

**SURGERY SIMULATOR DESIGN FOR
MINIMALLY INVASIVE PITUITARY GLAND
SURGERY**

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**by
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ABSTRACT

SURGERY SIMULATOR DESIGN FOR MINIMALLY INVASIVE PITUITARY GLAND SURGERY

Today, interest in robotics applications in the medical field has increased as well as in every field of the industry due to the development in robotic technology and control. The use of robots in surgeries has become widespread. Researchers in Izmir Institute of Technology and Hacettepe University have produced a surgical assistance robot named NeuRoboScope for minimal invasive pituitary gland tumor surgeries. This robot handles and directs the endoscope during the surgery by receiving motion demands from the surgeon via a master system that is composed of a wearable ring and a foot pedal. This thesis study aims to develop a simulator to train the surgeons for using the NeuRoboScope system. For this purpose, NeuRoboScope Surgery Simulator v2 (NSSv2) has been developed in which it is aimed to simulate operation conditions as well as the ideal conditions for NeuRoboScope education. To simulate the operation conditions, surgical instruments, endoscope, and NeuRoboScope system controlling this endoscope are included in the simulator replicating the process of minimally invasive pituitary gland tumor surgery. NSSv2 system uses 2 haptic devices, a specially designed control ring that controls the active part of the NeuRoboScope system and has an inertial measurement unit and also wirelessly communicates with the system, a foot pedal activating the control of the ring, a model skull to determine the surgery region and a monitor that receives the visual feedback of the simulation to control the surgical instruments from the physical environment. In addition to training, it is aimed to customize the NeuRoboScope's teleoperation system with respect to user needs and operation styles. In line with this objective, the user calibration mode is generated. In this way, an efficient and customized control system is created for the use of the NeuRoboScope system. A training procedure is developed with several scenarios within the NSSv2 system. When users carry out this training, the completion time of the scenario, the number of pedal usage, and the amount of motion of the surgical tools are recorded by the system. Improvements in the capabilities of users can be observed and the efficiency of NSSv2 can be evaluated owing to these data.

ÖZET

MİNİMAL İNVAZİV HIPOFİZ BEZİ AMELİYATI İÇİN CERRAHİ SİMÜLATÖR TASARIMI

Günümüzde robot teknolojisi ve kontrolündeki gelişmelere bağlı olarak endüstrinin her alanında olduğu gibi tıp alanında da robotik uygulamalara olan ilgi artmıştır. Ameliyatlarda robot kullanımı yaygınlaşmıştır. İzmir Yüksek Teknoloji Enstitüsü ve Hacettepe Üniversitesi araştırmacıları, minimal invaziv hipofiz bezi tümörü ameliyatları için NeuRoboScope adlı bir cerrahi yardım robotu üretmiştir. Bu robot, giyilebilir bir yüzük ve ayak pedalından oluşan bir kumanda sistemi aracılığıyla cerrahtan hareket taleplerini alarak ameliyat esnasında endoskopu yönetmektedir. Bu tez çalışması, cerrahları NeuRoboScope sistemini kullanma konusunda eğitmek için bir simülatör geliştirmeyi amaçlamaktadır. Bu amaçla, operasyon koşullarının yanı sıra NeuRoboScope eğitimi için ideal koşulların simüle edilmesinin amaçlandığı NeuRoboScope Surgery Simulator v2 (NSSv2) geliştirilmiştir. Operasyon koşullarını simüle etmek için, cerrahi aletler, endoskop ve endoskobu kontrol eden NeuRoboScope sistemi, minimal invaziv hipofiz bezi tümörü cerrahisi sürecini kopyalayan simülatöre dahil edilmiştir. NSSv2 sistemi, 2 dokunsal cihaz, NeuRoboScope sisteminin aktif kısmını kontrol eden ve bir atalet ölçüm birimine sahip olup, ayrıca sistemle kablosuz olarak iletişim kuran özel olarak tasarlanmış bir kontrol yüzüğü, yüzük kontrolünü etkinleştiren bir ayak pedalı, ameliyat bölgesini belirlemek için bir model kafatası ve cerrahi aletleri fiziksel ortamdan kontrol etmek için simülasyonun görsel geri bildirimini alan bir monitör kullanmaktadır. Eğitime ek olarak, NeuRoboScope'un teleoperasyon sisteminin kullanıcı ihtiyaçları ve çalışma stillerine göre özelleştirilmesi hedeflenmektedir. Bu amaç doğrultusunda kullanıcı kalibrasyon modu oluşturulmuştur. Bu şekilde, NeuRoboScope sisteminin kullanımı için verimli ve özelleştirilmiş bir kontrol sistemi oluşturulur. NSSv2 sistemi içinde çeşitli senaryolarla bir eğitim prosedürü geliştirilmiştir. Kullanıcılar bu eğitimi gerçekleştirirken senaryonun tamamlanma süresi, pedal kullanım sayısı ve cerrahi aletlerin hareket miktarı sistem tarafından kayıt altına alınmaktadır. Bu veriler sayesinde kullanıcıların yeteneklerindeki gelişmeler gözlemlenebilir ve NSSv2'nin verimliliği değerlendirilebilir.

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CHAPTER 1

INTRODUCTION

The development of robotic and control systems, especially in the last 20 years, has led researchers and engineers to robotic solutions in the medical field. Although these studies have gained momentum in recent years, many studies have been conducted on surgical assistance robots in the past 30 years. In 1989, a robotic system has been developed to be used in the treatment of prostate cancer (Davies et al., 1989). The idea of using robotic systems in operations has been evaluated in many studies and it is thought that it will create a positive process in treatment. The development of computers and especially imaging technology has led to the idea of performing minimal-invasive surgery. The benefits and some applications of the use of an endoscope for surgeries are mentioned by Buckingham (1994). Minimally-invasive surgeries significantly shorten the postoperative recovery period of the patient. For this reason, if possible minimally-invasive surgical methods are preferred by surgeons. These developments in surgical methods have opened the path for new designs of robotic systems. Robots for surgical systems are primarily developed for carrying out the minimally invasive surgeries. There are also robots that are designed to train the surgeons to get experience on specific surgery protocols. In addition, simulators are being developed to gain experience in the use of surgical robots. In this thesis, a surgery simulator is designed for the NeuRoboScope system which is assistive robotic system specifically designed for the minimally-invasive pituitary gland surgery.

1.1. Minimally Invasive Surgery

At the end of 1970, a new method called minimally-invasive surgery was defined. In this method, it is aimed to cause the least deformation in the patient's body during the operation. Basically, it is an operation that is performed by inserting special equipment from small incisions into the patient's body. The most important equipment in this method is the endoscope, which provides visual feedback of the surgery area to the surgeon while the surgeon operates. The endoscope view is projected on a screen and the surgeon operates by viewing the operation environment from the screen. A visual from a minimally-invasive surgery is shown in Figure 1.1. In this visual, the surgical tools are

inserted from incision points with minimal dimensions to the patient's abdominal cavity. The endoscope, which is covered with a blue material in the figure, provides visual monitoring. The tool seen in his/her right hand is the surgical scissors and the rightmost tool is the aspirator that aspirates blood and removed tissues from the surgical zone. The preference rate of this method is gradually increasing. One of the most important reasons for this is that when the patient is operated via a minimally invasive method, the recovery period is shorter than the open surgery (Rahman et al., 2008). Also, the patient's postoperative life comfort is higher than open surgery in terms of sleeping positions, use of the corset, easy breathing, bleeding in surgical sutures, etc.

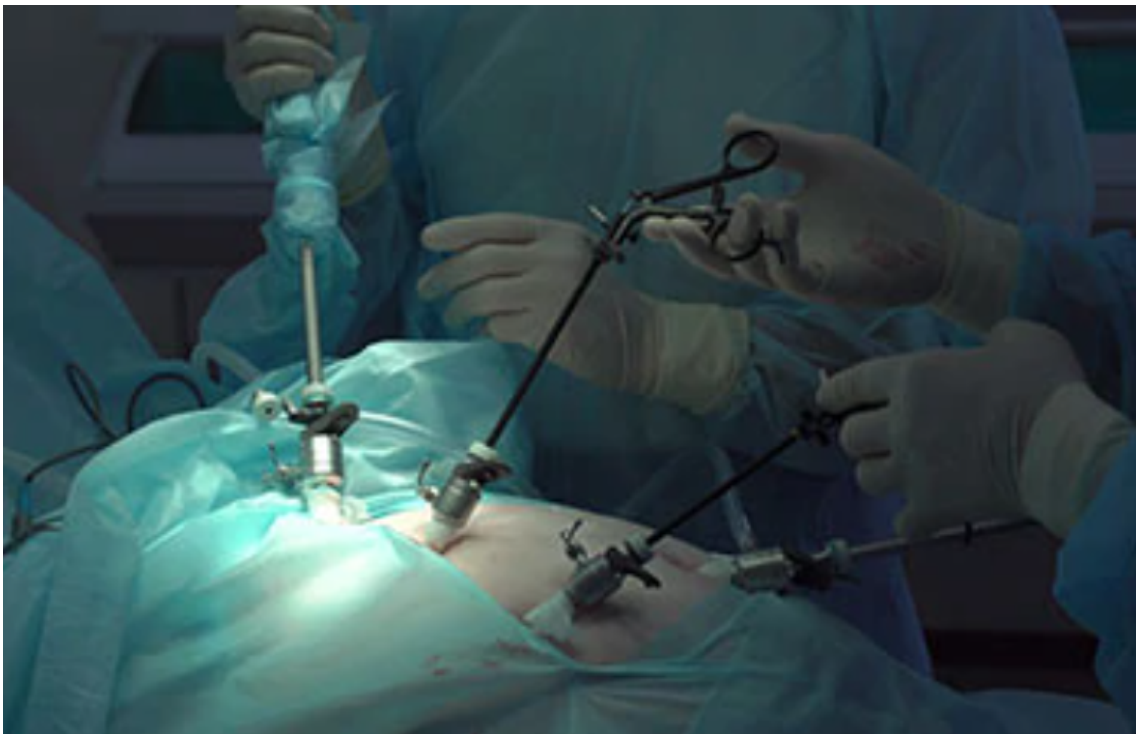


Figure 1.1. A minimally invasive laparoscopic surgery
(Source: Siddhi Vinayak Hospital 2020)

One of the minimally invasive surgery equipment is shown in Figure 1.2. The figure shows the special structure of the equipment. It has a long and thin body so that it can be easily inserted through an incision point with minimal dimensions. Cutting blades are controlled by a hand holder. The visual shows the main idea of minimally-invasive surgery which is to perform operations from minimal openings with the modification of standardized surgical instruments.

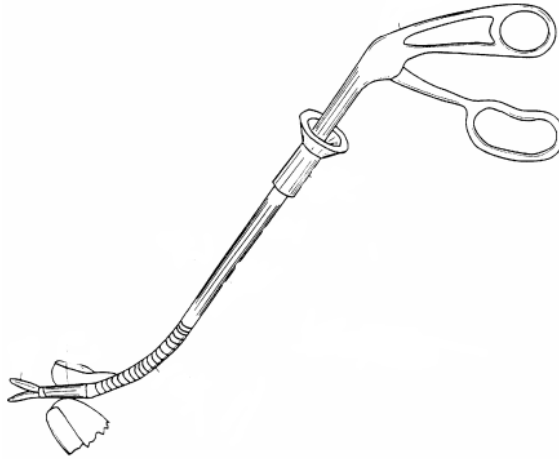


Figure 1.2. Minimally invasive flexible body surgical scissors
(Source: Verdura et al. 2000)

1.1.1. Pituitary Tumor Surgery

The pituitary is an endocrine gland located in the lower part of the brain that secretes various hormones weighing about 0.5 grams. Endocrine glands produce various hormones and release them into the circulation, stimulating target organs in other parts of the body and allowing them to function. A disease or tumor in the pituitary gland disrupts the body's metabolic system and causes too little or too many hormones to be secreted (Shimon and Melmed, 1997). If this disease is not treated, it causes serious problems that may result in the death of the patient. The pituitary gland tumor is removed by a surgery that requires expertise. In the surgery performed with the endoscope, the surgeon uses many instruments to remove the tumor. Figure 1.3 shows the standard surgery for the removal of pituitary tumors. The endoscope and a surgical tool are shown in this figure. Operators generally use the left hand to hold the endoscope. In order not to harm the patient, the surgeon uses the patient's nose tip as a pivot point while he/she moves the endoscope inside the nostrils. Also, contact of the endoscope with any tissue reduces the vision quality due to body fluids and blood covering the camera lens. In this case, the endoscope is removed and cleaned and the operation continues. When the tumor is removed from the pituitary, a lipid tissue, which is taken from the patient's body, is placed to the gap of the removed tumor for faster recovery of the injured tissue. After the surgery, the patient must be monitored to perceive any negativity.

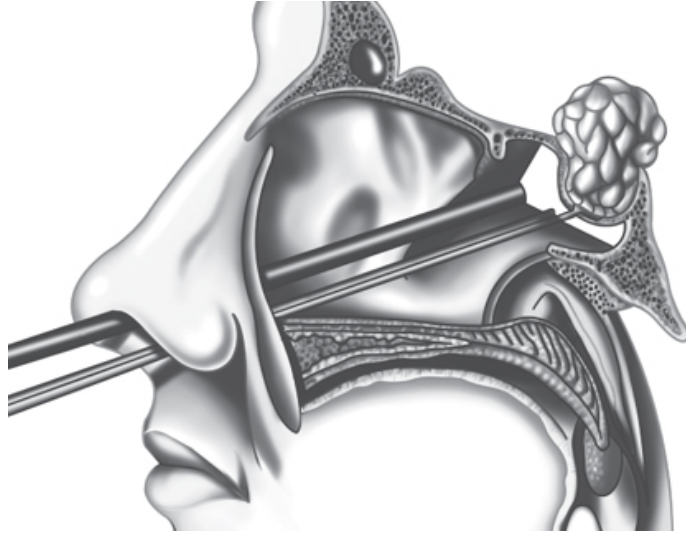


Figure 1.3. Surgery for remove pituitary tumors
(Source: Rinehart et al. 2013)

1.1.2. Minimally Invasive Surgery Robots

Minimally invasive operations are very suitable for robot-assisted procedures compared to other surgery methods. Movement of the equipment or endoscope by a robotic arm can be beneficial for surgeons in these operations performed with 2-dimensional (2D) images from the endoscope. Coordination difficulties due to the image coming from the camera and using the equipment in the correct position can be facilitated in this way. Minimal invasive robots can be categorized in the two main titles as teleoperation robots and assistant surgical robots. Teleoperation robots are the systems that the surgeon performs the operation with a master system/robot that sends command to the slave system/robot that is working on the patient. An example of the operator position and haptic control device which is used as the master system can be seen in Figure 1.4. The lack of contact with the tissue was studied and the surgeon was provided with this touch feeling by creating haptic feedback (Okamura, 2019).

1.1.3. The NeuRoboScope System

The Neuroscope system is a robot-assisted surgery system that handles and directs an endoscope for use in minimally invasive pituitary gland tumor surgeries while the surgeon operates with the other surgical tools on the patient. It has 8 degree-of-freedom



Figure 1.4. Da Vinci Surgical Robot
(Source: Okamura 2019)

(DoF) that is composed of 3 DoF active arm and 5 DoF passive arm. The surgeon sends commands to drive the surgical robot via a master system that is composed of a ring, which has an inertial measurement unit (IMU), and a foot pedal. The ring communicates with the main controller of the NeuRoboScope systems via Bluetooth interface. Consequently, the surgeon controls the endoscope via the ring while he/she can use the operational equipment with both hands.

1.2. Problem Definition

Operators must be trained to use robots, which is the case with all devices and machines that require physical skills. Especially for surgical robots, it is not possible to obtain this experience on humans considering the patient health. These trainings are also necessary for the NeuRoboScope system. The training for the use of this robot can be obtained through a large number of repetitions. Robot usage training can be done by using human models and/or cadavers. However, considering the ethical issues and costs, this method is not suitable in terms of repeatability. The sophistication of haptic devices and computer simulations makes it possible to develop and use a training simulator that is built in the computer environment for the training of surgeons. In this way, surgeons will gain experience in NeuRoboScope control through a simulator.

1.3. Aim of the Study

This study aims to develop a simulator built in a computer environment for NeuRoboScope system training. This simulator is aimed to be specialized for the minimally invasive pituitary gland surgery and aims to improve the device control of the surgeons. Within the content of this simulator, surgery scenarios and tasks that the operator can perform are aimed to be designed. The duration to execute the tasks, the number of times surgeon gives new commands and the amount of surgical tool's motion while performing the test scenarios are aimed to be recorded. In this way, the improvement of the surgeons' capability to use the NeuRoboScope system as a result of the training can be monitored and the efficiency of the simulator can be evaluated. Additionally, a procedure to identify the surgeon's preferred motion axes is aimed to be formulated. In this way, the NeuRoboScope system's control can be customized for each surgeon.

1.4. Outline of the Thesis

The study consists of 6 chapters. In Chapter 2, previous research on surgical robots and surgery training in virtual reality environments are reviewed. In addition, the ECE simulator developed by the members of Atılım University and Hacettepe University is examined in detail. In Chapter 3, the NeuRoboScope project is described in detail and NeuRoboScope Simulator v1 is investigated. In Chapters 4 and 5, the hardware and software structure of NeuRoboScope Surgery Simulator v2 are explained. In the conclusion chapter, which has been prepared to evaluate the efficiency of this study. Besides, user tests and results have also been given. The efficiency of the study has been evaluated by using this data.

CHAPTER 2

LITERATURE REVIEW

2.1. Surgery Simulator Systems

The use of simulators in medicine dates back to the 1950s. The first medical simulators are mannequins that are called "phantoms" which were used in education between the 16th-17th centuries. They are non-systematic practices that stand out in training and testing obstetrical abilities to reduce infant and maternal mortality (McGaghie et al., 2010).

The first important breakthrough in medical simulation was with Ressusi-Anni, a collaborative product of anesthesiologists and industry in the 20th century. This model set an example for other models which are related to revival and basic abilities training (Bradley, 2006).

The next development in this area was a simulator called Sim One which is the first human anatomy simulator produced by Abrahamson and Denson in the 1960s. This simulator, which has a heartbeat and synchronized carotid pulse, imitates human movements, opens and closes its mouth, blinks its eyes, responds to intravenous gas and drug applications, and blood pressure can also be measured. It did not become widespread because it could not be produced due to the conditions of the time. In the 1980s, two groups from Stanford and the University of Florida worked on high-end simulator development. Anesthesia simulators known as Comprehensive Anaesthesia Simulation Environment (CASE) have been developed under the leadership of David Gaba, and Gainesville Anaesthesia Simulator (GAS) under the leadership of Michael Good and JS Gravenstein (Good, 2003).

The third development was during the medical training reform in the 1990s, with the worldwide recognition of the use of simulation in the education and evaluation of medical students. Simulators, which were used in clinical skills laboratories in the past due to their expensiveness, have become an indispensable part of postgraduate and pre-graduate education programs today, and simulation-based education has found widespread use as one of the innovative educational approaches in the medicine field (Midik, 2010).

Simulators can be in the form of mechanical simulators, as well as simulators with

virtual reality, hybrid simulators or models of human cadavers and animals. All these simulators have various advantages and disadvantages. Simulators that do not contain advanced technology are used for educational purposes and are not generally managed by a computer. Three-dimensional organ models (trainingaids) are in the form of basic plastic dummies (used for training physical examination skills, suturing), human cadaver and animal models (used in anatomy and physiology education). These models are cheap and non-recyclable models with low accuracy. Advanced technology simulations are controlled via computers. Screen-based simulation and virtual reality simulators can be given as examples to these. In the virtual reality model, training studies are performed on the model by using an adult-sized mannequin with a certain fiction planned as close to the computer-controlled real environment. In these models, there is user feedback, but the cost of these systems is high. In hybrid systems, plausibility has been increased by using mechanical and virtual reality simulators together (Gardner and Raemer, 2008). The must-have feature in all types of simulations is the "fidelity" criterion. This feature reflects the reality of experiences. There must be a real-world role within the system, with obligations and responsibilities for the participants. It should be able to imitate all possible situations that exist, and a rich environment should be provided in which the participant can respond realistically. There should be ways that the participant can follow the change of the problem and the current situation or in unclear situations such as in the real world, the simulator should be able to react according to the different movements of the user. The more such features are presented in the simulation system, the better the users can apply their learning to real events (Maran and Glavin, 2003).

The degree of accuracy of the simulators is not only related to the physical structure. The "psychological" structure it carries, that is, the responses given to events and tasks, and the possible ways that are constructed for possible situations make the simulator more qualified (Fincher and Lewis, 2002). Simulations are usually used for three purposes:

1. D1. Do research and planning; Examples include designing a new medical device, testing a new surgical technique or equipment before it is put on the market, and identifying problem areas before investing. It is mostly used in the industry for reasons such as the development of new ideas. Saving money and time is at the forefront here.
2. Evaluate mastery; At this point, the mastery of a physician to perform endoscopy before performing an endoscopy application. Testing and evaluation phases can be given as an example.

3. Education; The ability to learn the skill of administering drugs intramuscularly under supervision before contacting the patient is an example of simulation for educational purposes (Patrick, 1992).

One of the important simulators in medicine is surgery simulators which is an advanced computer technology to simulate surgical procedures to educate medical specialists without the need for patients, cadavers, or animals. Surgery simulators are evolving at a rapid pace, from basic artificial dummies to high-tech machines and computers that can simulate much more realistic physiological states. As medical procedures are of vital importance, the training of specialists who will perform these procedures is important. For instance, since an epidural injection is a difficult procedure to perform and involves some serious risks for the patient if mistakes are made, surgical simulators are used to reduce the number of errors that may occur during this procedure. Many simulator types have been developed and released. These simulators produce a real surgical scenario and allow the user to interact with the anatomy through different interfaces that can be realistic with surgery, and because of this interaction, they display haptic feedback to the user. This process, known as haptic feedback, is to transform the results of interactions in the virtual environment into a format that the user can feel in the physical environment. Surgery simulators consist of physical and virtual environment interaction. This interaction is added to the simulator, allowing experts to feel this interaction and perform a realistic operation. Surgery simulators provide a safe and risk-free environment to learn the procedure and also provide a higher level of patient safety (Güven, 2016).

The use of surgical simulators for educational purposes is increasing day by day. The techniques of education and training have been changing over the years. Surgery simulator applications have led to the emergence of a new trend in the medical field. Thanks to the development in technology, students can practice on every subject over and over. It is aimed to reduce the error rates in applications. There are many examples of surgery simulators on the market. TechRepublic™, VRS©, WMG©, Techcrunch©, Medelita™, Vrphobia©, Wired©, Topphysio® and Ispr© companies develop surgical simulators with virtual reality feature for different surgical procedures (Atıcı, 2017).

2.1.1. Virtual Reality Simulators

The trend towards alternative education methods is increasing. Especially in medical education with the emergence of the pandemic period, different methods have been

used. These include cadaver, animal and anatomical model courses and virtual reality computer simulations. Training with cadaver and animal models in laboratories is a costly and limited method. For this reason, the importance of virtual reality simulators, which are more affordable and offer the opportunity to try repeatedly, has increased. Numerous studies have been conducted on the effectiveness and limitations of this method.

The most important aspect of virtual reality simulation training is that it provides training without the use of real patients. Simulation provides a risk-free learning tool, especially in critical or rare situations. It also encourages interdisciplinary approaches to learning in health care. It can also play an important role in outcome evaluation and accreditation. In other words, it is a computer simulation of real-life skills (Yiannakopoulou et al., 2015).

Yiannakopoulou et al. (2015) compared different training models such as cadaver models, laboratory animals, augmented reality simulators, virtual reality simulators, hybrid simulators and box trainers. According to their findings, virtual reality simulator training led to the acquisition of important skills, such as the acquisition of basic laparoscopic skills and advanced sewing skills. They also reported that they gained the skills of laparoscopic cholecystectomy. On the other hand, they found limited data on improving performance in advanced laparoscopic procedures and non-technical skills.

Gurusamy et al. (2009) examined the effectiveness of virtual reality simulator training in their research. They investigated whether the training given to candidates with no surgical experience using a simulator would complement or replace traditional laparoscopic training. In the study involving 622 participants, video instructor training, standard laparoscopic training, different virtual reality training methods and virtual reality simulator training were compared with other training tools. One of the important findings of the authors is that simulator training improves standard surgical training. Another finding is that it is at least as effective as video trainer training, and it has been found to shorten the operative time and increase operative performance compared to other trainings. However, the effect of this reduced operative time and improved operative performance is unknown in terms of possible outcomes or reduced costs.

Dawe et al. (2014) evaluated virtual reality simulation training in comparison to patient-based training. In most of the cases, patient-based training programs were used as the basis, and simulation-based training was provided in addition to this. For laparoscopic cholecystectomy and endoscopy, participants who achieved simulation-based skill proficiency before patient-based assessment scored higher in assessment and made fewer errors in the operating room than those who did not. On the other hand, while patient-

based education was more effective in sigmoidoscopy, there was no significant difference for colonoscopy.

Some studies investigated virtual reality simulators as an assessment tool. Lee et al. (2012), compared 13 novice and 7 experienced robotic surgeons with dV-Trainer robotic surgical simulator, which is one of the most commonly used surgical robot trainer. Experienced surgeons got better results than novice ones as expected. In addition, the study demonstrated evidence that dV-Trainer could be used as an assessment tool.



Figure 2.1. Simulators of the da Vinci Surgical Robot
(Source: Smith et al. 2015)

From left to right: da Vinci Skill Simulator (Intuitive Surgical Inc., Sunnyvale, CA, USA); dV-Trainer (Mimic Technologies, Inc., Seattle, WA, USA); and RoSS (Simulated Surgical Skills LLC, Williamsville, NY, USA) are shown from left to right in Figure 2.1 (Smith et al., 2015).

Another research about validity of virtual reality simulator dV-Trainer is conducted by Perrenot et al. (2012). According to the surgical training they received, 75 participants were divided into five groups. In the next step, they were tested on robotic specific skills: camera control, EndoWrist manipulation, visual force feedback, gripping, and 3D sensing. Their findings showed that the da Vinci-Trainer simulator is an acceptable tool for assessing robotic surgery skills.

Kang et al. (2014) used virtual reality simulators to practice surgeons with more exercises. Vesicourethral anastomosis (VUA) was developed by the researchers, one of

the most complex steps in the robot-assisted radical prostatectomy procedure. They used a novice group consisted of 10 residents and an experienced group who had previously performed at least 10 robotic surgeries.

Hung et al. (2015) also investigated the validity of simulators and found similar results as Kang et al. (2014) performed. They used three different groups to evaluate virtual reality simulators, novice who has no surgical training, intermediate has less than 100 robotic cases and expert who perform 100 or more robotic procedures. According to the experts, virtual reality simulators are realistic and helpful for residents. It is also good for teaching anatomy and operative steps.

On this issue other notable works are carried out by Carter et al. (2005), Seixas-Mikelus et al. (2010), Van der Meijden et al. (2010), Gavazzi et al. (2011), Finnegan et al. (2012), Hung et al. (2012), Kelly et al. (2012), Liss et al. (2012), Chowriappa et al. (2015), Lyons et al. (2013), Stegemann et al. (2013), Connolly et al. (2014), Culligan et al. (2014), Ramos et al. (2014), Raza et al. (2014), Schreuder et al. (2014), Chowriappa et al. (2015). These studies have confirmed the validity of virtual reality simulators in medical education/training.

2.1.2. Haptics Enabled Virtual Reality Simulators

These simulators are software-supported devices developed especially for interventional application skills. These devices, which are based on the effective use of the sense of touch and have the feature of giving detailed feedback after the application, support the mastery of novice/inexperienced users. Haptic refers to the sense of touch. Haptic processing allows the user to touch, feel and manipulate virtual objects through the probe of a haptic device.

One step further of the virtual reality simulator is haptic enabled ones. This type of simulators especially designed for training robotic surgery. Among these, the dVT system consists of a two-handed haptic system with grips that emulate the master grips on the surgeon's console and pedals and a high-definition stereoscopic display as presented in Figure 2.2.

The dVT's training program is subdivided in two sections. While the first one is the overview and basic skills training the second one is the surgical skills training. Each section consists of four modules. First section includes surgeons console overview, Endo Wrist manipulation, camera and clutching, and trouble shooting. Second section consists of needle control, needle driving, energy and dissection, and games.



Figure 2.2. Haptics Enabled The da Vinci Trainer; Console, Grips, and Pedals (Mimic Technologies, Inc., Seattle, WA)
(Source: Schreuder et al. 2014)

Schreuder et al. (2014) established face and constructed validity of dV-Trainer and conducted a research with 42 participants. They used two basic skills exercise (Camera Targeting and Peg Board) and one surgical skill exercise (Thread the Rings). Their findings confirm validity of face and construct. Experts performed better than novices in the simulator. According to data, the simulator is in general realistic, in terms of visual graphics, movements of instruments, interaction with objects, and the depth perception. Li et al. (2017) evaluated most common haptic enabled virtual reality simulators which are LapSim (Essence and haptic system), Lap Mentor (LAP Mentor III), MIST-VR (VIST G5), Simendo (Pro3 laparoscopy), ProCedicus KSA VR, ProCedicus virtual arthroscopy simulator, Insight Arthro VR Shoulder, Simulator (Arthro Mentor), TraumaVision, Visible Ear Simulator. According to research, the experience generated by VR simulation provides trainees with a better understanding of complex 3D body structures and instruments in a controlled, risk-free environment. In addition, the tactile feedback experience in surgical simulation helps trainees to get used to the operation process and improve their operation and decision-making skills without harming the patients. However, the accuracy and efficiency of VR simulation needs to be improved. Although it is acknowledged that it is not simple to simulate density, tactile properties and convex surfaces in a virtual environment, they reported that the response rate and density feedback of tactile devices are too weak to accurately simulate vibration during drilling.

Haptic systems can also be useful when the trainer wants to evaluate the student in detail. Students can work in a real hospital environment as if an intervention were applied to real patients. In this way, educators can evaluate students more efficiently. Students can perform operations (blood taking, vascular access, positioning, etc.) over the representations of patients in daily life in the virtual environment. In this way, interventions are implemented without deteriorating the well-being of individuals, more risk-free practices can be made, and students' anxiety is reduced or prevented. At the same time, students perform these attempts with an unlimited patient and illness scenario. These scenarios allow students to choose the right option during the intervention and implementation phases. This allows students to see more patients/diseases, ensuring that they do not have professional difficulties in their professional lives Davis (2015).

According to Jung et al. (2012), medical students use haptic systems quite frequently, especially in tissue and muscle structures and in surgical procedures. Nursing students frequently use haptic systems in intravenous interventions. In accordance with the feedback received from the students, the efficiency of the haptic system was determined to be quite high. Students stated that the reality rate of the interventions is quite high due to tactile feedback.

Jamison et al. (2006) examined the effects of traditional method and IV virtual simulation system on the academic achievement and skill performance of nursing students for intravenous catheterization, and the students were divided into two groups. A significant increase was found in the intravenous catheter skill performance and post-test scores of the students who used virtual reality simulation (Cath Sim) in their study in which they applied pretest-posttest knowledge test and skill performance exam for intravenous catheter application to the students in the intervention and control groups.

2.2. Overview of the ECE Simulator

The development of virtual reality environments has revealed the idea of conducting surgery training in a computer environment in researchers. In this context, a simulator has been developed by members of Atılım University and Hacettepe University to be used by surgeons in minimally invasive pituitary tumor surgery training. This simulator is called ECE which means "Educational Computer-Based Simulation Environment". Structure of the general system is shown in Figure 2.3. It is a system created using general-purpose haptic devices and a visual interface on the computer. It is developed for surgeon training, which consists of scenarios prepared for many situations about en-

doscopy. These scenarios include the use of different surgical instruments during different processes of surgery. The operator keeps haptic devices while using the simulator. Operator implements the training by performing the desired actions according to the information and job descriptions obtained from the visual feedback. This tutorial includes difficulty levels and challenges. Haptic devices held by the operator are shown in Figure 2.3 C and D parts. By using these devices, they control the surgical instruments in the simulator. The simulator system records the completion time, the mistakes, and the successful tasks of the operator during the scenario. In this way, the improvements in the operator's skills become observable. As a result of the tests and observations, it was observed that the use of a simulator improves and facilitates operator training, especially in the field of neurosurgery where the reproducibility of practical training is low.



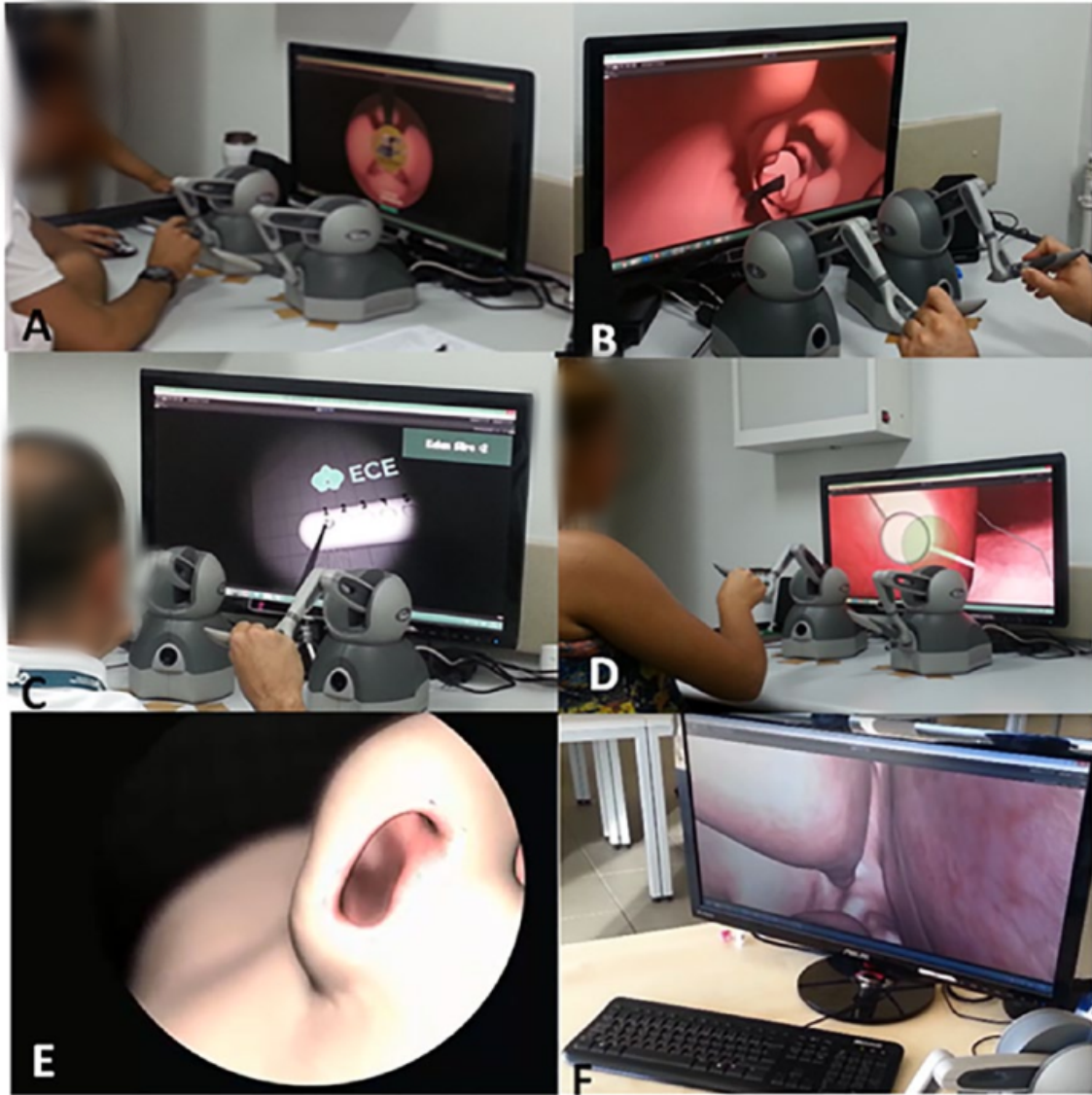


Figure 2.3. ECE operational scenarios
(Source: Cagiltay et al. 2019)

CHAPTER 3

NEUROBOSCOPE SURGICAL SYSTEM'S DESCRIPTION

NeuRoboScope is the specialized robotic system developed to assist surgeons in pituitary gland surgery. It was designed by academics and project assistants of Izmir Institute of Technology and Hacettepe University surgeons, who are the specialists in pituitary gland surgery. The system has been developed as a result of the TÜBITAK 115E725 and 115E726 projects in 2018.

3.1. Overview of the NeuRoboScope System

The NeuRoboScope system is developed to provide a third arm to the main surgeon during the minimally invasive pituitary tumor surgery. This third arm handles the endoscope which is the camera system. The system is designed as a unilateral teleoperation system which consists of three main parts: (1) master system consisting of a wearable ring and a foot pedal (2) control subsystem consisting of communication modules and motor drivers (3) slave system consisting of passive and active arms holding the endoscope. Figure 3.1 shows the passive and active arms of the slave system. The active arm is an remote-center-of-motion (RCM) mechanism which can control the endoscope's motion in three degrees-of-freedom (DoF). These DoFs are two rotational DoF about a pivot point and a translational DoF along the pivot point. The pivot point is indicated by laser sensor for the surgeon to observe during the surgery. This point is indicated with a blue circle in Figure 3.1. The active arm is placed to the surgical area by the help of the passive arm. The passive arm is a gravity compensated manipulator without any actuators. Its main purpose is to carry the active arm and locate it to the surgical area. Since the passive arm does not include any actuators, it is passively backdriven by the surgeon during the surgery to insert the endoscope inside the surgical zone (inside the nostril in this case). For the passive arm to act as an inertial frame when the active arm has a motion relative to the passive arm, electro-mechanical brakes are coupled to the joints of the passive arm. The joints of the passive arm are indicated in Figure 3.1 with red circles. The green circles in Figure 3.1 indicate the actuators of the active arm.

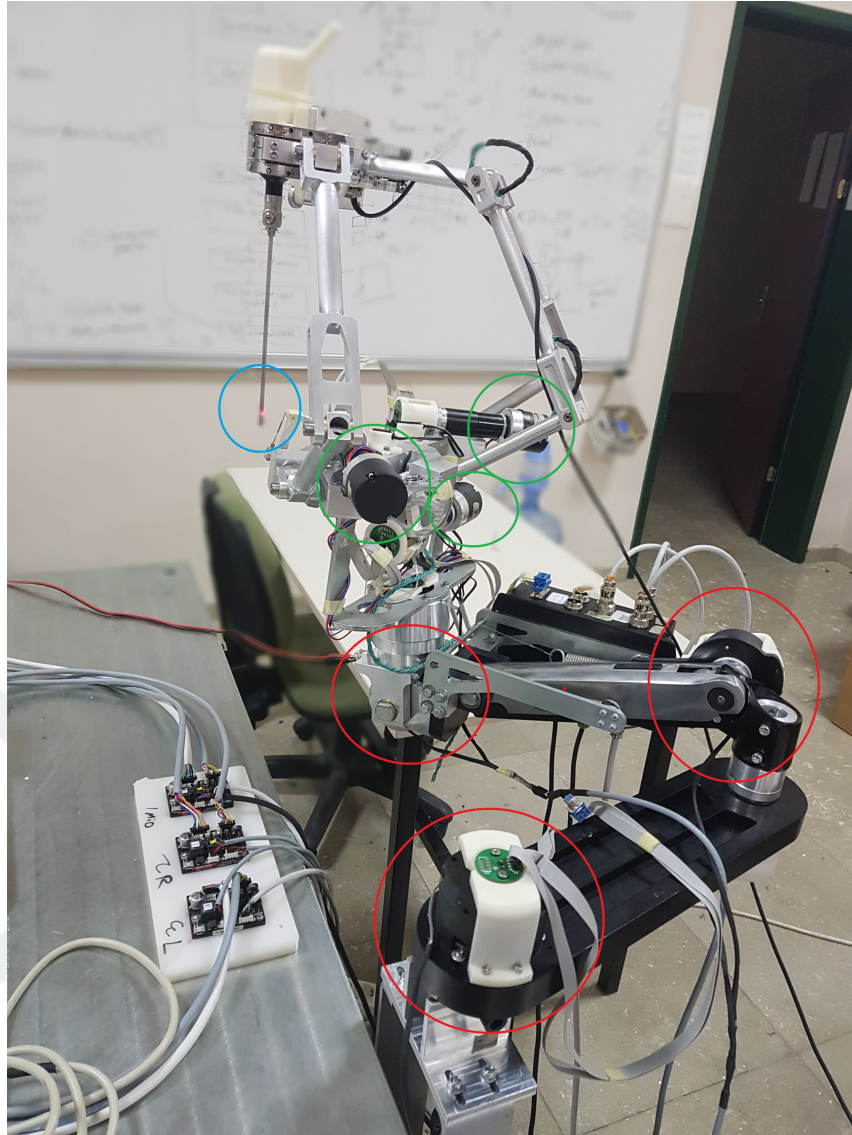


Figure 3.1. NeuRoboScope's actuators

The master-slave teleoperation system of the NeuRoboScope system works as the master system sends motion inputs to the slave system. The information exchange is initiated when the foot pedal is pressed. The foot pedal is shown in Figure 3.2. The acquired motion information from the wearable ring is received by the main controller and issued as motion commands to the slave system. The main controller is also shown in Figure 3.2. This controller consists of communication subsystems and motor drivers. A user interface is included to the system with three buttons. These buttons are used for emergency stop, indicating the surgical zone at the beginning of the surgery and activating/deactivating the brakes on the passive arm. When the surgeon wants to move the passive arm, manual control button which activates/deactivates the brakes is used.

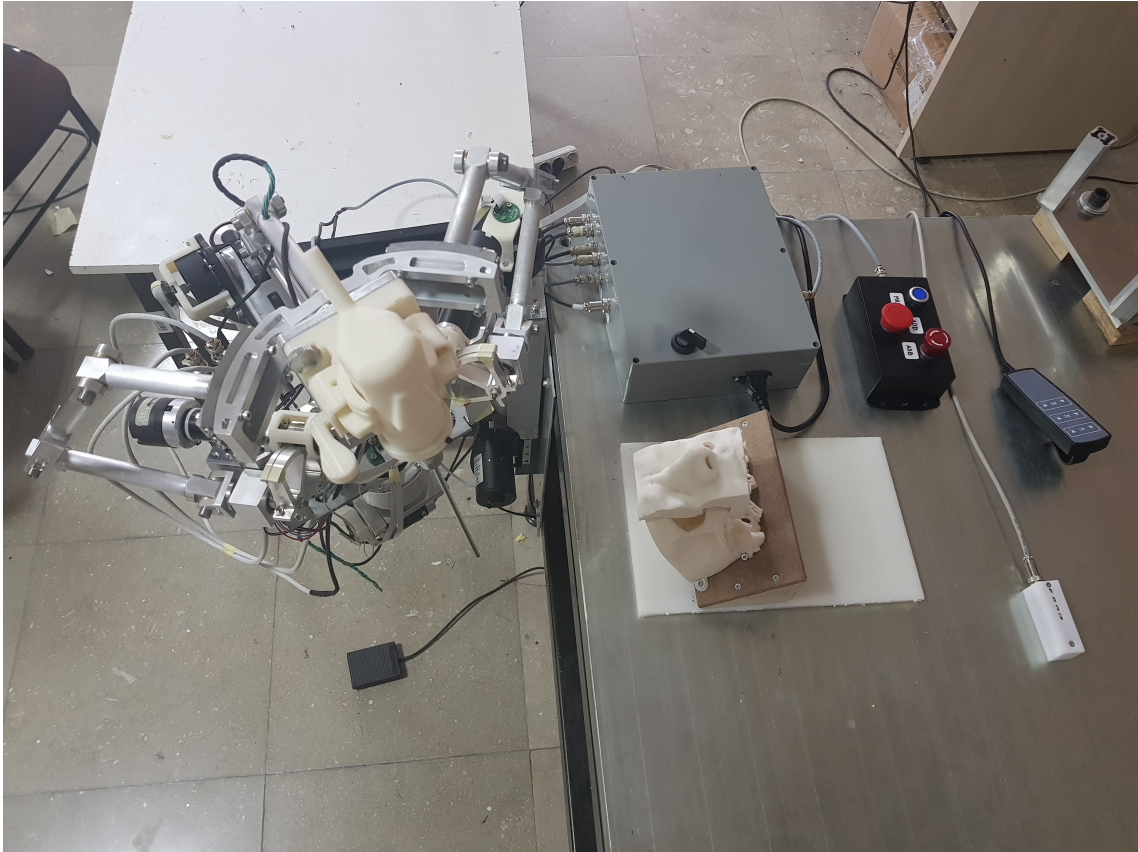


Figure 3.2. Top view of NeuRoboScope

3.1.1. Brief Introduction of the Subsystems

NeuroboScope system includes five main subsystems among which three of them compose the teleoperation system. The requirements of these systems have emerged from the work of the engineering and surgical team. According to the working principle of the system that should be (Dede et al., 2021);

1. The robot is active only in the surgical field. In this way, macro movements are performed by the surgeon and the surgery can continue faster and more safely.
2. When the robot is active, the surgeon should be able to use both hands actively and to control the robot as well.
3. At any time, the surgeon can physically hold the robot in the operation area and bring it to the desired position. It is a method that can be applied with the main control system in case of a problem encountered in the surgery or when the surgeon does not want to use the main control system.

4. The surgeon should be able to easily separate the endoscope from the robot at any time. In addition, if an angled telescope is used, the endoscope must be able to rotate the endoscope around the telescope axis while the endoscope is on the robot.
5. The surgeon must be able to cut off all the energy in the system in an emergency situation by an emergency switch.

Considering these requirements, the following subsystems have been used in the NeuRoboScope design;

1. Active Endoscope Holder (AEH): AEH is the active arm mechanism that holds the endoscope. Thanks to its mechanical design, it moves only around the determined pivot point. It is moved in three DoFs of motion by three motors. Movements are controlled by the surgeon sending motion demands through the master system. When the surgeon presses the pedal to activate the ring, information exchange is initiated and the measured orientation changes from the sensor inside the ring are sent to the controller by the communication system and the necessary driving signals are issued to the motor drivers that drive the motor.
2. Passive Balanced Arm (PBA): PBA is the balanced mechanical structure that carries the AEH. It is also used to mount the whole system to a fixed structure. The system can be moved via physical interaction of the surgeon when desired. In order to accommodate this, the brakes that keep the system fixed to earth must first be unlocked by activating the brake manual control button. When it is taken to the desired position as the surgeon back drives the PBA, it is fixed via the deactivating the brake manual control button which puts on the electromechanical brakes. In this way, the robot is placed in the operation area quickly and safely.
3. Communication System (CS): It provides communication between the ring and the main control unit via the Bluetooth interface. This information is only to be used when the pedal is pressed. Information about this communication system is given under the heading of teleoperation architecture.
4. Main Control Unit (MCU): This system that consists of a wearable ring and a foot pedal. It is master system which is the interface between the surgeon and the robot.
5. User Interface (UI): It is the control box with buttons for user interface that are required for safety and ease of use. Also, within the definition of UI, there is a visual indicator that uses LEDs to report the situation to the surgeon during the surgery.

3.2. Teleoperation Architecture

The NeuRoboScope system is a robot-assisted surgery (RAS) system that is controlled by teleoperation. This communication architecture is based on the master-slave system. The ring that is worn and controlled by the surgeon, works as a master system. On the other hand, the PBA and the AEH work as slave systems. However, just Active Endoscope Holder (AEH) is controlled by the master system (Dede et al., 2021). The system always requests information that includes the rotation angle and the rotation acceleration from the ring. But the information is only processed by the surgeon when the pedal is pressed. There are two pedals in the system. While the first pedal initiates rotational movements to the endoscope, the other pedal initiates the endoscope's linear movement along the pivot point. When the pedal is pressed, the brakes on the AEH are released and AEH is driven by three motor controllers according to the issued demands based on the data received from the ring. This demands are issued by calculating speed values for the received angular position data. So, if the surgeon performs a minimal movement and continues to press the pedal, the endoscope continues to move in the desired direction. In this way, the surgeon performs minimal motion while moving the endoscope by the ring. The ring prototype is shown in Figure 3.3 that includes Smartbond Development Kit and the body of the ring which is manufactured by a 3D printer. The development kit is a programmable controller including an internal measurement unit and Bluetooth communication. This ring, which acts as the master, is programmed to send data to the master controller by 100 times a second (100 Hz).

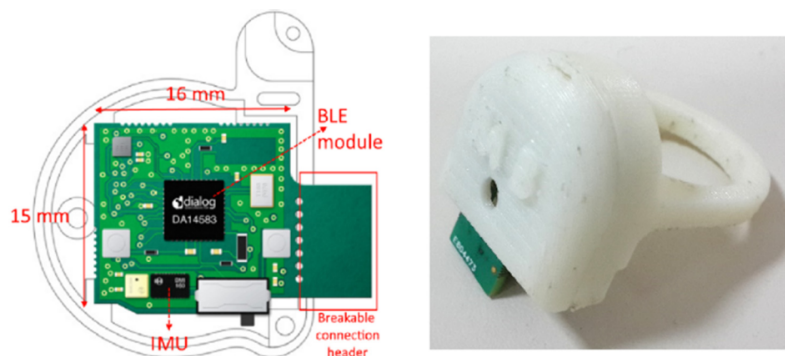


Figure 3.3. Smartbond Development Kit and the ring prototype
(Source: Dede et al. 2021)

Data from the ring is processed by the main controller. The processed data pro-

vides the movement by sending the necessary signals to the motor drives and other sub-systems. The detailed data stream and master-slave relationship are shown in Figure 3.4. Master-slave subsystems and communication lines are examined in the subheadings below.

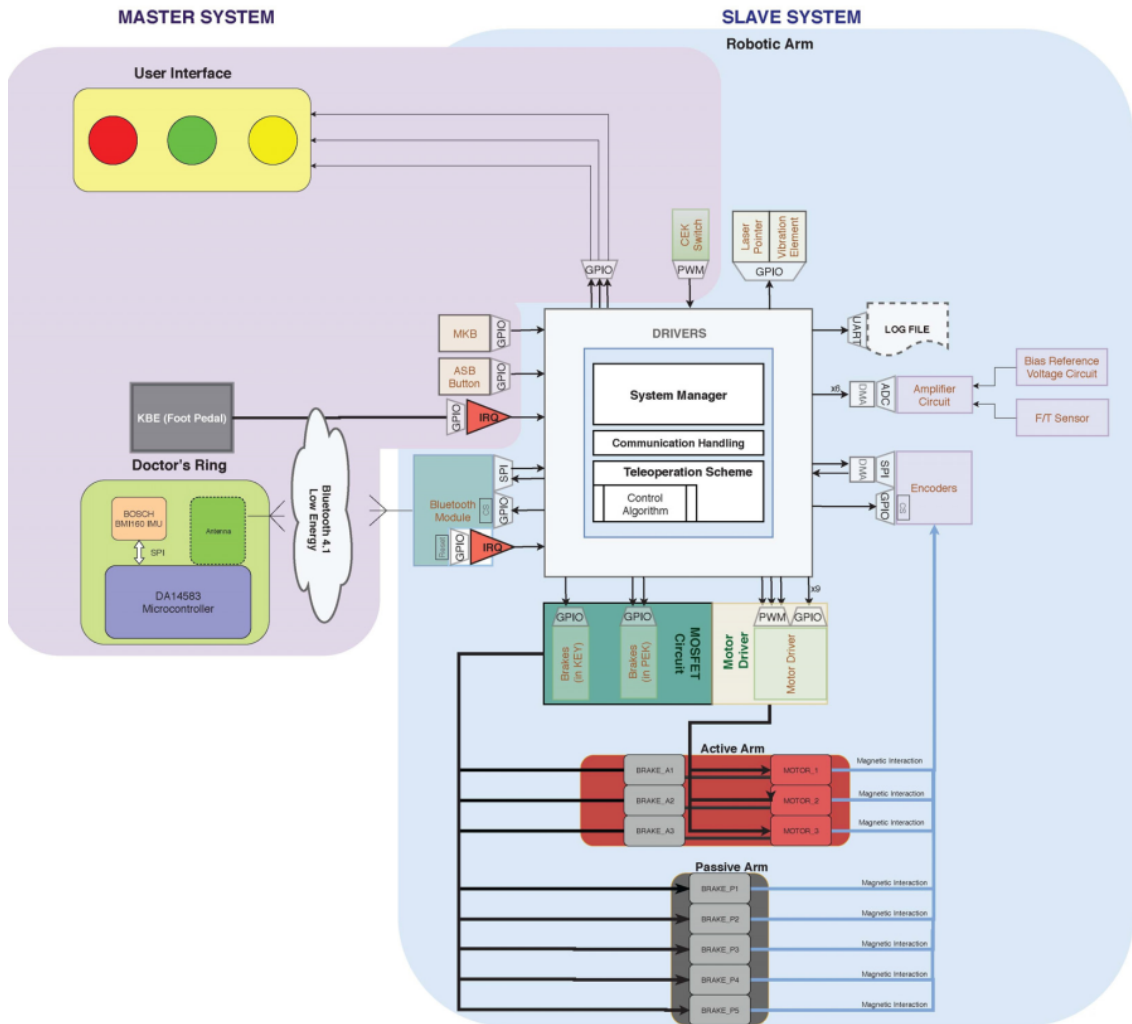


Figure 3.4. Information exchange between the NeuRoboScope’s master and slave sub-systems

(Source: Dede et al. 2021)

3.2.1. Master System Description

The master system of the NeuRoboScope system is mainly composed of the wearable ring and the foot pedal. However, this definition can be extended by including the Manuel Control Button (MKB), the Surgery Zone Button (ASB), and the Surgeon Holds

Endoscope (CEK) switch, to the definition of the master system. Detailed explanations of master system's components are given in the next sub-sections.

3.2.1.1. Controller Ring

The ring shown in Figure 3.3 is the main master component of the NeuRoboScope. This ring contains an inertial measurement unit (IMU) and sends the measured angular position data to the controller via a Bluetooth interface. These data are continuously processed as input by the controller, but the controller generates output only if the foot pedal is pressed by the surgeon.

3.2.1.2. Foot Pedal

The foot pedal is an essential system element that is a switch that can be pressed by the foot of the surgeon. The foot pedal used in the NeuRoboScope system consists of 2 switches. One of these switches activates the rotational movements of the AEH and the other switch activates the linear movement of the AEH. The foot pedal used in the system is shown in Figure 3.5. While the yellow pedal on the left activates the rotational movement in 2 axes, the blue pedal on the right activates the linear movement of the endoscope.



Figure 3.5. NeuRoboScope's foot pedal

3.2.1.3. Manuel Control Button

When the Manuel Control Button (MKB) is activated, the brakes on the joints of the PBS are disabled and the system is manually moved by the surgeon. This button is normally used to place the endoscope quickly in the operation area manually. When this button on the control panel is active, AEH cannot be controlled by motors according to the definition of the algorithm. The MKB is shown in Figure 3.2 and it is the blue button in the black box that is positioned on the right of the figure.

3.2.1.4. Surgery Zone Button

This button is used to define the surgery zone. When the button is pressed, the encoder values of the PBA are saved in the memory by the microcontroller. By using these values, the initial positioning of the AEH is done by the microcontroller.

3.2.1.5. Surgeon Holds Endoscope Information

Surgeon holds endoscope (CEK) is located on the quick-release system which is located between the tip of the AEH and the endoscope. CEK can be used in fully pressed mode to release the endoscope from the robotic system. In this case, a signal is issued to the system that the endoscope is not placed on the robot. CEK can be also pressed half-way to enable the manual rotation of the endoscope about its telescope axis. This is required in some situation when an angled telescope is used to view a larger area of the surgical workspace.

3.2.1.6. User Interface

The User Interface (UI) is a basic visual structure consisting of LEDs. This system aims to inform the surgeon about the safety force sensor condition, the ring connection status, and the position of the buttons. These situations are defined by using different colored LEDs.

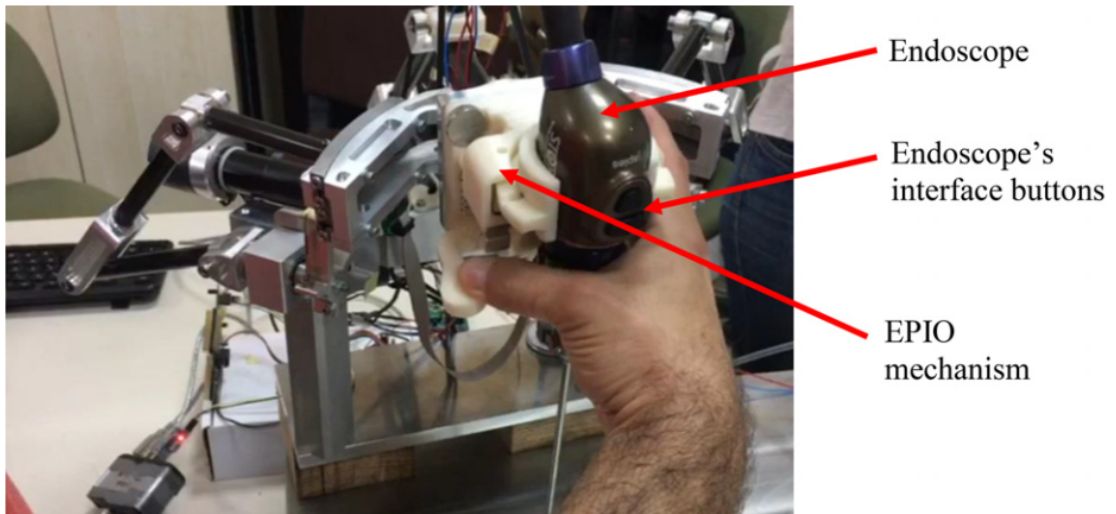


Figure 3.6. Endoscope quick release mechanism
(Source: Dede et al. 2021)

3.2.2. Slave System

The slave system of the NeuroboScope acts only according to the data sent by the master system. In the NeuRoboScope system, slave system is composed of PBA and AEH. These systems are controlled by the microcontroller according to the algorithm outputs determined according to received information from the master system.

3.2.2.1. Active Endoscope Holder

AEH is the slave system that is controlled by the teleoperation system. This system has 3 DoFs: 2 rotational DoFs and 1 translational DoF. The kinematic scheme of the AEH is given in Figure 3.7. AEH moves around the pivot point D. This feature, which makes this system an RCM robot.

3.2.2.2. Passive Balanced Arm

PBA is a statically balanced 6-DoFs mechanical structure carrying AEH. This structure, which is presented in Figure 3.8, is not controlled by commands that are calculated by using data received from the ring. However, this structure is controlled by

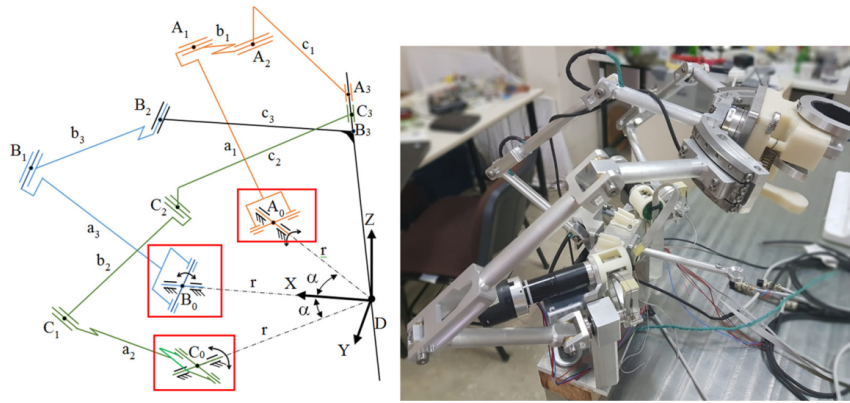


Figure 3.7. Kinematic architecture and prototype of AEH
(Source: Dede et al. 2021)

the surgeon manually. Therefore, it is defined as a part of the slave system. There are electromechanical brakes in the PBA system. When an electric current is applied to these brakes, the brakes are unlocked and the system is released from its fixed position. When the system is desired to be moved manually, MKB is activated by the surgeon and the brakes in the system are unlocked. In addition, when the system reaches the desired position, MKB is deactivated and the brakes are locked.

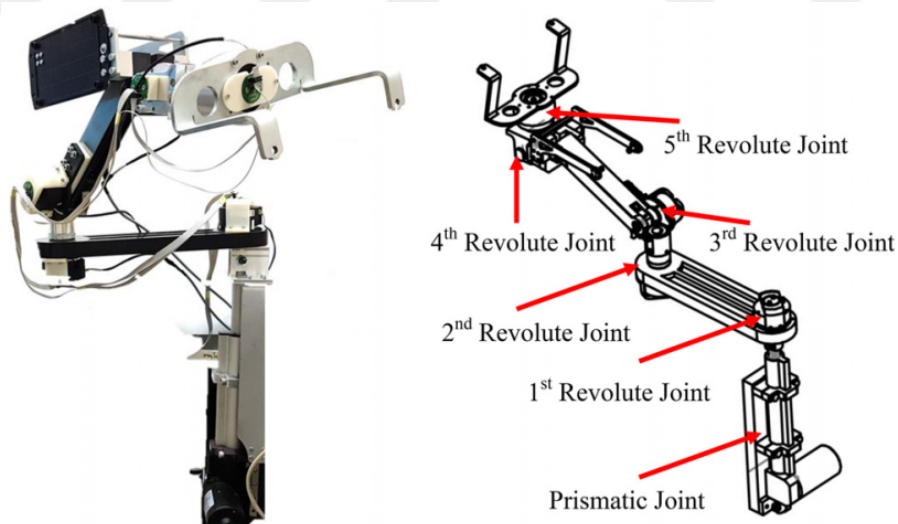


Figure 3.8. Computer aided design and prototype model of PEK
(Source: Dede et al. 2021)

3.2.3. Communication Line

The start of data exchange between master and slave systems starts with the activation of the Bluetooth interface between the ring and the microcontroller via pressing the foot pedal. The acceleration and gyroscope data measured from the ring are processed by the microcontroller in the ring and the data are sent to the microcontroller in the main system via Bluetooth interface. The system microcontroller decodes this data and converts it into usable values. Although the values are calculated, the controller does not send any signals to the motor drivers if the foot pedal is not pressed. The communication algorithm system model is given in Figure 3.9. in which data are transmitted from the ring at a frequency of 100 Hz. Incoming data is filtered by the microcontroller and noises are eliminated. The data is packed as a 1x30 array. When the data is decoded, a data set with 6 elements is formed. 3-axis gyro data and 3-axis acceleration data are processed according to the determined algorithm and instantaneous orientation information of the ring is generated. In addition to these wireless processes, wired lines where status information and operator controls are observed are also indirect parts of the teleoperation process. In terms of patient safety, the system activates all brakes and protects the patient in case of any connection problem. In such an unfavorable situation, the surgeon can manually remove the system from the patient and continue the operation without a robot.

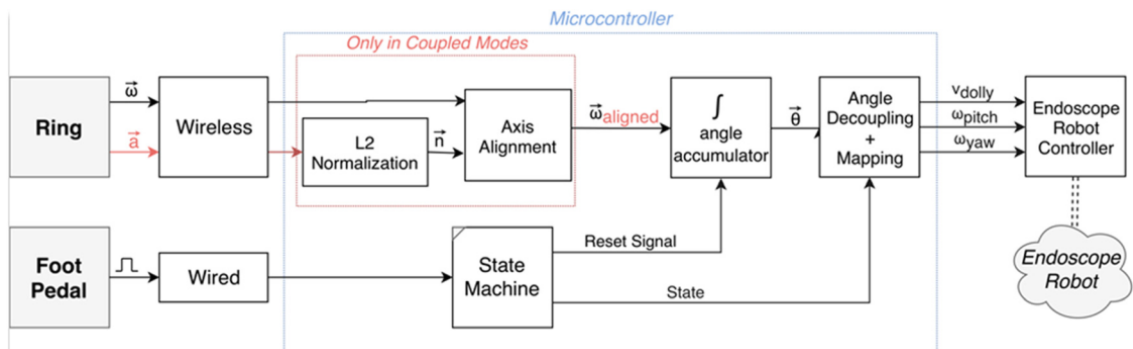


Figure 3.9. Information exchange of the teleoperation system
(Source: Dede et al. 2021)

3.3. Overview of the NeuRoboScope's Surgery Simulator v1

A simulator has been developed to train operators for the use of the NeuRoboScope system's teleoperation subsystem. This system includes the ring and foot pedal,

which are the most important parts of the master system in the control of the NeuRoboScope system. In this system, the virtual representation of the AEH of the NeuRoboScope is controlled by the ring. The gyroscope and accelerometer data from the IMU and the status information of the user received from the foot pedal are processed by the microcontroller and information flow is provided to the computer environment by using the serial port interface. The flow diagram that is shown in Figure 3.10 is utilized to facilitate the explanation.

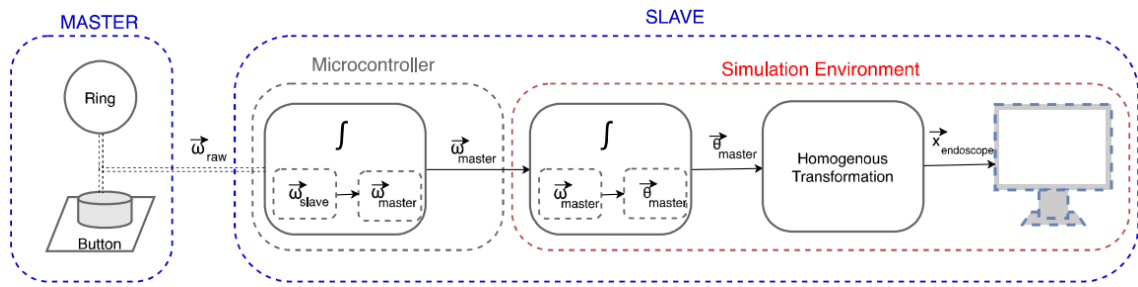


Figure 3.10. Information flow between master and slave system of the NSSv1
(Source: Ateş 2018)

The visual feedback of this simulator does not contain any surgical images or surgical tools. However, while using the simulator, the operator physically holds the surgical tool on the skull mock-up in accordance with the surgery scenario as shown in Figure 3.12. The data starts to be processed when the pedal is pressed. The grey ball is controlled by the movement of the ring. The change in diameter of the ball simulates the linear motion of the actuator, and the change in position simulates the rotational motion of the actuator. The grey ball is to be brought to the targeted yellow ball via pressing the pedal and moving the ring in the appropriate way and then the grey ball's diameter should be adjusted to match the diameter of the yellow ball. When this is done, the color of the ball turns green and the next task is activated by changing the color of a red ball to yellow. While an operator trains with this simulator, the number of pedal activities and the time to complete the task are recorded. In this way, the improvement in the ability of operators to use the NeuRoboScope's teleoperation system is assessed. The results of this simulator in learning and improving the use of the teleoperation system of the NeuRoboScope were shared previously by Ateş (2018).

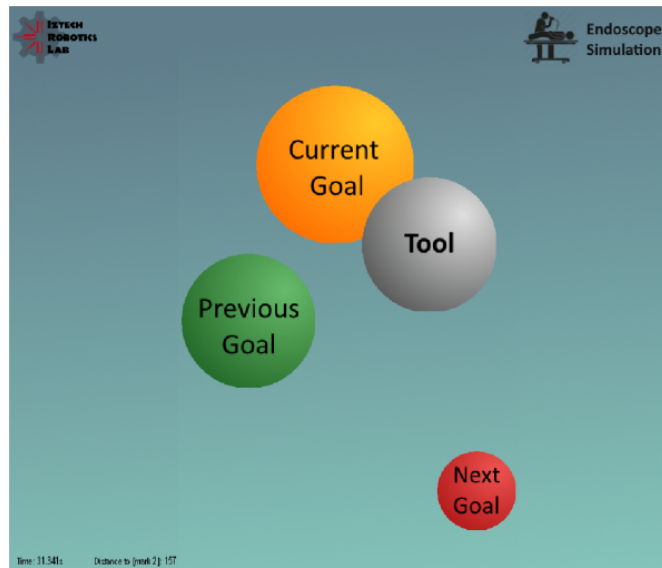


Figure 3.11. Visual from NSSv1's Scenerio (Source: Ateş 2018)

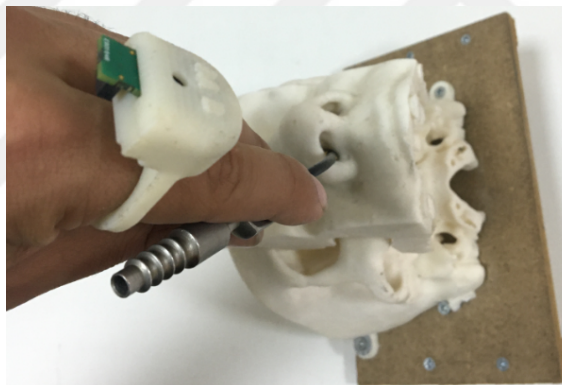


Figure 3.12. Ring wearing pose and surgical tool holding while traning on software

When the comments and test results of the surgeons are evaluated, it is concluded that NSSv1 should have a realistic user interface and should be a method of use that includes more comprehensive surgery conditions. In this context, while designing NSSv2, it was aimed to include surgical instruments in the simulation environment by using haptic devices and to make a realistic user interface. In Chapter 4, the NSSv2 system is explained in detail.

CHAPTER 4

DESCRIPTION OF THE NEUROBOSCOPE'S SURGERY SIMULATOR V2

In this chapter, the software and hardware architecture of version 2 of NeuRoboScope's Surgery Simulator (NSSv2) is explained in detail. The main purpose of the development of this simulator is to train the surgeons to use the NeuRoboScope in surgery conditions. Virtual representations of two surgical instruments, the endoscope view, and the teleoperation algorithm of NeuRoboScope are created to simulate the operating conditions. Two haptic devices are physically controlled by the hands of the surgeon. These haptic devices replicate the surgical tools in an actual surgery and the tool position and orientation data are issued as the motion of virtual representations of the surgical instruments in the virtual reality scene. The visual feedback that is acquired by the endoscope in a real surgery is generated in the virtual reality environment and the displayed view of the surgical area changes according to the motion demands issued by the NeuRoboScope teleoperation algorithm. The master systems of the NeuRoboScope, the ring that enables the surgeon to control the NeuRoboScope system and the foot pedal that activates the control, are included in the simulator as the hardware. By this way, the surgeon is able to gain experience in operating conditions while training with the simulator, and NeuRoboScope training is carried out in the closest possible way to real conditions. In addition, thanks to the calibration mode created specifically for the NeuRoboScope ring, surgeons can customize the teleoperation algorithm according to their usage preference. The details of these systems and their integration are explained in the next sections.

4.1. Description of the Framework of the NSSv2

The NSSv2's hardware consists of 2 Phantom OMNI haptic devices, NeuRoboScope's controller ring, foot pedal, STM32 Nucleo developer board, a PC, and a monitor. Haptic devices are used to control virtual surgical tools within the virtual reality screen of NSSv2. The data acquired from the ring is used for controlling the virtual model of the endoscope according to the teleoperation algorithm of the NeuRoboScope system. STM32 Nucleo microcontroller is used to process the data received from the ring and foot pedal

and it sends this data to the PC. The communication structure between the systems is presented in Figure 4.1. MATLAB software is used to process the data received by the PC. The Simulink is used performing the necessary mathematical operations. In addition, the VR Sink block, a block available within the 3D Animation toolbox of Simulink, is used for creating the virtual reality environment. The data received by the PC and processed by the Simulink model is the input to the virtual reality block and the visual interface screen of NSSv2 is formed as an output from the virtual reality block. A physical input by the user via the master system affects the simulation's output which is the endoscope view in real time. In this way, the user performs the determined tasks by monitoring the virtual reality interface screen and completes training.

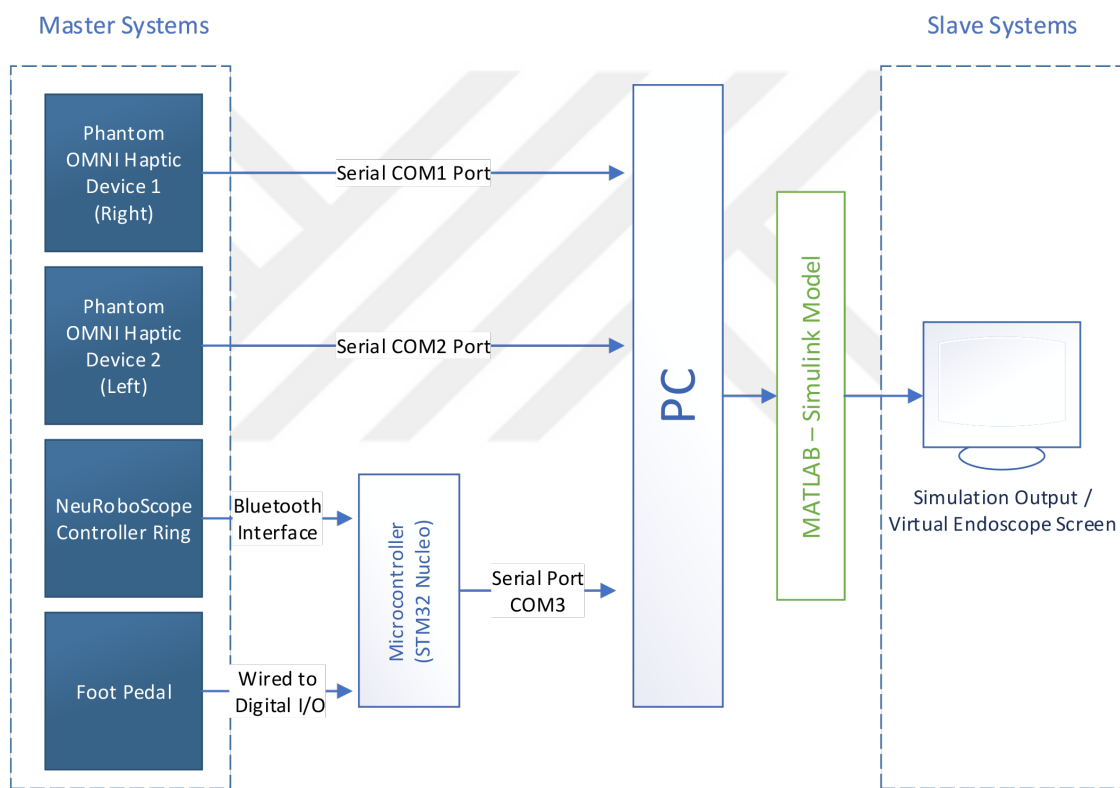


Figure 4.1. General system structure of NSSv2

4.2. Master Systems of NSSv2

The interaction between the surgeon and NSSv2 takes place via master systems. The master systems that are used for controlling the motion of the virtual surgical tools are 2 Phantom OMNI haptic devices. The master systems used for controlling the endoscope

view are the ring with the IMU and the foot pedal. The detailed information on how these master systems are used are explained in the next sub-sections.

4.2.1. Phantom OMNI Haptic Device

The Phantom OMNI haptic device is a 6 DoF robot arm and it has a stylus as its end-effector (Figure 4.2). The operator holds onto this stylus and moves it in 6 DoF to replicate the motion of a surgical tool during the surgery. In real-time, this device acquires the motion information of the stylus and sends it to the NNSv2 software developed in Matlab. In this way, the virtual surgical tools' motion is controlled in the virtual reality screen. However, in NNSv2, it is not aimed to provide haptic feedback to the operator. Therefore, the haptic feedback capabilities of these haptic devices are not used in this study.

It is necessary to determine the locations of the haptic devices in order to match the standing position of the surgeon during the surgery. To ensure that, a wooden plate is manufactured on which the haptic devices and the skull-mock up are positioned and used as presented in Figure 4.3. The haptic devices' positions that are the most suitable for the working area is chosen according to the surgeon's hand movements and skull-mock up position. The placement of haptic devices and skull-mock up on the plate is presented in Figure 4.4.

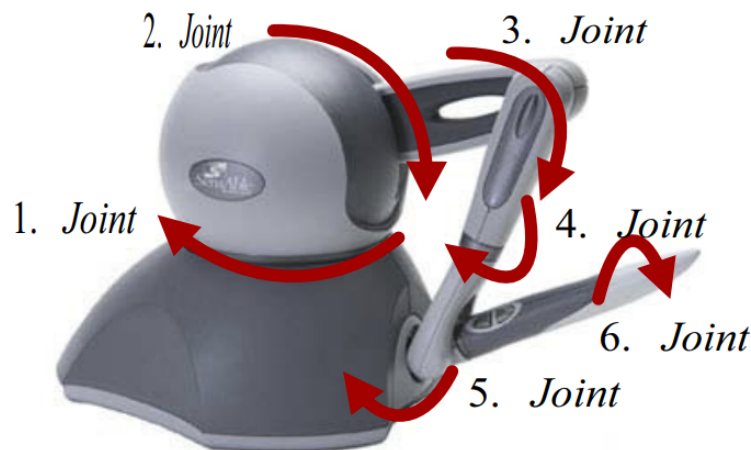


Figure 4.2. Phantom OMNI Haptic Device's Axes of Rotation
(Source: Soyguder and Abut 2016)



Figure 4.3. Reference settlement plate and its 2D design



Figure 4.4. Haptic devices and skull-mock up positions on the plate

4.2.1.1. Forward Kinematics of Phantom OMNI Haptic Device

To find the stylus orientation of the haptic device with respect to base frame, forward kinematic formulation is used. The joint variables of the haptic device are showed in Figure 4.2. In Table 4.1, rotational parameters of the Denavit-Hartenberg convention for the Phantom-Omni device is derived. Equation 4.1 is derived for a single link's orientation calculation. The orientation of the stylus is calculated via Equation 4.2. The transformation matrix, $\hat{C}^{(0,6)}$, is then used for calculating the Euler angles for X-Y-Z Euler sequence to represent the orientation information in terms of Euler angles.

Table 4.1. Denavit-Hartenberg Table for Orientation of End-effector

Joint number(i)	Relative rotation of Link(i) with respect to Link ($i-1$) θ_i	α_i
1	Joint variable: θ_1	$+\pi/2$
2	Joint variable: θ_2	0
3	Joint variable: θ_3	$+\pi/2$
4	Joint variable: θ_4	$-\pi/2$
5	Joint variable: θ_5	$-\pi/2$
6	Joint variable: θ_6	0

$$\hat{R}_z(\theta_i)\hat{R}_x(\alpha_i) = \begin{bmatrix} \cos\theta_i & -\sin\theta_i\cos\alpha_i & \sin\theta_i\sin\alpha_i \\ \sin\theta_i & \cos\theta_i\cos\alpha_i & -\cos\theta_i\sin\alpha_i \\ 0 & \sin\alpha_i & \cos\alpha_i \end{bmatrix} \quad (4.1)$$

$$\hat{C}^{(0,6)} = \hat{R}_z(\theta_1)\hat{R}_x(\alpha_1)\hat{R}_z(\theta_2)\hat{R}_x(\alpha_2)\dots\hat{R}_z(\theta_6)\hat{R}_x(\alpha_6) \quad (4.2)$$

4.2.2. The NeuRoboScope System Controller Ring and The Foot Pedal

In the NSSv2, just as in the NeuRoboScope system, the function and operation algorithm of the ring and foot pedal are the same. The ring's IMU is used for acquiring the orientation of the ring which controls the movements of the endoscope created in the virtual environment and the foot pedal activates the information exchange of the ring. The structure and operating system of the ring and foot pedal are described in section 3.2.

4.2.2.1. Processing The NeuRoboScope Controller Ring Sensor Data

The angle data obtained from the IMU is measured relative to the earth frame. In order to represent the rotation angles at the frame fixed to the ring, earth frame rotation angles need to be transformed to ring frame rotation angles. Basic rotation matrices are used to achieve this transformation. The following three basic rotation matrices given in Equation 4.3 rotate vectors by an angle θ about the x-, y-, and z-axis with respect to the right-hand rule.

$$\hat{R}_x(\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix} \quad \hat{R}_y(\theta) = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \quad \hat{R}_z(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (4.3)$$

The rotation matrix given in the Equation 4.4 defines the orientation of the ring frame with respect to the earth frame that is measured when the foot pedal is pressed. Hence the orientation of the ring frame at that instant is identified as is and the earth frame is denoted as e .

$$\hat{C}^{(e,is)} = \hat{R}_x(\theta_x^{is}) \hat{R}_y(\theta_y^{is}) \hat{R}_z(\theta_z^{is}) \quad (4.4)$$

Using the same method, the rotation matrix given in the Equation 4.5 defines the orientation of the ring frame at time t respect to the earth frame.

$$\hat{C}^{(e,ts)} = \hat{R}_x(\theta_x^{ts}) \hat{R}_y(\theta_y^{ts}) \hat{R}_z(\theta_z^{ts}) \quad (4.5)$$

The rotations executed at ring frame between any two states (is to ts) can be calculated by using the Equation 4.6. For example, the amount of rotation matrix between the two states in Figure 4.5 is obtained using Equation 4.6. To calculate the Euler angles representing the rotation between two states, the rotation matrix obtained in Equation 4.6 is used for the Euler XYZ sequence resolution.

$$\hat{C}^{(is,ts)} = \left(\hat{C}^{(e,is)} \right)^{-1} \hat{C}^{(e,ts)} = \hat{C}^{(is,e)} \hat{C}^{(e,ts)} \quad (4.6)$$

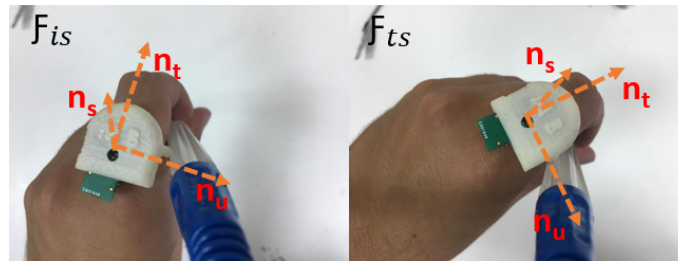


Figure 4.5. Example ring frames between any two states

4.2.3. Defining Ring Frames for each Surgeon

Depending on how the ring is worn by the surgeon the data acquired from the ring would be different for the same motion achieved by the surgeon. Therefore, for each surgeon depending on their preference of wearing the ring, a new frame for measurement has to be defined. The ring's original frame of measurement is shown in Figure 4.6 in yellow. The motion of the endoscope is accomplished with respect to the frame identified with green color on Figure 4.6. The aim is to modify the yellow frame to a preferred frame of motion and measure the motion of the ring with respect to the axes of this preferred frame. The next sub-sections describe the procedure on how to determine the preferred frame's axes and how this information can be used in the control of the NeuRoboScope system.

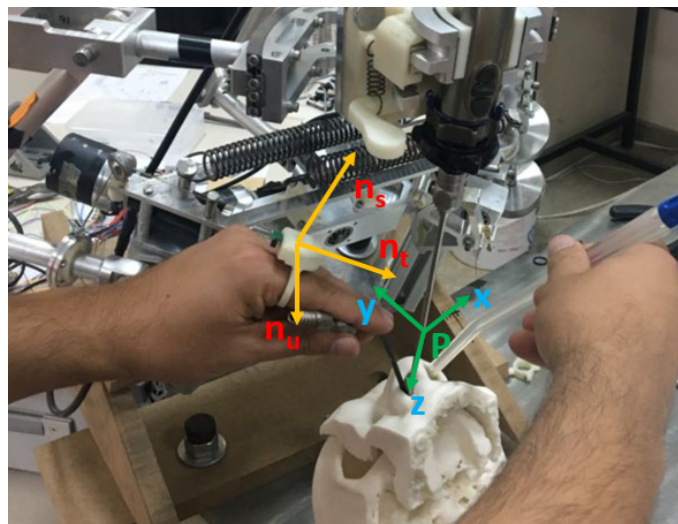


Figure 4.6. Original frame of the controller ring (yellow) and the frame on which the endoscope's motion is defined (green)

4.2.3.1. Defining Axis Frame of User-Specified Mode

The following steps are applied to define a user-specified axis frame which is actually the preferred frame in which the user moves the ring while moving up-down and right left:

1. Find the first axis of preferred frame while the user moves the ring sideways (left to right). As the user presses the pedal, the initial orientation of the ring is recorded as $C^{(e,ts)}$ and the final orientation is $C^{(e,ts)}$ is recorded when the foot pedal is released. The motion in between these two frames is calculated using Equation 4.6. Then by using the Rodrigues' equation which is denoted in Equation 4.7, \vec{n} is calculated.
2. Find the second axis of preferred frame while user moves the ring upwards. The same methodology in part 1 is used to identify \vec{n}_u this time.
3. These 2 axes will may not be perpendicular in real caseto each other. Then, we can find the perpendicular vector by $\vec{n}_t = \vec{n}_s \times \vec{n}_u$.
4. Find the angle ψ between \vec{n}_s and \vec{n}_u .
5. Then, find the angle $\alpha = (90^\circ - \psi)/2$
6. Rotate \vec{n}_s and \vec{n}_u amount of α and $-\alpha$ about \vec{n}_t respectively. Consequently, these new \vec{n}_s and \vec{n}_u will be perpendicular to each other.

$$\hat{C}^{(is,ts)} = \hat{R}n_s(\theta_s) = \hat{I}cos\theta_s + \tilde{n}_s sin\theta_s + \vec{n}_s \vec{n}_s^t (1 - cos\theta_s) \quad (4.7)$$

An example of the mentioned preferred axis assignment procedure is represented in Figure 4.7. First, the user performs the desired movement to shift the endoscope image up. Afterwards, the user performs the desired movement to shift the image to the right. After these processes, a user-specified axes frame is defined using the algorithm defined above.

After the preferred frame is identified, the transformation matrix between the earth frame (e) and the preferred frame (pf) can be formed as follows: $C^{(e,pf)} = [\vec{n}_s \ \vec{n}_u \ \vec{n}_t]$ where \vec{n}_s , \vec{n}_u and \vec{n}_t are the column vectors of \vec{n}_s , \vec{n}_u and \vec{n}_t expressed with respect to earth frame (e), respectively.

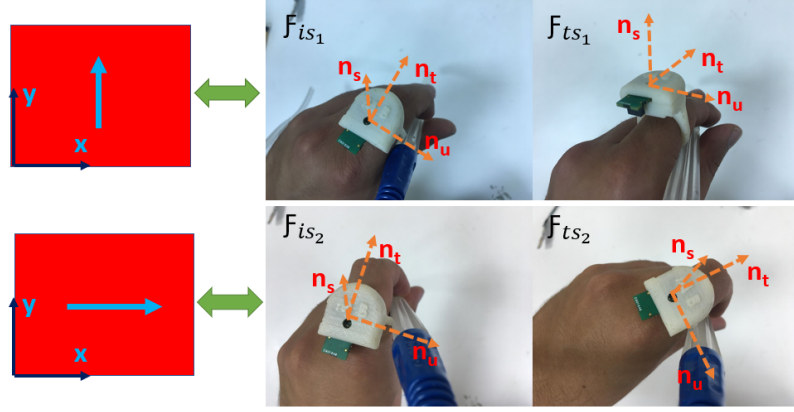


Figure 4.7. Example of defining user-specified axis frame process

4.2.3.2. Issuing Control Signal Based on Measurement Obtained from the Ring

Two modes that are used in the NSSv2 system are 2D-Coupled (2DC) mode and user-specified frame (USF) mode. In 2DC Mode, the original ring frame is used for calculating the motion demands to be sent to the NeuRoboScope system's slave robot.

In 2DC mode, the relative motion between the time when the foot pedal is initially pressed and time t is converted to the Euler angles using the original frame attached to the ring as follows: $\hat{C}^{(is,ts)} = \hat{R}_x(\theta_x)\hat{R}_y(\theta_y)\hat{R}_z(\theta_z)$ and angles calculated about X and Y axes $((\theta_x),(\theta_y))$ are directly used as motion demands. However, in USF mode, the measured orientation change information of the ring $\hat{C}^{(is,ts)}$ is rotated to the preferred frame using Equation 4.8. Then, the related Euler angles $((\theta_s),(\theta_u),(\theta_t))$ are calculated and $(\theta_s),(\theta_u)$ are used as input command to be sent to the NeuRoboScope's slave robot.

$$\hat{C}^{(pf,e)}\hat{C}^{(is,ts)}\hat{C}^{(e,pf)} = \hat{R}_x(\theta_s)\hat{R}_y(\theta_u)\hat{R}_z(\theta_t) \quad (4.8)$$

4.3. Integration of the NeuRoboScope's Master System to the Surgical Simulator

In the NeuRoboScope system, the ring and foot pedal are directly connected to the main controller of the system. Therefore, these systems are not suitable for direct connection with a computer. An interface has to be created to obtain the data of these

systems by the computer. STM32Nucleo developer board, which is a type of arm microcontroller, is used to establish this communication line. The ring is connected to the microcontroller via Bluetooth, and the foot pedal is wired to the digital port of the microcontroller. The controller processes the data from the ring and pedal and outputs the data from the serial port. TTL-USB converter module (PL2303) has to be used to ensure compatibility between microcontroller serial port and computer USB port. Components of the communication interface are presented in Figure 4.8. The TTL-USB converter is shown with the green circle, the foot pedal connection is marked with the red circle, and the STM32Nucleo is denoted by the blue circle in the figure. These data received by the computer are processed within the simulation software developed in Matlab, and thus the master system of the NeuRoboScope system is integrated into the NSSv2.

4.4. Virtual Reality Scenario Generation

The virtual reality screen of NSSv2 is created by using the MATLAB Simulink. In this software, a third-party product called the QUARC library, which is the library that contains the interface for Phantom OMNI Haptic Device, is used. The serial port interface connection of this library is used for communication with the ring and the VR Sink tool within the 3D Animation toolbox of Simulink is used for creating the virtual reality environment. In the following sections, the data flow between the systems, the software structure of NSSv2, and the generation of the virtual reality screen are explained.

4.4.1. Information Flow Between Master and Slave Systems

In NSSv2, data is received from the master system, and these data are processed in the Simulink model to create an input for the slave system. As presented in Figure 4.9, data from haptic devices, ring and pedal are transferred to the computer running the simulation via Serial (USB) ports. The ring and foot pedal are not directly connected to the computer. The data incoming from the ring and pedal are transferred to the computer by the microcontroller via serial port. The microcontroller does not process the data, it sends it to the computer in an array form. Phantom devices also send data to the computer in an array form. 6 joints' position data is received by the computer and thus, input signals are issued to the simulation program developed in MATLAB. Angular position data from haptic devices are fed directly to the haptic device model created within the VR Sink tool.

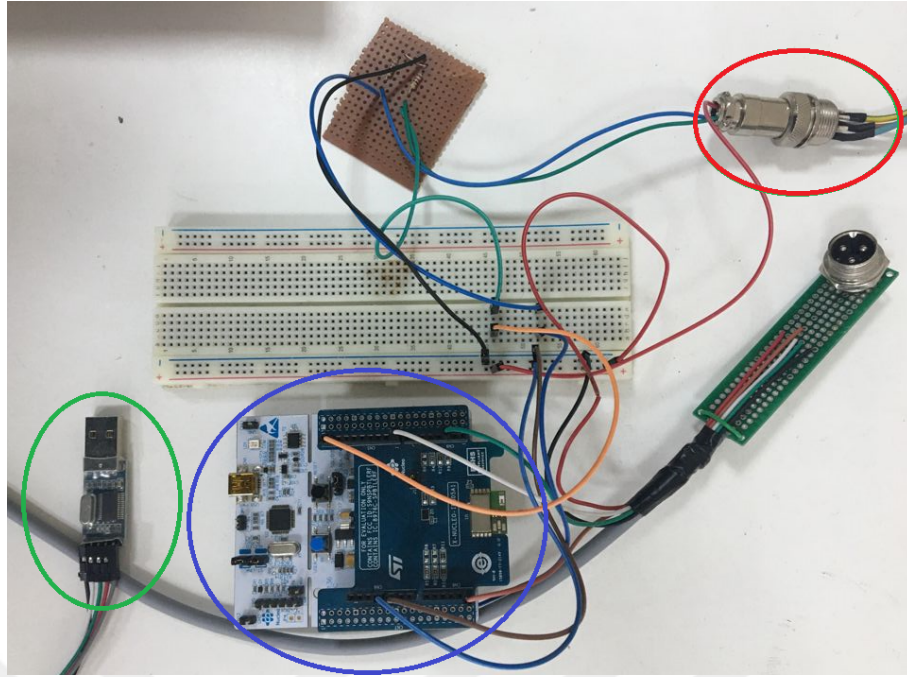


Figure 4.8. Communication interface system between NeuRoboScope’s master system and computer’s USB port

Since the model created matching the dimensions of the reference plane where the haptic devices are located, it exactly matches the real environment. Thus, no transformation is applied in the Simulink model. Ring and foot pedal data from the microcontroller have to be processed by the Simulink model to obtain usable data. This process includes data encoding and filtering. As a result of this process, a 3x1 array is created according to the received ring data. These data correspond to the motion demand for the AEH handling the endoscope in the NeuRoboScope system. By combining 2 haptic devices and these data, a 15x1 array is created and issued into the VR Sink simulation model.

4.4.2. Slave System’s Model

The NSSv2 system does not contain any physical slave systems. Slave systems in the simulator are created in the software. The interface seen in Figure 4.10 is created in the VR Sink tool. Figure 4.10 shows the haptic device models and the NeuRoboScope system’s endoscope equivalent model within the virtual reality screen. The endoscope model can make 2 rotational and 1 linear movements about a pivot point as in the NeuRoboScope system. Haptic devices are modeled using their actual dimensions with 6

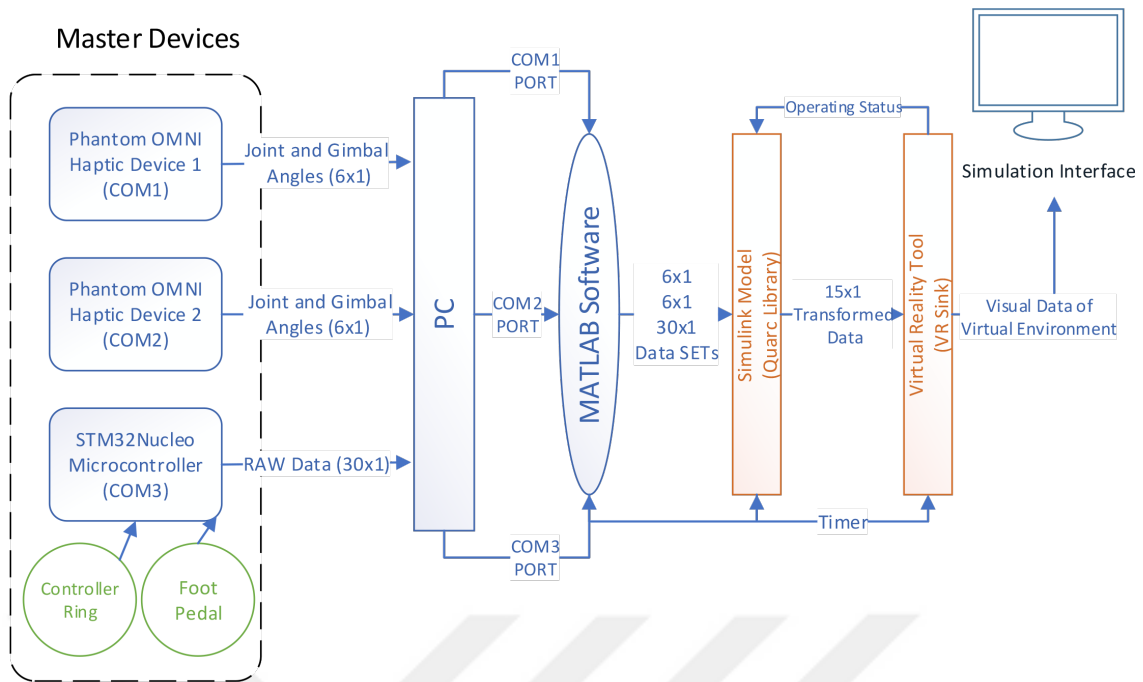


Figure 4.9. Information flow from the input devices to the Matlab model of the NSSv2

DoFs.

4.4.3. Generation of the Virtual Reality Screen

A virtual reality screen is created in a virtual environment by placing a 2D surgical endoscope image taken from a surgery placed at suitable viewing angle of the endoscope's model. The light blue rod on the left in the upper part of Figure 4.11 is the endoscope's model. In the upper part of the figure, a zoomed-out image is used to explain the system operation by showing the endoscope's and haptic devices' models. When the viewing angle is taken to the tip of the endoscope model (this is the view point during a surgery), the screen of the simulation shown at the bottom figure is formed. The 2 blue rods are the models of surgical instruments controlled by a haptic device. Consequently, NSSv2's screen is obtained in a virtual environment.

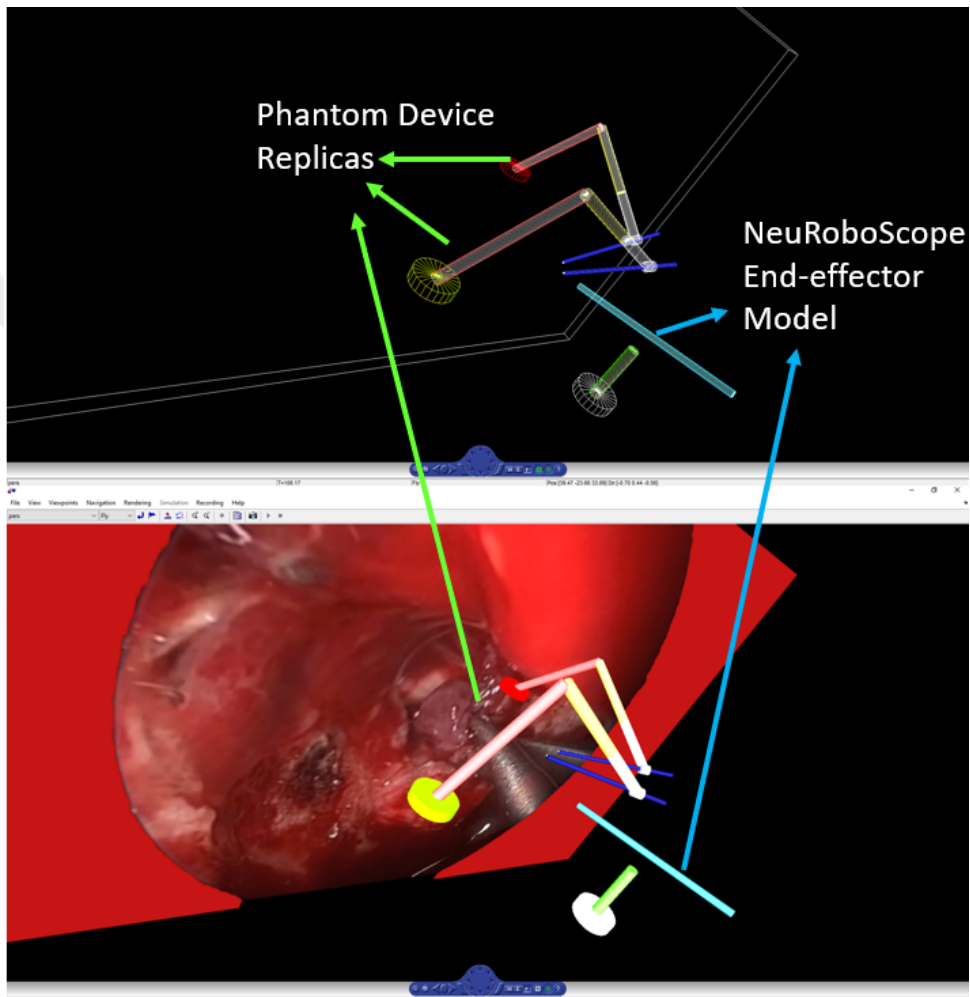


Figure 4.10. Slave system structure of NSSv2

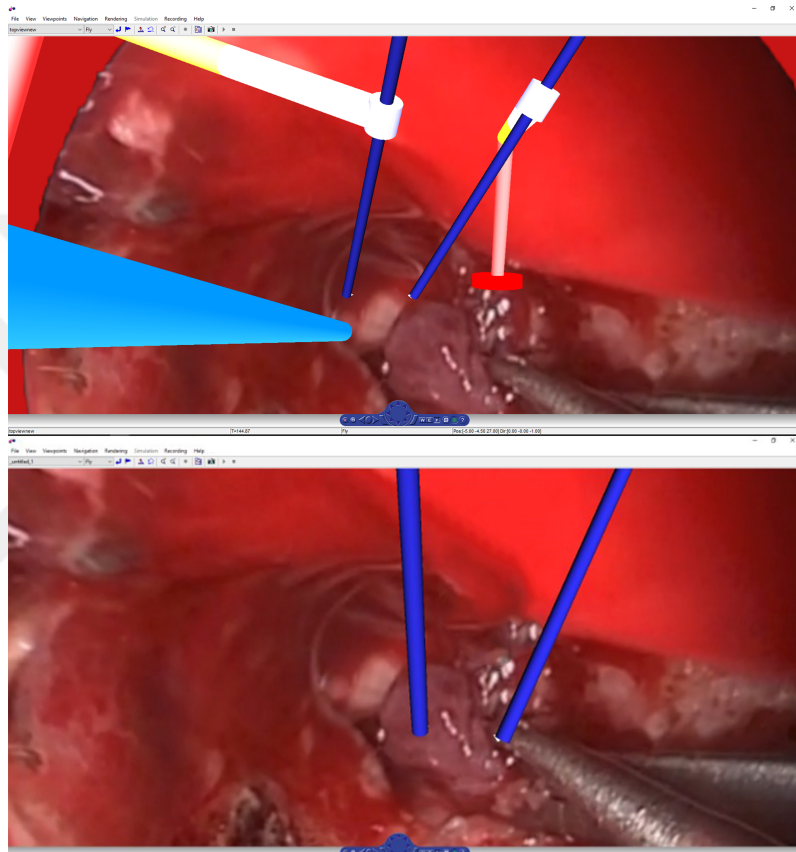


Figure 4.11. (top image) Position of endoscope and haptic devices' models (bottom image) the view from the tip of the endoscope with surgical instruments in blue color

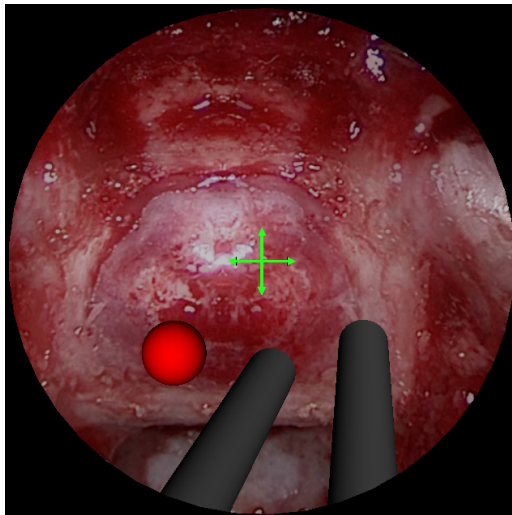
CHAPTER 5

DESIGN OF THE USER TESTS AND TEST RESULTS

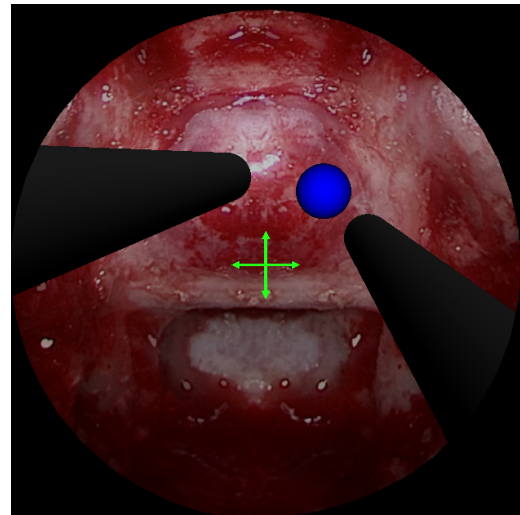
5.1. Task Definitions of the Tests

The aim of the user tests is to evaluate the ease of use of the two distinct methodologies in processing the data acquired by the IMU in the wearable ring. Tasks are designed within the simulator software giving indications of the expected motion of the endoscope via the virtual reality screen. Two double-sided green arrows that are perpendicular to each other are fixed to the middle of the endoscope screen. As the endoscope view is changed the location of these double sided arrows maintain their position at the middle of the screen. The location to be reached is identified by a blue or a red sphere. The user is commanded to move the double-sided arrows in the middle of this sphere. The color of the sphere identifies the depth of the sphere. The user is commanded to move in the screen if the sphere's color is blue and move out the screen if the sphere's color is red (Figure 5.1). If the user reaches the correct depth the sphere's color turns to green. The aforementioned motion is actually the motion of the NeuRoboScope systems AEH in three DoFs and the information acquired from the ring is used for generating these motion demands.

When the user moves the screen view to the defined depth and the double-sided arrows to the middle of the sphere, the sphere disappears and this indicates that the first part of the task is completed. Then, at a different location in the surgical zone, a new sphere appears indicating the second part of the task. In total, there are 3 parts for each task and 10 different tasks are defined in which the locations of the spheres are different but the amount of parts are the same. In this way, it is aimed to observe the learning curve of the users as they complete 10 distinct tasks.



(a) Zoom out and focusing scenario



(b) Zoom in and focusing scenario

Figure 5.1. Scenarios displayed on the virtual reality screen of the simulator

5.2. Procedures for Using the Simulator

Here, the user is defined as the test subject. The procedure for using the NSSv2 simulator is defined as:

1. The task is explained to the user.
2. The test subject wears the controller ring on his/her finger.
3. For the user-specific mode, the calibration process is carried out to identify the test subject's preferred axes.
4. The test subject holds the haptic devices in the way that the surgical instruments are handled and positioned on the skull mockup on top of the nose tip.
5. The foot pedal is positioned at a suitable location as desired by the test subject.
6. The scenario starts when the foot pedal is pressed.

The test scenarios are completed by using haptic devices, the foot pedal, and the ring and recording the data collected from these devices. The photograph that is taken during the use of NSSv2 is shown in Figure 5.2.

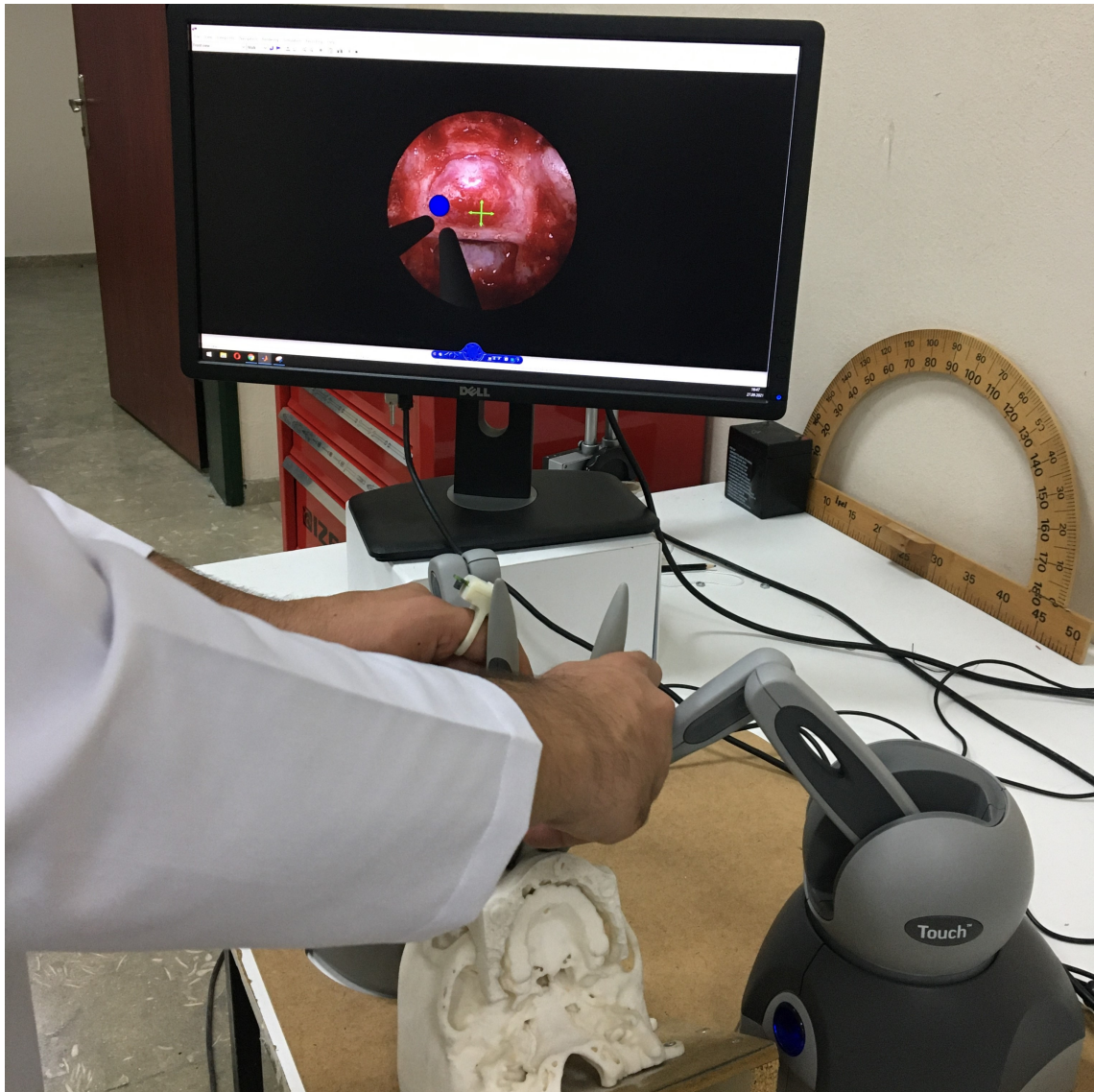


Figure 5.2. A visual from NSSv2 experience

5.3. Definitions of Success Criteria

While the test subjects carry out the tasks, measurement signals are acquired from the ring's IMU, haptic device that is held by the test subject's hand wearing the ring and the foot pedal. Based on these signals, virtual reality feedback is displayed on the monitor and three important aspects for evaluating the success of the test subjects are calculated: (1) task completion duration, (2) total amount of foot pedal press by the test subject, (3) the total motion of the virtual surgical tool that is handled by the test subject's hand wearing the ring while the pedal is pressed.

The task completion duration indicates the ease of use of the master system com-

posed of the ring and the pedal. Since there are 10 repetitions with each method of processing the ring's measurements as motion demand, it is possible to observe the learning curve of the test subjects.

Total amount of foot pedal provides the indication of the test subject's effort while using the master system. If the pedal press count is more, this indicates that the endoscope control was not trivial and the test subject had to stop the motion and restart the motion. Similar to the task completion duration, it is expected that as the test subjects have more experience with the system, the pedal press count may be less than the initial trials. Hence, the results of press counts with 10 trails indicate the learning curve as well.

The aim of the NeuRoboScope system is to enable the surgeon to control the endoscope's motion with minimal distraction from the surgeon's main task. Therefore, it is aimed to move the surgeon's hand wearing the ring in the minimal amount so that the surgical procedure is not affected during this event. Accordingly, the total motion of the virtual surgical tool that is handled by the test subject's hand wearing the ring while the pedal is pressed is an important outcome of the tests.

Overall, the success criteria are based on these three aspects and the learning curve observed based on these aspects.

5.4. Assessment of the Test Results

The data obtained as a result of the NSSv2 tests are evaluated. Five graphs are created in order to observe the success of the test subjects based on the obtained data. Figure 5.3 and Figure 5.4 show the task completion durations of the test subjects in 2D-Coupled mode and User-Specified mode, respectively. According to these graphs, as the test subjects perform more repetitions, the task completion duration decreases. The learning curve is steeper for the 2D-Coupled mode. In order to evaluate the test results of both modes, the graph in Figure 5.5 is developed. This graph displays the average values of the task completion duration of test subjects at each repetition. In both modes, the task completion duration converges to the vicinity of final value after 5 repetitions. After 5 repetitions the task completion durations obtained with both modes is similar but the performance obtained with the User-Specific Frame mode is slightly better.

The foot pedal is used for to activate control of ring. When the desired direction and amount of movement cannot be achieved comfortably, the number of pedal uses increases. Figure 5.6 presents the graph for the number of pedal activities recorded during tests with both modes. A similar result is observed from this graph relative to the task

completion durations. Initially, it is harder for the test subject to use the 2D-Coupled mode relative to the User-Specific Frame mode. After some repetitions, the number of total pedal activities is recorded to be almost the same for both modes. A difference is observed between the types of pedal used. The number of pedal activity to move the endoscope inside and outside in both modes is the same throughout the tests for both modes.

The mean value of the total rotation of the surgical instrument around the pivot point when the foot pedal is pressed is calculated based on the recorded data obtained from the haptic device measurements. Although the test subjects had to move the virtual surgical instrument more in the initial trials with the 2D-Coupled mode, after 6 repetitions, similar amounts of motion of the surgical tool are recorded in both modes (Figure 5.7).

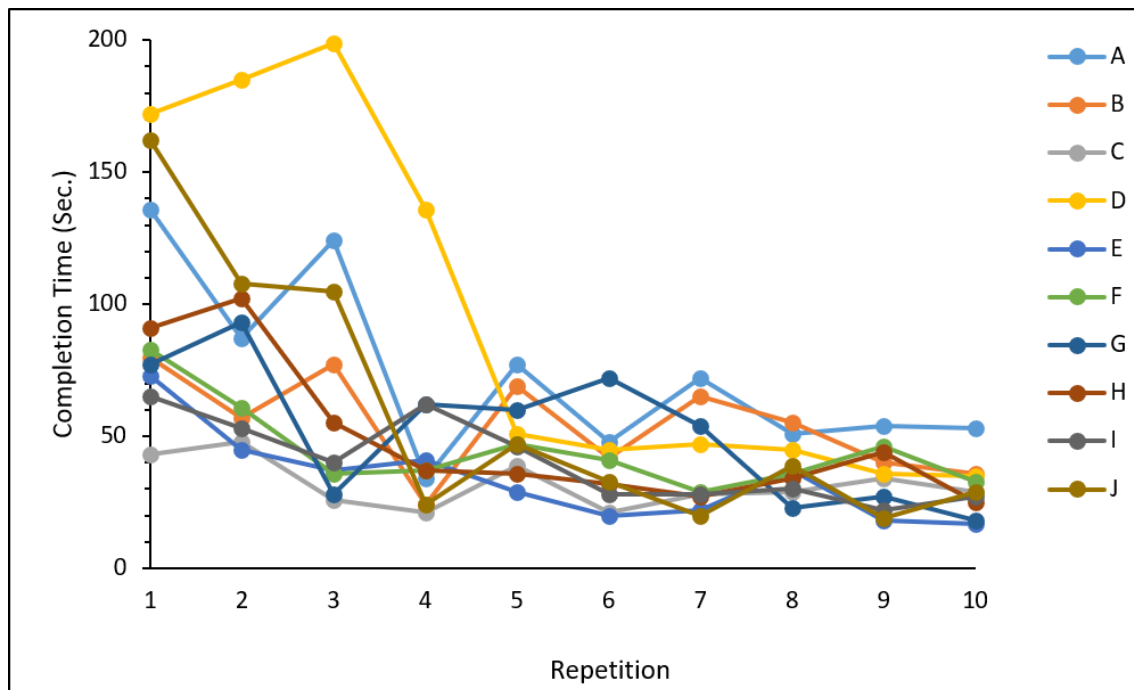


Figure 5.3. Task completion duration versus repetition graph obtained during the 2D-Coupled mode tests

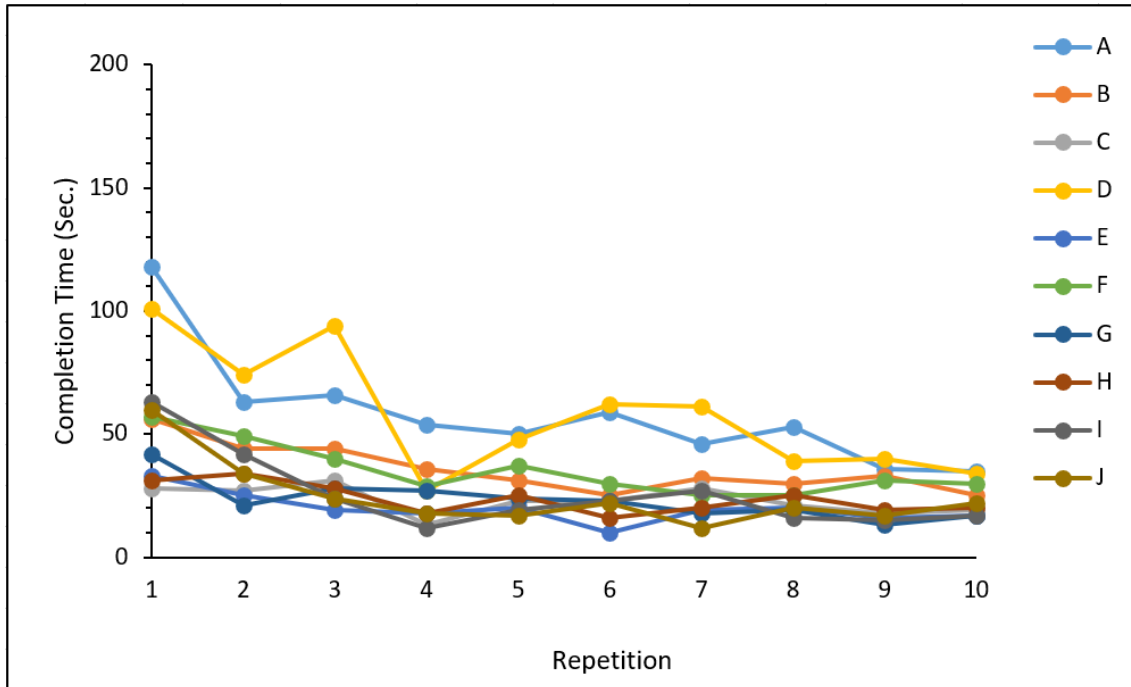


Figure 5.4. Task completion duration versus repetition graph obtained during the User-Specified Frame mode tests

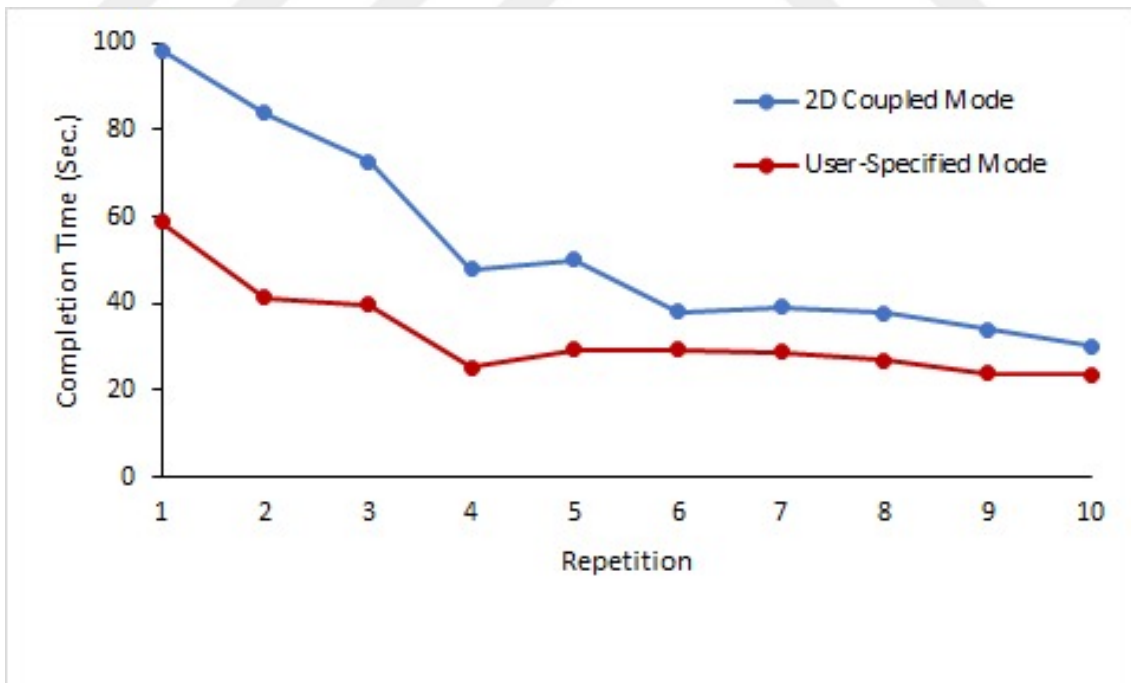


Figure 5.5. Comparison of the mean values of task completion durations obtained during the 2D-Coupled and User-Specified Frame mode tests

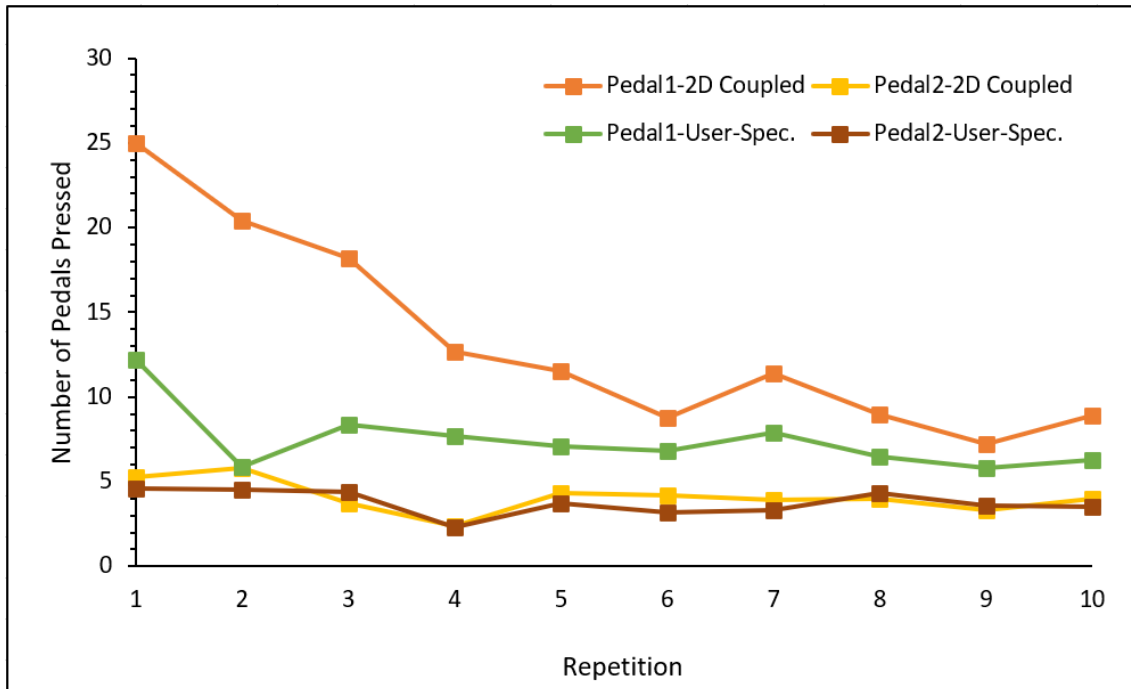


Figure 5.6. Average number of pedals pressed versus repetition graph obtained during tests with both modes

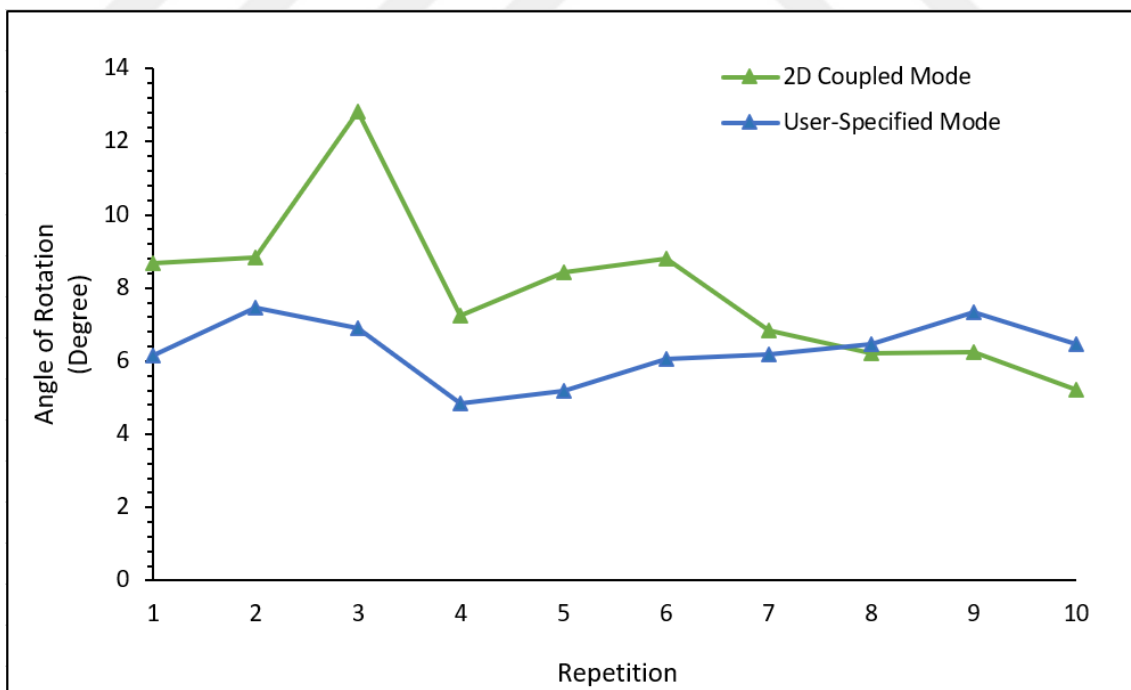


Figure 5.7. Average rotation of the surgical instrument while using the ring and the pedal is pressed

5.5. Discussions on the NSSv2 Test Results

Same test subjects worked on both 2D-Coupled mode and User-Specific Frame mode. Initially, the test subjects worked on the 2D-Coupled mode. In the initial repetitions with this mode, larger task completion durations and more pedal press counts are measured. One reason for this could be that the test subjects did not have a previous experience with the system before working with the 2D-Coupled mode. After the test subjects complete the 2D-Couple mode test, they started to work with User-Specific Frame mode. Therefore, when the test subjects worked with the User-Specific Frame mode, they already had an experience with the system. This could be the reason of the steep learning curve observed in 2D-Coupled mode. In other words, this could be the reason why the User-Specific Frame mode results indicate that the tests subjects adapted to this method quicker than the other mode. Nevertheless, the final results indicate that the User-Specific Frame mode is relatively more suitable for the surgeon's use.

CHAPTER 6

DISCUSSION AND CONCLUSION

In this study, a simulator titled NeuRoboScope Surgery Simulator v2 is developed for training purposes of the NeuRoboScope robot which is specially designed and produced for minimally invasive pituitary gland surgery. Different from the previous version of this simulator, haptic devices are used in NSSv2 to increase human-robot interaction, and an image recorded during the minimally invasive pituitary surgery is used in visual feedback. It should be noted that the haptic display capability of the haptic devices are not used and these haptic devices are used only for measuring the pose of their stylus which is forwarded to the simulator as the motion information for the virtual surgical tools. In addition, a User-Specific Frame mode is developed. In this mode, surgeons can create their personal control methods by assigning their preferred frame for defining the motion.

Improvements in NSSv2 had a positive impact in training users to use the NeuRoboScope system. Success levels of the users increase when the created NSSv2 training scenarios are completed. These success levels are evaluated via calculating the task completion time, the number of pedal press usages and minimized motion of the surgical tool while controlling the endoscope.

The User-Specific Frame mode produced better results relative to the 2D-Coupled mode. By applying this new method, control of the NeuRoboScope's active system via the controller ring can be improved.

In future studies, improvements may be made in the algorithm of the User-Specific Frame mode by categorizing the motion demands measured from the ring via a fuzzy logic algorithm. Thanks to this improvement, while controlling the robot, the system will be able to anticipate the surgeon's demands and make inferences for unidentified movements. In this way, the surgeon will be able to have a better experience when controlling the NeuRoboScope system.

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