Position Tracking Performance of a Redundant Teleoperation System

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ABSTRACT

Teleoperation has captured the interest of robotics researchers for more than two decades. Many focused on the stability problem when the system experiences time delays. Most of the time, guaranteeing stability has overshadowed the tracking performance. This work differentiates teleoperation systems into two groups as limited and unlimited-workspace teleoperation depending on their position tracking priorities. Specifically, this paper examines limited-workspace teleoperation on a redundant system. The slave is modeled to be the virtual representation of a Fanuc LR Mate 100iB, a five degree-of-freedom (DOF) serial industrial manipulator. The master is selected as a two-DOF force-reflecting joystick. Hence, the teleoperation system is redundant since the degree-of-freedom of the slave is greater than the master. Teleoperation experiments have been conducted for this system under constant time delays and communication losses. The results are presented when the customary and modified wave variable techniques are utilized.

Keywords

Teleoperation, Redundant, Real-Time, Force-Reflecting, Position Tracking, Matlab, Wave Variable, Fanuc LR Mate 100iB

1. INTRODUCTION

Teleoperation represents an area where robotics and controls are tightly integrated. It is mostly used in tasks where the job to be accomplished can not be achieved by the humans either because the task is too dangerous for the humans or it is to be carried out at a distant site from the main control location. The robots that work in radioactive and hazardous environments are examples to the robotics tasks that are very dangerous for the humans to accomplish. The robots that work in space exploration, undersea applications or remote surgery are typical examples for teleoperation where these tasks are usually carried out at a remote site.

Teleoperation studies have been an area of increased interest for the past two decades for several researchers. A majority of the research has focused on the stability problem that arises as a result of time delays [1-6]. There is always a communications line involved in teleoperation systems since the local controller (master robot) and the remote system (slave robot) are connected at all times. The information flow from one robotic system to the other can be achieved through various media including the Internet, intranet, satellite or radio signals. The common shortcoming of these communication systems is that they will make the teleoperation system experience more significant time delays as the distance between the controller and the remote system increases.

A control algorithm based on the wave variable technique has provided an acceptable solution for the time delay problem [3]. This algorithm basically stabilizes the manipulation in the face of time delays in the communications line.

Teleoperation can be investigated in two subgroups considering the workspace of the slave robot. First subgroup is titled limited-workspace teleoperation and the other is unlimited-workspace teleoperation. These subgroups are further discussed in the next section.

Teleoperation of a serial industrial robotic arm manufactured by Fanuc, LR Mate 100iB, is used in this work. This specific teleoperation falls into the limited-workspace teleoperation subgroup. Main focus of this study is to investigate the performance of position tracking while guaranteeing the stability under time delays. The following section explains the customary and modified wave variable techniques to enhance the position tracking performance.

Teleoperation test system is configured as a two-DOF gimbal-based master joystick and the virtual representation of the slave, Fanuc LR Mate 100iB arm which is a five-DOF serial robot. Specifications of both manipulators and their integration for use in real-time tests are also explained in the following sections.

Experimants are conducted for constant time-delayed teleoperation as well as for teleoperation systems experiencing communication loss for limited periods. Position tracking and the stability of the teleoperation are also examined using the results of these tests for the customary wave variable technique and its modified version.

2. TELEOPERATION BACKGROUND

Robotics engineers usually employ teleoperation systems under two conditions. One condition is when it is necessary to accomplish a task at a distant site from the operator. The other condition is where the task is carried on in an environment, which is hazardous for a human to work in. In both cases, human operator is placed at the other end of the teleoperation system, sending signals to control the slave robot via a master system. It can be summarized that the slave robot controlled by the human operator takes place of the human that is expected to work on the task in teleoperation systems. This substantially reduces the risk to humans and the costs associated with manned mission while increasing the precision.

There are many applications of the teleoperation systems. For instance, Japan's National Institute of Advanced Industrial Science & Technology is studying the ground-space telerobotics [7]. The study by Cavusoglu [8] involves transforming a surgical robot for human telesurgery. Sitti [9] investigates teleoperated nanomanipulation. There are also numerous examples for military, hazardous environment and undersea teleoperations.

Telepresence can be explained as the quality of a teleoperation experience. Ideally, the information from the remote environment (visual, aural, haptic, etc.) is displayed in such a way that the operator "feels" as if he/she is actually present at the remote environment. Teleoperation systems can be branched to two types considering the concept of telepresence.

The slave robot does not send back any sensory information to the master in unilateral teleoperation. In this type of teleoperation, the telepresence concept does not exist. The teleoperation system where the slave sends back any type of sensory information is called bilateral teleoperation. This means that the information flow is bidirectional.

One of the most common bilateral teleoperation is called force-reflecting bilateral teleoperation. The slave robot reflects back the interaction forces to the master side. The actuators of the master are then driven with the sensory information to make the human operator feel the slave's environment. Many researchers widely agree that having force-reflection accompanied with visual feedback provides sufficient telepresence for most of the teleoperation applications [10].

In this work, bilateral teleoperation systems are further investigated as limited and unlimited-workspace teleoperation. Teleoperation systems using serial or parallel slave manipulators with limited-workspace are considered as limited-workspace teleoperation. Telemanipulation of an industrial robot arm is an example to this type of teleoperation.

Teleoperation systems composed of a mobile platform or any unlimited-workspace slave is referred as unlimited-workspace teleoperation. Telemanipulation of any mobile robotic system whether it operates on ground, water or in air is grouped as unlimited-workspace teleoperation.

It is noted that the motion mapping of the two teleoperation types are not the same. In limited-workspace teleoperation, master position information is mapped to the Cartesian position of the end-effector. In unlimited-workspace teleoperation, the same position information from the master is mapped as velocity demand for the end-effector of the slave. Therefore, position tracking is the priority for the limited-workspace case while velocity tracking is the priority for unlimited-workspace teleoperation.

3. WAVE VARIABLE TECHNIQUE

The block diagram in Figure 1 below presents the wave variable technique in terms of the scattering transformation – a mapping between the velocity and force signals, and the wave variables [3].

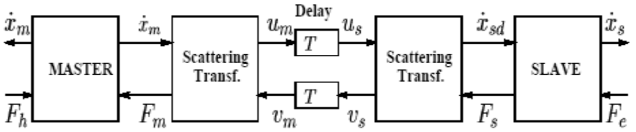

Figure 1. Scattering transformation for teleoperation with constant time delay

This transformation using the notation in [2] is described as follows:

$$
\begin{aligned}
u_s &= \frac{1}{\sqrt{2b}}(b\dot{x}_{sd} + F_s) \\
u_m &= \frac{1}{\sqrt{2b}}(b\dot{x}_m + F_m) \\
v_s &= \frac{1}{\sqrt{2b}}(b\dot{x}_{sd} - F_s) \\
v_m &= \frac{1}{\sqrt{2b}}(b\dot{x}_m - F_m)
\end{aligned} \tag{1}
$$

where $\dot{x}_m$ and $\dot{x}_s$ are the respective velocities of the master and the slave. F_h is the torque applied by the operator, and F_e is the torque applied externally on the remote system. F_m is the force reflected back to the master from the slave robot. F_s is the force information sent from the slave to master. $\dot{x}_{sd}$ is the velocity derived from the scattering transformation at the slave side. The wave variables are defined by u and v.

The power, P_{in}, entering a system can be defined as the scalar product between the input vector x and the output vector y. Such a system is defined to be passive if and only if the following holds:

$$\int_0^t P_{in}(t) = \int_0^t x^T y d\tau \geq E_{store}(t) - E_{store}(0) \tag{2}$$

where $E(t)$ is the energy stored at time t and $E(0)$ is the initially stored energy. The power into the communication block at any time is given by

$$P_{in}(t) = \dot{x}_{md}(t)F_m(t) - \dot{x}_{sd}(t)F_s(t) \tag{3}$$

In the case of the constant communications delay where the time delay *T* is constant,

$$
\begin{aligned}
u_s(t) &= u_m(t-T) \\
v_m(t) &= v_s(t-T)
\end{aligned} \tag{4}
$$

Substituting these equations into (3), and assuming that the initial energy is zero, the total energy *E* stored in communications during the signal transmission between master and slave is found as

$$E = \int_0^t P_{in}(\tau)d\tau = \int_0^t (\dot{x}_{md}(\tau)F_m(\tau) - \dot{x}_{sd}(\tau)F_s(\tau))d\tau$$

$$= \frac{1}{2}\int_0^t (u_m^T(\tau)u_m(\tau) - v_m^T(\tau)v_m(\tau) + v_s^T(\tau)v_s(\tau) - u_s^T(\tau)u_s(\tau))d\tau$$

$$= \frac{1}{2} \int_{t-T}^{t} (u_m^T(\tau) u_m(\tau) + v_s^T(\tau) v_s(\tau)) d\tau \geq 0 \qquad (5)$$

Therefore, the system is passive independent of the magnitude of the delay *T*. In other words, the time delay does not produce energy if the wave variable technique is used. Therefore, it guarantees stability for the time-delayed teleoperation.

For multi-DOF teleoperation systems, the inputs and outputs from the master and the slave are in vector form:

$$\underline{\dot{x}}_{sd} = \begin{bmatrix} \dot{x}_{sd} \\ \dot{y}_{sd} \end{bmatrix}; \ \underline{\dot{x}}_m = \begin{bmatrix} \dot{x}_m \\ \dot{y}_m \end{bmatrix}; \ \underline{F}_s = \begin{bmatrix} F_s^x \\ F_s^y \end{bmatrix}; \ \underline{F}_m = \begin{bmatrix} F_m^x \\ F_m^y \end{bmatrix} \qquad (6)$$

These inputs and outputs from the master and the slave sub-systems are transformed to wave variables using the *B* matrix for the multi-DOF case. For the simulations in this paper, the wave impedance matrix, B, is selected to be uncoupled as shown below:

$$B = \begin{bmatrix} b_x & 0 \\ 0 & b_y \end{bmatrix} \qquad (7)$$

Munir and Book [2] write the wave transformation relation of equations in (1) in matrix notation to generalize it to multi-DOF systems as follows:

$$\begin{aligned} \underline{u}_s &= A_w \underline{\dot{x}}_{sd} + B_w \underline{F}_s \\ \underline{u}_m &= A_w \underline{\dot{x}}_m + B_w \underline{F}_m \\ \underline{v}_s &= C_w \underline{\dot{x}}_{sd} - D_w \underline{F}_s \\ \underline{v}_m &= C_w \underline{\dot{x}}_m - D_w \underline{F}_m \end{aligned} \qquad (8)$$

where A_w, B_w, C_w, D_w, $B \in R^{nxn}$ (are *nxn* matrices); $\underline{u}_s$, $\underline{u}_m$, $\underline{v}_s$, $\underline{v}_m$, $\underline{\dot{x}}_{sd}$, $\underline{\dot{x}}_m$, $\underline{F}_s$, $\underline{F}_m \in R^n$ (are *nx1* vectors). A_w, B_w, C_w and D_w are the scaling matrices and n is the degree-of-freedom of the teleoperation system. In this paper, $n = 2$ for the teleoperation system having three degrees of freedom. Scaling matrices are determined using the impedance matrix (B), as follows:

$$A_w = \frac{\sqrt{2B}}{2}, \quad B_w = \frac{\sqrt{2B}}{2}(B^{-1}) \qquad (9)$$

where usually C_w is selected to be the same as A_w, and D_w is selected to be the same as B_w.

4. MODIFIED WAVE VARIABLE TECHNIQUE

In the previous sections, it was explained that position-tracking performance is the priority for limited-workspace teleoperation. In order to guarantee stability under time delays, the wave variable technique is employed. This algorithm involves translation of velocity and force information between the master and the slave. Therefore, the slave system is driven with the velocity demands received from the master. It is foreseen that position drifts between the master and the slave motion can be formed under two conditions. One condition is the initialization of teleoperation at mismatching positions of the master and slave. The second condition is when the teleoperation system experiences communication failure for limited periods at any point of teleoperation. In this work, it is proposed to send the position information of the master in addition to the velocity information (which was coupled with force information to form a wave variable).

A feedforward position demand is used to modify the wave variable technique [11]. This demand is sent from the master system directly to the slave system without integrating into the scattering transform. The authors have not experienced instability or drift conditions in force translation from the slave to the master in their previous tests [12]. Hence, no feedforward force demand is used for the master side as proposed in [13]. The block diagram of the proposed algorithm is given in Figure 2.

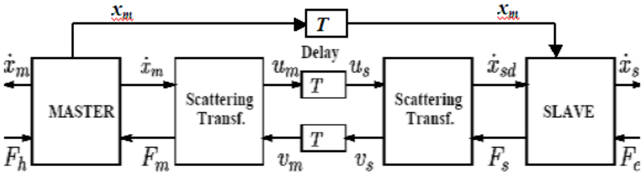

Figure 2. Modification to wave variable block diagram.

The slave controller block diagram is also modified to comply with the new setting of the wave variable technique. As observed in Figure 3, the position error is calculated in the joint space. The motion demand from the master received in Cartesian space is transformed into the joint space by using the inverse of the Jacobian, *J*, and the inverse kinematics, *IK*. Later, the demand in joint space is compared with the joint sensor readings to form joint motion errors to be fed into the controller. This type of controller is of course feasible for those manipulators for which the inverse kinematics solutions are easy to obtain. Fortunately, almost all of the industrial manipulators are of this kind [14].

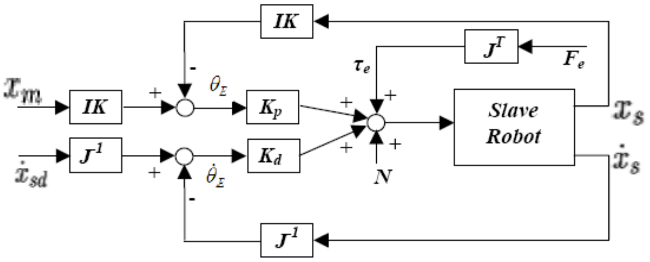

Figure 3. Modified slave controller.

In the slave controller block diagram (Figure 3), *N* is the feedforward torque input to counteract the centrifugal, Coriolis and gravitational force components.

5. REAL-TIME 2-DOF MASTER JOYSTICK

The joystick that was built at the Robotics and Automation Laboratory of Mechanical Engineering in FIU has uncoupled two DOF. Both degrees of freedom are composed of revolute joints. Each joint is designed to be bedded in between two servomotors. Hence, joint level fault tolerance is achieved by having two servomotors connected to each link. Each servomotor has an encoder connected to the rear end of its shaft. The detailed specifications of the brushless servomotors are given in Table 1, and the master joystick is illustrated in Figure 4.

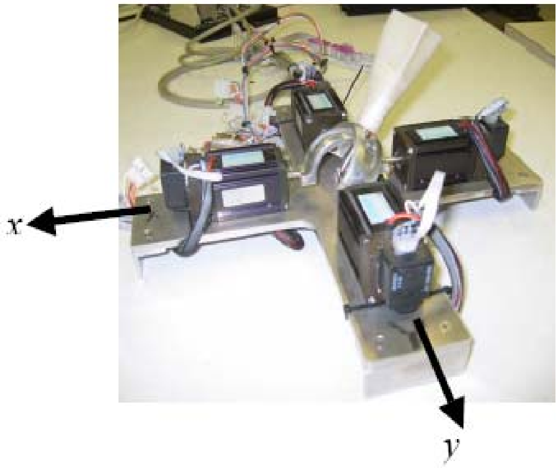

Figure 4. 2-DOF master joystick

Table 1. Specifications of the ELCOM 4441S010 servomotor

Parameter	Sym	Unit	ELCOM
Continuous Torque Max	T_C	oz·in (N·m)	12.00 (.084)
Peak Torque-Stall	T_{PK}	oz·in (N·m)	71 (0.5)
Friction Torque	T_F	oz·in (N·m)	0.15 (1.1×10^{-3})
No Load Speed	S_{NL}	rpm (rad/s)	5780 (605)
Rotor Inertia	J_M	oz·in·s^2 (kg·m^2)	6.4×10^{-4} ($4.5 \text{ X } 10^{-6}$)
Electrical Time Const.	τ_E	ms	0.18
Mechanical Time Const.	τ_M	ms	5.5
Viscous Damp. - Infinite Source Imp.	D	oz·in/krpm (N·m/(rad/s))	0.038 (2.6×10^{-6})
Damping Const— Zero Source Imp.	K_D	oz·in/krpm (N·m/(rad/s))	12.3 (8.3×10^{-4})
Max Winding Temp	θ_{MAX}	°F (°C)	266 (130)
Thermal Impedance	R_{TH}	°F/watt °C/watt	44 (6.7)
Thermal Time Const.	τ_{TH}	min.	22.8
Motor Weight	W_M	oz (Mass) (g)	17 (482)
Motor Constant	K_M	oz·in/√W (N·m/√W)	4.07 (.0287)
Motor Length	L_1	in max. (mm max.)	4.375 (111.1)

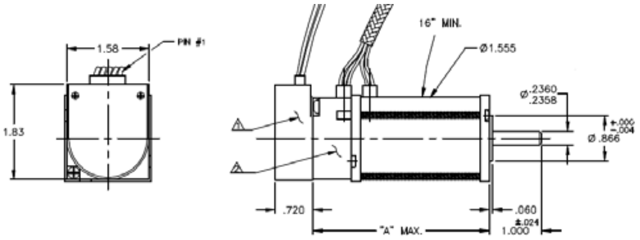

Figure 5. ELCOM 4441S010 servomotor dimensions

6. SLAVE SYSTEM DESCRIPTION

As indicated earlier, the slave system is a serial industrial robot, Fanuc LR Mate 100iB. The Fanuc LR Mate 100iB is a five-axis, electric servo-driven robot. It is capable of a wide variety of tasks in a broad range of industrial and commercial applications including machine tending and part transfer processes. Fanuc describes this manipulator to have high joint speed that maximizes throughput, capability of flipping over backwards for a larger work envelope, and absolute encoder positioning that eliminates homing at power-up [15]. The link and joint parameters of the manipulator is presented in Table 2 whereas Table 3 tabulates the manipulator specifications.

Table 2. Link and joint parameters of the Fanuc LR Mate 100iB

Joints	α_k (deg)	s_k (mm)	a_k (mm)	θ_k (deg)
1	-π/2	0	151	θ_1
2	0	0	250	θ_2
3	0	0	200	θ_3
4	0	0	80	θ_4
5	π/2	0	0	θ_5

The serial arm described above is integrated into the teleoperation system as a virtual representation of the original manipulator. The concept of Rapid Virtual Robot Prototyping has been presented in [16] to construct a manipulator in the Matlab simulation environment. That concept has been used to construct the model for the Fanuc robot.

The teleoperation task is defined as tracing horizontal surfaces maintaining a point contact. While tracking the contour, the end-effector is required to maintain its orientation parallel to the normal of the surface. Therefore, for the designed task only four-DOF of the manipulator are used. The last (fifth) joint is kept at a constant position throughout the tests. First three joints are used for positioning while the fourth joint is used to maintain the orientation of the end-effector.

During the manipulation, if any of the joints two, three or four fails, the orientation objective can be sacrificed but the position tracking can be continued. This redundancy for the specific teleoperation task also promotes fault tolerance in the slave system. The actual manipulator and its virtual representation as used in the tests are shown in Figure 6.

Table 3. Specifications of the Fanuc LR Mate 100iB

Controlled axes		5 axes
Max. load capacity at wrist		5kg
Motion range	J1	5.59rad (320deg)
	J2	3.23rad (185deg)
	J3	6.37rad (365deg)
	J4	4.19rad (240deg)
	J5	12.6rad (720deg)
	J6	-
Max. speed	J1	4.19rad/s (240deg/s)
	J2	4.71rad/s (270deg/s)
	J3	4.71rad/s (270deg/s)
	J4	5.76rad/s (330deg/s)
	J5	8.38rad/s (480deg/s)
	J6	-
Repeatability		+/-0.04mm
Mechanical unit mass		38kg
Application	Arc welding	x
	Spot welding	-
	Handling	x
	Sealing	x
	Assembling	x
	Others	Mold release spray Deburring
Remarks		Controller is R-J3iB Mate.

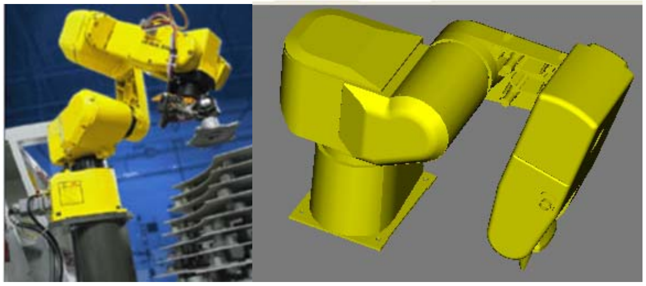

Figure 6. Fanuc LR Mate 100iB and its virtual representation

7. REAL-TIME SYSTEM INTEGRATION

GALIL motion controller is used for the control of the joystick servomotors through the computer. An interface program for Matlab Simulink environment is developed to communicate with the servomotors through this motion controller [17]. This interface enables the data transfer between the virtual environment and the actual joystick.

Force reflection information that was created in the virtual slave side is forwarded to the actual joystick through the interface. As the motion controller receives encoder readings from the servomotors of the joystick, this information is received at the slave side again using this interface. A time synchronizer is used to synchronize the simulation time with the real-time clock. The tests are run in 100 Hz sampling rate with the configuration described above.

8. EXPERIMENTS

The task for the experiments is defined as tracing a horizontal surface with obstacles. These obstacles enable creation of force information as the human operator runs into them operating the slave. The presence of these obstacles is observed by range sensors instead of force sensors. The readings from the range sensors are then transformed into force-reflection data. The tests are performed at 100 Hz sampling rate in real-time clock. The time delays for all of the tests are set at 0.5 second.

Customary wave variable technique is utilized for the first set of experiments [3]. The second set of experiments employed the modified wave variable technique described in this paper. For both sets of tests, communication loss condition is considered.

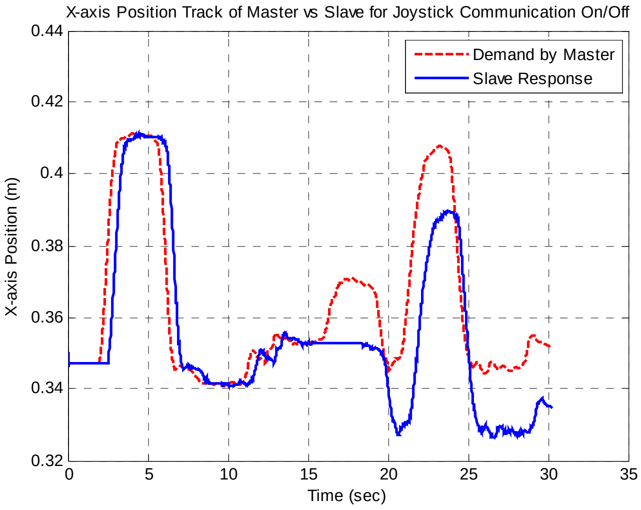

Figure 7. Position tracking performance on X-axis with customary wave variable technique (Communication loss occurs between t=15 and 18 sec)

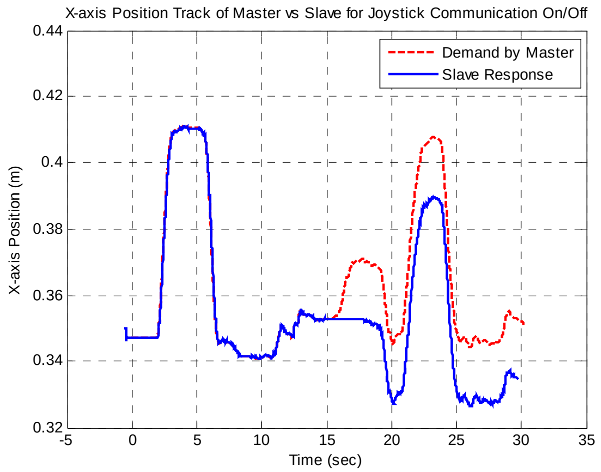

Figure 8. Position tracking performance on X-axis with customary wave variable technique (T_s-0.5 sec)

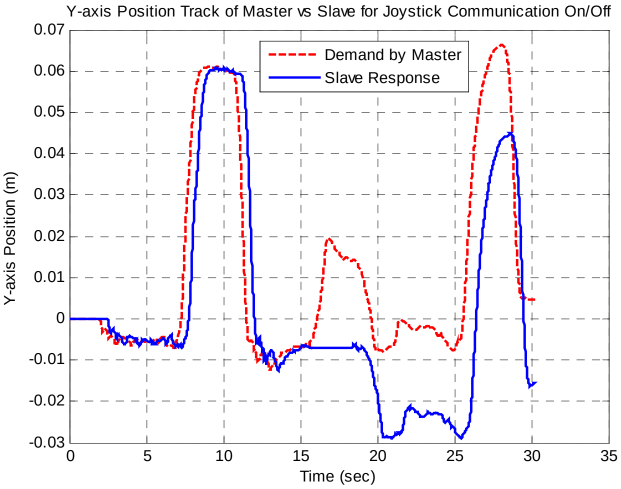

Figure 9. Position tracking performance on Y-axis with customary wave variable technique

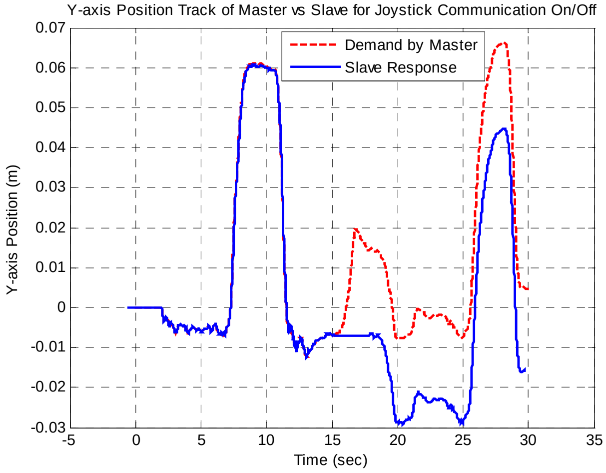

Figure 10. Position tracking performance on Y-axis with customary wave variable technique (Ts-0.5 sec)

Figures 7-10 show the position tracking performance of the customary wave variable control obtained in the first set of experiments. Figures 8 and 10 are developed by plotting the slave position data 0.5 second prior to its occurrence to have a clear graph of master-slave position tracking performance. The communication loss is realized between the 15th and 18th seconds of the telemanipulation task. During the communication loss, null data is received at the slave side, which makes the manipulator remain in the last position before the failure. As the communication is reestablished, the slave starts receiving velocity commands from the master but loses its position relative to the master as observed in the figures.

Next set of graphs are developed for the experiments conducted by using the modified wave variable technique.

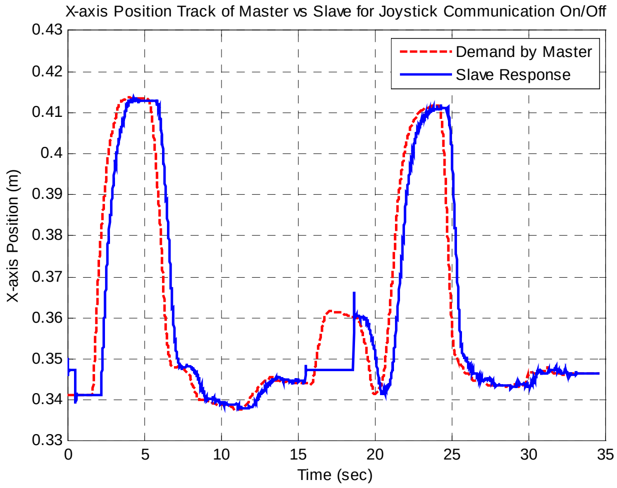

Figure 11. Position tracking performance on X-axis with modified wave variable technique (Communication loss between t=16 and 18 sec)

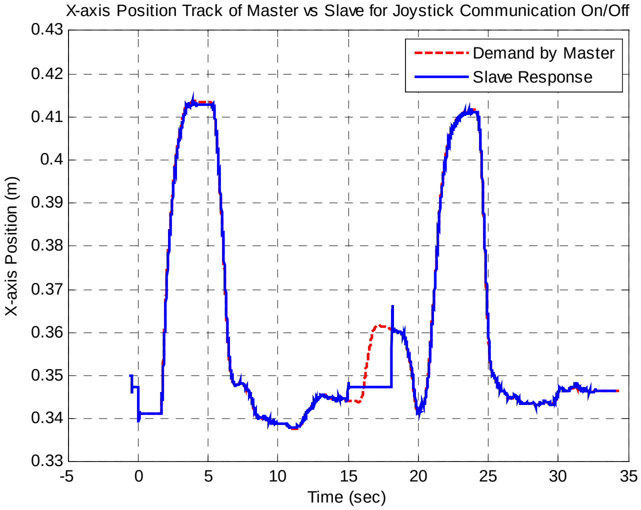

Figure 12. Position tracking performance on X-axis with modified wave variable technique (Ts-0.5 sec)

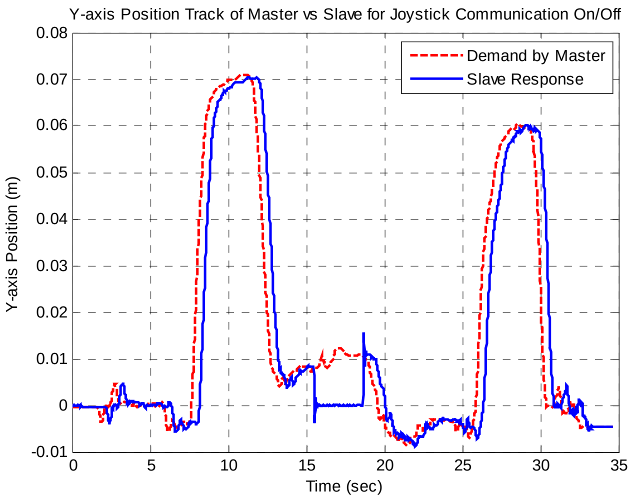

Figure 13. Position tracking performance on Y-axis with modified wave variable technique

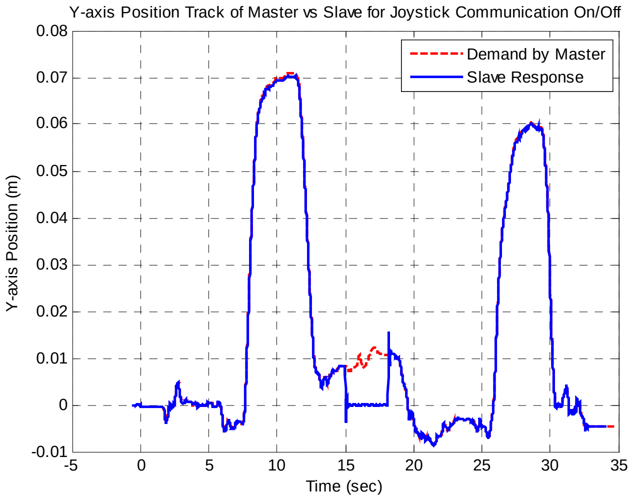

Figure 14. Position tracking performance on Y-axis with modified wave variable technique (Ts-0.5 sec)

Figures 11-14 clearly indicate that the addition of a feedforward position demand compensates for steady state errors, which can be named as position drifts. At t=16 seconds, the communication is switched off and on again at t=18 seconds. During the time of no communication, the slave manipulator remains in its current position. As the slave starts receiving signals from the master, the steady state error is compensated and the position tracking resumes stably. The next set of figures shows the force translation from slave to the master. It is observed from Figure 15 and 16 that there are no problems in force tracking performance before or after the communication loss phenomenon.

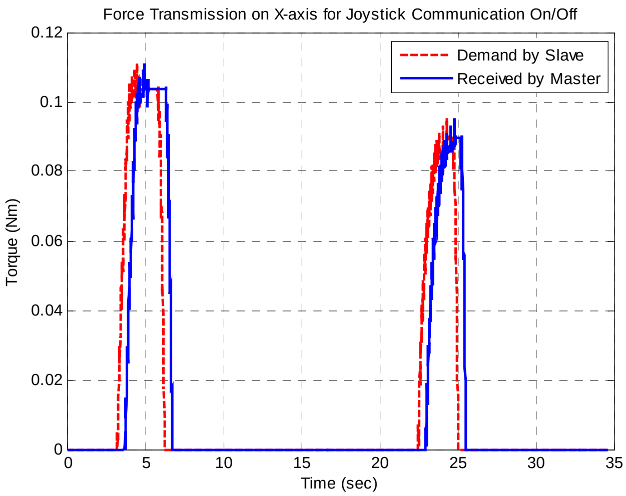

Figure 15. Force tracking performance on X-axis with modified wave variable technique

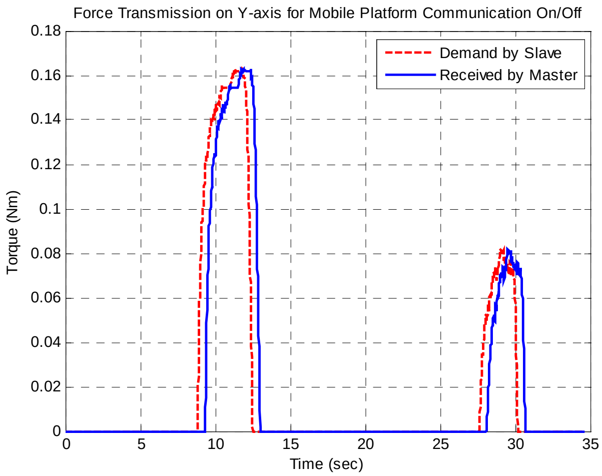

Figure 16. Force tracking performance on Y-axis with modified wave variable technique

9. CONCLUSIONS

In this work, a test system is developed for redundant limited-workspace teleoperation. Constant time-delayed teleoperation tests are conducted using this test system. The tests indicate that stability of the system under the modeled time delays is ensured with the wave variable technique. While position-tracking performance may suffer from the anticipated accuracy under the failures considered in this paper, overall system stability is still guaranteed.

Certain conditions have increased the occurrence of drifts between the master and slave positions. These conditions are listed as initialization of the telemanipulation in random positioning, communication loss or failure of the wave variable technique for limited periods. Addition of feedforward position demand from the master was shown to compensate for these drifts when the master and slave robots are identical [11]. In this paper, the slave system has two more DOF than the master but it still has limited workspace. This qualifies the teleoperation type to be redundant and limited-workspace teleoperation.

Experiments are conducted by using both customary and modified wave variable techniques. Communication loss for limited periods is considered in both experiments. The results indicate that the drifts due to failure conditions are compensated successfully without compromising the system stability by using the modified wave variable technique described in this paper.

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