Teleoperation of a Robot Using a Haptic Device with Different Kinematics

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Abstract. This paper presents a bilateral control method by state convergence for teleoperation systems where the master and slave robots do not necessarily have homothetic kinematics. This method uses a virtual robot to relate the kinematics of the master and slave robots. An application of this type of control is also presented in which a robot of three degrees of freedom is teleoperated by using a commercial haptic device with six degrees of freedom.

Keywords: Haptic,Telerobotic, robot control, robotic manipulators.

1 Introduction

The telerobotic systems allow human operators to properly interact with a telerobot (slave robot) to telemanipulate objects located in a remote environment [1]. The device that the human operator touches and moves is a master robot. The slave robot should follow the movements of the master robot with high fidelity and fast. When the slave robot is in contact with the environment the interaction forces have to be reflected to the human operator through the master robot, with the purpose to improve and facilitate the development of the task [4].

Now, the algorithms of bilateral control by state convergence permit the teleoperation of the slave robots by using haptic devices (Masters) with homothetic kinematics, this is due to the fact that each couple of joints (master joint - slave joint) is controlled separately [3]. This paper presents a method that permits the implementation of teleoperation systems by state convergence where the masters and slaves have different kinematics. It is possible because the control relates the end effectors of the master and the slave and not each their joints. An application of this type of control is also presented in which a robot of three degrees of freedom (DOF) is teleoperated by using a commercial haptic device (Phantom) with six DOF.

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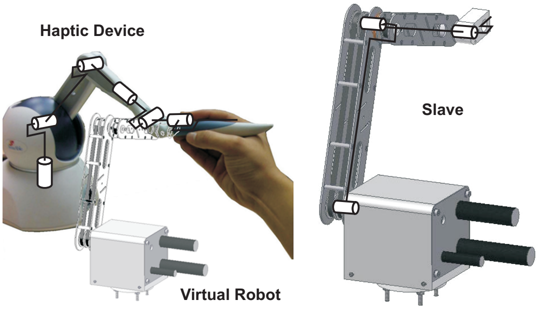


Fig. 1. Master-slave with different kinematics and relations between the virtual robot and the haptic device

2 Relation between the Haptic Device and the Slave Manipulator

This bilateral control method by state convergence is an uncoupled control, hence a direct relation between each master and slave joint exists. Figure 1 shows the different kinematics between the master and the slave in the proposed teleoperation system. The haptic device has six DOF and the slave has three DOF. Due to the different kinematics between the two robots, it is necessary make a relation between them, so the bilateral control systems by state convergence can be applied.

2.1 A Virtual Robot with a Similar Kinematics with the Slave Robot

With the purpose to establish a kinematics relation between the master and the slave manipulators, a virtual robot is created which has similar kinematics and dynamics to the slave manipulator and whose joint coordinates depend on the position and orientation of the haptic device end effector. With these guidelines it is possible to create a bilateral control by state convergence, where each joint of the slave manipulator follows the equivalent joint on a virtual robot. The figure 1 shows the relations between the virtual robot and the haptic device where their end effectors tend to fit in position and orientation.

2.2 Interaction Forces with the Master

With the goal of having the end effectors of the haptic device and the virtual robot corresponding at all times it is necessary to create additional forces that restrict the haptics device movements into the workspace of the virtual robot. As the slave robot has three DOF and their joint axis are parallel the virtual robot workspace is within a plane, hence the haptic device should restrict the human operator to the workspace of the slave robot. By using the scale and the dimensions between the virtual and slave robots it is possible to create the constraints and mark the boundaries of the workspace in the mentioned plane. It is also was necessary to take into account that the virtual robot workspace varies according to the orientation of the end effector.

Theses constraints for the teleopteration depend on the robots geometry, however other restrictions also exist that depend on the robots dynamics. A particular case exists where the human operator cannot move the haptic device faster than the maximum velocity of the slave robot, this is to avoid a large position error between the virtual robot end effector and the haptic device end effector. For this propose additional forces are created that are proportional to the position error between the master and the virtual robot, this limits the haptics device movements to the establish dynamics of the virtual robot. It should be noted that if the human operator moves the haptic device according to the capacities of the slave dynamics the forces tend to be null.

3 Teleoperation System Model

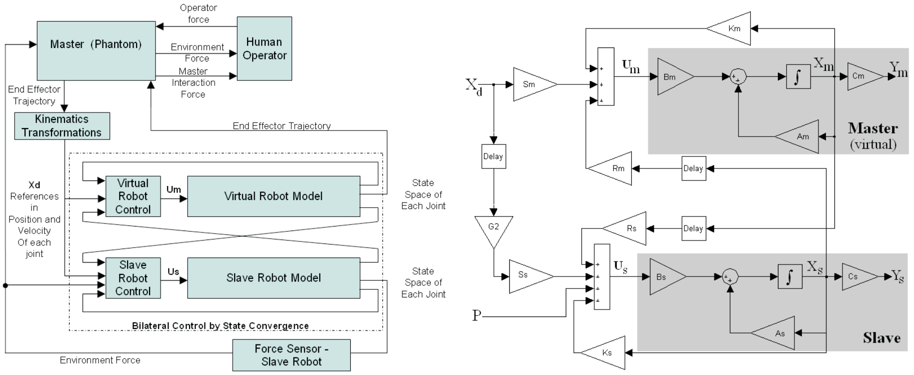
The figure 2(a) shows a teleoperation system diagram where the human operator interacts with a haptic device. It reflects the environment force and the interation between the operator and master robot. The human operator applies a force over the haptic device in order to obtain a desired position and orientation. The position and velocity of the haptic device end effector can represent the references in position and velocity of each virtual robot joint through kinematic transformations. With theses references it is possible to design a bilateral control by state convergence, in which the slave robot follows the virtual robot.

The slave manipulator has a force sensor over the end effector which measures the environment interaction force, which is then reflected to the human operator through the haptic device. The human operator is limited to the virtual robot workspace by the calculation of the master interaction forces, this is the case when the slave robot cannot make the unrealized trajectory due to the electromechanical settings, these forces are also reflected to the human operator through the use of the haptic device.

4 Bilateral Control by State Convergence Based in Position and Velocity References

The method presented in [2] has the characteristic that the input to the control system is the force executed by the human operator. As the haptic device does not have force sensors it is necessary to modify the input of the control system. The proposed master control law is: The torque in each joint is proportional to the error between the master state vector (virtual robot) and the references $\tilde{x}_m \in R^{n\times 1}$ and is also proportional to error between the slave and the master state vector $\tilde{x}_b \in R^{n\times 1}$. The slave control is developed in a similar way as shown in the equations (1)

$$u_m(t) = S_m\tilde{x}_m(t) + R_m\tilde{x}_b(t); \qquad u_s(t) = S_s\tilde{x}_s(t) - R_s\tilde{x}_b(t) \tag{1}$$



(a) Teleoperation system diagram (b) Bilateral control by state convergence

Fig. 2. Teleoperation system model

Where the error between the master-slave states and between the slave state and references can be expressed as follows:

$$\tilde{x}_m(t) = x_d(t) - x_m(t); \qquad \tilde{x}_s(t) = G_2 x_d(t) - x_s(t); \qquad \tilde{x}_b(t) = x_s(t) - x_m(t) \quad (2)$$

Where:

- $x_d(t) \in R^{n\times 1}$ is reference for each joint which is calculated from end effector haptic device
- $x_m(t) \in R^{n\times 1}$ is the master joint state (virtual robot joint state)
- $x_s(t) \in R^{n\times 1}$ is the slave joint state
- $G_2 \in R^{n\times n}$ is an auxiliar matrix of gains which allows use of different inertial and friction parameters between the virtual robot and the slave robot.

The figure 2(b) shows a bilateral control model by state convergence for each master-slave joint couple, where:

- $A_m, A_s \in R^{n\times n}$, $B_m, B_s \in R^{n\times 1}$ y $C_m, C_s \in R^{1\times n}$ are the master (Virtual Robot) and slave systems in state space.
- $S_m = [S_{m1},\ S_{m2}, \ldots S_{mn}]$, $S_s = [S_{s1},\ S_{s2}, \ldots S_{sn}]$, $R_m = [R_{m1},\ R_{m2}, \ldots R_{mn}]$, $R_s = [R_{s1},\ R_{s2}, \ldots R_{sn}]$, $K_m = [K_{m1},\ K_{m2}, \ldots K_{mn}]$ y $K_s = [K_{s1},\ K_{s2}, \ldots K_{sn}]$ are the control gains

With the control law in (1) the gains K_m y K_s of the bilateral teleoperation system model as seen in figure 2(b) can be expressed as (3). The input P of the model is the perturbation produced by the differentia between the measured environment force and the real environment force.

$$K_m = -S_m - R_m; \qquad K_s = -S_s - R_s \quad (3)$$

Therefore, the state equations of the teleoperation system are:

$$\begin{bmatrix} \dot{x}_s(t) \\ \dot{x}_m(t) \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} x_s(t) \\ x_m(t) \end{bmatrix} + \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} \begin{bmatrix} x_d(t) \\ x_d(t) \end{bmatrix} \quad (4)$$

Where:

$$A_{11} = A_s + B_s K_s \qquad A_{12} = B_s R_s \qquad A_{21} = B_m R_m$$
$$A_{22} = A_m + B_m K_m \qquad B_1 = B_s S_s G_2 \qquad B_2 = B_m S_m$$

If a linear transformation is applied, the state equation could be expressed as:

$$\begin{bmatrix} \dot{x}_s(t) \\ \dot{x}_s(t) - \dot{x}_m(t) \end{bmatrix} = \begin{bmatrix} \tilde{A}_{11} & \tilde{A}_{12} \\ \tilde{A}_{21} & \tilde{A}_{22} \end{bmatrix} \begin{bmatrix} x_s(t) \\ x_s(t) - x_m(t) \end{bmatrix} \begin{bmatrix} \tilde{B}_1(t) \\ \tilde{B}_2(t) \end{bmatrix} \begin{bmatrix} x_d(t) \\ x_d(t) \end{bmatrix} \tag{5}$$

Given that $\tilde{x}_b = x_s(t) - x_m(t)$ represents the error between the slave and master states, the error state equation can be represented as: $\dot{\tilde{x}}_b = \tilde{A}_{21} x_s(t) - \tilde{A}_{22} \tilde{x}_b(t) + \tilde{B}_2 x_d(t)$ If $\tilde{A}_{21}$ and $\tilde{B}_2$ are nulls the system will be autonomous and the error will tend to be zero if the poles of $\tilde{A}_{22}$ are located in the left part of the s plane. The slave will follow the master and the error will tend to be eliminated. If these conditions are achieved the characteristic polynomial will be represented as $det(sI - A_{11}) det(sI - A_{22})$, where the first determinant defines the dynamics of the slave and the second defines the slave-master error.

The figure 2(b) shows the behavior of the slave that depends on haptic device references as the master state (virtual robot) through the gains S_s and R_s. Therefore it is possible to define a relation between theses gains and hence control the contribution grade of theses signals. If the contributions of theses signals are equal: $S_s = R_s$, a number of equations would be completed to solve for all proposed variables.

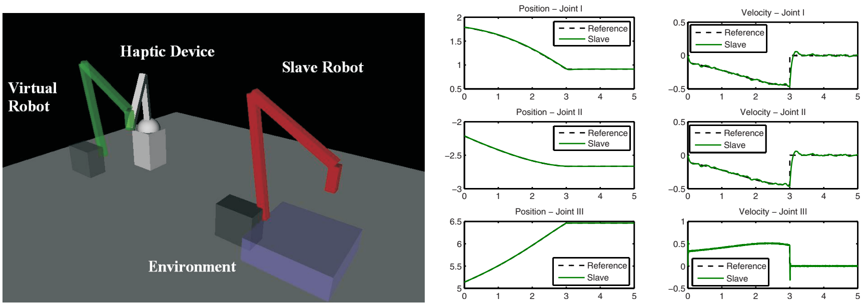
5 Experimental Results

The figure 3(a) shows the simulation of the teleoperation system in which the haptic device end effector and virtual robot end effector keep up a correspondence by the existence of a bilateral control by state convergence. The forces that are reflected to the haptic device are equal to the slave manipulator forces. The inertial (J_m and J_s) and friction parameters (b_m and b_s) are also the same between the robots (virtual-slave). The table 1 presents the design parameters for the control where the slave dynamics and the error dynamics have the form imposed by: $p(s) = s^2 + p_1 s + p_0$ and $q(s) = s^2 + q_1 s + q_0$ respectively. The gains of the parameters g_{2v} in all joints are one. This is a consequence of using the same inertial and friction coefficients between the virtual and slave robots.

A vertical trajectory was simulated for the experiment and realized by the haptic device, the slave manipulator began in a position where the environment

Table 1. Parameters and control gains

Parameter	J	b	p_1	p_0	q_1	q_0	g_{2v}	S_m, S_s, R_s	K_{m1}	K_{m2}	K_{s1}	K_{s1}	R_{m1}	R_{m2}
Joint I	0.028	0.05	22	121	30	225	1	[3.34, 0.56]	-2.87	-0.22	-6.68	-1.11	-0.47	-0.34
Joint II	0.005	0.05	50	625	40	400	1	[3.38, 0.22]	1.21	0.054	-6.75	-0.44	-4.59	-0.27
Joint III	2e-4	0.05	640	1e5	600	9e4	1	[20.4, 0.08]	2.48	0.008	-40.9	-0.16	-22.9	-0.086



(a) Teleoperation system simulated (b) Position-velocity references and Position-velocity slave joints

Fig. 3. Simulations

forces were null and continued down until contact with an object was made hence producing a force. The figure 3(b) shows the position-velocity references obtained from the haptic device and the corresponding execution of each slave manipulator joint. In the simulations the slave robot follows so fast the master robot

6 Conclusions

This paper presents a design of a bilateral control by convergence state where a commercial haptic device is used as master to teleoperate a serial robot with three DOF. The advantage of this method is the possibility of coupling masters and slaves with different kinematics through a virtual robot. With proposed control is possible to execute forces that a human operator applies from a haptic devices without force sensors. Only the slave robot has a force sensor to feedback the human operator

References

1. Aracil, R., Buss, M., Ferre, M., Peer, A., Cobos, S., Hirche, S., Kuschel, M.: The human role in telerobotics. In: Advances in Telerobotics: Human System Interfaces, Control, and Applications. STAR series, Springer, Heidelberg (2007)
2. Azorin, J.M., Reinoso, O., Aracil, R., Ferre, M.: Generalized control method by state convergence for teleoperation systems with time delay. Automatica 40(9), 1575–1582 (2004)
3. Azorín, J.M., Sabater, J.M., García, N.M., Pérez, C., Aracil, R.: Transparency in the Bilateral Control Methodology by State Convergence. In: International Conference on Control Applications, pp. 175–180. IEEE, Los Alamitos (2006)
4. Hokayem, P.F., Spong, M.W.: Bilateral teleoperation: An historical survey. Automatica 42(12), 2035–2057 (2006)