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IMMERSIVE VIRTUAL REALITY SUPPORTING CONTENT FOR EVALUATING INTERFACE USING OCULUS RIFT AND LEAP MOTION

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Abstract. *In this study, the head-mounted display (HMD) and the haptic device are used in conjunction as a method to provide feedback to the users in order for more realistic work to be conducted in the virtual space. The VR environment was created with Unity, which can manipulate machines in a virtual space. A Leap Motion controller was used to track and display the hand of each subject in a VR environment. The haptic device was configured using Arduino and a vibration motor to provide feedback on the fingertips. As a result, the tracking of the hand using Leap Motion together with gloves shows that the detection rate greatly differs depending on the material of the glove. Using the VR environment and the haptic feedback, we demonstrate the effectiveness of intuitive operation, which is similar to reality.*
Keywords: Virtual reality, Engineers, Work training support, Haptic feedback, Fabrication

1. **Introduction.** According to the Goldman Sachs Global Investment Research Division regarding the global augmented reality/virtual reality (AR/VR) market, the AR/VR market will expand to approximately US $95 billion by 2025; it is expected that the AV/RV market will become a great computing platform, following the success of PCs and smartphones. However, the 2025 market breakdown of VR-related software indicates that the entertainment-related business will account for 75% of the entire market and that this may challenge how VR will be applied in the industrial field in the future [1].

Moreover, the domestic AR/VR market has begun to grow rapidly. Particularly 2016 was said to have been the "the year of VR", owing to the fact that low-cost head-mounted displays (HMDs), which are essential for VR, appeared in the market [2]. In the past, systems using VR and HMD were particularly costly and were only accessible to large companies. However, in recent years, these systems have been commercialized; they have reached an affordable price range and high quality for general consumers owing to the popularization of HMDs. Consumers can now enjoy VR comfortably. In addition, owing to its low cost, VR has attracted attention as a sales tool for commercial use, such as in customer services and tourism. Although the VR market has attracted significant attention, the domestic VR market has fallen behind compared with the rest of the world.

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On the other hand, in Japan, accidents in factories occur constantly owing to the incorrect and dangerous operation of machines because the safety manual is ignored. In addition, several basic human errors occur – such as manual violation, accidental mistakes, and misjudgment – which constitute reasons for factory accidents. In 2016, a 36-year-old lathe operator at the Carlson Tool & Manufacturing Corp. in Cedarsburg, Wisc., became entangled in the machine's operating spindle and suffered injuries when he hand-polished a 40-inch long metal cylinder. This led to his death two days later [3]. However, it can be inferred from the successive accidents that not enough knowledge and experience has been successfully passed on to young workers owing to the mass retirement of veteran workers who were part of the baby-boom generation [4]. Meanwhile, as the automation of machines progresses and the work up to now has been left to the machine, the "work force" of the young workers corresponding to the trouble tends to decrease. Here, the term "work force" means the ability to resolve problems in all types of situations that may occur. Experienced engineers have retired and young engineers are still professionally immature; therefore, companies have started taking countermeasures for this crisis.

For the purpose of this study, we will utilize VR technology, which is a state-of-the-art technology, to support the training of young engineers without the risk of injuries and to develop a system to support training in the operation of dangerous industrial machines or to alert staff regarding incorrect operations in order to reduce plant accidents, which frequently occur in Japan. Moreover, through the use of haptic feedback, usability can be improved by providing more information to the user and by obtaining accurate information. Because haptic feedback is still in the process of development and presents high potential, we will present its ability to play an active part in fields other than entertainment. Haptic feedback can offer various types of haptic sensations, such as whether an object or surface is soft, sharp, hard, and dull, thus replicating the unique feeling that can be identified by experienced technicians. Therefore, it is aimed to improve the efficiency of acquiring skills by exposing young engineers to haptic and tactile sensations that are well known to experienced engineers; this can lead to the transfer of know-how. This study is a feasibility study to verify the effect of VR and haptic feedback on the training of engineers; hence, we developed a user interface with a push button that is controlled in the VR space. This interface simulates machines such as numerical control (NC) lathes, which require accurate operation.

The remainder of this paper is organized as follows. In Section 2, we introduce previous development. In Section 3, the engineer training support system will be comprehensively proposed. In Section 4, the hardware setup will be described and in Section 5, the fabrication of the haptic device will be presented. In Section 6, the software setup will be introduced and the results of the verification of the developed system will be presented. Finally, in Section 7, the main findings of the research will be summarized. Some concluding remarks will be given in Section 8.

2. **Previous Development.** In the worldwide VR industry landscape, major IT companies, such as Facebook and Google, as well as other well-known companies, such as Amazon and SAMSUNG, stand out. On the other hand, only a few Japanese companies, such as SONY, Nikon, and RICOH, are involved in the VR industry landscape.

From the point of purpose for preventing accidents in factories, for example, Microsimulation Technology Corp. developed PC-based Nuclear Power Plant Simulator in order to instill basic knowledge on plant operation and strengthen accident management [5]. Moreover, Hitachi Zosen created a skills training system in 2011, in which veterans and others who retired workers can train young engineers [6]. High quality, safety, and high efficiency – which are the qualities that constitute the strength of Japanese manufacturing – can be achieved via the aforementioned "work force". However, how young workers should be trained to support the "work force" technique has now become a great undertaking.

In addition, we introduce two previous simulator systems. One is Osso VR, the other is Job Simulator. Osso VR is a clinically-validated surgical training platform designed for surgeons, sales teams, and hospital staff of all skill levels. This system offers realistic hand-based interactions in an immersive environment. Osso VR projects user's hand into virtual environment enabling to pick up things or use tools naturally with high level of precision. Also, Osso VR can be used with a wide variety of VR headsets for experience in high immersive training environment. As it is clinically-validated, Osso VR provides high level accuracy to any surgical procedure. In spite of its convenience, it enables to do surgeon training at anywhere without any high-end equipment. In 2017, Osso VR won a grand prize of "EdSim Challenge" for excellent educational AR/VR simulation and its development companies. "EdSim Challenge" is a competition organized by the US Department of Education. It is held to find the next generation educational method making use of immersive technology. Job Simulator was developed and published by Owlchemy labs in 2016. It is a virtual reality simulation video game which is available in PlayStation 4 and Windows. It won the game award for best VR games at the 2017 Game Developers Conference. The year in this game is 2050, in a world where robots have taken all human jobs and players to participate the "Job Simulator" to learn what it was like "to job". Players can experience 4 different jobs, gourmet chef, office worker, convenience store clerk, and automotive mechanic.

3. **Proposal of the Engineer Training Support System.** The aim of this study is to simulate industrial machines in a virtual environment and to use haptic gloves to provide arbitrary haptic feedback to the fingers of the user during operations, to develop a training system through which accidents caused by incorrect operation could be prevented, and to efficiently transfer skills to young engineers. In addition, the proposed system will be quicker and more efficient than the skilled veterans who train young engineers one-to-one because its immersive feeling is highly effective and trainees can experience realistic feelings, as if they were trained by actual veterans.

The industrial machine that will be simulated in this system is a lathe. It is one of the most common industrial machines operated in numerous factories and its operation method is very direct, meaning that operators use levers, handles or buttons, rather than a touch panel or other digital interfaces. Also, develop dedicated haptic device to enhance affinity with this system. The feedback that the users experienced from this dedicated haptic device was a slight vibration when the button was pushed or a lever/handle was turned; a strong constant pattern of vibration was implemented in the case of dangerous behavior. As previously described, in this study, we focused on the button interface because of our preliminary examination.

VR is the technology through which a user becomes immersed in a virtual environment that is an equivalent reproduction of the actual real-world environment. Its immersive feeling is tremendous; in addition, through the use of an HMD – a device providing visual space replication experienced in the first person – the sense of presence becomes reinforced. Through VR technology, users can feel as if they are present at the actual real-world environment by looking at the display of the virtual space, which is a reproduction of the original environment. This experience is referred to as an ultra-realistic feeling. The more realistically the real environment has been reproduced, the more the sense of presence in the environment becomes heightened, thus inducing the ultra-realistic feeling.

Humans have five senses, namely vision, hearing, olfaction, touch, and taste. It has been reported that daily, the information obtained from vision accounts for more than 80% of the total information; in addition, this percentage becomes 90% or more when combined with auditory information [7]. Therefore, by using an HMD that covers the senses of vision and hearing and can control more than 90% of the total information obtained from human senses, an overwhelming immersive feeling can be induced and the users can experience a more realistic feeling than they can in 2D. In addition to the aforementioned, it is possible for users to acquire more spontaneous information by exploring a space with the HMD than by looking at footage on a television monitor. By preparing information of the surroundings in a manner that they correspond to the reality, information can be obtained no matter where you look at the intentions of the subject, or by touching the object. Users gain greater advantages when VR is used together with an HMD because they can move within the virtual space, and select and acquire information, which further enhances the realistic feeling. In this research, we will emphasize this ultra-realistic feeling. By simulating dangerous work in the virtual space, engineers can be trained while experiencing realistic feelings, which will lead to the prevention of accidents or to the prevention of incorrect machine operation in the actual work environment. Thus, in this study, a haptic device was used to obtain skin sensation feedback by applying force, vibration, movement, etc. When grasping objects or manipulating machines in a virtual space, a vibration motor attached to the fingertips of the glove will vibrate to provide feedback to the user. In addition, the fingertips can vibrate as a warning when dangerous or incorrect operations take place.

This diagram shows how each device interacts with other devices (Figure 1). "Output" indicates that Unity is sending a video signal to the Oculus Rift. The hands of the user are tracked using a Leap Motion controller that is mounted on the front of the HMD; the controller uses as input the hand motion data to Unity and projects the hands to the virtual space. The haptic glove was made of a golf glove with motors attached; by wearing, users can obtain haptic feedback when their hand collides with an object. The motors were controlled with Arduino. Three tracking sensors were used in this system to obtain the accurate position and behavior of the HMD (Figure 1).

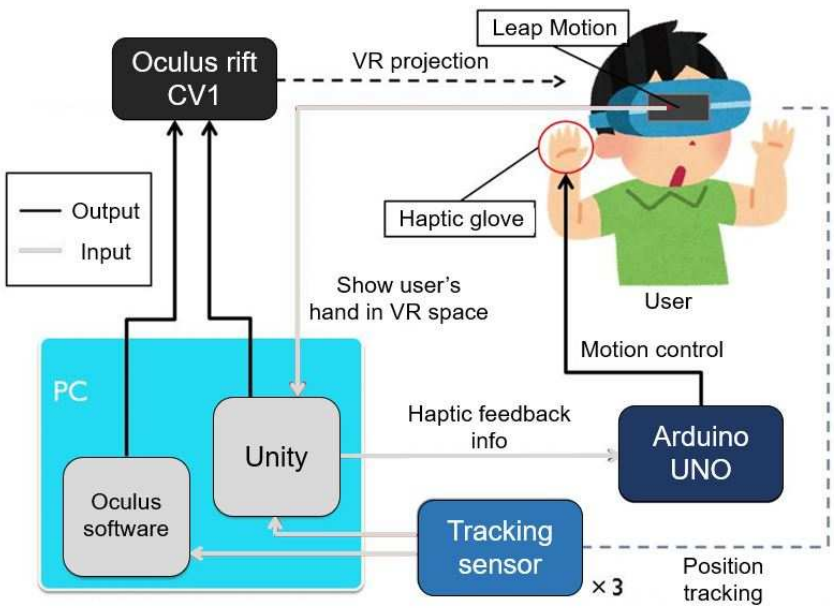


Figure 1. System block diagram

4. **Hardware Setup.**

4.1. **Arduino UNO.** Arduino is an open-source platform used for building electronics projects. Arduino boards are able to read inputs – e.g., light on a sensor, pushing button, or even read twitter messages – and convert them into output – e.g., lighting a light-emitting diode (LED), activating a motor, or sending a character string to LCD. Originally, Arduino was developed in order for persons who are unfamiliar with circuits and programming to be able to easily and quickly create devices. Hence, inexperienced persons can start a project immediately. Therefore, Arduino is one of the recommended items for starting electronic work. Arduino UNO has an 8-bit AVR microcomputer with low processing power. Although it is inferior to the 32-bit Arduino, which has a high-performance processor, namely the Cortex processor, Arduino UNO is a representative Arduino board; therefore, ample related information is available in books and online, such as example projects, circuits, and programs.

In this study, Arduino UNO was employed to communicate with Unity via USB; it controls the vibration motor according to the value that was obtained from Unity. Both Arduino UNO and the vibration motors are powered via the USB.

4.2. **Motor circuit.** The current obtained from each pin of the Arduino board is small. Although it is possible to drive one LED, if a high-current device – such as a motor or an LCD – are constantly driven, a great load will be applied to the Arduino and there is a risk damage of the Arduino. In this study, it is necessary to avoid this because five motors are controlled by one Arduino. As a solution, a motor circuit was fabricated using a MOSFET, which can switch to and from high and low current. Because the MOSFET can switch current at ultra-high speed, there is no risk of latency. Regarding the response delay, we determined that the serial communication speed between the Arduino and the PC was the default value of 9600 bps; therefore, the time required was approximately 1.04 ms per byte. In general, this value is low in terms of data communication speed; however, we were only interested in simple data transmission/reception, and setting the communication speed above this value could have caused data to be lost. Thus, the serial communication speed was set to 9600 bps. An LED was sandwiched between each MOSFET and the vibration motor (described in Section 5.2). As a result, it was possible to confirm the operation in a simple manner, as well as to quickly identify collision events for each finger. Figure 2 shows the developed motor circuit using MOSFET and Figure 3 shows the actual circuit using MOSFET.

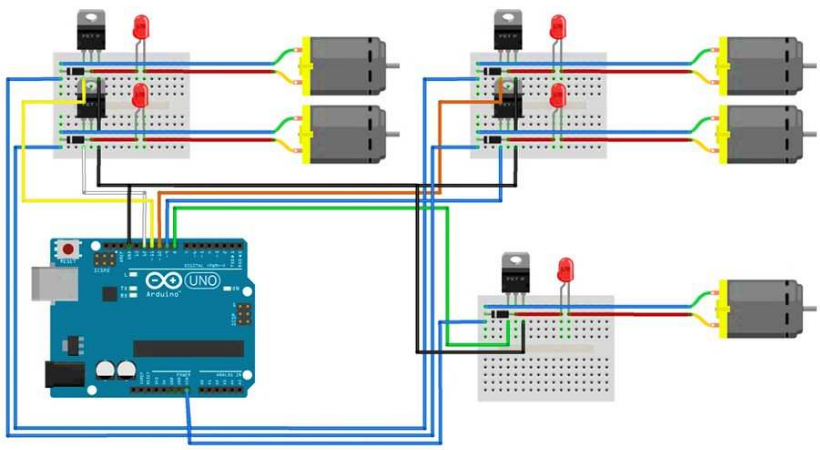


FIGURE 2. Motor circuit using MOSFET

Figure 3. Actual circuit using MOSFET

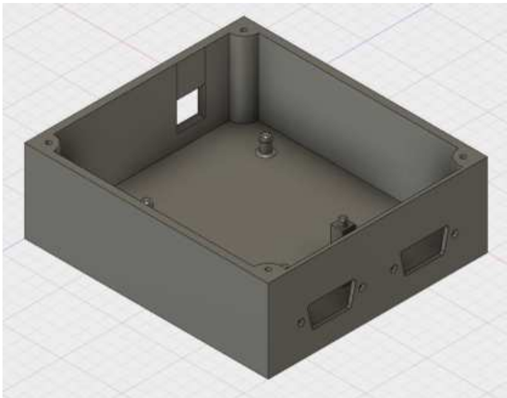


Figure 4. Model of the fabricated housing case

4.3. **Fabrication of the housing case.** To secure the wiring would be compact, a housing case was fabricated using a 3D printer (Figure 4). The upper part of the housing case was acrylic in order for the LED to be visible. By labeling each LED according to each corresponding finger, it became easy to identify which fingers were active. The 9-pin connector on the side part served to extend the motor to the hand of the user. In this study, we only considered the right hand. In the future, to ensure sensory feedback to both hands, we plan to manufacture a glove for the lift hand as well.

The current status of the Oculus Rift is the consumer version, known as CV1, which uses the visual constellation tracking system with optical LEDs; this enables CV1 to track quite accurately compared with the previous Rift series.

4.4. **Oculus Rift.** The Oculus Rift is a set of VR goggles. It was developed and manufactured by Oculus VR, a division of Facebook Inc., and was released in 2016. The Rift has gone through various pre-production models labelled as "Development Kits" (DK), namely DK1 in mid-2013 and DK2 in mid-2014, to give developers a chance to develop contents before the release of Rift. It uses a PenTile OLED display, and has a resolution of 1080×1200 per eye, 90 Hz refresh rate, and a 110° field-of-view. The current status of the Oculus Rift is the consumer version, known as CV1, which uses the visual constellation tracking system with optical LEDs; this enables CV1 to track quite accurately compared with the previous Rift series.

4.5. **Leap Motion.** The Leap Motion controller is a hand-input device, which uses stereo cameras and infrared (IR) LEDs to track and capture stereoscopic images of the hands of the user. With calibrated camera positions and proprietary software algorithms, it is possible to calculate the finger, hand, and wrist positions. Because this system uses an HMD, it completely covers the eyes. Tracking from hand to arm using Leap Motion enables hand recognition even after mounting the HMD, showing the hands and arms of the user in the virtual space. The Leap Motion controller can be attached to any HMD, including the Oculus Rift via a separately sold VR mount. Instead, we fabricated our own mount using a 3D printer (Figure 5). It should be noted that the separately sold VR mount requires double-sided tape in order to be attached to the HMD; however, the adhesive on the tape becomes viscous because it is warmed up by the Leap Motion controller and eventually falls off. To prevent this, we applied a method in which we hooked one end of the mount to a bottom dent on the Oculus Rift and we secured the other end to one of the headbands of the Rift. In this method, the mount is tightly secured in place without the use of adhesive tape.

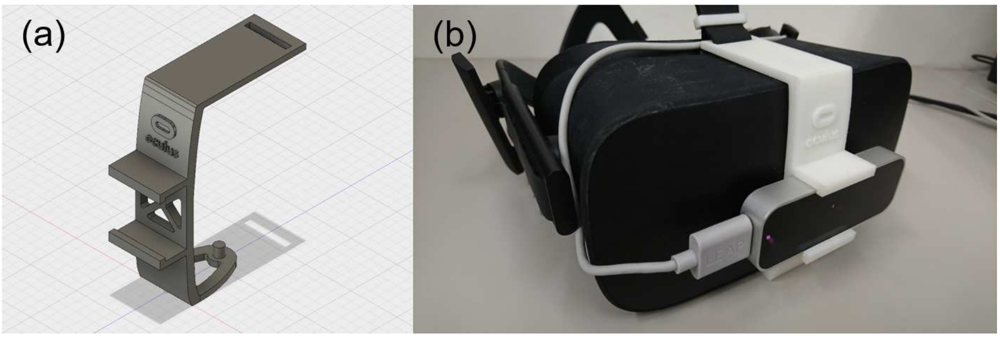


Figure 5. (a) Dedicated Leap Motion mount for the Oculus Rift CV1 and (b) the Oculus Rift CV1 with 3D-printed Leap Motion mount

Because the Leap Motion controller reaches high temperatures when in use, the mount was made of acrylonitrile butadiene styrene (ABS) in order to endure the heat. If the mount is installed vertically on the desk, its range becomes limited; therefore, the hand can only be recognized if it is in proximity. By adjusting the front of the HMD in the forward direction, eye area becomes the recognition range; thus, it is possible to track the hand anywhere (Figure 5). Tracking sensors that can track human bodies, such as Leap Motion and Kinect, are the most efficient manner to interact with the virtual environment. Particularly for training operation, their usability is significantly higher regarding gestures and hand movements, as opposed to other special controllers or buttons. Furthermore, by interacting with physical movement, users can experience a more immersive feeling compared with a situation in which they would need to perform operations while holding, e.g., a controller.

5. **Fabrication of the Haptic Device.**

5.1. **Affinities between the glove types and Leap Motion.** Thus far, various glove-type haptic feedback devices have been developed; however, they were not suitable for use in this study. Existing glove-type haptic feedback devices use their own tracking system and are not designed to be used in conjunction with Leap Motion. In addition, their affinity with game engines, such as Unity and Unreal Engine, is unclear. Therefore, it is necessary to independently develop a glove-type haptic feedback device that can be used with Leap Motion.

According to a team of Leap Motion developers, the tracking performance of Leap Motion depends on the lighting and the environment; however, this applies only when tracking bare hands. When gloves are used, the material and the color of the gloves affect the tracking performance. Moreover, the controller is optimized for human skin. Therefore, a material that resembles human skin in IR needs to be selected to achieve better tracking performance. Because the Leap Motion controller contains a stereo IR camera, we can easily test which material performs best merely by looking at the glove through the camera. The brighter the hand appears, the better the tracking quality is, particularly at a far distance. Furthermore, from our experience, cotton and nylon gloves appeared to be quite bright in IR and were well suitable. However, materials that are reflective resulted in poor tracking and should be avoided. In addition, it is best that the fitting of the glove be as skin-tight as possible in order for the hand proportions to appear accurate in the virtual environment.

Based on the aforementioned, four different types of gloves are listed in Table 1. These were selected to be tested in terms of which performs the best for our tracking purposes.

Table 1. Different types of gloves

Types of glove	Color	Material	Fitting state
Disposable glove	transparent	polyethylene	loose
Rubberized work glove	gray/black	nylon/rubber	loose
Batting glove	white/red	synthetic leather	tight
Golf glove	white	natural leather	tight

The test was conducted for each glove by looking at the glove through the Leap Motion controller that was mounted in front of the Oculus Rift, as shown in Figure 5. The VR Visualizer from the Leap Motion software development kit (SDK) was used during this test. Figure 6 illustrates a bare hand, which was first tested to obtain reference points. The white line that outlines the shape of the hand illustrates an actual hand, whereas the bones have been generated by data from the Leap Motion tracking. In a similar manner, Figures 7, 8, 9, and 10 illustrate tracking images of a disposable glove, a rubberized work glove, a batting glove, and a golf glove, respectively.

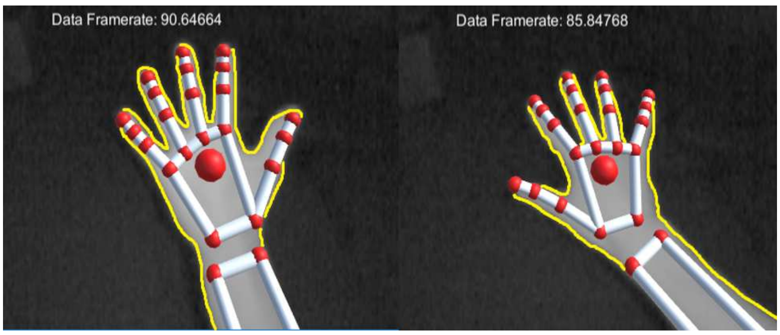


Figure 6. Bare hand-tracking image

As may be observed, the golf glove performed the best and the work glove had the poorest performance. At first glance, the disposable glove seems to be performing the best; however, because it is meant to be disposed, it was not comfortable to be worn for a long period. Therefore, the golf glove was chosen to be used in this research. In addition, the golf glove was the most skin-tight of all four, and its white color appeared the brightest

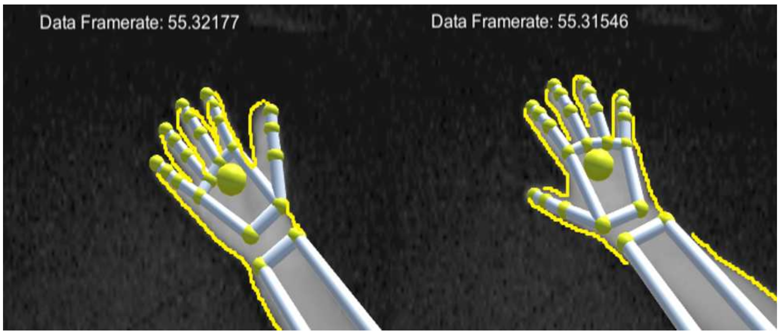


Figure 7. Disposable glove tracking image

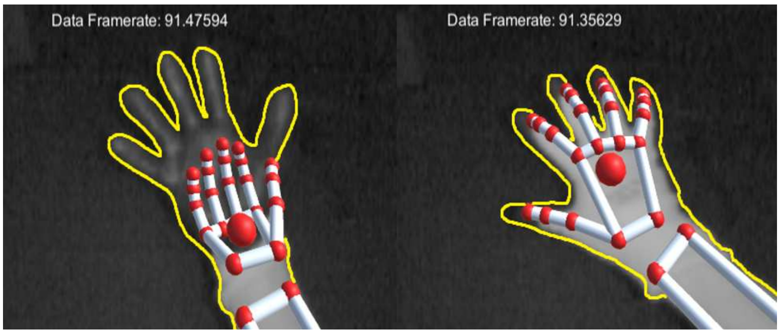


Figure 8. Tracking image of rubberized work glove

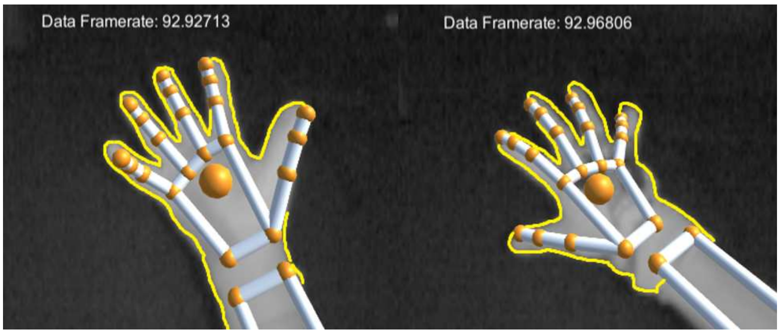


Figure 9. Baseball glove tracking image

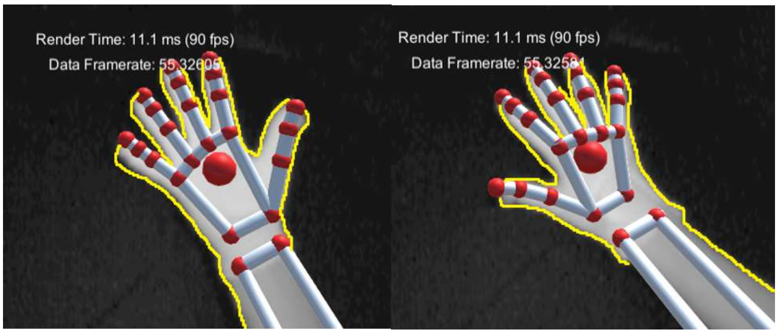


Figure 10. Golf glove tracking image

compared with the remaining glove types. As may be observed in the figures, the lighter the material color is, the brighter it appears in the VR Visualizer. The IR sensor can react to colors that are closer to white rather than black. This occurs because IR rays are reflected on white surfaces and absorbed by black surfaces. A representative example may be found in line tracing cars, as they adjust their course according to white and black colors using IR sensors. Thus, the IR sensor used in the Leap Motion controller is a reflection-type sensor and not a light-shielding type sensor, which performs detection by blocking IR rays.

5.2. **Types of vibration motors.** For the vibration motor, three types of motors were selected, namely the disk-type brushless vibration motor, the cylindrical-eccentric-type vibration motor, and the linear vibration motor (Figure 11). To select the most suitable motor, each motor was fixed to the golf glove at the position corresponding to the antinode of the finger, and each motor was vibrated several times.

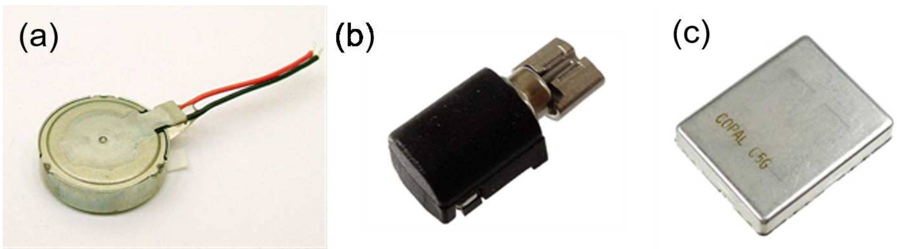


FIGURE 11. (a) Disk-type brushless motor, (b) cylindrical-eccentric-type vibration motor, and (c) linear vibration motor

To control each motor, the Adafruit haptic motor controller DRV2605L was used. This is a module through which the vibration motor can be controlled in order to induce the tactile sense, and can produce a click feeling, can cause a smooth change in the vibration, etc. Moreover, 123 types of vibration patterns were stored in the memory; by using I2C communication, the controller was able to operate from a microcomputer, such as Arduino. In this module, both the eccentric rotating mass (ERM) motor and the linear resonant actuator (LRA) can be operated, which was best suited for this test.

The selection criterion was whether it was possible to obtain a sharp pseudo-click feel or not, as in the Taptic Engine. The Taptic Engine is a term that Apple created to refer to its technology (derived from the combination of "tap" and "haptic feedback"), which provides sharp tactile sensations in the form of vibrations to users of Apple devices, such as the Apple Watch, iPhones, and MacBook laptops.

As a result, the cylindrical vibration motor was able to produce vibrations closest to those produced by the Taptic Engine of Apple. The response of the disk-type brushless vibration motor was slightly slow and the vibration was weak. Regarding the cylindrical vibration motor, because the weight of eccentricity was small, the response was quick and the vibration was sharp. The linear-type actuator was the weakest among the three, probably because the driving method was different from that of the others. However, as its response was quick and the actuator was able to finely adjust the oscillation cycle, its further investigation will be set as a future task.

5.3. **Vibration motor mounting position.** Adopting the same method as the previously mentioned, the position of the vibration motor was selected. As a criterion for selection, we sought to obtain a more realistic sense of touch without disturbing the operation. Four different positions were examined in order to finalize the mounting position of

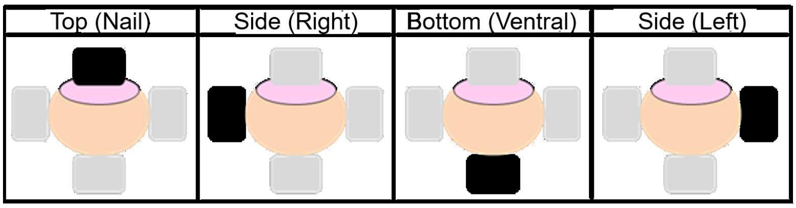


Figure 12. Mounting positions of the vibration motor

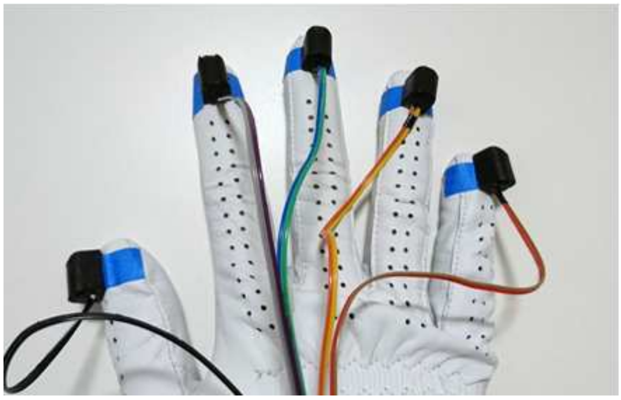


Figure 13. Vibration motors attached to the nail side of the golf glove

the vibration motor, namely the finger top (nail), the right side of the finger, the bottom (ventral) side, and the left side of the finger (Figure 12).

The results indicated that there was no significant difference in the feeling when attached to the ventral and the nail side of the finger. However, when the motor was attached to the side, the induced feeling did not resemble something hitting the fingers; it was merely a finger being vibrated. In addition, when the motor was attached to the side, the fingers would interfere with one another, and it was impossible for the finger to move properly. When the motor was attached to the ventral side of the finger, there were implications when making a fist; therefore, as there was no significant difference in the feeling between the ventral and the nail side, the nail side was selected for the vibration motor to be attached. Figure 13 illustrates the vibration motors attached to the nail side of the golf glove (described in Section 5.1).

6. Software Setup.

6.1. **Area setup.** Without recreating a 3D model of the machine tool from the beginning, we created a system capable of providing simple haptic feedback, and confirmed the usefulness of the feedback via the vibration and the haptic device that was fabricated for the purposes of this study. Because this is a feasibility study for the validation of the effectiveness of the VR user interface with haptic feedback, we developed the VR user interface with only one push button. This interface is shown in Figure 14.

Unity 5.6.2f was used in this system; this version is very suitable because it is compatible with the Oculus Software and the Leap Motion SDK. When the blue button was pressed, the finger of the user would vibrate and haptic feedback would be produced. Each finger has its own script in terms of how to vibrate when it collides with an object. More specifically, when the index finger collided with the button, the motor would vibrate (Figure 15).

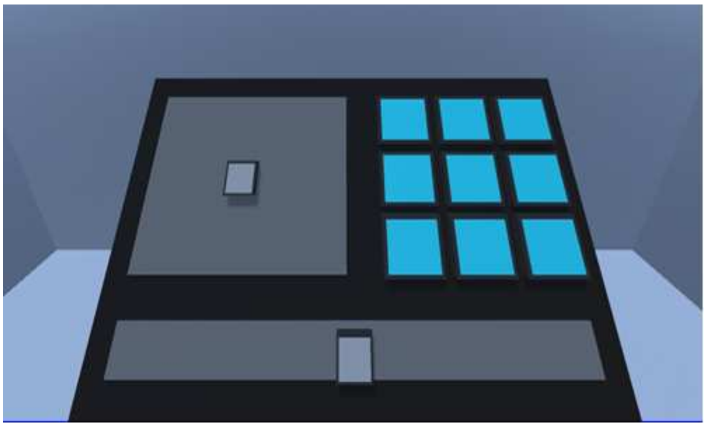


Figure 14. Push-button VR user interface

Figure 15. (color online) User interface panel and haptic device

6.2. **About Interaction Engine 1.0.1.** Interaction Engine 1.0.1 was used for the hand collision behavior. The underlying objective of the Interaction Engine was to properly handle the interaction with digital objects. Certain simple contacts may cause interactions that require more complex processing. For example, when a user manipulates an object by hand, the following relationship between actions is considered: "contact", "grab", and "approach". The act of "contacting" the object by hand is one. Whether the object will roll, break, or be handled will be mentioned. The user "grasps" the object by hand. What type of treatment is necessary for grabbing the object naturally or releasing it naturally? What users seek is a consistent experience that is common across applications. If the feeling of the operation differs depending on the application, the user will be confused and feel stress. Thus, the Interaction Engine plays an important role in avoiding such discrepancies.

6.3. **Interaction with Arduino UNO.** There are certain items that need to be set for serial communication between Unity and Arduino. In the Player Settings, the "Virtual Reality Supported" option in the rendering column has to be checked in order for the Oculus Rift CV1 to be used as an HMD. In addition to that, the "Api Compatibility Level*" option in the configuration column has to be changed from the .Net 2.0 subset to .NET 2.0. This action is necessary because the System.IO.Ports.SerialPort class, which performs serial communication from Unity, is not included to the .NET 2.0 subset.

Second, a specific script named "SerialHandler.cs" has to be created. This is the part that Unity reads to which serial communication is logged. This is applied by attaching the Serial Handler to the object that will be in use. Because the port number varies widely for each PC, this value has to be changed each time the environment changes. The baud rate was set to the value that was set for Arduino, namely 9600.

Arduino was programmed when arbitrary data were received via serial communication and the user would then experience vibration; the vibration pattern would be associated with the arbitrary data. More specifically, when the user would push a button in the virtual area with the index finger, the tip of the index finger would vibrate for a moment.

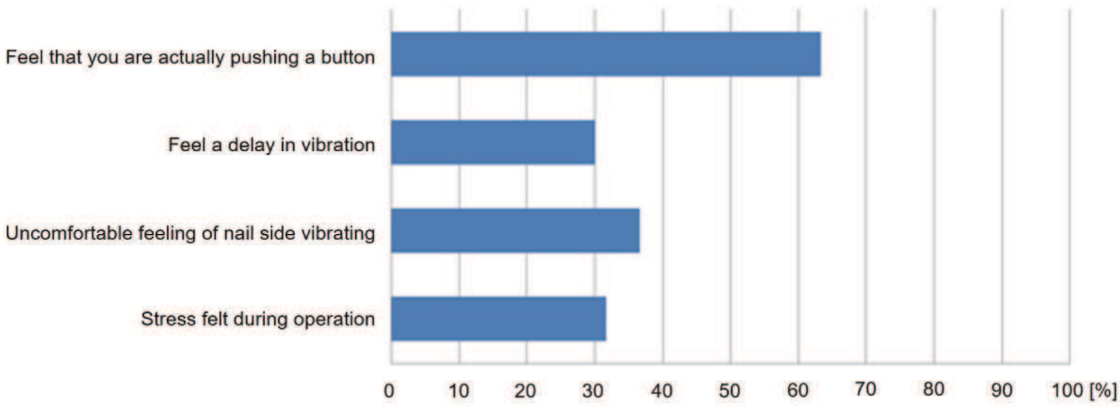
Using these hardware and software, any operator will be expected to train and improve his/her skill on operating machine. Compared with other previous systems, our system need not have or grasp any interface to operate and enable anyone to operate as if he/she operate machine naturally via virtual reality space. For example, Job Simulator, which is stated in Section 2, needs for users to have controllers. It is that Job Simulator is effective simulator; however, operation with controllers seems to be away from real operation. From these points, our system seems to have advantages to previous developments.

7. Verification.

7.1. Verification based on questionnaire.

We have verified the usability of the developed system from the point of questionnaire. To measure the usefulness and usability of this system, 15 people participated in the verification of the proposed system. The verification was based upon how the users felt when they pushed the buttons, their discomfort to the vibration delay, the feeling of discomfort caused by the vibration that originated from the nail side, and the overall stress during the operation. The verification process involved the following: the users would wear the HMD and the haptic feedback glove; then, they would press nine buttons from the top, in order. The results are shown in Figure 16.

Because the Leap Motion controller would occasionally incorrectly recognize the haptic glove, the collision judgment would present strange behavior; hence, the stress level was simultaneously verified during system operation. Here, we define "stress" as whether the users were successful in completing the task they intended to complete. The results show that 30% of users experienced stress during operation. The most frequent claim was



	Feel that you are actually pushing a button	Feel a delay in vibration	Uncomfortable feeling of nail side vibrating	Stress felt during operation
Rate	63.3%	30.0%	36.7%	31.7%

Figure 16. System and haptic device test results

"Although I pointed my index finger, the sensor incorrectly recognized other fingers, I felt stress."

7.2. **Response time-based verification.** We have verified the usability of the developed system from the viewpoint of the response time during operation. To measure the effectiveness of the haptic feedback system, another 10 people participated in the verification of the proposed system. Each participant was instructed to sit down and place his hand near his face (Figure 17). After a specific amount of time, he was instructed to move his hand and push the lower right corner button with and without haptic feedback. The time interval from the start of the movement until pushing the button (i.e., the response time) was measured. These tests were repeated ten times each with and without haptic feedback. Considering the order effect, five participants were first tested with haptic feedback, and the other five participants were first tested without haptic feedback.

Figure 18 shows the average response time and the standard deviation (SD). The t-test showed that there is a significant difference between the response time with and without haptic feedback ($p < 0.01$, $t(198) = 2.0 \times 10^{-6}$). This suggests that haptic feedback is useful for informing users of the pushing sensation.

FIGURE 17. Initial position on verification test

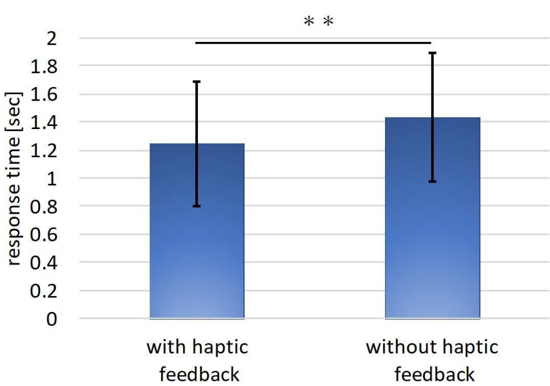


FIGURE 18. Means $\pm$ SD of response time with and without haptic feedback. ** indicates a significant difference ($p < 0.01$).

Figure 19 shows the response time in each of the test re-runs of the test. Figure 19(a) shows the response times with haptic feedback, and Figure 19(b) shows the response times without haptic feedback. Comparing Figure 19(a) with Figure 19(b), the response time with haptic feedback seems to decrease as the number of tries increases. This result suggests that people learn to recognize feeling of touch quickly.

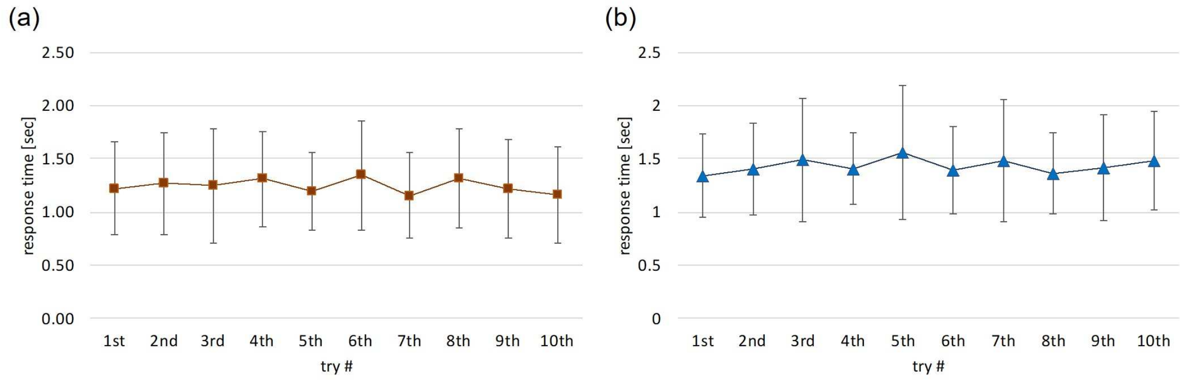


Figure 19. Means ± SD of response time of each try: (a) response time with haptic feedback and (b) response time without haptic feedback

8. **Conclusion.** In this study, we proposed a basic VR system that incorporated haptic feedback in order to train engineers to avoid incorrect operations. In addition, we verified the effectiveness of this system. In the present work, we verified only the operability and usability of the VR user interface in conjunction with haptic devices. As a future task, we wish to develop an environment in which the same machine tool would be operated in the VR space. In addition to that, we aim to add more types of machines in the VR space in order to increase flexibility; thus, young engineers would be able to master machine tools other than lathes. Moreover, we would like to increase the number of subjects and to further verify the usefulness of the proposed system.

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