Internet-Based Teleoperation Using Wave Variables and Correction of Position Error

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Abstract— **Teleoperation over Internet is an area that is more and more applied and it expands day by day. Reason for this is the great advantage of the Internet as a communication medium (distribution, easy access, low price and so on). However, the Internet as a communication medium has flaws which hinder the development of this area. These are primarily variable communication delay and data loss. This can cause loss of stability of teleoperation system. This problem can be resolved by using the wave variables. However, when wave variables and variable communication delay are used under such conditions, position error appears. An idea for solving this problem is using the correction of position error. A new way of resolving problem for the correction of position error is suggested in this paper by using wave variable proposed by Laurence Bate.**

Keywords— master; slave; teleoperation; Internet; correction of position error

I. INTRODUCTION

Teleoperation is a technique of controlling system from a remote location, which consists of master and slave system. Master system usually represents the model (copy) of the slave system which is controlled by operator. The slave system is usually dislocated to the master system and is controlled by commands sent from the master system through communication channel. During master-slave communication mode, due to existence of the communication delay caused by distance between master and slave systems, occurs a problem of ensuring the stability of teleoperation system [1]-[3].

One of the ways to resolve this problem is the use of wave transformation that provides passivity of system regardless of the communication delays in the system [4]-[7].

The Internet is often used as relatively inexpensive medium for transferring information between master and slave systems and it causes variable delay of information and loss of part of data. As a result of variable communication delays while using wave variables, position error also occurs, which is necessary to compensate by applying advanced control structures [1], [5].

This problem is solved by using the correction of position error. General solution to solve the problem of position error does not exist. Mostly, small correction of waves is used on the master side [1] and [8], or small correction of waves on slave side [9], which both does not jeopardize stability of the bilateral teleoperator. Besides these, there are other solutions for correction of the position error (for example eg. Yokokohji, Tsujioka and Yoshikawa (2002) [10].

To resolve problem of position error is proposed a new solution based on correction of waves on master side. The basic idea of this concept is that a small correction of wave that moves to the right and which will not endanger passivity of the communication system should be performed. Size of correction of position error directly depends of the difference in positions on the side of the master and on the side of the slave system. In that way, the control principle is applied which is based on the accumulated energy in the remote system. The main problem that arises when this solution is used, is the choice of parameters, which are used to adjust the correction of position errors on the side of the master system. Choosing the wrong parameters may violate the passivity of communication system, or in the second case the correction of position error does not resolve that problem. In order to obtain optimal results for any amount of the communication delay, the use of dynamic parameter, in the system of correcting position errors on the master system, is proposed, whereby the value of the dynamic parameter decreases with the increase of communication delay. In this way it is ensured that correction of position error does not violate passivity of the communication system, because with an increase of communication delay, the value of correction wave decreases. This is especially important during short interruptions of a few seconds, which are common in the

use of the Internet as a communication media and occur due to congestion of communication. In these cases, accurate monitoring of the position is less important than the stability of bilateral teleoperator with wave variables. If there is no correction of position error or if it is very small, passivity of communication system will be guaranteed by the use of wave variables. In normal working conditions, parameters are adjusted to obtain the optimum solution.

The accuracy of the proposed solution is confirmed by simulation and experimental analysis.

II. BILATERAL TELEOPERATOR WITH WAVE VARIABLES

Bilateral teleoperator is consisted of master and slave system which are connected by communication channel. Wave variables are used to solve the problem of stability bilateral teleoperator at the communication delay in a closed loop.

Wave variables ensure passivity of communication channel. If the remote system is stable and communication system is passive then the whole teleoperation system is stable [1], [5], [6]. Wave variables proposed by Laurence Bate 2010 [5] are suggested in this paper. Analytically they can be expressed as:

$$u_m(t) = \frac{b\dot{\theta}_m(t) + \tau_s(t - T_L)}{\sqrt{2b}}, \quad (1)$$

$$\tau_m(t) = b\dot{\theta}_m(t) + \tau_s(t - T_L), \quad (2)$$

$$\dot{\theta}_{sd}(t) = \dot{\theta}_m(t - T_R) + \frac{\tau_s}{b}(t - T_R - T_L) - \frac{\tau_s(t)}{b}, \quad (3)$$

$$v_s(t) = \frac{\tau_s(t)}{\sqrt{2b}}. \quad (4)$$

Where is:

- $\dot{\theta}_m, \dot{\theta}_{sd}$ velocities on the master and slave side system
- τ_m, τ_s torques on the master and slave side system r
- b characteristic impedance
- T_R, T_L communication delay right and left respectively

Equation (4) shows that the return wave v_s depends only of the torque τ_s, i.e. does not depends of the velocity $\dot{\theta}_{sd}$, which is a great advantage for these wave transformations.

Fig.1 reflects communication system with wave variables described in equations (1-4).
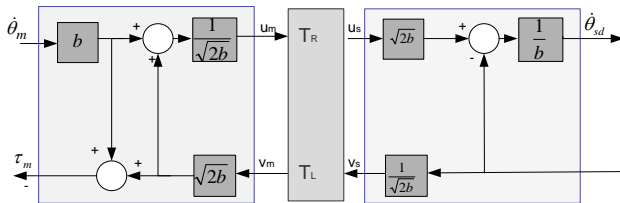

Figure 1. Block diagram of the communication system with wave variables

If described communication system consists wave variables applied on the bilateral teleoperator, then it will be bilateral teleoperator with wave variables shown in Fig. 2.
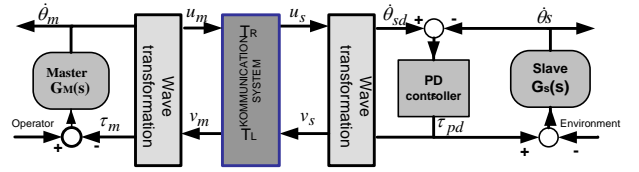

Figure 2. Block diagram of the bilateral teleoperator with wave variables

In the next pages, simulation analysis of work of this kind of teleoperator will be presented. Thereby, variable communication delay that occurs when the Internet is used as a communication medium, will be used. In these analyzes, the stability of bilateral teleoperator is not considered because it is insured by using wave variables [4] - [7].

In Fig. 3 are shown simulation results for the block diagram system which is given in Fig. 2.

The data used in the simulations are given in Table I.

TABLE I.
DATA FOR BILATERALTELEOPERATOR WITH WAVE VARIABLES

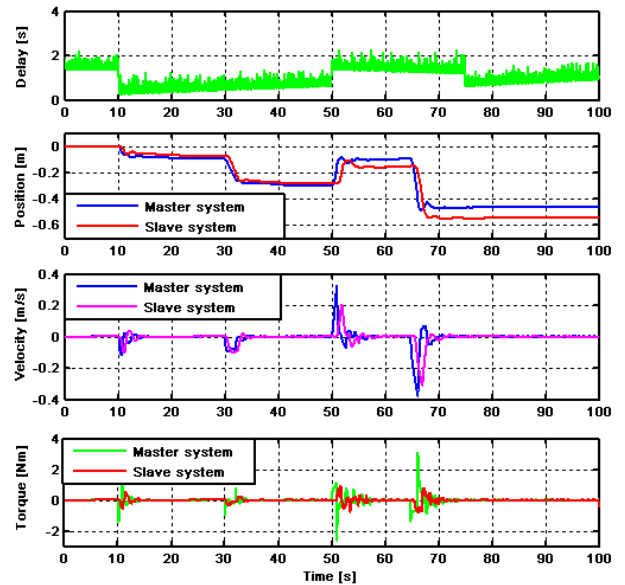| Parameter	Value
j_m	2 kg m^2
j_s	2 kg m^2
b_m	1 kg m/s
b_s	1 kg m/s
k_{pd}	50 kg m/s^2
b_{pd}	5 kg m/s
b	8
γ_l	1
δ_l	0.5
δ	0.05

Figure 3. Variable communication time delay, positions, velocities and torques at that delay

Based on Fig. 3, it can be concluded that although there is big and variable communication delay bilateral teleoperator with wave variables remains stable. If the variable wave is not used, bilateral teleoperator is unstable [1]. Also, it can be concluded that there is a difference between position on the side of master and slave system, although the velocities and torques fell to zero. Respectively, there is a position error. Without additional corrections of system, this problem can not be resolved.

III. BILATERAL TELEOPERATOR WITH WAVE VARIABLES AND CORRECTION OF POSITION ERROR

In this part of the paper, the correction of position errors on the side of master system is proposed. The starting point is monitoring of positions on the side of master and slave system at any time, but with the fact that position of a slave system is delayed for the value of communication delay T_L. Based on the difference position, it designs correction member that performs corrections wave which moves to the right. This is shown in Fig. 4.
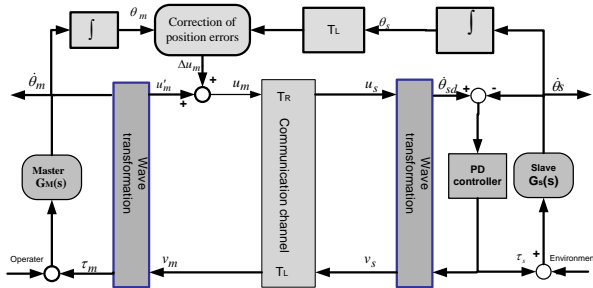

Figure 4. Block diagram of the bilateral teleoperator with wave variables and correction of position error

Due to limitations with the number of pages, here is only mentioned the final expression for the correction of position errors. In general, proposed correction of position errors must act to reduce position errors all the time.
Correction member is calculated as

$$\Delta u_m = -\gamma_1 e^{-\delta_1 T_T} \left(1 - e^{-\delta E_d(t)}\right) A_\omega d(t), \qquad (5)$$

Where:
- $\gamma_1, \delta_1, \delta$ positive constants and they are used to set the optimal performance of level for the correction of position error
- $E_d(t)$ reservoir of energy
- $d(t)$ difference between estimated and actual difference of position
- T_T total delay time in a closed loop
- $A_\omega = \frac{b}{\sqrt{2b}}$, b is characteristic impedance

After completion of the simulation with the bilateral teleoperator with wave variables and correction of position errors on the side of the master system, are obtained simulation results shown in Fig. 5. In this simulation, the values for the parameters in the block for correction of position errors, are given in Table 1.
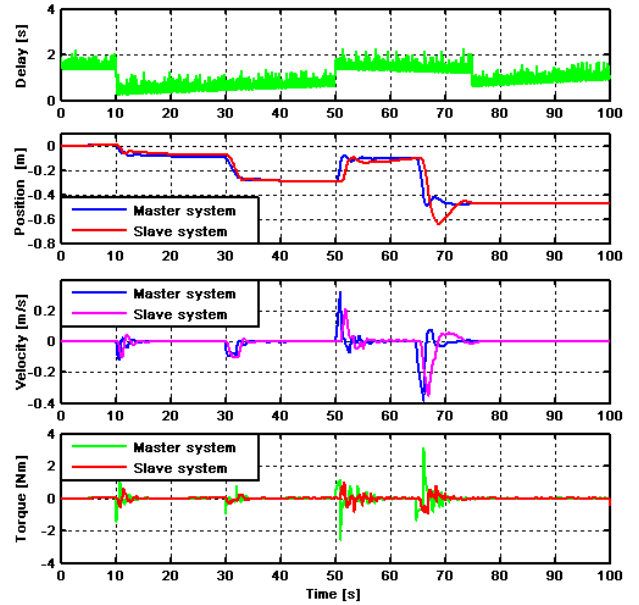

Figure 5. Variable communication time delay, positions, velocities and torques at that delay

Fig.5 shows that the proposed solution for the correction of position errors, on the side of a master system, solves the problem of positional error that occurs as a result of changing communication delays in a closed loop. In this case, described teleoperator is not loaded.

If slave system is loaded with a constant load at time $t = 20\ s$, the simulation results will be obtained for described teleoperator without correction of position errors which are shown in Fig. 6.
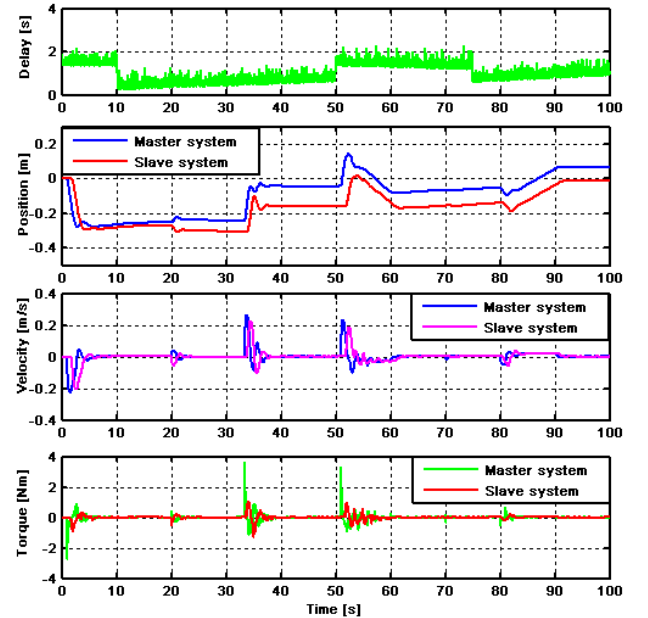

Figure 6. Variable communication time delay, positions, velocities and torques at that delay (constant load)

From Fig. 6 can be seen that the constant load on the slave system also causes position error. It is necessary to perform correction of position error to solve this problem. Now, it is

used the proposed correction of position errors on the side of a master system, at the same conditions.

Fig.7 shows the simulation results for described teleoperator with correction of position error on the side of a master system.
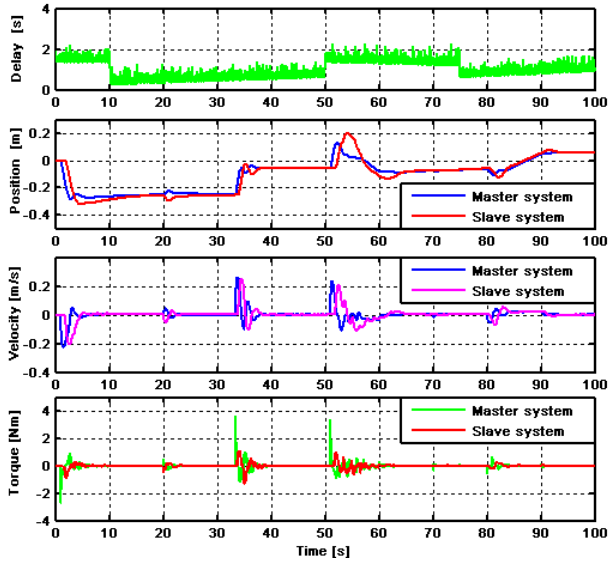

Figure 7. Variable communication time delay, positions, velocities and torques at that delay (constant load)

Fig. 7 shows that the correction of position error decreases and leads to zero position error that occurs as a result of constant load, which is applied to load the slave system at time $t = 20\ s$, and variable communication delay in a closed loop.

Now, the simulation analysis is presented for systems with more degrees of freedom. After the simulation with bilateral teleoperator with wave variables without correction of position error, there are simulation results shown in Fig. 8.
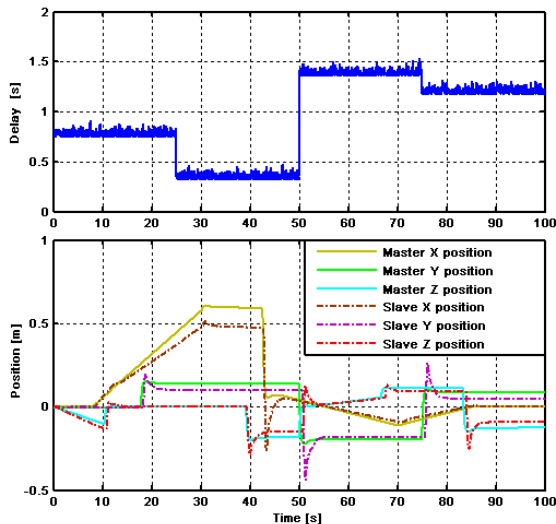

Figure 8. Variable communication time delay and positions at that delay

From Fig.8 can be seen that in this case occurs position error due to variable communication delay. If the proposed solution for the correction of position errors is applied, the results that will be obtained are shown in Fig. 9.
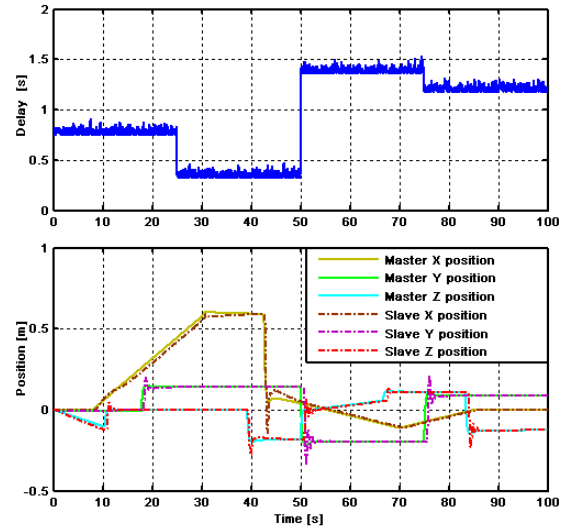

Figure 9. Variable communication time delay and positions at that delay

In Fig. 9 can be seen that now position error isn't occurring due to the influence of correction of position error. That means that the proposed solution works well in systems with more degrees of freedom too.

Based on the simulation analysis, it can be concluded that the proposed solution solves the problem of position error regardless of the source of its origin.

System which experimentally verified the presented solution to correct position error on the side of master system is described in the next pages of this paper.

IV. BILATERAL TELEOPERATOR WITH WAVE VARIABLES FOR EXPERIMENTAL VERIFICATION

Fig. 10 shows a block diagram of a bilateral teleoperator with wave variables which is used for experimental verification of the correctness of the presented solution.
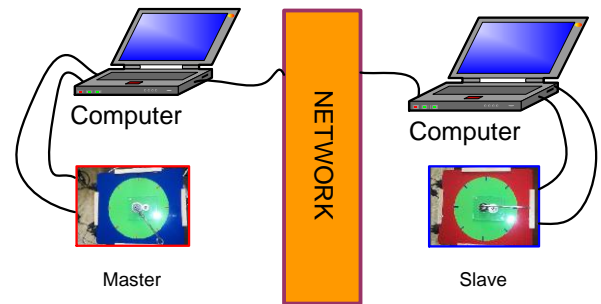

Fig. 10. Block diagram system for experimental verification

The bilateral teleoperator with wave variables is composed of master and slave system, two laptops and network. Real appearance of designed system for experimental verification is shown in Fig.11.

Fig. 11. Appearance of designed system for experimental verification

Designed bilateral teleoperator with wave variables is used four PIC microcontrollers 16F877A, two encoders to measure speed, two integrated circuits L298 to control DC motors, etc.

Programming, which is very demanding, is performed in the programming language Matlab. To work in real time, is used the Real-Time toolbox.

For communication between master and slave system that can be placed on any two geographically separated locations that have access to the Internet, is used UDP protocol.

It is also designed S-function which provides the information about the position of the master and slave system.

V. EXPERIMENTAL RESULTS

In this part of the paper, experimental verification of effect of the proposed solutions to correct position error on the master system is given. The experiments were performed in the global network Internet. Master and slave system had been located on geographically different locations (two towns in Bosnia and Herzegovina). With the intention to create more extreme conditions that may arise in such systems, it was also used additional virtual delay. If bilateral teleoperator works well in these conditions, it will work well in all other situations.

Fig. 12 shows the block diagram of the bilateral teleoperator with wave variables and proposed correction of position errors on the master side.
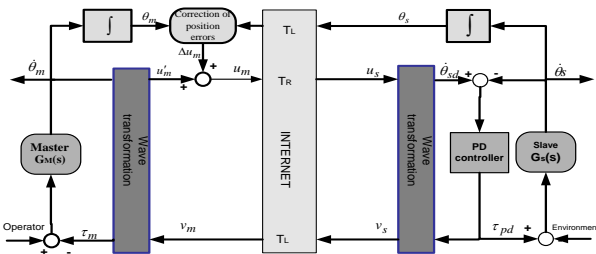

Fig. 12. Block diagram of the bilateral teleoperator with wave variables and correcting position error on the master side

In the first case, an experiment with bilateral teleoperator with wave variables without correction of position error is performed. The aim of this experiment is to show that position

error occurs at variable communication delay in a closed loop. The experimental results for this case are shown in Fig. 13.
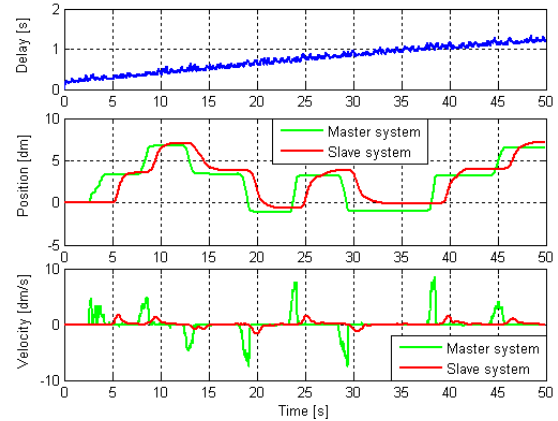

Figure 13. Variable communication time delay, positions and velocities at that delay

From Fig. 13 it can be seen that, as in the simulation, position error occurs as a result of variable delay in closed loop.

When the experiment is repeated, but with correction of position error on the side of the master system are obtained experimental results as shown in Fig. 14. The parameters of the system for correction of position error are the same as in simulations. In this case the bilateral teleoperator with wave variables is not loaded.
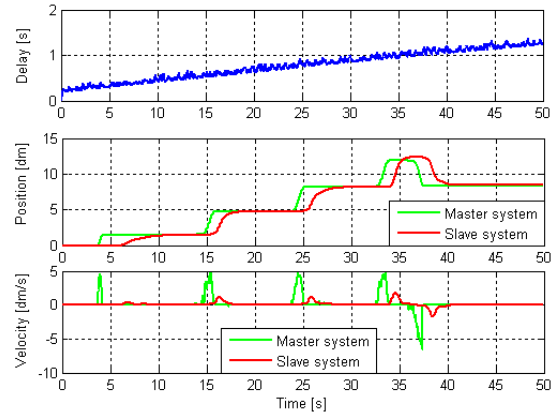

Figure 14. Variable communication time delay, positions and velocities at that delay

From Fig.14 it can be seen that at variable communication delay there is no position error. It means that slave system follows master system in the stationary state.

Based on the experimental analysis, it can be concluded that the presented solution for the correction of position error on the side of master system, solves the problem of position error caused by variable communication delay.

Another reason for the occurrence of position error is influence of various loads which act on slave system. For this experimental analysis, are used constant load and "solid wall" load on the slave system.

After the completion of the experiments are obtained experimental results shown in Fig. 15.
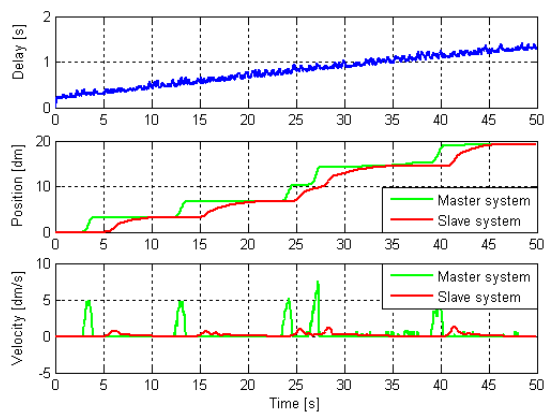
Figure 15. Variable communication time delay, positions and velocities at that delay (constant load)

From Fig. 15 it can be seen that the proposed solution for correction of position error on the side of master system works well and when there is constant load on the slave system.

Bilateral teleoperator with wave variables must remain stable and at the interacting of slave system with "solid wall" load (maximum load on the slave system). In this case the important thing is that stability of the mentioned teleoperator while the tracking position is not possible.

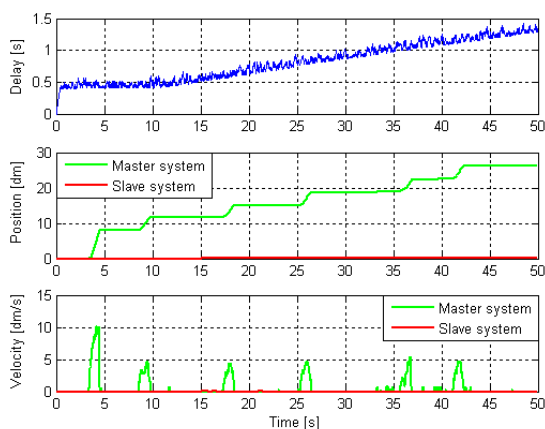In Fig. 16 are shown experimental results for this case.

Figure 16. Variable communication time delay, positions and velocities at that delay (solid wall)

The bilateral teleoperator with wave variables keeps stable even if the load on the slave system is "solid wall" (see Fig. 16)

Based on the experimental analysis, it can be concluded that the proposed solution for the position error on the side of master system solves the problem of position error.

VI. CONCLUSION

Based on the results of simulation and experimental analysis, the conclusion is that the variable communication delay always causes lower or higher position error when is used bilateral teleoperator with wave variables. To resolve this problem, it was proposed the use of new correction of position errors on the side of master system. Based on the simulation and experimental results, it can be concluded that the new solution

for the correction of position error works well and is resolving the problem of position error regardless of the its cause.

Similar results are obtained when other variables are used, and conclusion is that the proposed solution for the correction of position error can be applied to bilateral teleoperator with other wave variables.

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