Applying Model Mediation Method to a Mobile Robot Bilateral Teleoperation System Experiencing Time Delays in Communication

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Abstract— *Teleoperation systems consist of two sub-systems namely, the master and the slave. Master is used by the human operator to send commands to the slave to achieve a task. In bilateral teleoperation, the interaction forces acquired from the slave sub-system is sent to the master to increase the level of tele-presence. In this kind of a setting, data has to be transferred through a communication line in which package losses and time delays occur. Such deficiencies in the communication line results in stability problems in the system. In this paper, HIPHAD desktop haptic device as the master sub-system and an omni-directional mobile robot as the slave sub-system is used to develop an unlimited workspace teleoperation system. The system's stability and tracking performance under a constant time delay is measured for direct teleoperation and when model mediation method is applied to ensure stability. The results of the tests are given and the conclusions are derived.*

Keywords: haptics, unlimited-workspace teleoperation, model mediation technique, bilateral teleoperation

I. Introduction

The prefix "tele" from Greek origin means at a distance and teleoperation, naturally indicates operating at a distance. Thus, teleoperation extends the human capability to manipulating objects remotely by providing the operator with similar conditions as those at the remote location. This is achieved via employing a similar manipulator or joystick, called the master sub-system, at the human's end to capture the motion commands to be sent to the slave sub-system which is performing the actual task[1].[1]

Teleoperation systems having one way direction in communication, which is from master to slave, are called unilateral teleoperation systems. However, in teleoperation systems, force, auditory, visual, temperature and other kinds of valuable information can be acquired from the slave environment which can be transferred back to the master system to enhance the sensation of being present in the slave environment. Sensation of being present in the remote environment is called tele-presence [2]. Teleoperation systems using force feedback and possibly one or more of the other types of feedback and mimic the slave environment in the master side are called bilateral teleoperation or haptic teleoperation [2]. These bilateral teleoperation systems can further be categorized as limited- and unlimited-workspace teleoperation systems according to the slave robot's workspace [2]. As the name implies, the teleoperation systems having limited-workspace robot manipulators in the slave side are called limited- and others having unlimited-workspace mobile robots in the slave side are called unlimited-workspace teleoperation systems [3].

In any kind of bilateral teleoperation, task performance is mainly determined by how effectively the operator can use the feedback to manipulate the system. It has been shown that using the force feedback from the environment decreases task completion time, energy expenditure and failures in proceeding the tasks. The precision and the quality of haptic information transmitted is certainly significant in enhancing the operator's performance and stability of the haptic system[4]. As the master and the slave systems are controlled over a communication line, data losses and delays in transmission of information are the factors that affect the stability of the haptic system [5].

Control algorithms, which are introduced by researchers to ensure stable and safe control of haptic teleoperation systems experiencing constant and variable time delays, are listed by Uzunoglu[5], such as move and wait strategy [6], network theory through impedance representation [7], hybrid control representation [8], scattering theory with passivity control or otherwise known as the wave variable technique [2]. A recent approach is presented by Mitra and Niemeyer [9] as model mediation method, which eliminates the instabilities induced by constant and variable time delays occur in communication line regardless of the magnitude or the change in magnitude of time delays. This method

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has been applied to limited-workspace teleoperation in the previous studies [5]. Although other methods, such as wave variables technique [1, 2], has been applied to unlimited-workspace bilateral teleoperation, to the best knowledge of the authors, model mediation technique has not been applied to an unlimited-workspace bilateral teleoperation system that experience time delays.

In this paper, *for the first time*, model mediation method is applied to an unlimited-workspace bilateral teleoperation system experiencing constant time delays. The teleoperation system is composed of an omni-directional mobile platform as the slave device and the HIPHAD haptic device as the master. Making use of this teleoperation system, the system stability is evaluated through the tracking performance and the force magnitudes exerted to the human operator.

In following section, direct and model mediated teleoperation control architectures are given in details. The common controllers of the slave and the master systems are given in the third section where the test setup and test procedure are also introduced. The fourth section is reserved to present the test results and conclusions are derived from these results in the last section of this paper.

II. Teleoperation Controllers

In this paper, in order to show the stability problems, direct exchange of the information is used and named as the direct bilateral teleoperation. Model mediation method is later employed to resolve these stability problems. The teleoperation system is composed of a limited-workspace haptic master system and an unlimited-workspace omni-directional mobile robot platform. The details of these subsystems are given in the next section, named experimental setup. In the following sub-sections, the teleoperation controllers and the information flow in between the two sub-systems are explained. Since the master and slave sub-systems have different kinematics and workspace characteristics, a mapping strategy is applied to transfer the commands from the master to the slave.

In the slave side, information about the interaction of the slave with its environment is estimated based on the sensory information. Usually a force sensor is used to acquire the necessary sensory information. However, in this work, a mobile robot platform is used and the task is designed so that the mobile platform will not collide with an obstacle. The distance between the obstacle and the robot is measured through range sensors and then this distance information is coupled with the velocity of the robot to formulate the virtual interaction forces.

The details of this formulation, to keep the robot in a safe distance from the obstacle while calculating the virtual interaction forces, is given in the next section.

A. Direct Bilateral Teleoperation

Information flow between the master and the slave system in direct teleoperation is explained in Figure 2.1. The mapping between the master and the slave sub-system motion is done in position level. The main reason for doing so is that the slave is required to follow the position demand from the master as well as the demand in velocity domain without any offset. In order to accommodate such a mapping, the position of the human hand motion is acquired through the master system and integrated at the master side and then the integrated signal is sent to the slave side as a position demand. Then, on the slave side, the position demand is differentiated with respect to time and a velocity command is calculated and fed into the slave controller.
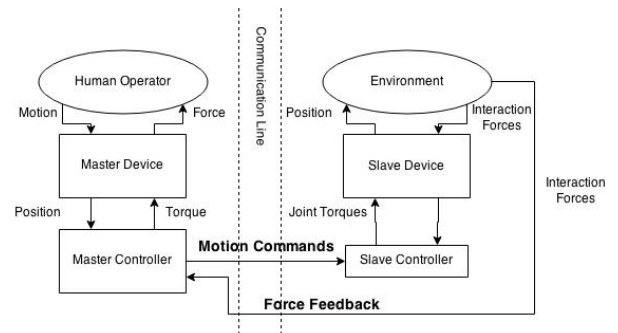

Figure 2.1. Control scheme of the direct bilateral teleoperation technique [5]

On the slave side, virtual interaction forces with the environment are constructed by measuring the distance between the slave and an obstacle, which acts as a constraint (see 3rd section for more details), and by using these distances as an input to a virtual spring and damper system. These calculated forces are then transmitted to the master sub-system to be exerted to the hand of the human operator through the haptic master device. Therefore, in direct teleoperation the motion and force signal are transmitted directly between the sub-systems with a constant delayed information exchange.

B. Model Mediated Bilateral Teleoperation

This method abstracts large data (accumulated from transferred force and position flow) by constructing the slave environment's model with respect to the estimated surface location of the constraint in the slave side. The human operator only interacts with the locally created haptic model of the slave environment within master system as shown in Figure 2.2.
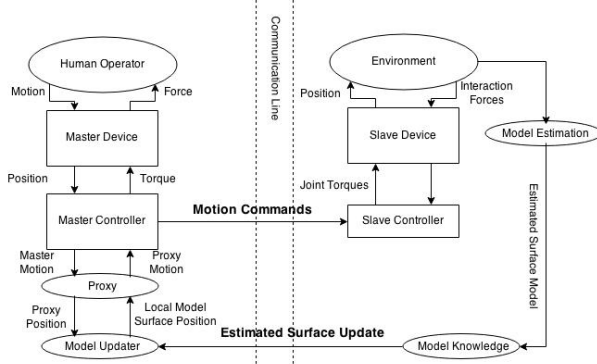
Figure 2.2. Control scheme of the model mediated bilateral teleoperation technique [5]

In this version of the model mediation method, the human operator sends motion commands through master device to the proxy. Motion of the user is acquired through the master device as position signals and used as velocity demands. This calculated velocity demand is called as master velocity, V_m.

The proxy is the representation of the slave system constructed within the master system, which has its own dynamics and differs from the actual slave dynamics. Therefore, instead of sending motion commands to slave side directly, the motion demands are first received by the proxy. The passivity of the system is guaranteed via the limitations of the contact surface modeling and proxy motion with its designed dynamics. Then, the motion of the proxy complying with the set limitations is sent to slave sub-system as a motion command. The motion of the proxy to be sent to the slave system is mapped in a similar way as it was in the direct teleoperation scenario. The position of the proxy is integrated on the master side and sent to the slave side as a position demand and then on the slave side, this signal is differentiated to issue a velocity command to the slave sub-system in its task space.

In model mediation method, the amount of the forces measured or calculated is not important since only the information about the presence of an obstacle surface is to be transferred to the master sub-system. The information of the obstacle surface is developed in the contact estimation block which is presented in Figure 2.3. This information is transmitted to master side to update the previously created model on the master side. In free motion of the slave device, the proxy follows the master's motion demands with its own dynamics and proxy's motion data is sent to slave side with the formulation explained previously. When a contact occurs in the slave side, the position of the slave in the opposite direction of the force is taken as constraint position (obstacle surface location) and transmitted to master side with a communication delay. In the master system, a local constraint model is constructed according to the constraint position complying with the limitations that ensures the passivity as explained in [5, 9]. Proxy interacts with the previously mentioned slave environment's estimated model.

One limitation for this interaction is given so that the proxy never penetrates the modeled surface. Therefore, the initial surface constructed is not at the same location with the real surface but it is placed just under the proxy. At that time, the proxy and the master are at the same place and no forces are transmitted to the user. However, the human operator can move the master inside the surface. In this case, interaction forces are calculated and reflected to the human operator through the master device and the proxy still stays above the constructed surface.

When the master moves above the surface, the proxy starts to track the master's motion. Until the two of them reaches the estimated surface location, if the master is directed in the opposite direction from the direction to get to the actual surface, interaction forces are created to be sent to the human operator. This working strategy ensures that no excessive forces are transmitted to the user as a result of an instantaneous collision of the slave with an obstacle. This ensures the passivity of the total teleoperation system.

The limitations and the necessary calculation taking place on the sub-systems of the model mediated teleoperation controller are explained in the next sub-section namely; Master Sub-system and Slave Sub-system.

B1. Implementations to Guarantee Passivity

The master system in model mediation method has a model constructed with the constraint information received from the slave side, which is proposed by [9]. The proxy that is interacting with the constraints within this model has its own dynamics and this dynamic behavior is based on calculating a dynamic reference velocity, V_r, which is given in equation 2.1.

$$V_r = V_m + \frac{k_{pm}}{k_{dm}}(x_m - x_p) \qquad (2.1)$$

In equation 2.1, v_m, x_m and x_p are master velocity, master and proxy positions respectively [9]. k_{pm} and k_{dm} are the control parameters used to calculate the force to be exerted to the human operator. The calculation of the forces to be applied to the human operator is shown in equation 2.2.

$$F_m = k_{pm} \cdot (x_m - x_p) + k_{dm} \cdot (\dot{x}_m - \dot{x}_p) \quad (2.2)$$

It can be observed from equation 2.1 that after the proxy reaches the master system's position, when $x_p = x_m$,

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the proxy follows the master system perfectly and responds to any commands sent from the master system instantly.

Using equations 2.1 and 2.2, it can be derived that:

$$F_m = k_{dm}(V_r - V_p) \qquad (2.3)$$

where V_p is the proxy velocity. The surface normal n is defined such that $(V_p) \cdot n$ is positive while moving towards the surface. Considering β is the distance to surface and ΔT is the cycle time, velocity of the proxy is subjected to a limitation given in equation 2.4.

$$(V_p)^T \cdot n < \beta\alpha, \quad \alpha \le \frac{1}{\Delta T} \qquad (2.4)$$

Since the proxy velocity is calculated from equation 2.1 with the surface restrictions given by equation 2.4, surface will never be penetrated by the proxy [9] as defined in equation 2.5. and 2.6. which mean contact constraints are active and inactive respectively.

$$V_p = V_r \qquad \text{if} \qquad (V_p)^T \cdot n < \beta\alpha \quad (2.5)$$

$$V_p = 0 \qquad \text{if} \qquad (V_p)^T \cdot n > \beta\alpha \quad (2.6)$$

As the proxy is massless and penetration of the virtual wall is restricted, energy is not stored in the system and passivity [5] of the system is assured with the following condition.

$$\left(V_p\right)^T(-F_m) \ge 0 \qquad (2.7)$$

It is seen that if the proxy is away from the constraint, the condition in equation 2.5 is satisfied and passivity condition defined in 2.7 becomes equal to zero, since F_m given in equation 2.3 is calculated to be zero.

When the proxy is on the surface of virtual wall, which is the constraint, the proxy velocity, V_p, becomes equal to zero with respect to equation 2.6. In this case, the passivity is maintained since the equation 2.7 becomes also equal zero as V_p goes to zero velocity.

In master system, estimated constraints are modeled and updated by a model estimator. This model update is done complying with the same limitations presented in the proxy to ensure the stability of the system response by not forming excessive forces to be exerted to the human operator during an initial contact case. Hence, when the constraints are transmitted to master side, they are first examined if they satisfy limitation, which is equation 2.3, then updated as new model surface positions. In equation 2.3, F_e is the environmental interaction force.

$$X_{model} \cdot sgn(F_e) \le X_{proxy} \cdot sgn(F_e) \qquad (2.3)$$

B2. Implementations in Slave Sub-system

In model mediation, instead of sending the forces calculated from the sensory information to master side, a contact surface estimation algorithm is implemented in the slave controller. This algorithm is shown in equation 2.4. F_e given in this equation is the calculated environmental force given in equation 3.1. $X_{ssurface}$ represents the position of the constraint. When F_e is greater than zero, this means that mobile platform is close to constraint and the $X_{ssurface}$ receives the surface location information from the slave system's position, X_s. Eventually constraint position is generated according to the condition given in equation 2.4. as.

$$\begin{cases} X_{ssurface} = X_s & ; & |F_e| > 0 \\ X_{ssurface} = \infty & ; & |F_e| = 0 \end{cases} \qquad (2.4)$$

$X_{ssurface}$ is initially a value larger which is close to infinity. As this constraint parameter is found, it is transmitted to master side. The surface constraint is compared with the proxy location as addressed in equation 2.3 and it is renamed as X_{model}, which is the updated surface location in the model within the master system.

III. Experimental Test Setup

Test setup is a teleoperation system composed of a virtual slave device and a haptic master system. Since the remote site is constructed virtually, communication line is modeled in computational environment [2]. The master device is the HIPHAD haptic device built in Iztech Robotics Laboratory by[10].

In the following sub-sections local controller and kinematics of the omni-directional slave device, master device and model of the communication line are given. Afterwards, the remote environment model and test procedure is explained. In the tests, a PC, the HIPHAD haptic device, and Quanser Q8 DAQ Card are used as hardware and Matlab Simulink and Quarc v2.1 are used as the software.

Virtual representation of the models (the slave device and its environment) are constructed in SolidWorks and Blender and then they are translated to Matlab Simulink environment with the visualization support of Quarc v2.1 Quanser. This simulation is run in Hardware in the loop (HIL) simulation in discrete time having 0.002 s sampling time. The control gains (k_{pm}, k_{dm} of proxy and PID gains of slave controller) of the slave- and master-subsystems, which are going to be presented in following sub-sections, are set through iterations.

A. Common Controller and Kinematics of Omni-directional Slave Device

The slave device is an omni-directional vehicle with 4 wheels that are placed by 90° angles from the previous one [11]. The top view of the device is given in Figure 3.1. The two wheels having same rotational axis are motion pairs, which means that they rotate in clockwise and counter clockwise to move vehicle in direction perpendicular to their rotational axes and they do not interfere with the motion along the other axis. The kinematics of the device are provided in [11]
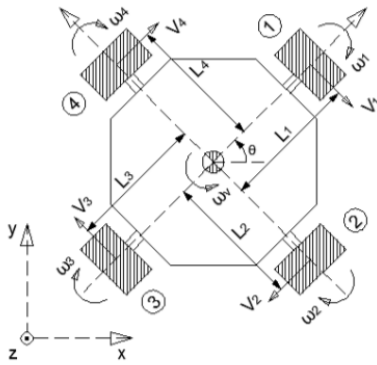
Figure 3.1. Kinematic representation of omni-directional Slave Device [11]

As a result of that, device has kinematic redundancy due to having 4 degrees-of-freedom (DoF) in planar workspace[11]. In this experiments, the rotational DoF is not considered since it will be directed by the master device with translational 3 DoF. Therefore, the slave device is restricted to move along translational axes, which are x- and y-axis.

In the common local controller of the slave system, velocity commands received from the master system are first compared with the measured slave velocity to calculate the velocity error in task space. This error is than converted to joint space velocity errors and joint-level controller are used to issue necessary commands to drive the actuator attached to the wheels. The controllers are designed as PID-based independent joint controllers. The traction forces generated by the controlled wheels are fed into the simplified vehicle dynamics module. This module simply makes use of forces along one direction as input and calculates the subsequent acceleration. The overview of the local slave device controller is presented in Figure 3.2.
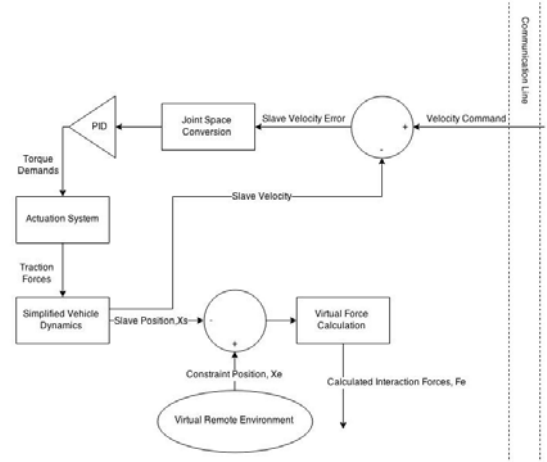

Figure 3.2. Overall control scheme of the common slave device controller

The interaction force calculation mechanism, also runs within the slave system. If the range sensors detects a penetration into the threshold distance, which is set at a safe distance from the wall, it starts to calculate a virtual interaction force to be used in both types of teleoperation techniques. The walls are located at equal distances from the task coordinate frame origin. The force calculation is executed by equation 3.1.

$$F_e = (k_{vw}(p) + b_{vw}(\dot{p})) \qquad (3.1)$$

where $p = sgn(x_{slave}) \cdot (x_{wall} - x_{slave})$. k_{vw} and b_{vw} are the gains for spring damper model of the wall-slave interaction. This calculated interaction force is not superposed with the traction forces since the omni-directional vehicle is not designed to collide with the constraints in remote environment.

B. Common Controller and Kinematics of the Master Device

The HIPHAD, is a kinesthetic and parallel structured haptic device with 3 DoF. It has a direct drive actuation, therefore, it is designed to be of impedance type haptic device [10]. The direct and inverse kinematics of the device are straightforward and provided in [12]. The haptic device is shown in Figure 3.3. along with the rest of the test setup.
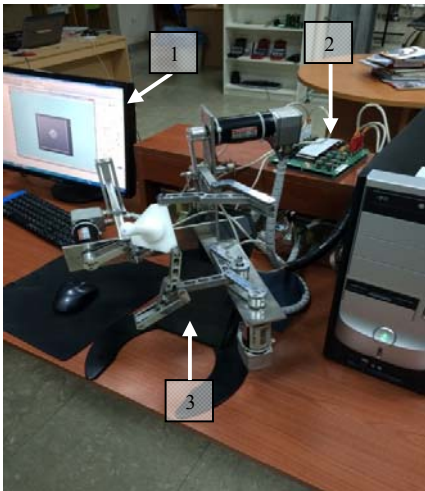
Figure 3.3. Test Setup (HIPHAD and virtual slave environment) 1. Virtual Slave Environment with slave Device, 2.Quanser Q8 DAQ Card, 3. The Master Device HIPHAD

Figure 3.4. Slave environment and slave device from top view

Communication line in between the two sub-systems are modeled in simulation environment. A transport delay is inserted in the communication line model to simulate time delays in communication of the master and the slave [2].

C. *Test Procedure of the Teleoperation System*

Test procedure is designed to observe position tracking error performance and stability of the slave device when there is a constant 1 s time delay in the communication line in both directions. First, the tracking performance and stability of the slave device is observed and recorded for the direct teleoperation where the motion and force signals are sent and received directly. Then model mediation technique is employed to change the configuration of the teleoperation system information exchange to improve the tracking performance and stability of the overall system.

With the presence of a constant time delay, the slave device is driven to the wall and when the contact occurs, the slave device is forced by the commands from the human operator to stay in contact with the constraint. Virtual environment and the slave device is presented in Figure 3.4 Virtual environment is a square box having walls at 5 m distance from the origin of the task coordinate frame. However, as explained earlier, interaction forces are started to be calculated at 1 m distance from the wall, which is the threshold value to start constructing virtual forces. Therefore, proxy is expected to start interacting with the model surface, x_{model}, at +4 m distance in y-direction, which is the only constraint in the slave environment.
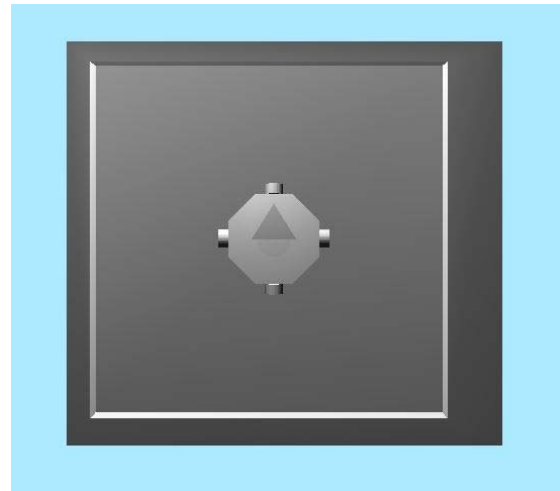
IV. Results

After some iteration to choose control gains for the slave system, suitable gain values are selected for an acceptable transient and steady-state response. PID gains, k_{ps}, k_{ds} and k_{is}, used in calculation of torque commands. For slave system, k_{ps}, k_{ds} and k_{is} are chosen to eliminate the tracking error of the slave device with respect to the master command. The selected gains for the slave system in both of the tests (direct teleoperation and model mediation) are k_{ps}=3.5, k_{ds}=0.0075, k_{is}=0.05. With these selected gains, in free motion, root mean square error of the position tracking of the slave system in a meter displacement is calculated to be 1.2 mm. Master system's controller gains, k_{pm} and k_{dm}, are chosen to apply a sufficient damping while fast a traction by proxy to catch the master after collusions. These parameters are not subjected to PID tuning methods and selected as k_{pm}=1 and k_{dm}=0.25 after some iterations. However, the gains are selected to provide an acceptable tracking performance for following the master commands in free motion with bounded errors.

A. *Test Results for Direct Teleoperation*

In both teleoperation configuration tests, the tracking performance of the slave device is evaluated. It is first evaluated in free motion of the slave device in which there is no constraints involved. Direct teleoperation technique is shown to track motion commands with some accuracy as it can be observed from Figure 4.2. until the 10th second. However, one second after the contact at the 11th second, the master starts to receive the force feedback from the slave side and immediately torque rises up to 0.3 Nm. Since there is a large force demand as feedback to the human operator, master device is moved backwards to 3 m after first contact is felt by the user. In other contact trials, the operator has a previous

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knowledge about the wall position, and therefore approaches the wall slowly. This helps keeping the contact for a while, as seen in simulation data after the 35th second in Figure 4.2. However, still it is moderately hard to maintain the position. It is also seen in the test results that keeping the contact at 4 m line generates an oscillated motion of the slave.

The slave device in direct teleoperation, after reaching the physical limitation of its workspace at 20th and 38th seconds, has a positional offset with respect to the master's position provided with red solid line in Figure 4.3. This is caused by the type of information exchange used in the system, which is velocity-force in this case. Since the vehicle is controlled by velocity commands, when the tracking is interrupted by a physical blockage or communication failures, vehicle cannot compensate the positional offset as it can be observed from Figure 4.2. after 20th and the 38th seconds.

Figure 4.3. Position tracking error of the slave device in direct teleoperation tests (red line), Master device's position (blue Line), Slave device's shifted position (green Line)
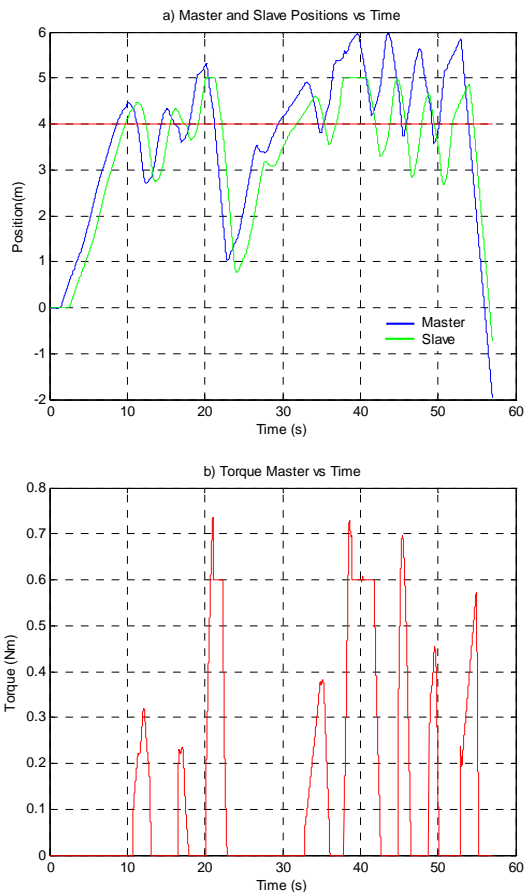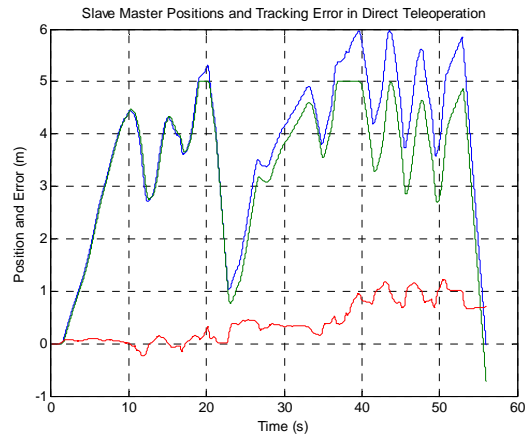

Figure 4.2. Test results of the direct teleoperation technique: a) Tracking performance of the slave device, b) Force outputs of the master system to the human operator

B. *Test Results for Model Mediated Teleoperation*

In the model mediation technique, the gains k_{pm} and k_{dm} are selected to form suitable dynamics between the master and the proxy after collisions. The same test procedure is applied in model mediation technique tests so that performance of two teleoperation system configurations are compared.

The test results for the model mediation technique is provided in Figure 4.4, where the master position is identified with blue, the slave position is indicated with red and the proxy position is shown with green solid lines. In the beginning of the test, as there is no constraint, proxy follows the master freely and the commands transmitted to the slave system with time delay become the commands sent directly from the master. This is the same as the procedure for the direct teleoperation. In this condition, the tracking performance of the slave is given in Figure 4.4. until the 11th second when the contact occurs as indicated with the dashed red line.

In the model mediation technique test, the slave follows motion commands, which is the proxy velocity. As the device passes 4 m line, which is given with black solid line in Figure 4.4, a virtual force is computed and then estimator records the slave position, x_s, as constraint position, $x_{ssurface}$. The time of contact is shown in Figure 4.4. as dashed red vertical line at the 11th second of the simulation. However, as there is a time delay, this data can only be taken in the model updater after one second at the 12th second. When model surface is updated, then the force feedback is calculated and applied to the master according to the equation 3.2. As the operator tries to retrieve to somewhere below 4 m, proxy follows the

master back to the actual position of the wall. If the operator tries to move further into the wall, then the force will be calculated to have an increase and the proxy stays still until master moves away from the constraint. Afterwards, master is pulled to its initial position in y-axis and slave follows it back. At this time, the model updater has the knowledge of the actual position of the wall and if there is no change in the wall position in slave environment, model updater and proxy will secure the passivity of the system by calculating forces locally in the master system. After the 24th second of the test, master is again pushed above the wall and proxy does not move beyond the 4 m line as there is a pre-knowledge of the constraint location within the model. As a result of this, the slave does not pass the 4 m line due to commands provided by proxy.
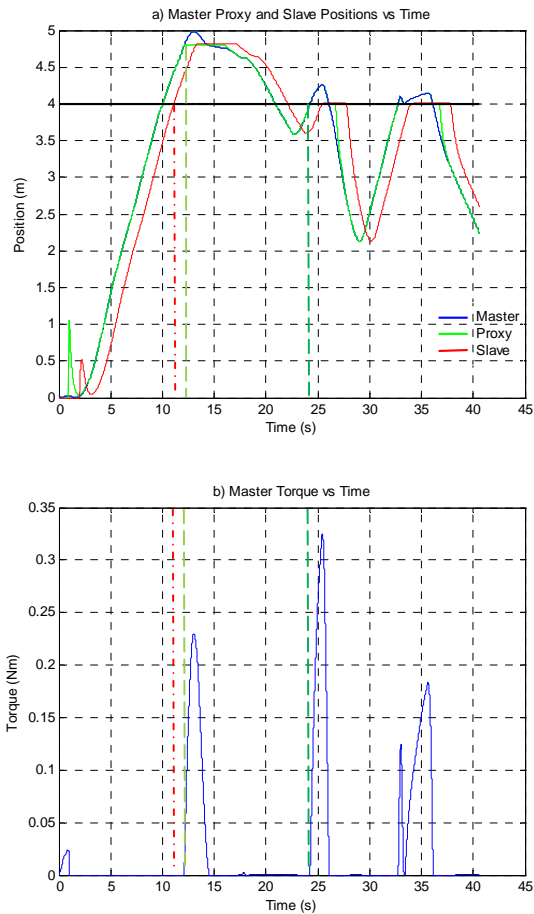

Figure 4.4. Test results of the model mediation technique: a) Tracking performance of the slave device, b) Force outputs of the master system to the human operator

As it can be observed from Figure 4.5, the slave is able to follow the commands, in free motion and contact condition, that are sent from the master side through the proxy in the test with better tracking performance compared to the direct teleoperation case. There are offsets during the contact situation between the master and the proxy positions, however, these are expected offsets and proxy starts to follow the master as it was explained in the rules of the model mediation technique.
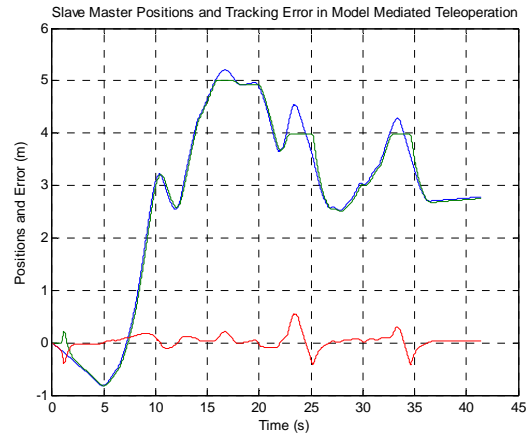

Figure 4.5. Position tracking error of the slave device in model-mediated teleoperation tests (red line), Master device's position (blue Line), Slave device's shifted position (green Line)

V. Comments and Conclusions

In this work, model mediated teleoperation technique is applied to a teleoperation system composed of a unlimited-workspace mobile robot as virtual slave device and the HIPHAD as haptic master device. The performance of the model mediated teleoperation with this test setup is compared with the results obtained from the direct teleoperation test. Performance parameters to compare both techniques are set to be the tracking performance and force outputs in the tests. It should be noted that only constant time delays are used in the test.

Direct teleoperation technique results in oscillations in slave position after the collisions with the virtual wall. During the test, the master device became harder to control by the human operator as the device stuck itself on the opposite side of the related axis or exerted unexpected forces. It is obvious that system generates a large force, which cannot be produced as a result of the slave interaction. This experimentally proves that a constant time delay in direct bilateral teleoperation results in unstable behavior of the system. Also, sending velocity as command caused the slave to drift away from the master position when the slave is blocked by a constraint, which is the virtual wall in the slave environment.

Model mediation technique, however, provides a better first contact force values, which is less than $1/100^{th}$ of the one occurred in direct teleoperation. It is also noted that, during the next contacts after the initial contact with the same constraint, the slave device follows the master motion complying with the limitations introduced to proxy. The master forces can be modified by tuning the proxy dynamics, which can be done by changing k_{pm} and k_{dm} parameters.

As a future work, model mediated teleoperation can be extended to apply constraints along the other axes of motion to cover all translational and the rotational degrees of freedom of the slave device, which is an omni-directional mobile platform. As a matter of fact, the model-mediation method was extended to multi-degree-of-freedom limited-workspace teleoperation in [5]. The main challenge in extending the work presented in this paper will be on mapping the information exchange between the master and the slave, especially mapping the rotational motion.

Acknowledgement

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