ABSTRACT

Bilateral teleoperation across significant time delays has been extensively studied and is posed to provide remote control of orbiting robots. Unfortunately, most standard approaches assume an impedance controlled, backdrivable robot. In this work, we apply wave variable control to Ranger, a large, space-qualified, geared robot. We incorporate local feedback of contact forces into the control framework to achieve backdrivable operation. In particular, this control framework imitates an idealized point mass to respect Ranger’s dynamic capabilities. Beyond perceiving steady state contact forces, the user’s perception can be enhanced with high-frequency acceleration feedback of contact transients. Experimental results from controlling Ranger using network communications show stable operation in free space and contact.

INTRODUCTION

Telerobotics allows a user to remotely operate a robot and manipulate its environment, hopefully while receiving appropriate feedback from the remote site via a master device. Space-based applications, together with deep sea or nuclear environment uses, have been a primary target since the earliest work in the 1950’s [1]. These systems share several noteworthy features. Most importantly, the slave robots are generally large and designed to withstand harsh conditions. As a result, they tend to have very high inertial and friction properties, large gear reductions, and are typically non-backdrivable. Dynamic and friction forces can easily overshadow external contact forces, making the robot insensitive and dangerous to its environment. In addition, these systems often need to be controlled across substantial communication delay, due either to large distances or slow data rates. Nonetheless, it is desirable to present the user with haptic feedback, allowing the user to feel the environment, improve task performance, and minimize the danger of accidental damage due to force overloads.

Creating a bilateral control system to achieve user feedback is a challenging problem. Previously proposed designs have
sought to provide transparency for the user with a general 4-channel architecture [2] and have been further enhanced with the addition of local force feedback [3]. Passivity based bilateral controllers are often used to maintain stability across time delay [4], and wave variable controllers provide a simple method to maintain passive communication between the master and slave in the presence of time delay [5, 6]. The performance of wave variable controllers has been further improved by including prediction and drift control [7] and adding high-frequency acceleration feedback to improve user perception [8]. These designs, however, are generally intended for low-inertia, backdrivable robots.

Force feedback can be used to reduce the negative effects of highly-gearred slave devices. Feeding the slave tip force directly back to the master device will hide the large slave inertia and give the user accurate feeling of environment forces. However, stability becomes difficult to achieve when using direct force feedback. Force scaling can be used, but will be limited by the ratio of the master and slave inertias [9]. The presence of time delays further increases the difficulties.

Local force feedback provides a way of reducing the effect of slave friction and inertia while increasing slave sensitivity to environment forces [10] and allowing for passivity-based control to provide stability despite time delays [11]. In this work, we assume a master-slave connection via a passive controller as shown in Fig.2, and focus our attention on the force local regulation. In particular, we address the application to a high-inertia, high-friction, practically non-backdrivable slave robot designed for space operations. In our case the slave device is position controlled. We command a desired tip position, which is internally converted to joint and motor positions and then tracked by low level motion controllers. Contact forces are measured at the slave tip so that the robot requires admittance control.

We also assume communication delays and utilize a wave-variable-based controller to achieve stability independent of delay. This architecture further provides a framework for the local force feedback, which we present in this work. Finally, the framework also utilizes the addition of high-frequency acceleration feedback [8] to provide the user with perception of the contact transient dynamics.

We first introduce the slave system in Section 2, then detail the control architecture and local force loop in Section 3. Section 4 gives experimental results of the force loop and overall system operation, demonstrating stable operation and robust performance. We offer some concluding remarks in Section 5.

**SLAVE SYSTEM**

The Ranger satellite servicing system (Fig. 1) is designed for on-orbit robotic servicing of spacecraft and satellites, a task requiring multiple manipulators to grapple a satellite or component, provide video feedback to operators, and execute tool-based operations on components being serviced. The robot consists of a central body housing the main computers and serving as a base platform for all the manipulators. Ranger’s current incarnation has two eight-degree-of-freedom (DOF) dexterous manipulators for object manipulation, a seven-DOF video manipulator for positioning a stereo camera, and a six-DOF positioning leg used to grapple or dock to a spacecraft [12].

Ranger was originally designed as the Ranger Telerobotic Flight Experiment (RTFX), a low-cost, free-flying, flight demonstration experiment. The neutral buoyancy version of RTFX underwent hundreds of hours testing, demonstrating structural assembly and satellite servicing of the Hubble space telescope (HST) [13]. A subsequent evolution was the Ranger Telerobotic Shuttle Experiment (RTSX), which was to have flown aboard NASA’s Space Shuttle. This flight demonstration experiment was to show on-orbit robotic servicing, principally by replacing standard orbital replacement units (ORU) from both the International Space Station and the HST [14, 15]. This revised system design was explicitly modular, and has evidenced nearly two...
appropriate two meters long, giving a total vehicle reach from the base of the positioning leg to the tip of an outstretched manipulator of about 4.5 meters. This configuration has a mass of 450 Kg. The custom-designed joints are capable of 45 deg/s velocities and 900 deg/s² acceleration, with tool-tip velocities in excess of eight meters per second. It’s also capable of exerting 130 N and 40 N/m in any direction at each dexterous tool tip. In the extended configuration used to evaluate HST servicing, the total vehicle vertical reach is almost 9 meters, with a wingspan of over 7 meters as shown in Fig. 1. The experiments reported here utilized the Ranger arm in RTSX configuration in a 1g environment.

For the experiments described in this paper Ranger was placed in a standard test pose, with the dexterous arm horizontal and facing the test stand (Fig. 3). The manipulator is controlled by the Data Management Unit (DMU), a desktop PC running realtime Linux that executes a cartesian control loop at 125Hz. The DMU also senses forces and torques at the manipulator tip, through a 6-axis force-torque sensor that is sampled at 125Hz. Joint control computers that are co-located at the shoulder, elbow and wrist, run a custom realtime operating system that executes joint PD control loops at 750 Hz. Previous teleoperated control of ranger was achieved using two 3-DOF hand controllers that provide rate commands to the DMU, which translates these into joint position commands through the cartesian controller [16].

Basic characterization of Ranger was conducted by commanding 1mm position steps while the tip was in constant contact with the environment (Fig. 4). From the resulting position and force plots, the settling time is about 100 ms, and there is a 40 ms time delay between the steps in commanded and measured position which corresponds to 5 cycles at 125 Hz. From the plots we compute the combined mechanical stiffness of the environment and robot as

$$K_{env} + K_{robo} = \frac{\Delta force}{\Delta position} \approx 25000 \text{ N/m}$$  \hspace{1cm} (1)

We also compute the stiffness of Ranger’s internal controller, which is effectively the proportional position gain

$$K_{control} = \frac{\Delta force}{\Delta position \text{ error}} \approx 50000 \text{ N/m}$$  \hspace{1cm} (2)

**LOCAL SLAVE CONTROLLER**

The Ranger arm is a position controlled robot that was initially designed to be used without force feedback. In order to provide local force control as well as force feedback to the user while maintaining a passive communication channel with typical network delays $T_d$ a modified 3-DOF wave variable controller was used. Each degree of freedom can be represented by the block diagram shown in Fig. 5 where (3) describes the transformation between wave variables $u, v$ and power variables $x, F$ [6].

$$u = \frac{b \dot{x} + F}{\sqrt{2b}} \quad v = \frac{b \dot{x} - F}{\sqrt{2b}}$$  \hspace{1cm} (3)

Here $b$ is the wave impedance which controls the relative weighting between force and velocity.

Note the delay $T_d$ in the forward and return path as well as a first order wave filter with cutoff frequency $\lambda_w$. As mentioned in [8], the wave filter is included in the forward wave path to minimize wave reflections as well as to maintain frequency separation between the low-frequency wave controller and the direct high-frequency acceleration feedback. Also note the wave signals are passed through an inertial model, described below, before being applied to the robot. In addition, unlike standard wave variable controllers, a scaled version of the measured environment force

$$F^*_e = \frac{F_e}{\alpha}$$  \hspace{1cm} (4)

is used in the wave variable transformation to find the desired velocity instead of the actuation force produced by Ranger’s internal controller.

$$\dot{x}_d = \frac{\sqrt{2b}u - F^*_e}{b}$$  \hspace{1cm} (5)
Ranger’s structural dynamics as well as the computational time delay, using control problem. However, using the environment force in the wave variable transformation presents a stability issue. As the measurement $F^e$ and the motor position commands are separated by Ranger’s structural dynamics as well as the computational time delay, using $F^e$ to calculate $\dot{x}_d$ is very much a non-collocated control problem.

Impact with stiff environments will produce high-frequency force signals, creating high-frequency motion commands which Ranger is not able to track due to the limited bandwidth and delays in its internal controller. As the actual velocity and the contact force lag behind the desired velocity, an unstable feedback loop develops if the environment is too rigid, resulting in contact instabilities.

In order to avoid contact instabilities, the controller must be slowed down to be compatible with Ranger’s ability to respond. To provide the controller with some knowledge of Ranger’s capabilities, an inertial model is included in the wave channel. As described in [11], a pure inertial element with mass $M$ can be depicted as a combination of high- and low-pass filters in wave space with a cutoff frequency of $\lambda_m = 2b/M$. This is shown in Fig. 6. If an ideal inertial model is inserted in the wave channel, the wave variables $u_s$, used to determine Ranger’s desired velocity, and $v_s$, used for force feedback, behave as if a mass $M$ is interacting with the environment and the user.

$$u_s = \frac{2b}{M + 2b} u_m - \frac{Ms}{M + 2b} v_e$$  \hspace{1cm} (6)

$$v_s = \frac{2b}{M + 2b} v_e - \frac{Ms}{M + 2b} u_m$$  \hspace{1cm} (7)

As long as Ranger is able to respond faster than a mass $M$ to the excitations $u_m$ and $v_e$, the system will remain stable. At the master side, the combination of the inertial model and Ranger simply feels like a point mass slave with mass $M$.

In Fig 5 it can be seen that the mass model used in the modified wave variable controller does not match the ideal model from Fig. 6 in two ways. First, the high-frequency reflection on the master side of the inertial model in Fig 5 has been eliminated to remove a wave reflection path and extend stability bounds. As most high-frequency information in $u_m$ will have already been removed by the low-pass wave filter with cutoff frequency $\lambda_m$, only a small portion of information is lost.

The second difference, the gain $K_v$ on velocity in the $v_e$ reflection path, can be explained by an in-depth look at the slave side controller. If the inertial model is only fed back $v_e$ instead of $v_e$ and $v_e^*$ ($K_v = 1$ in Fig. 5), the inertial model and wave transformation can be converted into power variables to provide an expression for $\dot{x}_d$.

$$\dot{x}_d = \frac{2b}{M + 2b} \left( \frac{\sqrt{2b}}{b} u_m - \frac{F^e}{b} \right) - \frac{Ms}{M + 2b} \dot{x}_s$$  \hspace{1cm} (8)

The above expression shows the desired velocity sent to Ranger.
The apparent additional mass due to the time delay in the communication channel and the wave filter [17].

\[
\dot{x}_d = \frac{2b}{Ms + 2b} \left( \frac{\sqrt{2b}}{b} u_s - \frac{F_s^*}{b} \right) - K_v \frac{Ms}{Ms + 2b} \dot{x}_s
\]

From the user’s perspective, \( K_v \) allows a trade-off between the damping in the system due to the velocity feedback term and the apparent mass of the system.

As the cutoff frequency \( \lambda_m = 2b/M \) in the inertial model of Fig.6 is a function of the ratio \( b/M \), it would appear that the mass \( M \) felt by the user can be minimized by increasing the wave impedance without changing performance. Unfortunately, in addition to the mass of the inertial model, the user will also feel an apparent additional mass due to the time delay in the communication channel and the wave filter [17].

\[
M_{comm} = \frac{b}{2\lambda_w} + bT_d
\]

In order to achieve a telerobotic system with a reasonable mass, a trade-off between \( M \) and \( b \) based on the expected time delay and the bandwidth of the slave system will be needed.

**EXPERIMENTAL RESULTS**

To test the effectiveness of the modified wave variable controller, two sets of tests were run. The first set of tests was designed to determine the ability of the controller to make stable contact with rigid environments. The second set of tests combined the entire telerobotic system, including both high-frequency acceleration feedback and network communications.

**Constant Wave Input Test**

To ensure that the modified wave variable controller was capable of maintaining stable contact, Ranger was positioned as shown in Fig. 3 and given a constant wave variable input \( u_m \) in the negative \( x \) direction. After moving a few centimeters in free-space, Ranger would impact a piece of plywood mounted to a uni-strut frame. The position, velocity and force sensor reading were recorded during the entire motion.

For the test shown in Fig. 7, the wave impedance \( b \) was set to 200\( Ns/m \), the inertial model mass \( M \) was set to 40\( kg \) for a cutoff frequency \( \lambda_m = 10rad/s \) while the force scale \( \alpha \) was set to 10. The incoming wave variable \( u_m \) was set to a constant \(-0.2\sqrt{\text{watt}}\) which corresponds to a steady state velocity of \(-0.02m/s \) in free space, or a steady state force of \(-40N \) in contact before scaling by \( \alpha \). The velocity feedback gain \( K_v \) was set to 0.5. From the velocity oscillations before contact is made, it is clear that at high frequency the desired and actual velocity are out of phase, indicating the need for a \( K_v < 1 \) to maintain a positive gain margin. Once contact is made, both the velocity and force measurements show that the system reaches the desired steady state force in approximately 1 second, consistent with the cutoff frequency \( \lambda_m \).

In Fig. 8, the wave impedance was set to 100\( Ns/m \) and the inertial model mass set to 20\( kg \), keeping the cutoff frequency \( \lambda_m = 10rad/s \) unchanged. The force scale was maintained at 10 while the incoming wave variable \( u_m \) was reduced to \(-0.1\sqrt{\text{watt}}\). This resulted in a steady state velocity of \(-0.014m/s \) and a desired steady state force of \(-14N \). Additionally, the velocity feedback term was reduced to 0.3. From (9) it can be seen that the force feedback term has a gain of \( 1/b \). Reducing \( b \) in this case increases the force feedback gain by a factor of 2 over the test in Fig. 7. Combined with the reduced damping from the smaller \( K_v \), it is clear the bouncing displayed here is a contact instability caused by the doubled gain combined with inadequate damping.
Teleoperated Test

The complete teleoperation system consisted of Ranger as slave and a Phantom™ haptic device as master running a local control loop at 1000Hz. Communications between master and slave consisted of UDP packets exchanged over the local network every 8 ms, the maximum permitted by the rate of the DMU. Packets from slave to master had three wave variables (one per degree of freedom) and a time-stamp. Packets from master to slave additionally included all constants to be used in the slave control calculations. Time delay due to network travel was less than 0.5 ms.

With the master and slave connected and the high-frequency acceleration feedback included, a simple test was run where the user would try to move Ranger into contact at a constant velocity and then apply a constant force. Due to the additional coupling between master and slave and implicit additional force feedback gain, the wave impedance and inertial model mass had to be increased slightly in order to maintain stable contact. For the test shown in Fig. 9, the wave impedance was set to 250Ns/m and the model mass set to 50kg. The velocity feedback gain was set to 0.5 and contact was made in the y direction, as opposed to the x direction used in the previous test.

From the force plot, the inertial force on the master device due to the inertia model is apparent during the first half of the test, while the slave in free space experiences no environmental force. Once contact is made, the slave environment force rises and begins to track the force applied by the user. The difference in master and slave position represents the compliance in the system both due to the wave channel and Rangers internal controller.

To provide the user with the high-frequency information needed to detect contact, the acceleration of Ranger’s fingertip was sampled at 1000Hz and high-pass filtered at $\lambda_{hf} = 200$rad/s. The resulting signal was multiplied by a gain $K_a$ and added to the master force profile. Unfortunately, due to the low-amplitude but high-frequency oscillations at the tip in free space, a relatively small acceleration gain of $K_a = 0.01$Ns/m was required to keep the system from feeling too jittery. Even so, although hard to see in the master force profile of Fig. 9, the user reported feeling a definite impulse when making contact.

CONCLUSION

This work has successfully demonstrated that wave-variable-based, bilateral teleoperation across network communications can be extended to highly geared, large robots. The nature of such robots requires force feedback to create backdrivable behavior and make the system sensitive to contact forces.
While any lag in the system response limits the force gains, stable operation is achieved when imitating a pure mass. The wave framework adds a passive communication as well as high frequency acceleration feedback.

When using the above described teleoperated system, the user experiences the apparent inertia of the mass model, effectively limiting their speed of motion. They also feel contact transients and steady state contact forces. Together this creates a safe, bilateral system. We hope these efforts will enhance on-orbit and similar telerobotic applications and allow such systems to achieve their long-held promise of safe remote manipulation.

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REFERENCES