TrC-IFToMM Symposium on Theory of Machines and Mechanisms, Izmir, Turkey, June 14-17, 2015

A Study on Selecting the Method of Constructing the Information to be Exchanged in Unlimited-workspace Bilateral Teleoperation

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Abstract— *In this paper, a study on selecting the mapping method for information exchange in unlimited-workspace teleoperation is presented. In spite the fact that in most of the bilateral teleoperation systems, the master system sends motion demands and receives interaction force from the slave system, the information to be exchanged through the communication line between master and slave is selected to be force in both directions in this study. This approach is expected to ease the navigation of the user when a limited-workspace master system is used to control an unlimited-workspace slave system. As the unlimited-workspace slave system, a virtual flying scalpel is used and human skin is modeled to represent the environment around the slave system. Two methods of constructing force information, or in other words, information mapping between the two systems, are developed and evaluated via user studies. However, one of them comes out to provide acceptable results in the selected unlimited-workspace teleoperation task. Experimental results for the method that provides acceptable results are presented.*

Keywords: unlimited-workspace teleoperation, workspace mapping, bilateral teleoperation.

I. Introduction

Teleoperation systems allow the human operators to execute tasks in remote or hazardous environments, such as space, underwater, nuclear plants, medicine and military applications. Having a crucial role in robotics, many scientific studies dealing with the teleoperation have been done in the last decades [1, 2].

In bilateral teleoperation, the master and the slave systems are coupled with a communication line in which information flows in both directions (from master to slave and slave to master). Bilateral teleoperation systems can be grouped into two regarding their limitations of the workspace, as unlimited- and limited-workspace teleoperation. In general, the operator manipulates the slave robot from a distant location. Therefore, the success of operation depends on the information supplied by in between the master and slave systems using the communication line [3, 4].

In unlimited-workspace teleoperation, the main problem in information exchange is on mapping a limited-workspace master system to an unlimited-workspace slave system motion. Mapping methods are generally chosen with respect to the workspace limits. The selection criteria for the mapping methods are studied by Lee et al. [5], Elhaji et al. [6], Farkhatdinov and Ryu [7]. The mapping methods for bilateral teleoperation systems having limited-workspace slave robots have already been well-studied in the literature [8, 9]. However, the workspace of slave and master device is limited by the smaller of the two. A solution can be derived by scaling up or down the workspace that causes drop in the accuracy or limits teleoperation system workspace [10, 11]. Therefore, compared to the limited-workspace teleoperation systems, unlimited-workspace teleoperation systems have workspace mapping problem [5] due to kinematic diversity of two sub-system. A proposed method to overcome for the stated problem above for unlimited-workspace teleoperation systems is the position-velocity mapping [5-7, 9, 10]. Position-velocity mapping is only limited by the slave device's workspace, which is theoretically infinite. On the other hand, this type of control is inadequate in terms of positional accuracy [9]. In order to provide a solution to this problem, a control method for the bilateral teleoperation of a mobile robot that combines position-position and position-speed was presented by Farkhatdinov and Ryu [7]. A haptic teleoperation control algorithm based on kinetic scrolling-based position mapping for unmanned aerial vehicles was presented in [12]. Kinetic scrolling, which is adapted to this control algorithm, is used in all modern smart phones, where the user can interact with the kinetic scrolling in a natural and intuitive manner.

In order to configure an unlimited-workspace teleoperation system, usually a virtual interaction force computed on the basis of obstacles surrounding the mobile vehicle is used in to increase the user's perception of the mobile robot's workspace [13]. Only in this way, this type of a system can be called unlimited-workspace bilateral teleoperation system. In the case where a mapping scheme is selected based on motion capabilities, such as position-velocity, the conventional mapping strategies fail to reflect the forces in a suitable way, which are acquired from the slave, to the human operator

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through the master system. The novelty of this study is that we are attempting to formulate a new way of mapping for unlimited-workspace bilateral teleoperation systems.

In this paper, after giving a review of the main concepts and definitions about unlimited-workspace bilateral teleoperation system, a comparative study on two techniques formulated for mapping the information exchange between the master and the slave systems in unlimited-workspace bilateral teleoperation are presented. The developed methods are examined by designing a benchmark test scenario. Novint Falcon is used as the master device and the virtually constructed flying scalpel is selected as the slave object. An interaction with a an object that has relatively less mechanical impedance (e.g. soft tissue) is modeled for the test scenario. In order to evaluate the methods, the performance of operator in path tracking and task completion time are measured in the tests. Finally, the test results in terms of statistical evaluations are presented. As a result of this study, it is shown that one of the proposed methods overcome the master workspace limitations and increase the performance of the user in teleoperation task by selecting mapping parameters carefully.

II. Unlimited-Workspace Teleoperation

If a robot's workspace is relatively very large with respect to the workspace of the master system's workspace or if it is practically without any bounds, this system can be defined as the unlimited-workspace teleoperation. Unlimited-workspace teleoperation is widely used for controlling mobile vehicles, underwater remotely operated vehicles (ROVs) and unmanned aerial vehicles (UAVs). However, in our study we selected the flying scalpel as a slave system which also has an unlimited-workspace when it is not attached to a robot arm.

Unlimited teleoperation system can be divided into two main categories as unilateral and bilateral.

A. *Unilateral teleoperation*

In unilateral teleoperation, the slave system is driven by the operator's demands such as position, velocity, or force which is acquired by the master system is shown in Fig. 1. However, information flows only in one direction through the communication line. In this type of teleoperation, there is not a feedback from the slave to inform operator about the slave environment[3].

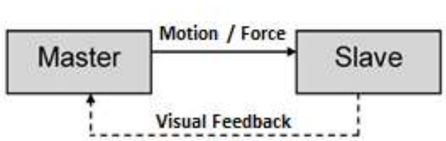

Fig. 1. Unilateral teleoperation (no force feedback is available from the slave unit)

B. *Bilateral teleoperation*

In bilateral teleoperation, the information flows in two directions, not only from the master to the slave system but also from the slave to the master system. In this kind of a setting, the slave robot is driven by the operator's commands and the necessary feedback such as visual, force, auditory feedback(s) are sent from the slave to the master system in order to inform operator about the slave environment [8]. This helps the operator to increase his feeling of being present in the slave environment. A common case in bilateral teleoperation is that motion demand is sent to the slave and force feedback is received from the slave. This type is presented in Fig. 2.

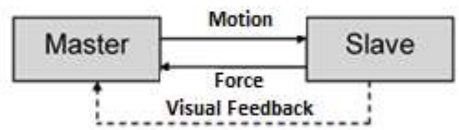

Fig. 2. Bilateral teleoperation (force-feedback signal is available from the slave to the master control unit)

III. Selection of the Information Exchange Method

In this section, two methods are presented in generation of motion commands that are sent to slave sub-system and force feedback that is applied to the operator. Both methods are devised to ease the use of the teleoperation system by the human operator and enhance the teleoperation systems overall precision. In both methods, the motion of captured from the master system is mapped to the force demand to be sent to the slave system in order to control the slave object in its unlimited-workspace. The information between master and slave is delivered through the communication line. The block diagram in Fig. 3, presents the information flow in this teleoperation system setting.

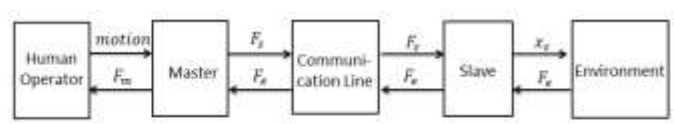

Fig. 3. Information flow scheme for the designed bilateral teleoperation system

In Fig. 3, F_s is the force constructed in the master system to be sent as a demand to the slave system. F_e is the interaction forces measured at the slave system's environment. F_m is the force applied to the user through the haptic master system. The calculation of the above information differs in each method presented in the next sub-sections.

A. *Position-force methodology*

In this method, a virtual spring is introduced to the system in order to calculate a force demand to be sent to the slave system. The method has an analogy with the gas pedals in automobiles. For example, gas pedal's position is mapped to the torque to be supplied to the driving shaft through regulating the fuel and air supply to the engine. Therefore, the driver controls the acceleration of the car by changing the position of the gas pedal.

In addition, the gas pedal returns to its initial position when it is not pressed by the driver. Similarly, the virtual spring used in this method brings the haptic master system's end-efector to its initial position when the user is not applying any forces on its handle.

The aim of using the virtual spring force which is applied to the master is to direct the operator to the determined mid-point of Falcon workspace.

F_s, is the restoring force produced from the displacement of the virtual spring by the human operator input. The virtually constructed force, F_s, is sent to the slave system as demand. The calculation of the F_s force along each direction of motion with respect to the coordinate frame $\mathcal{F}\{0;\vec{u}_i;\mathrm{i}=1,2,3\}$ is provided in Eq. 1.

$$\vec{F}_s^i = k \cdot p_m^i \cdot \vec{u}_i; \quad i = 1,2,3 \tag{1}$$

In Eq. 1, $\mathrm{p}_\mathrm{m}^\mathrm{i}$ is the position of the master handle with respect to the initial position along the $\vec{u}_i$ axis, and k is the virtual linear spring constant along every direction of motion. $\mathrm{F}_\mathrm{m}^\mathrm{i}$ is the force applied through the master system to the human operator along the $\vec{u}_i$ axis. This force is calculated by summing the transmitted slave environmental forces, F_e, and restoring force as shown in Eq. 2.

$$F_m^i = F_s^i + F_e^i \tag{2}$$

The restoring force sent to the slave is used as force command in its equation of motion as presented in Eq. 3.

$$F_s^i = m_s a_s^i + B v_s^i + F_e^i\,; \quad i = 1,2,3 \tag{3}$$

We introduce the viscous friction constant, B, for the system to limit slave object motion in free space. Otherwise, even though the master handle is at the initial position, the slave object continues its motion under the given force by user. a_s is the acceleration of slave where the master position is mapped. v_s is the velocity of the slave object. m_s is the mass of slave object, which is defined as a scalpel. From the given equations, the slave acceleration can be derived as follows:

$$a_s^i = \frac{F_s^i - B v_s - F_e^i}{m_s}; \quad i = 1,2,3 \tag{4}$$

Finally, the master position is mapped to the slave system's acceleration by creating virtual spring in master system and transmitting the information from the master to the slave in terms of forces. As a result of this, the slave object could be driven in unlimited workspace, though the master system has a limited workspace.

B. Velocity-force methodology

In this method, a virtual damper is introduced in master system, so that the information can be sent as a force demand to the slave system. In this case, F_s, is the force information to be sent to the slave as the demand. This force calculation is defined in Eq. 5.

$$F_s^i = c v_m^i; \quad i = 1,2,3 \tag{5}$$

In Eq. 5, v_m is the relative velocity of the master handle, and c is the damping constant. After sending force demand to the slave system, this force information is used in the dynamic equation of motion of the slave as it was presented in Eq. 3 and the respective acceleration of the slave is calculated by using Eq. 4.

As a result, the velocity of the master system is mapped to the acceleration of slave by means of creating virtual damping in the master system. This methodology allows us to deliver the information to the slave system as a damping force through the communication line.

C. The contact model

The spring-damper model is used to simulate the interaction forces between two virtual bodies, which are placed at the slave system's environment. In Fig. 4, spring-damper representation of the slave system and the position of scalpel body, x_d, relative to the contact surface of human skin are shown. There is no interaction force applied on master when $x_d > 0$. An interaction force is generated by spring-damper equation depending on the position and the velocity of the scalpel when $x_d < 0$.

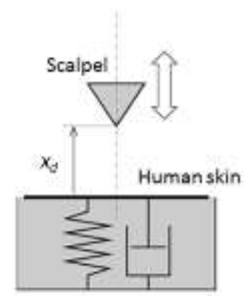

Fig. 4. Spring-damper contact model

It should be noted that the modeled skin is assumed to be on the $\vec{u}_2 - \vec{u}_3$ plane. Therefore, interaction force at the slave's environment along the normal of the surface, $\vec{u}_1$ axis, F_e, is calculated as presented in Eq. 6.

$$F_e^1 = m_s \ddot{x}_d^1 + c_e \dot{x}_d^1 + k_e x_d^1 \tag{6}$$

In Eq. 6, k_e is the spring constant and c_e is the damping constant.

D. Viscous resistance

When the object is moving through a fluid at relatively slow speeds, the equation of viscous resistance is applied in opposite direction of movement. Similarly, during cutting operation in surgery, the assumption made in this work is that the surgeon feels a low resistance (drag) force stemming from the interaction between scalpel and the human skin. This force is approximately proportional to velocity, but opposite in the direction of motion. The equation of the viscous resistance force calculation along the $\vec{u}_2$ and $\vec{u}_3$ axis is given in Eq. 7.

$$F_e^i = b\mathrm{v}_\mathrm{d}^\mathrm{i}\,; \quad i = 2, 3 \tag{7}$$

In Eq. 7, F_e^i is the viscous resistance force at the slave's environment along the $\vec{u}_2$ and the $\vec{u}_3$ axis. b is a viscous friction constant, which depends on the human skin characteristics. v_d^i is the velocity of the slave object along the $\vec{u}_i$ axis.

IV. Experimental Tests

The motion demand from the master device (Novint Falcon) is acquired along the $\vec{u}_1$, $\vec{u}_2$ and $\vec{u}_3$ axes as shown in.

A. Experimental test setup

Teleoperation systems mentioned in this work are tested in a semi-experimental test setup, shown in Fig. 6. The test setup is composed of a haptic master device and a virtual slave system that is modeled and visualized in Matlab Simulink. The master device used in the tests are Novint Falcon, which is a 3 degrees-of-freedom haptic device represented with 1 in Fig. 5.

The virtual slave system consists of a scalpel, which has an unlimited-workspace, and a relatively low impedance object (e.g. human skin), which is defined as a virtual wall. The virtual scalpel and the virtual object's surface to be interacted with are indicated in Fig. 5 with 2 and 3 respectively. The object to be interacted with is modeled based on a linear mass spring damper model in Matlab Simulink. It should be noted that the scalpel is not connected to a robot arm but it is moving freely without bounds in its virtual environment.

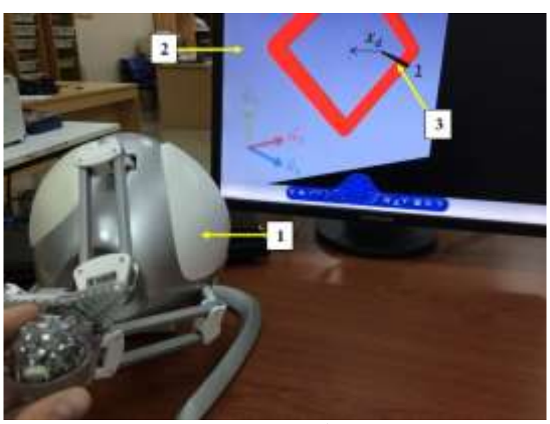

Fig. 5. Experimental setup composed of a haptic master device and a virtual slave system

Mapping strategies tested by taking force commands from the user through Novint Falcon. Then the displacements and velocities of the master device along $\vec{u}_1$, $\vec{u}_2$ and $\vec{u}_3$ axes (Fig. 6) are used in the mapping procedure.

Fig. 6. Novint Falcon Haptic Device

The test setup's sampling rate is set to 500 Hz. The task is designed so that the operator tracks three times the path indicated with the red line on the skin surface in Fig. 7. The scalpel is indicated with (1) in Fig. 7 and the skin to be interacted with is indicated with (2). x_d is the distance between bodies along the $\vec{u}_1$ axis.

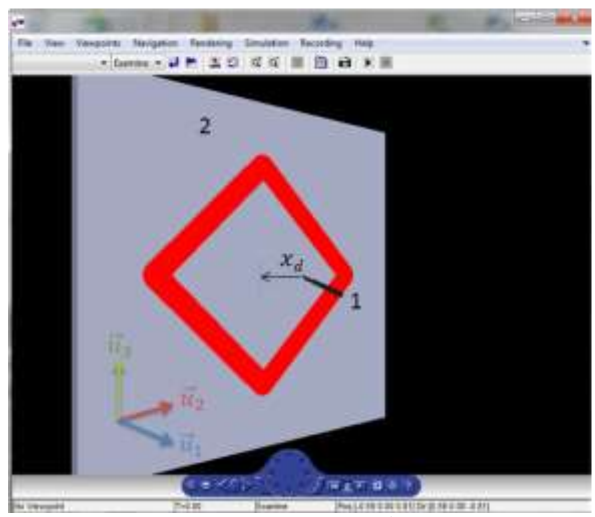

Fig. 7. Virtual reality representation of the slave system

The user is exposed to the forces applied through the master system along the 3 axes as mentioned in the methodology section. The normal force is the summation of the restoring force and the contact force along the $\vec{u}_1$ axis. While the operator moves inside the human skin, the viscous resistance force as well as the restoring force is applied along the $\vec{u}_2$, and $\vec{u}_3$ axes to simulate cutting process. The magnitudes of generated forces by the master system in N are shown in Fig. 8 in which the contact moment is indicated with the dashed line.

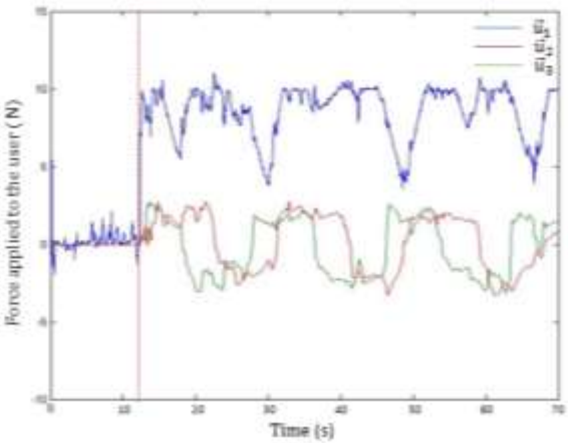

Fig. 8. Forces applied to the user along each axis by the haptic device

B. *Experimental test results*

The operator carries out the task using the velocity-force information exchange technique. The task is carried out by 10 different operators. One of the operator's test results is shown in Fig. 9. The route to be followed is shown in blue colored solid line and the recording from user's motion tracking is shown in red colored solid line. During the task, the user must complete 3 rounds around the assigned zone. The aim of this task is not to go out of assigned red zone shown in Fig. 7 while the scalpel is inside of the human skin. In order to make a statistical assessment, the user's path tracking performance as well as the task completion time is recorded after the contact between the scalpel and the human skin is achieved.

The tests are performed 10 times for velocity-force method by assigning 0 and 2 values for the viscous friction constant B in free motion. When viscous friction constant B is selected to be 0, the user is able to control the slave object without a workspace limitation since there is no opposite force to the motion. On the other hand, when the viscous friction constant B is selected to be larger than 0, the resistance force works against to the motion of the slave object. Therefore, the slave workspace is partially limited. However, the control of the slave's motion becomes more convenient for the user. In our case, the optimal value is found to be 2 considering the ease of use and the slave workspace limitation.

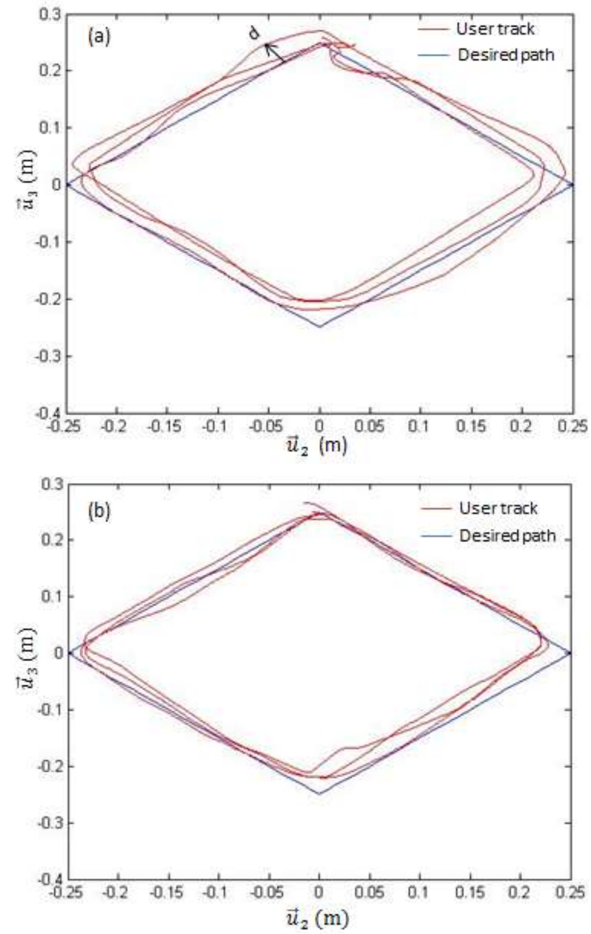

Fig. 9. The test sample recording for velocity-force method that shows the assigned route to be followed and the user performance (a) B=0; (b) B=2

C. *Evaluation of the test results*

For each node along the user's tracked line, the distance to the assigned route is named as d and this is shown in Fig. 9 (a). The calculation method for d is shown in Fig. 10. From each node, the distance to the lines is calculated.

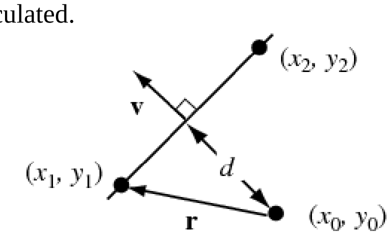

Fig. 10. Point-line distance

In Fig. 9, the line is specified by selected two points $\boldsymbol{x_1}=(x_1, y_1)$ and $\boldsymbol{x_2}=(x_2, y_2)$. Then, the vector perpendicular to the line is given by:

$$\boldsymbol{v} = \begin{bmatrix} y_2 - y_1 \\ -(x_2 - x_1) \end{bmatrix} \tag{8}$$

Let $\boldsymbol{r}$ be a vector from the point $\boldsymbol{x_0}=(x_0, y_0)$ to the first point on the line:

$$\boldsymbol{r} = \begin{bmatrix} x_1 - x_0 \\ y_1 - y_0 \end{bmatrix} \quad (9)$$

The distance d from (x_0, y_0) to the line again given by projecting $\boldsymbol{r}$ onto $\boldsymbol{v}$ is calculated in Eq. 10.

$$d = |\boldsymbol{v}.\boldsymbol{r}| = \frac{|(x_2-x_1)(y_1-y_0)-(x_1-x_0)(y_2-y_1)|}{\sqrt{(x_2-x_1)^2+(y_2-y_1)^2}} \quad (10)$$

This calculation is repeated for the four lines that constitute the path. The smallest d is selected to be the offset from the middle of the red zone line at that point.

As a restriction, the operator must remain within the red zone on the surface during the operation. When the operator goes out of the red zone, then the error is calculated by counting the pikes which are higher than 0.03 m. The upper limit is shown with red dashed line and the top of pikes higher than dashed line are marked with the red dots as seen in Fig. 11.

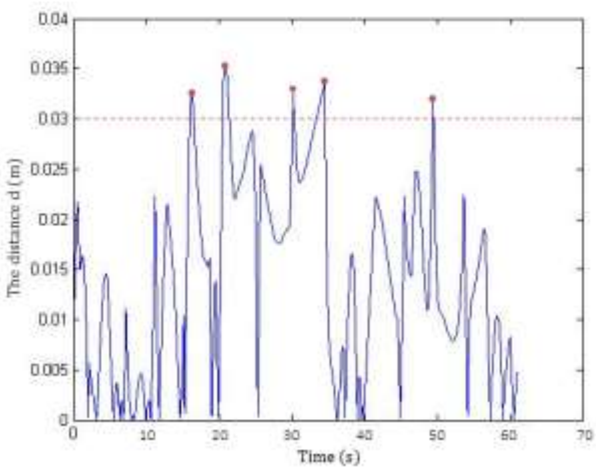

Fig. 11. The operator's error calculation

D. Statistical assessment

Test results which have been recorded during the operations are tabulated in TABLE 1 and Table 2. The tests are performed 10 times by using different value for the viscous friction constant, B. As a reminder, d is the distance between desired path and the operator's path. During the teleoperation task, scalpel must be controlled in a desired depth inside the human skin. To do so, the distance between the tip point of the scalpel and the desired depth inside the human skin is defined as x. For each trial, mean value and the standard deviation of distance d and x are given as well as error and the task competition time. Comparative assessment is done after inspecting the collected data.

Trials	velocity-force method (B=0)					
	mean d (mm)	mean x (mm)	std d (mm)	std x (mm)	time (sec)	error
1	9.8	22.4	6.8	17.5	57.5	1
2	16.6	32.2	12.1	20.5	51.2	4
3	13.5	23.4	9.2	16.8	42.6	5
4	18	19.7	1.4	19.3	44.8	7
5	11.5	14.7	8.3	15.1	29.4	3
6	13.3	14.4	10.3	21.1	34.9	3
7	11.1	14.7	9	16.1	36.6	2
8	14.2	21.3	9.1	21.5	34.5	5
9	13.5	19.4	12.2	16.4	36.5	6
10	13.2	11.6	19.3	19	38.1	8
Avg.	13.47	19.38	9.77	18.33	40.61	4.4

TABLE 1. Experiment results for velocity-force method (B=0)

Trials	velocity-force method (B=2)					
	mean d (mm)	mean x (mm)	std d (mm)	std x (mm)	time (sec)	error
1	9.6	6.1	7.8	10.3	48.8	1
2	12	9.1	9	12.6	41.2	3
3	8.2	17.5	6.6	11.4	34.5	2
4	12.1	11.1	8.2	11.5	39.3	2
5	14	8.5	9.1	10.1	35.9	1
6	10.9	9.7	8.2	9.6	38.5	2
7	13.2	12.5	9.8	9.1	39.5	2
8	14.2	11.3	9.3	12.5	35.4	3
9	11.7	6.7	10.1	10.4	40.6	1
10	8.7	13.3	6.7	8.3	33.5	3
Avg.	11.46	10.58	8.48	10.58	38.72	2

TABLE 2. Experiment results for velocity-force method (B=2)

The overall averages of all the recorded test data are tabulated in TABLE 3. The standard deviation on the average of d and x distances are relatively high. The teleoperation system is examined by different users with various levels of hand-eye coordination performance and this is why there is a relatively large value for standard deviation. It is observed that the user error is reduced by increasing the viscous friction constant, B. In addition, the magnitude of distances d and x are decreased when the viscous friction constant B is selected as 2. The task completion time is also decreased relatively. In conclusion, a more convenient usage condition is provided to the operator by introducing an optimal the viscous friction for the motion of the slave system.

Overall Avg.	velocity-foce method	
	B=0	B=2
mean d (mm)	13.47	11.46
mean x (mm)	19.38	10.58
std d (mm)	9.77	8.48
std x (mm)	18.33	10.58
time (sec)	40.61	38.72
error	4.4	2

TABLE 3. Overall averages of the results for velocity-force method

V. Conclusion

In this paper, an unlimited-workspace teleoperation system is considered. The information exchange between the master and the slave is selected to be force in both directions. This is done to accommodate the control of an unlimited-workspace slave with a limited-workspace master. In order to construct force information on the master side to send to the slave system, two methods are developed and examined. Among these, the position to force method did not produce acceptable results since the operators during the test were not able finish the tests. Using the velocity to force methodology, the tests were able to be carried out by the operators with success. However, in order to ease the control of the user a viscous friction effect is added for the slave system's equation of motion. The addition of this effect provided better performance results as it can be observed from the statistical test results.

In teleoperation systems, one of the main areas of study is the stability of the systems under communication time delays. As a future work of this study, our aim is to investigate the performance of this information exchange methodology in time delayed teleoperation systems and develop necessary algorithms to guarantee a stable operation.

Acknowledgement

The authors would like to thank to The Scientific and Technological Research Council of Turkey for funding the research presented in this work. (grant number 113E147)

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