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Master's Thesis

A Telediagnosis Platform based on Telexistence: Investigation of the Roles of Presence and Tactile Information in Telemedicine

（テレイグジスタンスに基づく遠隔診断プラットフォーム—遠隔医療における存在感と触覚手がかりの役割の調査—）

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by

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Abstract

This paper proposes a telediagnosis system that allows medical staff to examine remote patients through telexistence robot system with tactile sensor/display. The system consists of three components of an audio-visual telexistence system for telecommunication, a skin-like tactile display equipped with thermal and pressure display devices, and body temperature and heartbeat measurement equipment. In comparison with conventional telephone and videophone, this MR system is expected to allow a medical staff to examine the patient more carefully as if he or she is observing the patient face to face. To test this, 12 medical doctors and nurses evaluated this system. According to the results, the effects of telexistence and tactile display on telediagnosis are discussed. Also, the feasibility of the system for improving the realism of telediagnosis is verified and discussed.

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1 Introduction

1.1 Virtual Reality (VR)

VR is defined as something that makes an experiencer can feel he is in a place where he is not actually in there. It produces the same feeling of presence [1]. The picture below shows a simulation of flight training [2] (Figure1.1-1). The picture below shows a simulation of flight training. The device is on the ground, and there is no plane and enough space for the real plane to fly in. but through this simulation system, the user can get a feeling that as if piloting the real plane. This feeling is extremely the same as the real piloting. This is a typical example of a VR system.

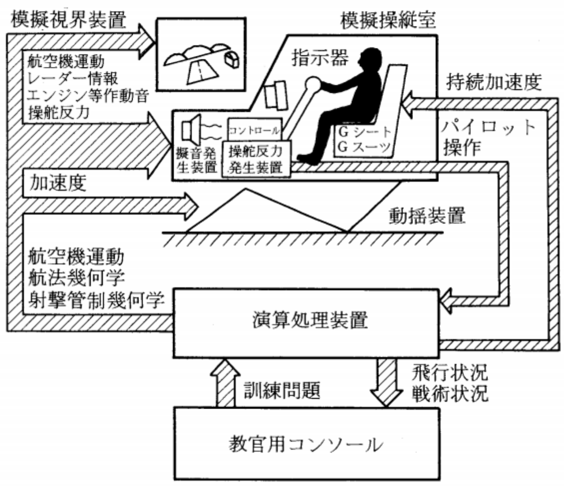


Figure 1.1-1: A sample of car driving simulator[2]

To generate this feeling, the VR system must have the following two abilities: the system needs to be able to generate the stimulates same as the mechanism of how humans perceiving the world. Besides, the system is supposed to receive the input of the user and according to the input to provide a proper real-time interaction. The foundation of VR can be accomplished when a VR system fulfills these two aspects.

1.1.1 Three elements of Virtual Reality

In the previous section, it was described that by reproducing the sensory input given by a specific real space, the same sense of presence could be generated. This is an essential mechanism for constructing a VR system. For a general VR system, the primary approach is simulating sensory input given by a real space as similar as possible. By the way, should the VR system reproduce all the sensory inputs that humans can perceive in the target real space? The necessary sensory inputs usually decide by the real space that VR targets. In other words, it is necessary to consider how the sensory input is reproduced according to the real space and what effect is supposed to be achieved. Appropriate sensory input, which always satisfies the three elements of VR[1], "three-dimensional spatiality," "real-time interaction," and "self-projection," can give the user a great VR experience. In the following, we explain the three-dimensional spatiality, real-time interaction, and self-projection, which are the fundamentals to realize VR.

- Three-dimensional spatiality

Three-dimensional space's spatiality refers to the three-dimensional space created by the VR system. Humans usually live in a three-dimensional space and recognize things in that space. If this spatiality is not considered in the VR system, for example, the sound from the rear and the sound from the front are heard in the same way, or the depth of the scene is lost. The image which is looking at will be recognized as just a two-dimensional photograph. Therefore, the sense of realism is impaired.

On the other hand, the three-dimensional spatiality is not necessary for airplane pilot simulators. This is because most of what the pilot sees is just an image of a distant object, the parallax effect is small, and there are few differences in the depth. In such a system, it is allowed to generate a sense of presence for a user without a 3D image.

- Real-time interaction

Real-time operability means that user input acts on the VR system, events in the virtual space feedback to the user, and interaction between the user and the system occurs in real-time. For example, in the case of a computer game, the game screen is always synchronized with the user's operations. It means that the user's controller operations were processed immediately in the game system and reflected on the user via a feedback system called the game screen. If this characteristic is lost, the sense of the subjectivity of the game is lost. Also, for the input of VR systems, not only using the controller to input various specific instructions but also real-world actions such as head position and posture can be used as one of the input methods. If the video presented to the user does not switch in real-time with respect to the movement of the head, the realism of VR will be lost due to a sense of incongruity with the phenomenon perceived in daily life, and sometimes symptoms such as VR sickness may occur.

- Self-projection

Self-projection means immersing yourself in the virtual environment generated by the VR system. It exists in a system in which there is no contradiction between one's body sensation and audiovisual. Body sensation refers to sensations related to one's physical condition, including somatic sensation and vestibular sensations. For example, the position of one's hand and tilt of the body can be felt without sight and hearing. That body is in what kind of posture is called body sensation. Others include the sense of audiovisual, which belongs to the category of perception. Various senses work together to realize perception in real space. If in a virtual environment that can reproduce this collaborative relationship of senses, the human body can also behave like in reality. But if there is a contradiction between the senses, it will significantly reduce the realism. For example, when the tilt angle of the head in the virtual space is larger than in reality, the vision in the HMD will also have a larger tilt, which can easily cause VR sickness.

1.2Telexistance

Telexistence[1] is a concept advocated by Tachi Susumu in 1980 that enables a human being to have a real-time sensation of being at a place other than where he or she actually exists and being able to interact with the remote environment, which may be real, virtual, or a combination of both. It also refers to an advanced type of teleoperation system that enables an operator at the control to perform remote tasks dexterously with the feeling of existing in a surrogate robot working in a remote environment[3].

1.2.1 History of telexistance

The concept of teleoperation originally appeared for handling radioactive material from a distance[4]. People on the local side operate a robot arm that is on the radioactive remote side to complete the moving task. This operation mode is generally called the master-slave. The operating side is the master, and the following is the slave. The goal of the entire system is that when the master side does an action, the slave side can replicate the same action. This kind of system makes up the fundamental of the telexistence. Then, in the 1960s, the exoskeleton human amplifier was proposed. It puts the user in armor-like devices, which can enhance the user's power. When the user makes an action, the exoskeleton will provide strength enhancement. However, such an exoskeleton also has its shortcomings. Problems with the mechanical structure and possible danger to the user make it challenging to implement.

To solve this problem, telexistence combines the advantages of exoskeleton human amplifiers with supervisory control. The concept of supervisory control was introduced in the 1870s[5]. It allows the slave-side to be controlled by a computer which is programmed in advance. So, telexistence can control the slave-side through supervisory control, and at the same time, it allows the user to move a surrogate like an exoskeleton human amplifier in the slave-side environment. In this way, the intuitive operation of the exoskeleton human amplifier is retained while avoiding the dangers caused by exposure in the real environment. The slave-side can also operate in a pre-designed program, ensuring the advantages of supervisory control.

1.2.2 Telexistance system

Telexistence is a high-presence technology that enables master-side users to work as intuitively as slave-side. In other words, to achieve telexistence, there must be a system that can provide this presence to the operator.

For a telexistence system, the user's sense of ownership of his own body and action is an important feature. For the slave-side robot to operate freely and intuitively, the master-side operator should have the feeling of ownership of the surrogate robot. If the robot's actions are inconsistent with the user's predictions of their actions, then this sense of ownership cannot be established. Therefore, a telexistence system must also meet the requirements of the three elements of VR.

More detail, for a telexistence system, users do not need specialized training and can complete the control of the system by relying on their own experience in the past. Therefore, the system is required to be unified in spatiality with reality. According to the purpose of the system, there must be real-time feedback from the slave-side so that the operator can have the same experience as reality. When a user makes a movement, his movement must be accurately measured and reflected in the slave-side as well. And the feedback from the patient-side should also be transferred to the user in time to let the user know what he needs to do next. The positions of the hands and feet of the slave-side robot must be consistent with the user's own perception of the body. Only by giving users a high sense of presence can self-projection be achieved. Only by meeting these requirements can a telexistence system achieve.

1.3Telemedicine

Telemedicine is getting more and more attention and development in the scope of international medical and health services. The concept of "telemedicine" can be understood literally as " treatment from a remote distance," that is, using Information and communications technology (ICT) to expand the medical treatment approach and medical information to improve the healing effect of patients. Different definitions of telemedicine by authoritative telemedicine organizations such as the World Health Organization (WHO), American Telemedicine Association (ATA), and European Telehealth Information Association (EH-TEL) can be seen in (Table 1). The development is rapid, so the definitions and the scope covered are still changing. From a qualitative point of view, the definition of ATA is more inclined to the telemedicine diagnosis and treatment service, while the definition of WHO is more inclined to telehealth, although both are considered the same in many papers or reports. In general, both include a series of broad applications of telemedicine, such as remote diagnostic consultation under video conferencing, the transmission of medical images, e-health systems including customer ports, remote signal monitoring, medical education training, customer wireless applications, and the nurse called centers. Telemedicine systems are usually closely related to Health Information Technology (HIT), but the latter generally refers only to information systems such as electronic medical records, while telemedicine refers to the process of completing telediagnosis and treatment services through information technology.

Table 1: Definition of telemedicine[6]–[8]

organization	time	definition
European Commission	1993	"Telemedicine is the rapid access to shared and remote medical expertise by means of telecommunications and information technologies, no matter where the patient or the relevant information is located."
American Telemedicine Association (ATA)	1996	"An advanced medical diagnostic system that improves the level of medical diagnosis of patients by exchanging patient medical information between different locations through electronic communication."
World Health Organization (WHO)	1998	"Telemedicine is the delivery of healthcare services, where distance is a critical factor, by all healthcare professionals using information and communications technologies , all in the interests of advancing the health of individuals and their communities."
the European Health Telematics Association (EHTEL)	2008	"Telemedicine services provide means to improve accessibility to high-quality health care in case of shortage of appropriate health professionals or the necessary medical expertise or skills at the site of the patient."

Because telemedicine is essentially the sharing of superior medical resources, especially intellectual resources, through network communication technology, for remote villages or unusual environments, remote medical services can be used to obtain high-quality medical care services that could not be obtained or challenging to obtain[9]. At the same time, it can also reduce the travel time and cost of the patient and the patient's observation and treatment time in the hospital. Therefore, the global market demand for telemedicine is apparent. Its application scope is developing rapidly. After more than 40 years of development, it has expanded the location from the initial diagnosis and treatment in remote areas to the hospital's surgical department and home health department, doctor's office, and patient home or office. Besides, the countries and regions implementing telemedicine projects have gradually expanded from initially limited to developed countries such as Europe and the United States to regions where concentrate the developing countries such as Asia and Africa. Telemedicine has great potential for reducing diagnostic differences, improving clinical management, and providing healthcare services worldwide, due to its greater availability, quality, efficiency, and cost-effectiveness. In particular, telemedicine can do benefit communities' lack of ability (remote or rural areas with few medical services) as it overcomes the distance and time constraints between medical staff and patients. In addition, there is evidence that this has significant socio-economic benefits for patients, medical staff and the medical system, which includes better doctor-patient communication and educational opportunities. In general, based on telemedicine case reports worldwide, the telemedicine system can provide improvements or improvements in the following aspects: expand the service scope to areas not covered by medical services or rural community areas, provide more effective control of chronic diseases, and improve the treatment of elderly patients, patients with reduced mobility, or disabled patients. It is conducive to controlling the costs of medical care and improve the overall health of the community and society and reducing cross-infection from patients to hospitals, etc.

1.3.1 Telemedicine with VR

From the above, we can see that telemedicine aims to break the limitation of distance and solve the uneven distribution of medical resources. In order to enable medical staff to work across the distance, a lot of research has been done. In the past, telemedicine mostly relied on traditional communication equipment, such as mobile phones and computers, by audio and videophones. This method has its limitations. It is far from the usual way when medical staff works, which will cause a tremendously adverse effect on medical workers to understand the condition and guide patients. Therefore, in order to make telemedicine closer to reality, combining with VR is the best choice[10]. According to purpose, it can be divided into telesurgery, telemedicine training, telediagnosis, etc.

1.3.1.1 Telesurgery

The combination of virtual reality and network technology enables doctors to perform surgery on remote patients. It means doctors can judge the patient through the images transmitted from the remote and perform surgical operations through some special input devices. A doctor's every move can be transmitted to the remote controlling the devices to complete the surgery. The world's first telesurgery was completed in 2001. It was conducted by a surgical team in New York, USA, using the ZEUS robotic system (Intuitive Surgical, Sunnyvale, CA, USA)[11]. The surgery lasts two hours to complete the laparoscopic cholecystectomy. After that, the patient recovered uneventfully. Also, due to the high accuracy, this kind of surgery system such as the da Vinci telerobotic surgical system (Intuitive Surgical, Mountain View, Calif) has been increasingly used[12]. It usually has a console and an operating table. The image of the operating table will be enlarged and presented to the doctor. The operation of the doctor will also be transmitted to the robot arm on the operating table so that the doctor can complete some subtle tasks.

Figure 1.3-1: Master controllers and the patient side manipulators

of the da Vinci Si surgical system

1.3.1.2 Telemedicine training

Medical staffs have a significant demand for the experience. In order to solve the unbalance of medical resources in remote areas, the medical level of local can be improved through telemedicine training. And through the way of virtual reality, the principles can be easy to clarify, making the training more intuitive and more straightforward. In previous researches, mixed reality is often applied. By projecting local images to the remote experts, the trainees can get real-time guidance from the experts during the actual operation. Mahesh B Shenai et al.[13] created an AR telemedicine training system, which allows the mentor works with the trainees in the same space to provide medical guidance. Marina Carbone et al.[14] also proposed an AR telemedicine platform using Head-mounted display (HMD) to realize remote palpation training.

1.3.1.3 Telediagnosis

Telediagnosis is defined as the determination of the nature of a disease at a site remote from the patient on the basis of telehealth methods of transmitted data[15]. It allows us to get medical treatment without leaving home. It saves time spent on the road, simplifies the process of diagnosis and treatment of some chronic diseases. Also, it is significant for improving the medical level in a rural area. The traditional telediagnosis by telephone and videophone has developed for a long time, and its disadvantages are also apparent. Doctors can only obtain limited information through traditional electronic devices. And because it is very different from the usual way to diagnose and treat, it is easy to cause doctors to slacken and influence the effect of consultation further. However, by combining virtual reality, the communication between doctors and patients can be similar to reality, thereby improving the efficiency and accuracy of consultation. In order to achieve telediagnosis, there are often surrogate robots using to replace patients or doctors to achieve mutual interaction. Ruzena Bajcsy et al.[16] using Microsoft Kinect collected RGB+D video of the patient and then reconstructed a real-time 3D patient in an AR device for the expert physician to interact with. Garingo et al. apply a mobile robot into neonatal intensive care to help people from a distance[17].

1.4 Purpose and significance of research

However, most of the current researches on telediagnosis are still at the level of system construction or based on visual hearing. The research with haptic is still at the initial stage. What does tactile mean for telemedicine still need s to find out. In telesurgery and telemedicine training, Bernhard Weber et al. have proved that haptic feedback does have an impact on the teleoperation system[18]. Timothy et al. use artificial force to simulate the feeling of human skin and apply the system into the palpation and injection training[19]. It did improve the accuracy and authenticity of the injection training. Therefore, we want to find out in telediagnosis is similar or not. And for a telexistence system with feedback, what will it affect the telediagnosis.

For the purposes above, we put forward the following requirements

- The doctor must be able to communicate with the patient, as usual. The communication must be in real-time.
- Some bio-signal such as temperature and pulse can get and used to judge the condition.
- The bio-signal must have haptic feedback at the doctor-side.

The traditional telediagnosis always sends the bio-signal that can be read in number such as blood pressure. But there are many diseases that can only be recognized by the medical staff's experience. Those symptoms can not or hard to be transferred into data in number. But if the tactile feedback can be reproduced. The situation could be easily understood by the medical staff. Our target is to use telediagnosis in this kind of disease in the future. In this study, we choose temperature and pulse as the bio-signal to be measured and reproduced because those two features are comfort for reproducing but always necessary in all kinds of diagnosis. If the tactile display of pulse and temperature is useful, the development of more bio-signal reproduction will also be meaningful.

1.5 Chapter summary

This chapter has a brief introduction to the theoretical basis of this research, explained the concepts and critical points of VR and telexistence. We surveyed the current business about telemedicine, and we expounded the significance of this research on telediagnosis with a haptic feedback telexistence system.

2 Proposed telediagnosis system (prototype)

2.1 System requirements

There are many ways to diagnose, and palpation is one of the common. Palpation in Chinese medicine also has a history of thousands of years. The basic skills of medical examination include percussion, auscultation, and palpation. Pulse, blood pressure, and body temperature are usually measured as vital signs. We decided to reproduce palpation to acquire these vital signs as a minimum requirement for telediagnosis. By palpation medical staff can know the pulse, sweating, swelling, tenderness, and temperature, or other features. Many diseases can be judged by palpation. In our system, we focus on reproducing the temperature and pulse because these are vital information but more comfortable to measure and replicate. The human's regular pulse is between 60~120 bpm. Pulse's left and right differences, tension, pulse rate, and irregularity are predictors of increased complications and poor prognosis in many diseases. These disease may cause the heart rate beyond the range. For example, paroxysmal supraventricular tachycardia (PSVT) is the most common symptom of tachycardia. The pulse can reach 140~180 bpm[20]. Besides, the temperature and pulse are in positive correlation. Usually, pulse increases by 10 bpm when the temperature rises by 0.5℃. Hyperthermia and hypothermia are both manifestations of the disease.

Purpose

- To realize a remote palpation system with temperature and pulse feedback.

Requirement

- Pulse: 60-180BPM
- Temperature: 25-45℃
- The doctor can feel as touching the patient's body to palpation and communicate with the patient as if face to face.

Method

- Develop a surrogate robot to achieve telexistence
- Using chroma key to increase the doctor's presence.

- Develop a sensor unit to measure temperature and pulse from the patient.
- Develop a surrogate arm to replicate the body temperature and pulse.

By the method above, we can propose a telediagnosis system, in which a doctor can see, hear, and touch the patient and communicate with the patient in real-time.

2.2 System overview

The system consists of two parts, like figure2.2-1. One is the patient-side, the other is the doctor-side. The roles of them are as follows:

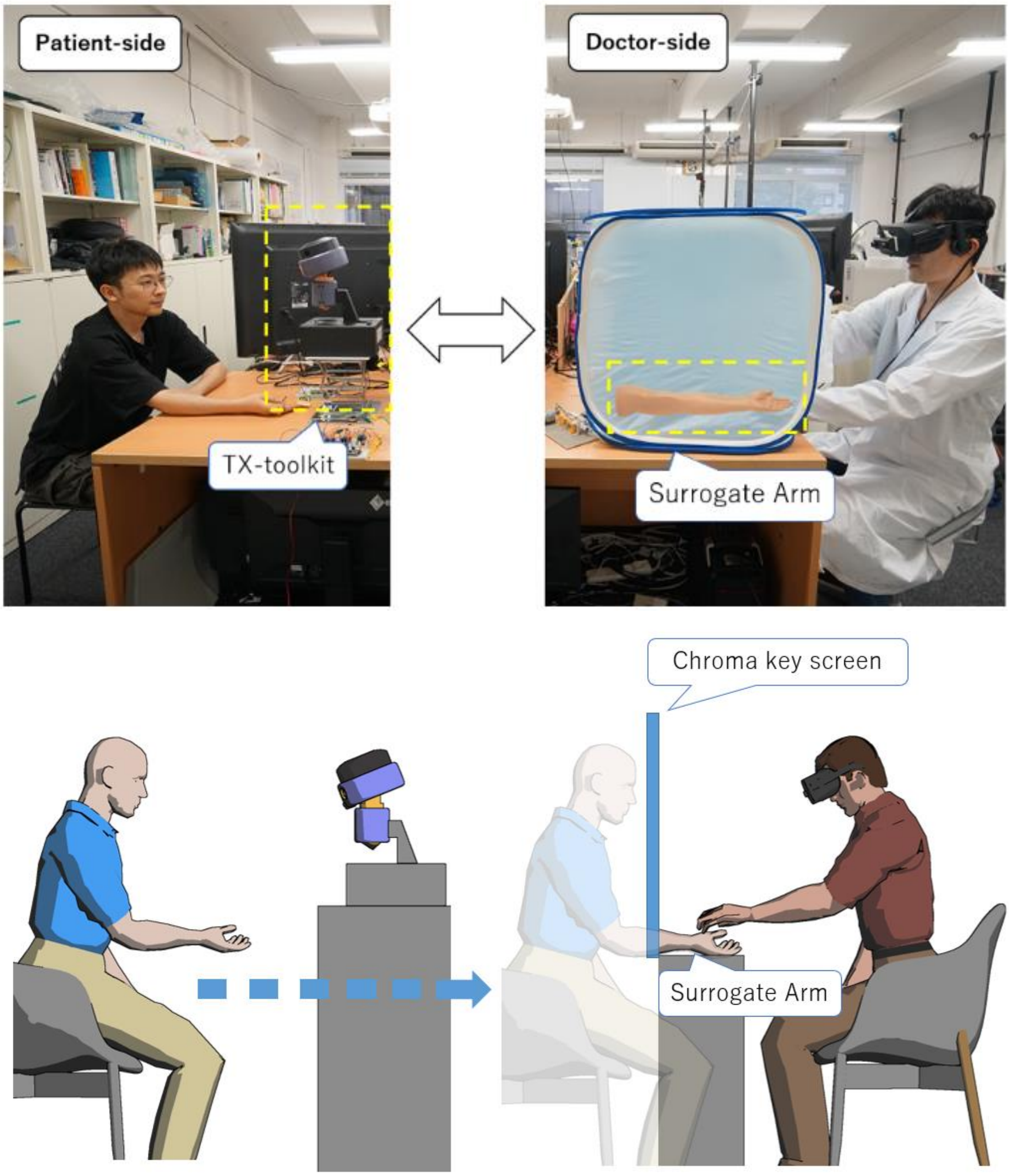


Figure 2.2-1: System overview: Patient-side and doctor-side

Patient-side (remote consultation room): The patient is supposed to wear a glove with sensors and sit in front of a robot. With the sensors embedded in the robot and glove, the audio-video information and bio-signal of the patient are recorded and transmitted to the doctor-side. This part is made up of two components: (1) A doctor-surrogate robot is supposed to perceive the surrounding's information including the patient's appearance and voice and to reproduce the doctor's voice and gestures recorded from the doctor-side. (2) Sensors on the glove measure the bio-signals of the patient. The sensor data are stored and processed in a micro control unit (MCU), and then the bio-signal information is transmitted to the doctor-side.

Doctor-side (local clinic): The doctor wears a Head-mounted display (HMD) connected to the surrogate robot in the patient-side, which reconstruct the surrounding of the patient's remote consultation room. Also, the HMD is equipped with a stereo camera for achieving video-seethrough; that is, the doctor can recognize his/her own hands overlapping in the image of the patient-side. The obstructive doctor-side's image except for the hands is eliminated by using chroma key screens in a Unity project. This method realizes the mixed reality. Furthermore, a patient-surrogate arm equipped with many devices is placed in front of the doctor to reproduce the bio-signal information of the patient. Owing to the system, it is expected that the doctor can feel as if he/she were diagnosing the patients face to face.

According to the system overview mentioned above, a data diagram between patient-side and doctor-side is designed as follows. Figure2.2-2 shows how the information exchanges between the two sides. As seen in the figure, the system also can be divided into upper and lower halves. The upper half describes how the surrogate robot at the patient-side corresponds to the HMD at the doctor-side. This part is explained in the "Audio-Video reproduction." The lower half shows how the bio-signal information gotten from the patient-side reproduces on the surrogate arm in the doctor-side. This is explained in the bio-signal reproduction part.

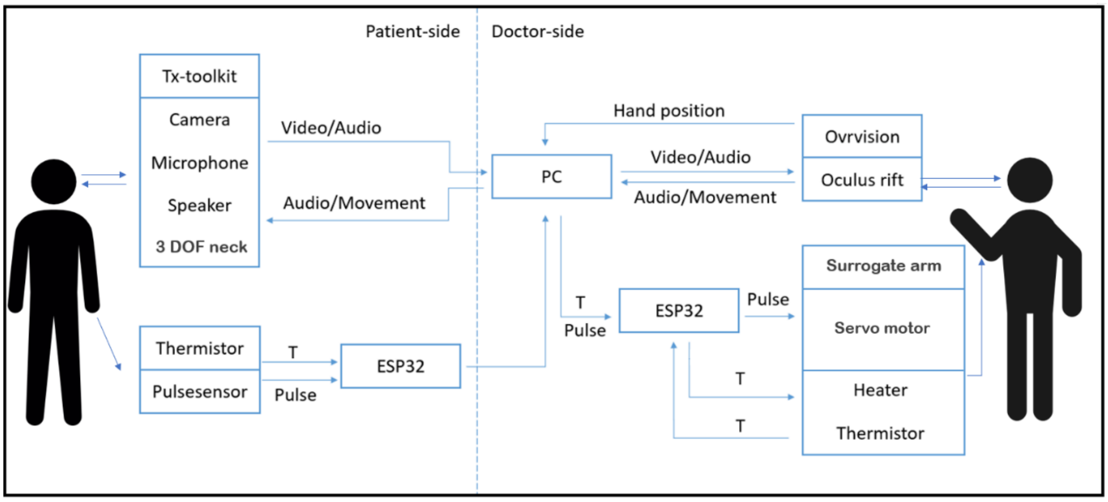


Figure 2.2-2 : System data diagram

2.3 Audio-Video reproduction

This part mainly explains how the audio and video information is obtained and reproduced on the two sides.

2.3.1 Patient-side: TX-toolkit

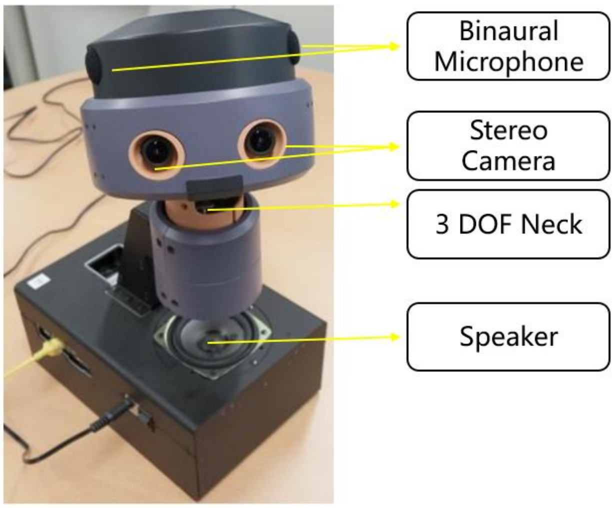


Figure 2.3-1: Mechanical construction of TX-toolkit

According to telexistence, to reproduce one's existence, there is usually a master-slave system. The user is in the master-side while a robot is as a surrogate of the user at the slave-side. Therefore, at the patient-side, it supposed to have a surrogate robot to replace the doctor to interact with the patient. To achieve this, a robot that has human-resemble sensorimotor capabilities is necessary. However, recent popularized telecommunication/telepresence robot such as Double2 (Double Robotics, Inc.) and BeamPro (Suitable Technologies, Inc.) is still insufficient to achieve the immersive telexistence/telepresence experience. Therefore, a custom-developed telexistence system named “Telexistence-toolkit (TX-toolkit)” is applied for this study. TX-toolkit is designed to achieve the telecommunication in high telepresence[21]. As shown in figure2.3-1, TX-toolkit is equipped with a stereo camera, a binaural microphone, and a speaker, making itself able to communicate like a human. With the 3-DOF mechanical system and network function, TX-toolkit allows the local user to connect to the remote environment and look around there in stereoscopic view by using an HMD (Oculus Rift CV2, Facebook Technologies, LLC)[22] to show the camera image and control robot‘s head movement.

Table 2: Specification of TX-toolkit

Size	**362mm×167mm×232mm**
Weight	**2.5kg (include battery)**
Dimension of Free	**3**
Power Source	**DC16V (or external power)**
Rotation Range	**Yaw ±90℃, Pitch ±20℃, Roll±20℃**
Field of View	**Horizontal 100℃, Vertical 98℃**
Resolution	**960×950 pixel/eye @60fps**
Latency	**Under 100ms**

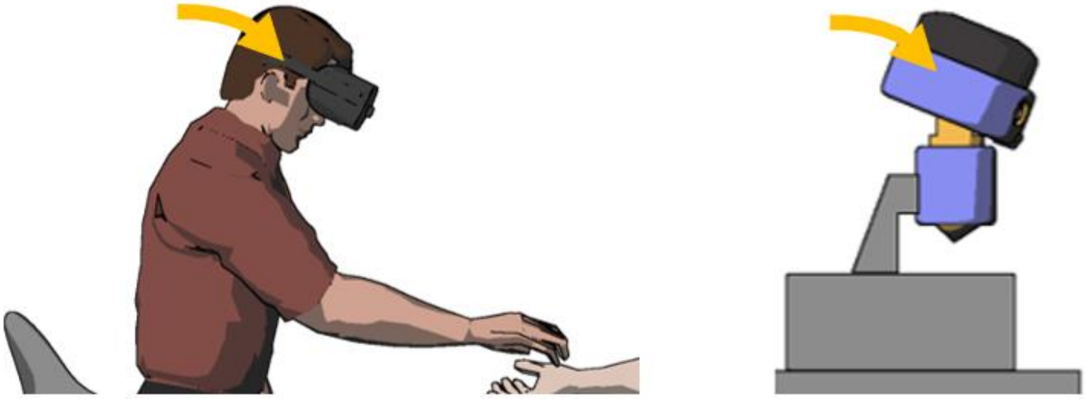


Figure 2.3-2: Synchronization between TX-toolkit and user

In this application, for the patient, the TX-toolkit acts as the doctor's surrogate body and makes the verbal communication more relaxed. For the doctor, the robot brings the audio and video information of the remote consultation room to immerse in the environment with the presence of the patient.

2.3.2 Doctor-side

2.3.2.1 HMD system

TX-toolkit has 3 degrees of freedom (DOF) of 3-axis head rotation. To synchronize with the doctor's head movement, it is necessary to know the doctor's head rotation angles (i.e., roll, pitch, yaw). Recently, HMD devices are a convenient way to measure the head movement because many of them are equipped with a posture sensor for VR application. While there are kinds of headsets on the market, Oculus rift cv2 is applied for TX-toolkit. To ensure the quality of telexistence, at the robot's side, the head rotation angles of the robot and the doctor must keep the same so that the doctor can see the robot's camera image from the same head orientation. The HMD can measure the 3D rotation angles with sufficient resolution for controlling the robot. Therefore the posture data is sent to the robot in real-time for tracking the head motion.

Figure 2.3-3: Oculus rift CV2 with tracking sensors
(via: https://www.oculus.com/)

2.3.2.2 Mixed reality

In telexistence, there is supposed to be an artificial object as an expansion of the user's bodily consciousness. The user has the ability to freely move and control the slave object in a similar way to how his/her body moves[23]. Without this, the user can not think of himself as a natural human as before. The realism will lose a lot. This means that for the telediagnosis system, the doctor needs his/her hand for performing the palpation. Otherwise, while he/she looks down to find his/her hand but sees nothing, the feeling is weird, just like losing his/her body. The feeling of strangeness will lead to a significant reduction in realism. For this reason, the doctor must see his hand while he is palpating. However, the object of palpation (patient's body) is located on the patient-side and is seen from the robot's camera, whereas the subject of palpation (doctor's hand) is placed in the doctor-side. Therefore, it is required to develop the method to project the doctor's hand to the remote scene.

Due to the absence of robot arms and hands in TX-toolkit, the mixed reality technology is used to present the doctor's hand image overlapping in the remote consulting room, instead. To achieve this, chroma key composting is used to extract the doctor's hand from the background and project the hand image to the remote scene. Chroma key composing, which is commonly used for weather forecast broadcasts, is a visual effects/post-production technique for compositing two images or video streams together based on color hues[24].

Figure 2.3-4: Stereo camera attached the front of the HMD

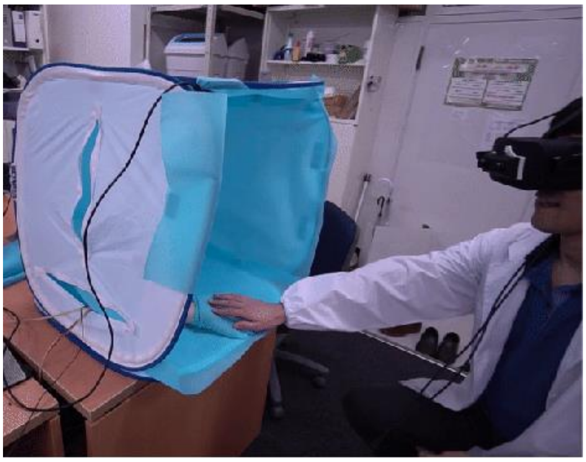


Figure 2.3-5: A box color in blue for chroma key

As shown in the picture above figure2.3-4, A stereo camera (Ovrvision, Shinobiya.com Co., Ltd)[25] attached in front of the HMD shoots the user's eyesight view instead of the naked eyes. The video-seethrough is realized by presenting the camera image on the HMD by keeping the same viewing angle. Here, the camera image shoot from the HMD-attached camera is processed to extract the hand area and compose it in the remote scene.Figure2.3-5 shows the surroundings where the doctor is sitting. There is a large flat panel on the opposite side. The panel is in blue, which is the complementary color of skin, to ensure the body can be separated from the background correctly.

All the VR environment seen in the HMD is generated and designed by using an existing game engine, Unity (Unity Technologies). In the VR environment, two sets of screens are fixed in front of the camera. On the one set of the screen shows the scene caught by the stereo camera in the local, while the other set shows the video stream from the remote. Due to the chroma key, all the blue on the local screen will be discarded. Therefore, the doctor who wears the HMD will see nothing but his own hand, and the remote scene will replace the discarded image. In this way, the doctor can have a view in the patient's room and see his own body at the same time. The realism that as if sitting in a remote place is much improved. Figure2.3-6 shows the Mixed reality in the HMD.

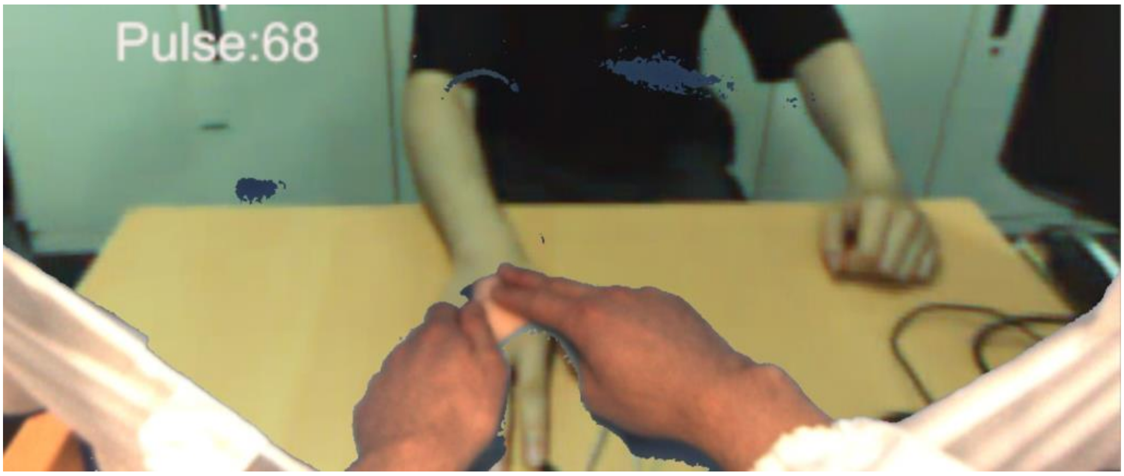


Figure 2.3-6: Mixed reality image

2.3.3 Summary of Audio-Video reproduction

Audio-Video reproduction is achieved by TX-toolkit and an HMD system. With TX-toolkit, the image, sound at the patient-side can be transferred to the doctor-side through the video, audio stream, and playback on the HMD at the same time. In this way, the doctor will feel like sitting in front of the patient and move his sight as he wishes. The robot has a 3-DOF neck, which allows it to replicate the movement the same with the doctor's head. And the movement information is obtained from the HMD. Moreover, the patient can realize the doctor's eyesight and hear his voice through the robot's rotation and its speaker. Hence Patient-side will know about what the doctor is looking at and follow his guidance. By that, it provides an efficient way for each other to communicate freely and realistically.

2.4 Bio-signal measurement and reproduction

This part mainly explains how the bio-signal information is measured from the patient and reproduced for the doctor.

2.4.1 Measurement of bio-signals on Patient-side

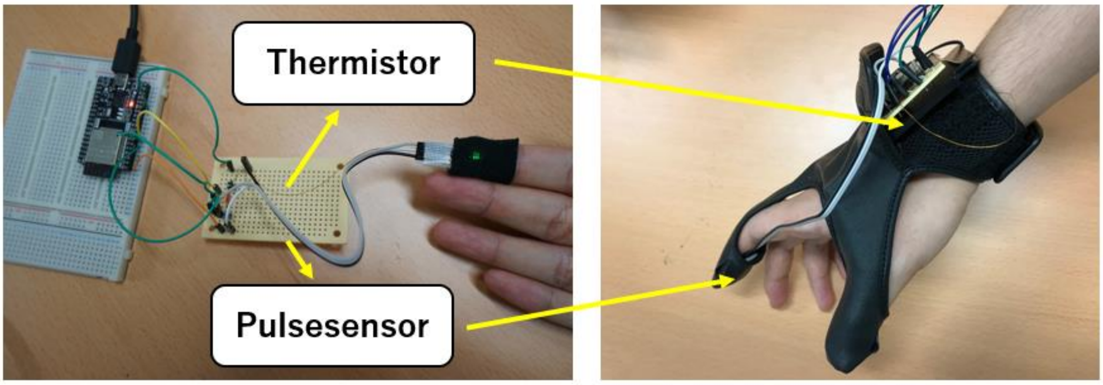


Figure 2.4-1: Bio-signal import

According to the system requirement, the patient-side system is supposed to have a measurement function of the patient's heart rate and body temperature. Also, the measurement should be performed easily and comfortably for the patient. Therefore, the measurement devices, including sensors, microcontrollers, and power supply, are integrated on a wearable glove (figure2.4-1). Once the patient put on the glove, an MCU (ESP32-WROOM-32D, Espressif Systems Pte. Ltd) embedded in the wrist part of the glove captures the raw data of bio-signals obtained from two sensors attached to the fingertip part (pulse sensor) and wrist part (thermistor) of the glove. After data processing explained later, the MCU is transmitted to the bio-signal information to the doctor-side in real-time by using the wireless communication function of a Wi-Fi module installed in the MCU. Also, the MCU and sensors work by using a light-weight USB mobile battery attached in the wrist part. Therefore the measurement is entirely performed by wireless.

2.4.1.1 Measurement of pulse

To use an optical pulse sensor (PulseSensor, World Famous Electronics llc.) attached to the skin is a simple but effective way to measure the blood flow. Therefore this kind of optical measurement device known as pulse-oximeter is applied to measure the heart rate of the patient in the medical field. The principle of the measurement is below: The pulse sensor contains an LED and a light detector. While the sensor and patient's skin is in contact, light from LED spread into the skin. The strength of the diffuse light from the skin reflects the blood flow under the skin, and the detector measures the light to know the heart rate, which is calculated from the blood flow data.

Figure 2.4-2 shows the time series of blood flow data.

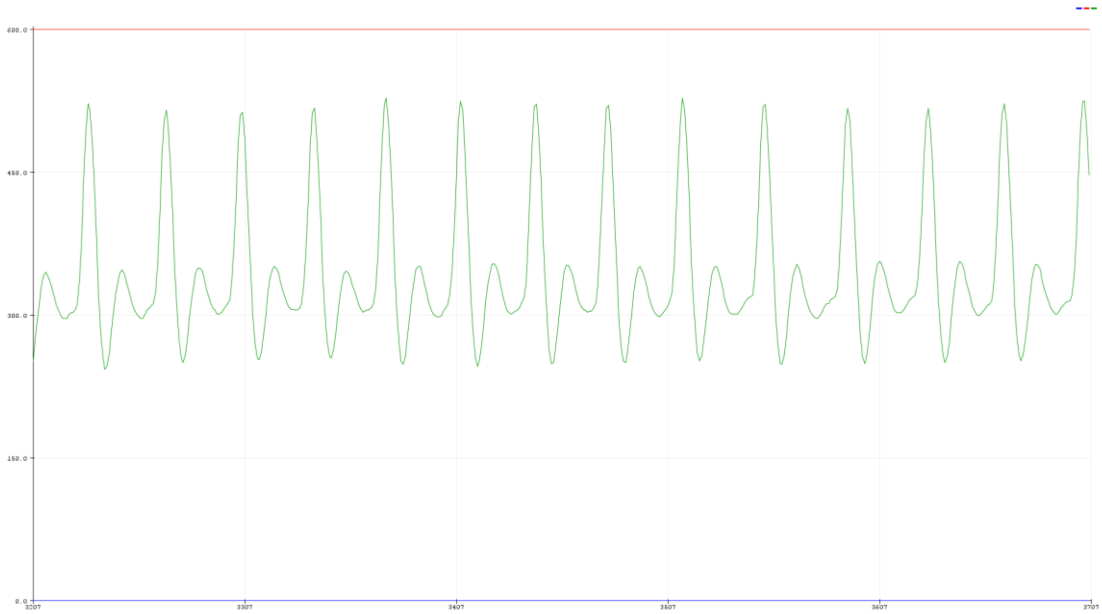
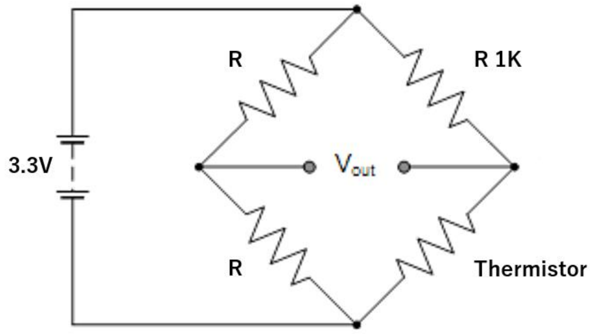


Figure 2.4-2: Waveform of Blood flow depending on the heartbeat

By processing the raw signal data, the heartbeat per minute (BPM) information of the patient is obtained. In this system, the calculation algorithm to extract BPM is by measuring the time between every two peaks to calculate the instantaneous value of BPM.

2.4.1.2 Measurement of temperature

A negative temperature coefficient (NTC) thermistor (56A1002-C3, Alpha Sensors, Inc.) is used to measure the patient's body temperature. The thermistor has resistance in 10000 Ohms at 25°C. Tolerance is ±0.2°C from 0 to 70°C. The voltage supplied by MCU is 3.3V. To improve accuracy, the thermistor is fixed in a bridge rectifier. The bridge circuit is as follows:



The resistance changes linearly with temperature.

$$R_{Ther} = R \times \frac{\frac{3.3}{2} - V_{out}}{\frac{3.3}{2} + V_{out}} \quad (1)$$

By testing the voltage, according to the datasheet of the thermistor, the temperature can be calculated as follows.

$$T = -1 \times 10^{-11} R^3 + 5 \times 10^{-7} R^2 - 9.2 \times 10^{-3} R + 75.724 \quad (2)$$

Furthermore, to avoid measurement noise arising from body movement, the thermistor is attached to the wrist parts of the glove to make sure tight contact between skin and sensor.

2.4.2 Reproduction of bio-signals on Doctor-side

According to the system requirement, the doctor-side system is supposed to have a presentation function of the patient’s bio-signal information. Also, to realize remote palpation, these bio-signals have to be actually reproduced on a presentation device. Therefore, the bio-signal information is presented both visual and tactile modalities. More specifically, the patient’s heart rate and temperature data are presented on the HMD screen as a digital number. Furthermore, the same data are physically reproduced on a bio-signal reproduction device which contains actuator and heater. As shown in the figure2.4-3, the doctor-side system consists of two parts. One of those is a patient’s surrogate arm, which allows the doctor to feel the heartbeat and body temperature of the patient on the human-resemble silicone rubber surface. The bio-signal is reproduced by the devices embedded in the surrogate arm. The other is the control unit, which receives the bio-signal information from the patient-side and controls the devices in order to reproduce the current heart rate and temperature of the patient on the surrogate arm.

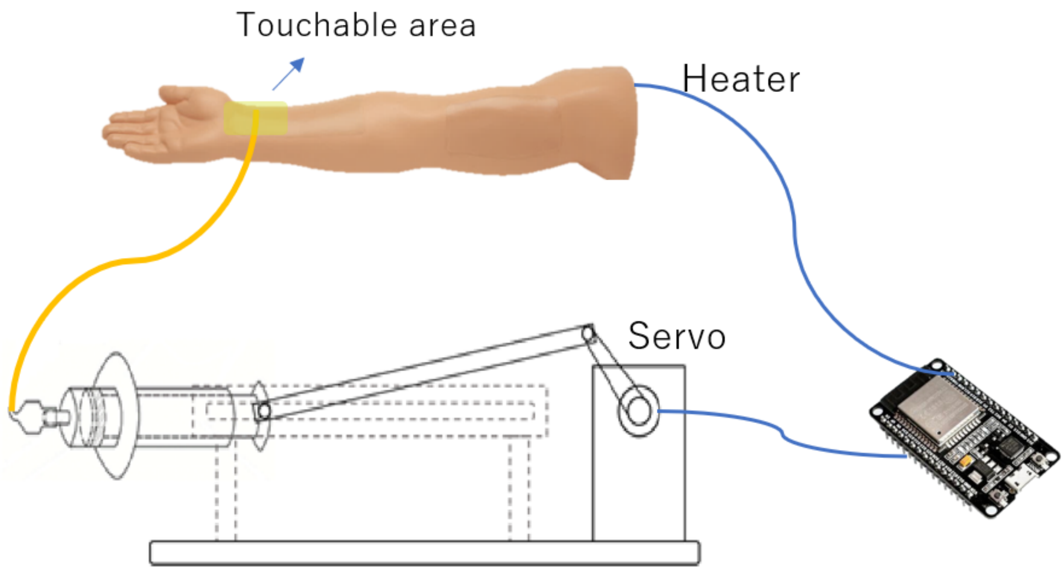


Figure 2.4-3: Bio-signal reproduction mechanism of doctor-side

2.4.2.1 Surrogate arm

Figure 2.4-4: Silicone rubber wrapped dummy arm

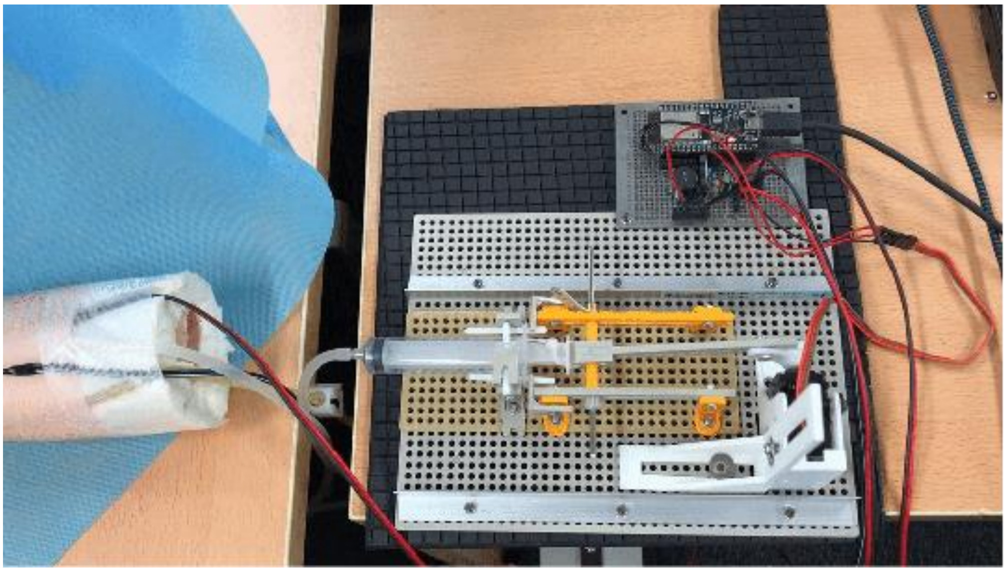
To make realistic tactile sensation while the virtual palpation, the surrogate arm is supposed to be similar to the human's arm as much as possible, no matter in shape or in tactile. Thus, a dummy arm wrapped in human-resemble silicone rubber is used as the surrogate arm, which is often used in medical training such as injection practice and is suitable for the system requirements. The outer layer of the surrogate arm is made of silicone, which is soft and flexible, like a human's skin. Furthermore, under the artificial skin, there are many rubber tubes of artificial blood vessels (artery) covered by the skin. These tubes are flexible and filling the tubes with liquid. Therefore, it is possible to simulate the pulse of a vessel by applying the liquid pressure in the tube. While performing cyclic pressurizing and depressurizing of the tube, slight inflation and deflation of the tube make a virtual heartbeat on the silicone skin. This is the realization way to reproduce the patient's heart rate in the doctor-side system.

Table 3: Specification of silicone arm

Size	**391mm×145mm× 73mm**
Weight	**421g**
Perimeter (wrist)	**180mm**
Skin thickness	**2.1mm**
Tube diameter	**5mm**

2.4.2.2 Reproduction of pulse

To simulate the pulse of a vessel caused by heartbeat, pulse generating actuator, which repeatedly applies liquid pressure in the tube. Therefore, a water-filled syringe connected to the tube and activated by a servo motor is used to generate constant liquid pressure change. The mechanism is shown in figure2.4-5.



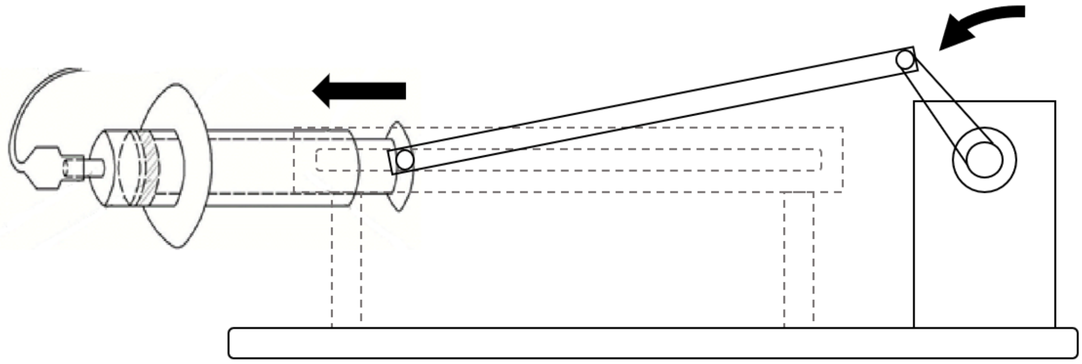


Figure 2.4-5: pulse generator by using a servo motor with a water-filled syringe

To make an artificial heartbeat, a rotary servo motor (S19CLN, GWS. Ltd) is used to push the plunger rod of the syringe. A crank mechanism is attached to the servo motor in order to convert motion. When the motor runs, the crank drives the plunger rod back and forth. The needle adapter of the syringe connects to the terminal of the artificial vessel tube, which goes out from the surrogate arm. In response to motor activation, the rubber tube is squeezed and relaxed, which imitate the pressure pulsation process of blood vessel activated by the heart.

The servo motor is controlled by an MCU (ESP32-WROOM-32D, Espressif Systems Pte. Ltd), which receives current bio-signal data of the patient in real-time. The frequency of pulse can be accurately reproduced by adjusting the interval time of servo activation. Based on the study of heartbeat in medicine, the moment when the human heart contracts last about 230ms (including PR interval and QRS interval), then relax[26]. For this, the tube of the surrogate arm should be squeezed, which is equal to the heart contraction, under 230ms to keep consistent with this time. So the motor, which causes the tube squeezed, its spin time is limited to 230ms. And the rest time depends on the BPM. For example, if the BPM is 60, it means the heartbeat interval is 1000ms, so the relaxed time should be 770ms. Therefore, the reproduced pulse is up to 200BPM (with at least 50ms rest time for motor's gear resetting). Also, the pulse intensity can be controlled by adjusting the rotation angle of the servo at one beat.

Therefore, the servo motor can be activated according to the bio-signal data in order to keep the pulse the same.

2.4.2.3 Reproduction of temperature

While the servo motor system generates the pulse, the temperature on the surface must be felt at the same time in order not to be like touching an icy machine. To present body temperature with natural feelings, a film heater is inserted under the silicone rubber skin to conduct temperature to the surface. Also, to replicate the patient's current temperature, a thermistor detects the surface temperature in real-time, and MUC performs on-off control of the heater in order to follow the patient's body temperature as the target value.

2.4.3 Summary of bio-signal reproduction

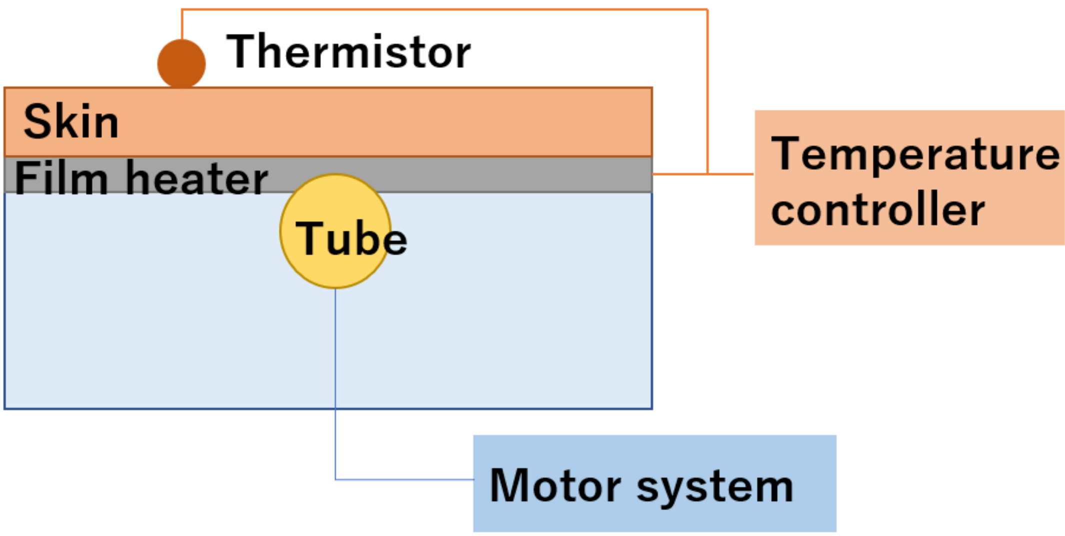


Figure 2.4-6: Cross image

Bio-signal reproduction is unidirectional. The information is obtained from the patient-side and reproduced on the surrogated arm at the doctor-side. At the patient-side, there is a glove equipped with a thermistor and a pulse sensor. The temperature and pulse are calculated in an MCU the send to the doctor-side. Doctor-side has a surrogate arm similar to a human arm. A tube under the wrist connects to a servo motor system. When the motor system works, the tube shrinks and swells, feeling like the pulse beat. The BPM is controlled by an MCU at the doctor-side. Temperature is reproduced by a film heater under the skin. While the patient wears the glove, the same temperature and BPM can be felt on the surrogate arm in real-time.

2.5 System performance and analysis

2.5.1 System specification

The prototype was implemented with the following specification.

- Robot: TX-toolkit with a built-in stereo camera, binaural microphone, speaker, and 3-DOF mechanical system.
- MCU: ESP32-WROOM-32D
- VR headset: Oculus Rift CV2 with Ovrvision
- Sensor: Pulsesensor and NTC thermistor
- Display: Servo motor (GWS S19CLN), and film heater on a surrogate arm.

Table 4: Specification of system

Temperature range measured	0～70℃
Pulse range measured	0～533BPM (Theoretical value)
Temperature range reproduced	Room temperature～63.5℃
Pulse range reproduced	0～200BPM
Video latency of TX-toolkit	100ms
Video latency of Ovrvision	100ms
Motion latency (between HMD and TX-toolkit)	125ms

2.5.2 System performance

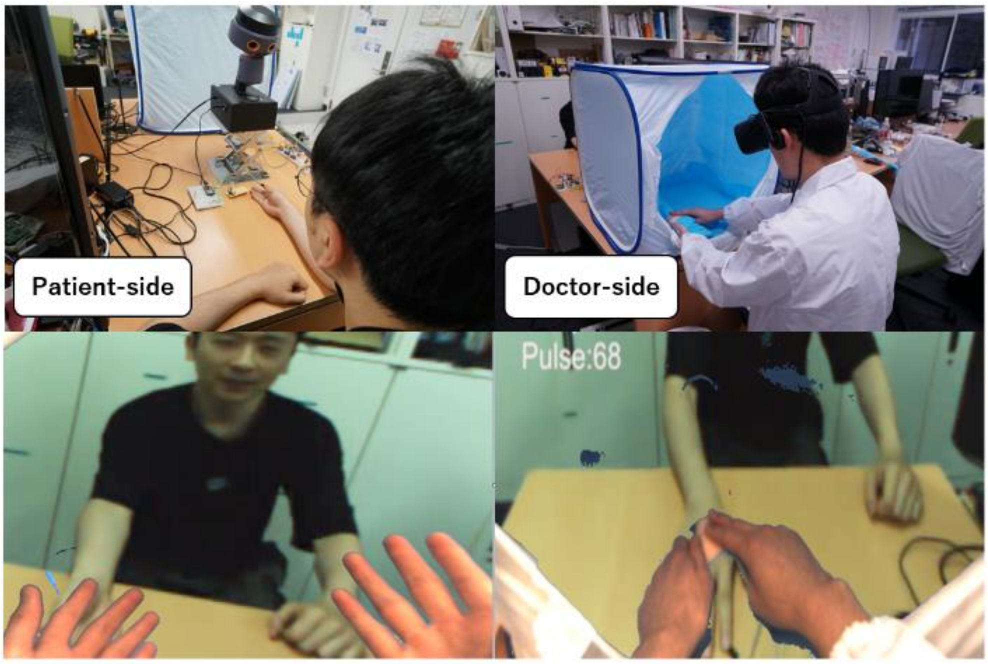


Figure 2.5-1: System in different angles and doctor-side view: Patient-side's image mixed with the doctor's hand

This system achieves a simple application scenario for telediagnosis. The patient sat in front of the TX-toolkit and put his arm on the desk, following the doctor's guidance. At the same time, the doctor faces a blue background box. In the box, the surrogate arm is also in blue. With the Ovrvision, all the background and the surrogate arm will become transparent by using chroma key. Like figure2.5-1, the image is shown on the HMD only contains his own arm and what the robot sees at the patient-side. Therefore, the doctor just like sitting in the same room and naturally put his own arm on the patient's wrist to diagnose. The surrogate arm reproduces the bio-signal got from the patient-side. So, the doctor can feel the warmth and the pulse as he is touching the real arm. By this, the telediagnosis is achieved. The doctor can talk and look freely, making the palpating comfortable and relaxed.

2.5.3 Discussion

Through the actual use and observation of the prototype, there are still many shortcomings and deficiencies.

1) **Visual dislocation in palpation:** Because the TX-toolkit only has 3DOF, it can only synchronize to the movement in terms of head rotation, and cannot track the head position of the doctor. That is, if the doctor moves his/her body, the head position changes from the original position, and the viewpoint also changes; However, the robot just changes the head direction at that time, but the origin of the viewpoint is immovable. It causes the visual dislocation of hand contact on the screen. In other words, the patient side's view moves according to the head movement in the doctor-side, even though doctor-side's view is fixed in the local coordinate system. Therefore, it is challenging to keep hand to hand coincide while performing the virtual palpation. Once the doctor's head position moves, the dislocation of view definitely occurs, leading to some fatal effects on realism.

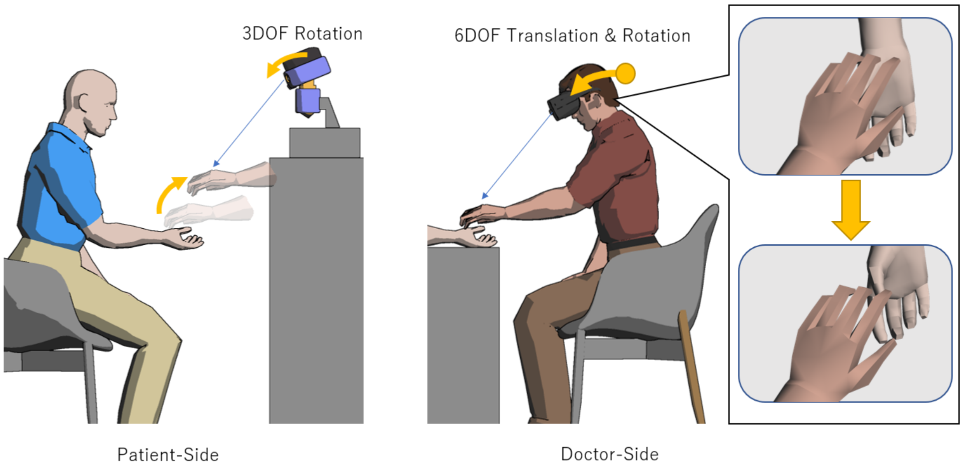


Figure 2.5-2: Visual dislocation

2) **Temperature control:** Due to the lack of a cooling function in the temperature reproduction system, the room temperature severely limits the reproduced range of temperature and influences the performance. When the room temperature is above the body surface temperature, the system will never reach the correct value. Also, only applying on-off control of heater leads the response delay, particularly when the temperature drops suddenly. Also, due to the poor thermal conductivity of silicone, after the temperature reaches the set value. It will still rise for a while and then fall to the correct temperature. Adding a cooling system can accelerate the process.

3) **Head movement:** Although the robot head's rotation is set to rotate the same degree (in roll, pitch, yaw) as the doctor's head, there are many factors that will influence the accuracy. Firstly, the doctor head's rotation is detected by the HMD system; however, all the position and rotation of the HMD is detected by an infrared sensor and accelerometer in itself. This approach is not completely accurate. Besides, the robot head's rotation is accomplished by several servo motors. Due to the limitation of motor capacity, no matter how to set, the motor can not reach the angle completely. There must be errors. It means it is impossible to synchronize the head movement with the robot's, which leading a visual mismatch between the doctor's hand and the patient's hand.

4) **Video resolution:** During the palpation, it can be found that the patient's possible disease manifestations (such as skin color is red or not, etc.) cannot be distinguished clearly. Because to maintain a high frame rate, the video

resolution is fixed at 720p and the HMD itself has not enough resolution. It will make it difficult to diagnose the disease.

5) **Chroma key background:** At the doctor-side, the screen in blue will be replaced by the image from the patient-side. But the screen is too narrow. In anticipation, the doctor's gaze is mainly focused on the surrogate arm. At this point, most of the vision will be replaced. But in reality, when the doctor moves his head, it always beyond the range of the screen, which will cause the doctor still to see his own environment still. It does great damage to the presence.

2.6 Chapter summary

This chapter describes how the telediagnosis system built. The system consists of two parts for the patient and the doctor. Among them, patient-side consists of surrogate robot and sensor unit. The surrogate robot acts surrogate of the doctor as if the patient actually meet the doctor. And the sensor unit measures bio-signals (pulse and temperature) of the patient. On the other hand, doctor-side contains HMD system and surrogate arm. HMD provides immersive experience of the patient’s room. And the surrogate arm is used to reproduce the patient’s pulse and temperature as if the doctor felt actual examination. Through the system, the basic function for achieving telediagnosis is realized; The telexistence experience of the doctor is achieved, and the patient’s vital information including pulse and temperature can be successfully reproduced.

3 Improved telediagnosis system

3.1 Defect and solution

Considering the defects in the prototype, we proposed a new telediagnosis system with many aspects upgraded. According to the 2.5.3, the main defect to influence realism is the visual dislocation in palpation. We focus on this problem and use a 6DOF robot to replace the TX-toolkit to avoid dislocation. We also proposed a new surrogate arm to improve temperature control. Also, there are many improvements in detail.

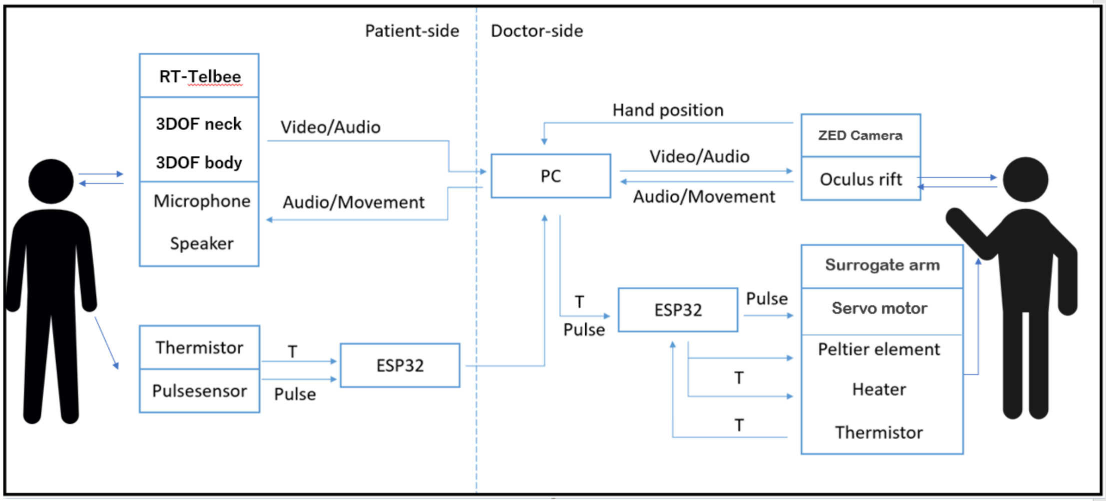


Figure 3.1-1: System data diagram of the improved system

Figure3.1-1 is the system diagram of the improved system. Compared to the prototype, at the patient-side, the robot is replaced by a 6DOF robot named RT-Telbee. At the doctor-side, the stereo camera is replaced by a new one (ZED camera, Stereolabs Inc.)[27] and the new surrogate arm consists of a cooling module collaborating with the heater.

3.2 Audio-Video reproduction

To solve the visual dislocation, it is necessary to replicate the doctor's head movement more to the robot more precisely in order to correspond with their view position. For that reason, the surrogate robot should be updated to a 6 DOF robot which can move the head in terms of both translation and rotation. Also, the palpation position of the surrogate arm relative to the doctor's head position should be accurately defined in order to correspond to the patient's hand position seen in the patient-side's view.

3.2.1 Patient -side: RT-Telbee

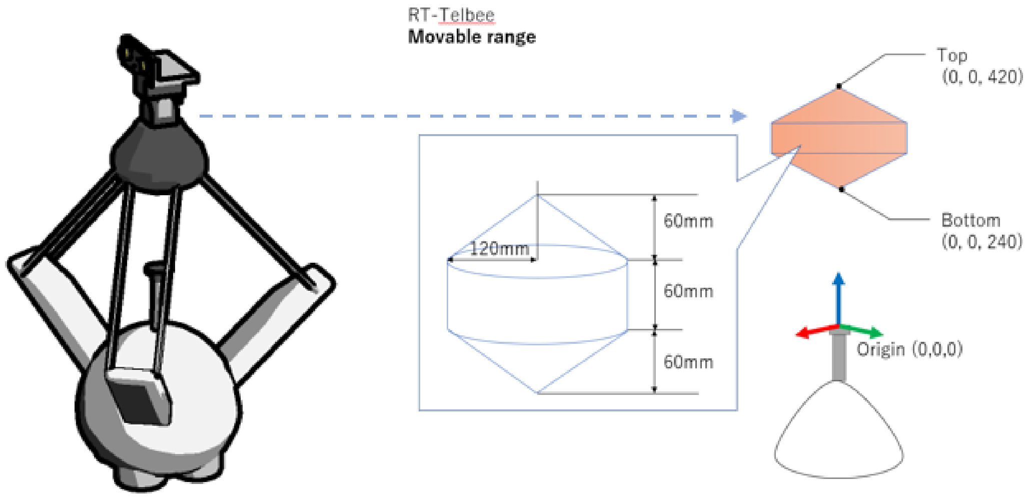


Figure 3.2-1: The 6 DOF robot: RT-Telbee and its movable range

As mentioned above, the surrogate robot should provide head translation function as well as a head rotation for precise head tracking. Therefore a custom-developed robot named RT-Telbee, which has these 6DOF motion functions with telecommunication functions the same as a previous robot (figure2.3-1, Table 2), is applied for the improved system. In comparison to the previous 3DOF robot, the robot has a parallel link mechanism to realize the three-dimensional translation of head-part. Besides the function, the robot is equipped with the same functions of the previous robot (head rotation, master-slave control, and audio-video telecommunication) to be used for telexitence application. That is, the robot's head can reproduce both the doctor's head position (x, y, z) and rotation angles (roll, pitch, yaw) in order to realize precise head motion tracking. The control signals of the doctor's motion are recorded by HMD's position tracking sensor as well as attitude sensor.

Table 5: Specification of RT-Telbee

Head	Degree of Freedom	3
	Maximum angular velocity	95rpm
	Range of movement	Roll: ±51.6deg Pitch: -40deg ~ +60deg Yaw: ±100deg
Delta mechanism Velocity		x: 70cm/s y: 60cm/s

The stereo camera is attached to the robot's head. The previous camera is replaced by the ZED mini. This new stereo camera has a higher resolution and more accessible to be used.

Table 6: Specification of ZED mini

Dimensions	124.5 x 30.5 x 26.5 mm
Weight	62.9 g
Field of View	90° (H) x 60° (V) x 100° (D) max.
Video Output	2.2K 15FPS, 1080P 30FPS, 720P 60FPS, WVGA 100FPS

3.2.1.1 Coordinate transformation

The position data of the doctor's head measured by the HMD's sensor is not compatible with the new surrogate robot, because the coordinate systems used in the robot control system is different from the head motion measurement system. Furthermore, the rotation orders of Euler angles are also different between them. These differences bring the necessity of coordinate transformation. The straightforward transformation is shown below.

First of all, the axes of the two coordinate systems should be unified. The robot control system is described by the right-handed system commonly used in the context of robotics (X-forward, Y-left, Z-up) whereas the measurement system is based on the left-handed system commonly used in computer graphics (Z-forward, X-right, Y-up). The difference between the two coordinate systems is shown as follows.

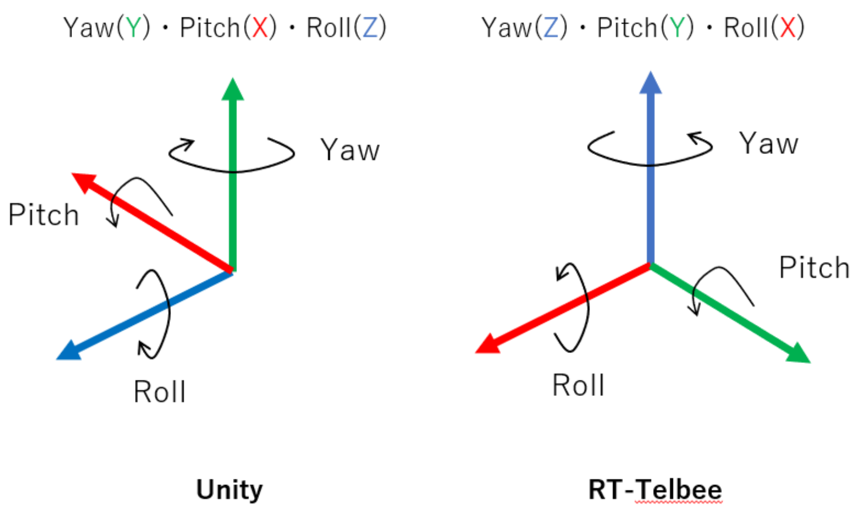


Figure 3.2-2: the coordinate system of Unity and RT-Telbee

As shown in the figure3.2-2, the correspondence of axes between two coordinate systems can be determined. That is, the rotation direction of them are inverted except for the pitch-axis.

$$\text{Yaw : RotY}_{\text{unity}} = -\text{RotZ}_{\text{robot}}$$

$$\text{Pitch: RotX}_{\text{unity}} = +\text{RotY}_{\text{robot}}$$

$$\text{Roll: RotZ}_{\text{unity}} = -\text{RotX}_{\text{robot}}$$

After unifying these coordinate systems, it is also necessary to calculate the multiplication of rotation matrix to obtain conversion fomula of the Euler angles. This is because the order of rotation is also a difference between the robot system (roll→pitch→yaw) and the measurement system (yaw→pitch→roll), meaning that these angles are incompatible to each other. What we have to know is how the rotation matrixes of them after applying the 3-axis rotation keeps the same regardless of the rotation order. It means no matter how it rotates, the rotation matrix always be the same between the position before and after.

$$ {}^{mes\_before}_{mes\_after}T = {}^{robot\_before}_{robot\_after}T $$

To obtain the same representation of rotation, we have to calculate the conversion equation of the Euler angles in different rotation orders. Figure 2.5-1 illustrates the difference in rotation order.

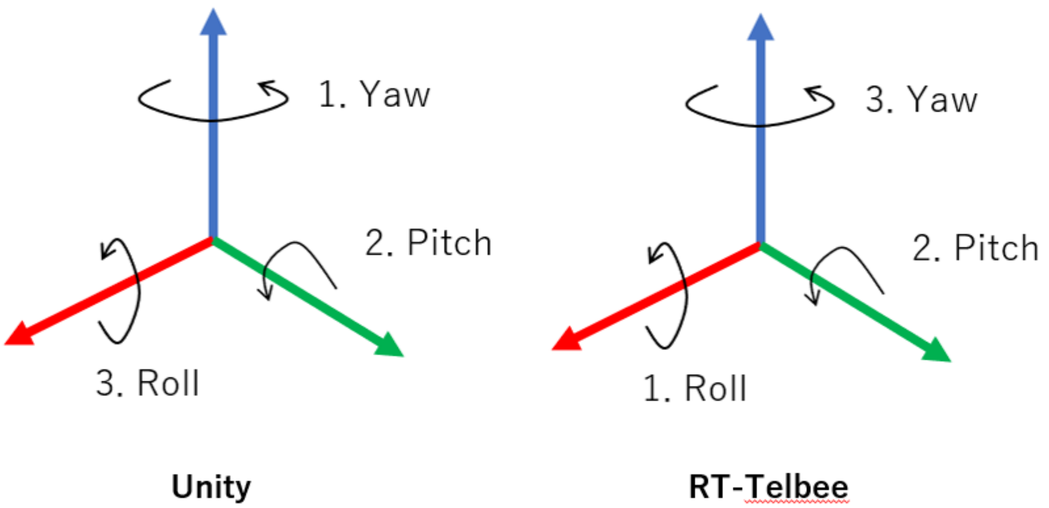


Figure 3.2-3: Rotation order in Unity and RT-Telbee

The rotation matrixes of them are calculated by matrix multiplication of single-axis rotations. In the measurement system, yaw, pitch, and roll axis rotation are severally described as below;

$$ Rot\left(yaw_{mes}\right) = \begin{bmatrix} cosz_{mes} & -sinz_{mes} & 0 \\ sinz_{mes} & cosz_{mes} & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (3) $$

$$Rot\left(pitch_{mes}\right) = \begin{bmatrix} cosy_{mes} & 0 & siny_{mes} \\ 0 & 1 & 0 \\ -siny_{mes} & 0 & cosy_{mes} \end{bmatrix} \quad (4)$$

$$Rot\left(roll_{mes}\right) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cosx_{mes} & -sinx_{mes} \\ 0 & sinx_{mes} & cosx_{mes} \end{bmatrix} \quad (5)$$

By contrast, roll, pitch, and yaw rotation in the robot system are severally described as below;

$$Rot\left(roll_{robot}\right) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cosx_{robot} & -sinx_{robot} \\ 0 & sinx_{robot} & cosx_{robot} \end{bmatrix} \quad (6)$$

$$Rot\left(pitch_{robot}\right) = \begin{bmatrix} cosy_{robot} & 0 & siny_{robot} \\ 0 & 1 & 0 \\ -siny_{robot} & 0 & cosy_{robot} \end{bmatrix} \quad (7)$$

$$Rot\left(yaw_{robot}\right) = \begin{bmatrix} cosz_{robot} & -sinz_{robot} & 0 \\ sinz_{robot} & cosz_{robot} & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (8)$$

According to the rotation order, the conclusive rotation matrixes of them are obtained by multiplying the single rotation matrixes from left to right as below.

$$R_{mes} = Rot(Z_{mes}) \times Rot(Y_{mes}) \times R(X_{mes})$$

$$=$$

$$\begin{bmatrix} cz_{mes}cy_{mes} & cz_{mes}sy_{mes}sx_{mes} - sz_{mes}cx_{mes} & cz_{mes}sy_{mes}cx_{mes} + sz_{mes}sx_{mes} \\ sz_{mes}cy_{mes} & -sz_{mes}sy_{mes}sx_{mes} + cz_{mes}cx_{mes} & -sz_{mes}sy_{mes}cx_{mes} - cz_{mes}sx_{mes} \\ -sy_{mes} & cy_{mes}sx_{mes} & cy_{mes}cx_{mes} \end{bmatrix} \quad (9)$$

$$R_{robot} = R(X_{robot}) \times Rot(Y_{robot}) \times Rot(Z_{robot})$$

$$=$$

$$\begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix} \quad (10)$$

Where

$m_{11} = cy_{robot}cz_{robot}$

$m_{12} = -cy_{robot}sz_{robot}$

$m_{13} = sy_{robot}$

$m_{21} = sx_{robot}sy_{robot}cz_{robot} + cx_{robot}sz_{robot}$

$m_{22} = -sx_{robot}sy_{robot}sz_{robot} + cx_{robot}cz_{robot}$

$m_{23} = -sx_{robot}cy_{robot}$

$m_{31} = -cx_{robot}sy_{robot}cz_{robot} + sx_{robot}sz_{robot}$

$m_{32} = cx_{robot}sy_{robot}sz_{robot} + sx_{robot}cz_{robot}$

$m_{33} = cx_{robot}cy_{robot}$

Here, assuming that the elements of the two rotation matrixes are identical, the conversion equations between Euler angles in different rotation orders are found as below.

$$\mathrm{X_{robot}} = \tan^{-1}\frac{-m_{2,3}}{m_{3,3}} = \tan^{-1}\frac{\sin(z_{mes})\sin(y_{mes})\cos(x_{mes}) - \cos(y_{mes})\sin(x_{mes})}{\cos(y_{mes})\cos(x_{mes})} \tag{11}$$

$$\mathrm{Y_{robot}} = \sin^{-1} m_{1,3} = \tan^{-1}\left(\cos(z_{mes})\sin(y_{mes})\cos(x_{mes}) - \sin(z_{mes})\sin(x_{mes})\right) \tag{12}$$

$$\mathrm{Z_{robot}} = \tan^{-1}\frac{-m_{1,2}}{m_{1,1}} = \tan^{-1}\frac{\cos(x_{mes})\sin(z_{mes}) - \sin(x_{mes})\sin(y_{mes})\cos(z_{mes})}{\cos(z_{mes})\cos(x_{mes})} \tag{13}$$

By applying these transformations, the measurement data of HMD are adjusted, and the position and attitude of the robot's head are correctly matched with the doctor's head in real-time.

3.2.2 Doctor-side

3.2.2.1 Update of the video presentation system

Same as the robot's camera, the HMD-attached camera for video-see through is replaced to ZED-mini keep the video qualities of the video data of the patient-side is transmitted to the doctor-side via IP network (Ethernet), while those of the doctor-side is captured directly (USB 3.0). These two camera images are composited to realize the mixed-reality scene.

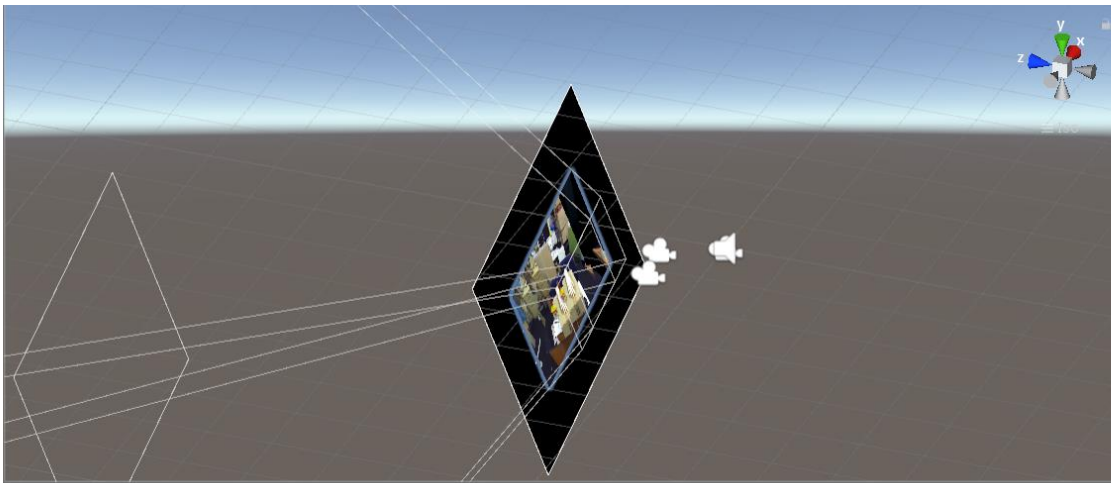


Figure 3.2-4: Scene in Unity project

In the VR scene, there are two screens and two cameras. Remote video streaming is shown on one screen, which has a higher rendering priority. Local video is shown on another screen. The two screens overlap with each other. Because of the remote screen's higher rendering priority, it will be rendered first. The local screen will be rendered later and cover the remote screen. Through chroma key, which is the same as the prototype, the pixel in blue will be discarded to expose the remote screen at the back. In this way, the object in local and the surrounds in remote will be combined to construct an MR space as figure3.2-5.

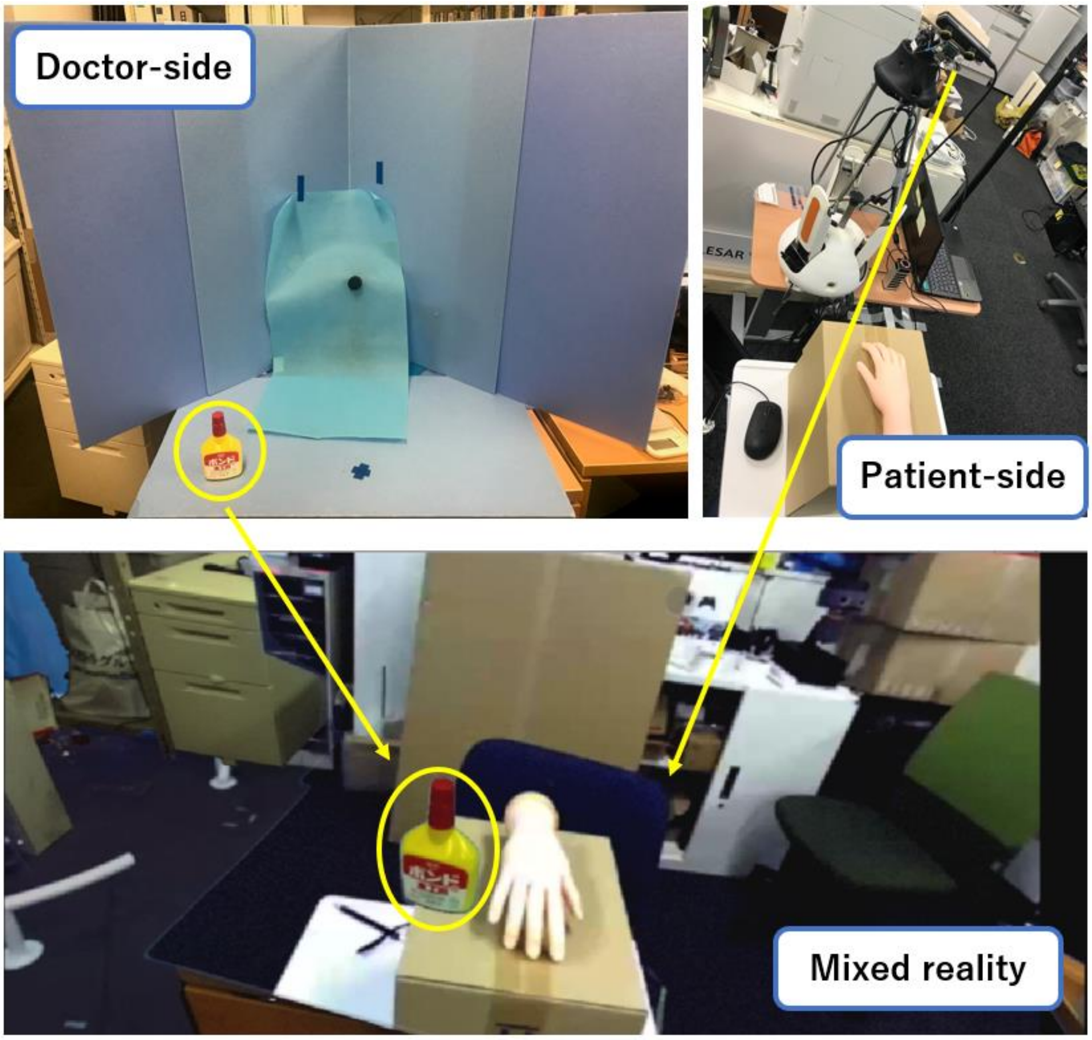


Figure 3.2-5: Mixed reality in the HMD

3.2.2.2 Field of View Adjustment

In the test, the patient sits down with the robot face to face and out his arm on the desk naturally. We found when the doctor looked down, it was hard to see the patient's hand. It is because the hand's position has already beyond the robot's camera's field of view(FOV). The vertical range of the visual field in humans is around 150 degrees[28]. But the ZED camera only has a view of about 60 degrees in vertical. And the RT-Telbee has a limitation in movement of pitch about 40 degrees. For this, when in the normal sitting position, it's difficult to see the patient's hand.

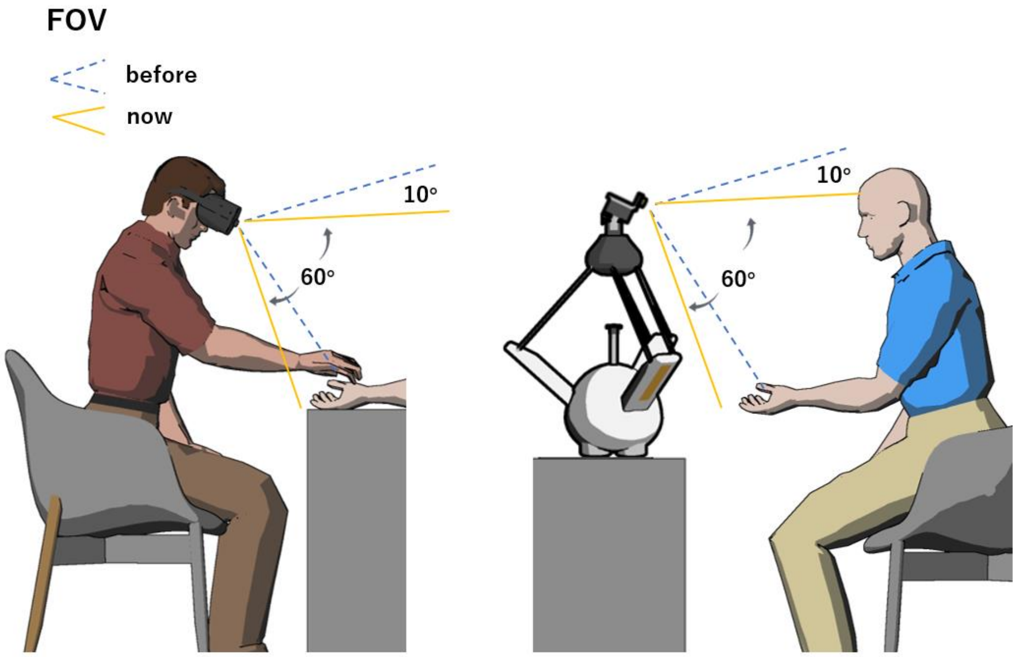


Figure 3.2-6: Adjustment of FOV

In this respect, we have to adjust the camera angle. As shown in the figure3.2-6. We make the camera both the patient-side and the doctor-side have a 10 degrees slope in pitch. After that, doctor-side can obtain a better view, when moving his head, he can see the patient's hand and his face.

3.3 Bio-signal reproduction

This part basically keeps the same as the prototype. But the system has many improvements in detail. Besides, to solve the second defect, we proposed a new device to replace the old surrogate arm. At the patient-side, the sensor unit has no change. So the following mainly describes how doctor-side changes.

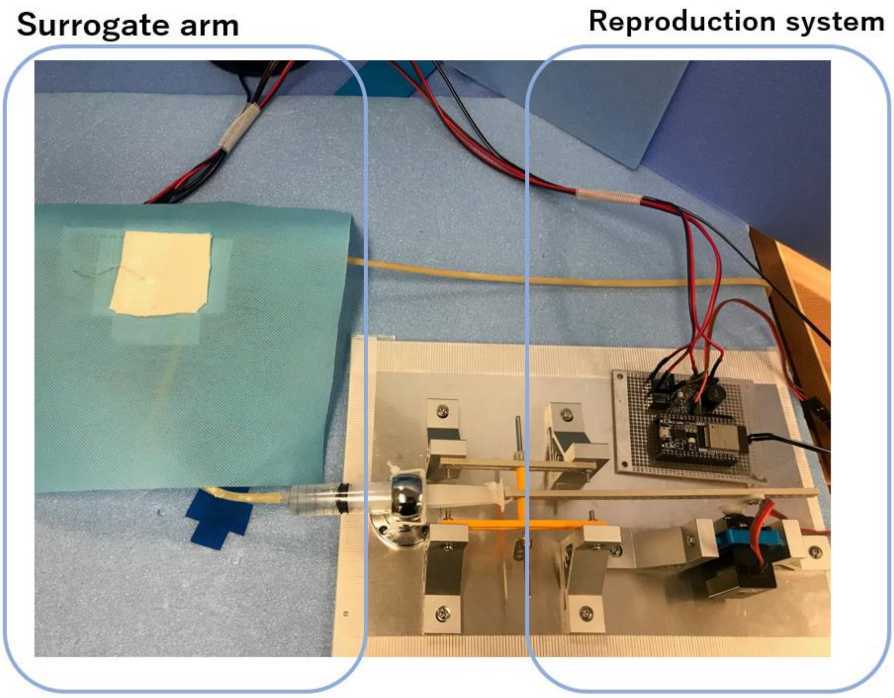


Figure 3.3-1: Overview of the updated bio-signal reproduction part

3.3.1 Update of doctor-side

At first, we reinforced the structure of the servo motor system. Before the crank mechanism and chassis are in plastic, which causes this part cannot afford the motor running for a long time. To enhance stability, we reworked this part. Using metal parts substitute the plastic parts; when servo running, vibration will be less than before, allowing the system to run longer.

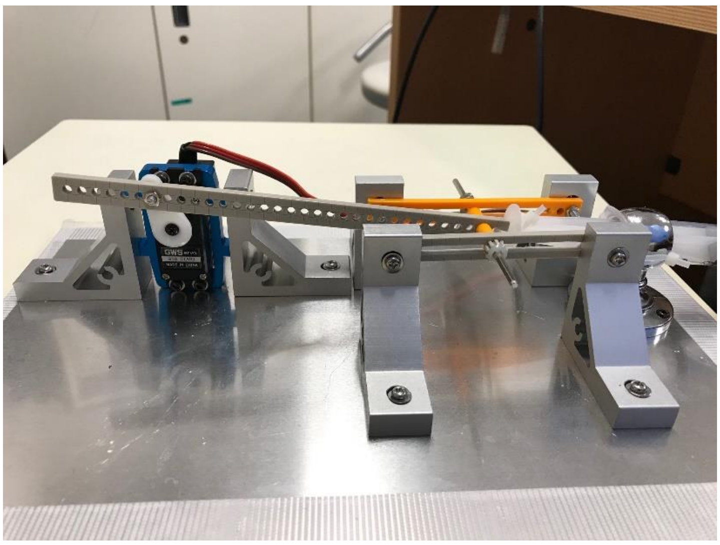


Figure 3.3-2: Servo motor system rebuilt in metal

3.3.1.1 A new type of surrogate arm

In the experience of the prototype, it can be recognized that the surrogate in what kind of shape does not matter. The whole arm is twined with cloth in blue except for the wrist. The doctor can not figure out the shape of the surrogate arm at all. Because the shape of the human hand is complicated, when the doctor touches the dummy hand part by coincidence, the touching feedback is always different from it supposed to be (the supposed feeling is generated by judging the relative position between the doctor's hand and the patient's hand on the HMD's screen). Under this situation, realism will lose a lot. Therefore, using a smaller module rather than the whole arm, not only become more convenient but also avoid this trouble.

To mitigate the influence of room temperature, there must be a cooling module under the skin. The new structure of the surrogate arm is shown in the figure3.3-4.

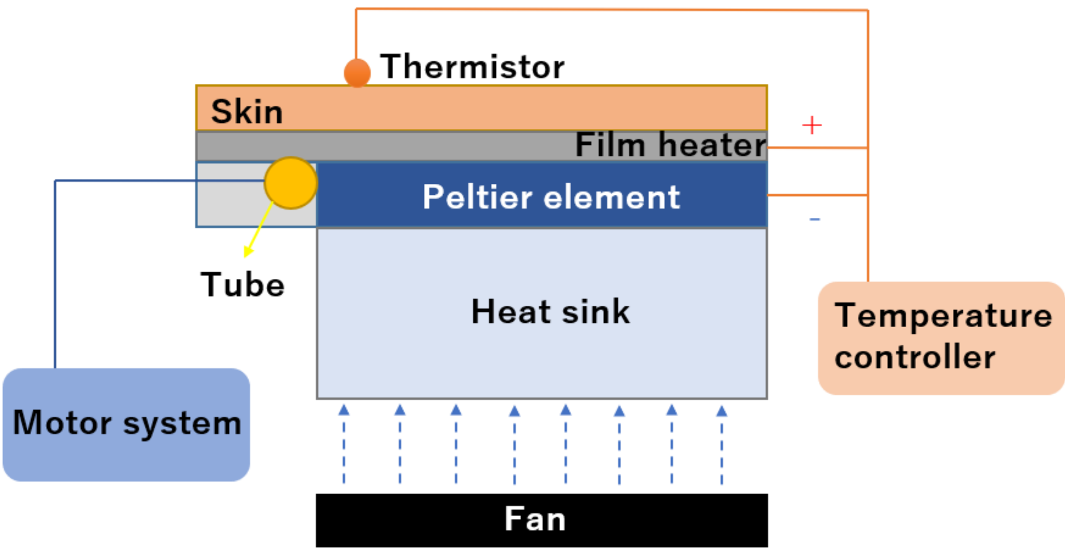


Figure 3.3-3: Cross image of the new surrogate arm

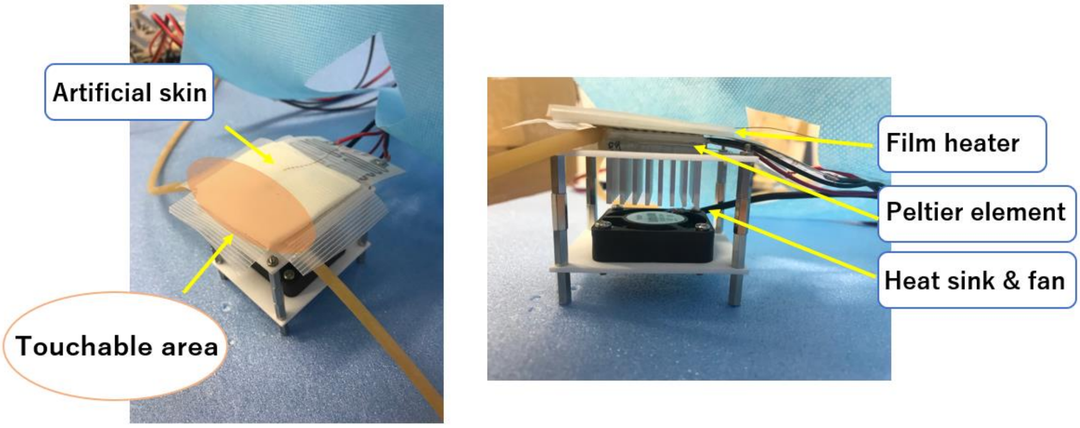


Figure 3.3-4: Constucture of surrogate arm

Hierarchy keeps the same as before. The top layer is artificial skin. In order to improve realism, make the touch more like real human skin, the artificial skin is made from silicone and hardener mixed in a specific ratio. The thickness is about 2mm to allow the temperature to be transmitted to the surface. Under the skin, a film heater is attached as before. A silicone tube is buried beneath the heater. The silicone tube plays the role of the artery as the prototype. Next to the tube places a 3cm×3cm Peltier element. When powering it up, one side of the Peltier element will become cold quickly. The other side will release a lot of heat simultaneously. Thus, to maintain the cold surface, there must be a heat sink attached to the hot side. The heat sink makes up the module's base. The whole device is a 6cm×6cm×6cm cube, which is much smaller than the silicone arm.

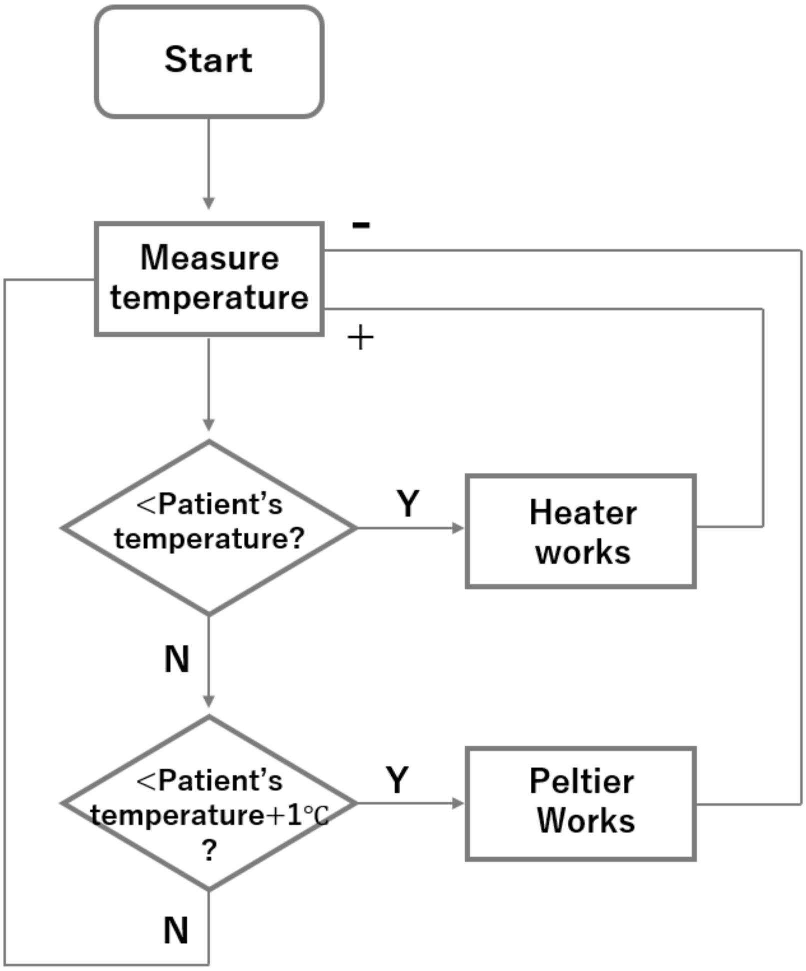


Figure 3.3-5: Flow chart of temperature control

The control loop is shown as above. When the surrogate wrist's temperature is less than the patient's temperature, heater works, heating the skin to the same temperature. If the temperature is 2℃ higher, the Peltier will work, accelerating the cooling process. The two components work together to maintain the skin at a stable temperature.

3.4 System defect and improvement

After the essential functions of the system are completed, the system experience cannot reach the expected level. In response to various problems, various subsequent adjustments were made to optimize the system further.

3.4.1 Improvement of video stability

At the doctor-side, when the doctor moves his head, the view on the HMD constantly shakes, which causes an uncomfortable feeling and terrible user experience. There are many reasons to account for this problem.

- Oculus rift cv2 uses an infrared ray to track the HMD's position. The obtained data has specific errors and fluctuations. This data will be sent to the RT-Telbee ultimately. The errors and fluctuations cause the robot to move discontinuously. To smooth the data change of position, in the RT-Telbee, added a low pass IIR filter. Robot's moving speed is limited to under 3Hz, which is similar to humans. By this, abnormal data can be filtered out. The view shown on the HMD can be more stable.
- RT-Telbee has a built-in timer based on Windows. This timer is limited to at least 15ms per loop. It means the robot's refresh rate up to 60Hz. The robot receives the data up to 60Hz. So we use a new timer to replace the built-in timer. The loop interval is shortened to 3ms. With the faster timer, received position data will be steadier.
- RT-Telbee is a 6DOF robot. All the movements are achieved by 6 servo motor. Gears in the motor are not wholly meshed. When the robot tries to get to a specified position, the servo motors will adjust its angle continuously. The uncomplete mesh will cause the shaking of the robot when the motion slows down. Servo motor movements are influenced by the PID parameter. If the parameter is set too smooth, the move will be slow down correspondingly. The latency at the doctor-side will cause a loss in realism. So, we need to adjust the PID parameter to a suitable value.
- Also, there are three springs used to decreasing the robot's shaking. Replacing by a set of springs in a bigger spring coefficient can improve the performance.

3.4.2 Video latency

For a telexistence system, system latency is one of the issues that cannot be ignored. Due to the transmission delay, the robot's motion delay, the latency cannot be avoided. It is a significant problem to get ethical realism with such delays. The system is a master-slave system. The video shown on the HMD mixed the patient-side with the doctor-side. If the two sides have different delays, the feeling will be extraordinary. For example, the doctor put his hand on patient's wrist in the HMD, when he moves his head because the local side has a lower delay, his hand will keep moving with his head, but the remote scene due to the high delay will keep still for a while then start moving. This will cause a misalignment of the relative position. The realism is very wired.

While the remote delay cannot be reduced to the same as the local, we tried to increase the local delay to keep the same as the remote. We added a video buffer into the camera at the doctor-side. Local videos will be delayed for a while. But with the local delay increasing, the slow response in the HMD will also do significant damage to the realism. To avoid this problem, we let the local delay varies according to a different situation.

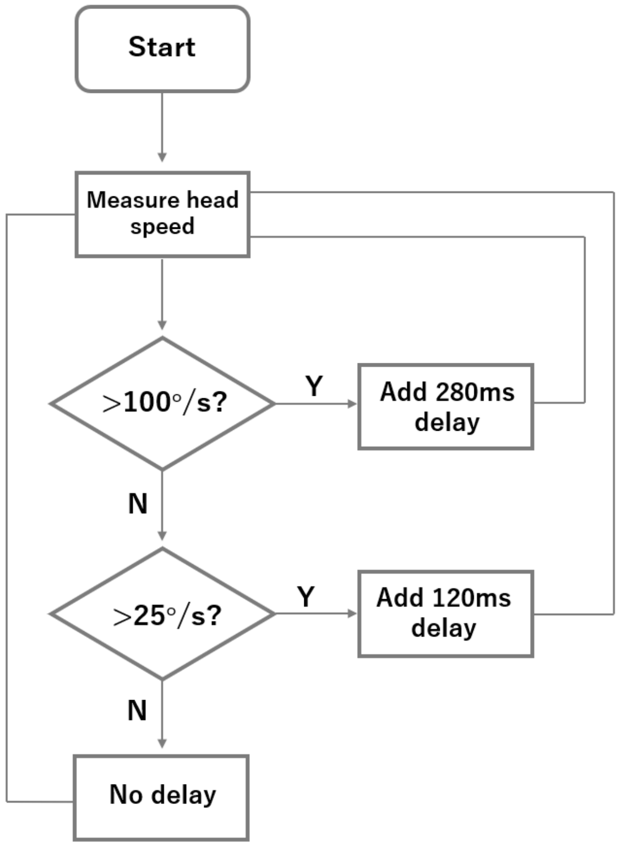


Figure 3.4-1: Flow chart of delay adding

When the doctor's head moves fast (Rotation higher than 100°/s), the local delay gradually increases to maximum, which is the same as the patient-side. When the doctor's moving not so fast (Rotation higher than 25°/s), the delay increases to half of the maximum. And when the doctor merely doesn't move, the added delay will be 0. In this way, visual strangeness can be reduced significantly.

3.5 System performance and analysis

3.5.1 System specification

The prototype was implemented with the following specification.

- Robot: RT-Telbee (6 DOF robot) with ZED camera
- MCU: ESP32-WROOM-32D
- VR headset: Oculus Rift CV2 with ZED camera
- Sensor: Pulsesensor and NTC thermistor
- Display: Servo motor (GWS S19CLN), film heater, and 3cm×3cm Peltier element on a surrogate arm.

3.5.2 System work process

The work process basically the same as the prototype. The patient sits in front of the RT-Telbee, which is the surrogate of the doctor. The doctor sits opposite a blue panel. He can see and communicate with the patient through the robot. By chroma key, the doctor can also see his own body. He just needs to put his hand on the wrist shown on the HMD to palpate. Even if the doctor's head moves, the RT-Telbee will also act the same move to keep the relative position in the HMD. The surrogate arm reproduces the bio-signal got from the patient-side. If the patient's temperature higher than the surrogate arm, the Peltier will work to cool it down. The doctor can feel the warmth, the pulse, and the soft feeling of the artificial skin, making the palpating more free and real.

3.6 Chapter summary

In this chapter, improved VR telediagnosis system was developed to solve concerns about the system's defects found in the prototype. The proposed system achieves following improvements; It replaced the TX-toolkit (3DOF) with RT-Telbee (6DOF). The additional 3DOF ensures that when the doctor moves his head in position, the robot will do the same to keep the relative position as before. In addition, we proposed a new surrogate arm. The new one equips a cooling module, which allows the device to work in a broader temperature range and gets faster to the set temperature. To have a better user experience, we adjusted many parts in detail. The field of view of the robot's camera tilted down 10 degrees in vertical for showing wide view of the patient particularly his/her hand. Also, video buffer is used to solve the latency problem. All of these modifications bring excellent benefit to the increasing of realism.

4 Experiments

4.1 Purpose

To test this telexistence based telediagnosis system is useful or not, in detail, compared to the traditional telediagnosis system, this system have a better realism or not, with a tactile display can this system brings more clues and do benefits to the telediagnosis, we did an experiment of using both of this system and a traditional videophone. All the participants should be medical staff or have a medical background. Only If they have an experience of diagnosis, the results of this experiment can be valuable. Through questionnaires and inquiries after the experiment, we can realize the value and defects this system has, what role the telexistence and tactile play, and how much can it do to help telediagnosis.

4.2 Method

The whole process of the experiment is a simulation of an actual diagnosis. There will be a patient communicating with the participant. And they have two medical records prepared in advance. The diagnosis process is like in actual. After the diagnosis, there will be a questionnaire to evaluate the system they used before.

The entire experiment was divided into two parts; every participant is required to make the same diagnosis in each part. The difference between the two pats is that in one part, the participant uses this new telediagnosis system to communicate with the patient. In the other part, they are asked to use the traditional videophone. By controlling the variable, we can find out the difference between the two systems.

4.2.1 Participants

Three medical personnel who had a medical license (Medical doctors = 10, nurses = 2) participated in the experiment because the proposed system had to be tested by the experts of clinical examination. After receiving instructions and explanation, they gave written informed consent. They received a gift voucher equivalent to 3,000 Yen as the reward of participation. This research was approved by the ethics committee of the University of Tokyo.

4.2.2 Evaluation items

While participants experience the telediagnosis system, the subjective impressions about the system were evaluated by using questionnaires as below.

Q1. I felt as if I were actually in the room where the patient is in.

Q2. I felt as if the patient were actually in front of me.

Q3. I felt as if the medical examination was actually performed.

Q4. I felt tense while performing a medical examination.

Each statement is established for clarifying (1) the sense of presence about own existence, (2) sense of presence about other's existence, (3) sense of reality about medical examination, and (4) sense of tension for medical examination, respectively.

After the questionnaire completed in VR telediagnosis and skype. There are 2 questionnaires about the impression of the VR telediagnosis system and the influence after they using the VR system. The general items about the impression are as follows:

Q1. Have you experienced other telemedicine systems?

(If Q1 yes) Q2.1 Compared to that, does this system have a better realism?

(If Q1 no) Q2.1 Does this system have a realism of diagnosis?

Q3. Is VR useful for diagnosing the patient?

Q4. Is tactile display useful for diagnosing the patient?

Q5. Do you want to try the Telediagnosis system in actual practice?

Q1 and Q2 are established for the evaluation of the realism of the system. Q3 and Q4 are the usefulness of VR and tactile display. Q5 is to test if the system has practical application value now.

The last questionnaire asks whether the user has a VR sickness or not after using the telediagnosis system. For example, the symptoms like nausea, oculomotor, disorientation are asked.

4.2.3 Procedure

At first, participants wore the HMD and then sat down in front of the experimental booth, where the chroma-key screen and the tactile display were placed. After performing position adjustment, the experimenter started the system. While working the system, participants saw both their own hands and the other experimenter who pretended to act patient. Also, participants could talk with the patient through the system. The task of the participants was to perform a standard medical examination by interview. While performing the examination, participants asked to let the patient use a commercially available pulse-oximeter (Oximan S114, SEASTAR CORPORATION) and tell the information. Also, by using the tactile display, participants were asked to touch the tactile display for performing virtual palpation. Note that the position of the tactile display was exactly fixed to match the position of the touchable area seen in the camera image with the position of the patient's right wrist. After performing the medical examination, participants were asked to answer the questionnaires about subjective impressions based on a 7-point Likert scale ranging from -3 (strongly disagree) to +3 (strongly agree). Besides the system's evaluation, Simulator Sickness Questionnaires (SSQ) was examined to check the stress of the VR experience. The procedure described above lasted at least 30 minutes.

For investigating the merit of the proposed system in comparison with the conventional videophone-based telecommunication system, almost the same experiment was performed separately by using Skype. The evaluation of the conventional system was performed before or after participants experienced the proposed system; The order was randomized for each participant. Except for the absence of an immersive 3D view of HMD and virtual palpation, the procedure of the experiment was the same for the proposed VR system.

After finishing the evaluations for these two system configurations, general questionnaires about (1) experienced for other telemedicine systems, (2) realism of VR examination, (3) usefulness of VR telemedicine, (4) usefulness of tactile display, and (5) desire of system use. Each statement was asked to be answered "Yes" or "No."

4.3 Results and Discussion

Figure4.3-1 shows the average of each evaluation item.

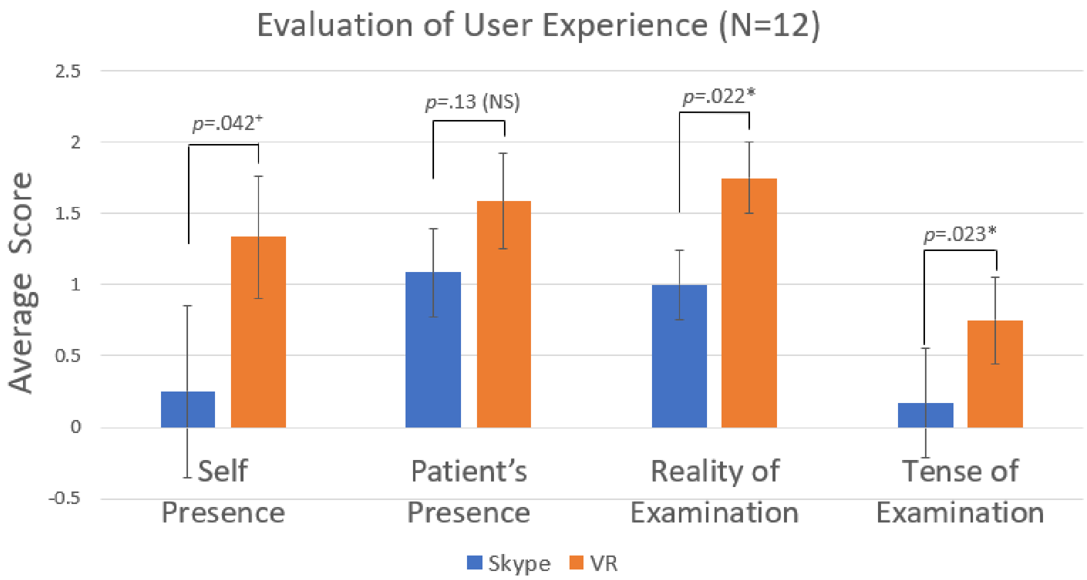


Figure 4.3-1: Evaluation of User Experience

According to the evaluation of the 12 experts, we can clearly see that the scores for the VR system are significantly better than the videophone system except for the question2 "patient's presence".

For the first question, the score of self-presence in this VR system is much better than the videophone. It means that the telexistence is accomplished; the user's presence is successfully transferred to a remote place. This difference is benefit from the high immersion of the telexistence system; while the participant moves his body, what he sees will also change according to his movements. When the participant reaches out, he can also feel the tactile feedback. In the videophone, these features cannot be realized. All of these ensure the system have a better self-presence. During the experiment of the VR system, we noticed that doctors sometimes tried to read the medical record. But due to the poor quality of the image in the HMD, it is hard to recognize the text clearly. If the video quality can be upgraded or add a virtual medical record as an MR object to allow the doctor to read the text naturally and comfortably, the self-presence can be further improved.

Secondly, regarding the presence of the patient, the difference between the two average scores is not so obvious. And through the t-test, the p-value is also much higher in 0.13. From the interview after the examination, we know that the main reason which causes this situation is the image quality in HMD. The vision in the HMD, which is cached by the stereo camera, is stereopsis like a human. It supposed to be better than videophone in presence. The reason why many experts evaluated the VR system lower is probably due to the quality degradation of head tracking while performing the examination. According to the observation of experimenters, when the expert looked down for palpation, the angles of the head of the expert sometimes tilted beyond the motion range of the robot, causing visual dislocation. The pulse and temperature can be felt, but the touched place wasn't the wrist in the participant's perspective. This inconsistent feeling will significantly decrease the presence of the patient. In addition, compared to question 1, although both the image of two sides are cached by the stereo camera, the local side's image quality is usually better than the remote side benefited from the transmission method and less noise. So, it makes sense that the performance of self-presence is much better than the presence of the patients. Also, the tactile display also does an indispensable devotion to the score of question 1.

Thirdly, regarding the realism of examination, the experts show a positive overall judgment. It means that, by using the VR system, the participants could have a more realistic feel for the examination. This questionnaire item refers to their usual consultation experience. Because all participated, experts are medical staff with a lot of experience of diagnosis at hospital, compare those two systems with their daily diagnosis, the score can be graded easily.

Fourthly, the scores of tension show an important difference between these two methods. The tension here means the level they devoted to this telediagnosis. It reflects how serious the experts treat the process of the diagnosis in a certain degree. Before the experiment, we want to find something as the index of the concentration during the examination. After discussing with medical staff, we assumed that the actual medical practice brings some amount of mental stress for the medical staff, the more tension the more concentration[29]. From the result, we can see the VR system brings more stress clearly. As our thought, it means the experts treat it more seriously and more like the actual diagnosis. But according to the interview after the experiment, some participants said that the unfamiliar experience in VR environment will also bring some stress. This influence should also be count into this result.

Next, the result of general questionnaires is summarized in Table7.

Table 7: Answer of questionaire2

	YES	NO
Q1: Have you ever experienced another telemedicine system?	*1*	*11*
Q2.1: If Q1 is "YES," do you think the VR system is more real?	*1*	*0*
Q2.2: If Q1 is "NO," do you think the VR system is real?	*10*	*1*
Q3: Do you think VR experience is useful for the examination?	*12*	*0*
Q4: Do you think the tactile display is useful for the examination?	*10*	*1*
Q5: Do you want to use a VR telediagnosis system?	*11*	*1*

As shown in the table, most of the participants have never used similar telemedicine system including videophone before. However, some of them told that they sometimes perform the examination by using a telephone. This suggests that even the videophone for clinical examination has not become popular yet, currently. Also, most of them agreed that the VR system presented realistic experience like an actual examination. Furthermore, they generally showed a positive attitude to the VR system with the tactile display and agreed on the usefulness of the system for the clinical examination. Therefore, most of them answered that they wanted to try the VR telediagnosis system in real practice.

According to the questionnaire results, the experts seemed to evaluate the proposed system higher. However, interview hearing from them revealed that the positive evaluation is likely to include expectations of the VR telediagnosis system developed in the future. This is because many of them pointed out the problems of the current system particularly in terms of the quality of video image. Even though some of them answered positive evaluation of the system in questionnaires, they also said later that the view of the VR system was poorer than the videophone. There are many factors for their inconsistent evaluation. Firstly, the resolution of the HMD used in the system is still insufficient to provide a clear view in comparison with the normal PC display used for the videophone. Also, the quality of the video image captured by the stereo camera is also still poor. Secondary, because the robot's head movement has delay and vibration, the video images of the VR system were degraded. These can cause uncomfortable and unrealistic feelings to the experts during the examination[30]. However, the limitations caused by the hardware's issues can be solved by the improvement of them. Also, if they kept their heads steady, the degradation of the video image disappeared. With many sensory clues such as immersive stereo view and touch, it is probable that they can convince the usability of the VR telediagnosis, even though the current system is still developing. In fact, we got many comments on the current system limitations. For example, the skin's color is often used to judge the presence of symptoms such as inflammation. Therefore, chromatic aberration of the camera image obstructs the correct judgment of the expert. One of them claimed that chromatic clues must be presented more correctly. Actually, the determining process of disease is complicated. Therefore, to derive a correct conclusion, it is necessary to obtain many kinds of bio-signal with high accuracy. Only with enough information about the patient, the doctor can make confident to determine the disease. In that sense, palpating the heart rate and body temperature is obviously insufficient to make them confident. According to the comment of one participant, the skin's thickness, hardness and the moisture of the skin surface always do help to the diagnosis. To achieve a more realistic system, more functions should be added like those.

After the interview of the 12 experts, we realized that this system achieved many useful features in telediagnosis and can be developed one step further. Some experts said they feel the pulse and temperature on the wrist can be felt clearly and naturally. It shows that the reproduction of bio-signal is feasible. But according to their repercussions, the diagnosis should contain more items. Nowadays, the medical staff does the palpation not only on the patient's wrist but always on the neck, foot, and other pats either. These areas are more effective for judging local lesions. So, this system should have wilder applicability. Since the surrogate in what kind of shape does not matter, it may be improved to adapt more reproduction of bio-signal.

In the opinion of the experts, the patient is expected to be diagnosed directly because many problems won't notice if not face to face. It means the telediagnosis must provide information as much as possible, that is the advantage of VR telediagnosis compared to the videophone. This kind of system should not be limited to telediagnosis, the high reality also does great help to medical training. Using this system for some medical student or in the education of medical training, it will help them to improve their diagnosis skill or other ability.

Some experts have experiences of diagnosis at the patient's home. It's very inconvenient they said. Telediagnosis can solve the difficulty of distance. And considering the cost, there is no need for every home to have a surrogate robot. People with reduced mobility are usually elderly, the surrogate robot can be placed in elderly communities to reduce the cost and provide services for more people. Because most of the remote patients are elderly. It may have trouble making the elderly understand. As they said, a comprehensive examination is best at first diagnosis. So, this system is better to use in the follow-up diagnosis to protect their health every day.

Finally, they are dissatisfied with the comfort when wearing an HMD. It is necessary to be considered in real practice. Many participants have shown VR sickness after using this VR telediagnosis system. And the helmet is too heavy for a long time wearing. The medical staff will get tired easily. It is obviously not practical in daily telediagnosis. So, it is necessary to improve their VR experience when diagnosing. The weight of the helmet only can be solved when hardware has improvements. But the software can be developed better. Due to the limitation of a surrogate robot, the doctor can only move in a small range, otherwise, the visual dislocation will occur. Using a robot with more DoF could be better. In diagnosis, reading and writing the medical record is necessary. Adding a function of the medical record will greatly improve the system. And to have efficient communication with the patients, it is better to equip an arm on the surrogate robot at the patient-side replacing the doctor to press the patient skin, helping the patient to realize the doctor’s instructions better.

4.4 Chapter Summary

This chapter describes experiments to examine the evaluation of this VR telediagnosis system compared with traditional videophone. From the result, we can see that this new VR telediagnosis system shows better performance in terms of the realistic feeling of clinical examination. Compared with videophone, it can make the doctor feel like being in the same room with the patient, which means the telediagnosis would be more real and comfortable. And the feeling of touching in real can be reproduced. Because the doctor could have a higher degree of tension when using this system, it helps to do benefit the efficiency and concentration when diagnosing. However, the current system is still far from expectation. First, the image quality is not enough to satisfy the needs of diagnosis, and it is hard to distinguish the detail symptoms of patients. The poor image quality can even cause VR sickness for users. Also, due to the limitations of the robot's capacity and range of motion, the user can only move within a very limited range. Any movement beyond the range will cause visual dislocation and damage realism. Also, the difficulty and uncomfortable of wearing HMD has brought great inconvenience to the user; the medical record is still needed in VR space. Therefore, people are still more willing to use convenient and simple videophones. Besides, for the palpation, too few judgments of the disease can be made by relying only on pulse and body surface temperature, and the judgment of disease still requires more detailed and professional measurement. But our purpose in this study until now is mainly to evaluate the usability of tactile feedback in telediagnosis, and it has shown positive feedback. We can imagine with more bio-signal such as skin thickness, hardness, etc. reproduced into a tactile display, the performance of telediagnosis will be much better. Even though, for tactile features that cannot be transmission by data, which is usually necessary to rely on the doctor's experience to judge the condition, there is great difficulty in both patient sides feature collection and doctor-side’s feature reproduction. Moreover, the first diagnosis often requires a more detailed examination, and telediagnosis is often difficult to meet the requirements.

5 Conclusion

Aiming at the current situation of telemedicine, this paper proposes a telediagnosis system based on Telexistence and tactile display. Firstly, the prototype is constructed with a hand-shape surrogate and a 3 DoF robot. Then to improve the usability, a 6 DoF surrogate robot and a new surrogate is developed to replace the parts in the prototype. The patient-side's 6DOF robot and sensors are used to measure the patient's temperature and pulse and reproduced on the doctor-side using MR and tactile display devices. So that the doctor can feel the face-to-face palpation with the patient after wearing the HMD. And through the contrast experiment with the traditional telediagnosis method, the effects of telexistence and tactile display on telediagnosis are discussed. The feasibility of the system for improving the realism of telediagnosis is verified. At the same time, analysis and discussion are made according to various shortcomings of this system.

In future work, the most urgent need for improvement is the image quality and the resolution of stereo camera and HMD. Only with higher image quality can the telediagnosis system have practical value. Then, more measurable bio-signal indicators should be added, such as blood pressure. Furthermore, there must be a convenient application in the MR space to achieve functions such as reading and writing medical records commonly used in real diagnosis and treatment. In future research, it should not be limited to palpation of the wrist; different surrogate units with the tactile display such as feet and neck can be designed to satisfy different symptoms and patient needs making the system widely available. And this system also has great prospects in virtual medical practice and medical staff training. In the future, if using a human-like robot with tactile feedback to the user's finger, the palpation on the whole body is not hard to be achieved.

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