2013 IEEE/RSJ International Conference on
Intelligent Robots and Systems (IROS)
November 3-7, 2013. Tokyo, Japan

Human-Centered Evaluation of Multi-User Teleoperation for Mobile Manipulator in Unmanned Offshore Plants

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Abstract— **Recently, offshore plants are demanded to secure natural resources more and more and it is strongly required unmanned ones for safety of human operators and less running costs. In this paper, a practical multi-user teleoperation system is proposed for monitoring, inspection, operation, and maintenance of the unmanned offshore plants. The proposed system is developed to control mobile manipulator in a cooperative way among multiple human operators for better performance. For this, two control schemes, hand-eye coordination and disjoint axes were introduced for easier intuitive control of the mobile manipulator and for better cooperative control among multi-user, respectively. A well-known passivity-based approach, the time-domain passivity approach was, in addition, adopted to maintain system stability. And then, the proposed multi-user teleoperation system was evaluated via a human-centered method with several quantitative metrics regarding task completion time and interaction forces. Experimental results showed that the proposed multi-user teleoperation system has the benefit in tasks requiring less task completion time and interaction forces.**

I. Introduction

The demand of the age is to secure natural resources. The ocean, a rich repository of natural resources, is being pioneered, and offshore plants are built up for big oil and gas fields into the ocean. Jackups, platform rigs, semisubs, and submersibles are different types of offshore plant, and the number of them is approximately seven hundreds and it is still increasing [1]. The objective of offshore plants is to raise the medium up from the ocean to the surface and send it to ships which carry the medium to the land. Operation of offshore plants is not only important to produce a high performance such as tremendous profits but maintenance of them is also crucial to prevent accidents (e.g., gas leakage and fire). Those accidents could cause an enormous financial loss with an environmental disaster. The most frightful accident is the disaster in Piper Alpha platform, which is the most expensive and deadliest one. It was destroyed by explosion and fire with the cost loss of $1.27 billion and 167 victims in the blaze [2].

To prevent accidents in advance, workers are required to stay on offshore plants for monitoring, inspecting, and maintaining them regularly. However, the offshore environment is neither safe nor friendly to workers for staying in long-term period because of explosive, toxic, and corrosive atmosphere, unsheltered maritime environment, heavy weather, extreme ambient temperature, and long walkways [3]. Not only for these reasons, moreover, the running costs of operators for operating and maintaining offshore planform is $35∼150 thousands per day [3]. From this background, the concept of unmanned offshore plant was introduced and it is strongly required.

Some heavy industries companies including us, Samsung Heavy Industries, are, recently, challenging to build up the unmanned offshore plants. Our company is, for example, involved in a project to produce natural gas and condensate in Norwegian continental shelf (called as *Valemon* project) and main role is to construct a production platform. Without human operators, in the unmanned offshore plant, mobile manipulators (i.e., mobile robots equipped with a robotic manipulator) have to be deployed for performing tasks such as monitoring, inspection, operation, and maintenance. In detail, inspection tasks such as gauge reading and valve/lever position reading, monitoring tasks (e.g., gas level, acoustic anomalies, surface condition, and leakage and intruders), and gas and fire detector test, sampling, pigging, cleaning, and refilling for maintenance task have to be performed by the mobile manipulators. Among those tasks, operation tasks regarding valve and lever, and gas leakage and fire monitoring are most frequently operated as well as important ones [3].

For a success of unmanned offshore plants, a teleoperation system for mobile manipulator is highly demanded because, currently, a fully autonomous operation of mobile manipulator is practically impossible. Our research group is, therefore, challenging to develop a teleoperation system for unmanned offshore plants, which is very robust to harsh environments and could perform tasks efficiently with multiple mobile manipulators and human operators.

Various teleoperation systems have been developed over the past 60 years and those were applied in various areas such as handling radioactive material in nuclear plant, surgical robot in telesurgery, maneuvering of underwater vehicles, manipulation for space robots, and mobile robots in hazardous environments [4]. In teleoperation, however, time delay between a human operator and a slave robot and data loss from the slave to the operator disturb the human operator to control the slave robot so that it decreases system performance, and moreover, those factors could cause system unstable. With multi-robot and multi-operator, these issues become more crucial and complex to analyze and solve. To achieve both stability robustness and high performance in multi-robot-multi-user teleoperation is still an open problem,

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and many researches have been investigated.

A. Related Works

Some researchers studied cooperative control for multi-manipulators to enhance operational effectiveness [5], [6], [7], [8]. Wei R. *et al.* [5] provided excellent surveys about applications and capabilities of cooperative control. Applications of cooperative control are space, combat (surveillance and reconnaissance systems), hazardous material handling, and distributed reconfigurable sensor network areas. It was also applied in microsurgical manipulation system, which is cooperative human/robot system [6]. In cooperative control, consensus of multi-robots enhances operational effectiveness [5]. To increase consensus, a cooperation control performing a shared task using inter-vehicle communication to coordinate their actions was studied [7]. Recently, a decentralized strategy was introduced to improve concurrent synchronization of each slave with others to perform a same task simultaneously [8].

Some researches addressed multi-user teleoperation system rather than single-user one in [9], [10], [11], [12], [13]. The internet was used to connect between distributed groups of users for collaboration to teleoperate a robot [9], [10], and a multi-site cooperative control was suggested to overcome random time delay, which could affect on task synchronization in human-robot interaction [9]. Multi-user teleoperation system was, furthermore, also used to solve how to control kinematically redundant robotic manipulators in [12]. To enhance the interaction among users, recently, the whole system architecture and the appropriate design of feedback system (e.g., auditory, visual, and haptic system) was proposed [11]. In [13], a distributed control was analyzed and proved that it has larger stability margins and is superior to centralized control.

The effectiveness of various teleoperation systems was, recently, studied via human-centered evaluation. Task completion time, path accuracy, and energy exchange between users were defined as measures to evaluate statistically the performance of dual-user collaborative haptic guidance system in [14], [15]. In detail, a human-centered evaluation was carried out to figure out the performance difference for various task trajectories [14] and geometries of environment along with view points on virtual environment [15]. For bilateral teleoperation of multiple unmanned aerial vehicles (UAVs), a human-centered evaluation was also carried out to show how information from the remote UAVs can be properly transmitted to human operator as haptic cues via master device [16]. For the evaluation, several measures were defined, which were related to maneuverability and perceptual sensitivity.

Although it is clear that several researchers focused their attention on human perspective studies in single-user teleoperation system, still few works have been progressed for multi-user teleoperation system.

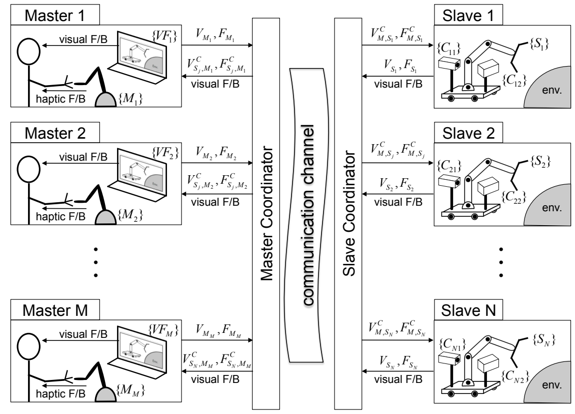


Fig. 1. Architecture of multi-user teleoperation system

B. Objective

In this paper, we evaluate benefits of multi-user teleoperation for mobile manipulator in unmanned offshore plants via human-centered evaluation. To achieve this, firstly, a practical multi-user teleoperation system is proposed, which has higher performance for tasks required in the unmanned offshore plant, by introducing several control schemes, hand-eye coordination and disjoint axes. And a well-known passivity algorithm is applied to stabilize the system even with time delay and data loss in communication channel. Quantitative measures are, then, presented to analyze experimental results in a rigorous way. Finally, we suggest human-centered evaluation method to evaluate performances of the multi-user teleoperation system in terms of the proposed measures.

The rest of the paper is organized as follows. In Sect. II, system configuration of the proposed multi-user teleoperation is introduced. Then, the human-centered evaluation method and experimental setup is presented in Sect. III. Following that, experimental results are reported and discussed in Sect. IV. Finally, the paper is concluded with a direction of future work in Sect. V.

II. Teleoperation System for Mobile Manipulator

A. System Configuration

The configuration of multi-user teleoperation system is illustrated in Fig. 1. There are masters, master coordinator, communication channel, slave coordinator, and slaves in the system. Human operators control the slaves by controlling the masters and receive visual and haptic feedbacks via a display device and the masters, respectively to aware states of the remote slaves and environments. The human operators could choose the slaves and cameras manually if he/she wants to operate so that those could be most effectively used for a given task. The master coordinator manages whole signals (e.g., control commands and visual/haptic feedback) for the masters and connections between the controlling masters and the selected slaves by communicating with the slave coordinator which also manages signals regarding the slaves. And the master coordinator also has a workspace mapping module. The coordinates and workspaces of each master and slave could be different due to kinematic dissimilarities between the master and the slave, therefore, whenever operators change the slaves to control the coordinates and workspaces should be mapped automatically. The workspace mapping module is performing the coordinate/workspace mapping.

The masters and the master coordinator are located at a close distance while the masters and the slave coordinator are located at a long distance physically. The role of the slave coordinator is to communicate with the master coordinator robustly in spite of the long distance and he/she manages whole signals regarding the slaves and decides how to use and transmit signals from multiple masters to a selected slave. When the multi-master operate the single-slave, the slave coordinator divides the role of each master so that the masters could cooperate well to accomplish given tasks. And the slaves receive control signals from the slave coordinator and perform tasks. In both the masters and the slaves, a bilateral controller including passivity algorithm to maintain system stability is implemented. The control scheme and passivity algorithm are, in detail, explained in Sect. II-B and II-C, respectively.

B. Control Schemes

We propose two control schemes, *hand-eye coordination* and *disjoint axes*, for an enhanced teleoperation with multi-user and multi-mobile-manipulators. Briefly, the hand-eye coordination maps the coordinate of controlling master onto one of visual and haptic feedbacks identically to reduce the operators' cognitive loads. And the disjoint axes divides axes of slave to be controlled by multi-user for easy maneuvering of the slave. Overall control command flow is illustrated in Fig. 2.

1) Hand-Eye Coordination: In this subsection, we bring the method that maps master and slave commands, implemented in master coordinator. From operators' perspective, they receive visual and haptic feedbacks to aware both the state of the slaves and environment. To operate masters intuitively, it is critical to match velocity and force of the master, V_{M_i} and F_{Mi} with commanded velocity and force to slave, $V^{C}_{M_i,S_j}$ and $F^{C}_{M_i,S_j}$. To decrease cognitive loads of the operators, in other words, the direction of master motions and slave motions on visual feedback should be same as the operator controls the master. Therefore, the velocity and force of the master device on visual feedback (i.e., monitor) frame located at the master side, VF_i and the commanded velocity and force (from the master to the slave) on camera frame located at the slave side, C_{jk} have to be identically matched. This mapping is called as hand-eye coordination in the paper.

The relation between V_{M_i} and $V^{M.C.}_{M_i,S_j}$ is defined in (1). The slave velocity and force commanded is considered as the same with (1), and the relation between V_{S_j} and $V^{S.C.}_{S_j,M_i}$ is defined in (2).

$$\begin{cases} {}^{C_{jk}}V^{M.C.}_{M_i,S_j} = {}^{VF_i}\,V_{M_i} \\ {}^{C_{jk}}F^{M.C.}_{M_i,S_j} = {}^{VF_i}\,F_{M_i} \end{cases} \tag{1}$$

$$\begin{cases} {}^{VF_i}V^{C}_{S_j,M_i} = {}^{C_{jk}}\,V^{S.C.}_{S_j,M_i} \\ {}^{VF_i}F^{C}_{S_j,M_i} = {}^{C_{jk}}\,F^{S.C.}_{S_j,M_i} \end{cases} \tag{2}$$

2) Disjoint Axes: In multi-user teleoperation system, multiple masters could control single slave cooperatively for easy maneuvering and, for this, each master could control a subset of degree-of-freedom (DOF) of the slave. As shown in Fig. 3, 2D cameras and monitors are used therefore, depth information of monitors and cameras is not available. In general, the slave should be controlled in more than 3 DOFs so that more than two cameras are needed to let the operator aware states of the slave.

With this background, we introduced control scheme, disjoint axes, implemented in slave coordinator, to regulate control commands from the master by transmitting only necessary components of the control commands (i.e., specific axes of the slave displayed on the monitor at the master side) and neglecting other components so that total DOFs of the slave could be controlled intuitively by multiple masters in a cooperative way. Mathematically, the control objective is to derive and implement $V^{C}_{M,S_j}/F^{C}_{M,S_j}$ with a certain combination of $V^{C}_{M_i,S_j}/F^{C}_{M_i,S_j}$ and $V^{C}_{S_j,M_i}/F^{C}_{S_j,M_i}$ using V_{S_j}/F_{S_j}.

To identify the relation between j-th slave (slave j) and i-th master (master i), disjoint matrices, $D_{j,i}$ $(i \in M, j \in N)$, are defined. Disjoint matrices are orthogonal projection matrices and they are null spaces each other, which satisfies (3).

$$\begin{array}{l} \sum_i {}^{S_j}D_{j,i} = I \\ where {}^{S_j}D_{j,i_1}{}^{T} \cdot {}^{S_j}D_{j,i_2} = O_{3,3},\ \forall i_1, i_2\ (i_1 \neq i_2) \end{array} \tag{3}$$

X_{VF_1}, Y_{VF_1} components of the velocity/force of Master1, represented as the red lines in Fig. 3 are selected to control the subset of the DOFs of the slave and then those are mapped into $X_{C_{j1}}$ and $Y_{C_{j1}}$ by hand-eye coordination control. In the case of master 2, X_{VF_2} component of the velocity/force is used and mapped into X_{VF_2}. With this control, slave j is controllable. In a similar way, $V^{C}_{M,S_j}/V^{C}_{M,S_j}$ is derived in (4).

$$\begin{cases} {}^{S_j}V^{C}_{M,S_j} = \sum_i {}^{S_j}D_{j,i} \cdot {}^{S_j}V^{M.C.}_{M_i,S_j} \\ {}^{S_j}F^{C}_{M,S_j} = \sum_i {}^{S_j}D_{j,i} \cdot {}^{S_j}F^{M.C.}_{M_i,S_j} \end{cases} \tag{4}$$

By substituting (1) to (4), we combine the proposed control schemes, hand-eye coordination and disjoint axes in (5) to derive final control commands ${}^{S_j}V^{C}_{M,S_j}$ to slave j.

$$\begin{aligned} {}^{S_j}V^{C}_{M,S_j} &= \sum_i {}^{S_j}D_{j,i} \cdot {}^{S_j}_{C_{jk}}R \cdot {}^{VF_i}V_{M_i} \\ &= {}^{S_j}_{C_j}R \sum_i {}^{C_{jk}}D_{j,i} \cdot {}^{VF_i}_{M_i}R \cdot {}^{M_i}V_{M_i} \end{aligned} \tag{5}$$

where ${}^{C_{jk}}D_{j,i} = {}^{C_{jk}}_{S_j}R \cdot {}^{S_j}\,D_{j,i} \cdot {}^{S_j}_{C_{jk}}R$.

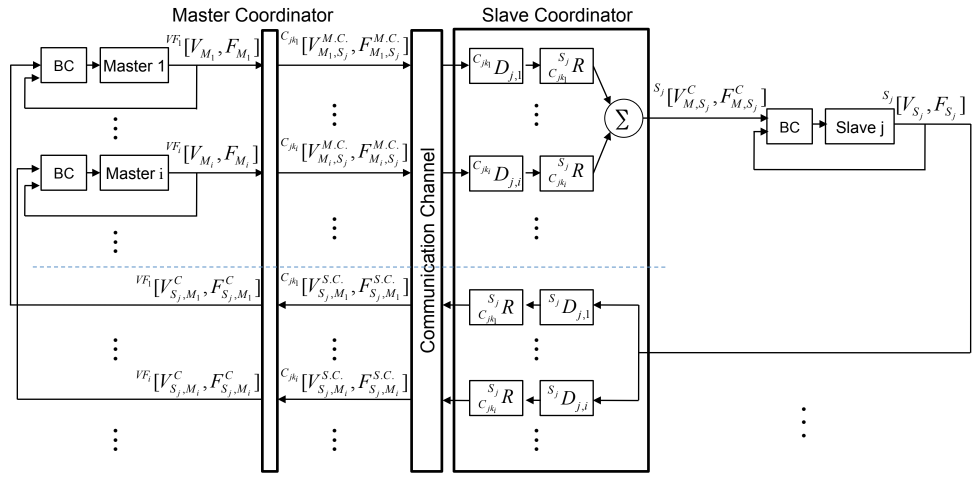


Fig. 2. Control command flow in multi-user teleoperation system

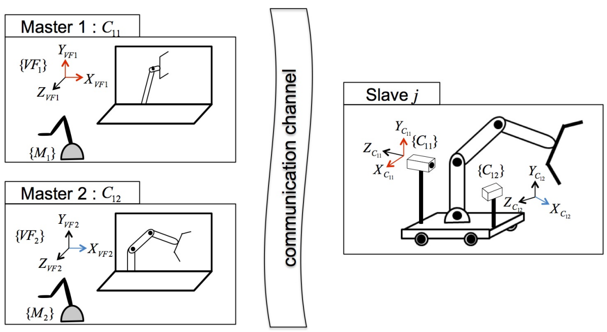


Fig. 3. Disjoint axes

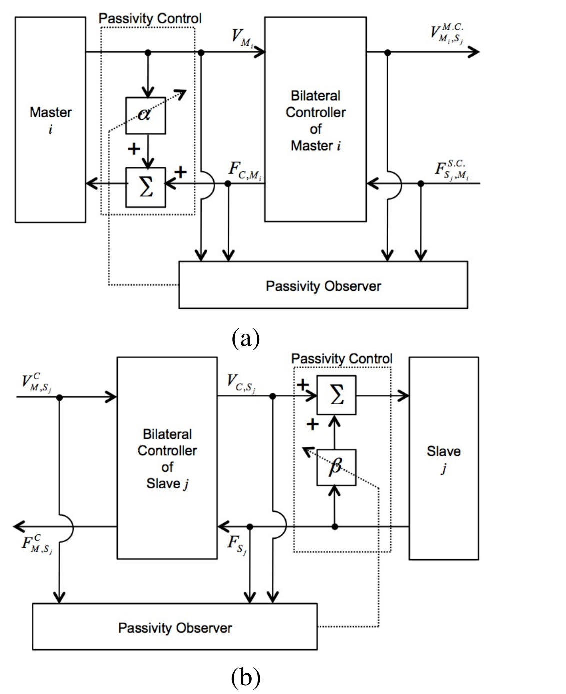


Fig. 4. Time-Domain Passivity Approach (TDPA) for Multi-User Teleoperation System. (a) TDPA for master i. (b) TDPA for slave i.

$V^{C}_{S_j,M_i}/F^{C}_{S_j,M_i}$ is derived in a similar way shown in (6). Here, we define Moore-Penrose pseudoinverse of joint matrices, $D^{+}_{j,i}$, which satisfies $D_{j,i}D^{+}_{j,i}D_{j,i} = D_{j,i}$ and $D^{+}_{j,i}D_{j,i}D^{+}_{j,i} = D^{+}_{j,i}$.

$$\begin{cases} {}^{C_{jk}}V^{S.C.}_{S_j,M_i} = \sum_i {}^{C_{jk}}_{S_j}R \cdot {}^{S_j}D^{+}_{j,i} \cdot {}^{S_j}V_{S_j} \\ {}^{C_{jk}}F^{S.C.}_{S_j,M_i} = \sum_i {}^{C_{jk}}_{S_j}R \cdot {}^{S_j}D^{+}_{j,i} \cdot {}^{S_j}V_{S_j} \end{cases} \tag{6}$$

By substituting (2) to (6), finally, final feedback ${}^{M_i}V^{C}_{S_j,M_i}$ to master i is derived in (7).

$${}^{M_i}V^{C}_{S_j,M_i} = \sum_i {}^{M_i}_{VF_i}R \cdot {}^{C_{jk}}_{S_j}R \cdot {}^{S_j}D^{+}_{j,i} \cdot {}^{S_j}V_{S_j} \tag{7}$$

With (5) and (7), bilateral controllers of whole masters and slaves are realized.

C. Stability

In [17], the time-domain passivity approach (TDPA) was proposed to guarantee the passivity of haptic interfaces. Afterward, it was extended for teleoperation systems [18], [19]. In TDPA, a passivity observer (PO) was developed to monitor energy in real-time and a passivity controller (PC) was also developed to dissipate the certain amount of energy (which could make the system unstable) based on PO.

Figures 4 (a) and (b) show two-port network models of multi-user teleoperation system for master and slave, respectively. In general, haptic master is impedance-type device but one for mobile manipulator is, usually, admittance-type device as shown represented in Fig. 4. Two-port PO is designed to observe the passivity of the system and monitor the energy flow of the bilateral controller. In addition, PCs are attached on each port of masters and slaves to dissipate the active energy flow by adjusting the damping elements, α and β.

$$E_{obs}(t_j) = \Delta T \sum_{i=0}^{t_j} F_m(t_i)V_m(t_i) + F_s(t_i)V_s(t_i) \tag{8}$$

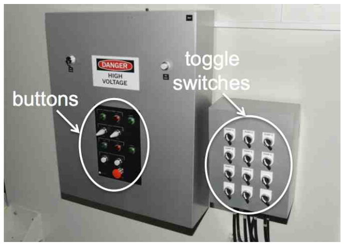


Fig. 5. Experimental environment.

III. Experimental Method

A. Participants

Twelve subjects (age range: 28–40 years), six ones from Samsung Heavy Industries and the others from several Korean universities, participated in this study, which consisted of three tests. The participants were grouped as six (i.e., two participants in each group) for multi-user teleoperation. All participants were naive to the experiment and apparatus. They possessed normal or corrected-to-normal eyesight and possessed no physical disability. The experiment was conducted in accordance with the requirement of the Helsinki Declaration.

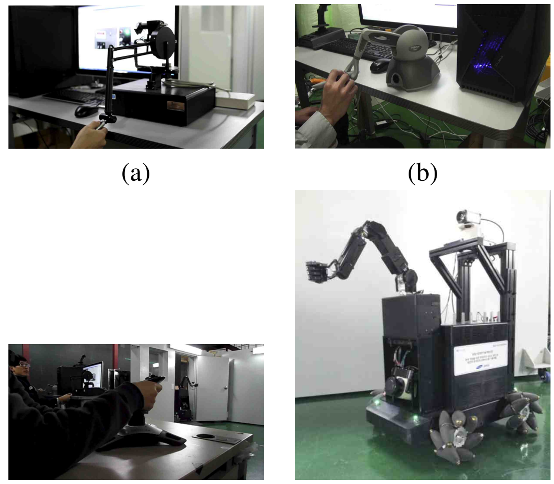
B. Task

As mentioned in Sect. I, monitoring, inspection, operation, and maintenance should be performed in unmanned offshore plants. Among them, pushing button operation in electric panels is one of the most frequently operated tasks as well as very important one. With this in mind, in this study, pushing two buttons by tele-operating a mobile manipulator is defined as task. For the task, a practical electric panel which has buttons and toggle switches, used in unmanned offshore plant is implemented as shown in Fig. 5.

C. Experimental Setup

Multi-user-multi-robot teleoperation system implemented for this study is presented in Fig. 6. There were three masters and one mobile manipulator in the system. In detail, Master 1 (PHANToM Premium 1.5HF, 6 DOFs) and 2 (PHANToM Omni, 3 DOFs) were used for tele-operating the manipulator while Master 3 (Logitech freedom 2.4 cordless joystick, 2 DOFs) was used for controlling the mobile robot. The robotic manipulator of the mobile manipulator was developed by Samsung Heavy Industries in cooperation with Rainbow company, which is specialized for performing tasks in unmanned offshore plants. It has 6 DOFs and 6 DOFs force/torque sensor (ATI Mini45) was installed. There are four omni wheels in the mobile robots developed by us with RobotValley company so that it has 3 degree-of-mobilities (DOMs). The mobile robot has 1 DOM more as compared with a differential type one so that there are multiple ways to reach a desired position, which could give benefits in unmanned offshore plants which has many obstacles and narrow passages.

There were three 2D cameras in the teleoperation system. Two cameras feed back perpendicular visual information of



(a) (b) (c) (d)

Fig. 6. Experimental setup. (a) Master 1. (b) Master 2. (c) Master 3. (d) Mobile Manipulator.

remote environments, i.e., xy and xz planes therefore, 3D visual information is available to human operator. In addition, the disjoint axes control scheme presented in Sect. II-B.2 was implemented with these two cameras for controlling of xy axes and xz axes of the manipulator by Master 1 and 2, respectively. The third camera was installed at the hand of the manipulator, which could give visual feedback in detail. The rotation matrices between the cameras and the manipulator for implementation of the hand-eye coordination scheme in Sect. II-B.1 is defined in (9).

$$ {}^{S_1}_{C_{11}}R = \begin{bmatrix} 0 & 0 & -1 \\ -1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}, \quad {}^{S_1}_{C_{12}}R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{bmatrix} \tag{9} $$

Task level of pushing buttons in this study could be characterized using a precision value defined in (10), which is similar with one for peg-in-the-hole task.

$$ I = log_2 \left(\frac{d_B}{d_T} \right) \tag{10} $$

where d_B and d_T is the diameter of the bottom and top of the button, respectively. The precision value of our experimental setup is $I = 1.3219$ (d_B=20mm and d_T=8mm), which shows more precise level as compared with other studies [20].

D. Procedure

Three tests were performed in the paper to evaluate the proposed multi-user teleoperation system, which are *test of multi-user*, *test of data loss*, and *test of time delay*. Test of multi-user is designed to show better performance with multi-user teleoperation than single-user case. Second test, test of data loss, is to show performance enhancement with TDPA under 10% data loss in multi-user teleoperation system. It is studied that to show TDPA could increase performance of multi-user teleoperation system under 1sec time delay in the test of time delay.

We designed the following six cases for the tests:

1) Case 1: normal teleoperation with single-user;
2) Case 2: normal teleoperation with multi-user;
3) Case 3: multi-user teleoperation under 10% data loss without TDPA;
4) Case 4: multi-user teleoperation under 10% data loss with TDPA;
5) Case 5: multi-user teleoperation under 1sec time delay;
6) Case 6: multi-user teleoperation under 1sec time delay with TDPA.

In the test of multi-user, results of Case 1 and 2 were analyzed. Case 2, 3, and 4 were performed in the test of data loss while Case 2, 5, and 6 were performed in the test of time delay.

One master device was used only for Case 1 while two masters were installed for the other cases. Please note that third master was not used with assumption that mobile robot is fixed. As we introduced in Sect. III-C the proposed control schemes (i.e., hand-eye coordination and disjoint axes) were implemented for Cases 2–6.

E. Data Analysis

Five measures were defined to evaluate performance of teleoperation system quantitatively as follows.

Definition 1 Completion Time *is defined as time to complete the task shown in below.*

$$P_T = \int_0^{t_f} dt \tag{11}$$

Definition 2 Number of Contact *is defined as*

$$P_C = \sum_{t=0}^{t_f} C(t)$$
$$where\ C(t) = \begin{cases} 1 & \textit{if}\ \ f(t) \geq f^{threshold} \\ 0 & \textit{otherwise} \end{cases} \tag{12}$$

, where $f(t)$ is measured contact force at t and $f^{threshold}$ is threshold of the contact force to judge if contacted.

Definition 3 Sum of Interaction Forces *is defined as the sum of square of interaction forces,*

$$P_F = \int_{t=0}^{t_f} |f(t)|^2 dt. \tag{13}$$

Definition 4 Average of Interaction Forces *is defined as the average of square of interaction forces,*

$$P_F^{avg} = \frac{1}{P_T} \int_{t=0}^{t_f} |f(t)|^2 dt. \tag{14}$$

Definition 5 Maximum of Interaction Forces *is defined as the 95% of maximum interaction forces shown in below.*

$$P_F^{95\%} = 0.95 \times max(|f(t)|) \tag{15}$$

These measures were separately computed for the x-, y-, and z-axis components of interaction forces. The interaction forces were measured using the installed force/torque sensor.

TABLE I
t-TEST RESULTS ON TEST OF MULTI-USER

Measures	p-value x-axis	y-axis	z-axis
P_T		0.0362⋆	
P_C	0.1248	0.6686	0.8194
P_F	0.4234	0.7762	0.1183
P_F^{avg}	0.0176⋆	0.1746	0.0168
$P_F^{95\%}$	0.0018⋆	0.0154⋆	0.0073⋆

For statistical analysis, t-test and two-way analysis of variance (ANOVA) test were conducted to formally determine if there were statistically significant differences in performance (i.e., five measures) among six cases. An alpha level of 0.05 was taken to indicate statistical significance. Both means and standard deviations (SDs) of each axis component of five measures (i.e., P_T, P_C, P_F, P_F^{avg}, and $P_F^{95\%}$) were, finally, served for the statistical analysis.

IV. Experimental Results and Discussion

A. Test of multi-user

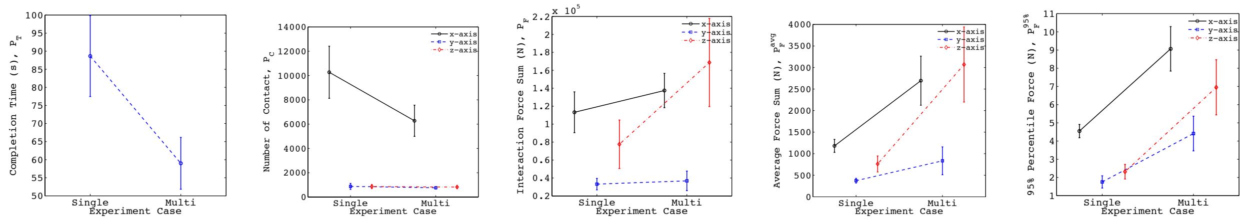
Figures 7 (a)–(e) show summaries of performance in test of multi-user in terms of P_T, P_C, P_F, P_F^{avg}, and $P_F^{95\%}$ for Case 1 and 2. It is noticeable that P_T was significantly decreased from 88.66 to 58.99 with multi-user teleoperation. Also note that SD of P_T was decreased from 11.20 (single-user case) to 7.17 (multi-user case). P_C for x-axis was also decreased with multi-user case however, there were no significant changes in y- and z-axis. Interestingly, all measures regarding interaction forces (i.e., P_F, P_F^{avg}, and $P_F^{95\%}$) were increased with multi-user teleoperation as compared with single-user one.

Statistical analysis results for this test were summarized in Table I. Note that statistically significant results were marked with ⋆. As expected, the decrease of P_T with multi-user teleoperation had statistical significance ($p < 0.05$). However, P_F^{avg} ($p < 0.05$) and $P_F^{95\%}$ ($p < 0.01$) in x-axis were increased significantly with multi-user teleoperation. In the case of $P_F^{95\%}$, there were also significant increases in both y- ($p < 0.05$) and z-axis ($p < 0.01$).

In general, multi-user teleoperation shows less task completion time than single-user one. We could argue that multi-user teleoperation easier scheme to learn and perform than single-user one based on the fact that SD of P_T with multi-user teleoperation was decreased. In spite of this, we couldn't conclude that multi-user teleoperation is a better choice than single-user one because all measures regarding interaction forces were increased with multi-user teleoperation. In conclusion, depending on tasks (e.g., if less P_T is more important than less P_F otherwise, if less P_F is more important) a teleoperation scheme (i.e., multi-user one or single-user one) should be selected.

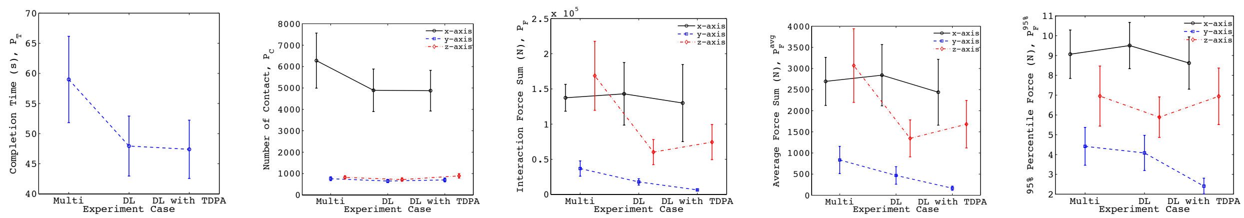
B. Test of data loss

Experimental results for test of data loss were shown in Figs. 8 (a)–(e), which are for Case 2, 3, and 4. As shown in Fig. 8 (a), P_T of multi-user teleoperation system was decreased (i.e., performance was increased) from 58.99



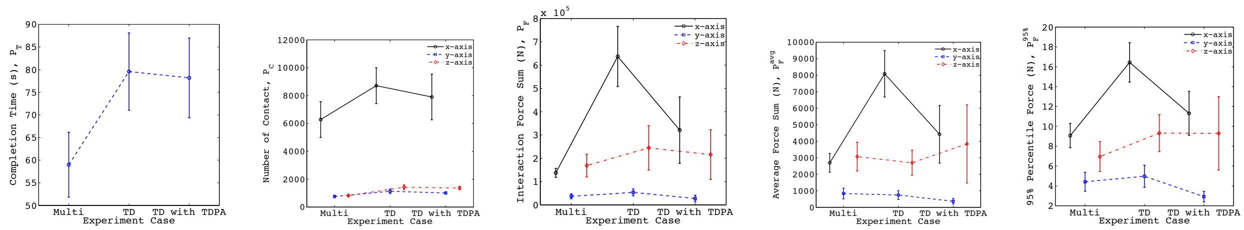
(a) (b) (c) (d) (e)

Fig. 7. Experimental results on test of multi-user. (a) P_T. (b) P_C. (c) P_F. (d) P_F^{avg}. (e) $P_F^{95\%}$.



(a) (b) (c) (d) (e)

Fig. 8. Experimental results on test of data loss. (a) P_T. (b) P_C. (c) P_F. (d) P_F^{avg}. (e) $P_F^{95\%}$.



(a) (b) (c) (d) (e)

Fig. 9. Experimental results on test of time delay. (a) P_T. (b) P_C. (c) P_F. (d) P_F^{avg}. (e) $P_F^{95\%}$.

to 47.94 under 10% data loss in communication channel. However, note that there was no difference in P_T between multi-user teleoperation system with/without TPDA under data loss. Similarly, P_C was also decreased under data loss and TDPA also did not contribute to enhance P_C metric under data loss. For the other metrics (i.e., P_F, P_F^{avg}, and $P_F^{95\%}$), data lose decreased the metrics in y- and z-axis while it was increased in x-axis. With TDPA under data loss in communication channel, those metrics were decreased in x- and y-axis while those were increased in z-axis.

Statistical analysis of the experimental results were summarized in Table II. There were no significant difference on any performance measure except P_F for y-axis ($p < 0.05$). This represents that P_F in y-axis was significantly decreased under data loss regardless of TDPA.

As summary, it is noticeable that data loss in communication channel does not decrease performance of multi-user teleoperation system significantly and, in addition, TDPA does not contribute to enhance the performance under data loss.

C. Test of time delay

Figures 9 (a)–(e) show experimental results of Case 2, 5, and 6 (i.e., test of time delay). Overall, time delay of 1 sec tremendously declined the performances of multi-user teleoperation system. In detail, there was significant increase of P_T under time delay approximately 20sec (i.e., from 58.99sec to 79.58sec). However, P_T with TDPA under time delay was decreased slightly. For the other measures, P_C, P_F, P_F^{avg}, and $P_F^{95\%}$, time delay decreased the performance of measures for all axes. Among them, the metrics for x-axis were significantly increased. It is remarkable that all five measures were decreased with TDPA under time delay and, especially, the measures regarding interaction forces (i.e., P_F, P_F^{avg}, and $P_F^{95\%}$) for x-axis were decreased significantly. On the other hand, P_T, P_C, P_F, and y- and z-axis component of P_F^{avg} and $P_F^{95\%}$ were decreased slightly.

TABLE II
TWO-WAY ANOVA TEST RESULTS ON TEST OF DATA LOSS

Evaluation Measures	p-value		
	x-axis	y-axis	z-axis
P_T		0.2892	
P_C	0.5829	0.6950	0.3715
P_F	0.9761	0.0127$\star$	0.0580
P_F^{avg}	0.9180	0.1236	0.1546
$P_F^{95\%}$	0.8813	0.1711	0.8125

Table III summarized statistical analysis for test of time delay using two-way ANOVA test. Note that statistically significant results were marked with $\star$. In the case of P_T

TABLE III

TWO-WAY ANOVA TEST RESULTS ON TEST OF TIME DELAY.

Evaluation Measures	p-value		
	x-axis	y-axis	z-axis
P_T		0.1561	
P_C	0.4720	0.1095	0.0039⋆
P_F	0.0115⋆	0.3890	0.8258
P_F^{avg}	0.0226⋆	0.4104	0.8650
$P_F^{95\%}$	0.0247⋆	0.2651	0.7541

under time delay, the decrease did not have statistical significance ($p > 0.05$) with/without TDPA while TDPA decreased P_C for z-axis with statistical significance ($p < 0.01$). In addition, x-axis component of all measures about interaction forces (i.e., P_F, P_F^{avg}, and $P_F^{95\%}$) decreased with statistical significance ($p < 0.05$).

It is evident that time delay decreases performance in multi-user teleoperation system however, TDPA contributes to enhancement of performance even under time delay. Interestingly, in spite of this, TDPA did not contribute to decrease P_T (i.e., task completion time) as well as it did not increase P_T significantly. As summary, we conclude that TDPA should be implemented only with under time delay in communication channel to achieve the best performance in multi-user teleoperation.

V. CONCLUSION

In this paper, we proposed a practical multi-user teleoperation system for monitoring, inspection, operation, and maintenance of unmanned offshore plants. Two control schemes, hand-eye coordination and disjoint axes were introduced for easier intuitive control of mobile manipulator even with mismatched coordination between master device and camera frames and for better cooperative control among multi-user, respectively. To maintain system stability even under data loss and time delay in communication channel between the masters and the mobile manipulator, in addition, the time-domain passivity approach (TPDA) was implemented in the proposed teleoperation system.

The proposed multi-user teleoperation system was also evaluated via a human-centered method. Several metrics regarding task completion time and interaction forces between the manipulator and remote environments were defined for quantitative and statistical analysis. From the human-centered evaluation, the followings were revealed:

- Task completion time with hand-eye coordination and disjoint axes control schemes in multi-user teleoperation system was decreased as compared with single-user case however, maximum interaction forces was increased even with the proposed controls;
- TDPA did not enhance any performance in multi-user teleoperation system under 10% data loss;
- TDPA reduced sum, average, and maximum of interaction forces in multi-user teleoperation system under 1sec time delay.

In summary, the proposed multi-user teleoperation system has the benefit in tasks requiring less task completion time and interaction forces.

We will further this study by proposing better control schemes for practical multi-user teleoperation and evaluating the proposed controls by employing various tasks in unmanned offshore plants.

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