

원격제어 시스템에서 햅틱 가이드언스의 위치 및 방향 오차가 작업 성능에 미치는 영향: Peg-in-hole 작업

Effects of the Position and Orientation Inaccuracies in Haptic Guidance on the Task Performance in Teleoperation Systems: Peg-in-hole Task

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Abstract: This study evaluates the usefulness of haptic guidance and investigates the effect of inaccuracy in haptic guidance on the task performance. Both position inaccuracy and orientation inaccuracy were considered. The peg-in-hole task was conducted as a benchmark test for evaluation, and a psychophysical study was performed and analyzed on eight inaccuracy combinations. In conclusion, the haptic guidance showed outstanding performance in terms of task completion time, position tracking performance, contact force, and total force, but the haptic guidance with severe orientation inaccuracy caused serious complications.

Keywords: haptic guidance, task performance, inaccuracy, peg-in-hole task, psychophysical study

1. INTRODUCTION

Teleoperation systems can allow a human operator to manipulate a slave robot at the remote site by sending a motion and force command to the slave robot, as if he/she were working directly at the remote site. This is particularly useful in hazardous environments such as micro/nano worlds, disaster rescue areas, deep underwater exploration/construction, outer space, nuclear plants, military battlefields, and medical operations [1-3]. For a realistic feeling, the human operator needs to receive multi-modal sensations such as audiovisual information from the remote site to provide an immersive experience. Furthermore, haptic force feedback can overcome the limitations of audiovisual information by providing the feeling of physical interaction to the human operator. Several studies have shown that haptic feedback helps in the performance of remote tasks [4,5].

In addition, many studies have shown that haptic guidance can improve task performance for remote operation [6-11]. Haptic guidance gives an operational direction for the given tasks to the operator through force information. It allows the operator to perform given tasks safely, quickly, and easily. Such haptic guidance can be presented in various ways depending on the type of the task. Typically, the haptic guidance has two types of guidance force, such as repulsive

force and attractive force. The repulsive force is to limit the workspace of the slave robot using the haptic guidance, thus safety can be enhanced. For instance, in order for the slave robot to avoid collision with dangerous objects in the vicinity, a reaction force can be presented to the operator so that the operator can no longer instruct the slave robot not to approach dangerous objects. On the other hand, the attractive force can provide the operator with operational convenience by instructing actions such as a proper operating motion to the operator. For example, when performing remote welding, the operator can easily locate the slave robot, which is a welder, to the target position of the workpiece by using the force that pulls the operator to the target position. Thus, the attractive force may be very helpful in terms of task performance such as task completion time, or task precision.

In general, haptic guidance such as for collision avoidance or for movement instruction can be generated based on geometrical information of the workpiece derived from sources such as design drawing information or 3D camera measurement data. For example, when performing a remote peg-in-hole task, the operator can easily align the peg and the hole, if the peg position is located on the normal vector of the hole center by using the haptic guidance. For this, the normal vector of the hole center has to be accurately obtained. However, it can be difficult to obtain accurate geometric information due to manufacturing errors or measurement errors. Such inaccurate geometric information can cause inaccuracies in the haptic guidance. It can occur for a variety of reasons besides both manufacturing and measurement errors, as the slave robot can pick up the tool to contact the workpiece in various configurations, and both the tool and workpiece can be deformed. In spite of these problems, most studies [6-11] show only the usefulness of haptic guidance in performing various tasks without consideration of inaccuracy.

Recently, Oosterhout et al. [12] performed the peg-in-hole task as a benchmark test and presented the haptic guidance for

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Manuscript received May 24, 2017 / revised September 5, 2017 / accepted September 19, 2017

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※ This research was supported in part by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT and Future Planning under Grant NRF-2015R1C1A1A02036875 and in part by the Technology Innovation Program (10060070) funded by the Ministry of Trade, Industry and Energy (MAFRA, Korea).

the peg to be centered in the hole. They investigated the haptic guidance system has a small inaccuracy in the translational direction from the hole center, and found that it could still improve task performance compared to the conventional haptic teleoperation system that only provides force feedback related to physical interaction. Later, they [13] further investigated the effects of inaccuracy in the haptic guidance on task performance with a similar peg-in-hole system. Although there are benefits of the haptic guidance despite a small inaccuracy, in which degradation in task performance is minor (20%), large inaccuracy substantially degrades task performance (29 - 77%). In [13], position inaccuracy, which is the translational difference of the haptic guidance from the hole center, was the only considered. However, in a practical teleoperation system, there may also be an orientation inaccuracy, which is the directional difference of the haptic guidance from the normal direction of the hole. If there is an orientation inaccuracy for the peg-in-hole task, the haptic guidance as presented to the operator is tilted relative to the hole. Although [14] and [15] show that task performance can be improved when operating with tilted peg-in-hole tasks, severe tilting may adversely affect task performance. Therefore, the effect of orientation inaccuracy on task performance should also be investigated.

This paper not only assesses the usefulness of haptic guidance when performing peg-in-hole tasks, but also examines the effect of two inaccuracies, position and orientation, of haptic guidance on task performance. We anticipate that the haptic guidance will have a positive effect on task performance, but that if there are position and orientation inaccuracy in the haptic guidance, it will have a detrimental impact on task performance. For the evaluation, the peg-in-hole system is virtually constructed, and the operator performs the given task by operating the peg in the virtual reality. The performance was evaluated by measuring and analyzing task completion time, position tracking performance, and contact/attractive force.

II. EXPERIMENTAL METHOD

1. Participants

Ten right handed students (10 males; age range: 22 - 30 years) of Chonnam National University, Gwang-ju, Korea participated in this experiment. All participants of different backgrounds were paid approximately 30 USD to take part in

this study. Five of them are familiar with haptics or psychophysics. The experiments were conducted in accordance with the requirement of the Declaration of Helsinki.

2. Apparatus

Fig. 1 shows the apparatus that consists mainly of a monitor screen and a haptic device. A virtual environment for the peg-in-hole task is presented on the monitor screen. The graphical and dynamical control of the peg-in-hole task were simulated in a virtual environment. This environment was presented based on the CHAI3D libraries for 3D graphical and haptical rendering, on the Open Dynamics Engine for simulating the physical interaction between the peg and the hole, and on the Qt API (Application Programming Interface) for GUI (Graphical User Interfaces). In the graphical simulation, the visual scene is rendered from a camera perspective that was a certain distance away from the virtual objects. The graphical and haptical simulations run at 60 Hz and 1000 Hz, respectively.

In addition, participants can move the virtual peg by manipulating the Geomagic Touch X (formerly Sensable Phantom Desktop) haptic device. This haptic device has a rubber stylus handle and a rectangular parallelepiped workspace of 160W × 120H × 120D mm. The Geomagic Touch X is a 6 degree-of-freedom (DOF) haptic device with 3 translational actuated axes. It can generate 3 degree-of-freedom force feedback up to 7.9 N at nominal position. The apparent mass at tip is 45 g and the control rate for the device is approximately 1000 Hz.

3. Experimental Task

The final goal of the peg-in-hole task is to position the peg in the hole as shown in the left-hand side of Fig. 2. This task is a benchmark task for assembly, maintenance, construction, and so on. This paper considered the peg and hole as rigid objects. The heights of the peg and hole are 45 mm and 60 mm, respectively. The peg should be inserted into 75% of the hole depth with a specified task precision level. In comparing peg-in-hole tolerances among studies, a useful measurement is an information measure of precision, I :

$$I = \log_2 \left(\frac{H}{H-P} \right) \quad (1)$$

where, H is the hole diameter and P is the peg diameter. The precision value of our experimental setup is $I = 6.644$ ($H = 31.5$ mm and tolerance = 1%), which gives a higher level of precision than other studies [16].

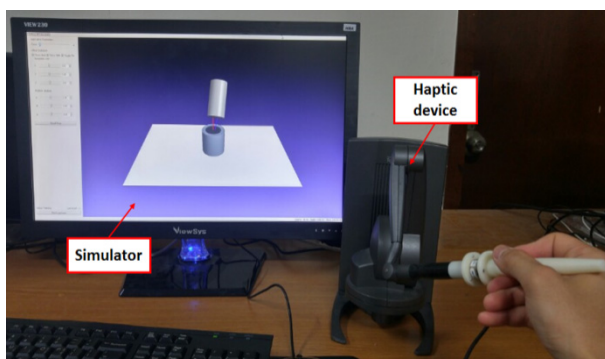


그림 1. 장치.

Fig. 1. Apparatus.

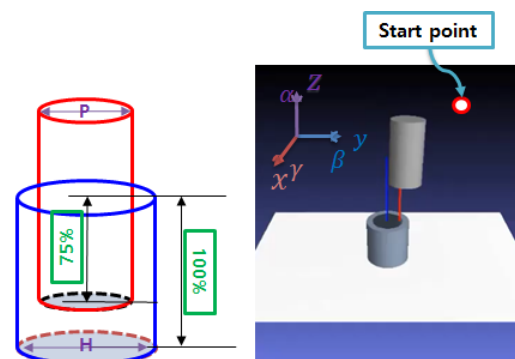


그림 2. Peg-in-hole 작업 설명.

Fig. 2. Peg-in-hole task description.

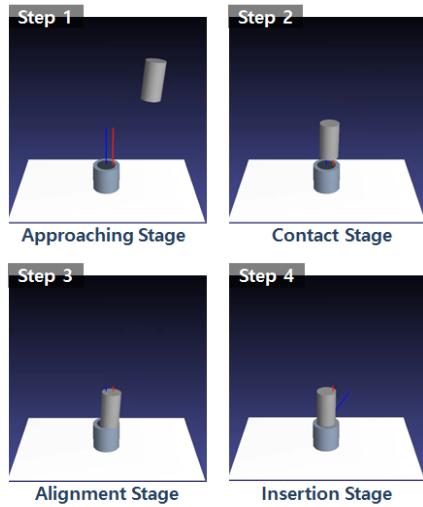


그림 3. Peg-in-hole 작업의 과정.

Fig. 3. Process of the peg-in-hole task.

The peg is actuated by the haptic device via the simulation from the starting point as shown in the right-hand side of Fig. 2. The peg-in-hole task consists of four subsequent steps as shown in Fig. 3.

Approaching Transition (Step 1): This step begins when the operator moves the peg at the starting point, and ends at 500 ms before the peg contacts the hole. During this process there is no contact force between the peg and hole because the peg is in free space. This process is the first step in approaching the peg to the hole, and the operator is expected to potentially be careless in dealing with the peg.

Contact Transition (Step 2): This step goes is from the end of the Approaching Transition step to when the peg contacts the hole. Note that the overall process takes place for constant time (500ms). Similar to in step 1, the contact force is not presented due to the free space motion of the peg. In this process, the operator is expected to more carefully approach the hole with the peg than in step 1.

Alignment Transition (Step 3): The process begins after contact so there is a contact force between the peg and the hole. It finishes when the peg enters a depth of 3% of the hole. During this step, the movement of the peg is restricted by the constraints of the hole. Carefulness on the part of the operator is required during this step.

Insertion Stage (Step 4): This step is defined as while the peg is inserted from 3% to 75% of the hole depth. This step finishes when the success criteria is achieved. The success criteria are as follows: 1) the peg is inserted more than 75% of the hole depth, 2) the position tolerance between the position on the peg and the center of the hole is within 1 mm, 3) the angle tolerance between the normal vector of the peg and the z-axis is within 5° , and 4) when the contact force is less than 5 N. Such success criteria mean that the peg should be deeply inserted into the hole and horizontally aligned with the centerline of hole without large contact forces as shown in Fig. 4.

4. Haptic Feedback

There are two types of haptic feedback: contact force and attractive force. The contact force presents the force to the

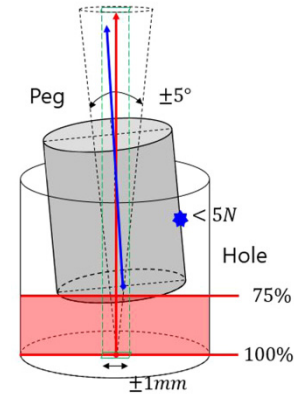


그림 4. 성공 기준.

Fig. 4. Success criteria.

operator reflecting the physical interaction between the peg and the hole. This contact force can provide the operator with a feeling of touching the actual hole. In this paper, the Fig. 3. Process of the peg-in-hole task contact force (F_c) is presented as follows to provide force information about the hole to the operator.

$$F_c = k_H \times \|P_P - P_H\| + b_H \times \|\dot{P}_P - \dot{P}_H\| \quad (2)$$

where, k_H and b_H are the stiffness and damping parameters of the hole; P_P and P_H are positions of the peg and hole. In (2), the contact force is presented to the operator in proportion to the depth and velocity at which the peg penetrates the hole as shown in Fig. 5(a). This penalty-based method is the most widely known haptic rendering method [17]. As mentioned above, since the peg and the hole are regarded as rigid objects, k_H and b_H should have infinite values. However, due to the limitation of the haptic system, this paper sets k_H and b_H to 900 N/m and 40 Ns/m, respectively, based on empirical methods. These values provide stable ranges when presenting the contact force to the operator using the Geomagic Touch X.

Fig. 5(b) shows the haptic guidance related to the attractive force. The attractive force (red arrow) is applied towards the normal vector of the hole (black arrow). It induces the peg position to be placed on the normal vector of the hole. For this, the attractive force is given by

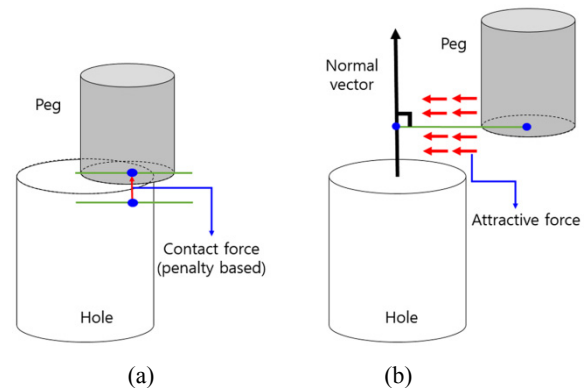


그림 5. 햅틱 피드백.

Fig. 5. Haptic Feedback.

$$F_a = k_l \times \|P_P - P_N\| \quad (3)$$

$$\tau_a = k_a \times \|R_P - R_N\| \quad (4)$$

where, F_a is the attractive force, k_l is a proportional gain (linear), τ_a is the attractive torque, k_a is a proportional gain (angular), R_P is the rotation of the peg, and R_H is the rotation of the normal vector. P_N is a position closest to P_P in the point on the normal vector of the hole. The attractive force is proportional to the distance of the peg from the normal vector, so it pulls the peg toward the normal vector. Thus, the human operator can easily align the peg position to the normal vector of the hole. In addition, this paper sets k_l to 450 N/m. This value is also in a stable range when presenting the attractive force.

5. Experimental Design

As mentioned above, manufacturing error or measurement error of the workpiece can occur, which can result in inaccuracy of the haptic guidance. In the peg-in-hole task, when haptic guidance is generated, errors in the normal vector of the hole can occur. These errors can be represented by position inaccuracy and orientation inaccuracy. In this paper, position and orientation inaccuracies of the normal vector of the hole are defined as follows. Note that the haptic guidance is rendered based on the normal vector of the hole.

Position inaccuracy: Fig. 6(a) shows the position inaccuracy of the normal vector of the hole. The position inaccuracy means an error in which the normal vector deviates in the translational direction from the center of the hole. The inaccuracy is 0% when the normal vector is located at the center of the hole, and the inaccuracy is 100% when the normal vector is located at the end of the inner diameter of the hole. In this paper, the experiments were performed considering position inaccuracy of 30% and 70%. Note that each inaccuracy has a noise of 5%, which follows a Gaussian distribution and the position inaccuracy only takes into account the position error for the y-axis.

Orientation inaccuracy: Fig. 6(b) represents the orientation inaccuracy of the normal vector of the hole. The orientation inaccuracy means that the normal vector of the hole is tilted in the y-axis direction as shown in Fig. 6(b). When the normal vector coincides with the z-axis direction, the orientation inaccuracy is 0%; when the normal vector is tilted 45° in the y-axis direction, the orientation inaccuracy is defined as being

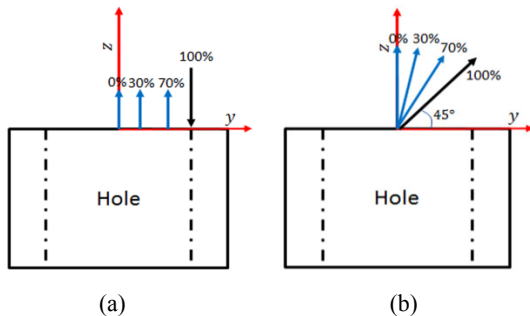


그림 6. 법선 벡터의 부정확성.

Fig. 6. Inaccuracies of normal vector.

	case1	case2	case3	case4	case5	case6	case7	case8
Fig.								
Position error	0%	0%	0%	30%	30%	70%	70%	No Haptic guidance
Orientation error	0%	30%	70%	0%	30%	0%	70%	

그림 7. 실험 시나리오(8가지 경우).

Fig. 7. Experimental scenario (8 cases).

100%. In this paper, experiments were conducted with the orientation inaccuracies of 30% and 70%. Note that each inaccuracy has a noise of 5%, which follows a Gaussian distribution and the orientation inaccuracy only takes into account the angle error for the y-axis (β).

To investigate the effect of such inaccuracies on task performance, experiments were conducted on eight inaccuracy cases as shown in Fig. 7. Participants performed 10 trials for each condition, giving a total of 80 trials during the experiment. Note that each case was presented at random. Before the experiment, instructions were handed out and verbally explained to participants. After the instruction, participants had time to practice. In this psychophysics experiment, participants are given a break time of 5 min after 40 trials.

6. Performance Measure

To investigate the effect of position and orientation inaccuracies in haptic guidance on task performance, we analyzed completion time, position tracking performance, contact force and attractive force.

Completion time: This is the time it takes the participant to successfully finish the given peg-in-hole task. Basically, when the tasks are executed on the teleoperation system, the better performance will be shown at the shorter completion time if the task accuracy is the same. We assumed that the completion time will increase as the position and orientation inaccuracies of the haptic guidance increase because the generated haptic guidance will affect the completion time of the peg-in-hole task. Since participants were required to perform tasks quickly during the experiment, the shorter the completion time, the better the task performance can be shown.

Position tracking performance: In conventional teleoperation research, the position tracking ability of the slave is commonly evaluated by estimating the discrepancy between the positions of the slave and the master. In the current work, position tracking is concerned with the target position on the intended reference path. Therefore, in this paper, the position tracking performance used in [18] is used as the performance metric. This is calculated as the area between the slave position and the ideal path until the experiment is complete. Position tracking performance can capture unnecessary movement when working with a remote control and is also associated with increased risks such as a collision with unfamiliar remote environments and decreased work efficiency. In conclusion, the higher the position tracking performance on the teleoperation system, the safer and the better the performance

of the peg-in-hole task. We assumed that the position tracking performance is higher than when there is no haptic guidance, and the position tracking performance will decrease as the position and orientation inaccuracies of the haptic guidance increase because the generated haptic guidance will affect the degree of the freedom of the peg.

Contact and attractive force: The contact force and the attractive force are generated by (2) when the peg and hole are in contact, and by (3) around the normal vector of the hole. These two forces not only provide information about physical interaction, but can also present appropriate movement to the operator. However, the peg or hole may be destroyed if the contact force is large in the practical teleoperation system. In this experiment, when the contact force exceeds 5 N, the experiment is terminated assuming that the situation that the peg is destroyed. Therefore, the contact force is very important indicator of the safety on the teleoperation system, also the lower the contact force, the safer and the better performance of the task can be shown. In addition, inappropriate haptic guidance can interfere with the operation of the operator. This may result in a large attractive force resisting motion of the operator. In this way, inappropriate attractive force can be used as an indicator of the operator's fatigue during teleoperation, so the larger the attractive force, the higher the operator's fatigue and the lower performance of the peg-in-hole task when the inaccuracies of the haptic guidance are generated. However, given the appropriate and accurate attractive force, it can be effective for the completion time or the accuracy of the peg-in-hole task. Finally, if the two forces presented to the operator are large, the fatigue of the operator can be increased. Therefore, we assumed that the attractive force and contact force will increase as the position and orientation inaccuracies of the haptic guidance increase in the peg-in-hole task because the generated haptic guidance affects the contact force and the attractive force by transmitting the physical information to the operator.

7. Data record

During an experiment, the position of the master (M_x, M_y, M_z), orientation of the master ($M_\alpha, M_\beta, M_\gamma$),

position of the peg (S_x, S_y, S_z), orientation of the peg ($S_\alpha, S_\beta, S_\gamma$), attractive force(F_x^a, F_y^a, F_z^a), contact force(F_x^c, F_y^c, F_z^c), and time (ms) were recorded at 1000 Hz. This recorded data is used to measure the performance of the operator during the peg-in-hole tasks.

III. RESULTS

Fig. 8 and Table 1 show a quantitative indication that peg-in-hole task was successfully completed in this experiment. This indication is the mean value of the numeral data for each subject when the experiment is completed. Success criteria in this experiment are explained in Fig. 4. First, Fig. 8 shows the mean value of the contact force at the end of the experiment for all subjects. The threshold of the contact force to complete the successful experiment is 5 N, and it does not exceed 5 N in all experiments as shown in Fig. 8. At this time, the mean value of the contact force is 1.0356 N for all experiments. Table 1 shows the mean value of the depth (the z position), the percentage of the hole depth, the y position and the orientation of the peg (the beta angle) when the experiment is completed. According to the success criteria, all experiments were completed when the peg was inserted more than 75% of the hole depth, the positional tolerance of the peg with the center of the

표 1. 실험 종료 시 피실험자별 데이터.

Table 1. Data for each subject at the end of the experiment.

	Depth (%)	Position (y)	Orientation (β)
Subject 1	10.39mm (76.94%)	-0.41mm	89.24°
Subject 2	9.57mm (78.76%)	0.31mm	88.01°
Subject 3	10.97mm (75.65%)	0.27mm	86.79°
Subject 4	10.46mm (76.78%)	-0.17mm	88.96°
Subject 5	9.27mm (79.42%)	-0.42mm	91.08°
Subject 6	10.76mm (76.12%)	0.25mm	86.59°
Subject 7	10.63mm (76.40%)	-0.36mm	88.85°
Subject 8	9.74mm (78.38%)	-0.16mm	86.01°
Subject 9	10.29mm (77.16%)	0.33mm	91.67°
Subject10	9.68mm (78.51%)	-0.12mm	89.15°

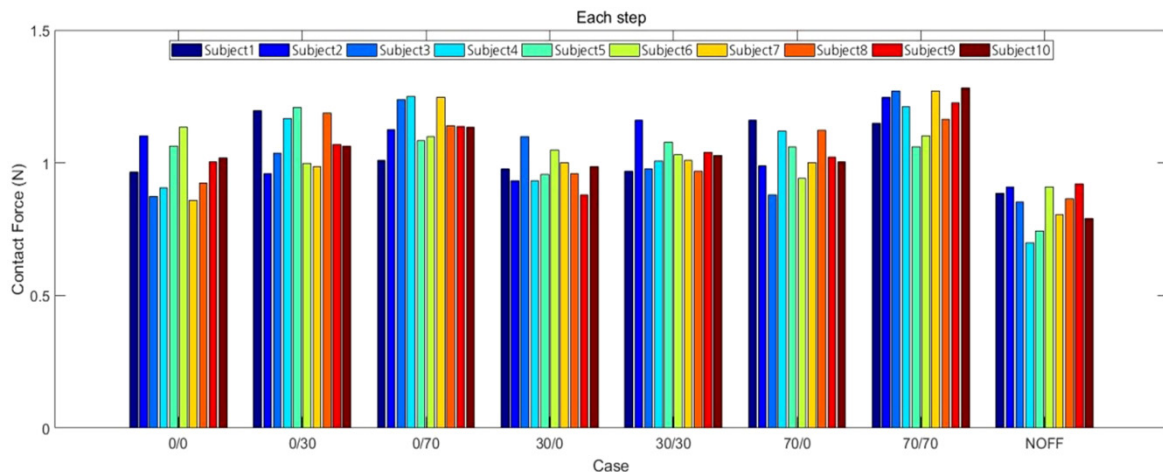


그림 8. 실험 종료 시 피실험자별 접촉력.

Fig. 8. Contact force for each subject at the end of the experiment.

hole was within 1mm and the angular tolerance of the peg with z-axis was within 5° as shown in Table 1.

Fig. 9 - 13 show the completion time, position tracking performance, contact force, and total force (summation of the contact and attractive force), respectively, for the eight cases shown in Fig. 7. Each experimental result shows the mean value during the overall step of the peg-in-hole task and the mean value during each step for the four steps presented in Sec II-3. Note that the position tracking performance shows only the values for each step because there was not a significant difference during the overall peg-in-hole task.

Fig. 9 shows the completion time when performing the peg-in-hole task. In the case of haptic guidance without error, it took about 2590 ms of task execution time, but when there is no haptic guidance, the task execution time was more than 3200 ms. The overall completion time was thus reduced by 15% through the haptic guidance. Particularly, the reduction of completion time is clearly seen in step 1 and step 3 (about 12% in step 1 and about 40% in step 3). In step 1, it is shown that the operator can access the hole quickly because the haptic guidance reduces the degree-of-freedom of operating motion of the operator. In addition, since the haptic guidance can easily align the peg with the hole, there is the large time reduction in step 3. Meanwhile, in step 4, there was no difference in the task execution time because the only degree of freedom of motion was perpendicular to the hole. Note that step 2 shows the same completion time because the time is constantly limited (500 ms). The effect of the size of the inaccuracy of the haptic guidance on the completion time is relatively small, but the completion time is slightly increased when the orientation inaccuracy is 70% (case 3 and 7).

Fig. 10 shows the position tracking performance for each step. The position tracking performance was measured only in the y-axis direction of Fig. 6. The overall position tracking performance is the worst in step 1, and improve as steps are taken. This is because the peg has the greatest freedom of motion in step 1, with available degrees of freedom decreasing as the steps proceed. Note that step 4 has no meaning for position tracking performance because the y-axis is constrained to the wall of the hole and there is no y-axis motion. In addition, the position tracking performance was significantly lower when there was no haptic guidance than when there was haptic

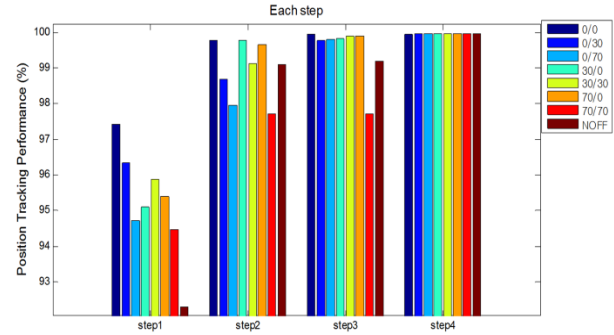


그림 10. 위치 추적 성능.

Fig. 10. Position tracking performance.

guidance from step 1 to step 3. This is because the haptic guidance reduces the degree of freedom by constraining the motion of the operator. On the other hand, if there is inaccuracy in the haptic guidance, the overall position tracking performance is degraded. If the orientation inaccuracy is 70% (case 3 and 7), the performance is seriously degraded. Furthermore, when both position inaccuracy and orientation inaccuracy are 70% in step 2 and step 3, the performance is lower than when there is no haptic guidance. In conclusion, haptic guidance helps position tracking performance by guiding the motion of the operator to the optimal path when performing a given task, but serious inaccuracy reduces performance so that it is worse than when there is no haptic guidance.

Fig. 11 shows the results of an attractive force for each case and for each step. The attractive force is large when the orientation error is larger for the same position error and when the position error is larger for the same orientation error. This is because when the operator tries to insert a peg into the hole without error, the wrong haptic guidance pulls the peg to the position and orientation where the error is present, so the larger the inaccuracies of the haptic guidance, the larger the attractive force. In addition, the attractive force is more influenced by orientation inaccuracy than by position inaccuracy because the attractive force is relatively larger where the orientation inaccuracy is 70%. If such an incorrect attractive force is generated, it can act as a reaction force to the operator and increase the operator's fatigue. Consequently, excessive or inappropriate attractive force interferes with the operator

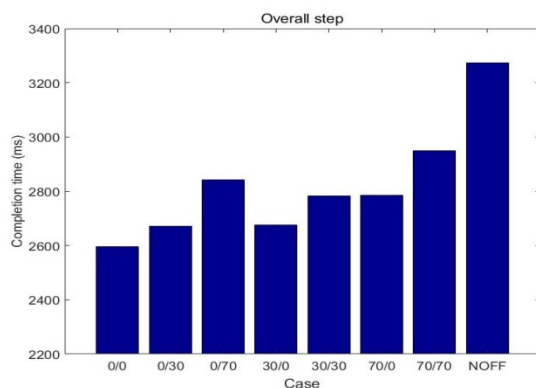
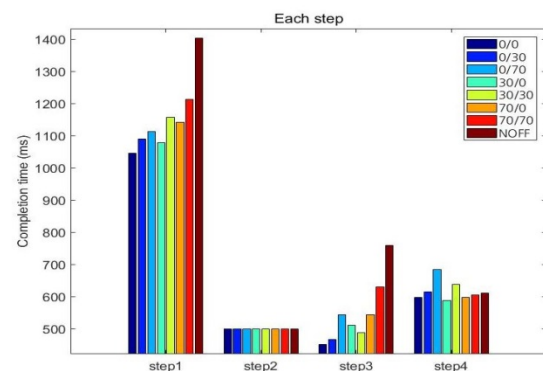


그림 9. 완료 시간.

Fig. 9. Completion time.



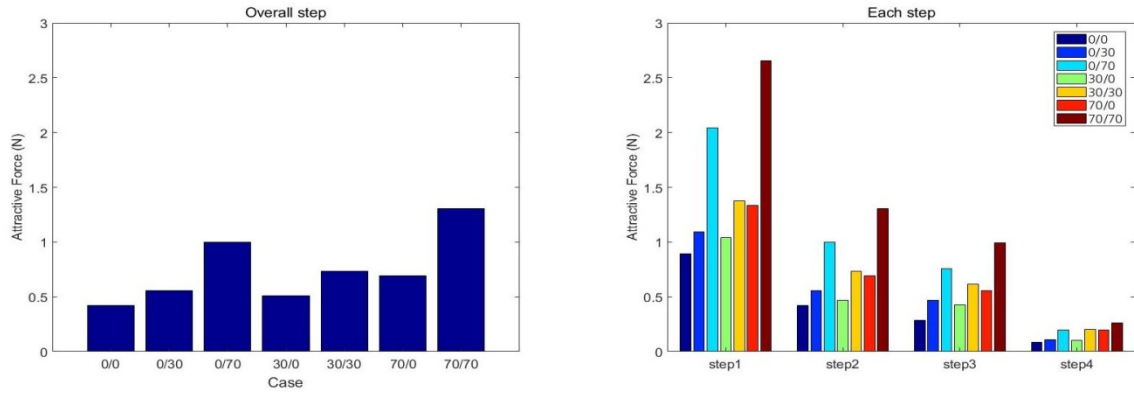


그림 11. 인력.

Fig. 11. Attractive force.

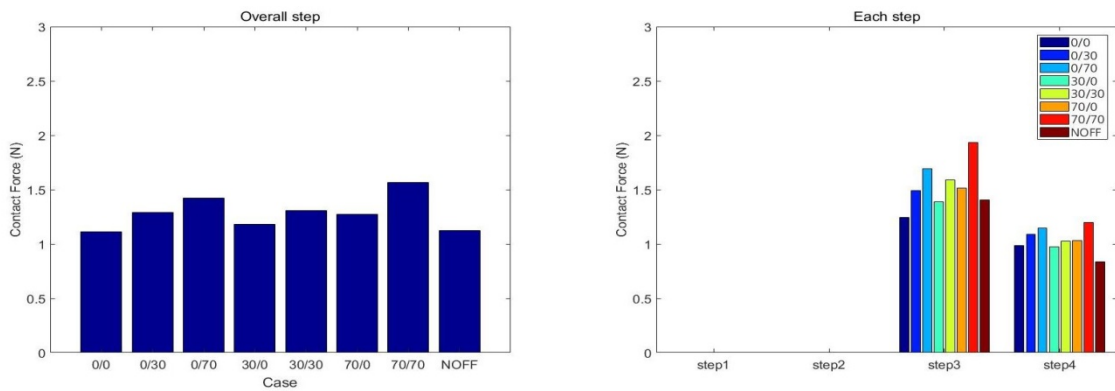


그림 12. 접촉력.

Fig. 12. Contact force.

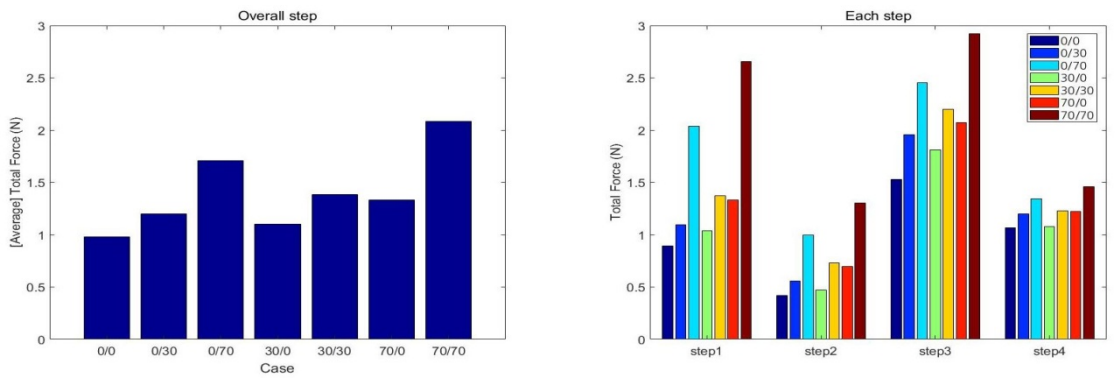


그림 13. 총 힘.

Fig. 13. Total Force.

performing the tasks in the teleoperation system, so accurate haptic guidance should be generated at all time.

Figs. 12 and 13 show contact force and total force, respectively. The contact force and the total force are considerably larger for the two cases where the orientation inaccuracy is 70%. This large force can cause damage to the peg or hole in the practical teleoperation system, and can increase operator fatigue because this large force is presented to the operator as reaction force. Furthermore, when there is a serious orien-

tation inaccuracy, such as the 70% inaccuracy (case 3 and 7), the force is larger than that generated when there is no haptic guidance. In [14] and [15], even though the tilted operation is effective when performing the peg-in-hole task, if the orientation inaccuracy is large it can cause serious large forces between the peg and hole, which means that the peg is severely tilted.

In conclusion, haptic guidance without inaccuracy reduces task completion time, position tracking performance, contact force, and total force by guiding the operator to the optimal

path. However, when there is the inaccuracy of the haptic guidance, the performance is degraded. In particular, when the orientation inaccuracy is 70% (case 3 and 7), the performance is lower than that without the haptic guidance.

IV. CONCLUSION AND FUTURE WORKS

This paper has preliminarily investigated the effect of haptic guidance and inaccuracy of haptic guidance on task performance. In the peg-in-hole task, eight experimental cases were presented to evaluate haptic guidance and the impact of directional and orientation inaccuracy. Four performance metrics, the completion time, position tracking performance, contact force, and total force, were measured and analyzed. When performing the peg-in-hole task, the haptic guidance system reduced the completion time by 15% and improved the position tracking performance as compared to the conventional teleoperation system. However, the haptic guidance system with severe orientation inaccuracy (70%) not only significantly degraded position tracking performance, but also overloaded the system or the person due to the large force of both contact force and total force.

Further investigations are needed: 1) experimental and statistical analysis of data from more than 20 subjects, 2) maneuverability [19] as measured by the force applied by the operator to the haptic device using a force sensor, and 3) comparison of experimental results using an actual slave robot and experimental results of haptic simulation. In case of (3), we are setting up an experiment for the actual peg-in-hole task using the UR10.

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