge joints on both sides (represented as points A_i on the base and B_i on the MF). A fixed base reference frame $\{O-xy\}$ and mobile reference frame $\{C-x'y'\}$ are assigned to the centroid of the base and the MF square plane, respectively.

The position vector of point A_i is defined by the vector $\mathbf{a}_i \equiv [a_{ix}, a_{iy}]^T$ expressed in the fixed frame $\{O\}$ whereas the position vector of point B_i is defined as $\mathbf{b}_i \equiv [b_{ix}, b_{iy}]^T$

Figure 4-1: The schematic diagram in (a) top view and (b) kinematic model of i th compression spring.

in the mobile frame $\{C\}$. They can be represented using a, b, a', b' , the lengths and widths of base the and the MF square, and c, c' , the distance between the laterally located linear spring guides, equal to lengths A_3A_5 and B_3B_5 . The position of the MF reference frame $\{C\}$ relative to the base reference frame $\{O\}$ is defined by the vector $\mathbf{p} = [x, y]^T$ connecting O to C , while its orientation is defined by the angle ϕ between the $\widehat{x}_O$ axis of the $\{O\}$ and the $\widehat{x}_C$ axis of the $\{C\}$. The length of i th spring guide between the attach points of base A_i and the MF B_i is denoted as L_i . Finally, let $\mathbf{u}_i \equiv \overrightarrow{B_iA_i}/L_i$ denote the unit vector along i th spring guide, and $\mathbf{L}_i \equiv L_i \mathbf{u}_i$.

Using these definitions, the closed mechanical chain of Fig. 4-1a can be expressed as

$$\mathbf{L}_i = \mathbf{a}_i - \mathbf{p} - \mathbf{R} \mathbf{b}_i, \quad \mathbf{R} \equiv \begin{bmatrix} \cos \phi & -\sin \phi \\ \sin \phi & \cos \phi \end{bmatrix}, \quad (4.1)$$

where $\mathbf{R}(\phi)$ is the rotation matrix from the fixed frame $\{O\}$ to the mobile frame $\{C\}$. For this parallel mechanism, the *inverse kinematics*, i.e., calculating the guide lengths L_i as a function of the pose translation $\mathbf{p} = [x, y]^T$ and rotation ϕ , can be computed

from the closure constraints:

$$L_i^2 = (x + b_{ix}c - b_{iy}s - a_{ix})^2 + (y + b_{ix}s + b_{iy}c - a_{iy})^2 \quad (4.2)$$

where $c \equiv \cos \phi$ and $s \equiv \sin \phi$. For the *forward kinematics*, given $\{L_i, i = 1, 2, \dots, 6\}$, $\mathbf{X} = [x, y, \phi]^T$ can be derived by solving the six scalar equations (4.2), yielding

$$\begin{aligned} x &= \frac{F(a'\sqrt{4P^2 - E^2} - 2aP) - 2bEG}{4Q\sqrt{4P^2 - E^2} - 8PM} \\ y &= \frac{2G(b'\sqrt{4P^2 - E^2} - 2bP) + a'EF}{4Q\sqrt{4P^2 - E^2} - 8PM} \\ \phi &= \arcsin \frac{E}{2P}, \quad P \equiv bc' - b'c \\ E &\equiv L_4^2 + L_5^2 - L_3^2 - L_6^2, \quad F \equiv L_3^2 + L_5^2 - L_4^2 - L_6^2, \\ G &\equiv L_2^2 - L_1^2, \quad M \equiv ab + a'b', \quad Q \equiv ab' + a'b. \end{aligned} \quad (4.3)$$

The magnitude of the guide length L_i is derived from the delta compression spring forces f_i via Hooke's Law:

$$L_i = L_{0i} + \frac{f_i}{k_i}, \quad f_i = f_{ci} - f_{0i}, \quad i = 1, 2, \dots, 6, \quad (4.4)$$

where k_i is the compression spring stiffness constant of i th spring. L_{0i} , f_{0i} are the original length and pretension force of i th spring guide and spring at home position, respectively. f_{ci} is i th load cell's reading. The pitch rotation angle is

$$\theta = \frac{M_x}{K_p}, \quad (4.5)$$

where M_x , K_p are the rotation torque and stiffness constant in pitch DoF which will be derived in eq.(4.12).

Figure 4-2: (a) statics forces in x - y horizontal plane and (b) pitch rotation DoF.

Statics

With the force analysis in the horizontal plane of Fig. 4-2a, the resultant elastic force and torque of $\mathbf{F}_R$ and $\mathbf{M}_z$ can be computed from the compression spring forces $\mathbf{f} = f_i \mathbf{u}_i$, $i = 1, 2, \dots, 6$. As we described in the last section, there is a pre-tension force for each spring to make sure the springs are working in any configuration in the workspace. Thus the forces f_i are always pulling forces to the MF.

The magnitudes of the spring force f_i are collected from load cell readings. The direction vector $\mathbf{u}_i$ are calculated from the kinematics model using the geometric relationship:

$$\overrightarrow{A_i B_i} = \overrightarrow{O B_i} - \overrightarrow{O A_i} = \begin{bmatrix} x + b_{ix} \cos \theta - b_{iy} \sin \theta - a_{ix} \\ y + b_{ix} \sin \theta - b_{iy} \cos \theta - a_{iy} \end{bmatrix} = \begin{bmatrix} x_{AB} \\ y_{AB} \end{bmatrix} \quad (4.6)$$

In elastic mode, the direction of $\mathbf{f}_i$, $\mathbf{u}_i$ is noted as the tangent value of angle α_i , and β_i is the angle between vector $\overrightarrow{C B_i}$ and $\overrightarrow{A_i B_i}$ which represent the angle between the force

vector $\mathbf{f}_i$ and the lever arm vector $\mathbf{b}_i$. They can be derived with equations:

$$\begin{aligned} \tan\alpha_i &= \frac{y_{AB}}{x_{AB}} = \frac{y + b_{ix}\sin\theta - b_{iy}\cos\theta - a_{iy}}{x + b_{ix}\cos\theta - b_{iy}\sin\theta - a_{ix}} \\ \cos\beta_i &= \frac{\overrightarrow{CB_i} \cdot \overrightarrow{A_iB_i}}{|\overrightarrow{CB_i}| |\overrightarrow{A_iB_i}|} \end{aligned} \quad (4.7)$$

Thus, the force $\mathbf{f}_i$ can be divide into component force in x and y directions, represented as $\mathbf{f}_{ix}$ and $\mathbf{f}_{iy}$, the moment due to i th spring compression force around MF mass center C is noted as $\mathbf{M}_i$:

$$\begin{aligned} \mathbf{f}_{ix} &= f_i \cos\alpha_i, \mathbf{f}_{iy} = f_i \sin\alpha_i \\ \mathbf{M}_i &= \mathbf{f}_i \times \mathbf{b}_i = |\overrightarrow{CB_i}| |f_i| \sin\beta_i \end{aligned} \quad (4.8)$$

When regarding the force interface structure as a rigid, the component force $\mathbf{f}_i$ can move to the center of the mass center C of MF with corresponding $\mathbf{M}_i$. Thus, the corresponding statics equations are:

$$\begin{aligned} \mathbf{F}_x &= \sum_1^6 \mathbf{f}_{ix}, \quad \mathbf{F}_y = \sum_1^6 \mathbf{f}_{iy}, \\ \mathbf{F}_R &= \sum_1^6 \mathbf{f}_i, \\ \mathbf{M}_z &= \sum_1^6 \mathbf{f}_i \times \mathbf{R} \mathbf{b}_i = \sum_1^6 \det(\mathbf{f}_i, \mathbf{R} \mathbf{b}_i), \end{aligned} \quad (4.9)$$

With the force analysis in the horizontal plane of Fig. 4-1b, the resultant elastic force and torque of $\mathbf{F}_R$ and $\mathbf{M}_z$ can be computed from the delta compression spring forces (the force sensor reading $\mathbf{f}_c$ minus initial force $\mathbf{f}_0$ at home position) $\mathbf{f} = f_i \mathbf{u}_i, i = 1, 2, \dots, 6$. The corresponding statics equations are:

which can be summarized in matrix form as,

$$\begin{aligned} \mathbf{W}_R = \mathbf{J}\mathbf{f}, \quad \mathbf{f} \equiv \begin{bmatrix} \mathbf{f}_1 \\ \vdots \\ \mathbf{f}_6 \end{bmatrix}, \quad \mathbf{W}_R \equiv \begin{bmatrix} \mathbf{F}_{xR} \\ \mathbf{F}_{yR} \\ \mathbf{M}_z \end{bmatrix}, \\ \mathbf{J} = \begin{bmatrix} \mathbf{u}_1, \dots, \mathbf{u}_6 \\ \det(\mathbf{u}_1, \mathbf{R}\mathbf{b}_1), \dots, \det(\mathbf{u}_6, \mathbf{R}\mathbf{b}_6) \end{bmatrix}, \end{aligned} \quad (4.10)$$

Where $\mathbf{J}$ is the structure matrix of the planar parallel structure. The stiffness matrix $\mathbf{K}$ in the motion workspace can be found by taking derivatives of $\mathbf{W}_R$ with respect to $\mathbf{X}$:

$$\begin{aligned} \mathbf{K} &= \frac{d\mathbf{W}_R}{d\mathbf{X}} = \mathbf{J} \frac{d\mathbf{f}}{d\mathbf{X}} + \frac{d\mathbf{J}}{d\mathbf{X}} \mathbf{f} = \mathbf{J}\mathbf{C}\mathbf{J}^T + \frac{d\mathbf{J}}{d\mathbf{X}} \mathbf{f}, \\ \mathbf{C} &\equiv \text{diag}(k_1 \dots k_6). \end{aligned} \quad (4.11)$$

The torque for the pitch rotation M_x around the center point C is obtained through the following equation:

$$M_x = f_7 b_7 - f_8 b_8, \quad K_p = \begin{cases} k_7 & \text{if } M_x > 0 \\ k_8 & \text{if } M_x < 0 \end{cases} \quad (4.12)$$

where f_7 and f_8 are delta tension force calculated from readings of load cells 7 and 8 minus the initial forces for the torsion springs at the home position (Fig. 4-2b). b_7 and b_8 are the arm lengths from pedal plate center C to positions of load cells 7 and 8, which can be modified according to the operators' habitual posture. The stiffness K_p in this DoF is directly reflected in k_7, k_8 , the stiffness constants of torsion springs 7 and 8, respectively.

The $\mathbf{J}_s$ and $\mathbf{K}_s$ of the four-DoF structure can then be rewritten as:

$$\mathbf{W} = \mathbf{J}_s \mathbf{f}, \quad \mathbf{f} = \begin{bmatrix} \mathbf{f}_1 \\ \vdots \\ \mathbf{f}_8 \end{bmatrix}, \quad \mathbf{W} = \begin{bmatrix} \mathbf{F}_{xR} \\ \mathbf{F}_{yR} \\ \mathbf{M}_z \\ \mathbf{M}_x \end{bmatrix}, \quad (4.13)$$

$$\mathbf{J}_s = \begin{bmatrix} \mathbf{J} & \mathbf{0} \\ \mathbf{0} & \mathbf{J}_p \end{bmatrix}, \quad \mathbf{J}_p = [b_7, -b_8], \quad \mathbf{K}_s = \begin{bmatrix} \mathbf{K} & \mathbf{0} \\ \mathbf{0} & \mathbf{K}_p \end{bmatrix}.$$

where the resultant wrench $\mathbf{W}$ is the feedback to the human. From the static equilibrium, the sum of the external force and moments $\mathbf{W}_e$ exerted on the pedal equal the resultant external wrench $\mathbf{W}$ exerted on the human foot.

When the pedal reaches a workspace's boundary, the system is in isometric mode. The force directions $\mathbf{u}_i$ are not changing as these are depending on the kinematics configurations. But the force magnitude can continue to increase as it is recorded by load cells coupled with the fully compressed compression spring(s) or the mechanically constrained torsion spring.

4.2.2 Data-driven approach to compute the motor command

The forces measured by the interface will reflect the operator's foot motion intention and can be used to control a device with four-DoF. A model that convert the force signals collected by the eight force sensors (Fig. 4-3a) $\mathbf{f}_i, i = 1, 2 \dots 8$ to the four-DoF intended motor command $\mathbf{D} \equiv \{x, y, \phi, \theta\}$ can be identified from the data of a specific operator.

In this data-driven approach, a calibration procedure is first conducted to collect single axis Cartesian motion data of left (L) & right (R), forward (F) & backward (B), left

(4.14)

where $\mathbf{f}_n$ is the z-score normalization form of delta force changes of the load cells' readings $\mathbf{f}$. The control command $\mathbf{D}$ is derived from the mapping matrix and the eight load cell readings. The FastICA algorithm [122] is then applied onto this data to derive a subject specific ICA model.

Once a subject-specific model is built using the calibration procedure described in the single direction task of Section 4.3.1, the subject-specific patterns are used online to predict further control commands with new inputs.

4.3 Experiment

Two experiments were conducted. The first experiment was to investigate subject-specific foot motion patterns, and the second to validate the use of the novel foot interface in a teleoperation system for controlling a robot.

4.3.1 Experiment1: Human motion intention and motion pattern

A pilot experiment was conducted with ten subjects (27.3 ± 2.2 years old, right foot dominant, 4 females) to study the precision with which they can control the interface in given directions using their dominant foot.

Experiment procedure

The subjects were seated comfortably on a chair in front of a table, and the foot interface was placed under the table at the home position. Each subject was asked to step their right foot on the pedal and adjust the positions of the fixture blocks to match their specific foot size. The *task* was to move the pedal from the home position along multiple specified directions to the boundary of the workspace. Once at the boundary, the pedal should be held for one second and returned back to the

home position. The task was shown to the subjects by the experimenter prior to data collection. The subjects were also informed of the desired target directions. No visual feedback of the foot posture was provided during the experiment. In this way, we could observe feedforward foot movements corresponding to any desired motion directions. Movements were carried out in single and diagonal directions:

Figure 4-4: Eight single Cartesian motion of the foot pedal.

Single Cartesian direction Each subject started at the home position. Three trials were conducted in each of the following eight directions: forward (F), backward (B), left (L), right (R), toe up rotation (TU), toe down rotation (TD), left lateral rotation (LL), and right lateral rotation (RL) in this order. This procedure was continuous without pause until all the $3 \times 8 = 24$ centre-out and back movements were completed. Then, the subject lifted down their foot and took a 30 seconds' break. Another group of 24 trials was repeated after that.

Common diagonal directions Each subject started at the home position. Three trials were conducted in the twelve common diagonal directions, which are the combination of the two single Cartesian directions, in the order of {left & forward (LF), right & forward (RF), left & backward (LB), right & backward (RB), left & toe up (LTU), right & toe up (RTU), left & toe down (LTD), right & toe down (RTD), forward &

Figure 4-5: Twelve diagonal motions of the foot pedal.

toe up (FTU), backward & toe up (BTU), forward & toe down (FTD), backward & toe down (BTD)}. $3 \times 12 = 36$ trials were conducted in diagonal directions.

Performance measure

Foot force data from load cells were recorded at 50Hz and smoothed offline by using a moving average filter with window size of 9. Then the force data were mapped to the pose vector $\mathbf{D} = [x, y, \phi, \theta]^T$ of the center point C on the pedal using the forward kinematics Eqs.(4.3, 4.5).

The actual initial position of the foot interface for each consecutive operation was considered as the calibrated home position. To compare different components of the pose, a point P on the pedal, $\mathbf{P} = [0, d, 0, 0]$ (with $d=11.5\text{cm}$) with respect to $\{C\}$, was selected as a reference point (see Fig. 4-1). The four-DoF position change of point P with respect to home position is represented as $\mathbf{P}_\delta = [P_x, P_y, P_\phi, P_\theta]$, where $P_x = x$, $P_y = y$, $P_\phi^2 = (d \sin \phi)^2 + (d - d \cos \phi)^2$, $P_\theta = d \sin \theta$, with the range $P_x, P_y, P_\theta \in [-2, 2]\text{cm}$, $P_\phi \in [-2.5, 2.5]\text{cm}$. A scaling factor $s=2/2.5$ was used for P_ϕ to bring the two

angles into the same range. The data of vector $\mathbf{P}$ was then filtered to remove the static position data using a resultant velocity threshold of 0.005m/s.

Foot-path error was used to quantify the performance in the trials,

$$E = \frac{1}{N} \sum_{i=1}^N \|\mathbf{e}_i\|, \quad \mathbf{e}_i \equiv \mathbf{p}_i - \hat{\mathbf{p}}_i = [e_{ix}, e_{iy}, e_{i\phi}, e_{i\theta}], \quad (4.15)$$

where $\mathbf{p}_i$ is the real trajectory points, $\hat{\mathbf{p}}_i$ the projection of $\mathbf{p}_i$ on the desired path, and N is the total number of samples for foot movements in each direction.

4.3.2 Experiment 2: Teleoperation

Four subjects (28.5 ± 3.3 years old, right foot dominant, 2 female) participated in the second experiment. A teleoperation system was built up using the proposed foot interface to command an industrial robot (IRB120, ABB robotics). The four-DoF motion of the foot in x, y, θ, ϕ are collected by the foot interface (Fig. 4-6a), which are used to control the speed of the robot in x_t, y_t, z_t, ϕ_t (Fig. 4-6b).

Figure 4-6: Mapping between (a) Pedal interface and (b) Slave robot.

Two tasks were used to test complex multi-DoF manipulation and speed control for accurate positioning, respectively. The experiment consisted of three phases: *i*) Calibration as described in the single direction task of Section 4.3.1, *ii*) Practice for five minutes, and *iii*) Testing consisting of the two tasks described below. At the end of this testing, the user answered the questionnaires to estimate the workload.

Figure 4-7: Teleoperation task 1. (a) Task scenario; (b) Task board; Enlarged view of (c) LED button and (d) robot end-effector tool.

Task 1: Spatial coordination

The first task consisted of following the 2D wire (of diameter 0.25cm, shown in Fig. 4-7b) with a ring (with inner diameter 0.8cm). The wire (fixed on a platform) has straight, curved, and diagonal sections. The ring is fixed to the robot end-effector and around the wire. It is initially placed at one end of the wire. The operator has to control it in x_t, y_t and ϕ_t and follow the wire without collision. One trial is completed when the tool reaches the other end of the wire. The trial is failed if a collision is detected and the robot then stops.

Two subjects started with ICA and the other with the kinematics mapping, but the subjects were not aware of the mapping method. Each subject conducted two successful trials with each mapping. A small zero band was defined in each DoF using the

calibration modeling data, the upper and lower limits in translation x, y and rotation ϕ, θ were identified as the 30% of the respective maximum and minimum values of the modeling data's mapping results in kinematics and ICA. The ranges are: $[-0.6, 0.6]$ cm for x, y , $[-4^\circ, 4^\circ]$ for ϕ , $[-3^\circ, 3^\circ]$ for θ when reported in the kinematic model. If a mapping's result falls into the zero band, it is regarded as zero output in the responding DoF. The robot speed was set at 0.6cm/s.

Task 2: Temporal coordination

Figure 4-8: Teleoperation task 2. (a) Task scenario; (b) Task board; Enlarged view of (c) LED button and (d) robot end-effector tool.

The second task required three DoFs control for accurate positioning. As shown in Fig. 4-8b, five LED buttons with different heights are placed on a platform. The diameter of the pressing area of each button is 0.9cm. The robot end-effector is equipped with a pressing tool with a compliant ending and a tool tip of 0.6cm diameter (Fig. 4-8d). The operator had to move the pressing tool in x_t, y_t and z_t and press a sequence of red lightened LED one by one without touching the aluminum button base.

The tool was located 5cm above the middle LED button at the initial position. Each trial included three sequentially random lighted LEDs, and each subject was required to conduct ten trials. Only the ICA mapping was used in this task to test speed control. The robot velocity was set proportional to the force exerted by the foot, with the maximum robot velocity of 3cm/s corresponding to 1.5 times the elastic-isometric boundary force.

Subjects' evaluation

Subjective evaluation of the interface was carried out using the NASA Task Load Index [123] which is a robust method to measure the subjective workload. Six factors are considered: Mental, physical, temporal demands, performance, effort and frustration, to estimate the overall workload, based on subjective answers. The assessment is carried out in two steps: the subjects first mark each factor (on a $\{0,5,10,\dots, 100\}$ scale in a questionnaire), then evaluate the contribution of each factor (by comparing these six factors in 15 pairs in a second questionnaire).

Figure 4-9: Foot-path error and its standard deviation over subjects and consecutive trials for each subject on (a) data set 1 of single-direction trials, (b) data set 2 of single-direction trial and (c) data set 3 of diagonal-direction trials.

4.4 Result

4.4.1 Experiment 1: Human motion intention and motion pattern

Subject-specific control pattern

The foot motions' performances are different depending on the direction and subject. Fig. 4-9 shows the foot-path error E over the ten subjects in various directions and the variability over the consecutive trials of each subject. We see that in the single directions (Figs. 4-9a,b) LT and RT have a larger error relative to the other directions, and translations in F/B and L/R have less error and deviations than rotations. Diagonal directions (Fig. 4-9c) that combine translations in $x - y$ planes have less error than the diagonal motions involving rotation and translation in the $x - \theta$ and $y - \theta$ planes.

In most cases, the deviation is large between subjects. On the other hand, the deviation is relatively small in the trials of each single subject, especially in single directions. There is no significant difference between the two single data sets for the average deviation within trials (t-test, $p=0.47$), meaning that there was no learning effect between these two periods. However, the movements in diagonal directions has larger deviation within trials than the single directions (t-test, $p<0.014$).

Evaluation of motion intention with analytical and data-driven mappings

Figure 4-10: (a-c) Comparison of foot motion path in directions F, B, L, R of three representative subjects for single Cartesian modeling data using kinematic and ICA models.

Using the analytical approach via the kinematics and statics mapping (of Sections 4.2.1 and 4.2.1) to command a motion direction, we see in Fig. 4-9 that the variability between different subjects is large, while the variability over consecutive trials of a single subject is relatively low. Therefore, it may be preferable to generate commands corresponding to each subject's habitual foot motion characteristics, corresponding to the data-driven approach of Section 4.2.2. Once a subject-specific model is built using the calibration procedure described in the single direction task of section 4.3.1, the subject-specific patterns are used online to interpret new control inputs.

To verify this subject-specific mapping method, we analysed the three sets of data collected in Section 4.3.1 that are used for modeling (single Cartesian data set 1)

Figure 4-11: Foot motion with kinematic transformation (red lines) and ICA (black lines) in all directions of subject 4 of (a) single Cartesian set 1, (b) single Cartesian set 2 and (c) diagonal directions.

and testing (single Cartesian data set 2 and diagonal direction data). For comparison purposes, the results from using the kinematics and ICA methods are converted to the same range $[-1, 1]$ through a min-max normalization. The ϕ DoF is not considered in the diagonal direction analysis: As it cannot reach the extreme value during diagonal motions, the normalized cannot be compared with the other DoFs. The original positions are calibrated to the zero for each consecutive set of data.

Figs. 4-10a-c illustrate the effect of using for subject-specific ICA compared to kinematics modeling, with three subjects foot trajectories in the $x - y$ plane. It is plotted by the result of $D_{xy} = [x, y]^T$ with single Cartesian data set 1 in directions of F, B, L, R, with three trials for each direction. The kinematics model (red traces) corresponding to the actual human foot motions exhibit different patterns over subjects. In contrast, the

results of ICA modeling yield a subject- and direction- specific mapping minimizing the foot-path error and performance variability of users. Figs. 4-11a-c further illustrate the results from the two mapping methods in four DoFs in both modeling and testing data in all directions of subject 4. The ICA method effectively fixes the issue of inaccurate motions coupling in multiple DoFs, for example, the directions of LT and RT in Fig. 4-11 a,b, four diagonal motions in $y - \theta$ plane in Fig. 4-10c.

Figure 4-12: Foot path error using the ICA model applied on: (a) the single Cartesian modeling data, (b) the single Cartesian testing data, and (c) the diagonal directions testing data.

To check the accuracy of control commands for all subjects and directions, the *foot path error* (Eq. 4.15) is computed using both of the control commands. The result is shown in Fig. 4-12. Compared to the results from the kinematics mapping, the deviation between subjects and directions are obviously reduced with the ICA mapping in the DoFs of rotations ϕ and θ . There are similar performance for translations using both methods as these foot motions already yield a good performance (small error and deviation).

4.4.2 Experiment 2: Teleoperation

Result of task 1

While the trials carried out with the ICA were successful for all subjects, using the kinematics method lead to some failed trials. The kinematics method yielded 100%,

Figure 4-13: Accurate tracking of the wire of Fig. 4-7b carried out with the ICA and Kinematics. (a) The trajectories in each method in two consecutive trials of a typical subject. (b) The path deviation between consecutive trials.

20%, 50%, 50% success rate for the four subjects. Fig. 4-13a shows that with the ICA mapping the subjects carry out more reproducible trials as with the kinematic mapping, suggesting that they need less exploration to generate desired commands. The path deviation between consecutive trials using both methods were calculated using dynamic time warping. Fig. 4-13b plots the normalized path deviation using ICA and kinematics. The subjects yield 11.3% less deviation between consecutive trials using ICA.

Result of task 2

As shown in Figs. 4-14a,b, the subjects control speed during the movement. The subjects use $37.7\% \pm 1.6\%$ time on high and middle speed moving to the the area near the target and spent around $34.1\% \pm 2.8\%$ on slower speed to conduct fine positioning to adjust and press the button. Furthermore, we see in Fig. 5-4c that movement often combines two dimensions and the proportion of time with such combinations increases over the trials. Note that this happens while the time to complete the task decreases i.e. the movements' combination is not at the cost of slower motion control

(Fig. 5-4d). This confirms the results of the first task by showing that the subjects had no difficulty in combining directions using the novel interface.

Figure 4-14: Using the novel foot interface to teleoperate accurate reaching. (a) Positions and velocity profile of the robot controlled by a typical subject. (b) Proportion of time at different speed levels over the four subjects. (c) Proportion of time with simultaneous movement in at least two dimensions for the four subjects. (d) Average completion time of first and last two trials.

Subjective assessment

The results of the first questionnaire indicate the raw rating of the factors, while the second one reflect the weights of each factor contributing to the workload. The results of these two questionnaires are shown in Fig. 4-15, including the factor contribution estimation (given in width of each column) and rating of these factors to the workload for the four subjects.

Figure 4-15: Subjects' NASA Task Load Index rating and weight.

Results for the four subjects exhibit an average raw rating for mental and physical demands with 42.5 ± 15.2 and 53.7 ± 13.1 respectively, which are in the middle levels. The temporal demand is relatively low (31.2 ± 7.5) and the effort's rating is high (67.5 ± 10.5) as the tasks require accurate positioning. The assessments on performance and frustration are diverse between subjects with 42.5 ± 19.4 and 48.7 ± 24.9 respectively. The average overall workload computed as weighted rating is 46.7 ± 9.4 in average over the four subjects, which indicates that using the proposed foot interface to control a robotic arm is not too difficult and does not require much mental, physical effort (compare e.g. with MetaArm[86]).

The importance of each factor was also evaluated by the subjects. The mental demand shows one of the lowest weight as $10.6\% \pm 7.8\%$, indicating that the foot operation with the proposed interface requires relatively low mental effort for motion planning. $20.4\% \pm 8.3\%$ and $22.1\% \pm 10.1\%$ of the overall workload are indicated for the physical demand and effort, which is logical as the task designed required accurate operation with physical motion and attention. The performance and frustration contributions to

the overall workload of $17.7\% \pm 5.0\%$ and $13.6\% \pm 9.8\%$ indicate that operating the robot with the foot interface does not stress the subjects.

4.5 Discussion and conclusion

In the analytical mapping method, the four-DoF output commands are derived based on the foot interface's structure and sensing. The analytical model provides indiscriminate control and mapping for different users. Users are required to adapt to the interface without considering human inside the control loop. A preliminary test with ten able-bodied subjects was performed to examine the human foot's motion in multiple directions, which verified whether the analytical model was sufficient or an individual specific mapping was preferred. The experimental result found that the characteristics of foot motions varied depending on the direction and subject. In particular, the movement patterns show evident variability among different subjects but less variability in the repeated trials of each subject. This result conforms to our previous assumption that human may exhibit diverse foot performance due to complex and diverse foot anatomy and biomechanics.

The foot motions in single Cartesian directions have shown a more stable and repeatable pattern than two-DoF combined diagonal directions, which are more appropriate to derive a new control basis. The eight load cells located around the foot record the four-DoF foot spatial motion/force information. All the force signals were selected as training data to predict each single direction's motion rather than considering a part of the force signals. The identification accuracy in classifying different motion directions using a supervised machine learning algorithm like k-nearest neighbors (KNN) falls short of expectations (see Appendix A.4). However, the independent component analysis (ICA) algorithm can effectively separate a single motion axis from the eight load cells' signal of the calibration data. A matrix is extracted to

reflect foot motion patterns and used to derive four-DoF output control commands for a specific user.

This chapter focused on the computation of the motor commands of the proposed foot interface. The analytical and data-driven mapping approaches were both developed and studied. The approach that can better reflect the user's control intention was selected as the mapping model of the foot interface. This motivated us to develop a subject-specific mapping from the foot movement space to an output command space using ICA. Compared to analytical methods, the subject-specific mapping has effectively reduced the deviation between subjects and directions. The teleoperation test further verified the two mapping methods and motion control of the proposed system. The subjects can control a remote robot in the four-DoF motion without experiencing difficulty using the novel foot interface. Nevertheless, the performance of the ICA method depends on the calibration procedure and data, which should best reflect the habitual motion pattern of the specific subject.

Chapter 5 Performance Evaluation of a Foot Interface to Operate a Robot Arm

5.1 Summary

Current foot interfaces used, e.g. to control a laparoscopic camera [56], [57], [62], consist of multi-directional switches placed on a planar platform, where each switch moves the robot in one direction with constant speed. Such interfaces are relatively easy to use for simple tasks where the binary foot input can capture the task. However, the operation may become more difficult and less efficient to control for multiple DoFs' movements of the robot when frequent or continuous direction adjustments are required. Furthermore, the number of buttons will grow with the number of directions to be controlled, increasing the complexity of operation and the risk of mistakes. These interfaces also demand the operator to plan the movement in discrete single Cartesian directions, identify correct buttons without looking at the foot, and then carry out a suitable pressing sequence and time. These operations may cause fatigue with float-in-air foot gestures and mental effort to select a correct buttons sequence.

Therefore, we have developed an alternative foot interface that can be used to continuously control a robot's movement in direction and speed magnitude (Chapter3 & 4). The objective of this chapter is to conduct a user study to explore the operation enabled by the novel foot interface in a four-DoF task characteristic of the targeted surgical application. The designed foot interface is integrated into a teleoperation system as a master controller to teleoperate an industrial robotic arm. The performance of

the developed interface is evaluated and compared with the conventional button foot interface. Ten naive participants were recruited to use these two interfaces to operate a robot and carry out tasks with the dominant foot. These tasks are geometrically complex path-following tasks which require accuracy and dexterity in four DoFs, similar to those in laparoscopic training. The performance was analyzed in terms of the operation error rate, task completion time, motion smoothness, as well as through a subjective questionnaire. The results demonstrate that the pedal interface can be used to control a robot for complex motion tasks. The rest of the chapter is organized as follows. Section 5.2 introduces the teleoperation system of foot interfaces and a robotic arm, with their mapping and control methods. Section 5.3 then describes the experiment protocol and performance measures. Section 5.4 presents and interprets the experimental results, and Section 5.5 give the discussion and conclusion.

5.2 Foot-controlled teleoperation system

Figure 5-1: Teleoperation control system framework.

The teleoperation system used in our skillful operation experiment, is shown in Fig. 5-1. The human operator moves the foot in the pedal or button foot interface; the continuous or discrete foot information is then transmitted to the computer through serial communication. The interface's output is then mapped to four-DoF robot velocity control commands through mapping models of foot interfaces. The corresponding

configuration is then sent to the robot controller through the User Datagram Protocol (UDP), in which the computer acts as the server and the robot controller is the client.

5.2.1 Foot interfaces

Button interface

The button interface (of dimension $65.2 \times 35.6 \times 5 \text{ cm}^3$) shown in Fig. 5-2a was designed similar to existing commercial foot interfaces [56], [59], [62] in robotic surgery. It enables four-DoF controlled using eight $9 \times 6.6 \times 2.4 \text{ cm}^3$ footswitches with $5.5 \times 5.5 \text{ cm}^2$ pressing area. Pressing one footswitch activates a constant speed movement in the related Cartesian direction. A skilled operator may use two buttons simultaneously with one foot to combine movement in two directions. The button interface is advantageous to control motion in single directions without direction deviation. However, more complicated tasks requiring movement combining multiple directions and frequent redirection will require planning, which may lead to long operation time, fatigue and yield jerky zigzag trajectory.

The footswitches are arranged to match the spatial azimuth relationship of the robot motion (Fig. 5-2). The left four switches control the translation and rotation of the robot's z_r axis. Buttons 5 and 6 control negative and positive z_r , respectively; buttons 7 and 8 map to the clockwise and anti-clockwise rotation around the z_r axis. The right four switches correspondingly control the robot in horizontal translations, i.e., buttons 1 and 2 activate the movements of the robot in y_r negative and positive directions; buttons 3 and 4 control positive and negative directions along x_r . The on/off state of each of the eight buttons is sent to the master computer and each pressing will command the robot to move at constant speed in the corresponding direction.

Figure 5-2: Mapping between (a) Button interface and (b) slave robot

Pedal interface

The structure of the novel pedal interface has described in Chapter 3 in detail. For each user, a calibration procedure is needed (see single direction task in Section 4.3.1 of Chapter 4). From the calibration data of the eight load cell readings $\mathbf{f} = [f_1 \dots f_8]^T$, the output commands $\mathbf{D} = [x, y, \phi, \theta]^T$ can be found through a mapping $\mathbf{D} = \mathbf{T}\mathbf{f}$. The 4×8 transformation matrix $\mathbf{T}$ is computed using ICA, which defines the motion axes based on the individual operator's motion characteristics. These control commands are mapped to the robot velocity $\mathbf{v}_r$, from which the robot's position $\mathbf{P}_r$ can be integrated:

$$\mathbf{P}_r = \int_{t_1}^{t_2} \mathbf{v}_r dt \equiv \begin{bmatrix} x_r \\ y_r \\ \phi_r \\ z_r \end{bmatrix}, \quad \mathbf{v}_t = \mathbf{s}\mathbf{D}, \quad (5.1)$$

where $\mathbf{s}$ is a diagonal weighing matrix. To intuitively control the robot, the foot coordinate x, y, θ are matching the frame x_r, y_r, θ_r of the robot (Fig. 4-6, Chapter 4). The ϕ maps to z_r with toe down rotation correspond to z_r positive and toe up rotation control z_r negative. The slave robot is operated in speed control without work-space limitation. The robot velocity is proportional to the force exerted by the foot. A dead

zone is used for each DoF control command to prevent the robot from moving with small involuntary foot movement. The maximum speed is limited to a target value based on different applications.

5.2.2 Slave robot

The slave robot is a six-DoF manipulator IRB120 (ABB robotics) with serial structure (Fig. 5-3,5-4a). The control of the robot is using the external guided motion (EGM) mode [124]. However, this control mode bypasses the path planning, the calculation of the robot's kinematics model is required (see Appendix A.5).

Communication latency in the teleoperation system between input foot motion and slave robot response is inevitable [125], [126]. However, the time delay will significantly degrade the human teleoperation performance when it is too long (e.g. 170ms [127], 300-320ms [128], 1s [128] etc.). Generally, when system latency is over about 1s, the operators begin to switch their control strategy to a “move and wait” one, instead of continuously commanding and trying to compensate for the delay [128]. It is recommended to reduce the time delay, preferably below the human perceivable time delay (10-20ms [129]).

External Guided Motion (EGM) mode [124] enables the slave robot to yield a fast response to commands from the foot interface. It is a control option of ABB robot which provides low-level interface to the robot controller. The command can directly go into the motor reference generation without path planning. The data transmission is using Google Protocol Buffers for encoding and User Datagram Protocol (UDP) as a transport protocol. With EGM, the robot path can be updated every four milliseconds (250 Hz), with a control lag of 8 to 20 milliseconds [124]. A low-pass filter with 10Hz cut-off frequency was used between the sensor signals and the robot motion controller. The maximum and constant speeds for the robot end-effector were set to

0.6 cm/s in translation and $10^\circ/s$ in rotation when controlling with the pedal interface and button interface, respectively. These limits were set in preliminary trials carried out by the experimenter with the aim to offer comfortable control.

Before using UDP communication, we have tried the Transmission Control Protocol (TCP), which is more reliable on data delivery. However, it is found that the robot has a constant time lag of about 448ms (used for motion planning), which is too long and introduce recognizable delay to the operator. Although EGM allows high communication rate with low time latency, the robot may move to awkward positions and trigger the emergency stop, especially when sending Cartesian pose to the robot. Without the path planning, the robot may not efficiently find optimal kinematics solution to move six motors.

5.3 Experiment

5.3.1 Experiment overview

An experimental study was conducted to evaluate the feasibility of using the pedal interface for controlling a robot in four DoFs; and to compare the performance with a conventional foot interface based on discrete switches. The experiment was approved by the Institutional Review Board of Nanyang Technological University (IRB-2018-05-051). Ten participants (five males) with an average age of 28.7 ± 2.2 years, without motor impairment, were recruited for the experiment. They were engineering students or staff without experience in surgical operation. None of them regularly used any foot based control systems. Their foot sizes ranged from 37 to 43 (40.1 ± 2.4) in the European standard. These participants were all right-footed according to the ball-kick dominant leg test [130]. They were informed about the experiment's purpose and protocol, and signed a consent form before starting it. The experiment consisted of three phases: *i*) Calibration and familiarization of the foot interfaces and their

mapping, *ii*) Practice for five minutes for each interface, and *iii*) Testing consisting of the tasks described below.

Experimental Setup

Figure 5-3: Experimental setup.

The experimental setup is shown in Fig. 5-3. Either foot interface was placed on the ground in the front of the subject, who comfortably sat on a fixed chair and controlled the robot end-effector (using dominant foot). A block view table ($66 \times 58 \times 80\text{cm}^3$) placed between the foot interface and the participant to prevent the operator from watching the foot or the interface during operation. The focus should be on the robot operation area. The default mappings between each of the foot interfaces and the slave robot are depicted in Section 5.2.1. The communication frequency is about 30Hz for the teleoperation system. The task board will record the task completion data with 20Hz frequency.

5.3.2 Task: Move without hitting the wire

The task designed is similar with the laparoscopic training task [131], but conducted in a teleoperation system and using foot control. The participant was asked to move

Figure 5-4: (a) Task scenario; (b) Task board; (c) Enlarged views of robot end-effector tool and (d-f) three training and testing wires.

the robot end-effector along each of the three paths as fast and accurately as possible without hitting the wire. The test scenario, robot end-effector tool and testing wires are shown in Fig. 5-4. A small ring with 8mm inner diameter is connected to the robot end-effector. The ring needs to be guided along an aluminum wire (0.25cm diameter) with specially designed shapes. Three wires with different shapes were used. The three wires define different paths including 1) single Cartesian path along x_r, y_r , 2) two-DoF diagonal path in $x_r - y_r$ plane, 3) two-DoF translation and one-DoF rotation circle path, 4) the above paths and combined translation in z_r and 5) turning points with angles of equal, less or larger than 90° . The wire 1 is a 2D horizontal path. The second and third paths are 3D routes requiring translation in z_r with 1.0cm. Experiment with the first two paths is considered as training and conducted on a first day while the third path is used on a second day to test the acquired skill. Half of the participants start (on both days) using the pedal interface and then the button interface while the other subjects start with the button interface. Each subject spent about two

to three hours totally conducting the experiment. Long time operation can effectively check the intuitiveness of the interfaces.

The starting position of the ring tool is at one side of the wire. One trial is completed when the tool is moved from one side of the path to another side. The odd-numbered trials start from left to right, and the others start from right to left. There is a ten-second short break between consecutive trials. After finishing ten trials at wire 1 with one interface, the subject relaxes for a two minutes break, after which wire two is used. After finishing practicing with these two wires with one interface, and a five minutes break, the same protocol is followed with the other foot interface. Test on wire 3 is carried out similarly on the second day.

The maximum speed for the robot end-effector was set to 0.6cm/s in translation and 10°/s in rotation when controlling with the pedal interface, which corresponds to the constant speed used with the button interface. These limits were set in preliminary trials carried out by the experimenter to offer comfortable control.

5.3.3 Performance measures

Figure 5-5: Possible control strategy for (a) the button interface (The numbers represent corresponding buttons) and (b) the pedal interface (B: backward, L:left, RT: right rotation, LT: left rotation, LB: left and backward, LF: left and forward).

A relatively strict accuracy constrain is selected for foot control of within $\pm 0.275\text{cm}$ in x_r, y_r and z_r , which is similar to the typical accuracy of of 0.1 to 0.5cm in hand

teleoperation systems [132]. The expected control strategies for both interfaces are shown in Fig. 5-5 with wire 1 in the top view as an example. The dash lines show the the maximum allowable deviation when the ring tool's cross-section is perpendicular to the path and concentric with the wire circle cross-section. The participants' performance with foot control is assessed through the error rate, completion time, smoothness and subjective questionnaire.

Completion time

The completion time is the most direct measure index of performance in teleoperation control. The time is recorded from when the robot starts to move (i.e., when quitting the start metal plate) until the ring tool touches the end metal block. The task is carried out back and forth, where one trial corresponds to either the forth or back movement.

Tracking error rate

The operator needs to dynamically adjust the ring via foot control while avoiding touching the wire. When the wire is touched, the buzzer is on which is recorded at 20Hz. The error rate in a trial is the percentage of touching time divided by the completion time.

Smoothness

Motion smoothness at the slave robot can be used to reflect the foot motion control performance. How smooth or jerky the movements of the slave robot is quantified using the absolute value of the spectral arc length smoothness metric [133].

Table 5-1: Subjective assessment questionnaire

Statement		Score					
1. The mapping between foot and robot movements is	not intuitive	1	2	3	4	5	very intuitive
2. Accurately following the path was	difficult	1	2	3	4	5	easy
3. The mental effort required for operation was	low	1	2	3	4	5	high
4. Foot fatigue was	none	1	2	3	4	5	very high
5. Operation speed was	too low	1	2	3	4	5	too fast
6. General comfort was	very uncomfortable	1	2	3	4	5	very comfortable
7. Overall the input device was	difficult	1	2	3	4	5	easy to use
8. Movement during the operation was	rough	1	2	3	4	5	smooth
9. In general, which interface do you prefer? Why? Please specify your reason(s)							

Questionnaire

At the end of the task, participants were given a questionnaire of Table 5-1, containing nine questions to assess the use of the two interfaces to control the robot. The first eight statements are rated on a discrete five-point Likert scale.

5.4 Results

5.4.1 Behavioural analysis

We see in Fig. 5-6a that using the pedal interface, the subjects could achieve a relatively high robot motion accuracy, characterized by a low error rate of 1-4%, with both the button and pedal interfaces (t-test, $p > 0.13$). Furthermore, the pedal interface enabled the subjects to reduce the time (Fig. 5-6b) to complete the task (t-test, $p < 0.006$) by about 30% with all three wires relative to when using the button interface.

The average jerkiness at the slave robot in translation (Fig. 5-6c, top row) and rotation (Fig. 5-6c, bottom row) were analyzed separately. The spectral smoothness index of translation increased (t-test, $p < 0.014$) by 63%, 59% and 56% using the pedal interface allowing continuous direction changes relative to the button interface for

Figure 5-6: Analysis of performance in the three tasks; Average (a) error rate (b) completion time and (c) motion jerkiness of first and last three trials for the button and pedal interfaces of wire 1, wire 2 and wire 3.

the three tracking paths. The robot's rotation movements also became smoother (t-test, $p < 0.045$), with the exception of the second path (t-test, $p = 0.060$), by 48%, 22%,

30% along the three wires, respectively, when using the pedal interface rather than the button interface.

Learning can be observed through the completion time and jerkiness. The completion time in the first wire reduced by about 28% in the last three trials compared to the initial three trials when using either the button or the pedal interface. The learning rate slowed down on the second path, probably due to the learning experience along the first path. Movement in the third wire was conducted on the second day, where the results suggest some re-learning. The pedal interface yielded a faster learning rate with 24% reduction on the completion time from the first three to the last three trials, and 9% with the button interface. The jerkiness on translation exhibited a similar learning effect as the completion time.

The results did not depend on the order in which the interfaces were used (t-test, $\min\{p\} > 0.07$) or the order of robot movement directions (left to right vs. right to left, t-test, $\min\{p\} > 0.17$) for all the metrics. Therefore, all data could be analyzed together. Fig. 5-6 compares the average performance metrics over the first and last three trials when using both interfaces.

5.4.2 Foot control in complex motion

To further examine the foot motion control capability, we analyzed performance along wire 1 separated in three parts: straight, then circle and then diagonal segments, as indicated through different colors in Fig. 5-5. Compared to the button interface, the pedal interface let the subjects save on 23.5%, 42.5% and 30.9% less time on the three sub-paths, respectively. The pedal interface led to improved performance especially on the circle path that requires three-DoF control.

As the number of samples in a trial is mainly affected by the time taken to complete the task, the dynamic time warping technique was used to determine the optimal

alignment between the reference trajectory and the trajectories with the two interfaces. The path deviation calculated as the sum of the Euclidean distances between corresponding points was then computed after alignment. Although the time and accuracy are in tradeoff, the pedal interface enabled the operators to both shorten the time and increase accuracy when completing the circle path, with 34.5% less deviation than when using the button interface.

Figure 5-7: Subjective assessment result of the pedal and the button foot interfaces.

5.4.3 Subjective assessment

Fig. 5-7 illustrates the average responses (and the standard deviation) of ten participants to the questionnaires of Table 5-1, developed to assess the robot control with the two interfaces. An Analysis of variance (ANOVA) was conducted on the ten subject's responses of the two foot interfaces, using a 5% significance level.

This test revealed that the choice of interface had a significant effect on the rating of *intuitiveness* ($F_{(0.05,1,18)}=40.02$, $p<10^{-5}$). Participants found that the mapping is more intuitive using continuous foot movements in all directions (with a mean responses of 4.4 for the pedal interface and 2.7 for the button interface). The ANOVA also revealed that the foot control strategies had a significant effect on *physical fatigue* ($F_{(0.05,1,18)}=14.4$, $p=0.0013$). The button interface (4.30 ± 0.82) was felt to require

larger physical effort than the pedal interface (3.10 ± 0.56). Significant effects were also found for the criteria of *comfort* ($F_{(0.05,1,18)}=13.46$, $p=0.0018$), *ease of use* ($F_{(0.05,1,18)}=8.23$, $p=0.0102$), and *smoothness* ($F_{(0.05,1,18)}=7.36$, $p=0.0142$), where participants generally found the pedal interface was superior in those aspects.

It is interesting to note that participants felt the robot moved at faster speed (ANOVA: $F_{(0.05,1,18)}=9.8$, $p=0.0058$) using the pedal interface, although the speed was smaller or equal to the constant speed used with the button interface. No significant effect was found on the *accuracy* ($F_{(0.05,1,18)}=2.95$, $p=0.1033$), which corresponded to the objective error rate results. Also *mental fatigue* ($F_{(0.05,1,18)}=0.88$, $p=0.3618$) was not deemed larger with the button interface. Overall, 9/10 of the participants clearly preferred the pedal interface due to the more efficient operation and reduced fatigue.

5.5 Discussion and conclusion

The average error rate (Fig. 5-6a) was small, generally 1-4% with both foot interfaces. This indicates that the novel pedal interface can be used to achieve the same accuracy level as with the state-of-art button interface. The 30% decrease of completion time (Fig. 5-6b) and the 60% motion smoothness increase (Fig. 5-6c) exhibit the superior performance enabled by using the pedal interface instead of the button interface.

These performance differences may stem from the different motion control strategies offered by the two interfaces. With the button interface, movements in different DoFs are separately controlled by the associated buttons, which results in discrete movements, time-consuming motion adjustment, and less smooth trajectories. In addition, the operator needs to plan the movement sequence, carry out many futile movements from one button to another, lift/drop the foot to release/press the buttons for multi-DoF motion control, which all prolong the motion adjustment and significantly increase physical fatigue. In contrast, with the four-DoF foot pedal interface, the

natural continuous movement of the foot in multi-DoF is directly mapped to the motion of the robotic arm, leading to more intuitive and efficient operation and smoother trajectories.

The advantages of the pedal interface become particularly clear in complicated movements which require multiple DoF, such as following a circular path accurately. We have found that the pedal interface can achieve both 42.5% shorter time and 34.5% higher control accuracy on the circle path. The operator tends to change the movement direction continuously rather than separating it to single direction movements.

The results of the questionnaire show how users perceive these advantages and the characteristics of the pedal interface. The subjects found the pedal interface superior to the button interface in terms of mapping, comfort and smoothness, which corresponds to the decrease of completion time and increase of smoothness. Interestingly, both objective and subjective measures of accuracy indicated no difference between the two interfaces. The button interface enables high accuracy (zero error if not pressing a wrong button) in controlling single direction motion but leads to deviation in multi-DoF movements. In contrast, the pedal interface has more deviation in the single directions but enables higher accuracy than the button interface in complicated tasks. The mental effort was also not different between the two interfaces. This may be explained as the pedal interface requires continuous movement direction control, while the button interface requires the subject to pay extensive attention to the motion-button mapping and motion planning. The perceived lower fatigue with the pedal interface can be explained as it supports the foot and provides a resting place, while using the button interface required to lift the foot between the button during the whole operation.

This chapter compared different foot control strategies to operate a robot, using a new foot pedal interface and a traditional button interface. Ten subjects were recruited to control the robot's end-effector in a task similar to robot-aided surgery training. The

subjects' behavior was analyzed using objective metrics of error, completion time and motion smoothness, as well as through subjective assessment of a questionnaire. The pedal interface indicates improved efficiency and motion smoothness as compared with the button interface. The pedal interface are more accurate in controlling complicated multiple DoFs motion (e.g. curved path) but has more deviation in single Cartesian directions than the button interface. When it comes to the subjective assessment, the questionnaire result shows that controlling the robot with the proposed foot interface is more intuitive, comfortable, and less tiring than with the button interface.

Chapter 6 Design and Evaluation of a Foot-controlled Robotic System for Endoscopic Surgery

6.1 Summary

In traditional endoscopic surgery, the surgeon manipulating the endoscopic instruments is supported by an assistant controlling the endoscope, where their coordination may be affected by communication errors. A robotic system enabling a surgeon to control three tools has the advantages of saving manpower, improve efficiency and avoiding communication errors. Some systems provide autonomous positioning of the endoscope [57], [134], [135] using visual servoing from the camera images. Regardless practical issues such as blood occluding the image, the automatic endoscope positioning may not match the surgeon's intention and may cause safety issues [136]. Therefore, most of the current robotic surgery systems use hand or hand-free interfaces to control the third tool.

A third tool can be controlled sequentially with the hands through a clutch-based interface or using a separate interface. For example, in the flexible endoscopic system K-Flex [31], the operator can press a pedal to swap between a surgical forceps and flexible overtube. Similarly, the Da Vinci Si system [9] provides a built-in master console with hand controllers and footswitches for swapping the arm control. In the Medrobotics Flex system [22], the operator first navigates the endoscope to the target

area using a joystick and then switches to the two manual instruments. However, with all these modalities using sequential hand control, it is not possible to move the endoscope and instruments at the same time, which limits the possible operation procedures.

This chapter presents a novel foot-controlled teleoperation robotic system for a flexible endoscope. The system consists of a foot interface collecting four-DoF foot gestures and a robotic driving system for a commercial flexible endoscope. Natural foot patterns are mapped to the movements of the endoscope using a dedicated interface providing force feedback. The robotic system can be integrated with standard gastrointestinal endoscopes and enables four-DoF motion control. The proposed system is evaluated in an experiment with ten participants, where the proposed system with foot teleoperation is compared with hand teleoperation and direct control of the endoscope with two hands. The participants could successfully teleoperate the endoscope with foot teleoperation and exhibited 40% faster task completion as with direct control. They found both foot and hand teleoperations comfortable and intuitive. Although hand teleoperation enabled the best performance, only foot teleoperation allows simultaneous control of three instruments. The rest of the chapter is organized as follows. Section 6.2 presents the system design. An evaluation experiment was conducted in 6.3 with 10 participants. Section 6.4 shows the experiment result and section 6.5 discuss the results and conclude this chapter.

6.2 Robotic system

The foot-controlled endoscopic system (shown in Figs.6-1a,b) is composed of the the slave robotic endoscope and the master foot-controlled interface. The operator, seated comfortably, tele-controls the flexible endoscope with their right foot based on the camera view.

Figure 6-1: Robotic endoscope teleoperation system: (a) Control console and operator; (b) Slave robotic endoscope system. (c) Foot interface prototype with foot. (d) Olympus gastrointestinal scope.

6.2.1 Master foot interface

The dedicated foot interface of was used as a master device to control the endoscope. The interface prototype with the operator's foot is shown in Fig.6-1c. Please see Chapter 3& 4 for detail.

6.2.2 Slave robotic endoscope

The flexible endoscope used in this study is the standard gastrointestinal scope (GIF-2T160, Olympus Medical System Corporation, Tokyo, Japan), shown in Fig.6-1d. It has a tube diameter of 12.6 mm and maximum insertion length of 103 mm, which is long enough to reach the surgical site of colon or stomach in gastrointestinal

endoscopic surgery. This commercialized endoscope can be easily and quickly mounted on or dismounted from the robotic system without any modification.

The robotic endoscope (Fig.6-1b in assembly view and Fig. 6-2 in exploded view) includes three modules motorizing the standard endoscope in four DoFs: 1) a bending module (BM) controlling the two-DoF bending of the distal tip; 2) a translation module (TM) executing the in/out DoF of the endoscope; and 3) a rotation module (RM) implementing the rolling DoF of the whole endoscope along the longitudinal axis.

Bending module

Fig.6-2a presents the assembly of the BM; the right panel shows the exploded view of the connection parts to the endoscope. The claw shape knob connector mechanism are attached to the control knobs of the endoscope. Once the endoscope is connected, lifting up a tightening ring ②② can secure the knobs with connected shafts. Two motors with gears can drive the connected shaft and knobs through the gear transmission mechanism. The movement can be controlled in the two directions separately, or simultaneously.

Rotation module

The rotation module (Fig.6-2b) can drive the tyre-shape BM and endoscope to rotate around endoscope's longitudinal axis. Weight block ①⑥ is added to BM to provide a counter moment to balance the rotation torque caused by ⑦, ⑨, ⑪ and ⑫ (Fig.6-2a). The rotation is transmitted through pulley and cable when motor ②⑥ rotates (Fig.6-2b). The rotation motion and translation motion of the endoscope are decoupled. When the rotation motion is activated, the TM will loose the endoscope to allow its rotation.

Figure 6-2: Robotic endoscope system design (3D drawing). Exploded view of bending module (a), rotation module (b) and translation module (c).

Translation module

The structure of TM is shown in Fig.6-2c. The endoscope can be easily passed through the four rollers by slightly lifting the L-shape plate ③②. In addition, the mechanism can fit the endoscope with different diameters by moving the width adjustment sleeves ③③. The driven cables ③④ are tightened after the assembly. The roller part is also a pulley with cables. Two sets of the cables ②, ③④ are driven by the same motor forming a push-pull mechanism, which brings the whole endoscope, including the BM and RM, forward/backward together along the guided rails. This design can

Figure 6-3: Endoscope control in four DoFs with the foot interface.(Note that the left or right is defined based on the endoscopic vision rather than external vision.)

keep a consistent configuration of the endoscope to maintain the accumulated angle unchanged. This ensures the accurate control of the distal tip [137]. The current system range of 500 mm translation can be extended by using longer guided rails.

6.2.3 Foot-endoscope mapping

The foot can move the pedal and mobile plate in four DoFs (Fig. 6-3). Motion signals from the foot act as references for the rotation of the proximal motors which drive the distal tip of the endoscope through cables. Foot-manipulation with the foot interface will control the corresponding movement of the endoscope: 1) Pressing/lifting the pedal activated by toe up/down rotation controls the up/down bending of the endoscope (Fig.6-3a). 2) The left-right rotation of the pedal is linked with the left-right bending

of the endoscope (Fig.6-3b). Bending in multiple DoF is allowed, e.g. lifting and rotating left of the pedal could lead to up-left bending of the endoscope. 3) The left-right swing of the pedal, activated by shank rotation around thigh, maps to the rotation of the endoscope (Fig.6-3c). 4) The forward-backward movement of pedal is linked to same movement of the endoscope (Fig.6-3d). The operator can imagine their toe as the tip of the endoscope and remote control the endoscope intuitively through isomorphic mapping.

In addition, the two bending DoFs can be commanded either using velocity or position control based on the practical application scenario. In position control mode, the foot positions are mapped to the endoscope's bending angles. The foot workspace corresponds to the bending workspace of the endoscope. In velocity control mode, the foot controls the velocity of the endoscope. Once the endoscope reaches the threshold of the movement, the output speed of the foot interface will change to zero in order to avoid safety issues. For the DoFs of translation and rotation of the endoscope, the foot positions are mapped to the velocity of the endoscope. The four-DoF movements of the foot to the corresponding movements of the endoscope in velocity control can be observed in supplementary video 1.

6.3 Experiment

The experiment was approved by the Institutional Review Board of Nanyang Technological University (IRB-2018-05-051). It was carried out by ten right handed and right footed subjects aged 29.3 ± 3.8 years (with four females) without known impairment in foot or hand control.

The experiment was designed to evaluate the control of the endoscopic robotic system, where foot teleoperation was compared with direct control and hand teleoperation. In *direct control*, the endoscopist manually controls the endoscope at the patient

Figure 6-4: Experimental flowchart.

side using its built-in dials while assisting the surgeon operating the robotic system. This is the conventional approach for maneuvering the flexible endoscope to perform diagnose or surgery, which is also used in endoscopic robotic systems MASTER [25], ViaCath [12]. Hand teleoperation and foot teleoperation both use a robotic system to move the endoscope remotely through a hand or foot interface, respectively. Hand teleoperation is the most common way to tele-operate robotic endoscope systems [22]–[24] while foot teleoperation is relatively new. The implementation of these three operation modes' implementation is described in more detail in Section 6.3.2.

6.3.1 Experiment overview

The experimental protocol is illustrated in Fig. 6-4. After having signed a consent form, the participants attended a *training section* consisting of: (i) a demo on how to use the foot interface, hand interface and direct control to move the flexible endoscope; (ii) They were given 15 minutes to try each control mode for five minutes; (iii) They were informed of the task procedure.

Each participant performed six sets of operation in the *task section*. The first two sets was for practice and trial, where data was not recorded. The last four sets of operation were recorded as test data. There was a one-minute break between each set and five minutes break after one control mode to prevent fatigue. The *subjective*

Table 6-1: Post experiment questionnaire

Statement		Score					
1. The mapping between foot and robot movements is	very intuitive	1	2	3	4	5	not intuitive
2. General comfort was	very comfortable	1	2	3	4	5	very uncomfortable
3. Overall the operation was	easy	1	2	3	4	5	difficult to use
4. Mental effort required for operation was	low	1	2	3	4	5	high
5. Physical fatigue was	none	1	2	3	4	5	very high

assessment section was conducted after the operation, i.e., each participant was asked to fill a questionnaire, as shown in Table 6-1, in order to assess the mapping, operation comfort, ease of use and mental & physical effort for the three control schemes with a Likert scale from 1 to 5.

6.3.2 Task and control schemes

In endoscopic surgery, the endoscope is a carrier with a camera that providing both movement and view [138]. The navigation of the endoscope transports the surgical instruments to the target operation areas and facilitates their manipulation. An endoscope locomotion task under camera view was tested in the experiment (Fig. 6-5). A red laser pointer was attached to the tip of the endoscope and its red projection point was shown in the endoscopic camera view, which provides the movement reference. Participants were asked to control the laser point to five circular targets (with radius 1 cm) located in the 3D space using visual feedback through the endoscopic camera. In each set of operation, the operator started from the initial position and moved sequentially to targets 1 to 5. The operation duration was recorded from the instant when the endoscope started to move until when the last target was reached. Each operator was required to perform the task using the hand, foot teleoperation and direct control modes, which are described in the next section. The participants were randomly assigned to start with the manual or robotic control modes of the hand/foot.

The proposed foot teleoperation control scheme (Figs. 6-3,6-5d) is compared with a hand teleoperation and direct control. Details of the foot teleoperation can be found in Section 6.2.3. The hand teleoperation setup is the same as in the foot teleoperation with the haptic interface (Omega.7, Force Dimension) replacing the foot interface (Fig. 6-5c). The four-DoF motion of the hands are mapped to the motion of the endoscope as follows: Left/right and up/down translations of the hand control the left/right and up/down bending of the endoscope, respectively. The forward-backward hand translation controls the in/out motion of the endoscope, and the forearm rotation controls the self rotation of the endoscope. For both hand and foot teleoperation, the two bending DoFs of the endoscope are position-controlled, providing intuitive and accurate mapping. As the motion range in translation (≥ 50 cm) and rotation (360°) on the robot side are large compared to the range of master interface, using position control would require frequent clutching operation. Thus velocity control is used for the translation and rotation DoFs in order to avoid workspace limits and uncomfortable postures. In direct control (Fig. 6-5b), the operator uses one hand to grab the control section of the endoscope and uses the fingers of their hand to rotate two control dials. Rotating the bottom or upper dial control the up/down, left/right bending DoFs of the endoscope respectively. The other hand of the operator should hold the distal end of the endoscope (about 15-20 cm from the tip) [139]. The translation/rotation DoF requires two hands to deliver or twist the whole body of the endoscope. The participants operate through the same endoscopic camera view for all three control modes, and are not allowed to look at the endoscope tip and targets directly.

6.3.3 Three instruments' operation

In endoscopic surgery, the two flexible instruments, passing through the channels inside the endoscope, can perform dexterous manipulation; the endoscope can enlarge

Figure 6-5: Experimental setup. (a) Endoscope in visual environment. (b) Direct control. (c) Hand teleoperation. (d) Foot teleoperation.

Figure 6-6: Operation time with the three control modes. (a) Mean operation time over the four trials; (b) Evolution of operation time in the four trials. *: statistically significant effects at $*p < 0.05$, $**p < 0.01$, $***p < 0.001$.

the workspace of the operation, bringing instruments to the target area. The proposed foot controlled robotic endoscope enables the surgeon to operate two surgical instruments using their hands without disruption and therefore carry out endoscopic surgery involving three tools. The detail of three instruments' operation using hand and foot interfaces can be found in Chapter 8.

6.4 Results

6.4.1 Operation efficiency

The resulting operation time is shown in Fig. 6-6. This data was normally distributed for each trials' set and control scheme, as assessed by Shapiro-Wilk's test ($p > 0.09$). A two-way repeated measures ANOVA was conducted to determine the effect of different control schemes and trials' sets on the operation time. No statistically significant interaction effect was found between the control scheme and trials' set parameters, $F(2.15, 19.39) = 0.61$, $p = 0.56$. Participants exhibited relatively consistent performance after two sets of practice in all three control modes (Fig. 6-6a). There was no statistically significant main effect of the four sets on the operation time, $F(3, 27) = 2.08$, $p = 0.12$. However, as shown in Fig. 6-6b, the operation time did depend on the control scheme $F(2, 18) = 26.72$, $p < 0.001$. A post hoc analysis (with Bonferroni adjustment) then revealed that the completion time decreased from using direct control (80.7 ± 7.6 s) to hand teleoperation (31.1 ± 1.8 s), ($p < 0.001$), from direct control to foot teleoperation (48.6 ± 4.1 s) ($p = 0.011$), and from foot teleoperation to hand teleoperation ($p = 0.005$).

6.4.2 Subjective assessment

Fig. 6-7 illustrates the average responses (and the standard deviation) of ten participants to the questionnaires of Table 8-1. The rating results were not normally distributed ($p < 0.014$), and a Friedman test was run to analyze how the control scheme affects the subjective rating. The control scheme had a significant effect on the rating of *intuitiveness*, $\chi^2(2) = 13.515$, $p = 0.001$. Post hoc analysis revealed that direct control (Median(Mdn) = 4) was felt non-intuitive, in contrast to hand (Mdn = 1, $p = 0.005$) or

Figure 6-7: Subjective assessment. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

foot (Mdn = 1.5, $p = 0.03$) teleoperation of the robotic system. Instead, subjects found hand and foot teleoperation similarly intuitive ($p = 0.9$).

Significant effects were also found for the other criteria of *comfort* ($\chi^2(2) = 16.722$, $p < 0.001$), *difficulty* ($\chi^2(2) = 15.600$, $p < 0.001$), *mental effort* ($\chi^2(2) = 8.061$, $p = 0.018$), and *physical fatigue* ($\chi^2(2) = 16.222$, $p < 0.001$). The participants generally found hand teleoperation superior in all those aspects to direct control ($p < 0.03$). Foot teleoperation was felt to provide more comfort ($p = 0.02$) and less fatigue ($p = 0.04$) than direct control, but no significant difference in difficulty ($p = 0.28$) and mental effort ($p = 0.44$). Similar to the result of intuitiveness, the participants felt that the foot teleoperation did not increase the difficulty of the operation, or bring more physical or mental effort, or discomfort, when compared to hand teleoperation ($p = 0.13$ for difficulty, $p = 0.35$ for physical fatigue, $p = 0.79$ for mental effort, $p = 0.66$ for comfort).

6.5 Discussion and conclusion

This paper presented the design and evaluation of a novel foot-controlled robotic endoscopic system. The teleoperation system provides four-DoF control of a flexible endoscope. Natural movements of the user's foot are captured by the foot interface

and then used to tele-manipulate the endoscope. The system can be easily integrated with the commercial endoscope. The experimental study validated the design and showed the feasibility of the novel foot-controlled robotic system. The participants could tele-manipulate the endoscope intuitively with their right foot and reach the targets area without difficulty. The foot teleoperation is more efficient and intuitive than conventional direct control. The average completion time per set was 43.6 - 54.7 s for the foot teleoperation and 73.0 - 89.2 s for the direct control, i.e. the time was reduced by about 40% with the proposed system. Furthermore, the participants felt that less physical effort is required to operate the robotic endoscope using the foot than directly controlling it, and that foot teleoperation is more comfortable.

In our experiment, hand teleoperation needed less operation time than foot teleoperation, which is expected as hand is the limb normally used to control objects in space. However, using two hands to control three surgical tools in endoscopic surgery may not be that efficient. For instance, when adjusting the camera view with some camera positioners [10], the surgeon needs to release the current instruments, disengage the locking mechanism, operate the third instrument, reengage the locking mechanism, pick up previous instruments, and resume the procedure. Some studies [20], [35] also reported that in the Da Vinci surgical system the swapping procedure using pedal clutching may disrupt the surgical flow and lead to errors or extended operation. In contrast, using the foot to operate a third tool does not disrupt the hands operation. The behaviour study in [36] also suggests that three-handed simultaneous positioning is preferred to - and more efficient than - bimanual operation.

The developed robotic endoscope system provides unique novel features relative to existing systems in endoscopic surgery: (i) natural foot gestures are used to control the endoscope based on an isomorphic mapping which is intuitive and easy to learn; (ii) using the foot interface enable the hands to control additional instruments and makes it possible to carry out operations requiring simultaneous operation of three

tools; (iii) can be integrated with a two-handed control system in a modular design. The successful foot teleoperation experiments conducted by participants without surgical experience/bias shows the effectiveness of the foot-controlled endoscopic robotic system. To test the system for standard surgical procedures, it will be necessary to carry out systematic compare studies involving professional surgeons and endoscopists with different levels of experience and skill.

Chapter 7 Tri-manipulation: An Evaluation of Human Performance in Three-handed Teleoperation

7.1 Summary

Three-hand manipulation could significantly increase the number of tasks that can be carried out, by using an artificial third arm that can be seamlessly controlled with the natural arms. The use of multi-modal interfaces enable one operator to telemanipulate the SRL both independently of and in coordination with the natural hands. The interface we developed could be used to control the SRL. Some recent studies [36], [140] have found that tri-manipulation with natural hands and foot controlled third hand has superior performance than bimanual operation and participants preferred three-handed simultaneous manipulation to bimanual operation requiring sequential control, with which they felt less physical fatigue and mental burden. Concurrent teleoperated SRL control of two robotic arms has also been demonstrated for the tasks of lifting, grasping, holding and music playing [86], [89], [141]. These researches suggest the possibility of human augmentation using foot and foot interface to control the third hand. They are still preliminary studies, where the control is confined to a single axis and the task is designed for specific applications that cannot be easily generalized.

Considering this state of the art in SRL control, we demonstrate the capability to simultaneously control the natural hands and a supernumerary limb controlled by foot in this Chapter. The experimental study focuses on understanding i) What effect the addition of supernumerary robotic limb (SRL) has on the performance of the natural limbs (NLs); and ii) How mechanical and/or cognitive coupling alters user performance. Twenty subjects were recruited to conduct three tasks requiring different levels of coordination and cognition with a teleoperation system of two hand interfaces, one foot interface and a virtual-reality environment. The performance of the natural hands in both tri-manual and typical bi-manual operations is analysed to check the effect that the addition of SRLs has on the performance of the natural limbs in different task scenarios.

7.2 System

7.2.1 Trimanipulation system

Fig. 7-1 depicts the experimental setup and tri-manual operation system used throughout this study. All experiments are conducted using two standard haptic interfaces for the hands in addition to the recently developed four-DoF passive foot interface presented in Chapters 3& 4. In the test, the operator sat comfortably on a chair, holding the handles of the hand interfaces with both hands and placing their dominant foot on the pedal of the foot interface. They faced the monitor which displayed feedback of the current virtual task.

The tri-manual operation system consists of two hand interfaces, one foot interface [142], and a virtual-reality testing environment. The hand interface is the Omega. 7 haptic interface from Force Dimensions Inc., Switzerland, which is commonly used as a master device to teleoperate robotic arms [16], [17]. The interface is controlled through motion of its handle, where the position of the hands x_{hi} and y_{hi} (workspace

Figure 7-1: (a) Experimental setup. (b) Virtual interface and master hand/foot interfaces.

$16 \times 16 \text{ cm}^2$) are used to control virtual hands (VH) 1 & 2 in x and y (Fig. 7-1b). Gravity compensation is enabled to limit physical fatigue and to facilitate hand control. Similarly, the foot interface [142] equipped with a pedal plate supports the leg against gravity minimizing the effort required to hold the leg in place. The movements in translations of x_f, y_f (workspace $4 \times 4 \text{ cm}^2$) activated by the foot are used to control VH3 (Fig. 7-1b) in x_3, y_3 .

To start, the handles and pedal are placed in their central position as shown in Fig. 7-1b right panel and the VHS were displayed in the configuration shown in Fig. 7-1b left panel. The hand and foot positions recorded by the interfaces are transmitted to the PC through serial ports at a frequency of 10Hz. The virtual task scenarios are displayed on the 54.61 cm wide screen located behind the hand interfaces onto a display window that was $47.3 \times 52.7 \text{ cm}^2$. Each VH is displayed with a 2.7cm length and a 1.0cm width with a $30 \times 30 \text{ cm}^2$ workspace. The workspace of the three VHS overlaps with each other and any VH can reach any target position required in a virtual task.

7.2.2 Operation scenarios

The tasks of this study are designed based on the basic movements following the tri-manipulation taxonomy and serve for the surgical application. In endoscopic surgery, the endoscope is a carrier with a camera providing both view and movement. The navigation of the endoscope transports the surgical instruments to the target operation areas and facilitates their manipulation. Thus the surgical instruments can reach the surgical site through natural orifice without incision. The movement of the instruments depends on the endoscope's movement. While in a laparoscopic surgical procedure the three surgical instruments can access to patient's body through different incisions. The operation of them could be independent motion or coupled motion based on the surgical procedures. For example, *i*) the three surgical instruments would first all move to the target surgical area, *ii*) two of three instruments would then move the organ to expose the tumor in a proper position, while the third tool marks the cutting area, *iii*) finally two hands would cooperate together to conduct cutting while the third hand suctions the blood. In the current study, we focus on three scenarios: 1) three independent motion without coupling; 2) two hands coupled together in a discrete motion and independent motion of the third hand. 3) Similar to scenario 2) but two coupled hands perform continuous motion. Please see Section 7.3.2 for more detail.

7.3 Experiment

Twenty participants (nine females) with an average age of 29.2 ± 3.1 years, without motor impairment, were recruited. Nineteen of twenty participants were right-footed according to the ball-kick dominant leg test [130], and none of them regularly used any foot based gesture system. The participants gave informed consent before starting the experiment. The experiment was approved by the Institutional Review Board of Nanyang Technological University (IRB-2018-05-051).

7.3.1 Experimental overview

The experiment consists of three tasks. Within a single task, trials are conducted considering both 2-handed and 3-handed operation. In the 2-handed trials, only the natural hands are involved in a related bi-manual task, while in the 3-handed case, both the hands and the foot control the motion of three VHS. In both the 2-handed and 3-handed trials, the natural limbs are required to perform the same action. Thus, the 2-handed trial can act as the reference to study how much and which aspects of hand operation have been affected by the addition of the foot's task.

Figure 7-2: The experimental flowchart.

The experimental flowchart is shown in Fig. 7-2. Before starting the tasks, there is a 10-minute *training phase* to get the subjects familiar with the operation of the hand/foot interfaces, virtual scene and mapping between natural limbs and VHS. Task operation then starts and each task consists of *practice phase*, *benchmark phase*, *task phase* and *assessment phase*. In the *practice phase*, the subjects were given a demonstration on how to perform the task in the 2-handed and 3-handed versions, then they were given time to practice 2/3-handed operation in 20 trials for each operation. After practice, the subjects were then randomly assigned to conduct the *benchmark phase* which consists of a single session of 2-handed operation in 20 trials or the *test phase* of 3-handed operation for three sessions with 60 trials. Between the sessions and tasks, the subjects are given 1 minute to take a rest. Finally, in the *assessment phase*, the subject fills in a questionnaire that evaluates the relative

difficulty of the tasks. Subjects were randomly assigned to perform the task in orders: One half of subjects starting with Task 1 followed by Task 2 and 3 and the other following the inverse sequence.

Figure 7-3: Virtual reality scenarios for the three tasks investigated. (a) In Task 1, the subjects move the three “limbs” independently to one of the three black targets each. (b) Task 2 is similar, but the hands have to maintain the tension of a virtual elastic band while using the center of the elastic band for tracking. (c) In Task 3, the center of the elastic band additionally has to follow a path.

7.3.2 Task operation

Based on the concept of the task design described in the above section, three tasks are conducted. These tasks are described in detail as follows.

Task 1

The subject is asked to control the VHs to reach three randomly moving targets simultaneously (Fig. 7-3a). Each target is a black ball with 2.6cm diameter. Any VH can reach any target. Once a target is reached, feedback is provided by the target changing colour to green. It is defined as reached when the distance between the centroid of the VH and the target is less than 2.5cm. The target set will be updated every 3 seconds. There are 20×3 targets shown in one trial. In the 2-handed trial, the

subject completes the same task, however, they only need to make the two VHs reach any two of the three targets.

Task 2

In this task, the subject is required to move the three VHs to track two targets (Fig. 7-3b). The two-hand-controlled VHs are connected with a virtual elastic band to mimic the physical coupling. The center of mass (CoM) of the elastic band (shown as a 2cm red ball) is controlled by the coordinated movement of VH1 & 2. The subject is asked to maintain the length of this band and move the CoM to one target, another independent target is reached with VH3 simultaneously. The two targets are moved on the screen every 3 seconds. Visual feedback is provided to remind the subject to maintain the coordinated motion: when the length of the connection band is too large (30% longer than of original length), it changes to be red and thins in width; and when it is too short (30% shorter of original length) it changes to be blue and thickens.

Task 3

Task 3 is shown in Fig. 7-3c, which is similar to Task 2, however, VH1 and VH2 are instead used to move the mass center of the elastic band such that it follows a S-shaped path back and forth. The subjects are encouraged to keep the center of mass within the path without exceeding the displayed bound. The path will change from yellow to red to warn the operator once the mass center oversteps the path boundary. At the same time, there is a randomly shown target ball updated every 3 seconds that VH3 should track.

7.3.3 Evaluation measures

Subject performance through all tasks is evaluated based upon five different measurement types: 1) task performance measures, which directly measure the subject's ability to complete the task; 2) general motion measures, which quantify the subject's motion characteristics; 3) coordination measures, which measure the coordinate between hands of subjects; and 4) load measures, which consider the cognitive and physical requirements of controlling two and three hands. A description of each of the measures is provided below:

Figure 7-4: Completion time and success/failed trial demonstration.

Task performance measure

For each trial of the pointing tasks (Task 1 and 2), the operator's performance can be classified into three states:

- **Success:** The virtual hand reaches the target and holds for more than two sample time (Fig. 7-4a, case 1).
- **Defective success:** The virtual hand reaches the target but there are oscillations, e.g., jumping out of the target zone before back (Fig. 7-4b, case 2).
- **Failure:** The virtual hand does not reach the target in 3 seconds (Fig. 7-4d, case 4). Short contact with the target may be from an accidental movement; as a result, it is also regraded as a failure when the target touching time is less than 200ms (Fig. 7-4c, case 3).

The **success rate** is the defined as the ratio of the number of the success (case 1) and the number of the total trials. The success rate of natural hands in Task 1 and 2 are measure by the average value of VH1 and 2 or the success rate of the CoM, respectively.

For Task 3, the performance of natural hands operation can be measured using the **deviation error**, defined as the difference between CoM and its ideal trajectory per path. It is given by

$$D = \frac{1}{N} \int_{t=0}^T \left| (||\mathbf{X}(t) - \mathbf{C}_k|| - ||\mathbf{T}(t) - \mathbf{C}_k||)^2 \right| dt \quad (7.1)$$

where $\mathbf{C}_k \in \mathbb{R}^2$, $k = 1, 2$, are the reference S-path center coordinates which consists of two connective circle paths, $\mathbf{X}(t) \in \mathbb{R}^2$ is the elastic band's CoM position controlled by the two natural hands and $\mathbf{T}(t) \in \mathbb{R}^2$ is the intersection point of the path center line and the line of $|XC|$. N is the round number of the S-path back and forth motions performed by the operator in each session. One round is recorded when the CoM moves from the start point to the end point.

Based on the performance, we can further check how the operator utilizes their time in each success or defective reach trial. The time can be separated into the **Response**

time t_r , from the time the targets appear on the screen to the time the VH start to move (moving speed larger than the threshold of 1cm /s); **Moving time** t_m , the period from the VH starting to move to finally reaching the target without moving out; *Holding time* t_t , the time of the VH when they are held in the target zone. The **completion time** t_c for one trial is the sum of the response time and the moving time. The metric for natural hand operation in Tasks 1 and 2 is represented by the average value of VH1 and 2 or from the CoM, respectively.

Motion and coordination measure

The **motion jerkiness** of the VHs quantifies the absolute value of the spectral arc length smoothness metric [143]. The response and holding phase data is filtered before this measure is taken. The **Travelled distance** is the total distance travelled in virtual space by each of the VHs. **Correlation of speed** measures the correlation coefficients of the speed of the VHs controlled by hands. In Task 2 and 3, the **coordination rate** is the time ratio of keeping the elastic band in the defined range and the total completion time.

Questionnaire

At the end of each task, the participants are required to fill a short questionnaire as shown in Table 7-1. This questionnaire provides a qualitative evaluation of the physical fatigue, mental load, motion smoothness, difficulty and time pressure of three-handed operation. Two-handed operation is part of the everyday operation and therefore it is expected that the addition of the supernumerary limb increases operational difficulty and mental effort [144]. The objective of the questionnaire is to evaluate the degrees of accepting and agreement of the “three hand” operation compared to the common two-handed operation in different tasks.

Table 7-1: Subjective assessment questionnaire

Statement		Score						
1. Compared to the two-handed operation, the three-handed operation is physically	equally tiring	0	1	2	3	4	5	extremely tiring
2. Compared to using two hands, the mental effort required for three-handed operation was	equivalent	0	1	2	3	4	5	very high
3. Compared to the two-handed operation, the three-handed operation is	equally difficult	0	1	2	3	4	5	more difficult
4. Compared to using two hands, the three-handed operation is	equally smooth	0	1	2	3	4	5	less smooth
5. Compared to the two-handed operation, the efficiency of three-handed operation felt	equivalent	0	1	2	3	4	5	very low
6. In general, in three-handed operation, which task/s is/are easy to achieve?								

7.4 Results

In this section, the subjects' performance in 2-handed and 3-handed trials across the different tasks will be evaluated for each of the different categories of metrics.

7.4.1 Task 1

Task performance

The average full success rate (case 1) for the natural hand operation in the 2-handed trials is about 82%. When the foot objective is added, the natural hands' success rate drops a little to 75%. After two sessions' trial, this value improves to 78% with no observed difference to the 2-handed trials. The defective success (case 2) and failure (case 3) rates for natural hands are keep consistent for both 2-handed and 3-handed trials around 9% to 12% and 2% to 4%, which means the operation accuracy did not

Figure 7-5: Task 1 result of (a) time distribution, (b) response time, (c) completion time, (d) holding time. (e) Illustration of the synchronicity of two hands and (f) the result.

reduce. However, the natural hands operation in 3-handed trials (11%, 10%, 8%) has a higher failure rate of case 4 than that in 2-handed trials (4%).

Fig. 7-5a shows the time distribution of response, motion and holding times for the success and defective reach trials. The response times are consistent for all four sessions (Fig. 7-5b). As shown in Fig. 7-5c), the subjects take about 13% more time to complete the tasks using their natural hands in the 3-handed trials compared to the 2-handed trials, thus have less holding time (Fig. 7-5d). The synchronicity of the hands-controlled VH1 & 2 in each trial is represented as the time percentage that the two VHs are moving sequentially, simultaneously or keeping static in success and defective reach trials. To be specific, firstly, we find the total motion time from VH1 or 2 start to move to both of them stop moving. For example, when $t_{r1} = \min[t_{r1}, t_{r2}]$ and $t_{c1} = \max[t_{c1}, t_{c2}]$, the whole motion time is from t_{r1} to t_{c2} , which is represented as the shadowed part in Fig. 7-5e. Then, the time in this range can be divided in: sequential motion time of VH1; the separate motion time of VH2; the simultaneous motion time of VH1 & 2; and the static time that both VH1 & 2 do not move. The results of the synchronicity are plotted in Fig. 7-5f, where it can be observed that the

simultaneous motion rate of two hands dropped around 12% when foot-controlled VH3 is added, accompanied by increased sequential movement and immovability. This may be because the participants split the attention to the third hand and spend time on planning the three VHs' motion control.

Motion and coordination

The general motion characteristics of both natural arms before and after the addition of VH3 and the foot relative to the natural arms, can be evaluated through the average value of the jerkiness and cumulative distance traveled of two limbs (Fig. 7-6). There is no statistically significant difference observed in the natural limbs' travel distance and speed correlation between 2h and 3h trials ($\min(p) = 0.06$). Furthermore, the jerkiness of the natural hands appears consistent across 2h and the three 3h trials ($p = 0.08$).

Figure 7-6: Task 1 result of (a) travel distance, (b) speed correlation and (c) motion smoothness of VH1 and 2.

The motion trajectories of three VHs in Task 1 were plotted in Fig. 7-7, from which the operators' control strategy can be observed. When dealing with the independent motion task, the participants divided the workspace into three parts with each limb then moving in the respective regions. 75% of subjects subdivide the workspace into three parts from left to right (Fig. 7-7a, left panel): The left hand is favoured on the left, the foot in the center and the right hand on the right. There is one subject put the foot on the left and the left hand in the middle (Fig. 7-7a, middle panel).

Figure 7-7: (a) Three workspace distribution patterns of Task 1 and (b-d) the motion trajectories of VH1,2& 3 of three representative subjects.

In addition, four subjects divided the workspace corresponds to the limbs' physical position (Fig. 7-7a, right panel) that (right) foot and right hand were in the right upper or lower space while the left hand was in the left. Irrespective the workspace occupation patterns, the subjects have stable motion trajectories of hands both with or without foot. Fig. 7-7b,c show two representative subjects' motion trajectories in four sessions of 2-handed and 3-handed trials. The control strategy seems to be already formed before the first session of 3-handed trials. Another representative subject's motion trajectory shown in Fig. 7-7d may reflect the derivation process of the control strategy. In the first two sessions of the 3-handed trials, the subject was in the exploring stages, both hands and foot moved irregularly in a relatively

large workspace. The motion becomes efficient and workspace has divided into three distinct areas in the third session of the 3-handed trials.

7.4.2 Task 2

Task performance

Figure 7-8: Task 2 result of (a) time distribution, (b) completion time and (c) synchronicity rate of natural hands.

In 2-handed trials, the coupled task can reach 97% success rate. This value is much higher than in the independent task. This may be because the coupled task requires one coordinated motion of two hands to one target; while the independent task requires two different movements of two hands to two targets, respectively. It can be found that, compared to independent task, the coupled task is more susceptible to the effect of the additional third hand. After VH3 was added, the success rate of the natural hands in 3h trials decreased to 82%-86%. The result on distribution of time is shown in Fig. 7-8a. Similar to Task 1, the response time of natural hands is not affected by the addition of the foot. However, the completion time increases by about 25% in 3-handed trials (Fig. 7-8b) while this value in Task 1 is 12%. As the coupled task requires coordinated motion of the natural hands, the hands' synchronous motion rate reaches 88% in 2-handed trials, which is around 24% higher than that in the independent pointing task.

Figure 7-9: Task 2 result of (a) motion smoothness,(b) travel distance, (c) speed correlation of VH1 and 2 and (d) coordination rate.

Figure 7-10: (a-c) The motion trajectories of VH1,2& 3 of three representative subjects in Task 2.

Motion and coordination

Similar to Task 1, the addition of a third VH has not impacted on this motion characteristic.

The motion jerkiness, speed correlation and coordination rate (Figs. 7-9a,c,d) showed no statistical significance between the third session of 3-handed trial and 2-handed trials ($\min(p) = 0.06$). Unlike the observation of the motion jerkiness and coordination, the traveled distance of VH1 & 2 increased when the foot was added (2h VS 3h(3), $p=0.001$), while this metric was not affected in Task 1. The motion trajectories of VHs are shown in Fig. 7-7. 40% of participants cannot come up with clear motion

trajectories of three VHs after three sessions of 3-handed trials, as illustrated in Fig. 7-10c. Another 35% of participants yield explicit control pattern before the first 3-handed trials, whose motion trajectories are stable for trials, as shown in Fig. 7-10a. The rest of the subjects could figure out an operating model after one or two session's practice, see Fig. 7-10b.

7.4.3 Task 3

Task performance

Compared to Tasks 1 and 2, Task 3 has increased difficulty requiring continuously accurate and coordinated motion of the natural hands. It can be observed from Fig. 7-11a that the subjects initially conducted a motion of 47.7mm deviation per path without consideration of the foot objective. Once VH3 was added, the path deviation increased to 76.9mm in the first 3-handed trials but reduced to 63.5mm after two sessions' operation.

Figure 7-11: Task 3 result of (a) path deviation/path number, (b) motion jerkiness, (c) speed correlation and (d) Coordination rate of natural hands.

Motion and coordination

The natural limbs' motion in Task 3 (Fig. 7-11b) does not show statistical difference on the motion jerkiness between 3h and 2h session ($p=0.13$). Fig. 7-11c shows the

correlation of speed measure between VH1 and 2 in Task 3. There is no statistical difference for this metric between the 2-handed and 3-handed trials ($p = 0.16$).

7.4.4 VH3 controlled by foot

Figure 7-12: The success rate (including both full success and defective success trials) of VH3 in three tasks.

In all three tasks, the foot controlled VH3 conducted the same pointing action. The performance of the VH3 is shown in Fig. 7-12. It can be found the performance of VH3 controlled by the foot is improved by trials. The success rate of VH3 improves from the first session to the third session of trials in Task 1 (3h(1) VS 3h(3), $p=0.02$) and Task 3 (3h(1) VS 3h(3), $p=0.01$).

7.4.5 Subjective assessment

Fig. 7-13 shows the questionnaire results. The subjects felt that Task 1 was easy (median=1, interquartile range (IQR)=1), smooth (median=1, IQR=2) and without much physical (median=1, IQR=2) and mental fatigue (median=1, IQR=1) compared to using 2-hands. Moreover, the subjects felt the 3h operation time increased (median=2, IQR=2), which matches the experimental data. For Task 2, the subjects felt similar to Task 1 in all aspects. They felt Task 3 was more challenging than Tasks 1 and 2 ($p<0.029$) except for jerkiness (Task 2 VS Task 3, $p=0.08$). The Task 3 mental load and difficulty ratings were very high, at the highest scores of 5 for the median

Figure 7-13: Results of assessment questionnaire.

values, along with increased physical fatigue (median=3, IQR=1) and operation time (median=4, IQR=2). 70% of subjects chose Task 1 as easiest while 30% of subjects instead preferred Task 2. All subjects rated Task 3 as most difficult.

7.5 Discussion and conclusion

This study evaluated the capability of a foot-controlled third hand working together with the NLs. A VR system integrating two hand interfaces and a foot interface was developed. The subjects' capability was then evaluated through three tasks with different coupling between the VHs. The results suggest that subjects possess the potential to use a foot-controlled interface when controlling an additional supernumerary degree of freedom in combination with their NLs. For future SL control it is however noted that the integration of the foot-interface appears to impose a limit on the speed at which bimanual tasks can be performed. Furthermore, differing levels of NL performance degradation was observed based upon the task's coupling level and path dependence.

In independent VH motion, the results suggest that a foot-controlled VH can be added with little performance loss. The addition of a foot-controlled third hand resulted in 13% slower NL operation, which may be a result of a serialisation of the tracking that occurs due to the multi-tasking taking place at the visuomotor level [145]. With minimal training there was no observed effect on the NL performance for success rate, jerkiness, travel distance and speed correlation. Subjects found the performance to be within acceptable limits and most felt the task to be easy requiring little mental effort.

In contrast, coupled NL tasks appear more sensitive to adding VH3. The success rate, completion time and travel distance were all negatively impacted, however, jerkiness was unaffected. Compared to independent motion, these tasks require NL coordination. The addition of a foot-controlled VH may therefore have a greater impact due to the continuous coordination constraint for which serialisation would more negatively impact performance. Furthermore, inter-limb coupling may have a differing impact across the two tasks. In Task 1, the actions of the hands are completely independent such that the noted negative effects of the foot's spatially incongruent motion [146] act independently on each hand. In contrast, in Task 2 the spring connection may make the negative effects of incongruency add across the congruently moving NLs, however, this would need to be further studied as it is likely a unique feature of trimanual manipulation.

In Task 3, the participants needed to dynamically follow the path accurately while coordinating their hands. When the foot was added, the participants complained about the difficulty and mental load of this task in the subjective assessment. This unsatisfactory performance may be due to the varied temporal organizations of the hands and foot, which are regarded as one of the major interference to interlimb coordination [147].

In general, the subject's foot performance was found to improve from the first to last session of trials. Given that the foot is used less for high dexterity, this result may indicate a potential such that with further sessions, the foot's operation may be less affected and even converge on the performance of the NLs. This also suggests that if sufficient and proper practice of each VH is provided, the participants may be able to successfully perform trimanual tasks without burden. However, a more systematic study of any learning is required.

Chapter 8 A Three-limb Teleoperated Robotic System with Foot Control for Flexible Endoscopic Surgery

8.1 Summary

Compared to the laparoscopic procedures with rigid tools, flexible endoscopic instruments can easily access the region of operation through a natural orifice with less invasiveness [4]. For example, natural orifice transluminal endoscopic surgery (NOTES) represent the surgery that access to the surgical site through natural orifice of human, which has less damage to patients' body and enables fast recover. However, it is difficult to manipulate the long soft endoscopic tools. The surgeon should spend longer training time to familiar with the operation of the endoscope and instruments. The integration between the robotic system and the surgery solves this problem and make the surgeon more focus on the diagnose and treatment.

In this chapter, we develop a novel three-limbed teleoperation robotic endoscopic system that enables one surgeon to control alone both the endoscope and two surgical tools. The system integrates the developed foot-controlled robotic endoscope and two robotic instruments (a robotic grasper and a robotic cauterizing hook, developed by other researchers in **caolin2019**). A foot-controlled human-machine interface maps the natural foot gestures to the four-DoF movements of the endoscope, and two hand-controlled interfaces map the movements of the two hands to the two instruments

individually. The proposed robotic system was validated in an ex-vivo experiment carried out by six subjects, where foot control was also compared with a sequential clutch-based hand control scheme. The participants could successfully teleoperate the endoscope and the two instruments to cut the tissues at scattered target areas in a porcine stomach. Foot control yielded 43.7% faster task completion and required less mental effort as compared to the clutch-based hand control scheme. The proposed system is intuitive for three-limb manipulation even for operators without the experience of handling the endoscope and robotic instruments. The rest of the chapter is organized as follows. Section 8.2 describes the mechanical structure of the master and slave devices of the teleoperation system. A system motion control study and a user study with ex-vivo test are presented in Section 8.3. Section 8.4 presents the result and Section 8.5 discusses the results and provides a conclusion.

Figure 8-1: Overview of the foot-controlled robotic endoscope teleoperation system (CAD drawing). (a) Master console and surgeon. (b) Slave surgical robot systems, one for the endoscope and one for the two endoscopic tools.

8.2 Robotic system

The developed system is sketched in Fig. 8-1. At the master site, two commercial hand interfaces are used to collect the motion signals of the hands, and a foot interface is used to capture the foot gestures of the surgeon. The slave system consists of three

robotic tools, i.e., an endoscope and two surgical instruments passing through the external tool channels which are attached to the endoscope. With this master-slave architecture, the motions of the surgeon's hands and foot are mapped to those of the slave arms. The design, setup and control aim to increase the transparency and intuitiveness between the master and slave control.

8.2.1 Master interface

Hand interface

Two Force Dimension Omega 7 haptic interfaces (Fig. 8-2a) are used to remotely control the robotic instruments. Each interface can control six-DoF movements and one-DoF grasping. Four DoFs of the hand motions are selected to control each slave tool.

Foot interface

The foot interface was specially designed to control the surgical instrument, please see Chapters 3&4 for detail.

8.2.2 Slave robotic system

Slave robotic endoscope

The robotic endoscope includes three modules motorizing the standard endoscope in four DoFs. The commercialized endoscope can be easily and quickly assembled or disassembled on the robotic system without any modification. Please see Chapter 6 for detail.

Figure 8-2: Master interfaces with (a) hand interface (CAD drawing) and (b) foot interface (CAD drawing). (c) Robotic instruments of grasper and mono-polar cauterizing hook (upper panel is photo and lower panel is CAD drawing). (d) Flexible endoscope (photo).

Slave robotic instruments

In the current implementation, the two robotic instruments are a grasper (lower) and a monopolar cauterizing hook (upper) as shown in Fig. 8-2c. They can be changed to other surgical instruments, such as a suturing device [13]. Each robotic arm can provide four-DoF motion (the grasper has an additional grasping motion). The bending and grasping DoFs are driven by a tendon-sheath mechanism, where each DoF is controlled by two antagonistical tendon-sheath mechanisms and motors. At the proximal end, pretension is applied to each tendon to reduce the effect of backlash and slacking. Load cells are used to monitor the proximal tension force for every tendon. The translation and rotation DoFs are actuated by a motorized linear slider and a rotary motor at the proximal side, respectively. The robotic instruments pass

through the external tool channels that are attached to the endoscope. The diameter of the instrument is 4.2 mm. The internal and external diameters of the tool channel are 5 mm and 6 mm respectively. The maximum length of the cross section of the endoscope with instruments is about 17 mm, which is in the appropriate size range of endoscopic multiple-tool platforms [8].

8.2.3 Control mapping

Left hand movements control the five DoFs of the surgical grasper (Figs. 8-2a,c), the right hand controls the four DoFs of the surgical hook, and the foot interface the four DoFs of the flexible endoscope. In the initial position, the two instruments extend out about 60 mm from the tip of the endoscope. They can be withdrawn a maximum of 40 mm. Each bending joint can rotate $[-83^\circ, 83^\circ]$. Each of the delicate surgical arms has a cylindrical workspace with a cross-sectional diameter of 25 mm. The endoscope has a larger workspace with a cross-sectional diameter of 160 mm which can significantly increase the workspace of the instruments.

The approach of the left hand controlling the grasper is described here, and the related variables are defined in Figs. 8-2a,c. The grasper's translation (relative to the endoscope camera) is controlled by the left hand forward/backward movement according to $y_i = \alpha_1 x_h$, $\alpha_1 > 0$. The grasper's L/R steering motions are controlled by the lateral hand movement as $\phi_i = \alpha_2 y_h$, $\alpha_2 > 0$, the U/D bending by the vertical hand movement as $\theta_i = \alpha_3 z_h$, $\alpha_3 > 0$. The grasper's rotation is controlled in velocity by the hand/forearm rotation according to $\gamma_i = \alpha_4 \dot{\gamma}_h$, $\alpha_4 > 0$. As forearm rotation has a very limited range of comfortable postures thus velocity control is more appropriate. The grasper's opening/closing is controlled by the hand gripper mechanism angle. The hook, with a similar design, is controlled in the same way. Note that the hook does not have an opening/closing jaw.

The four DoFs of the endoscope are controlled in velocity by foot motions through the foot interface as shown in Fig. 8-3. The endoscope in/out y_e is controlled by the foot forward/backward movement y_f according to $y_e = \beta_1 \int y_f$, $\beta_1 > 0$. The endoscope rotation γ_e is controlled by the foot lateral translation with $\gamma_e = \beta_2 \int x_f$, $\beta_2 > 0$. The foot flexion/extension controls the endoscope up/down movement as $\theta_e = \beta_3 \int \theta_f$, $\beta_3 > 0$, and the foot rotation the endoscope left/right bending with $\phi_e = \beta_4 \int \phi_f$, $\beta_4 > 0$. This mapping is intuitive as the selected movements of the foot are similar to the corresponding movements of the endoscope. For instance, the forefoot rotation around the ankle, can be intuitively regarded as the bending tip of the endoscope. The operator can take the foot and shank as the endoscope for metaphor. The foot can remote control the endoscope easily through isomorphic mapping.

Figure 8-3: Motion mapping between the foot and endoscope.

8.3 Experiments

To examine the system's performance, we firstly investigated the inherent motion hysteresis of the instruments and endoscope in the bending DoFs with a tendon-driven mechanisms. Six subjects were recruited for the experimental study within research staffs from the Engineering Faculty, Nanyang Technological University. These subjects aged 30.5 ± 2.9 year old were all right handed and footed, have no known sensorimotor impairment, and the group has 2 females. The same subjects also conducted an ex-vivo test with an surgical cutting task in order to assess the system for three-hand operation, and compare it with hand clutch control.

8.3.1 Robotic system motion control study

Tendon-driven mechanisms have the inherent drawback of backlash due to the slacking and elongation of the tendons, friction at the joint, etc. [138], [148], [149]. The robotic grasper and hook thus used an antagonistic system of cables for each bending DoF with adjustable pretension to reduce the backlash. In contrast, the endoscope used in the system has low, non-adjustable pretension which leads to larger backlash. Motion studies of robotic instruments and endoscope in two bending DoFs were conducted to study the respective backlash and deadzone.

Robotic instrument motion study

We have studied the proximal-distal motion behavior of tendon-sheath driven instruments for both pitch and yaw movements (Fig. 8-4a). When the operator uses the Omega 7 haptic device to manipulate the surgical tools, their movements are converted from distance into angles and then sent to the motor (desired proximal angle). The motor encoder then feed back the actual proximal angle. An encoder is attached to the

Figure 8-4: Robotic instrument motion study. (a) motion joints (b) set up. Endoscope motion study (c) set up and (d) angle calculation.

tool's joint to record the actual distal angle (Fig. 8-4b). In the test, an operator at the master side was asked to move the hand controller back and forth to control the distal joint of the instrument in seven cycles. The signals of the hand controller were first transmitted to the proximal end motors of the slave robot and then passed to the distal end tool joint through 2.5 meters' long tendon-sheath mechanisms. The motion study result of instrument and endoscope is shown in Section 8.4.1.

Robotic endoscope motion study

A motion study of the robotic endoscope is also conducted using the two bending DoFs. The test setup is shown in Fig. 8-4c. Ten yellow markers in a line with 6 mm

diameter and 10 mm spacing were attached to the upper surface of the endoscope bending section. The motion of the ten yellow markers was tracked a 2D camera and saved at a sampling rate of 30 Hz. The camera was calibrated before the test using the checkerboard to correct the lens' distortion and identify the camera parameters. During testing, the camera was located on the top of the endoscope's bending section, recording the motion of the yellow markers and the status of the LED indicator light (for synchronization purposes). After the test, the video was analyzed (offline) to compute the planar position of ten marker points using a color marker based object tracking method by thresholding the color channels. The center points of the markers were then extracted and aligned at the initial static position. Eighth to ten markers away from the endoscope tip shows almost constant position during the test and thus the position of the eighth marker is regarded as the bending origin. The bending angle of the endoscope could be calculated through the coordinates of the first and eight markers (Fig. 8-4d), with $2 \arctan(\Delta x / \Delta y)$.

A LED indicator light (Fig. 8-4c) was located in the camera's image. This was used to synchronize the data of the proximal end motor and distal end endoscope tip. The light was turned off at the beginning. It was turned on when the motion command was sent to the proximal motor and turned off again when the proximal motor stopped. The light-up period of the indicator can be identified from the video. Thus, the motion data of the proximal motor and the distal tip of the endoscope were synchronized by using the signal of the indicator light.

8.3.2 Ex-vivo test

The six subjects described above performed a surgical point cutting task. Two control modes for three-hand operation, foot & hands control and hand clutch control, are compared in this test.

Experimental procedure

The participants firstly attended a *training section* consisting of a demo on how to use the foot interface, hand clutch and hand interface followed by an individual practice of 20 minutes, after which they were informed about the task procedure. The participants were randomly assigned to start with one of the two control modes. Ten minutes were given for a *practice section* to conduct a trial operation. After completing four sets of operations with one control mode in the *task section*, the participants were asked to practice and run another four sets of operations using another control mode. To prevent fatigue, there were 1-minute breaks between each set and a 5-minute break interval between the two control modes. The *subjective assessment section* was conducted after the experiment was completed, i.e., each participant was asked to fill a questionnaire in order to assess the mental effort, physical effort, operation efficiency, easiness and comfort for the tests with a Likert scale from 1 to 5. They were also asked to choose their personal preference among the two control modes and specify their reasoning (Table. 8-1).

Table 8-1: Subjective assessment questionnaire

Statement		Score					
1. The mental effort required for operation was	low	1	2	3	4	5	high
2. The physical effort required for operation was	low	1	2	3	4	5	high
3. The operation mode is	not efficient	1	2	3	4	5	very efficient
4. General comfort was	very uncomfortable	1	2	3	4	5	very comfortable
5. Overall the system was	difficult	1	2	3	4	5	easy to use
6. In general, which control modes do you prefer? Why? Please specify your reason(s)							

Foot & hands control

See Section 8.2.3.

Table 8-2: Parameters of using foot or hand controlling the endoscope.

Hand			Foot			Endoscope	
DoF	Movement	Zero band	DoF	Movement	Zero band	DoF	Velocity
x_h	$[-50,50]\text{mm}$	$[-10,10]\text{mm}$	y_f	$[-20,20]\text{mm}$	$[-6,6]\text{mm}$	y_e	$[-20,20]\text{mm/s}$
y_h	$[-80,80]\text{mm}$	$[-16,-16]\text{mm}$	ϕ_f	$[-12.5,12.5]^\circ$	$[-4,4]^\circ$	ϕ_e	$[-20,20]^\circ/s$
z_h	$[-60,60]\text{mm}$	$[-12,12]\text{mm}$	θ_f	$[-10,10]^\circ$	$[-3,3]^\circ$	θ_e	$[-20,20]^\circ/s$
γ_h	$[-90,90]^\circ$	$[-27,27]^\circ$	x_f	$[-20,20]\text{mm}$	$[-6,6]\text{mm}$	γ_e	$[-20,20]^\circ/s$

Hand clutch control

The system also enabled a hand clutch control mode. In the hand clutch control mode, the endoscope and one tool are controlled by the same hand interface, swapping by clutch buttons. There are two clutch buttons attached to the handle of the hand interface, which can be easily pressed by the middle and ring fingers (Fig. 8-5a). Once the upper button is pressed, the hand interface will control the endoscope, and when the lower button is pressed, the interface will swap to control the surgical tool. The hand interface is set to control the endoscope at the initial state. Before commencing the task, participants are allowed to choose either their left or right hand interface to control the third tool.

The conditions of the hand clutch control are set to be the same with the foot control: translations in x_h, y_h, z_h, γ_h control in/out translation, L/R bending, U/D bending and rotation DoFs of the endoscope respectively. An outward-going linear increasing force feedback from -2 N to 2 N are provided to the hands, setting a automatic home position with minimal resistance force at middle position. The motion ranges of hand or foot are mapping to the same velocity range of the endoscope. All the movements and force feedback are set within a comfortable ranges. The parameters used for the foot and hand control as well as of the endoscope are summarized in Table 8-2.

Figure 8-5: Ex-vivo test setup. (a) Master console. (b) Operator controls the master system. (c) Slave robotic system and surgical devices. (d) Robotic surgical instruments and working tissue.

Setup and surgical task

The experimental setup is shown in Figs. 8-5. Fig. 8-5a,b depicts the master console for the operator including monitor with camera view, two hand interfaces, the foot interface and foot switches. The foot switches are used to activate monopolar option of Erbe electrosurgical unit. Which is commonly used in electrosurgery to cut the target tissue and/or coagulate bleeding. The operator uses two hands holding the hand controllers, one foot controlling the foot interface and another foot pressing

the monopolar foot switches. The slave robotic systems and endoscopy image and lighting system are shown in Fig. 8-5c.

A pseudo surgical task was used to test the system with three hand control. Surgical procedures such as Endoscopic Submucosal Dissection (ESD) are challenging to carry out even for professional endoscopists, who require years of training to perform it skillfully [150], [151]. Therefore, to test the system and three hand operation with naive subjects, we selected as a simplified task the point cutting and marking at the specified areas using the electrosurgical unit instrument. This is part of the ESD procedures, e.g. marking, precutting or hemostasis etc. [152]. The operators were asked to cut the tissue at four targets (e.g., locations) one by one from right to left. Cutting was defined as touching the tissue using the cauterizing hook knife. As shown in Fig. 8-5d, the porcine stomach weighing 0.6 kg was fixed on a 150×150 mm² inclined surface with a 45° slope. The four targets located spatially (in the zone of $100 \times 50 \times 50$ mm³) on the tissue marked by blue color dye, inclusive of two exposed and two covered targets. The exposed target was marked as circular zone with 8 mm diameter; the covered target had an incision width about 15mm in length, the marked area was inside the incision and cannot be reached by only lifting up the covered tissue. One set of operation is complete when all four targets are successfully reached and cut. The completion time was from the start of the endoscope movement to its stop when the final target is cut. The result of the ex-vivo test is shown in Section 8.4.2.

8.4 Results

8.4.1 Instrument and endoscope motion profiles

Figs. 8-6a,c show the practical input-output motion behavior of the instruments for both pitch and yaw motions. The motion is affected by hysteresis caused by the

Figure 8-6: Motion control of hands, proximal motor and distal tool in DoFs of (a) L/R bending and (c) U/D bending. Motion hysteresis profiles of the instrument in (b) L/R bending and (d) U/D bending. Motion hysteresis profiles of the endoscope in (e) L/R direction and (f) U/D direction.

friction and tendon elongation of the flexible tendon-sheath mechanisms. The effect of hysteresis on the proximal angle and actual distal angle for both yaw and pitch motions are shown in Fig. 8-6 b,d.

Figs. 8-6e,f depict the relationship between proximal motor position and distal bending angle for the endoscope when actuating each DoF individually. The hysteresis profile is similar as in previous studies [29], [153]. The proximal motor rotated bidirectionally (recorded as positive to negative angles) for two cycles in each level. There are non-linear areas, especially in the middle of the profiles (about $\pm 20-25^\circ$). At this range,

Table 8-3: Completion time of six participants

Operation mode	Set number	Completion time (second)					
		Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	Subject 6
Foot & hands	1	322	492	132	194	306	129
	2	305	353	158	185	122	158
	3	320	255	145	154	156	132
	4	265	248	211	131	181	164
Hand clutch	1	530	436	300	336	397	248
	2	442	363	187	409	290	318
	3	572	424	253	285	232	172
	4	243	242	231	240	204	146

the pair of cables on both sides are slacking and the distal tip does not move until the slacking is diminished. The result of the dead zone range provided a reference to determine the actual zero position of the endoscope in the initialization of the system. In addition, the operator could have more control over the system by being conscious of the motion states of the endoscope from the hysteresis profile (Fig. 8-6e,f). For example, when the endoscope approaching the dead zone, it is foreseeable there will be a delay between foot command and the endoscope tip bending motion. Accordingly, the operator could make proper control decisions to move the endoscope smoothly.

8.4.2 Surgical task performance

The operation of the surgical task is depicted in Fig. 8-7. The operators viewed the robotic instruments and tissue through the endoscopic camera view (Figs. 8-7b,d). For the exposed targets shown in Figs. 8-7a,b, each operator was required to directly cut the tissue within the marked zone; for the covered target, see Figs. 8-7c,d, the operator should lift the tissue using their left hand controlling the grasper and cut inside with hook. Figs. 8-7e,f show the cutting result of one participant. The trial was regarded as failure if the operator did not cut in the target zones.

Figure 8-7: Surgical operation of (a)(b)exposed and (c)(d) covered targets viewed from top camera and endoscope camera. Cutting result for (e) exposed and (f) covered targets.

The completion times of each subject using foot and hand clutch control modes in four sets are shown in Table 8-3. All the participants could complete the surgical task within ten minutes with both control modes. The whole surgical system is user-friendly for new users. In addition, the time was reduced in all participants by using foot rather than hand clutch control, with $217.4 \text{ s} \pm 93.3 \text{ s}$ relative to $312.5 \text{ s} \pm 112.5 \text{ s}$ ($p = 0.003$, Mann–Whitney U test). Four of six of the participants had their operation time reduced by 40 - 50% when using foot control {44.4%, 50.3%, 46.8% , 51.6%},

one participant exhibited a lower (8.7%) and one a higher (91.3%) time reduction relative to hand clutch control.

8.4.3 Subjective assessment

Figure 8-8: Results of questionnaire.

The questionnaire and its results are shown in Table 8-1 and Fig. 8-8. The participants felt that less mental effort was required in foot control than with the hand clutch ($p = 0.021$, Mann–Whitney U test). The rating of efficiency, comfort and easiness for foot and hand clutch control was not statistically different ($p = 0.74, 0.37, 0.16$, Mann–Whitney U test) but on average slightly higher with the foot than with the hand clutch. Five of six of the participants preferred using the foot interface working together with hands to operate the system. One participant reflected “Foot control is tiring, especially in the holding gesture to wait the endoscope to move”. However, most of the individual comments reflected the ambiguity of bimanual operation with clutch solved by the additional foot control, e.g. “Using hand clutch cannot conduct simultaneous movement of endoscope and instruments”, “There is coupling on both hands, i.e. when using one hand to control the endoscope, the other hand holding the tool moves together unconsciously”, “It is a little bit confusing sometimes whether the hand is controlling the endoscope or the tool”.

8.5 Discussion and conclusion

The experimental study has validated the design concept and the feasibility of the novel three-limb teleoperated endoscopic robotic system. All the participants could telemanipulate two surgical instruments and one endoscope to intuitively conduct the surgical task using hands and foot simultaneously. The average completion time per set ranged from [161.5 - 337.0] s for foot-hands three-hand control, and from [242.8 - 446.8] s for hand clutch bi-manual control, then the operation time was reduced in average by 43.7% using the proposed system. Furthermore, no discomfort or difficulty was reported by the participants, foot control enabled achieving a similar level of efficiency, comfort and ease of use compared to hand control. Most of the participants even felt the mental effort required for the operation using the foot-hands control mode as low.

The proposed system enables one operator to telemanipulate three tools using foot and hands, with the following advantages:

- The allocation of the tasks for hands and foot corresponds to the natural motion of the limbs and ergonomics. The proposed system yields a clear role for each limb avoiding confusion on which instrument is controlled, in contrast to control with hand clutch that was also tested in above experiment.
- The foot control provides unique features relative to existing systems in endoscopic surgery: (i) Foot control provides control independent from hands, avoiding potential coupling issues between left and right hands, or hands and fingers. (ii) The system uses natural foot gestures controlling the flexible endoscope in four DoFs based on isomorphic mapping. The foot interface collects continuous foot gestures, providing foot support and positioning assistance while minimizing the operation fatigue [142].

Few robotic systems have been proposed that are based on a long flexible shaft and allow three-tools robotics teleoperation. The EOR, FLEX, RAFE systems [22]–[24] have a robotic endoscope but with manually controlled instruments. The MASTER system [25], [154] developed by our group provides dexterous tele-manipulation of two instruments based on a dual-channel gastroscope with articulated arms at the distal tip, where the endoscope has to be manually controlled at the patient side by a second endoscopist. The K-Flex system [31] has an endoscope with enhanced payload capability allowing totally 14 DoFs movements of the three slave instruments. The bi-manual master interfaces could only control two surgical tools simultaneously, while the third tool is controlled by the left hand after pressing a foot clutch. In our system the 13 DoFs can all be activated simultaneously to perform a surgical operation. To our knowledge, this is the first teleoperated robotic system for endoscopic surgery with foot control offering the possibility to tele-manipulate the three flexible surgical instruments together.

While the experimental results reported in this chapter are promising, important limitations need to be mentioned. First, the current foot interface can control four DoFs, which may not be sufficient to control some surgical tools, such as Endowrist Instruments of the Da Vinci system, which has up to seven DoFs. Secondly, the current slave robotic system is bulky, and a more compact version would be needed in an actual operation room (OR). This new version will also include water/gas and suction control buttons in the master console, which could be commanded using the second foot [86], [89]. Furthermore, one participant reported fatigue while using the foot control, perhaps due to the large force he exerted when the endoscope was in the dead zone. This inherent motion backlash of the non-linear tendon-driven mechanism may be improved using machine learning techniques and adaptive control [155]–[157]. At the current stage, the surgical operation study was conducted with subjects without medical background, which was designed to validate the feasibility of the proposed robotic system. In the future, systematic studies for more complex surgical procedures like

ESD will be carried out with professionals, to further test its practicality in real-life surgery.

Chapter 9 Conclusions

9.1 Contributions

Robot-aided surgery facilitates surgeon's operation using robotic interfaces. However, current robotic interfaces are controlled by hands, so enable the surgeon to command at most two instruments simultaneously. An assistant is still required. The necessity to collaborate with an assistant may result in miscommunication, create efficiency issues and even affect the patient's health. A solution to address this issue is to let the surgeon control the additional instruments by themselves using hand-free interfaces.

This thesis work developed a passive foot interface to control a robotic manipulator. It can collect continuous and natural foot motions/ forces and provide dynamic haptic and position feedback. The interface allows a surgeon to remote control a surgical instrument in four-DoF without interrupting the hands' operation. It is essentially a parallel-serial hybrid mechanism with springs and force sensors. The rationally located springs provide a homing position and singularity-free workspace. The mobile pedal supports the foot against gravity with minimized friction and thus reduces human fatigue. A subject-specific mapping using ICA was integrated into the interface to adapt to specific user's motion pattern. This ICA method could accurately predict the subjects' motion intention as compared with the analytical approach.

The user performance using the pedal interface and the existing button interface were compared in an experiment. Users teleoperated the robot with both interfaces performing complex path-following tasks similar to laparoscopic training. The result

showed that the proposed interface directly control the robot based on the natural continuous movement of the foot and leads to more intuitive and efficient operation and smoother trajectories than the conventional button interface,

The human capability of tri-manipulation using hands and foot via two commercial hand-controlled interfaces and the developed foot interface was studied. Participants were asked to control three virtual hands to perform tasks with different coupling and cognition levels. The performance of two natural hands was regarded as a reference group to check the effect of the addition of the foot. The results show that coordinated task are more susceptible to the addition of the third hand than the independent task. In the independent task, in which three hands conduct independent pointing movements, participants could quickly yield a control strategy that specializes the virtual hand workspace into three zones based on physical limbs' locations or their preference and then control each virtual hand moving in the corresponding zones without conflict.

A three-limbed teleoperated robotic surgical system was finally developed to validate the feasibility of the foot interface and three-hand control concepts in the surgical application. The system constitutes three tools of endoscope, robotic grasper and cauterizing hook for flexible endoscopy. Two instruments are controlled by hands providing dexterous operation, while the endoscope controlled by the foot can adjust the view and enlarge the workspace of the surgical instruments. In an ex-vivo test, all participants could successfully teleoperate the endoscope and the two instruments to cut the tissues at scattered target areas in a porcine stomach without an assistant.

9.2 Novelties

9.2.1 A novel four-DoF foot interface

While the feet exhibit well-controlled multi-DoF movements, most current foot interfaces for robot-aided surgery use a simple range of buttons or switches to command the robot at constant speeds and in one direction at a time. Using such interfaces also requires the operator to move the whole leg (which can be tiring for long operations) and plan the combination and sequence of the buttons without haptic feedback.

This thesis work developed a passive foot interface to control a robotic surgical instrument with continuously changing direction and speed. In general, the novel foot-controlled interface possesses the following salient features:

- The interface is comfortably controlled by natural foot movements. The capability of this interface in controlling a robotic arm in multiple DoFs was verified in a teleoperation test.
- The mapping between the interface and the slave robot is intuitive and efficient, especially in controlling complex spatial motion. The user performance using the pedal interface was compared with an existing button interface. Users teleoperated the robot with both interfaces performing complex path-following tasks similar to laparoscopic training. The result showed that the button interface enables high accuracy in controlling single directions but exhibits more deviation in complex motion which combines multiple DoFs. In comparison, the pedal interface directly controls the robot based on the continuous natural movement of the foot and led to more intuitive and efficient operation and smoother trajectories.
- The feedback-sensing module made of a spring and a force sensor mounted in series provides rich position and force feedback to assist foot positioning

and closed-loop control, requiring only small foot movements without limiting the applied force range and end-effector's motion range. The carefully located springs provide a homing position and singularity-free workspace.

- The weight of the foot is supported by a ground support to save effort. The resulted friction was minimized using bearings and redundant joints.
- An ICA-based data-driven approach was developed to provide an intuitive mapping for subject-specific motion patterns. This is because subjects had substantially different movement patterns. The data-driven approach was compared with the analytical approach through a multi-directional motion test, whose result showed that the ICA method could accurately identify subjects' foot motion patterns and significantly improve the prediction accuracy of motion directions as compared with the analytical approach.

9.2.2 A foot-controlled robotic endoscope system

A novel foot-controlled robotic system was developed to use the proposed foot interface to teleoperate a remote flexible endoscope. The four-DoF motion of a flexible endoscope was driven intuitively by the foot gestures. The commercial endoscope could be easily assembled and disassembled to the system. The proposed robotic system was validated in teleoperation experiments, where foot teleoperation was compared with hand teleoperation and direct control of the endoscope with two hands. The participants could successfully teleoperate the endoscope with foot teleoperation and exhibited 40% faster task completion as with direct control. Although hand teleoperation enabled the best performance, only foot teleoperation allows simultaneous control of three instruments.

9.2.3 Human behavioral study on tri-manipulation

An experimental study was conducted to evaluate the capability of the human foot to control the third hand working together with natural limbs. The three-handed control capability test was conducted with two commercial hand-controlled interfaces and the proposed foot interface. Participants were asked to control three virtual hands to perform functional tasks with different coupling and cognition levels. The performance of two natural hands was regarded as a reference group to check the effect of the addition of the foot. In the independent task, in which three hands conducting independent pointing movements, participants are able to incorporate additional independent motion with their foot without a loss of natural bimanual performance. Although the addition of a third limb resulted in lower hand operation, there was no observed effect on the natural hand performance in terms of its success rate, motion jerkiness, travel distance and speed correlation. Participants could quickly adapt to the trimanipulation tasks. The experimental results showed the potential of integrating the foot into a tri-manual control system and may serve as the basis of further research in augmentation of human capabilities to teleoperate multiple robotic limbs.

9.2.4 A three-limb teleoperated robotic system

A three-limb teleoperated robotic endoscopic system with solo-surgeon was developed. To the best of our knowledge, this is the first three-limb teleoperated robotic system for endoscopic surgery with foot control to telemanipulate the flexible endoscope and instruments. The system integrates a foot-controlled endoscope and two hand-controlled robotic arms. The system is modular so that the foot-controlled robotic endoscope can also be combined with other robotic systems based on the standard endoscope. The foot-hands manipulation was proved intuitive and more efficient

than sequential hand control, even for operators without the experience of handling any surgical instruments. In addition, the three limbs simultaneous teleoperation with hands and one foot did not require much mental effort in contrast to two-handed operation.

The proposed robotic system was demonstrated in an endoscopic surgical task on an ex-vivo porcine stomach, and a comparison of simultaneous three tools operation with sequential control using hand-clutch was performed. This three-limb teleoperated robotic system enables one surgeon to intuitively control three endoscopic tools which normally require two operators, which may reduce manpower, avoid communication errors, and improve efficiency.

9.3 Limitations and future directions

This thesis presented a foot-controlled human-machine interface and a three-limb teleoperated robotic system to augment the human control capability and improve the operation efficiency. Future improvements can be pursued in many different directions, in particular:

9.3.1 Improvement of foot interface

The proposed foot interface can be used to control assistant surgical tools such as laparoscopic camera, endoscope or suction tool, etc. However, compared to hands, foot cannot perform dexterous and accurate manipulation, e.g. stitching or sewing up patients in surgery. The proposed foot interface supports four-DoF control. It is a question how to achieve six-DoF intuitive and efficient motion control without introducing much physical fatigue and guarantee the control repeatability. At the current stage, foot control with proposed interface still cannot use to control main

surgical tools such as a cutting knife or monopolar hook, which directly interact with tissue and require continuous fine operation. Data-driven mapping was developed in Chapter 4 to improve the foot accuracy in motion directions and reduce the errors from the individual specific motion patterns. However, accidental error of overshooting or undershooting the targets when performing the pointing task was observed. This may be due to the poor human neuro-motor control of foot, lack of practice and/or the interaction with the foot interface.

The further plan is optimize the foot interface and develop a methodology to design and optimize the elastic-isometric interface. A six-DoF foot interface will be developed to control more dexterous surgical instrument, e.g. Endowrist tool of Da Vinci system. We will study what kinds of passive force feedback could improve the foot motion control performance. And there is a strong possibility that the force field assisting the foot control is also subject specific. The developed methodology will help to optimize the foot interface configurations, including the amount, stiffness and arrangement of elastic elements, in order to design a compact interface not only saving operator's effort but also assisting accurate foot motion. Furthermore, this methodology will fully consider the human operator's specific characteristics, including their age, height, preferred chair height and sitting posture, weight etc. In addition, the subjective evaluation like user's convenience will also be considered in the optimization of the foot interface.

9.3.2 Human capability on three-handed manipulation

Three-handed control was investigated in only three tasks in Chapter 6, while human behaviors in three-handed operation are potentially much more rich. A series of experiments will be conducted to systematically study human three-handed control capabilities. More cases, including three-handed coordinated and dependent motions, will be studied with force feedback to render the physical coupling. Additionally, the

performance of one person's three-hand control will be compared with two-person three-hand control (one operator using the hands and the other with one foot). Human performance and control strategies in two-hand and three-hand operations will be studied through these experiments so as to understand human abilities to augment their motor control with supernumerary limbs.

9.3.3 Three-hand surgery

This Ph.D. work suggest that a foot can be used together with the hands to yield skillful and coordinated three-tools control. However, it is still a long way to apply the “three-hand surgery” concept in the real surgery. The ex-vivo test in Chapter 8 show the possibility of applying it in the flexible endoscopic surgery. We will continue to study the three-hand surgery in the widely used laparoscopic surgery. The next step is integrating the developed foot interface into the famous Da Vinci robotic system in order to control one of the laparoscopic robotic arms. The foot interface will work together with two hand controllers (e.g. Force dimension hand controllers or the Da Vinci hand console) to control three robotic arms. This system will enable us to systematically study the feasibility of multi-limbed surgical operation and investigate suitable surgical procedures where such a setup would be beneficial.

Meanwhile, other alternative interaction methods, such as muscle interfaces, graphic user interfaces, augmented reality may be integrated into the surgical system. We will deduce the intuitive control methods for the third tool for robotic surgery without affect the natural limbs' operation. The proposed three-hand surgery control methodology will not limited to foot control but applicable to other hand-free control schemes.

In addition, the surgical operation environment in the operation room (OR) will be very different from the current setup; the current experiments of testing the foot interface and surgical system was conducted in the laboratory with naive participants.

To accommodate those non-experienced participants, the surgical task conducted in Chapter 8 was a simplified surgical operation instead of the standard surgical procedure, like endoscopic submucosal dissection (ESD). Performance study of three hand surgery will be conducted with participants having medical background and various levels of experience. We will compare the three-hand operation with clutch control and co-manipulation of two persons and investigate the three-hand manipulation in different surgical scenarios using three tools, e.g., suction the blood while cutting using hands; manipulate a tissue being sutured by hands, etc.

Publications

Journal papers

[1] **Yanpei Huang**, Etienne Burdet, Lin Cao, Phuoc Thien Phan, Anthony Meng Hua Tiong, and Soo Jay Phee, “A subject-specific four-degree-of-freedom foot interface to control a surgical robot,” in *IEEE/ASME Transactions on Mechatronics*, vol.25, no.2, pp.951-963, 2020.

[2] **Yanpei Huang**, Etienne Burdet, Lin Cao, Phuoc Thien Phan, Anthony Meng Hua Tiong, Zheng Pai, and Soo Jay Phee, “Performance Evaluation of a Foot Interface to Operate a Robot Arm,” in *IEEE Robotics and Automation Letters*, vol.4, no.4, pp.3302-3309, 2019.

[3] **Yanpei Huang**, Wenjie Lai, Lin Cao, Etienne Burdet, and Soo Jay Phee, “Design and evaluation of a foot-controlled robotic system for endoscopic surgery,” in *IEEE Robotics and Automation Letters*, vol.6, no.2, pp. 2469-2476, 2021.

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[5] **Yanpei Huang**, Wenjie Lai, Lin Cao, Jiajun Liu, Xiaoguo Li, Etienne Burdet, and Soo Jay Phee, “A Three-limb teleoperated robotic system with foot control for flexible endoscopic surgery,” in *Annals of Biomedical Engineering*, 2021.

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Conference paper

[1] **Yanpei Huang**, Wenjie Lai, Lin Cao, Etienne Burdet, and Soo Jay Phee, “Design and evaluation of a foot-controlled robotic system for endoscopic surgery,” accepted for presentation at the 2021 IEEE International Conference on Robotics and Automation (ICRA).

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Appendix

A.1 Foot motion and pressure/force

We assume that the foot planar motion will change the pressure applied by the foot. A small test was conducted to monitor the foot pressure changes during foot three-DoF planar motion. The test setup is shown in Fig. A.1.1. Six Force sensitive resistors (FSRs) were placed at the bottom of the insole then one subject was asked to move on the planar ground in three DoFs.

Figure A.1.1: Foot dynamic pressure test setup. (a) Foot area partition. (b) Location of FSR at the bottom of insole. (c) Coordinate of the FSR. (d) Motion of the foot.

The position of the center of pressure (CoP) of the foot $[X_{cop}, Y_{cop}]$ can be calculated from multiple force sensors:

$$X_{cop} = \frac{\sum_{i=1}^n F_i x_i}{\sum_{i=1}^n F_i}, \quad Y_{cop} = \frac{\sum_{i=1}^n F_i y_i}{\sum_{i=1}^n F_i} \quad (1)$$

where F_i, x_i, y_i are the force and positions of the FSR sensor, respectively. Then the mean pressure of foot, sole and heel can be computed as:

$$F_{foot} = \frac{\sum_{i=1}^n F_i}{n}, n = 1, 2 \dots 6 \quad F_{sole} = \frac{\sum_{i=1}^n F_i}{3}, \quad F_{heel} = \frac{\sum_{i=4}^5 F_i}{n}, \quad (2)$$

Fig. A.1.2 shows the CoP trajectories and force profile. The foot planar movement may be accompanied by foot pressure. For example, when foot moving forward, the pressure under sole gradually increases and foot CoP also moves forward to sole area; and when the motion of the foot changes to the backward direction, the CoP then also moves backward in the sole (Fig. A.1.2a,d,e). In contrast, the operator tends to put more pressure on the heel (Fig. A.1.2b,c) when the foot moves in the direction of left-right translation/rotation.

Figure A.1.2: Trajectory of center of pressure (CoP) when foot (a) moving forward-backward, (b) left-right and (c) left-right lateral rotations. (d) Mean pressure of sole, heel and (e) their force difference when foot move in forward-backward DoF.

A.2 Serial foot interface design

An initial design of the foot interface is shown in Fig. A.2.1. This design uses a serial structure with four rotational joints RRRR. The joint 5 is a toe switch connected with the pedal.

Figure A.2.1: Design of the foot interface in serial structure.

A.3 Teleoperation test with analytical mapping

A teleoperation test with an operator is conducted to verify in two tasks the functionality of the foot interface as well as the kinematics and statics models.

A.3.1 Setup and tasks

The experimental setup is shown in Fig. A.3.1a. The user is comfortably sitting on the chair and stepping their foot on the foot interface. A table with white board and the slave robot is in the front of the user. *Task 1* is a modified Fitt's law [158] test as shown in Fig. A.3.1a,b. A laser pointer connected to the robot's end-effector is

Figure A.3.1: (a) Experimental setup. (b) Task 1 and (b) task 2.

controlled by the foot through the interface. Nine (2cm diameter) targets are shown as green circles on a white board marked as targets $\{0,1,2,3,4,5,6,7,8\}$. Target 0 is located in the center and the other targets are even-distributed forming a circle. In the initial position, the laser is pointing to the target 0 and 10cm above it. The user is asked to move to targets 1-8 three times for each direction. The moving sequences is from up to down, left to right in 1,5,3,7,2,8,4 and 6. After the eight 2D moves in the horizontal planes, the user is asked to conduct the other two-DoF control in vertical axis movements in z_r (moving up and down), and rotation ϕ_r around z_r axis (anti-clockwise and clockwise rotations). Totally $12 \times 3 = 36$ moves are conducted in Task 1.

Task 2 is following the pre-defined trajectory shown in Fig. A.3.1c. A line laser is connected with the end-effector of the robot instead of the point laser used in Task 1. The target path is a circular ring shape in black color on the white board. The user is asked to move the laser line from the start position and reached a full circle following the black track. During movement, the length of the laser line (adjusted via moving the laser source up and down in z_r axis) should be kept within the range of the path

and perpendicular with the white dashed guide lines (marked in the path every 22.5°). The maximum speed of the robot is set to 10mm/s and 10°/s for translations and rotations. Two trials were conducted by the operator in both clockwise and anticlockwise directions.

The foot trajectories are collected by the foot interface and then used to control the robot. In Task 1 the position of the foot is derived using the using the kinematics model (Section 4.2.1) and mapped to the position of the robot.

$$\mathbf{P}_r = \mathbf{sD}, \quad \mathbf{P}_r \equiv \begin{bmatrix} x_r \\ y_r \\ \phi_r \\ z_r \end{bmatrix}, \quad \mathbf{D} \equiv \begin{bmatrix} x \\ y \\ \phi \\ \theta \end{bmatrix}, \quad (3)$$

where $\mathbf{D}$ is the four-DoF output commands of the foot interface and $\mathbf{P}_r$ the corresponding robot movements in three translations and one rotation. The motion mapping range is shown in Table A.3.1.

In Task 2 the force of the foot derived from the statics model (Section 4.2.1) maps to the speed of the robot.

$$\mathbf{P}_r = \int_{t_1}^{t_2} \mathbf{v}_r dt, \quad \mathbf{v}_t = \mathbf{mD}, \quad \mathbf{v}_r \equiv \begin{bmatrix} v_{xr} \\ v_{yr} \\ v_{\phi r} \\ v_{zr} \end{bmatrix}, \quad \mathbf{D} \equiv \begin{bmatrix} F_x \\ F_y \\ M_z \\ M_x \end{bmatrix}, \quad (4)$$

where $\mathbf{s}, \mathbf{m}$ are a diagonal weighing matrices for position-position and force-speed mapping, respectively.

Table A.3.1: Master/slave mapping between the foot interface and robot

Foot motions	Foot interface	Foot workspace	Robot	Robot workspace
Forward-backward	y	$[-2,2](\text{cm})$	y_r	$[-6,6](\text{cm})$
Left-right	x	$[-2,2](\text{cm})$	x_r	$[-6,6](\text{cm})$
Toe up/down rotation	θ	$[-10,10]^\circ$	z_r	$[-5,5](\text{cm})$
Left/right torsion	ϕ	$[-12.5,12.5]^\circ$	ϕ_r	$[-40,40]^\circ$

Figure A.3.2: Motion trajectories in (a) $x_r - y_r$ plane and (b) $\phi_r - z_r$ plane. (c) Four-DoF motion with respect to time.

A.3.2 Results

Task 1 The motion trajectories of the robot in horizontal $x_r - y_r$ plane are shown in figure A.3.2a. The motions in $z - \theta$ plane in directions of TU, TD, LT and RT are shown in Fig. A.3.2b. In general, all the eight directions' movements can be

effectively reached without difficulty and single directions in translations have relatively higher repeatability as two-DoF diagonal translations and rotation in ϕ_r .

The motion coupling effect can be checked in the Fig. A.3.2c. The DoF in z_r has less coupling effect to the horizontal movement axes x and y . And the TU and TD movements are also not affected by the other three DoFs. This is because of the decoupled design in the foot interface in DoF of θ and structure consideration of the long arm length locating load cells 7 and 8 as described in Section 3.4. The motion in DoF θ_r (controlled by the foot lateral rotations) has a slightly inferior performance with the coupling effect in the other three DoFs.

Figure A.3.3: (a) Foot forces deriving from statics model with/without zero region; (b) four-DoF robot position with respect to time and (c) paths for two trials in $x_r - y_r$ plane with constraint trajectory.

Task 2 The force signal shown in Fig. A.3.3a is more noisy than the position signal (Fig. A.3.2c). There is a zero region added for each DoF to avoid unintended speeds $[-5,5]$ N for F_x and F_y , $[-7,7]$ N for z_r , and $[-75,75]$ N.cm. If the foot force signals falls into the zero region, no control command outputs to the robot. Figs. A.3.3b,c shows the four-DoF position and motion trajectories in $x_r - y_r$ of the robot. In general, the user could conduct the two tasks without difficulty.

A.4 Computation of motor commands using kNN method

K-Nearest Neighbors (kNN), a simple machine learning algorithm, can be used to identify operator specific foot moving directions. With this method, each foot motion direction is assigned a class label, e.g. 1 for the forward, 2 for the backward, etc. Then motion data with related labels about directions will be input to kNN model as training data. After the training is completed, new data can be tested to identify the direction labels using this kNN model. Two sets of single Cartesian data (from the preliminary foot motion study with 10 subjects, see Section 4.3.1) are used to test kNN and ICA methods. One set of data were used to train the mapping model and another set of data were used for testing.

Fig. A.1A.4.1 shows the prediction result of eight single directions when using a kNN classification method and ICA method. Both methods uses eight load cells reading f_1 to f_8 as input.

Comparing the result of ICA (Fig. A.1A.4.1b), kNN method exhibits relative low performance in prediction results. The total average prediction rate using kNN is about 64%. The left lateral rotation direction has the lowest accuracy with 58% and 49% in these two cases. The backward direction has the highest accuracy rate with 68%. As a whole, the result using kNN exhibits low performance, which cannot be used to control a slave robot.

Figure A.4.1: Accuracy result with (a) kNN method and (b) ICA method.

A.5 ABB Robot kinematics

To guarantee there is no singularity happening in the work space, we solved the kinematics of the robot as follows, then directly control robot in the joint space.

Figure A.5.1: (a) IRB120 robot initial position, (b) structure and (c) Denavit-Hartenberg coordinate frames decomposition.

Table A.5.1: DH Parameters of the slave robot

Link i	θ_i (anglelimit (deg))	d_i	a_i	α_i
1	θ_1 (-165 to 165)	L_1	0	$-\frac{\pi}{2}$
2	$\theta_2 - 90$ (-110 to 110)	0	L_2	0
3	θ_3 (-110 to 70)	0	L_3	$-\frac{\pi}{2}$
4	0	L_4	0	$\frac{\pi}{2}$
5	θ_5 (-120 to 120)	0	0	$-\frac{\pi}{2}$
6(with tool)	θ_6 (-400 to 400)	$L_5 + L_{tool}$	0	0

The Denavit-Hartenberg (DH) parameters [159] describing the structure of the robot with tool is shown in Table A.5.1. The tool and the last joints are fixed together, so they are regarded as one link. The lengths mentioned in Fig. A.5.1c and Table A.5.1 are $L_1=29\text{cm}$, $L_2=27\text{cm}$, $L_3=7.0\text{cm}$, $L_4=30.2\text{cm}$, $L_5=7.2\text{cm}$, and $L_{tool}=6.8\text{cm}$. The homogeneous transformation between two adjacent coordinates could be formulated using DH parameters as follows:

$${}^{i-1}T_i = \begin{bmatrix} C\theta_i & -S\theta_i C\alpha_i & S\theta_i S\alpha_i & a_i C\theta_i \\ S\theta_i & C\theta_i C\alpha_i & -C\theta_i S\alpha_i & a_i S\theta_i \\ 0 & S\alpha_i & C\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

where “C” and “S” stand for trigonometric function “cos” and “sin”, respectively. Then the forward kinematics of the robot can be derived as:

$$\mathbf{X} = {}^0T_n = {}^0T_1 {}^1T_2 {}^2T_3 \dots {}^{n-1}T_n \quad (6)$$

${}^{i-1}T_i (i = 0, 1, \dots, n-1)$ is the transformation matrix between adjacent joints. The position of the end-effector $\mathbf{X} = [x_r, y_r, z_r, \theta_x, \theta_y, \theta_z]$ ($\theta_x=0, \theta_y=0$), can be represented in the global coordination x_0, y_0, z_0 .

For the inverse kinematics,

$${}^0T_6 = \begin{bmatrix} T_{11} & T_{12} & T_{13} & T_{14} \\ T_{21} & T_{22} & T_{23} & T_{24} \\ T_{31} & T_{32} & T_{33} & T_{34} \\ T_{41} & T_{42} & T_{43} & T_{44} \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} & R_{13} & x \\ R_{21} & R_{22} & R_{23} & y \\ R_{31} & R_{32} & R_{33} & z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (7)$$

It is calculated as:

$$\begin{aligned}
 \theta_1 &= \text{Atan2}(B, A) \\
 \theta_3 &= \pm \text{Atan2}(\sqrt{|L_4^2 + L_3^2 - K^2|}) \\
 \theta_2 &= \frac{\pi}{2} + \text{Atan2}(rd, ru) \\
 \theta_4 &= 0 \\
 \theta_5 &= \text{Atan2}({}^4T_6(13), {}^4T_6(23)) \\
 \theta_6 &= \theta_z
 \end{aligned} \tag{8}$$

The transformation matrix of 4T_6 can be calculated from known 0T_6 and 0T_4 . The ${}^4T_6(12)$ and ${}^4T_6(23)$ represent the third items of the first and second row of 4T_6 , where

$$\begin{aligned}
 A &= y_r - L_5 T_{13} \\
 B &= x_r - L_5 T_{23} \\
 C &= z_r - L_1 - (L_5 + L_{tool}) T_{33} \\
 K &= \frac{A^2 + B^2 + C^2 - (L_4^2 + L_3^2 + L_2^2)}{2L_2} \\
 M &= -L_4 \sin \theta_3 + L_2 + L_3 \cos \theta_3 \\
 N &= L_3 \sin \theta_3 + L_4 \cos \theta_3 \\
 P &= \frac{A}{\cos \theta_1} \\
 Q &= -C \\
 ru &= MP + NQ \\
 rd &= MQ - NP
 \end{aligned} \tag{9}$$

As θ_3, θ_2 have two values, there are two solutions for the inverse kinematics. The unique solution can be selected after fulfilling two constraints. First, the result should satisfy the angle range shown in Table A.5.1. Second, the new configuration should

be the one closest to the present manipulator configuration. The original value of the slave robot is set to $X_0 = [0, 59, 0, 0, 32, 0]^\circ$ with the tool tip vertically located and point to the task board (Fig. A.5.1a).

A.6 Laparoscopic simulator for three-limb operation

Except the developing a foot-controlled robotic system for endoscopic surgery in the above sections, a surgical simulator for laparoscopic surgery was presented in this section. Complex surgical operation with three tools is decomposed and abstracted into multiple task scenarios. This simulator provides a platform to train teleoperation of three laparoscopic tools using hands and one foot.

A.6.1 System overview

As shown in Fig. A.6.1a, the simulator is built with up to four laparoscopic tools. The laparoscopic camera is inserted and located in the middle of the patient's abdominal cavity to provide a view of the surgical site while the other three laparoscopic instruments are arranged around the camera to conduct surgical operation with tissues or organs.

Two Omega. 7 haptic interfaces and our proposed foot interface form the master console. The position of the hands and foot will map to the virtual tools' position with the scaling index. The first tool is located on the right side controlling by the right hand, and the second tool on the left side mapping to the left hand. The third tool is controlled by the foot. The inputs to the virtual world are the four DoFs of hands in three translations and one rotation (Figs. A.6.1b,c). The measured foot position of the input interface is directly mapped to the third robot tooltip position with respect to global coordinates. Thus, the position of the tooltip $\mathbf{P}_{ti}, i = 1, 2, 3$ can

Figure A.6.1: Virtual laparoscopic simulator in (a) front and (b) camera views and the photos of (c) the foot/hands and corresponding interfaces.

be represented by the position of the operators' foot/hands $\mathbf{P}_h = [x_{hi}, y_{hi}, z_{hi}, \gamma_{hi}]$, $i = 1, 2, 3$ in position-position or position-velocity mappings.

A.6.2 Laparoscopic tool modeling

An intuitive mapping was provided for the hand/foot interfaces (Fig. A.6.1b,c), which directly map the position of the foot and hands to the position or speed of the virtual

tools. The operator can focus on the tooltip without bothering about the pivot effect of the long rigid tool.

The laparoscopic instrument is a long bar which is inserted into human body through a small hole. The end-effector $P_{ti}, i = 1, 2, 3$ of the instrument can only move around the pivot point P_i or along the bar axis in a cone space. Then the inputs to each tool of the simulator are the three rotations around the pivot point and one translation along the tool, as $\alpha_i, \beta_i, \gamma_i, \Delta L_i$.

Figure A.6.2: The motion principle diagram of the laparoscopic instrument in 2D (a) x-z plane and (b) 3D space.

A model of the laparoscopic tool motion mechanism is derived to and used as intuitive mapping of the master and slave devices, using the inputs $\alpha, \beta, \gamma, \Delta L$ of each tool of the simulator relative to the tool tip position $\Delta \mathbf{P}_t = [\Delta x_t, \Delta y_t, \Delta z_t, \gamma_t]$, $\Delta \mathbf{P}_t = \mathbf{P}_t - \mathbf{P}_{t0}$ (as shown in Fig. A.6.2).

$$\begin{aligned}\Delta x_t &= (L_0 + \Delta L)\sin(\beta) - L_0\sin(\beta_0), \\ \Delta y_t &= (L_0 + \Delta L)\sin(\gamma) - L_0\sin(\gamma_0), \\ \Delta z_t &= (L_0 + \Delta L)\cos(\theta) - L_0\cos(\theta_0),\end{aligned}\tag{10}$$

By solving the above equations, we can get the inputs to the laparoscopic simulator,

$$\begin{aligned}
 \alpha &= \arcsin\left(\frac{\Delta y}{\sqrt{\Delta x_t^2 + \Delta y_t^2 + \Delta z_t^2 + 2\Delta z_t L_0 + L_0^2}}\right), \\
 \beta &= \arcsin\left(\frac{\Delta x}{\sqrt{\Delta x_t^2 + \Delta y_t^2 + \Delta z_t^2 + 2\Delta z_t L_0 + L_0^2}}\right), \\
 \Delta L &= -L_0 + \sqrt{\Delta x_t^2 + \Delta y_t^2 + \Delta z_t^2 + 2\Delta z_t L_0 + L_0^2},
 \end{aligned} \tag{11}$$

where L_0 is the initial insert length of the tool. The rotation around the tool axis γ is directly mapping to the tool tip rotation around z_t axis γ_t .

A.6.3 Tasks

Figure A.6.3: Task scenarios of the laparoscopic simulator

To simulate the laparoscopic tasks using the third tool, six tasks are designed based on different roles of the three tools (Fig. A.6.3 and Table. A.6.1). These tasks correspond to the segmentation and abstraction of the surgical procedure. For example, task 2 can simulate the surgical scene of polyp cutting: lift the covered tissue and holding using a forcep (tool 1), then the tumor is exposed and can be cut using the monopolar hook (tool 2), at the same time using the suction tool (tool 3) to clear the blood.

The tasks for each hand can be divided into three levels based on the operation difficulty. The lowest level (L) is holding the target object maintaining in the target zone; the medium level (M) is moving to the target as fast as possible without limitation on the path; the most difficult task (H) is following the path continuously with accuracy and efficiency. The tasks designed for the third tool are medium or low level as the third tool is normally used for assistance. The tasks for the first and second tools include independent and dependent tasks with all three difficulty levels.

Table A.6.1: Tasks of laparoscopic simulator

Task	Description	Tool 1	Tool 2	Tool 3	3rd tool example
1	H-H-F	M (M)	M(M)	M(M)	Suction
2	H-H-F	M (H)	H (L)	M (M)	Suction
3	H-H-F	M (H)	H (L)	H (L)	Stapler,Suction
4	2H-F	H (L)	H (L)	M (M)	Screw
5	2H-F	M (H)	M (H)	H (L)	Suction
6	2H-F	M (H)	M (H)	M (M)	Screw,Camera

H-H-F: two hands and one foot conduct three independent tasks; 2H-F: two hands coordinated to conduct one task, the foot conduct another independent task; M: motion task; H: holding task; (H,M,L) represents the difficulty level.

Task 1

In this task, the subject is required to control three laparoscopic tool moving to three random shown targets. The targets should be reached within 3s using three tools simultaneously. Any tool can contact one of the target. Once the target reached, it will be changed to transparent enlarged green ball. The targets will be updated when all three tools reach any three targets or when 3 seconds is meet. One training round consists of 30×3 targets, with each round lasting for at most 90s.

Task 2

This task requires following a path back and forth accurately with the first tool and reaching the random red ball targets as fast as possible with the third tool. However,

the red ball targets and reference path are covered by an obstacle object, the second tool needs to grasp this obstacle and move it to reveal the target path and balls. Each round consists of one reference path and 30 target balls. This scene is abstract from the surgical procedure that holding the target tissue using one hand, performing the cutting via another hand and suction the blood through third hand.

Task 3

In this task, the foot-controlled third tool should hold the mobile plate in the target zone, and the second tool moves the obstacle object, then the first tool should follow the reference path accurately back and forth. The movement of the mobile plate will also affect the position of the reference path.

Task 4

In this task, the two hands control tool together hold an elastic mobile plate that should stay within the target zone. The hands motion may deform the mobile plate and fail to maintain it in the target zone. At the same time, the foot controlled tool is required to reach the random red target ball as fast as possible. The target should be reached within 3s, 30 targets are shown in one trial. Two trials will be conducted. With each new trial, the target zone of the mobile plate will be updated and another 30 targets will sequentially be shown on the screen. This task can simulate the surgical operation like myomectomy when the fibroid is exposed, a screw can be applied to insert into the fibroid to conduct traction, which can assist the cutting work of the hands.

Task 5

In this task, the first and second tools controlled by hands are holding an elastic bar with the mass center in green color. The operator needs to move the elastic bar and keep the mass center follow the reference path accurately back and forth at the same time keeping the elastic bar within a certain length range of 0.6 to 1.3 of the original length. The path will become red when the mass center has beyond the path boundary. The reference path will change to red color to show the warning once the mass center deviate from the reference path. The third tool is controlled by the foot to hold the mobile plate within the target zone.

Task 6

In this task, the first and second instruments controlled by hands are performing the same operation as Task 5. The hands should move in a coordinated way to move the mass center along the reference path. At the same time, the third tool is required to touch the random red ball target within 3 seconds. This is to simulate surgical scene that the primary hands conduct coordinated operation, such as suturing, and the third hand suction the blood.