공학석사 학위논문

복강경 수술 로봇을 위한 머리 장착형 마스터 인터페이스 개발

A Study on the Development of Head-Mounted Master Interface for Laparoscopic Surgical Robot System

2018년 8월

서울대학교 대학원

협동과정 바이오엔지니어링전공

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이 논문을 공학석사 학위논문으로 제출함

2018년 5월

서울대학교 대학원

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2018년 7월

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Abstract

A Study on the Development of Head-Mounted Master Interface for Laparoscopic Surgical Robot System

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The objective of this study is to design and control an additional master interface for laparoscopic surgical robot to control the endoscopic system using simple head motions. The additional master interface, called the head-mounted master interface (HMI), allows intuitive control of the endoscopic system and can be implemented to the existing surgical robot system enabling continuous surgical flow.

The proposed system consists of the HMI, a simple three-dimensional endoscope, a four-degrees of freedom endoscope system, and a da Vinci Research Kit. The hardware of HMI is designed to be ergonomic and to be implemented to the stereo viewer of the existing system. The 27 pressure sensors and a hall sensor are located in the HMI to detect the seven simple head movements of the user. The sensor data is collected and classified using support vector machine in near real-time to manipulate the endoscopic system.

The HMI has been evaluated of its usability through performing a modified peg transfer task and measuring the time latency of the interface in controlling the endoscopic system. The results from such tests confirmed that the use of HMI can shorten the surgical operation time and enable continuous surgical flow. Furthermore, the modified peg transfer task result showed that the HMI could reduce the completion time compared to the former developments utilizing index fingers to manipulate the endoscopic system.

The HMI can be implemented to the laparoscopic surgical robot system to ensure simultaneous operation of the vision system and the patient side manipulators in accordance with the user's intention. The HMI can be further developed to include the combination of head motions to make to control of vision system more intuitive. Consequently, the suggested HMI system could contribute to the advancements in medical field and even be applied to achieve industrial functions such as automated vision control.

Keywords: Head-Mounted Master Interface, da Vinci Surgical Robot, Laparoscopic Surgery, Continuous Surgical Flow

Student Number: 2016-24548

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1. Introduction

1.1. Background

Aging population due to a low birth rate and advancements in medical care has led to a rise in demand and interest for health and medicine globally [1, 2]. Consequently, medical technology has been dramatically improved over the last two decades to answer for the growing demand. More specifically, surgical methods have diversified to offer greater benefits to both the patients and the surgeons [3]. One of such surgical method is the robot-assisted surgical (RAS) system, laparoscopic RAS systems have inherent advantages over conventional open surgery and laparoscopic surgery including dexterous and precise control of end-effectors [4, 5]. The robot-assisted surgical systems have reduced the learning curve of the laparoscopic surgery whilst the benefits of minimally invasive surgery (MIS) are retained [6]. The benefits of MIS include limited incision, less bleeding, faster recovery, and better pain score [7, 8]. The benefits and limitation of different surgical techniques are summarized in Table 1.

Table 1. Advantages and disadvantages of different surgical techniques: Open surgery, conventional laparoscopic surgery, and robot-assisted laparoscopic surgery [14].

Surgical Technique	Benefits	Limitations
Open Surgery	Touch sensation	Excessive bleeding
	Proven efficiency	Painful recovery
	Ubiquitous	High infection risk
	Affordable	Large incision and scar
	Direct access	Prolonged hospital stay
Conventional Laparoscopic Surgery	Affordable	Reduced dexterity
	Faster recovery	Fulcrum effect
	Fewer incisions	Physiological tremors
	Less bleeding	Absence of haptic feedback
	Better cosmetic outcome	Poor ergonomics
Robot-Assisted Laparoscopic Surgery	3D visualization	Longer operation time
	Improved dexterity	High cost
	Scale motion	Absence of tactile feedback
	Intuitive control	Not ubiquitous
	Increased accuracy	Long training time

However, the robot-assisted surgery has several areas for improvement such as discontinuous surgical operation, increased operation time, increased level of surgeon fatigue, and high purchase and maintenance costs [9-11]. For laparoscopic RAS system, the discontinuous surgical operation results from utilizing a master-slave system with one master and two slave systems as can be observed in Figure 1 [12]. Therefore, the surgeon has to switch the control between the two slave systems which are the patient side manipulators (PSMs) and the vision system as illustrated in Figure 2. This kind of control technique may cause several issues such as collision between surgical tools, prolonged operation time, and surgeons operating under unsatisfactory or unsafe conditions to avoid pausing the operation to manipulate the view [13].

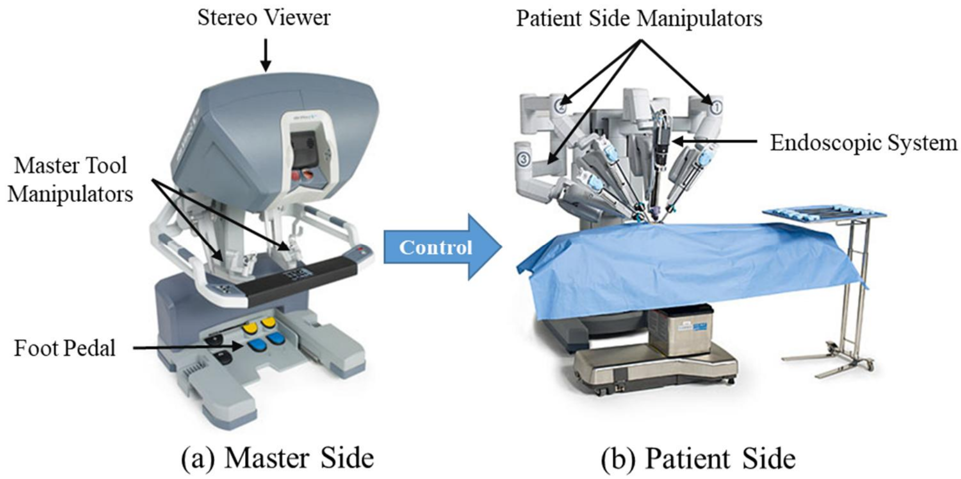

Figure 1. Components of commercial robot-assisted surgical system, da Vinci®, consisting of (a) master side and (b) patient side. Master tool manipulators are the master system, and the patient side manipulators and endoscopic system are the two slave systems. Copyright © 2018, Intuitive Surgical, Inc. [12].

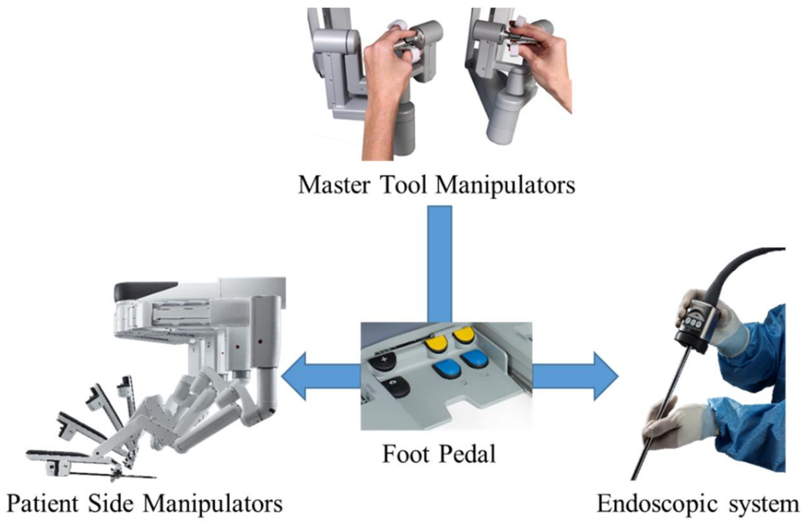

Figure 2. Control flow of current laparoscopic surgical robot system. Master tool manipulators on the master side are used to control the patient side manipulators and the endoscopic system in the patient side. Copyright © 2018, Intuitive Surgical, Inc. [12].

1.2. Research Trend

Nowadays, MIS surgical technique has become a predominantly used method for many areas of surgery due to its benefits listed in Table 1. Some of its application areas are cardiac, thoracic, gastrointestinal, and urologic surgeries. Also, the natural orifice transluminal endoscopic surgery (NOTES) is acquiring much attention recently due to its minimal to no invasiveness as it reaches surgical operation site via the natural orifices such as mouth, anus, and umbilicus [15]. The use of robot allows more detailed and stable surgery as it eliminates hand tremors and allows motions of scale. Furthermore, RAS has potential to be used in teleoperation providing medical services to the areas with limited access or under considerable danger such as the battlefields. Accounting for the listed reasons, the RAS global market evaluation is expected to be $12.6 billion by 2025, growing at an average of 11.4% [16].

There have been several studies developing an additional master interface for vision system control and they utilize various resources including but not limited to the surgeon's eyes, foot, mouth, and fingers [17-19]. In Figure 3(a), the pupil dilation in conjunction with the eye tracking control method is applied to an endoscopic manipulator for RAS. A camera was attached to the image viewer of a surgical robot platform and detected pupil dilation of the user to classify between intentional and non-intentional eye movements. A hands-free interface, Figure 3(b), uses six foot movements to manipulate the endoscopic holder and the movement is detected through an array of pressure sensors. A combination of mouth gesture and voice command has been presented to control three degrees of freedom (3 DOF) endoscopic system as can be seen in Figure 3(c).

Furthermore, a novel master interface (NMI) and an improved NMI (iNMI) have been proposed to allow endoscopic manipulation simultaneously with the PSM control [20-22]. NMI and iNMI are both wireless interfaces that originated from a flight control method in aerospace field called hands-on-throttle-and-stick (HOTAS). They can be installed to both sides of the master tool manipulators (MTMs) and the index fingers of the surgeon are used. They are illustrated in Figure 3(d) and (e). The concept of application of HOTAS to control surgical robot are patented in both US and Korea [23, 24].

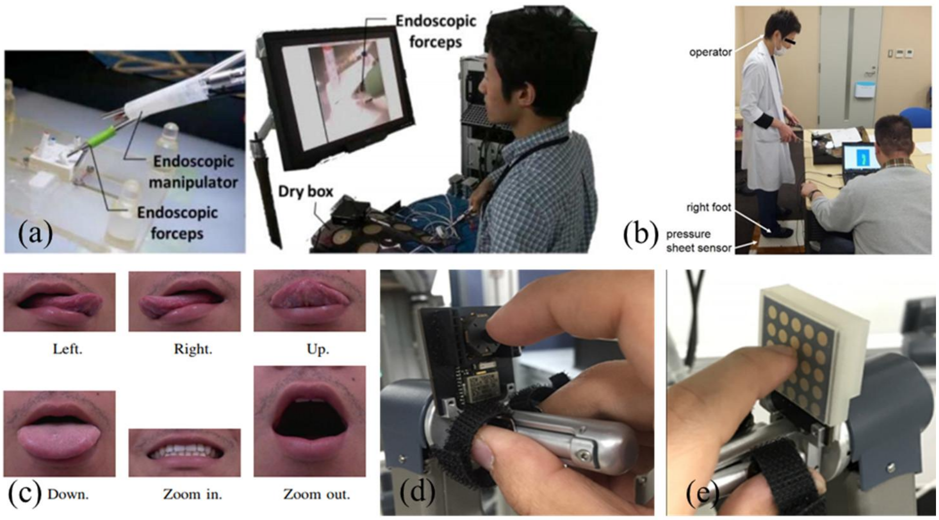

Figure 3. Additional master interfaces developed for endoscopic control using: (a) pupil variation and eye tracking, (b) foot movement patterns, (c) mouth gesture and voice command, (d) novel master interface, and (e) improved novel master interface. Reprinted with permission from [17-22].

Despite the merits of the aforementioned interfaces, they have several issues including not achieving sufficiently high accuracy to ensure clinical security, and for laparoscopic RAS, the hand and the foot of the surgeon are already occupied. Therefore, there have been studies that developed more intuitive additional master interface overcoming these issues using head movements and in some cases head-mounted displays. There have been increasing demand for more ergonomic and intuitive control of the vision system from the surgeons. The surgeons suggested for such control system when the evaluation of NMI was conducted and thus, lead to developments of iNMI and head-mounted master interface (HMI) to address these demands.

1.3. Objective of Study

The objective of this study is to design and control an additional master interface for laparoscopic surgical robot system to control the endoscopic system. The additional master interface can be implemented to current surgical robot to maneuver the endoscopic system using the simple head motion of the surgeon. The use of head motion to manipulate the endoscopic system would offer more intuitive and efficient control method. The head motion of the surgeon is detected through the sensors located in the forehead and nose regions of the stereo viewer and the data from these sensors are processed to classify them into appropriate head movements. The evaluation of the proposed HMI system is conducted by performing a modified peg transfer task and measuring time latency. Consequently, the HMI implemented to the existing surgical robot system enables continuous surgical flow through simultaneous operation of endoscopic system.

2. Materials and Method

2.1. Overall System Setup

The system developed in this study has a control scheme as described in the Figure 4. The HMI adapts a natural way of changing the view which is through moving the head and thereby controls the endoscopic vision system through the head movements. The PSMs equipped with surgical tools are controlled by the MTMs and thus, the PSMs and the endoscopic system can be simultaneously used in the proposed system.

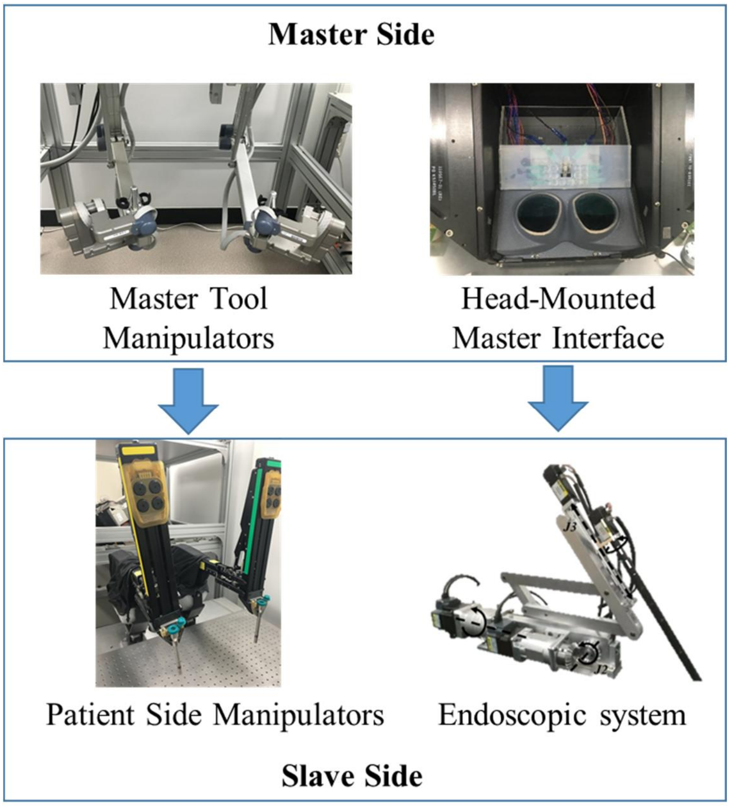

Figure 4. Control flow of the proposed head-mounted master interface (HMI) system. Master tool manipulators control the patient side manipulators and the HMI control the endoscopic system. Copyright © 2018, Intuitive Surgical, Inc. [12].

The proposed system consists of four major components: 1) a simple three-dimensional (3D) endoscope, 2) a 4 DOF endoscopic control system (ECS), 3) a da Vinci® Research Kit (dVRK) surgical robot platform, and 4) a HMI as illustrated in Figure 5. The 3D endoscope and the 4 DOF ECS are developed in the prior study to provide 3D images to the dVRK's stereo viewer during evaluation tasks [21, 22]. The 3D endoscope is comprised of two complementary metal-oxide-semiconductor (CMOS) camera modules to provide a real-time visual input to each monitor in dVRK's stereo viewer. Each CMOS camera modules contain six light emitting diode (LED) modules to illuminate the space. The images obtained from the 3D endoscope have to undergo a series of image processing steps including rectification and stereo calibration in order to provide a comprehendible 3D vision to the human eyes.

The 4 DOF ECS holds and maneuvers the 3D simple according to the given command from the HMI. It contains four motors each corresponding to four maneuverable joints performing the fulcrum point motions, a translational motion, and a rolling motion. For laparoscopic surgery, fulcrum point motion must be achieved and it is ensured through two parallel link structure.

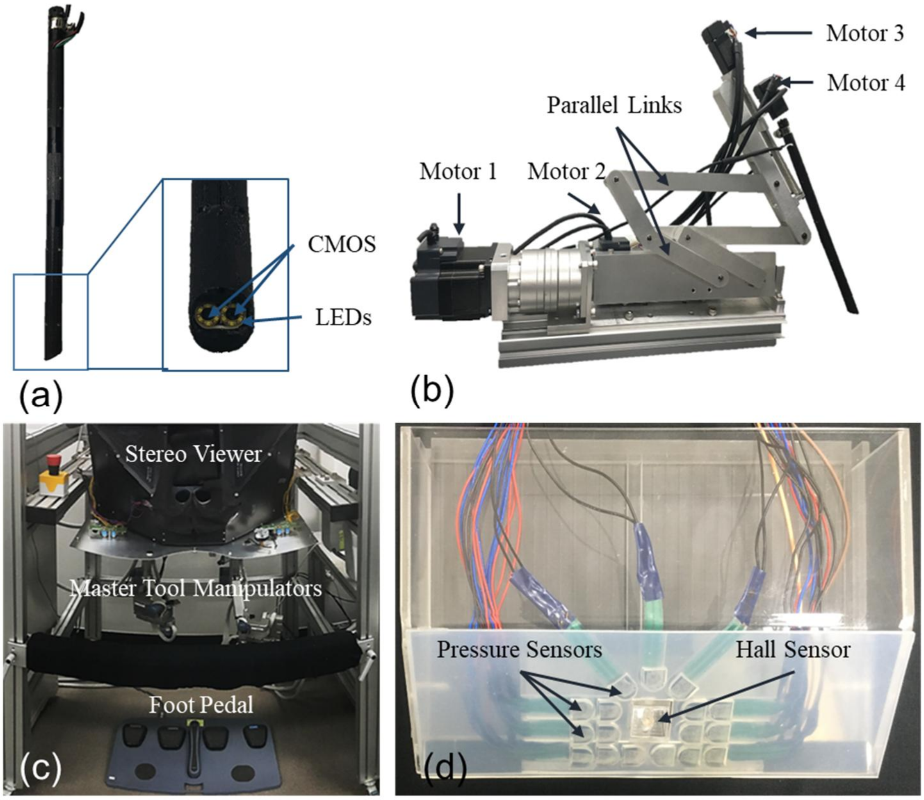

Figure 5. The four components of proposed head-mounted master interface (HMI) system consisting of (a) three-dimensional (3D) endoscope consisting of two complementary metal-oxide-semiconductor (CMOS) camera modules with 6 light emitting diode (LED) light sources, (b) four degrees of freedom (DOF) endoscopic control system (ECS) with four motors and a double parallel link structure for fulcrum point motion, (c) da Vinci Research Kit (dVRK) platform, and (d) HMI consisting of pressure sensors and a hall sensor.

The dVRK is donated by Intuitive Surgical, Inc., and is used as an operating surgical robot platform to implement and conduct tasks using the HMI. The dVRK consists of a stereo viewer, two MTMs, two PSMs, a foot pedal, and dVRK controllers. The dVRK components are from the first generation of da Vinci® surgical robot which is predominantly used around the world for RAS.

Lastly, the HMI proposed in this study is implemented to the dVRK system to detect head movement of the user and manipulate the 4 DOF ECS accordingly. The HMI contains pressure sensors and a hall sensor to collect data from the forehead and the nose regions.

2.2. Hardware Development

Sensor Selection

The type of sensors used in the proposed HMI system were selected considering working mechanism, sensitivity, dimensions, and hardware restriction. The HMI utilizes head movement of the surgeon to manipulate the endoscopic holder, 4 DOF ECS, thereby must be able to detect mainly two motions: planar and vertical as graphically shown in Figure 6. For planar motion detection, the sensors should be able to measure the magnitude of pressure exerted by the head in 2D space, along the surface of HMI. Likewise, for vertical motion detection, a sensor should be able to measure the degree of head placement that is whether the head is fully in touching the pressure sensors or slightly out. The HMI is designed to be installed to the head rest region of the dVRK. Thus, the dimension of sensors used in HMI should be small enough to ensure acquisition of local information of the head movement.

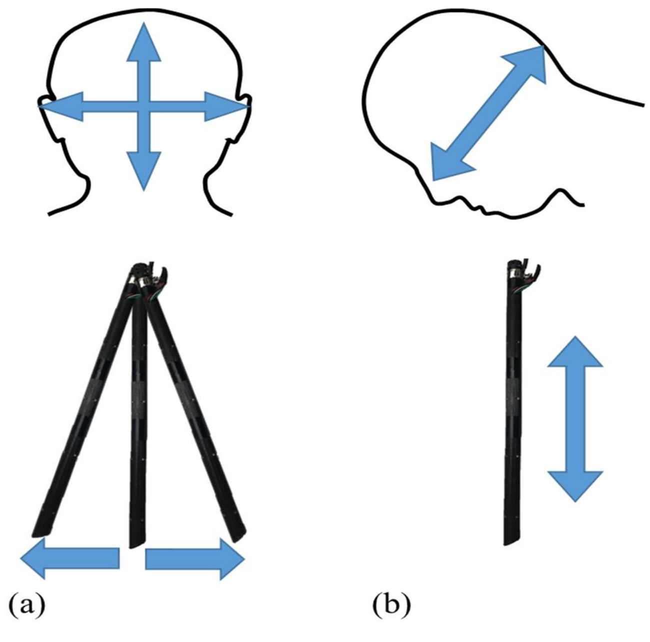

Figure 6. Head motions detected using the head-mounted master interface (HMI). (a) Planar head motion achieving fulcrum point motion for the endoscope, and (b) vertical head motion for translational motion of the endoscope.

As shown in Figure 7, the HMI contains 17 pressure sensors and a hall sensor in the forehead region and the other 10 pressure sensors are located in the nose region to increase the accuracy of head motion classification. The sensor’s sensitivity can be altered through changing the resistor value in the circuit, higher the resistor value, more sensitive the sensor is. The 100kΩ resistor value has been selected empirically. The data from the pressure sensors are received in either in an analog (0~5V) or a digital (0 or 1) depending on their frequency of usage and importance. The sensors closer to the center of the HMI are received as analog and those further away as digital.

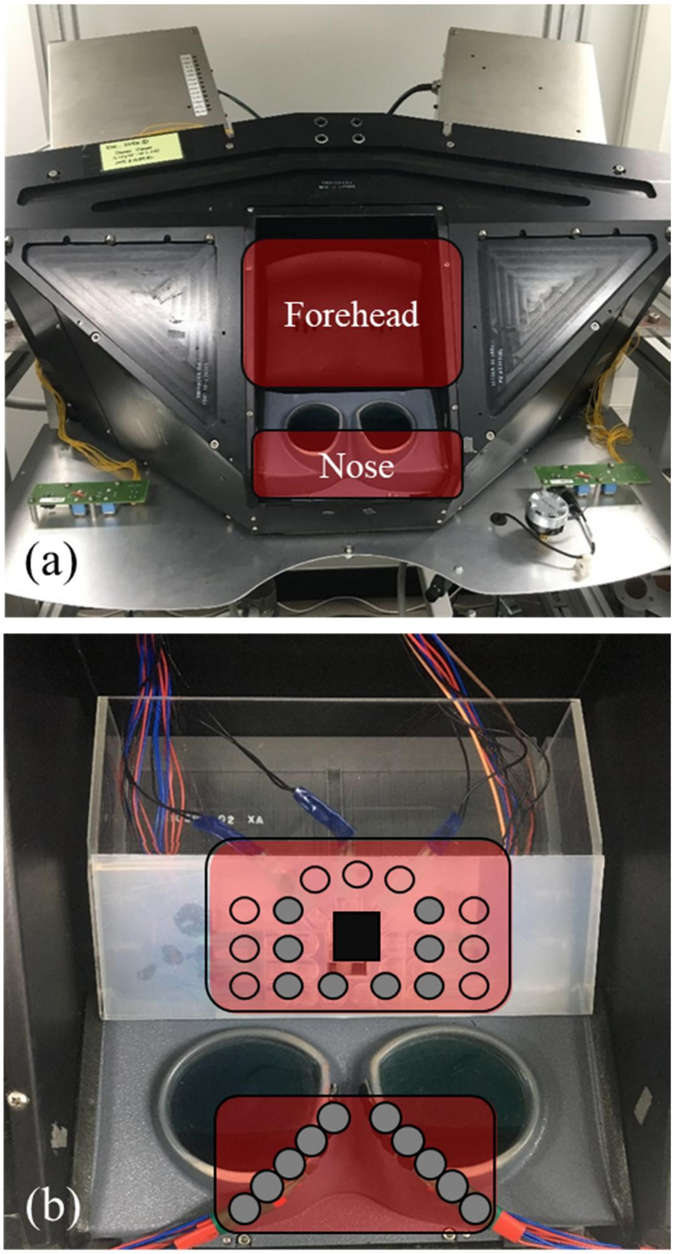

Figure 7. (a) Stereo viewer of the da Vinci Research Kit (dVRK) with head and nose regions highlighted, and (b) head-mounted master interface (HMI) sensor type and location. Colored circles indicate analog pressure sensors and blank circles for digital pressure sensors.

The hall sensor is located at the bottom of the HMI body detecting the proximity of the magnet placed on top of a spring as illustrated in Figure 8. As the forehead of the user presses the hall sensor bar, the spring is compressed bringing the magnet closer to the sensor and vice versa. Therefore, it can be used to measure the depth of head placement and determine zoom out motion.

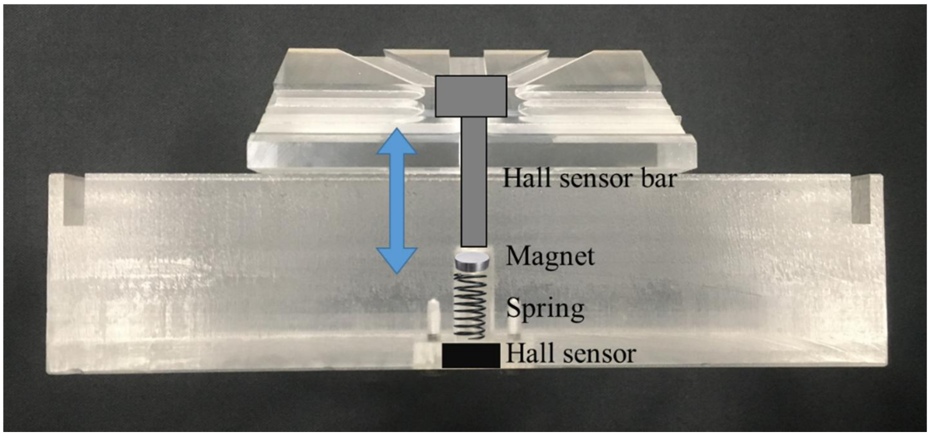

Figure 8. Working principle of the hall sensor in the head-mounted master interface (HMI). When the head presses the hall sensor bar, the spring is compressed bringing the magnet closer to the hall sensor. The magnet returns to its original position due to spring mechanism when the head is out.

All sensor data are transferred using data acquisition (DAQ) devices (NI USB-6216, National Instruments, Austin, TX, USA and Arduino UNO, Arduino, Italy) to a PC via wired connection at a frequency higher than 100 Hz. Data from the NI DAQ device is transmitted to the control program using data acquisition program offered by the manufacturer and data from the Arduino UNO devices are collected using the codes available open-source.

Ergonomic design

Ergonomic design should be considered as the proposed system will replace the head rest of dVRK where the surgeon would rest their head and acquire visual image of the operating area during the surgical process. The HMI hardware contains three components: 1) the main body, 2) the cover, and 3) a silicon cover layer as illustrated in Figure 9. The surface of the main body is inclined at 30˚ to ensure comfortable resting of the head on it. Also, it contains grooves for placement of sensors and wires for data transfer. The bottom of the HMI body contains a hall sensor, a spring, and a magnet. The cover protects the sensors from contamination and ensure that the sensors stay in their given positions during the usage. The silicon cover layer has a role as a cushioning layer as well as making sure the sensors are not misallocated.

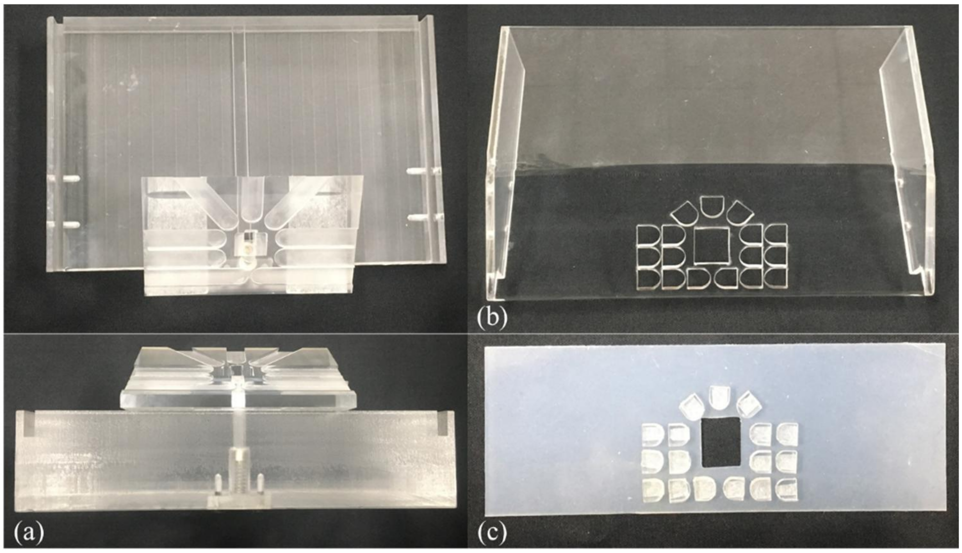

Figure 9. The head-mounted master interface (HMI) hardware consisting of (a) the main body providing the location for pressure sensors and a hall sensor, (b) the cover to protect the sensors and to provide a comfortable surface for the users, and (c) the silicon cover layer for added comfort for the users.

2.3. Development of Control and Classification Algorithms

Control Algorithm

The use of HMI allows head motion to control the vision system in a similar method to how humans naturally change the view. The HMI collects sensor data and classifies them to appropriate head motion. It will also alleviate the burden from the fingers using them for controlling the PSMs only as shown in Figure 10. The data collected from the 28 sensors are transferred to a PC where they are received through LabVIEW® program. The sensor data is acquired in real-time, then classification is conducted, and moves the 4 DOF ECS accordingly in near real-time.

The overall control flow is as described in the Figure 10, the two MTMs are used to control two PSMs respectively and the HMI is used to control the 4 DOF ECS. The four components of the proposed system are integrated with the PXIe controller and LabVIEW® program (PXIe 8135 and 1062Q, LabVIEW® 2015, National Instruments, Austin, TX, USA). The dVRK system operates with a C language program originally offered by the Intuitive Surgical, Inc., and the data from HMI is classified by machine learning algorithm, support vector machine (SVM), using MATLAB® (R2017a, Mathworks Inc., Natick, MA, USA). SVM classification algorithm is developed in this study and the result is used to control 4 DOF ECS using the LabVIEW® program. The SVM classification of head motion includes seven motions which are neutral (stationary), right, left, up, down, zoom in, and zoom out. Therefore, using the HMI, the user can maneuver the endoscopic system in 3 DOF motions as summarized in Figure 11.

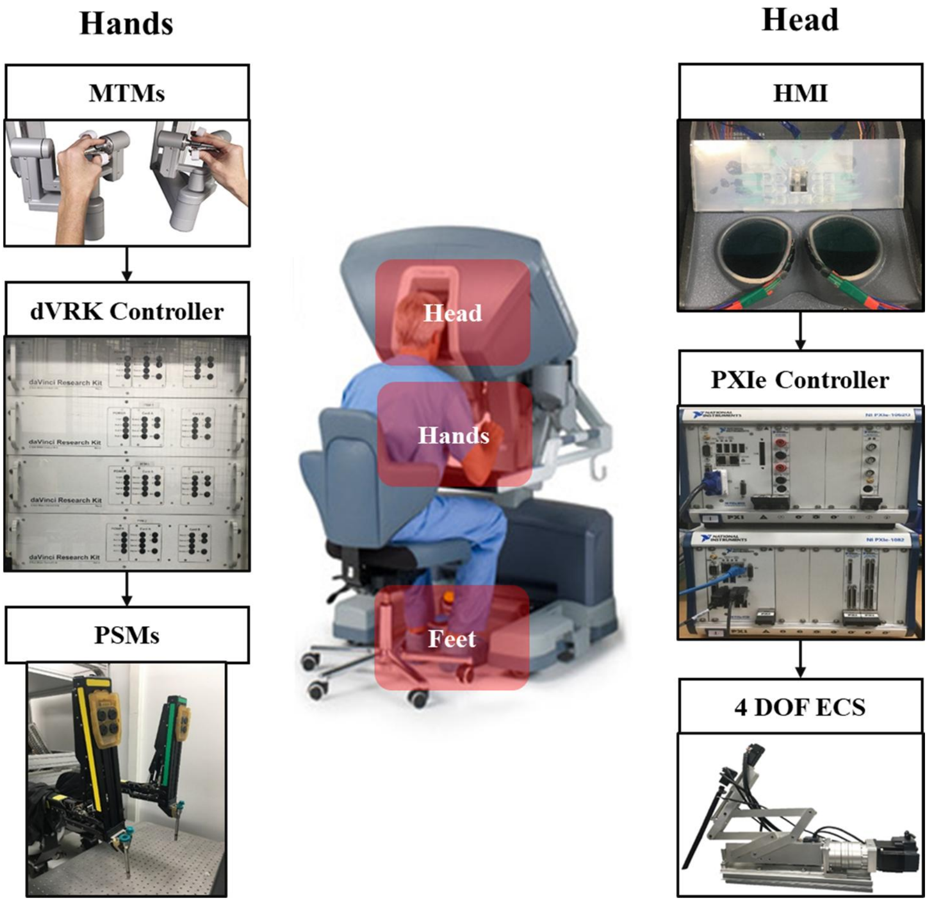

Figure 10. Control flow of proposed head-mounted master interface (HMI) system. Copyright © 2018, Intuitive Surgical, Inc. [12]. Surgical instruments are controlled using hands and the endoscopic image is controlled using head motions.

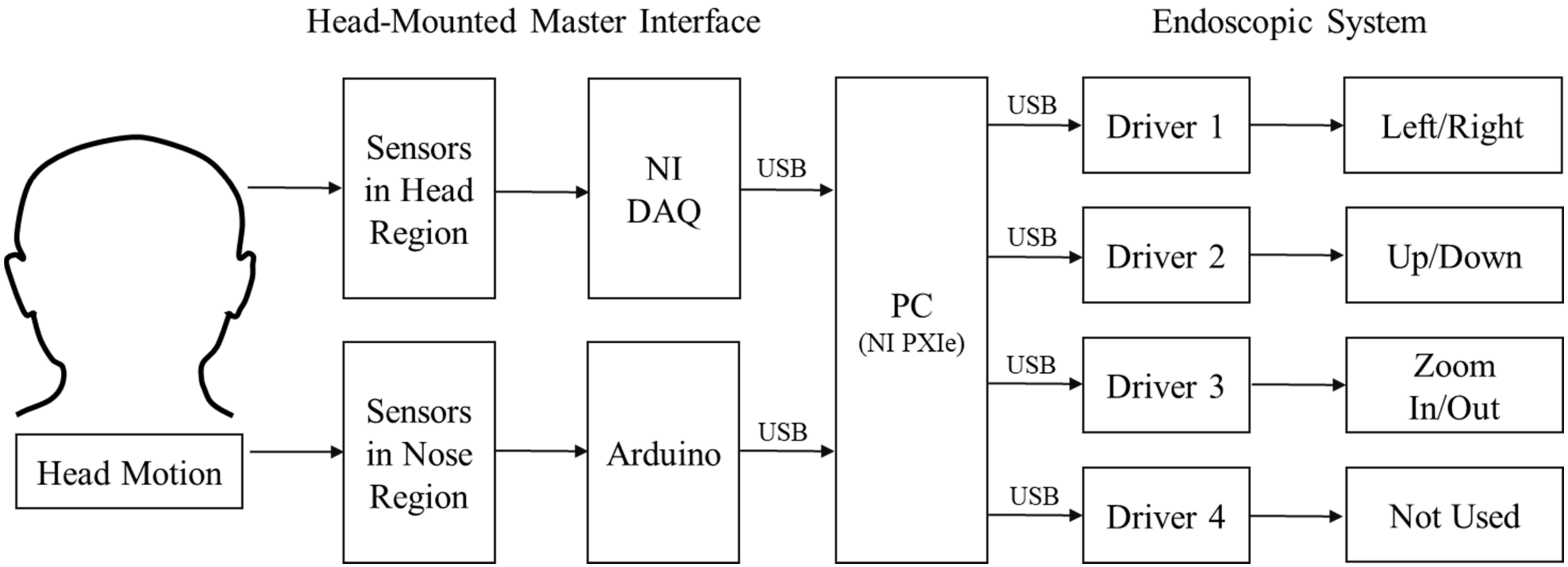

Figure 11. Data flow structure of the proposed head-mounted master interface (HMI) system. Data collected from the sensors of HMI is sent to the PC for motion classification through data acquisition devices. Based on the classification result, the motors are controlled via each drivers of endoscopic system.

Classification Algorithm

The SVM classification algorithm is a type of machine learning that uses a margin classifier to distinguish between two or more groups [25, 26]. There are several reasons for using SVM in this study: 1) high generalization capacity, 2) ease of searching optimal parameters, and 3) good computation speed. To train and test the SVM head motion classification algorithm, a total of eight volunteers are recruited and the data from all the sensors in HMI is recorded. The sensors comprise of 18 analog pressure sensors, nine digital pressure sensors, and a hall sensor. The determination of analog or digital readings is conducted according to the usage and variation in value. Eight participants performed five cycles consisting of seven simple head movements maintaining each motion for about five seconds as summarized in Figure 12.

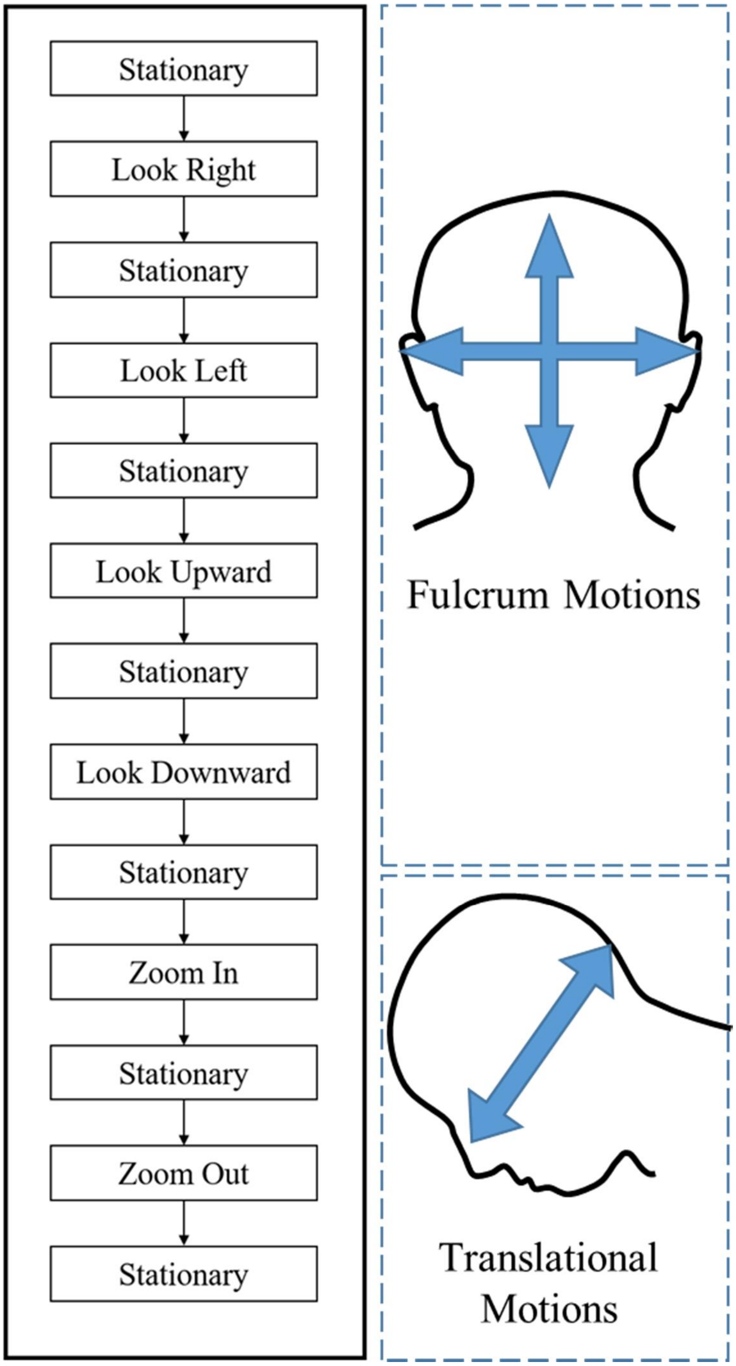

Figure 12. Head motion cycle of one trial. After each motion, stationary motion is added to ensure accuracy in performing each motion.

The recording of data for entire experiment is used in the SVM algorithm provided by MATLAB®. Accuracy of classification is calculated by the ten-fold cross validation results and to optimize its parameters, various data sets, kernel type functions, and the size of the kernels are explored. The kernel types used in this study are chosen from commonly used kernel types including linear, quadratic, polynomial, and Gaussian which are Equations 1-4 [25-28]. The size of Gaussian function is chosen empirically which are 0.5, 0.75, 0.85, 1, 2, and 3. The data types tested consists of four types: normalized and selected (N & S), normalized and full (N & F), not normalized and selected (NN & S), and not normalized and full (NN & F). The difference between the selected and full data is the frequency of the usage as there were some variation between the participants in the span of sensors used during the exercise. The collected data has a total of 7919 data sets including 999, 1152, 1067, 1237, 1075, 1354, and 1033 sets for neutral, looking right, left, up, and down, and zooming in and out motions respectively.

$$f(x) = sign(\sum \hat{\alpha}_i y_i K(x_i x) + \hat{\omega}_0) \tag{1}$$

$$\text{Linear: } K(x_i) = < x, y > \tag{2}$$

$$\text{Polynomial: } K(x, y) = (1 + < x, y >)^d \tag{3}$$

$$\text{Gaussian: } K(x, y) = \exp(-\frac{< (x-y), (x-y) >}{2\sigma^2}) \tag{4}$$

Equation 1 is the discriminant function, where $\hat{\alpha}_i$ is the estimated Lagrange multiplier, x_i are the support vector labels, are parameters, x is the input vector, and $\hat{\omega}_0$ is the estimated bias. For nonlinear transformations of features, kernel functions can be used such as Equation 2-4. The SVM classification is done by using the 'fitcsvm' function included in MATLAB® Statics and Machine Learning Toolbox. The SVM kernels are chosen as linear, polynomial (d = 2, 3), and Gaussian (σ = 0.5, 0.75, 0.85, 1, 2, 3). The accuracy of the SVM result is calculated using Equation 5 for the ten-fold cross validation.

$$\text{classification accuracy} = \frac{\text{number of correctly clasified data}}{\text{number of total data}} \times 100 \quad (5)$$

Ten-fold cross validation is a model validation technique assessing how accurate the predictive model will perform in practice. The goal is to test how accurately the model can estimate the unknown data. For the ten-fold cross validation, the whole data set is equally divided into ten subsets where one subset is set as a test set and the rest are training sets. Until all subsets has become the test set, the process is repeated as shown in Figure 13.

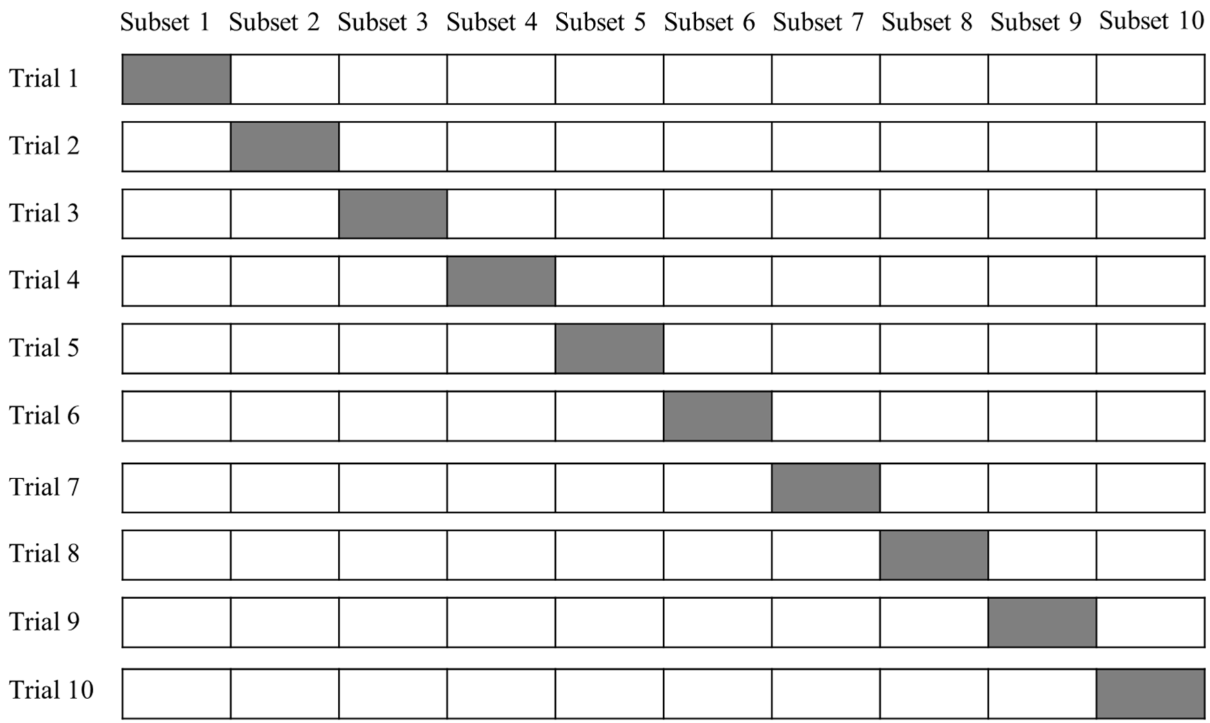

Figure 13. Ten-fold cross validation of a data set. The full data set, containing 7919 individual data sets, is equally divided into ten subsets and one subset is used as a test set for each trial. Shaded subsets are the test sets and unshaded subsets are used as training sets.

2.4. Evaluation

The usability of the proposed system is evaluated mainly by a modified peg transfer task testing its ability to manipulate the endoscopic system in practice. Also, the latency of the various processes involved is measured. The peg transfer task is one of vie tasks involved in the fundamentals of the laparoscopic surgery (FLS) and tests the surgeon's hands-on skills [29]. It contains six pegs to be transferred from one side of the small board to the other side. However, the original peg transfer board is small and thus does not require endoscopic manipulation. The modified peg transfer task which was developed in the earlier works to evaluate the additional interfaces has been used in this study. The modified peg transfer board has been lengthened, as can be observed in Figure 14, and require endoscopic manipulation to complete the given task. The time to complete the task is measured from the moment the first peg is picked up to the release of last peg. The FLS curriculum has set a time limit to complete the task which is 300 s and the same time limit is applied to the modified peg transfer task. For safety reasons, all tools must be observable in a single image.

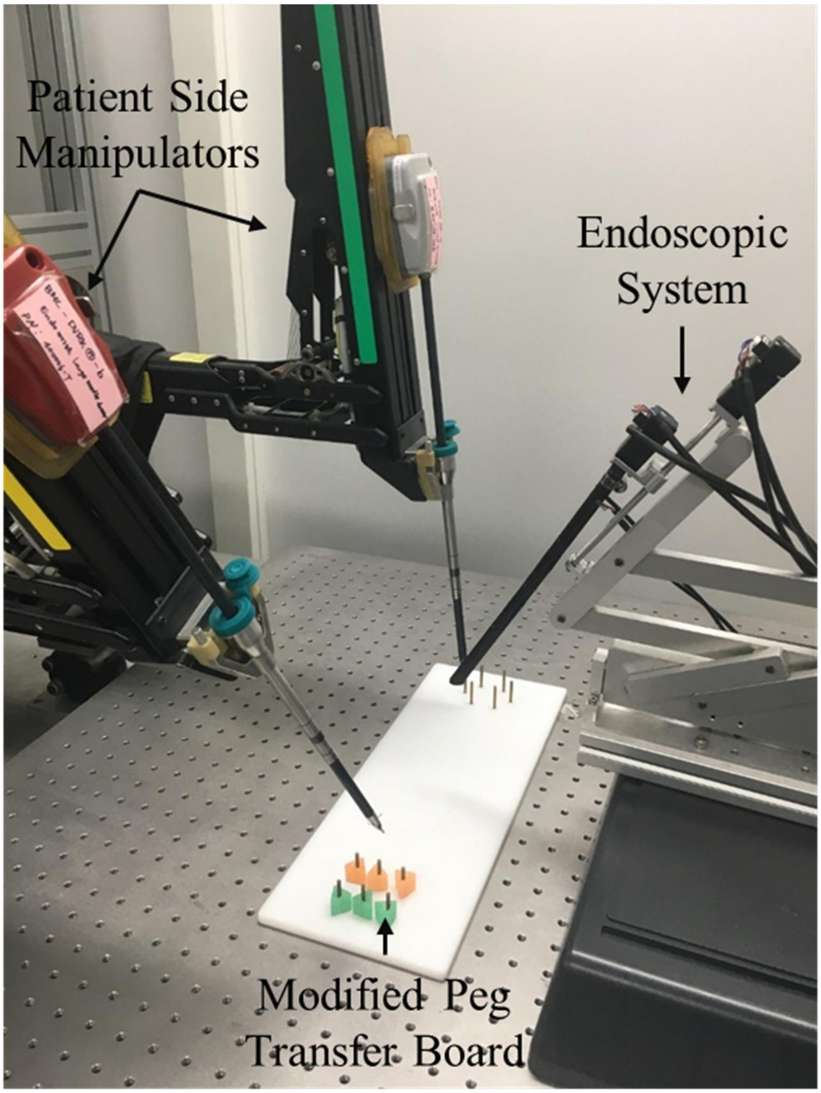

Figure 14. The modified peg transfer board consisting of six pegs and peg transfer task set up. The peg transfer board has been lengthened to necessitate the endoscopic movement.

A group of three novice volunteers has been recruited to perform the above task. They were given a brief explanation and demonstration of dVRK then, about three minutes were given to make themselves familiar to the dVRK system. Each participant performed the peg transfer task for six times and for each task, the time of completion is recorded. Three of six trials had a condition of simultaneous operation of PSMs and the endoscopic holder being not allowed, and for the other half, it was allowed. Thus, the effectiveness of the system could be tested as the results of simultaneous and non-simultaneous operation can be compared. The trials are conducted in alternating sequence to minimize the learning effect that is one trial when the simultaneous operation was not allowed and next trial it was allowed. The result was analyzed using statistical software (IBM SPSS Statistics for Windows, Version 21.0, Armonk, NY, USA). The paired t-test has been conducted to compare two situations.

The time latency of control process was evaluated to find whether the proposed HMI system can reflect the intention of the user in a reasonable time frame. The latency of the initial motion to the movement of the endoscopic camera was measured suing LabVIEW® program for 50 trials for looking right motions. The time taken for SVM classification was measured for 50 trials using MATLAB® program. The data acquisition devices were set to have 100 Hz transfer speed.

3. Results

The location of sensors in the proposed HMI system was optimized through trial and error, and the readings from the HMI sensors were received in either an analog or digital form depending on their frequency of usage and variation in value. The analog values had a resolution greater than 10-bit and digital reading had 0 or 1 value. The ergonomic design of HMI includes inclined surface and silicon cover layer ensuring that the HMI was comfortable enough to rest the head. The control algorithm of HMI has been developed utilizing the head motion classification result of the following section.

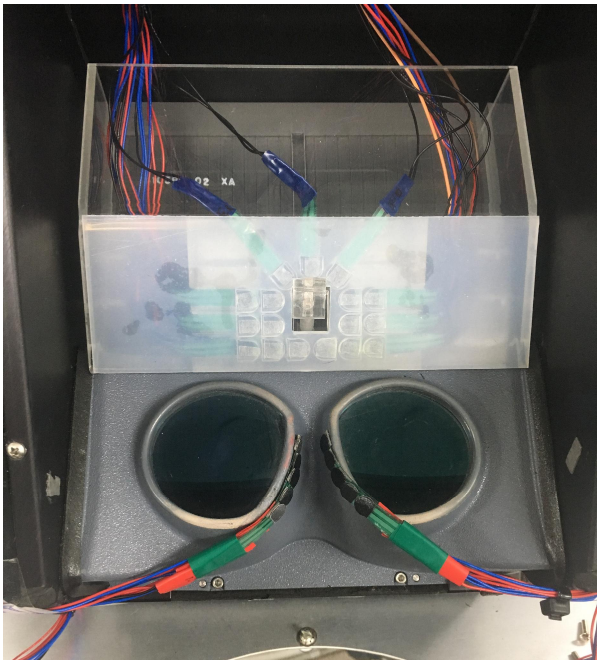

Figure 15. The head-mounted master interface (HMI) implemented to the stereo viewer of dVRK. It has sensors located in the forehead and nose regions.

3.1. Head Motion Classification

Ten-fold cross validation was used to evaluate the accuracy of SVM head motion classification result. Various kernel types including linear, quadratic, polynomial (d = 3), and Gaussian (σ = 1) were tested on the four data sets as described by Figure 14. The classification accuracy is shown in Figure 16. The linear kernel exhibited lowest accuracy while the Gaussian kernel had the best accuracy of all the kernels tested in different data sets.

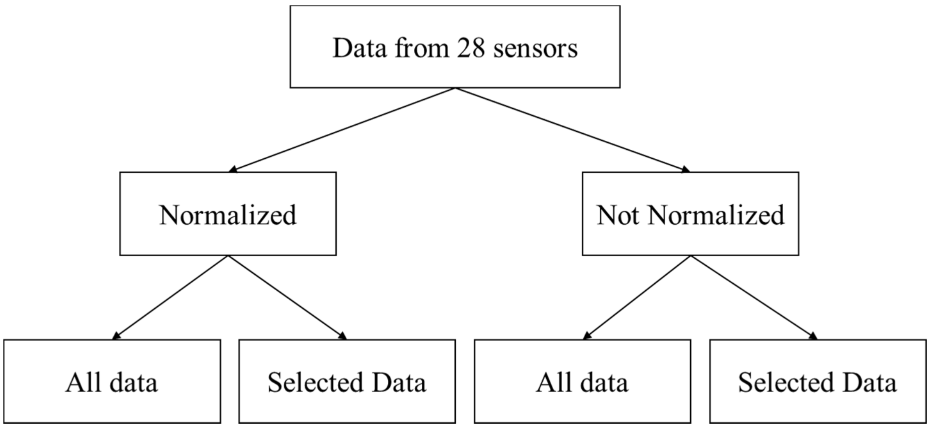

Figure 16. Data sets used in support vector machine (SVM) classifier. Selected data excludes data from 5 sensors in the forehead region with low frequency of usage.

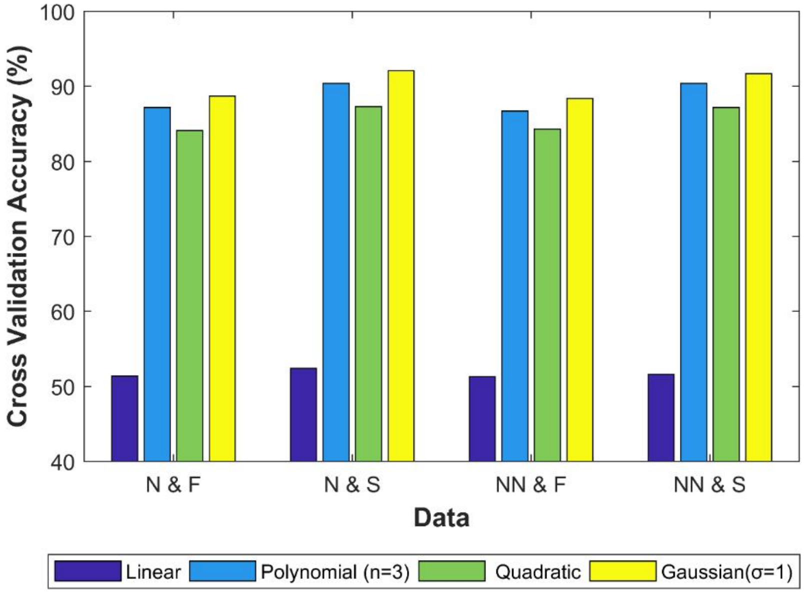

Figure 17. Ten-fold cross validation result of different kernel types tested for each of the different data types. Linear, polynomial (n=3), quadratic, and Guassian (σ=1) were tested for normalized and full (N&F), normalized and selected (N&S), not normalized and full (NN&F), and not normalized and selected (NN&S) data sets.

Additional experiment was conducted to find the optimal kernel size of the Gaussian kernel and six kernel sizes were empirically chosen. The result of changing kernel size on the ten-fold cross validation accuracy is illustrated in Figure 18. The Gaussian kernel with a radius of 0.85 performed well having 92.28% accuracy. From the result, it can be observed that for the radius smaller or larger than this radius, accuracy declines. Classification accuracy for each motion is summarized in the confusion table, Table 2. Columns indicate actual (true) motion of the user while the rows indicate predicted motion by the SVM classifier. For head motions containing visually distinguishable feature as can be seen in Figure 19, the accuracy of classification was higher.

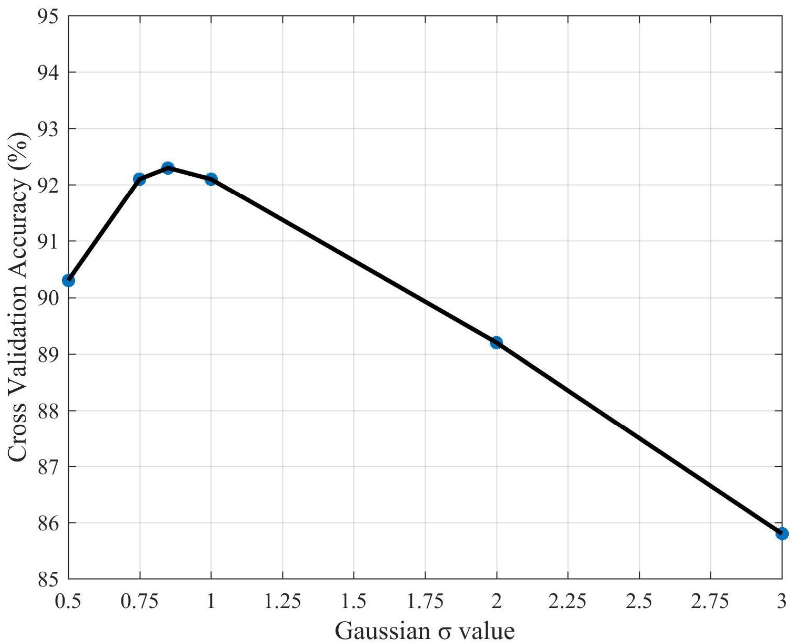

Figure 18. Ten-fold cross validation accuracy of SVM classifier with varying Gaussian kernel sizes.

Table 2. Confusion matrix of support vector machine (SVM) classification result (%). True values are listed on the column and classification results are listed on the row of the table.

	Neutral	Right	Left	Up	Down	Zoom In	Zoom Out
Neutral	98.8	0.0	0.0	0.1	0.3	0.0	0.8
Right	4.3	90.1	0.2	0.2	0.6	0.1	4.5
Left	0.3	4.6	90.9	0.0	0.1	0.1	4.0
Up	6.5	1.1	0.1	89.8	0.3	0.0	2.2
Down	3.2	0.6	0.0	0.6	91.1	0.0	4.4
Zoom In	0.0	7.5	0.1	0.0	0.7	88.8	2.9
Zoom Out	0.1	2.1	0.1	0.1	0.3	1.4	95.8

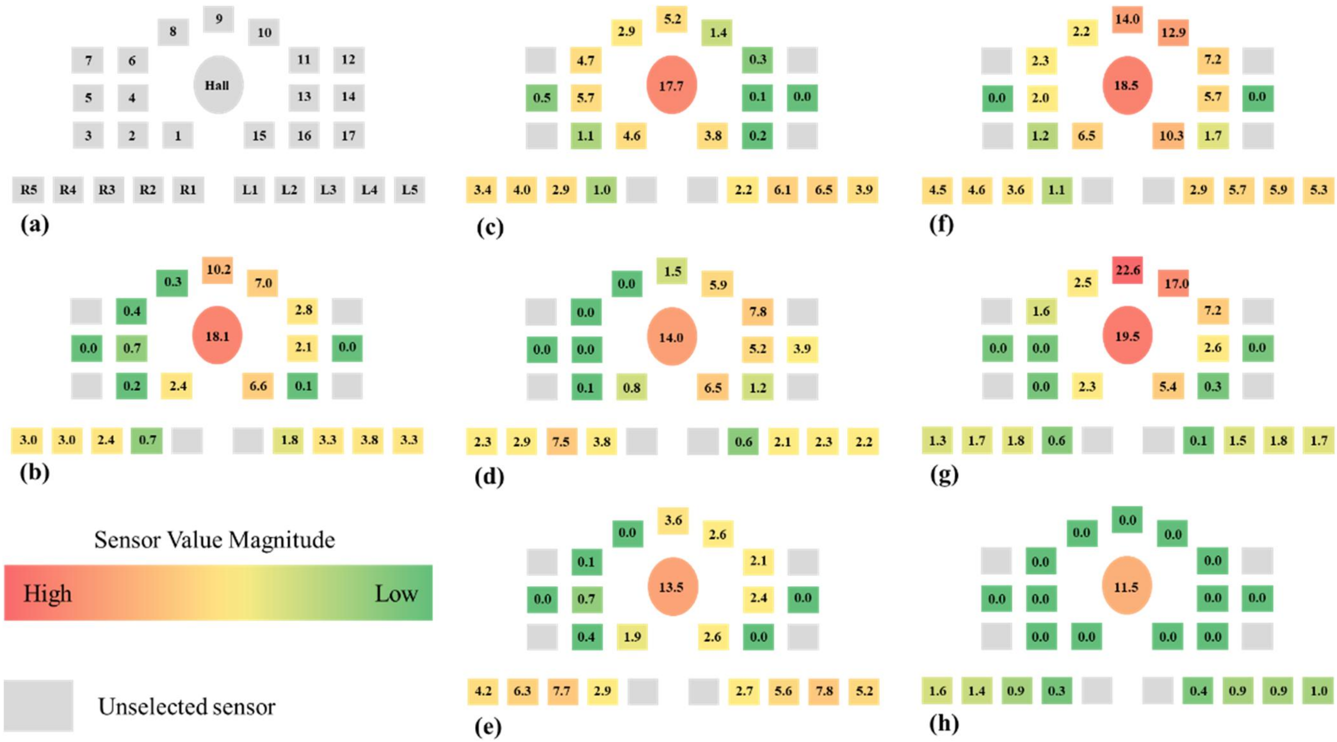

Figure 19. Activation map of the head-mounted master interface (HMI) according to the head movement. (a) Configuration of sensors, (b) neutral (stationary), (c) looking right, (d) looking left, (e) looking up, (f) looking down, (g) zoom in, and (h) zoom out. Color red is used for higher sensor value and green for low sensor values comparatively.

As summarized in Table 3, there was some variation between the individuals but had a mean accuracy greater than 90%. Few participants had poor accuracy while majority had accuracy above 95%. Furthermore, the classification accuracy for the first and last data set of the motions experienced lower accuracy which may imply that the motion was in a transitional state and the sensor values were also in transitional state.

Table 3. Ten-fold classification accuracy (%) amongst the eight participants.

Volunteers	Cross validation result (%)										
	1	2	3	4	5	6	7	8	9	10	Mean
1	87.7	96.2	85.0	92.2	96.9	100.0	97.5	97.4	92.5	69.6	91.5
2	62.1	82.5	74.2	95.1	78.1	85.5	86.2	91.9	73.1	71.0	80.0
3	87.0	96.8	100.0	98.4	98.7	100.0	100.0	100.0	91.0	87.5	95.9
4	92.1	93.2	96.9	95.0	100.0	100.0	100.0	100.0	96.9	81.0	95.5
5	91.3	94.6	96.0	99.2	99.3	100.0	100.0	100.0	98.4	90.5	96.9
6	67.2	97.6	97.2	100.0	75.1	76.4	86.9	78.4	87.3	86.0	85.2
7	87.3	99.1	100.0	99.1	98.4	99.1	99.2	98.3	99.1	91.4	97.1
8	82.5	100.0	100.0	98.1	98.2	100.0	92.5	100.0	99.1	95.1	96.6
Mean	82.1	95.0	93.7	97.1	93.1	95.1	95.3	95.8	92.2	84.0	92.3
Standard Deviation	11.3	5.5	9.3	2.7	10.2	9.1	5.9	7.5	8.8	9.4	8.0

3.2. System Evaluation

All three volunteers were able to successfully finish the modified peg transfer task six times consisting of three trials where the simultaneous operation was enable and the other three where it was disabled. The time taken for the first peg to be picked until the last one to be released was recorded and summarized in Table 4. There was about 30% difference between the completion time when the simultaneous operation of PSMs and endoscopic system was allowed and not allowed. The average time of completion when continuous operation was achieved was 190.1 s with a standard deviation of 16.8 s and when discontinuous operation was conducted the mean was 276.8 with 41.2 s standard deviation. The paired t-test of the result indicates that there is a statistical difference between the two conditions with t value of -8.37 ($p<0.001$).

Table 4. Time of completion (s) for modified peg transfer task. The results of a total of six trials from three participants are summarized into when the continuous operation was enable and disabled.

Continuous Operation	Volunteers	Trials			Mean
		1	2	3	
Enabled	1	204.0	183.0	173.0	186.7
	2	216.0	174.0	178.0	189.3
	3	213.0	191.0	179.0	194.3
	Mean	211.0	182.7	176.7	190.1
	Standard Deviation	6.2	8.5	3.2	3.9
Disabled	1	269.0	216.0	243.0	242.7
	2	365.0	265.0	270.0	300.0
	3	302.0	286.0	275.0	287.7
	Mean	312.0	255.7	262.7	276.8
	Standard Deviation	48.8	35.9	17.2	30.2

The measured time delay of the proposed system from the head movement to the endoscopic movement was 0.72 s with a standard deviation of 0.04 s. The SVM classifier consumed an average of 13 ms with a standard deviation of 6 ms. The data acquisition devices were set to have a minimum transfer speed of 100 Hz. Thus, the majority of the time delay was made in communication between the LabVIEW® algorithm and the motor system.

4. Discussion

The additional interface, HMI, has been proposed to intuitive control the endoscopic system in RAS. It could be easily installed to the stereo viewer of dVRK system fulfilling its role as a head rest as well as a control interface. The HMI uses "move and stop" mechanism when maneuvering the 4 DOF ECS and the speed of movement could be adjusted easily using the LabVIEW® program. Future work may include a pre-defined amount of movement in the direction of the head movement such as five degrees to the right and comparison can be made between the two methods.

The data from 28 sensors installed on the HMI was utilized to classify the seven head movements through SVM classifier and a mean accuracy of 92.28% was achieved. Every individual had a unique appearance regarding the shape and size of forehead and nose thereby leading to different sensor readings. The stationary and zoom out motions had the highest accuracy due to their distinctive and low variance among the individuals yet the zoom in and upward motions had the lowest accuracy for an opposite reason. To increase the accuracy of head motions, more people can be recruited to generalize the classifier further and some training can be added to the system to ensure that the participants move their head in a favorable manner. For clinical usage of the HMI, the rolling motion should be included and due to the limited space available, further experiment is required to realize it.

The usability of HMI has been tested using a modified peg transfer task and when the simultaneous operation was enabled the participants could complete the task earlier than when it was disable on average. The paired t-test confirmed that there exists a statistically significant difference between the two situations. The time delay of 0.73 s in average is hard to consider the system real-time but considering the majority of delay was due to the communication delay between the program and the motor system, it could be optimized further.

Compared to the modified peg transfer results using NMI and iNMI, HMI performed better on average and it is summarized in Table 5. NMI was used for standard peg transfer task and was not applied for the control of the vision system. Therefore, it can be concluded that the endoscopic control using head motion was more intuitive and time efficient than using fingers

Table 5. Comparison of average completion time (s) of the modified peg transfer task between the novel master interface (NMI), the improved novel master interface (iNMI), and the head-mounted master interface (HMI).

Simultaneous Operation		**NMI**	**iNMI**	**HMI**
Enabled	Average	250.0	215.0	190.1
	Standard Deviation	6.0	19.0	3.9
Disabled	Average	-	290.0	276.7
	Standard Deviation	-	11.0	30.2

5. Concluding Remarks and Future Work

5.1. Concluding Remarks

In this study, an additional master interface called HMI for endoscope holder was developed and controlled. The concept of HMI originates from the previous studies including NMI and iNMI and the HMI attempts to provide more intuitive and ergonomic control of the endoscopic system. The head motion of the user was used to control the vision system and the SVM classifier was optimized to classify the head movement at a high accuracy. The modified peg transfer task and measurement of time latency have been conducted to evaluate the proposed system of its validity.

The HMI aims to address the discontinuity issue in control of PSMs and endoscopic system which is one of major issues regarding laparoscopic RAS system. Considering that the virtual reality and head-up display system are receiving much of attention recently, HMI could be used as a stepping stone in control and display mechanism away from conventional methods. As result, the suggested control interface could contribute to the advancements in the medical and industrial fields.

5.2. Future Work

The limitation of conducted study is largely the absence of clinical evaluation from the surgeons and improvement of speed in the actuation of the endoscopic system. The proposed system has undergone evaluation by novice volunteers thus only examined whether the HMI can manipulate the endoscopic system according to the given command (head motion). However, to achieve clinically-relevant performance, surgeon's validation of the system is required. Also, at current state, the time taken for the actuation of the endoscopic system cannot be considered real-time which may cause difficulty in usage. Optimization of control algorithm must be conducted to shorten the time latency of the system and perhaps it can be written in C language rather than LabVIEW® for better performance.

Moreover, the accuracy of head motion classification can be improved by recruiting more subjects and training them to try achieve a unified head motion as there were some variation of performing the head motions in this study. Rolling motion of the HMI system must be added for clinical use and time serial analysis of the head motion may be required.

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국문 초록

복강경 수술 로봇을 위한 머리 장착형 마스터 인터페이스 개발

홍나영

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협동과정 바이오엔지니어링 전공

본 연구는 복강경 수술 로봇을 이용해 수술 진행 시, 머리 움직임으로 내시경 시스템을 제어할 수 있는 추가적 마스터 인터페이스 개발을 목적으로 한다. 본 연구에서 개발 된 추가적 마스터 인터페이스인 Head-mounted master interface (HMI)는 간단한 머리 동작으로 내시경 시스템을 조작할 수 있는 직관적인 인터페이스이다. 더불어, HMI 는 간단하게 기존의 복강경 수술 로봇에 부착되어 사용될 수 있으며 환측의 수술 도구와 내시경 로봇 팔을 동시 제어를 가능하게 하여 수술 시간을 단축하고 효율을 증진 시킨다.

본 연구에서 제안하는 시스템은 HMI, 4 축 내시경 로봇, 3 차원 내시경, 그리고 da Vinci Research Kit 를 포함한다. HMI 의 하드웨어는 인체 공학적으로 설계하였으며 기존의 복강경 수술 로봇에 쉽게 사용될 수 있도록 하였다. 본 시스템을 위해 사용된 센서는 일곱 가지 머리 동작 분류를 위해 배치 되었으며, 총 27 개의 압력 센서와 하나의 자기 센서를 포함한다. 머리 동작 분류를 위해서 머신 러닝 종류의 일종인 Support Vector Machine 을 이용하였다.

본 연구에서 개발 된 HMI 는 Modified Peg Transfer 실험과 지연 시간을 확인하여 사용성을 평가하였으며 평가 결과는 HMI 가 수술 시간을 단축하고 연속적 수술 진행이 가능하게 해주는 다는 목적을 입증하였다.

본 연구에서 제안한 HMI 는 기존 복강경 수술 로봇에 부착되어 연속적 수술 진행을 가능하게 해주며 집도의의 의도에 따라 내시경 시스템을 제어할 수 있다. 또한 본 연구에서 사용된 일곱 가지의 간단한 머리 동작 이외에 다른 머리 동작들을 포함하여 이용하며, 추후 전방 디스플레이 및 가상 현실 기기를 이용한 영상 제공 방식에 적용되어 의학적 그리고 산업적 목적으로 기여할 수 있을 것이다.

주요어: 머리 장착형 마스터 인터페이스, da Vinci 수술 로봇, 복강경 수술, 연속적 수술 진행
학 번: 2016-24548

Acknowledgement

This work was supported by the National Research Foundation of Korea grant funded by the Korea government (MSIP) (Grant 2017R1A2B2006163). The da Vinci Research Kit was donated by Intuitive Surgical, Inc. (Sunnyvale, CA, USA) in 2014.

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본 석사학위 논문을 마무리하며 학위 과정 동안 저를 위해 아낌없는 도움과 가르침 주신 모든 분들께 감사의 말씀을 드립니다.

복강경 수술 로봇을 위한 머리 장착형 마스터 인터페이스 개발

지도교수 Sungwan Kim

이 논문을 공학석사 학위논문으로 제출함

2018년 5월

서울대학교 대학원

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홍 나 영

홍나영의 석사학위논문을 인준함

2018년 7월

위 원 장 이 정 찬 (인)

부위원장 Sungwan Kim (인)

위 원 이 혁 준 (인)