

PARALLEL POSITION/FORCE CONTROLLER FOR TELEOPERATION SYSTEMS

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Abstract: Control system designers nowadays have a wide selection of teleoperation architectures to configure their systems. Regardless of the architecture, if the process requires application of forces to the outer media, monitoring these forces are necessary as well as the motion of the manipulator. Most of the time, customary control strategies fail when both the position and the force trajectories are to be followed. By contrast, parallel position/force controllers provide an acceptable solution to this problem. The two control architectures discussed in this paper are hybrid position/force and admittance controllers. The simulation results illustrating the performance of the controllers are also presented as applied on a SCARA manipulator. *Copyright © 2007 IFAC*

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1. INTRODUCTION

A teleoperation system usually consists of a master subsystem, slave subsystem, and a communications line to provide interaction between the two subsystems. Slave subsystem is placed in the task space, which is usually either hazardous or at an unreachable site for humans. Master subsystem is commonly located at the same site with the human operator that utilizes it as an interface to control the slave subsystem. Most of the scientists are interested in teleoperation research because it is utilized in a wide variety of applications such as military, space, nuclear reactors, undersea tasks, training and medical operations.

The purpose of a teleoperation system is to accomplish a task in the environment that the slave is placed at. Therefore, the slave interacts with the environment during the task. Most of the time, this interaction requires the application of forces to the task space. Customary motion control schemes in general do not provide satisfactory response for these types of applications. Implementation of a force controller may provide a more satisfactory solution. Another solution is utilization of parallel position/force controllers.

In this paper, our aim is to address the use of parallel position/force controllers in teleoperation applications. The following section is dedicated to description of teleoperation system architecture and teleoperation types. Subsequently, control schemes that are considered in this study are explained. Later, the test system is presented along with its subsystems. Finally, the results of the simulation studies are presented that evaluate the performance of the controllers.

2. TELEOPERATION BACKGROUND

A teleoperation system is usually employed in 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 conditions, 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.

Robotic devices can work in environments that are hazardous, remote, or require interactions at a

smaller or larger scale. This substantially reduces the risk to humans and the costs associated with manned missions.

In 1940's providing a direct physical connection with the remote environment through mechanical linkages was perhaps one of the first examples to teleoperation. Linkage connections were replaced with servomotors in 1950's that allowed greater distances between the master and the slave.

Today, 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 (Goshozono, et al., 2004). The study by Butner and Ghodoussi (2003) involves transforming a surgical robot for human telesurgery. Sitti (2003) 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.

2.1. Unilateral Teleoperation

In unilateral teleoperation, the information flow is in one direction or unidirectional. Master system that is driven by the human operator sends the necessary inputs (e.g., position, and/or velocity) through the communications line to drive the slave system. There is no feedback information sent to the master system or the human operator during this type of manipulation. Instead, in most of the cases, the slave system has a local closed-loop control system, which uses the feedback signals within this control system.

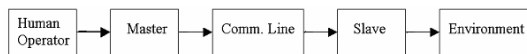


Fig. 1. Unilateral teleoperation system representation.

There seems to be a lack of applications of this type of teleoperation in the literature. The reason for this might be that this type of control is not significantly different than any classical control application. Although the human operator sends the command signals to the slave system, actually all the monitoring is accomplished in the control system of the slave.

2.2. Bilateral Teleoperation

A bilateral teleoperation system consists of a human operator interacting with the environment through a teleoperator system as presented in Fig. 2. Master devices vary from a one degree-of-freedom joystick to glove-based interfaces with many DOF (Griffin, 2003). The slave robotic device may vary from a one-degree-of-freedom "manipulator" to a complex

system with a dexterous robot hand attached to a multi degree-of-freedom arm even to multiple slave robots (Lee and Spong, 2005). Both sides of the teleoperation system typically have some type of local control operating on position, velocity, and/or force. The master and slave systems may be controlled by the same computer or by dedicated computers at distant locations.

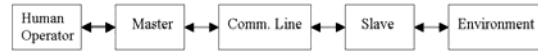


Fig. 2. Bilateral teleoperation system representation.

A common type of teleoperation architecture is one in which the master system sends position or velocity commands to a slave system. Force or torque information induced from interactions with the environment is fed back to the master system (by the slave system). This type of two-channel (one communication link in each direction) architecture, as depicted in Fig. 3, is often referred to as "position-force" architecture. Another type is the four-channel teleoperation, as shown in Fig. 4, where both positions (or velocities) and forces are transmitted between the master and slave (Lawrence, 1993).

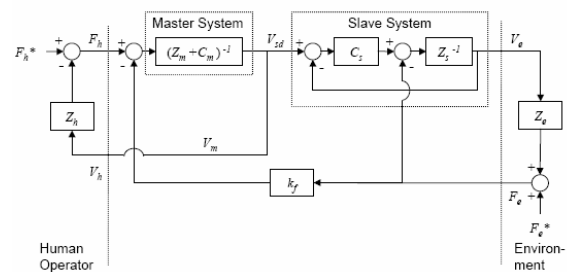


Fig. 3. Two-channel architecture for bilateral teleoperation (Lawrence, 1993).

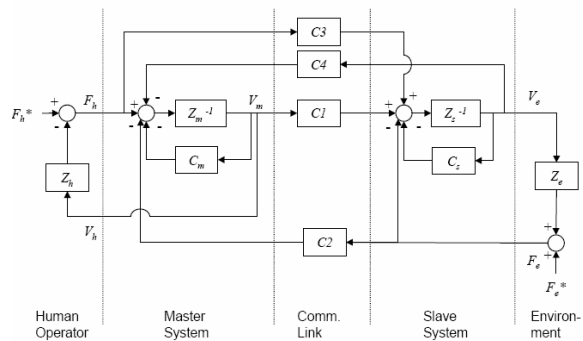


Fig. 4. Block diagram representing the general four-channel single degree-of-freedom (Lawrence, 1993).

It appears that some researchers chose to work with the four-channel model (Lawrence, 1993; Fite, et al., 2004) while others chose to work with the two-channel model because the information flow was sufficient enough for a stable teleoperation. These researchers also introduced the wave variable technique for stability even under time delays (Niemeyer, 1994; Lee and Spong, 2005; Munir and Book, 2003).

3. PARALLEL POSITION/FORCE CONTROLLERS

In this study, only hybrid position/force and admittance controllers are selected to be examined for competence in teleoperation tasks. These two controllers are probably the two widely used classical parallel position/force control algorithms.

3.1. Admittance Controller

Admittance control tracks not only the position trajectory but also the force trajectory. A pure position controller works on the principle of rejecting disturbance forces while following a reference motion. Instead of rejecting it, admittance control using a force compensator complies with the environmental interaction and reacts to contact forces by modifying the reference motion trajectory (Seraji, 1994). The mechanical admittance is defined by the equation below.

$$\dot{X}(t) = A(t)F(t) \quad (1)$$

This equation can be written in the s domain as

$$X(s) = K(s)F(s) \quad (2)$$

where

$$K(s) = \frac{1}{s} A(s) \quad (3)$$

In above equations and in Fig. 5, X and \dot{X} are the position and velocity vectors of the end-effector, A is the admittance matrix. Fig. 5 shows the schematic representation of a customary admittance control scheme.

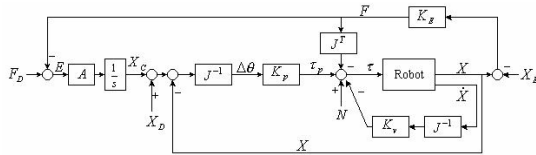


Fig. 5. Customary Admittance Control.

The admittance matrix A relates the force error vector E ($E = F_D - F$) to the required modification in the end-effector velocity vector. This leads to the following additive modification on the reference trajectory:

$$X_c = \int A(F_D - F)dt \quad (4)$$

Usually the admittance term, A , is not selected as a constant. It involves a variable matrix such as

$$A(s) = k_d s^2 + k_p s + k_i \quad (5)$$

which then results in the following PID force compensator when the Eq. 3 is applied:

$$K(s) = \frac{1}{s} \cdot A(s) = k_d s + k_p + \frac{k_i}{s} \quad (6)$$

3.2. Hybrid Position/Force Controller

Position and force information are combined into one control scheme to move the end-effector in nondeterministic environments in hybrid position/force control (Raibert and Craig, 1981). Separate controllers process the position and force information independently so that the controller designer can take advantage of well-known control techniques for each of them. The outcomes of these controllers are then combined only at the final stage when both have been converted to joint torques. Fig. 6 shows the application of the hybrid position/force control scheme as a block diagram.

In Fig. 6, $S = \text{diag}(s_j)$ ($j=1 \dots n$) is called the compliance selection matrix, n represents the degrees of freedom. The matrix S determines the subspaces in which force or position are to be controlled, and s_j is selected as either 1 or 0. When $s_j = 0$, force control must be used in the j th direction of the Cartesian space; otherwise, position control must be used in that direction. Depending on the required task, S matrix can be constant, or it can change in time according to the varying gradient of the task surface and the path followed on it.

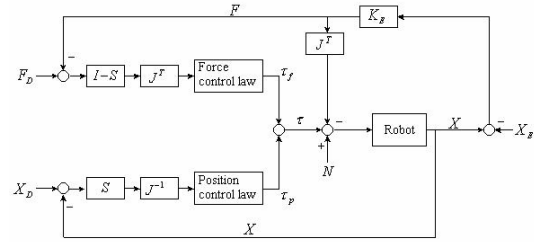


Fig. 6. Customary Hybrid Position/Force Control.

For each task configuration, a generalized surface can be defined with position constraints along the normals to this surface and force constraints along the tangents, which means, the end-effector can not move along the normals into the surface and can not cause reaction forces to arise along the tangents of the surface. These two types of constraints partition the freedom directions of possible end-effector motions into two orthogonal sets along which either position or force control must be used. Utilizing this partitioning, S matrix is formed appropriately in accordance with the required task.

In this control scheme, the command torque is calculated as

$$\tau = \tau_p + \tau_f \quad (7)$$

τ_p and τ_f are the command torques created by position and force subspaces, respectively. In this way, position control and force control are decoupled. In general, it so happens that PD action is satisfactory for position control, and PI action is satisfactory for force control (Zeng and Hemami, 1997).

3.3. Modified Admittance Controller

Admittance and hybrid position/force control formulations use the assumption that the error between the position demand and the actual position in Cartesian space is small. Therefore, it can be transformed into the joint space using the approximation in Eq. 8.

$$(\theta_{ref} - \theta) \approx J^{-1}(X_{ref} - X) \quad (8)$$

This assumption does not hold if there is a big enough time delay or communication loss during telemanipulation and the robot loses the track of its Cartesian coordinates. With the first command received the error range becomes unacceptable for this assumption.

Dede and Ozgoren (2004) introduced a modification to this algorithm that provides a solution that does not use the assumption mentioned above. The modification is on exact calculation of the error in joint space. Therefore, both the position demand and the actual position measured in Cartesian space are transformed to the joint space using inverse kinematics (IK) as shown in Eq. 9. Usually the actual positions of the joints are received from the joint sensors in joint space. Then the reference trajectory and the actual position can be compared in joint space without any assumptions. This solution is valid for the manipulators that have inverse kinematics solutions. Fortunately though, almost all of the industrial manipulators are of this kind (Ozgoren, 2002).

$$(\theta_{ref} - \theta) = IK(X_{ref}) - IK(X) \quad (9)$$

The block diagram of the modified admittance controller is presented in Fig. 7. As it can be observed, the modification is introduced in the inner position control loop where the error is calculated.

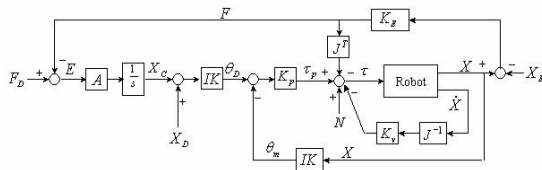


Fig. 7. Modified Admittance Control (Dede and Ozgoren, 2004).

Position feedback of the end-effector is changed to joint position feedback by inverse kinematics “IK” in the modified scheme. The inverse kinematics solutions can be achieved easily by using the methodology introduced in (Ozgoren, 2002). Besides, in a real time application, position feedback is received directly from the joint transducers. Therefore, it is sufficient to employ inverse kinematics only for the reference position $X_{ref} = X_C + X_D$ defined in the Cartesian space.

Dede and Ozgoren (2004) have also introduced a modified version of the customary hybrid

position/force controller in their paper. Although it also provides satisfactory behavior when large errors in Cartesian space are observed, the control algorithm requires dual controls. In order to approach the manipulator to the surface to make contact, the algorithm requires a pure position controller. As soon as the contact is formed, algorithm has to switch from pure position controller to hybrid position/force controller. In a teleoperation system that experiences time delays, this type of architecture would cause possible instabilities and chattering. Therefore, in this study the tests are carried out using the modified admittance controller, which is the most suitable controller for time-delayed teleoperation by its architecture.

4. TEST SYSTEM DESCRIPTION

A two-degree-of-freedom (DOF) gimbal-based joystick is used as the master (Dede and Tosunoglu, 2006a). The joystick has uncoupled motions about the two axes due to its gimbal-based design. Fig. 8 shows the master joystick with its x and y rotation axes.

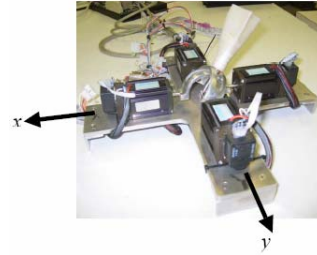


Fig. 8. Two-DOF master joystick.

The slave system is a three-DOF SCARA manipulator. Therefore, it has limited workspace and requires mapping between the joystick motion and the slave motion. It is designed to be used to trace surfaces by exerting controlled forces. The commands received in x - and y -axes are transmitted to the slave as Cartesian coordinate inputs. Then the forces created during the telemanipulation as a result of interaction and surface friction are fed back to the master.

The slave is constructed as a virtual manipulator. Therefore, the simulation requires a virtual reality representation of the robot. The specifications of the SCARA used in this study are given by Dede and Tosunoglu (2006c).

The virtual rapid robot prototyping concept presented by Dede and Tosunoglu (2006b) is used to construct the robot in virtual environment. First the manipulator is constructed in a computer-aided-design software environment. Then the material, inertial and mechanism parameters are translated into the Matlab[®] environment. Fig. 9 shows the visual representation of the manipulator along with the actual manipulator.

Interaction model between the end-effector and the surface is created using a planar contact. The material of the end-effector is selected to be lead

with a modulus of elasticity of 36.5 GPa. The surface is assumed to be rigid.

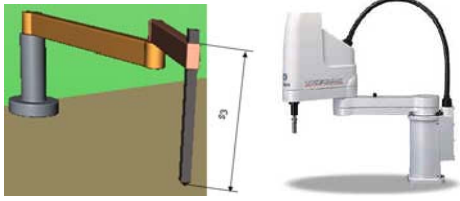


Fig. 9. Virtual representation of the SCARA accompanied with the actual manipulator.

The operator specifies the desired force to be applied to the environment through an input screen. This force profile can also be called the force trajectory. The interaction force between the surface and the end-effector as well as the surface friction force are created in the simulation environment. The friction forces in Cartesian space are then fed back into the servomotors of the joystick's respective axes. The friction forces are also sent back to the master as force feedback information.

5. SIMULATION RESULTS

In the simulations, independent joint control is used, which provides the flexibility of using different control algorithms for each joint. In the first set of simulations, Proportional-Derivative (PD) control was implemented for every joint. After tuning the PD parameters, the controller produced an acceptable error range when there was no contact with the surface. In order to control the force applied on the surface with this controller, the desired position trajectory was modified to penetrate into the surface so as to create the desired amount of contact force.

As expected, a pure position controller for the prismatic joint was not effective enough to follow the force trajectory while following the position trajectory. Another solution is to use dual controls. A position controller makes the end-effector approach the surface and create the contact. Then the control algorithm has to be switched to a pure force controller or to hybrid position/force controller to follow the force trajectory. This type of switching between the controls can cause instabilities and chattering in a teleoperation system where the communication can be delayed in an unacceptable amount.

One other possibility for a system that is required to follow both position and force trajectories is to use the modified admittance controller presented in (Dede and Ozgoren, 2004).

The following set of simulations is carried out by using a modified admittance controller for the prismatic joint and PD controller for the revolute joints. The PD control parameters were modified to compensate for the disturbances created by the friction forces at revolute joints.

The task used in the simulations is to follow a square path inside the workspace of the manipulator by

applying a constant force. The task was made more demanding by specifying the speed of the end-effector constant. It was expected to cause problems especially at the corners of the square where the end-effector is required to change its direction by 90° .

The change of direction acts as a step input because of the design of the task. This can be observed clearly from the velocity response of the manipulator in Cartesian space in Fig. 10.

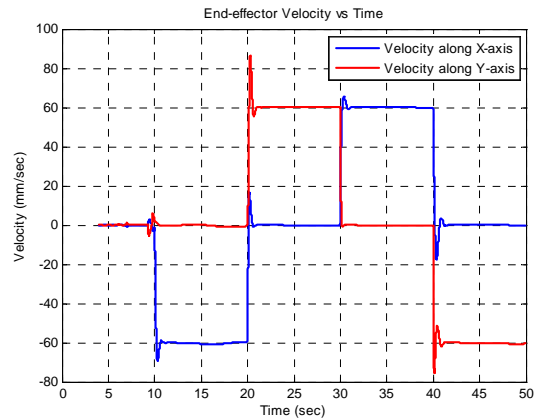


Fig. 10. End-effector velocity in x - and y - Axis.

The force applied to the surface is presented in Fig. 11. It is observed that after an acceptable transition period, the contact force is kept stable at the designated amount without any overshoots. The transition state characteristics can be changed by modifying the admittance term of the controller. The position control law however is kept constant as a PD controller. It was not necessary to modify the position control parameters. The position was tracked in acceptable error range with the inner position loop of the admittance controller.

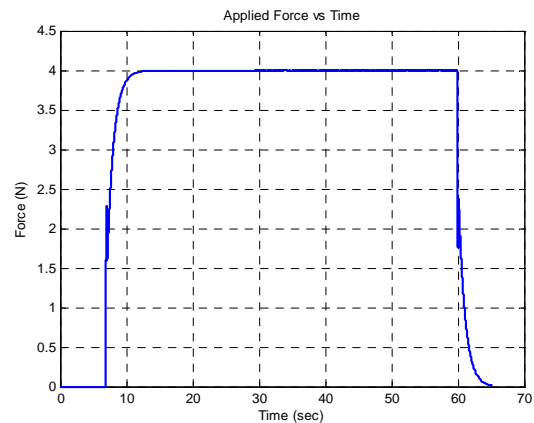


Fig. 11. Force applied by the end-effector to the surface.

The modification made by the outer force compensator loop for the inner position loop demand can be observed in Fig. 12.

The tests show that the virtual slave manipulator follows the force trajectory within an acceptable error range and with acceptable transients while following the motion trajectory. It also creates the

force feedback information for the operator to provide a feel of the remote environment.

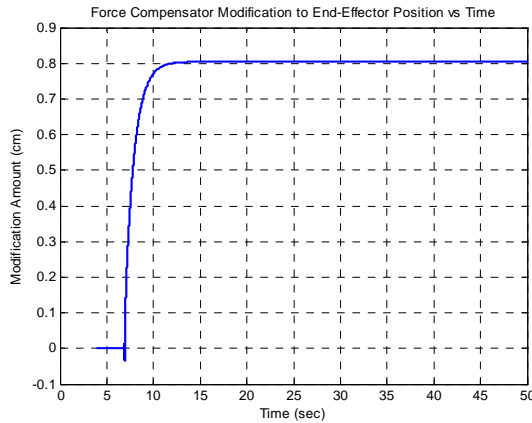


Fig. 12. Force compensator modification.

6. CONCLUSIONS

Generally time delays or communication losses are observed in teleoperation applications due to the communications line instabilities. However, a teleoperation system is required to be stable while performing critical tasks even though it experiences communications line problems. In that regard, the selection of parallel position/force controllers for teleoperation applications becomes very crucial.

In this paper, widely used two control algorithms are examined for use in teleoperation. The main objective was to compare the control algorithms for stability in case of time delays or communication losses.

The customary versions of the hybrid position/force and admittance controllers fail in teleoperation system applications. The reason for the failure is because of the assumption that the error between the demanded and the actual positions in Cartesian space is small for a finitely small amount of time. This assumption becomes invalid when the system experiences time delays or loss of communication.

This assumption is not necessary for modified versions of these controllers when the comparison between the demanded and the actual signals is made in joint space. On the other hand, hybrid position/force control requires a pure position controller for switching from one to another while in transition from contact to no contact. Therefore, possible instabilities and chattering are foreseen in case of time delays or communication losses.

Modified admittance controller does not require switching to a pure position controller regardless of the contact condition. The simulation results are also given as an examination of the controller in a telemanipulation task. Finally, it is concluded that among the controllers examined in this paper, admittance controller is seen as the best choice for teleoperation applications that may experience communications line problems.

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