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Powered Dissimilar Teleoperated System*

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To be presented at the
American Nuclear Society
1995 Winter Meeting
October 29 - November 2, 1995
San Francisco, California

CONTROL ISSUES FOR A HYDRAULICALLY POWERED DISSIMILAR TELEOPERATED SYSTEM

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ABSTRACT

This paper will address two issues associated with the implementation of a hydraulically powered dissimilar master-slave teleoperated system. These issues are the overall system control architecture and the design of robust hydraulic servo controllers for the position control problem. Finally, a discussion of overall system performance on an actual teleoperated system will be presented. (Schilling's Titan II hydraulic manipulators are the slave manipulators and the master manipulators are from the Oak Ridge National Laboratory-developed Advanced Servo Manipulator.)

I. INTRODUCTION

Many tasks slated for manipulators are highly unstructured (e.g. complicated assembly tasks, disassembly of unknown or sophisticated hardware, survey and characterization operations, clean-up of hazardous materials, etc.) and do not lend themselves to autonomous implementation. Often, operating procedures and regulatory requirements dictate that the decision-making process be retained with a human operator. As a result of the need to maintain operator control, teleoperator development began in the 1950's with Ray Goertz, continued through the 1960's with Carl Flateau, and is sustained today with a myriad of other contributors. This paper discusses the controller design for a new teleoperated system developed at Oak Ridge National Laboratory (ORNL). The paper is organized as follows: following the introduction is a section on the overview of the teleoperated system and its controller architecture. Next are sections on the servo and joint controllers, followed by results and conclusions.

II. OVERVIEW OF HARDWARE AND SOFTWARE

2.1 Overview of Selective Equipment Removal System

The Selective Equipment Removal System (SERS) is a reconfigurable and modular deployment system for the dual-arm work module (DAWM), which is a generic manipulation package designed to provide both dexterous teleoperation and robotic capability (only teleoperation will be addressed in this paper). The SERS is specifically designed to study and address the needs of facility decontamination and dismantlement (D&D). Multiple deployment options are provided to support the needs of different facilities. Some sites may have overhead cranes available. The initial implementation of SERS uses a rigid boom gantry overhead transporter system located in the Robotics and Technology Assessment Facility at ORNL. The transporter provides X, Y, Z, and boom rotation functions for gross positioning of the DAWM. Refer to Fig. 1. (All figures are at the end of the paper). The DAWM consists of a 5-Degree-of-Freedom (5-dof) base manufactured by RedZone Robotics and two 6-dof Schilling manipulator arms. The Schilling arms serve as the slaves of the teleoperated system. The Schilling manipulators (Figure 2) are servo valve controlled hydraulically actuated manipulators with a supply side pressure of 3000 psi. These manipulators provide higher lift capacity than that normally available for dexterous teleoperation with 240 lb in the elbows-up configuration dropping to 150 lb in the elbows-out configuration. Joint positions are measured by 12-bit resolvers and a linear variable differential transformer is used to indicate gripper position. A six axis force/torque sensor is located in the wrist of each arm. Presently the existing force/torque sensors have significant noise and offset.

For teleoperation, the master arms which serve as the operator interface to the DAWM are the master manipulator hardware converted from the Advanced Servo Manipulator (ASM), a manipulator designed at ORNL and extensively tested in the 1980's (Refer to...
Figure 3). The ASM is a fixed configuration, elbows-down, remotely maintainable manipulator that was designed to meet the needs of fuel reprocessing facilities. The master manipulator achieves torque transmission via tensioned steel cables.

The computer controller is Versa Module European (VME)-bus based and uses five Motorola 68030-based single board computers in the same back plane. One Central Processing Unit (CPU) handles each of the master controller arms and slave manipulators and runs synchronous deterministic control loops. The fifth CPU is used for asynchronous communications to the operator interface as well as overhead transporter and camera positioning where loop rate requirements are not stringent. Control is actually handled through two VME back planes separated by 300 ft and connected by a bus repeater card set through a set of four optical fibers. Control and sensor communication for all manipulator parameters is managed through a custom Schilling VME bus card and electronics module for each manipulator. All CPU's are located in the master rack in the control room. Only the bus repeater cards and Input/Output cards relevant to DAWM control are located in the back plane in the DAWM. All software is done in C or C++ and modules run under Wind River's VxWorks® real-time control architecture.

The manipulators are run continuously in the impedance control mode in teleoperation and adjusted to be stiff or compliant as the task requires. High compliance in one manipulator is a useful mode when executing coordinated two arm tasks robotically. Certain types of tasks, such as peg-in-hole, are best completed in an impedance control mode where the remote compliance center can be altered in addition to the compliance matrix.

The initial operator interface makes use of the existing ASM Advanced Integrated Maintenance System (AIMS) video console which includes three 19-in video views and six 9-in video views. Future development will examine alternate viewing schemes focusing on those methods which will accommodate extended use by operators. Operator interface menus are provided by Sun workstation, X-Window-based graphics, and Silicon Graphics machines running IGRIP® for 3D modeling of the task space and displaying DAWM orientations.

DAWM will have a collection of tools to address D&D tasks. Power tools include impact wrenches, grinders, cut-off saws, and a stainless steel wet/dry vacuum cleaner. A previously modified Hurst "Jaws-of-Life"® hydraulic cutter, originally designed for rescuing injured passengers from automotive accidents, was refitted to the overhead transporter and made available to the DAWM (Figure 4). Long-term goals have been identified to pursue plasma arc cutting, high pressure water cutting, CO₂ blasting, as well as other technologies necessary for large scale dismantlement of structures not designed for remote interaction.

2.2 Overview Control Architecture

Position-Force control is the strategy selected for the Titan II manipulators and the ASM masters for several reasons. First, the Titan II joints are not backdrivable (i.e., large joint friction exists in each joint). Second, the Force/Torque sensors (JR3) for each arm are on the wrist (i.e., no joint torque measurements). Having no joint torque sensors only adversely affects the wrist roll because of the large joint friction present in the wrist roll joint. Third, the kinematics between the ASM master arms and the Schilling slave arms are dissimilar. This last reason was probably the most critical because the two manipulators (master and slave) in this paper are not anthropomorphic, a Cartesian (i.e., x, y, z and Euler parameters) based scheme was chosen instead of a standard joint-to-joint type of controller. The master manipulators have a shoulder pitch, shoulder roll, elbow pitch, and a 3-dof spherical wrist (i.e., pitch, yaw, and roll). The slave manipulators have a shoulder azimuth (yaw), shoulder elevation (pitch), elbow pitch, and a wrist pitch and yaw (whose axes do not intersect) and a wrist roll. Furthermore, the relative link lengths of the master and slave manipulators are significantly different (e.g., the first two link lengths of the ASM master manipulators are 25 and 20 inches plus an offset of 1.125 inches and the first two link lengths of the Schilling Titan II slave manipulators are 33.5 and 19 inches). Also, Cartesian control has the advantage that the master manipulator controller software can be the same for teleoperation and for robotic operation. Only the software front end changes as to whether the master controller or a trajectory planner is driving the slave manipulator end effector.

Typically, joint position-position control strategies have been utilized in the past; however, the control architecture (see figure 5 below) for DAWM is a position-force type controller where Cartesian position from the master arm is transmitted to the slave manipulator and the slave's force signal is transmitted back to the master arm. The position-force control architecture was first demonstrated by Plateau. Briefly, the following is a summary of the function performed by each routine in the block diagram of Fig. 5.

1. inv_kin_t2() - inverse kinematic routine for the Schilling Titan II slave manipulator.
2. kin_joint_t2() - kinematic routine for the Schilling Titan II slave manipulator.
3. jr3_to_tool() - converts the force/torque signal to tool frame at the gripper. (The force/torque sensor is manufactured by JR3, Inc.)
4. impedance_control() - simple impedance controller.
5. indexing and move wrist are both associated with indexing of the master/slave manipulators.
6. motor_torque_to_current() - converts the torque commands to current commands.
7. kin_joint_Jac_Force_asm() - combines the software for the kinematic routine and the manipulator Jacobian code for the master manipulator into one routine.
8. motor_to_JtAngle() - converts motor angles to joint angles (this is needed since this is a cable driven system).
9. Sensor_to_Gripper_Force() and force_reflection ratio - converts the force/torque sensor signal to gripper forces and moments and then multiplies results with the desired force_reflection ratio required by the operator.
10. force_filter() - due to the noise level on the force/torque sensor a second order lag filter is utilized with a bandwidth set at 4Hz.
11. grav_comp() - removes the gravitational component from the force/torque signal. The input signal (angle_RedZone) is the angle from the 5-dof DAWM base manufactured by RedZone Robotics, Inc.
12. jr3_calibration() - using a least-mean squares algorithm, the bias and scale factor for the force/torque sensor (with the exception of the wrist roll) is estimated at the startup of the slave manipulators. The bias settings will change due to the residual hydraulic fluid pressure in the hydraulic lines that pass through the force/torque sensor.
13. servo_comp() - low level joint hydraulic servo controller.

Only the servo_comp routine will be addressed in the rest of this paper since it is fundamental to all of the other control loops in the system. It is shown as the shaded block in Fig. 5.

III. SERVO CONTROLLER DESIGN AND JOINT MODELING

Servo control of hydraulic-based systems can achieve similar positional tracking accuracies as more common electric-based drive systems; however, there are noticeable problems that have to be overcome. The low-level joint controller design construction is based on overcoming the following types of nonlinearities: Coulomb and stick-slip type of friction, orifice governing equation of the servovalves, changes in fluid properties with time and temperature (i.e., effective bulk modulus), and changing inertia parameters of the manipulator in different postures. The controller had to be robust to these large nonlinear forces.

Groups of linear models have been used to characterize the manipulator performance and to aid in the controller design. Linear models were used based on transfer functions derived in and derived from measured data. Figure 6 shows the block diagram of the joint controller. In Fig. 6, A is the actuator area, \( b_0 \) is the effective bulk modulus, \( G_c \) is the joint compensator (designed in the following section), A is the actuator area, \( V_T \) is the total system volume, \( M \) is the system mass, \( C_{tp} \) is the total leakage flow, \( K_p \) is the pressure gain of the servovalve, \( K_q \) is the flow gain of the servovalve, \( R \) is the effective resistance of the servovalve, and \( F_{frict}, F_{load}, F_{grav} \), are the friction, load and gravity forces respectively.

IV. JOINT COMPENSATORS

The goal in the design of the joint compensators was to use frequency response information to shape the response of the joint plant and joint compensator so that the controller would remain robust to large plant variations but avoid high-amplitude limit cycles resulting from significant nonlinearities such as joint friction. (Typical of hydraulically actuated manipulators.) Large plant variations result from changes in the hydraulic properties because of temperature variation during warm up and operation, as well as changing manipulator configuration, picking up payloads, and contact with different environments.

1) To achieve the dc stiffness requirements (i.e., joint deflection for rated load), a dc-gain of 10,000 was required for the joint compensator.
2) To provide adequate robustness margins to the possible variations in nonlinear friction as well as to plant operating conditions such as payload, configuration, and environmental impedance the following compensator was selected:

\[
G_c(s) = \frac{10,000 \left( \frac{s}{0.2} + 1 \right)}{\left( \frac{s}{0.06} + 1 \right) \left( \frac{s}{15} + 1 \right)} + \frac{K_i}{s} \quad (1)
\]

3) As expected, small limit cycles at low frequency have been observed on some of the joints (elbow, wrist pitch, and wrist yaw). These limit cycles can be reduced by careful design to a level where they are not visible.
4) The drive signal must be constrained to avoid actuator saturation. Following similar lines as those taken...
in Quantitative Feedback Theory, the drive constraint must satisfy the following inequality:

\[
\frac{G_c}{1 + G_c P} |\Theta_{\text{cmd}}| \leq 1000 \text{ cts}
\]  

(2)

where 1000 cts is roughly half (this was picked for conservatism) of the 12 bit range of the D/A card (2^{12} implies ±2048) and \(|\Theta_{\text{max}}|\) was selected to be 5 degrees.

V. CONCLUSION

This paper discussed the modeling and experimental development of a servo controller for a hydraulically actuated teleoperator system. Servo control of hydraulic based systems can achieve similar positional tracking accuracies as more common electrically actuated drive systems; however, there are noticeable problems that have to be overcome to achieve similar tracking performances. Applying the controllers to the teleoperated slave manipulators resulted in excellent performance. The manipulators are extremely stiff under all payload and operating conditions. The manipulators remain stable and the controllers are robust to system variations during extended operations. The arms and controllers have been used successfully through many hours of D&D operation.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support of the Department of Energy Robotics Technology Development Program headed by Dr. Lin Yarbrough.

REFERENCES


Fig. 1. SERS transporter for the DAWM.

Fig. 2. The DAWM showing the Schilling manipulator arms.

Fig. 3. The Advanced Servo Manipulator master arms.

Fig. 4. DAWM with "Jaws-of-Life" hydraulic cutter.
Fig. 5. Teleoperation block diagram for position-force control.

\[
\begin{align*}
F_{\text{fric}} + F_{\text{Load}} + F_{\text{grav}}
\end{align*}
\]

\[
\begin{align*}
\frac{K_p + C_v}{A} \frac{V_T}{s} + \frac{1}{4\beta_c A}
\end{align*}
\]

Fig. 6. Block diagram of the joint controller.
Fig. 7. Model and experimentally determined amplitude and phase for the elbow joint of the Schilling Titan II slave manipulator.

Fig. 8. Nichols plot of the model for the elbow joint of the Schilling Titan II slave manipulator showing the affect of joint nonlinear friction and compliance on stability (Describing function method).

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Fig. 9. Nichols plot of the plant model of Fig. 6 with the compensator, $G_c$, of Eq. 1.

Fig. 10. Magnitude of $\frac{G_c}{1 + G_c P}\|\theta_{\text{cmd}}\|_\text{cmd}^\text{cmd}$ (dB) versus frequency (rad/s) showing how the 1000 count (60 dB) constraint is avoided for all frequencies (Drive signal boundary).