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# Adaptive Haptic Control Interface for Safeguarding Robotic Teleoperation in Hazardous Steelmaking Environments

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*Abstract*— **Steel mill is one of the most extreme and hazardous working environments due to molten iron erupted from blast furnace. Current manual labor to remove lump iron near the outlet, which is essential to prevent lump iron from scattering or blocking of molten iron, is performed by equipped human workers using a long stick tool. Thus, implementation of robotic teleoperation system is in demand to ensure the safety of workers. However, the conventional command interface is not intuitive for tool manipulation (i.e. pivoting, sweeping). Besides, haptic interface, which is used to render interaction results efficiently, still limits performance due to narrow workspace and insufficient kinesthetic feedback output compared to requirements. This paper proposes a novel haptic command interface (POstick) specified to lump iron removal task with two types (KF and VF). Both POsticks have rod-shaped end tip which is identical to actual tool already used to accelerate training. POstick-KF has large workspace and high kinesthetic feedback output satisfying requirements. Further, POstick-VF has strength with unlimited workspace at the expense of the amount of haptic information from simple vibrotactile feedback. User study to compare the performance of POsticks and conventional interface reveals that POstick-KF and VF showed superior interaction and tracking ability, respectively. Moreover, these two properties are in trade-off relationship that cannot be compatible. Finally, we proposed a seamless and automatic conversion mechanism from POstick-VF to KF, and vice versa, to cover up inherent limits of haptic devices.**

## I. INTRODUCTION

Despite the advances in robotic automation, humans still play an important role in dangerous and extreme work environments. This is due to the knowledge and know-how obtained from human experience, which cannot be modeled to automate tasks. Therefore, robotic teleoperation is a promising solution to ensure worker safety while preserving irreplaceable human capabilities. One of the most extreme working environments is steel mill, due to the hot and glaring molten iron. In the first process of steelmaking, ironmaking, molten iron is erupted from the blast furnace outlet. The hot molten iron splashes around, gradually solidifies, and creates an object called “lump iron”. Over time, the lump grows larger and larger, even blocking the molten iron and causing it to scatter, so it must be constantly removed. Currently, workers wearing heat suits approach the outlet and remove the lump iron with a rod-shaped long stick. However, the high temperature over 1500 °C near outlet and splashing molten iron threaten the safety of the workers. Therefore, we developed robotic teleoperation system for lump iron removal task to ensure the safety of the human workers.

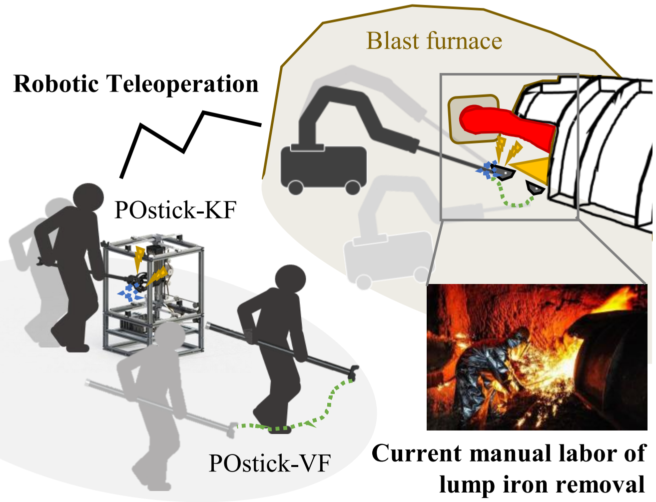

Fig. 1. POstick: Convertible haptic command interface specified for robotic teleoperation of lump iron removal task

We are envisioning teleoperation command interface specified to lump iron removal task. Existing robotic teleoperation system utilizes a keyboard and GUI interface or joystick as a control device, which is not an intuitive mechanism for robot tool manipulation. Conventional command interfaces also cannot provide any feedback about interaction between remote robot and surrounded environments. The intuitiveness and ease of operation of the remote robot using command interface directly affect the results and usability of the robotic teleoperation system. It is also necessary to reduce the cognitive burden on the operator with intuitive command interface, because the operator can only get limited visual information due to the dazzling lights from molten iron. In order to successfully perform removal task using long stick tool, it is also necessary to be able to perform tool manipulation intuitively such as pivoting and sweeping, where the fulcrum of movement is constantly changing. In our target contact-rich task, excessive force can be exerted to robot during removal of lump iron. If the operator is not aware of such interaction results, robot can be damaged or removed lump iron can be bounced off. Thus, haptic interface

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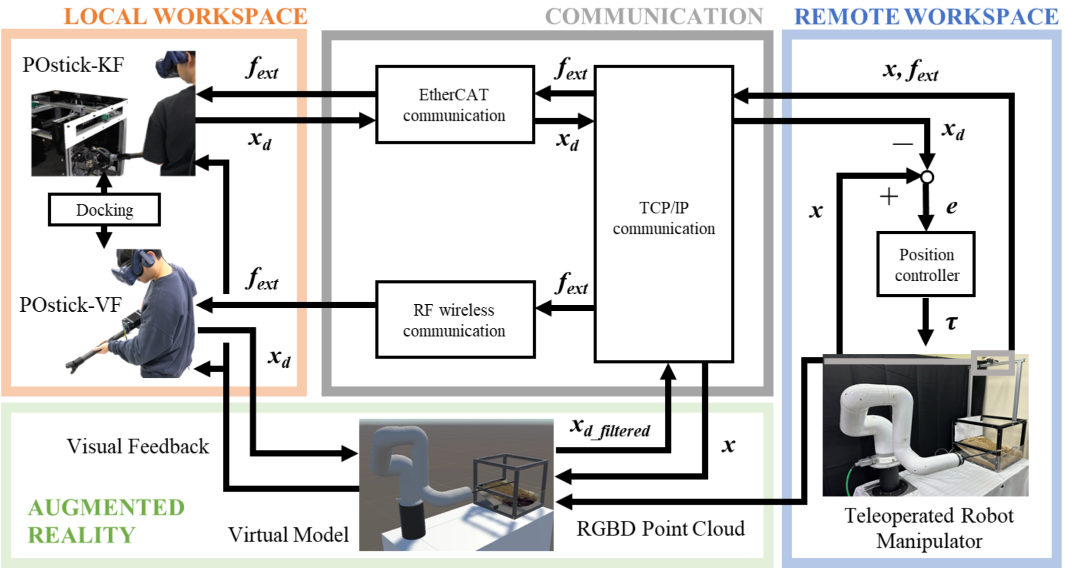


Fig. 2. Entire control structure of POstick for robotic teleoperation of lump iron removal task

is a good solution, because haptic feedback can render results of interaction between remote robot and environments to user intuitively in the form of kinesthetic or vibrotactile. We set required performance as 1) larger workspace than 300 mm × 300 mm × 300 mm, 2) higher continuous force feedback output than 30 N considering the actual environment near the blast furnace. Then, we aimed to implement haptic device to control robot which satisfies aforementioned requirements.

At the beginning of this project, we considered which configuration of haptic device is more appropriate solution. Haptic devices can be categorized into two types based on configuration: Grounded and ungrounded [1]. Grounded haptic command interfaces mainly generate kinesthetic feedback while the base is mounted on ground [2]. Kinesthetic feedback renders external wrench at robot, so user motion can be constrained. Linkage or cable driven mechanisms are used for transmission of power from actuators to end-effector. Each of them has unique merits such as high stiffness and low inertia, respectively. However, these grounded type interfaces have limited workspace, which utilize clutching motion to cover exceeded space over inherent workspace. Of course, large workspace can be achieved by scaling up entire system, nevertheless kinematic constraint such as friction and inertia would be bothering issues in development [3]. Ungrounded type haptic interface contains body-grounded or hand-held type. Larger workspace, even unlimited without any kinematic constraint, is the merit of ungrounded type devices. Meanwhile, these interfaces can only render simple information through vibrotactile haptic feedback. Further, low dimenstioanl kinesthetic feedback is also utilized with ungrounded device such as torque feedback based on gyro effect [4]. However, additional system to generate high dimensional kinesthetic feedback with ungrounded interface will introduce physical burden to user during teleoperated task. Thus, large workspace and high force feedback are in trade-off and cannot be compatible.

To this end, we developed new haptic command interfaces specialized for lump iron removal task which meets aforementioned performance requirements (Fig. 1). The end tip of the haptic interface is hollow shaft stick which is similar to real tool used in manual labor. Moreover, the new haptic device, POstick was developed into both types of grounded (POstick-KF) and ungrounded (POstick-VF) to maximize each merit of high kinesthetic feedback and large workspace, respectively. Worker can select command interface to use depends on the task process. For example, safe interaction between robot and environments using POstick-KF, or fast and accurate robot manipulation in free space using POstick-VF. User study to compare the performance of developed command interface to conventional device was performed. Further, we suggest convertible POstick to enable seamless and automatic conversion between POstick-KF and VF to merge their own merits. Through our proposed system, robotic teleoperated task can be completed safely and fast.

The remainder of this paper is organized as follows. Section II presents the developed teleoperation system, focusing on each interface. Section III describes evaluation through user study to compare the performance of the developed haptic command interfaces. Section IV presents seamless and automatic conversion between POsticks. Demonstration in testbed similar with real site is also described. Finally, conclusion is described in Section V.

## II. PROPOSED SYSTEM

Entire control structure of proposed robotic teleoperation system for lump iron removal task is followed as Fig. 2. POstick-KF and POstick-VF utilize bilateral and unilateral teleoperation, respectively, and these are connected to commercial 6-degrees of freedom (DoF) robot manipulator (Indy7, Neuromeka, South Korea). Low-level PID based

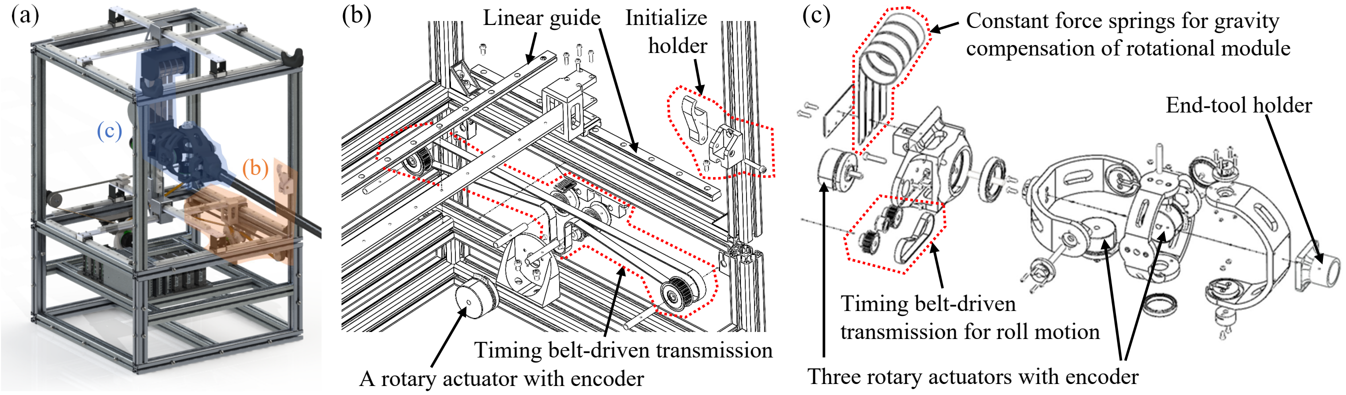


Fig. 3. (a) POstick-KF. 3D exploded view of (b) timing belt-driven transmission of translational axes. Initialize holder is used to set zero pose of tool, and (c) gimbal-type rotational module with gravity compensation by constant force springs.

TABLE I. Specifications of developed haptic command interfaces

| | **POstick-VF** | **POstick-KF** | |
|---|---|---|---|
| **Mechanism** | commercial wireless pose tracking | translational | belt-driven linear guide |
| | | rotational | direct-driven spherical joint |
| **Workspace** | limitless | translational | 450 × 450 × 400 mm |
| | | rotational | $\pm180°, \pm50°, \pm50°$ (RPY) |
| **Haptic Feedback** | vibrotactile | kinesthetic (output force) | $F_x = F_y = 30\text{N}, \text{F}_\text{z} = 35\text{N}$ |
| | | | $\tau_x = \tau_y = \tau_z = 150\text{mNm}$ |

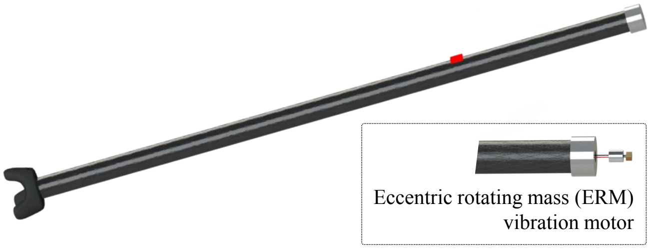


Fig. 4. POstick-VF with vibrotactile feedback.

position controller is embedded to teleoperated robot in real-time (1 kHz). Pose command from POstick-KF is transferred to low-level controller using TCP/IP communication in real time (1 kHz) to ensure stability of bilateral control loop. On the other hand, command from POstick-VF is transferred in 100 Hz, which is relatively slow due to inherent update rate of wireless communication of commercial pose tracker (Vive Tracker 3.0, HTC Corporation, Taiwan). Augmented reality (AR) based immersive and limitless visual feedback is provided through head mounted display. Remote situation is provided to user in live stream through RGBD point cloud captured from stereo camera (ZED2, Stereo labs, USA). Moreover, collision avoidance algorithm is implemented using replicated robot and structured testbed in virtual environment.

The performance of developed command interface is described in Table I. The details of haptic command interface are presented component by component in following sections.

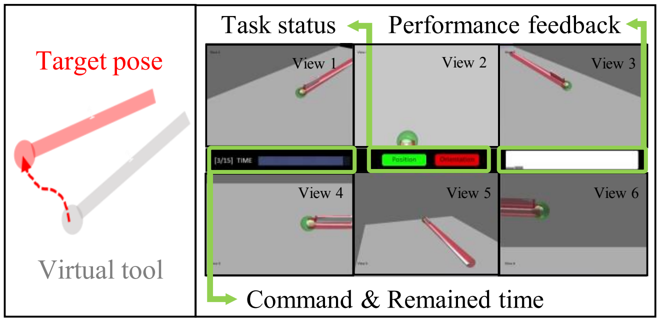
### A. POstick-Kinesthetic Feedback (KF) version

End tip of both command interfaces is carbon-fiber hollow shaft (outer diameter: 36mm, thickness: 3.5mm, and length: 1000mm) for intuitive fulcrum conversion (Fig. 3). Motion tracker on the end tool was used just as trigger button to start teleoperation. 3-DoF translational movement was implemented using coupled 13 linear guides (SSE2B20-520-WC, Misumi, Japan) (Fig. 3b). Two brushless DC (BLDC) motors (658811, Maxon, Switzerland) providing maximum torque of 0.45 Nm were implemented with a 14 mm pulley. The actuation of vertical axis requires higher output due to gravity compensation. Thus, BLDC motor (500269, Maxon, Switzerland) and 28.5 mm pulley was implemented, which provided a maximum torque of 0.887 Nm. All the motors we used were combined with magnetic encoder to measure rotational displacements.

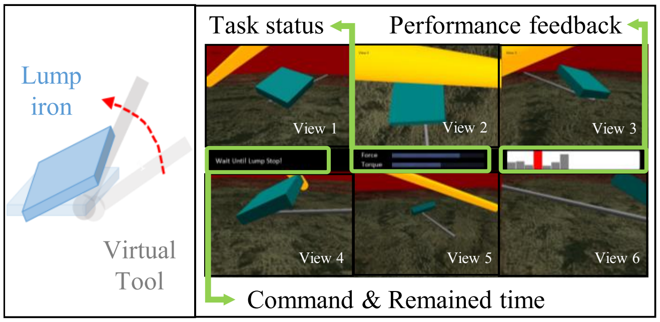
Rotation module was designed as gimbal-type to implement 3-DoF rotational movements (Fig. 3c). Module was manufactured by 3D printing to reduce the weight while ensuring high stiffness (materials: Nylon PA12). Three BLDC motors (658811, Maxon, Switzerland) were used to provide torque feedback. Motors for the pitch and yaw axes were placed inside the module to achieve compact design. However, motor for roll axis was moved to the side and transmission by belt-driven mechanism with a 14mm pulley was implemented. The rotation module was connected on the block of the linear guide in vertical axis. As a result, the magnitude of force feedback in vertical axis was decreased due to the weight of rotational module. To solve this problem, four constant force springs (9293K32, McMaster-Carr, USA), which always need identical load to be stretched, were implemented at the top of the vertical axis. Therefore, 24 N was supported with the benefit of constant force springs. 6-DoF kinesthetic feedback is generated by current based torque controller of each actuator.

### B. POstick-Vibrotactile Feedback (VF) version

POstick-VF was developed using commercial wireless 6-DoF motion tracker (Fig. 4). Current position and orientation of pose tracker is measured in 100 Hz update rate through



(a) Motor task: (1) Wait for 10 seconds before task started. (2) Move tool (white) to target pose (red). (3) Maintain current pose for 3 seconds after tool reached to target pose (green). (4) Rest for 5 seconds before next trial (15 repetition).



(b) Interaction task: (1) Wait for 10 seconds before task started. (2) Move tool near target lump. (3) Detach the lump by pivoting. (4) Rest for 5 seconds before next trial (15 repetition).

Fig. 5. Experimental procedure for each task in user study

radio frequency (RF) wireless communication. The pose tracker (Vive Tracker 3.0, HTC Corporation, Taiwan) was attached to the front of carbon-fiber hollow shaft. Motion tracker provides 6 Pogo pins which can control digital input or output. One of the Pogo pin is used as trigger button.

Vibrotactile haptic feedback was implemented to give information about interaction force to user. Eccentric rotating mass (ERM) vibration motor (DVM1220, Motorbank, South Korea) was attached to the end of stick. ERM vibration motor was operated with pulse position modulation (PPM) signal. Duration of +3.3 V pulse signal was fixed to 5 ms. Period between pulses was encoded from the magnitude of external wrench according to the following rules,

$$\Delta T = \begin{cases} -0.0062\|f_{ext}\| + 0.5008, & \text{if} \quad \|f_{ext}\| \leq 60 \text{ N} \\ 0.13, & \text{otherwise} \end{cases}$$

Constant parameters of linear mapping were chosen considering limited update rate of RF communication. External wrench was measured by 6-axis force/torque sensor attached to the robot end-effector. The converted PPM signal was amplified through a motor driver (L9110s, Motor Bank, South Korea).

## III. EVALUATION

This section presents the experimental evaluation of PO-sticks to compare the performance with conventional com-

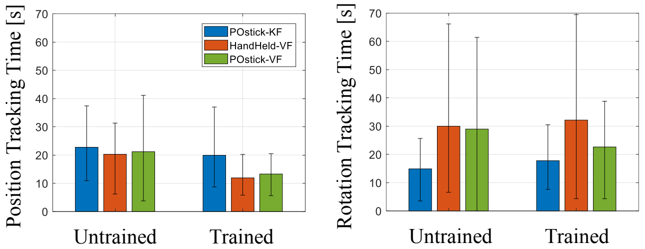


Fig. 6. Results of task 1 (tool manipulation in free space) for each metric.

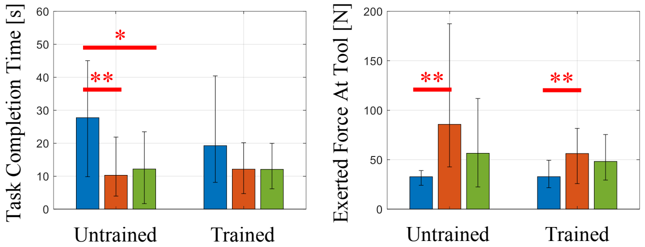


Fig. 7. Results of task 2 (interaction between robot and environments) for each metric. Red solid line with star symbol (*) indicates significance.

mand device (VR Controller, HTC Corporation, Taiwan) called HandHeld-VF.

### A. User Study

Experiments were designed in simulation environment to ensure identical condition (i.e. required force to detach lump iron, adhered position), which is difficult in real world. In lump iron removal task, two abilities are essential: fast and accurate robot manipulation to approach to target lump iron, and safe interaction between robot and environments to remove lump iron. To this end, two tasks were designed to evaluate each atomic action. The goal of the first task is to manipulate stick tool to randomly generated target 6-DoF pose (Fig. 5a) within 90 s. The goal of second task is to detach the adhered lump iron from sand while exerting required minimum wrench (not exceeds 200 N) with tool (Fig. 5b). Exerted force at tool has to be minimized to protect any damage of robot manipulator. Haptic feedback was provided to give contact information between robot tool and environments. Both tasks were repeated for 15 times with short break (5 s) after each trial to observe training effect of each device through long session [5], [6], [7], [8]. The sequence of command interfaces for each participant was determined based on Balanced Latin Square design to minimize order effect. Total 12 participants were recruited who had no experiences about teleoperation and virtual reality (mean age 23.3 years, standard deviation 1.54 years). Visual feedback was provided from 6 different perspectives at once through 65” 4k 2D screen panel. This is due to purely compare the performance of command interfaces without any limited field of view or depth information. All failed trials were removed, and remained data was averaged over all

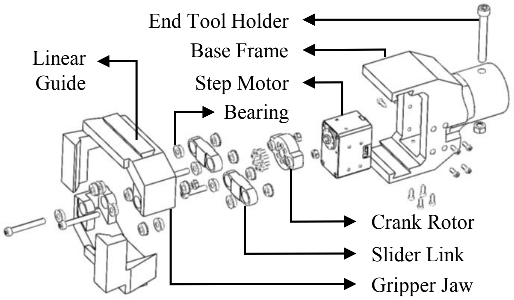


Fig. 8. Exploded view of POstick gripper

subjects to perform statistical analysis. First and last 2 trials were used to represent untrained and trained status of each participant, respectively. To investigate differences between command interfaces, one-way ANOVA test was performed.

### B. Results

For task 1, averaged success rates for untrained user were similarly high when using POstick-KF (75 %) and POstick-VF (79.17 %). However, the initial success rate for HandHeld-VF was relatively low (54.2 %). The success rates for each interface, based on repeated trials, gradually improved with training. However, HandHeld-VF still showed lowest success rate (70.83 %) compared to other two interfaces (KF: 83.33 % and VF: 79.17 %) although training was occurred enough. Required time to follow target position is similar with all devices before training. However, ungrounded-type devices, HandHeld-VF (11.91 s) and POstick-VF (13.28 s), showed decreased position tracking time as training occurred compared to POstick-KF (19.9 s). In the case of rotation tracking time, POstick-KF showed shorter time than other devices with the benefit of decoupled motion. Neverthless, POstick-VF (22.63 s) resulted in shorter time after training compared to HandHeld-VF (32.15 s), through kinematic similarity with actual tool used in daily life.

For task 2, The highest success rate for untrained subjects was achieved when using POstick-KF (83.3 %) and POstick-VF (79.17 %), meanwhile HandHeld-VF showed the lowest success rate (50 %). All three interfaces showed improved success rate over training. POstick-KF resulted in relatively long task completion time compared to other ungrounded-type interfaces, HandHeld-VF and POstick-VF, with significant differences ($p$=0.006 and $p$=0.045, respectively). External force was continuously maintained lower when using POstick-KF even with untrained subjects. In contrast, HandHeld-VF showed relatively high force (56.21 N) with significant difference compared to POstick-KF even after training. Surprisingly, POstick-VF showed comparable force control ability with POstick-KF regardless of training (no significant difference).

## IV. EXPERIMENTS

This section presents conversion system between POsticks to maximize merits of each device. Then, entire teleoperation system was validated through real world demonstration in testbed.

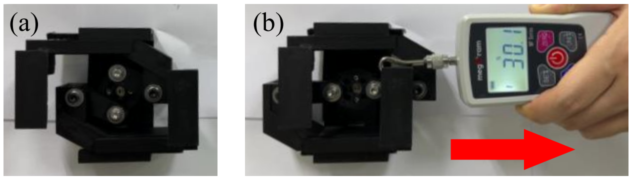


Fig. 9. Front view of developed POstick gripper: (a) Open (b) Close and breaking force exceeds 30 N

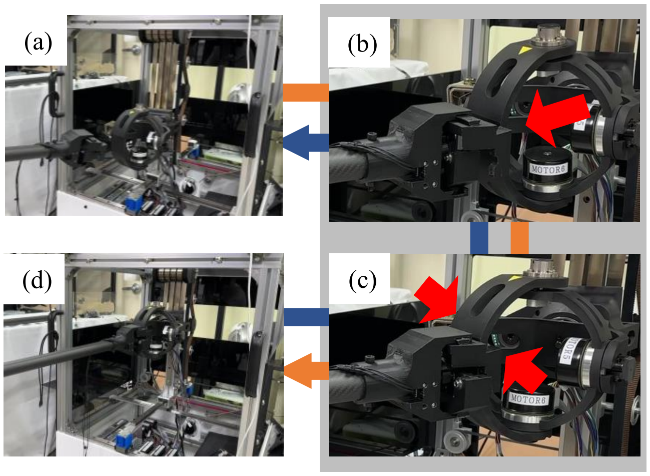


Fig. 10. Entire process of conversion from (a) POstick-VF to (d) KF (orange arrow), meanwhile conversion from KF to VF is performed in reversed order (blue arrow). Seamless and automatic conversion is achieved by (b) tracking and (c) docking

### A. Seamless and Automatic Conversion between POsticks

As results of user study, POstick-VF showed superior pose tracking ability, whether POstick-KF showed better interaction ability with low force. Each device marked different strength, and these are not replaceable due to inherent property of haptic interface.

To this end, we developed a seamless and automatic conversion mechanism. Especially, automated conversion becomes in demand during teleoperated task wearing head mounted display for stereo vision. Conversion from POstick-VF to KF can be completed successfully through tracking and docking process (Fig. 10). Conversion from KF to VF can also be executed in reversed order. Conversion of POstick between two types is performed through tracking and docking process. Each will be presented in detail.

*1) End-effector tracking method:* Previously developed ungrounded haptic command interface alreday used commercial pose tracker through wireless communication from 2 optical sensors. The pose of POstick-KF in global frame should be measured to calculate target command. To this end, additional 2 pose tracking devices were installed on

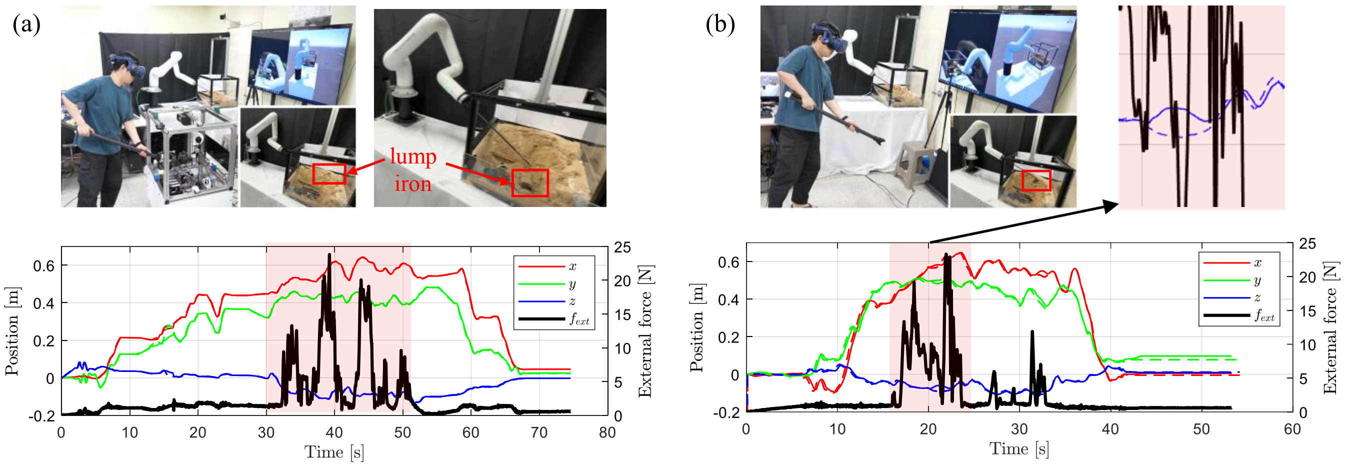


Fig. 11. Demonstration of teleoperated lump iron removal in testbed similar with real site, using (a) POstick-KF and (b) POstick-VF.

two point above POstick-KF. Finally, desired pose of end-tip of POstick-KF can be calculated through coordinate transformation. End-effector pose of POstick-KF is controlled through 1 kHz low-level EtherCAT based controller. Reachable workspace of end-effector during tracking was limited to protect collision to device frame.

*2) Docking mechanism:* For connection between end-effector of two interfaces, three methods can be considered: mechanical linkage-based grabber, electro-magnet, and suction. During teleoperated lump iron removal task, high force (up to 30 N) can be exerted in any axis from human operator. Thus, robust and fully constrained connection in 6-DoF of end-effector is necessary. Moreover, seamless connection has to be performed to prevent any discomfort feeling to user during docking while covering inherent pose tracking error of sensors. To this end, mechanical linkage-based grabber is chosen to our system with the merit of fast response time and sufficient breaking force.

Crank-slider mechanism was utilized to generate two reversed linear motion from rotary motion of actuator (Dynamixel XM430, ROBOTIS, South Korea) (Fig. 8). Moreover, kinematic singular pose was rather used to achieve robust connection after gripper is combined to end-effector of POstick-KF. In crank-slider mechanism, singular pose occurred when both crank and slider links were aligned in line. Unless motor rotates, gripper would not be opened in singular pose, which can achieve robust connection between two end-effectors. As a result, length of each link for crank and slider was determined which meets 0.02 m stroke per each jaw, and sufficient breaking force exceeds 30 N during grasping (Fig. 9).

## *B. Demonstration in Testbed*

To validate developed teleoperation system, demonstration of lump iron removal task was performed (Fig. 11). Testbed is similar with environment near outlet of blast furnace, and scale was reduced to 1/3. Splash cover to protect molten iron splashing is made with black aluminum frame, and a lump iron is duplicated to steel arch-shaped model with a weight of 700 g. Entire task consists of three steps; manipulate robot to target lump iron closely, remove the lump from sand, and return robot to initial pose.

## *C. Results*

Robot and command trajectory during task were plotted as solid and dashed line, respectively (in bottom of Fig. 11). Red colored box indicates interaction period between robot tool and environments such as sand and lump iron. Operator can perform removal task successfully with minimized wrench (10 to 20 N) through haptic feedback from both POsticks. Especially, collision avoidance algorithm usign physics engine with POstick-VF contributes to reduce the force by preventing excessive contact between tool and bottom slope. In detail, user command (dashed) which penetrates slope surface was filtered to utilize safe robot motion (solid) as enlarged red box in Fig. 11b. Thus, external force during task was comparable to POstick-KF although POstick-VF was used. Moreover, task completion time was 10 s shorter when using POstick-VF with direct approach to target lump at once.

## V. CONCLUSIONS

In this paper, novel haptic command interfaces specified to robotic teleoperated lump iron removal task in steel mill are developed. Developed intuitive haptic command interfaces which meet aforementioned requirements for lump iron removal contribute to both safety of workers and performance of teleoperated task compared to manual labor. Furthermore, we found meaningful result through user study that two types of POstick differ its own priority depends on the task process. Thus, we proposed a seamless and automatic conversion system from POstick-VF to KF, or vice versa, through tracking and docking mechanism. As a result, our target task can be completed safely and fast using our teleoperation interface. We figured additional improvements, and these will be addressed in our future work.

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