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Passivity Based Control of Teleoperated Electric Vehicle

Moussa Boukhnifer [1], Ahmed Chaibet [2], and Cherif Larouci [3]

[1] Laboratoire Commande et Systemes, ESTACA, moussa.boukhnifer@estaca.fr
[2] Laboratoire Commande et Systemes, ESTACA, ahmed.chaibet@estaca.fr
[3] Laboratoire Commande et Systemes, ESTACA, cherif.larouci@estaca.fr

Abstract

In this paper, a bilateral controller of teleoperated electric vehicle system with time delay is presented using passivity approaches. We showed that the application of wave variable formalism allows the stability of the system in spite of the communication delays and scaling factors between the operator and the electric vehicle. Conditions of the passivity are given and the stability is proved for our teleoperation system. Finally, for demonstration we used the proposed architecture in real network environment.

Keywords

teleoperation, wave variable, electric vehicle, stability, passivity

1. INTRODUCTION

Teleoperated electric vehicle play an important role especially in hazardous environments such as inspecting underwater structures [Kim et al., 2002], demining [Lin and Kuo, 1997], and cleaning nuclear plants [Smith et al., 1992]. During the past twenty years, the majority of work in electric vehicle teleoperation has centered on rate-controlled systems for hazardous environments. In these systems, a trained operator controls the electric vehicle's rotation and translation rates via hand-controllers and receives feedback from video cameras. McGovern reported on work with a fleet of wheeled ground electric vehicles: small indoor robots to large outdoor military automobiles [McGovern, 1988]. More recently, electric vehicle teleoperation systems have emphasized the use of multi-modal operator interfaces and supervisory control [Bapna et al., 1998] [Cooper, 1998].

In the teleoperation system, the information flow between electric vehicle and the operator affects significatively the operator's dexterousness and efficiency. So the two major issues in teleoperated electric vehicle are stability robustness and transparency performances.

Only a few works analyze these subjects collectively. A large part of the literature on the teleoperation is so dedicated to the study of the stability. A first approach, developed by [Sename, 2006] consists in using the theory of robust control: H∞ synthesis. These methodologies require a linear model for the master and the slave. It allows to develop a closed loop system robust to a class of uncertainties as well as to specify a performance level. In this case, the delay is modeled as an inverse multiplicative uncertainty [Sename, 2006]. Nevertheless, these methods are limited to the case of constant delays without scaling factors that is rather restrictive.

In [Khan et al., 2011], the authors describe an adaptation scheme for the teleoperation of an electric vehicle. The performance variation due to the varying network and packet losses is investigated and catered for by using an adaptive gain scheduling as well as varying time delay load in the design framework. In this application the authors develop their method without any scaling factors.

The transparency and robust stability (passivity) are conflicting design goals in teleoperation systems via passivity approach. That is to say, it is impossible to make teleoperation system passive due to varying time-delays, scaling effects and uncertainties on environment. This paper was in part motivated by the fact that prior publications on the topic seem to be uniformly incorporate network-based concepts to address transparency, and passivity-based concepts to address stability, the former necessitating the latter. Many researchers have employed velocity, force or impedance information to propose a variety of transparency-optimized bilateral controllers. For the delay problem, the majority of the research adopts concepts of passivity to ensure stability in the presence of time-delay. Anderson and Spong [Anderson and Spong, 1989] derived a control law based on passivity and scattering theory to ensure teleoperation stability subject to any time delay, but performance was shown to degrade as the time-delay was increased. Niemeyer and Slotine [Niemeyer and slotine, 1992] also proposed an approach based on passivity and scattering theory to address time-delay in teleoperation. The authors additionally present prediction techniques that further improve the system's performance under time-delay. Lawrence [Lawrence, 1993] addressed time delay in four-channel bilateral telemanipulation. Using passivity theory, filters were derived that ensured the stability. Yoshikawa and Ueda [Yoshikawa and Ueda, 1996] used scattering theory to assess the stability of four conventional teleoperation architectures subject to time delay.

In the presence of a multi-objective problem, i.e., time- delay and force scaling the presented passivity concepts, are too conservative, and as such, compromise system performance (i.e., transparency) more than necessary. In order to solve the conflicting design goals of transparency and stability (passivity) in teleoperation systems via passivity approach, this paper proposes a new wave-based controller which can satisfy passivity condition for optimized-stability

The paper is organized in the following way. In Section 2, the wave-based controller architecture subjected to time-delays and scaling factors is presented. Then, Section 3 derives conditions about the passivity and stability for teleoperation system. Finally, Section 5 presents experimental results to prove the effectiveness of the proposed approach.

2. PASSIVITY APPROACH

In this section, we will discuss the passivity analysis of the proposed teleoperated electric vehicle given in the Figure 1. Our system consists of three parts, that is, human operator, a bilateral controller and the electric vehicle as you can see in the Figure 2.

2.1 Wave-based bilateral controller

Figure 1 shows the scheme of teleoperation system which is constituted by a haptic interface $P_m(s)$ (master) to which a human operator applies a force F_h and a electric vehicle $P_s(s)$ (slave), interacting with the environment via a force F_e. Using this platform we can simulate the motion of the electric vehicle and give motion sensation to the operator. This increases the level of immersion of the operator in the remote scenario. The architecture of control can be represented by Figure 2 where e^{-T1}, e^{-T2} represent the time delays and k_p, k_f are the scaling factors for the position and the force respectively. The interaction force with the environment F_e is sent back to the operator as a reference for the haptic interface such that $F_m = k_f F_e$. This architecture can be used for teleoperation of different kind of ROVs, from a one to one scale electric electric vehicle to a small sized ROV. It is used in combination with classical teleoperation human machine interfaces with video, audio and force feedback.

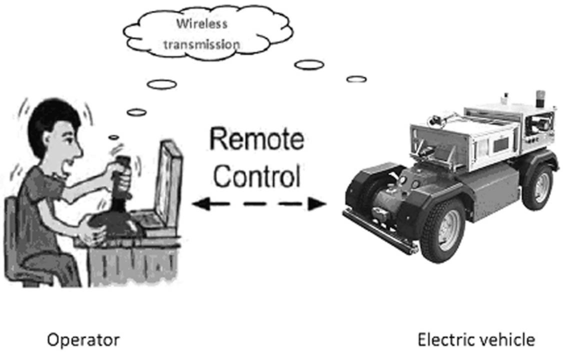


Fig. 1 Teleported electric vehicle system

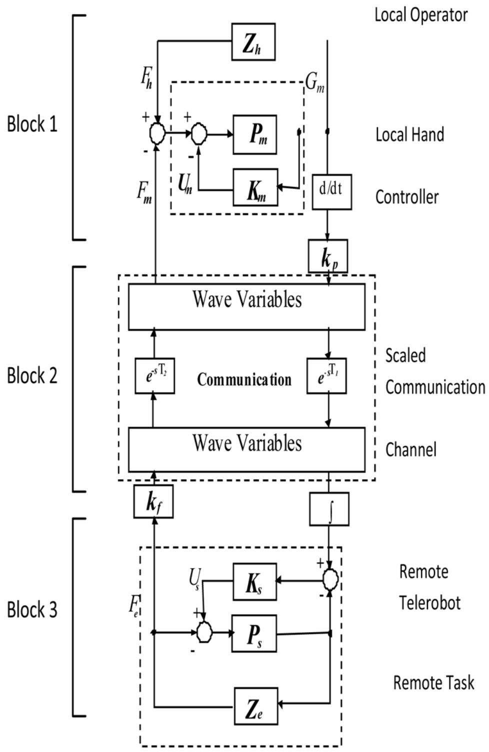


Fig. 2 Bilateral architecture control

The transfer functions of master $P_m(s)$ and slave $P_s(s)$ are given by the following equations [Sename, 2006]:

$$P_m(s) = \frac{1}{m_m s^2 + k_m s + b_m} \qquad P_s(s) = \frac{1}{m_s s^2 + k_s s + b_s} \qquad (1)$$

where m_m, m_s are respectively the mass of the master and slave; k_m, k_s are damping coefficients and b_m, b_s are spring coefficients. The bilateral architecture of Figure 2 can be viewed as the connection of three parallel blocks G_m, G_s and K. It is assumed that the blocks G_m G_s are passive; these blocks define respectively the master with its local force feedback controller and the slave, its local controller K_s and the passive environment Z_e. In order to prove the passivity of the overall system, it is required to prove the passivity of the communication block K with respect time-delay (T_1,

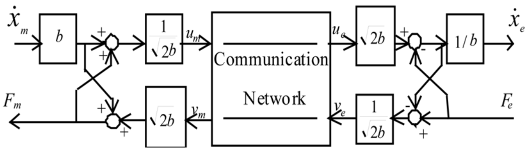


Fig. 3 Wave transformation using as inputs x_m and F_e

T_2) and scaling effects (k_p, k_f). By using the concept of wave variables [Niemeyer, 1997] and definition of dissipativity [Niemeyer, 1996], it can be shown that the following structure of Figure 3 is passive. First, let us define the power entering in the system of communication as:

$$P_{in} = \dot{x}_m^T F_m - \dot{x}_e^T F_e \tag{2}$$

where x_m and x_e are respectively the velocities of the haptic interface and the electric vehicle. The wave's variables ($u_{m,e}$; $v_{m,e}$) are defined as follows:

$$\begin{cases} u_m = \dfrac{b\dot{x}_m + F_m}{\sqrt{2b}} & u_e = \dfrac{b\dot{x}_e + F_e}{\sqrt{2b}} \\ v_m = \dfrac{b\dot{x}_m - F_m}{\sqrt{2b}} & v_e = \dfrac{b\dot{x}_e - F_e}{\sqrt{2b}} \end{cases} \tag{3}$$

Though the strictly parameter b can be chosen arbitrarily, it defines a characteristic impedance associated with the wave variables and directly affects the system behavior. Proper choice of this impedance is thus critical for achieving an acceptable response. The power transfer can also be rewritten as follows:

$$\begin{aligned} P_{in} &= \dot{x}_m^T F_m - \dot{x}_e^T F_e \\ &= \frac{1}{2}(u_m^T u_m - v_m^T v_m + v_e^T v_e - u_e^T u_e) \end{aligned} \tag{4}$$

From (4), the controlled telemanipulator part that consists of the master manipulator and the slave manipulator is passive against the human operator and the environment.

2.2 Passivity of master part

In general, when the operator carries out a task by using a teleoperation system, we assume that the operator does not make the whole system unstable on purpose, and in addition, the operator is passive against an external input [Murakami et al., 2004]. It follows that the master hand controller with its local force feedback *PI* controller (namely, $K_m = B_{m1} + \frac{K_{m1}}{S}$) is passive against the human operator when force feedback controller values are chosen adequately in order to passivate the human-master dynamics.

2.3 Passivity of controller part

As mentioned previously in [Boukhnifer and Fereira, 2005], the motion and force scaling had been considered to violate the passivity condition. In order to prove the passivity of the proposed scaled teleoperation system with scaling factors k_p and k_f, we will rewrite the constraints in the waves space and derive conditions between the parameters. The scaling factors represented by the gains k_p and k_f:

$$\begin{cases} \dot{x}_e = k_p \dot{x}_m \\ F_m = k_f F_e \end{cases} \tag{5}$$

As each system is expressed in the power variables ($\dot{x}$, F), it can be written in terms of the wave variables (u, v) which are useful to convert dimensional scaling factors from one domain to another. Let us consider the following bilateral controller expressed in the waves space (Figure 4) where A, B, C, D are the transfer of the scaling factors k_p and k_f in the wave domain in presence of the delays T. According to the equivalent diagram of Fig.4, the scaling factors can be expressed as follows:

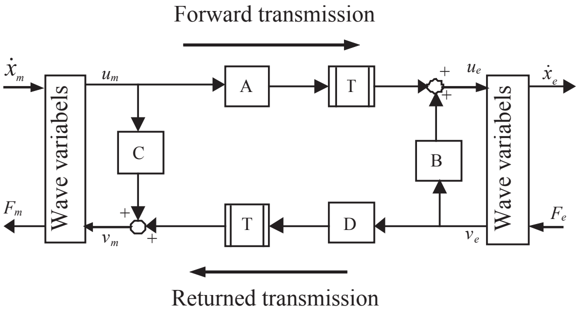


Fig. 4 Equivalent diagram in wave domain of the position and the force scaling factors

$$\begin{pmatrix} u_e \\ v_m \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \cdot \begin{pmatrix} u_m \\ v_e \end{pmatrix} \tag{6}$$

or

$$\begin{cases} u_e = Au_m + Bv_e \\ v_m = Cu_m + Dv_e \end{cases} \tag{7}$$

From the equation (3) and (5), the transformation matrix in the wave variables domain is expressed as:

$$\begin{aligned} u_e &= \frac{2k_p}{(1+k_p k_f)} u_m + \frac{k_p k_f - 1}{k_p k_f + 1} v_e \\ v_m &= \frac{1 - k_p k_f}{1 + k_p k_f} u_m + \frac{2k_f}{1 + k_p k_f} v_e \end{aligned} \tag{8}$$

By identifying (7) and (8), we obtain the following forms:

$$A=\frac{2k_p}{(1+k_pk_f)}\ ,\quad B=\frac{k_pk_f-1}{(1+k_pk_f)}$$
$$C=\frac{1-k_pk_f}{(1+k_pk_f)}\ ,\quad D=\frac{2k_f}{(1+k_pk_f)} \tag{9}$$

As the delay time T is assumed constant, the system is passive with the interconnections A, B, C and D, if and only if, the following three conditions are satisfied [Niemeyer, 1996]:

$$\begin{cases}|A|^2+|C|^2\leq 1\\ |B|^2+|D|^2\leq 1\\ |A|^2+|C|^2+|B|^2+|D|^2\leq 1+\left(|AD|-|BC|\right)^2\end{cases} \tag{10}$$

The teleoperation system preserves its passivity, if and only if the scaling factors are equal ($k_p = k_f$) and When considering different scaling factors($k_p \neq k_f$), the interconnections A, B, C and D should be redefined with respect to the manipulator-environment interaction at the scale. In order to ensure the passivity of our system in presence of time-delays, we introduced the impedance filters $G(s)$ and $F(s)$ after each delay block. According to the Niemeyer conditions, the system is passive, if and only if, the following three conditions are satisfied [Boukhnifer, 2005]:

$$\begin{cases}|F|^2\leq\dfrac{k_f}{k_p}\\ |G|^2\leq\dfrac{k_p}{k_f}\\ (k_pk_f+1)^2(k_p|F|-k_f\cdot|G|)^2-(2k_pk_f)^2(|G\cdot F|-1)^2\leq 0\end{cases} \tag{11}$$

3. STABILITY

In this section we extend the results of the previous sections to establish Lyapunov stability of the teleoperation system. Appropriately selected filters are chosen in order to ensure the passivity of the communication channel with scaling factors (block2). Furthermore, the human operator and the environment are modeled as passive systems. So the block 1 and the block 3 are passives.

The master and the slave dynamics are given by:

$$\begin{aligned}&M_m\ddot{x}_m+B_m\dot{x}_m+K_mx_m=F_h-F_m-U_m\\ &M_s\ddot{x}_s+B_s\dot{x}_s+K_sx_s=U_s-F_e\end{aligned} \tag{12}$$

Define a positive definite Lyapunov function for the system as

$$\begin{aligned}V=&\frac{1}{2}\left\{M_m\dot{x}_m{}^2+K_{m1}x_m^2\right\}+\int F_e\,\dot{x}_{sd}dt-\int F_h\,\dot{x}_mdt\\ &+\int(F_m\dot{x}_m-F_e\dot{x}_{sd})dt\end{aligned} \tag{13}$$

The human operator is passive. Hence

$$-\int F_h\,\dot{x}_mdt\geq 0 \tag{14}$$

The communications are passive with the filter (from the equation (11))

$$\int(F_m\dot{x}_m-F_e\dot{x}_{sd})\,dt\geq 0 \tag{15}$$

As the block 3 slave with environment is passive.

$$\int F_e\dot{x}_{sd}\geq 0 \tag{16}$$

Thus the candidate Lyapunov function is positive definite. Then its derivative is given by [Boukhnifer, 2011]:

$$\begin{aligned}\dot{V}&=M_m\dot{x}_m\ddot{x}_m+K_{m1}x_m\dot{x}_m+F_e\dot{x}_{sd}-F_h\dot{x}_m+F_m\dot{x}_m-F_e\dot{x}_{sd}\\ &=(F_h-F_m-U_m-B_m\dot{x}_m-K_mx_m)\dot{x}_m+K_{m1}x_m\dot{x}_m-F_h\dot{x}_m+F_m\dot{x}_m\\ &=-U_m\dot{x}_m-B_m\dot{x}_m^2-K_mx_m\dot{x}+K_{m1}x_m\dot{x}_m\\ &=-(K_{m1}x_m+B_{m1}\dot{x}_m)\dot{x}_m-B_m\dot{x}_m^2-K_mx_m\dot{x}+K_{m1}x_m\dot{x}_m\\ &=-B_{m1}\dot{x}_m^2-B_m\dot{x}_m^2-x_m\dot{x}(K_m-K_{m1})\end{aligned} \tag{17}$$

The derivative of the Lypunov is negative, if and only if, ($k_m - k_{m1}$) , so we take the integrator coefficient of the master *PI* controller equal to the damping coefficients of the master ($k_{m1} = k_m$). So:

$$\dot{V}=-B_{m1}\dot{x}_m^2-B_m\dot{x}_m^2\leq 0 \tag{18}$$

As the derivative of the Lyapunov function is negative, the system is stable in the sense of Lyapunov. Then the whole system is stable in view of passivity.

4. SIMULATION AND EXPERIMENTAL RESULTS

As mentioned before, the time-delay and motion and force scaling had been considered to violate the passivity condition. At first, we are going to show that the proposed controller does not violate the total stability of the system for a human operator and a passive environment.

To illustrate the behavior of the teleoperation system and to confirm the findings of the previous section, the parameters of simulation have been determined experimentally such as [Sename, 2006].

$$\begin{aligned} &M_s = 0.04 \quad K_s = 25.2 \quad B_s = 2 \\ &M_m = 0.03 \quad K_m = 1 \quad\;\; B_m = 0.277 \end{aligned} \tag{19}$$

with a nominal environment impedance:

$$\begin{aligned} &Z_e = B_e s + K_e \\ &B_e = 0.5, \quad K_e = 0.1 \end{aligned} \tag{20}$$

Then, we analyze the passivity of the scaled communication channel. Different filter transfer functions, namely $F(s)$ and $G(s)$ with the symbolic form $\lambda_i / s + \lambda_j$ are inserted in the forward and reverse communication line in order to preserve the passivity of the bilateral controller against variations of position and force scaling factors. These filters are chosen to respect the inequality conditions of (11). In the given environment Z_e, the operator can choose the couple of scaling parameters (k_p, k_f) in order to ensure a better control and good feeling of the position and force electric vehicle. For each scaling factors, we must choose a filter function to preserve the passivity. To solve this problem, the scaling parameters are chosen experimentally such as $k_p = 1.5$ and $k_f = 2.5$. With the proposed wave-based controller, we made a suitable choice of the channel interconnections $A = \frac{2k_p}{(1+k_p k_f)}$, $B = \frac{k_p k_f - 1}{(1+k_p k_f)}$, $C = \frac{1-k_p k_f}{(1+k_p k_f)}$, $D = \frac{2k_f}{(1+k_p k_f)}$ for similar scaling factors k_p and k_f. In order to ensure the passivity conditions (13) of our system, we choose the following filter functions $F(s) = \frac{10}{s+10}$ and $G(s) = \frac{10}{s+10}$.

To demonstrate the effectiveness of the proposed method in the experimental, we use Easy Java Simulations (EJS), this software tool design how to create an interactive simulation in java and turn existing models created with Simulink [Dormido et al., 2005]. For this, we connect variables in the EJS model to variables in the Simulink model using an easy to use, very natural interface as shown in Figure 5.

For the teleoperated electric vehicle system, we use a real network environments and the EJS takes than care of all technical tasks required to ensure a perfect synchronization between both tools and the existing Simulink architecture benefits of the extended graphic capabilities for a more realistic visualization as shown in Figure 6.

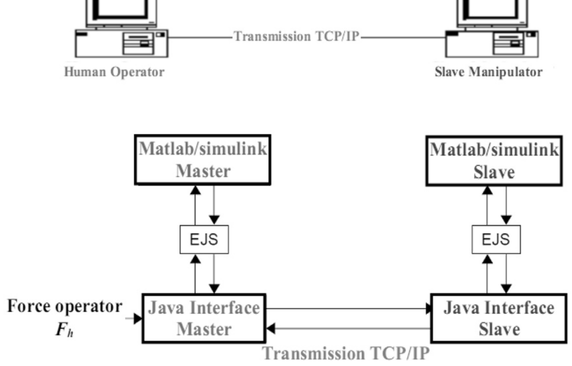
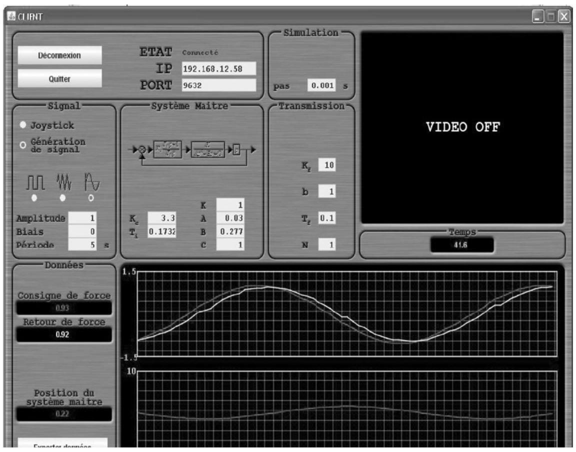


Fig. 5 Architecture of teleoperated electric vehicle developed with EJS, JAVA and Simulink



ETAT Connecté
IP 192.168.12.58
PORT 9632
pas 0.001 s
Amplitude 1
Biais 0
Période 5 s
K_c 3.3
T_i 0.1732
K 1
A 0.03
B 0.277
C 1
K_f 10
b 1
T_f 0.1
N 1
Temps 41.6
Consigne de force 0.93
Retour de force 0.92
Position du système maitre 0.22

Fig. 6 Interface environment developed with EJS, JAVA and Simulink

To demonstrate the system performance under the real network environment, we use the architecture as shown in the Figure 5. In this architecture, the operator sends the human force f_h, in our case the operator apply a sinusoidal force to the master and the master sends a sinusoidal trajectory x_m to the slave with local network of ESTACA (Laboratoire Commande et Systèmes) via TCP/IP transmission, the electric vehicle follows the reference $x_m(t\text{-}T)$ and the environment

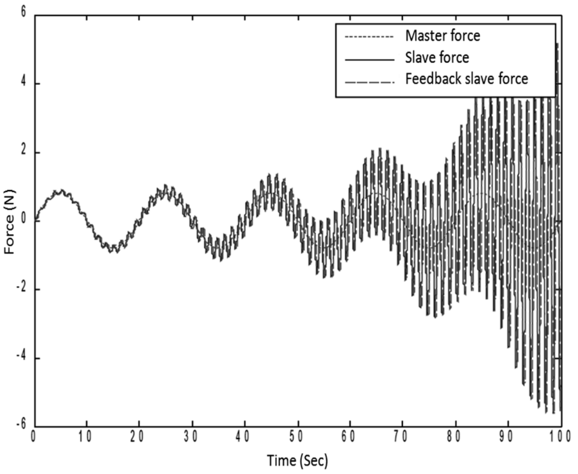


Fig. 7 Simulation results without bilateral controller in constrained motion and time delay $T = 0.2$ sec

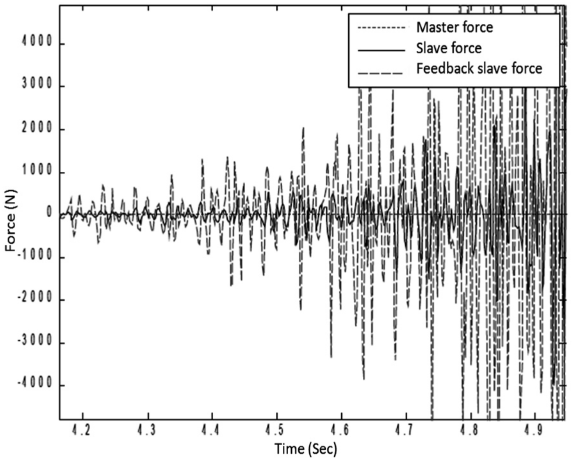


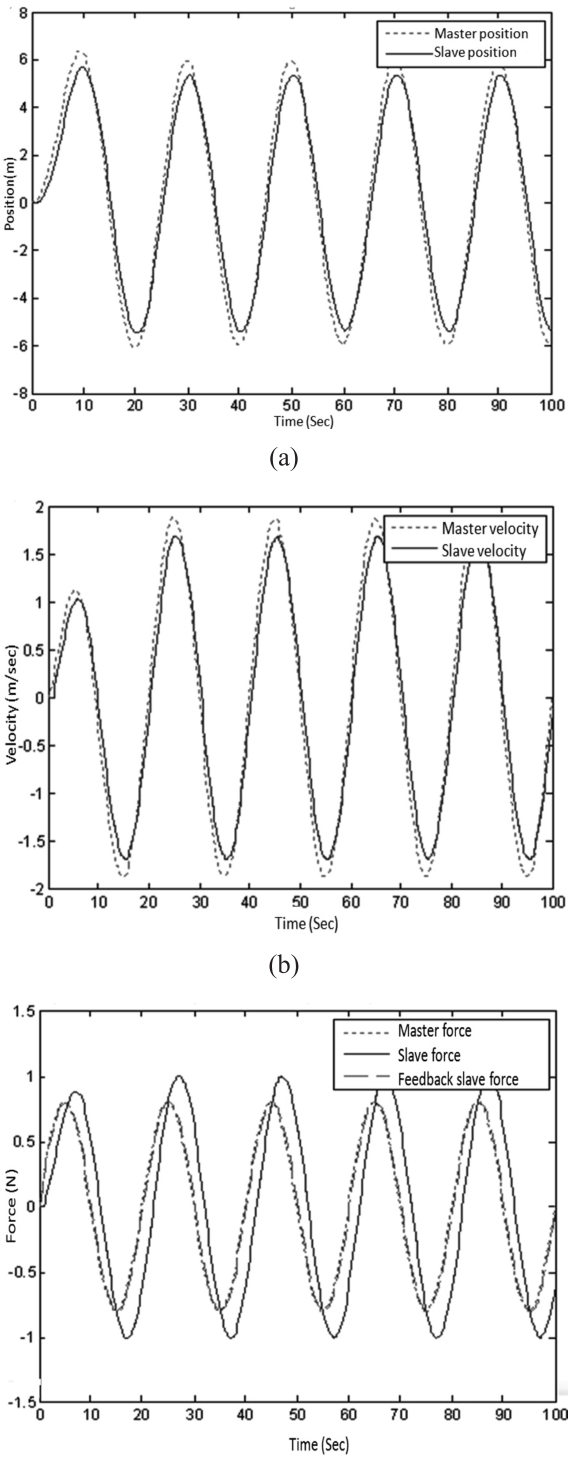
Fig. 8 Simulation results without bilateral controller in constrained motion and different scaling factors ($K_p \neq K_f$)

sends the force contact f_e to the operator via TCP/IP. To emphasize the delay problem over the internet and the scaling problem, Figure 7 and Figure 8 demonstrate the influence of theses parameters on the passivity (stability) of the tele-operated electric vehicle system without the wave variable bilateral controller. If not dealt with, the delay and the scaling factors might cause instabilities.

In the first, we test the bilateral control of the Figure 4 in the simulations with delay Simulink blocks, the simulations results of Figure 9 (a)-(c) show clearly a better tracking of position, velocity and force variables with significant constant time-delay of 1 sec and k_p = 1.5 and k_f = 2.5. So we can say that the bilateral controller ensures the stability with a good transparency force/velocity.

In the second, we test our bilateral control with a real network. For this, we use the architecture of the Figure 5 with local network of ESTACA (Laboratoire Commande et Systèmes), For the master, we have used a joystick but for the slave we have used a Matlab/Simulink model defined by the equation (1), the communication between the both sites is ensured via TCP/IP transmission (see Figure 5).

For the experimental results, the master and slave position, velocity and force tracking profiles are illustrated in Figures 10(a)-(c) in presence of the environment $Z_e = B_e s + K_e$ for scaling factors k_p = 1.5 and k_f = 2.5 and a local network time-delay. The results show the good transparency results without introducing instabilities. Notice that same results are obtained for all set of values (k_p, k_f) satisfying the passivity condition of the equation 11 with the adequate choice of the filter $F(s)$ and $G(s)$. Outside the passivity domain, the slave system experiences a lot of oscillations leading to instabilities of master interface.

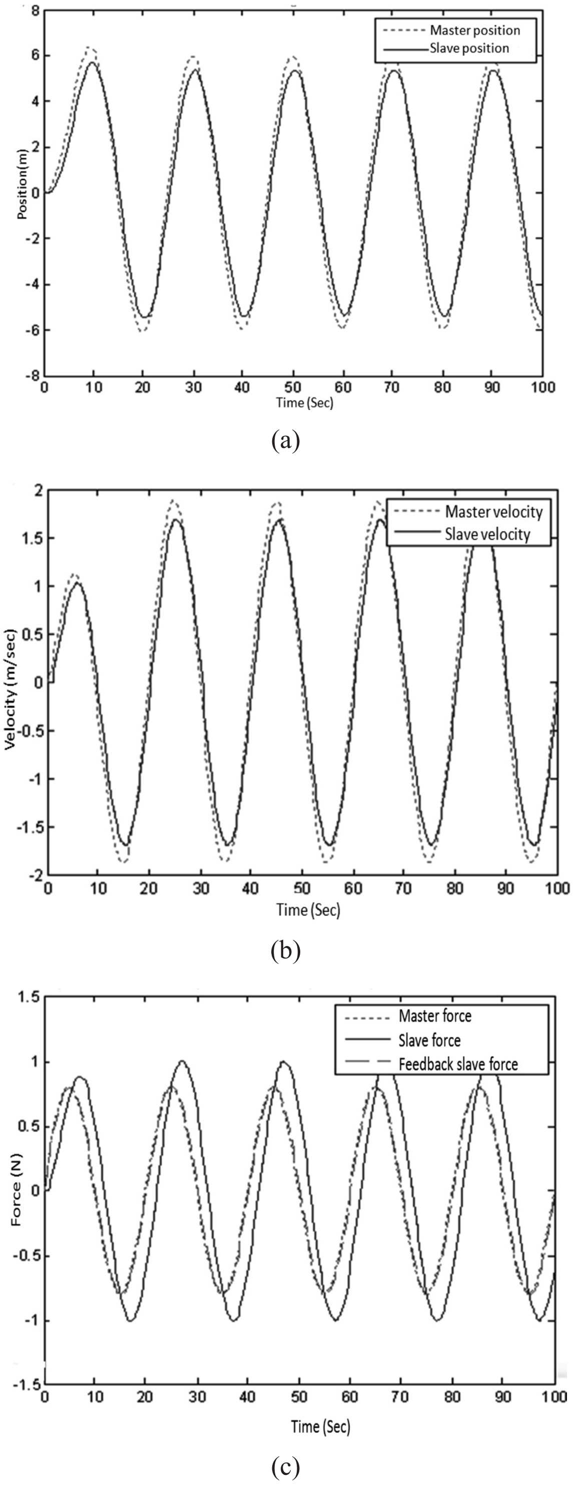


(c)

Fig. 9 Simulation results: (a) position, (b) velocity and (c) force tracking with 1 sec time-delay. Continue line (slave), broken lines (master)

5. CONCLUSION

In this paper, we have proposed the design of a bilateral controller for teleoperation electric vehicle under



(a)

(b)

(c)

Fig. 10 Simulation results: (a) position, (b) velocity and (c) force tracking with 1 sec time-delay. Continue line (slave), broken line (master)

a constant time delay and different scaling factors ($K_p \neq K_f$). This controller ensures the passivity and the stability of the teleoperation system and takes into account the communication delays as well as the scaling factors. To take into consideration the effects due to the delay and the scaling factors, we used a structure of impedance filtering in order to reflect energy excess in the communication lines. Then, we derived analytical passivity conditions to make the system of the teleoperated electric vehicle stable in view of passivity. The total stability of the system was guaranteed for a human operator and a passive environment with uncertain dynamic variations based on the passivity. The simulation results under a real network environment showed a good result when considering a constant time-delays with a different scaling factor in terms of stability and transparency.

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