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Cooperative control of virtual objects over the internet using haptic teleoperation

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Abstract: The feasibility of performing remote assessment and therapy of patients over the internet using robotic devices is explored. Using a force feedback device, the therapist can assess the range of motion, flexibility, strength, and spasticity of the patient's arm grasping a similar robotic device at a remote location. In addition, cooperative rehabilitation strategies can be developed whereby both the patient and therapist perform tasks in a shared virtual environment. To counter the destabilizing effects of time delay in the force feedback loop, a passive wave variable architecture is used to encode velocity and force information. The control scheme is validated experimentally over the internet using a pair of InMotion2 robots located several hundred miles apart.

Keywords: robotics, rehabilitation, virtual environment, cooperative control, bilateral control, time-delay, force-feedback, haptic interface

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INTRODUCTION

Robots have been explored as possible rehabilitation aids in laboratory settings for well over a decade. Such investigations have recently expanded into the field of *teletherapy*, whereby a clinician can interact with patients in remote locations using robotic devices. Time delays encountered in the force-feedback loop can cause instability in the system, however. Compensating for the time delay, which will be key to realizing this technology over the internet, is the cornerstone of the control architecture presented here.

The specific aims of our research are twofold: (1) to enable a clinician to assess the physical condition of a patient's arm using metrics such as strength, dexterity, range of motion, and spasticity; and (2) to help a clinician perform cooperative rehabilitative tasks with a patient using a virtual environment intended to simulate activities of daily living (ADL). The use of a *haptic* (force-feedback) device in conjunction with a video display will allow the clinician to assess the patient's condition remotely, as well as assist the patient when performing rehabilitation tasks.

The *Imaging Science and Information Systems (*ISIS) Center at Georgetown University Medical Center has assembled a robot rehabilitation testbed consisting of a pair of InMotion2 (IM2) robots from Interactive Motion Technology, Inc (1). The IM2 Robot is a direct-drive, four-bar linkage with a planar workspace of 90 x 60 cm and maximum continuous force output of 30 N in each direction (see Figure 1). The handle is pinned to the distal end of the outboard link providing a third, unactuated degree of freedom. The apparent mass at the handle of only 1.33 kg makes it well-suited for use as a haptic display.

Fig. 1: Subject performs virtual beam task with *InMotion2 Robot* while donning stereographic goggles.

This article begins with a brief review of previous work on internet therapy and cooperative haptic displays. The tele-assessment and cooperative rehabilitation modes are described, and the haptic controllers and time-delay compensation using wave variables outlined. Experimental results for both operational modes implemented on the IM2 testbed are presented, and then conclusions and future research directions are discussed.

PREVIOUS WORK

Telemedicine has already seen several successful demonstrations of rehabilitation robotics. A "java therapy" application was enabled using a commercial, force-feedback joystick connected to an orthopedic splint (2). Patients log into the website *javatherapy.com* and a physical or occupational therapist will guide them through a repetitive movement regimen intended to improve their sensorimotor skills. Such therapy has been demonstrated to be useful even several years following hemiplegic stroke.

The Rutgers Haptic Master II (RMII) has been used to increase hand strength in stroke patients using teletherapy (3). When the patient picks up an object like a rubber ball, the computer actuates the piezoelectric servo valves on the hand exoskeleton to provide sponge-like resistive *grasp* forces to the hand. The remote therapist can modify this resistance during the sessions to increase the patient's strength and to design an increasing complex array of virtual tasks for the patient to perform to challenge further their motor skills. Pilot clinical trials on post-stroke patients have indicated hand mechanical work increase when using the RMII.

Cooperative control using haptic devices has been attempted on several virtual reality platforms. A pair of 2-DOF master manipulators was used to simulate thumb and index fingertip contact with an object during a peg-in-hole insertion task (4-5). Dual-arm contact with a steering wheel was simulated using a pair of 6-DOF PHANToM devices for arm motor control training (6). A pair of 6-DOF, parallel mechanism force displays was used to perform interactive patient-therapist tasks over the internet (7). Although predictive displays helped operators adjust for up to 3-second delays, explicit time-delay compensation was not implemented.

Several investigators have incorporated explicit time-delay compensation in the force-feedback loops of haptic systems. Scattering theory was explored to produce passive communications during the teleoperation of a metal block (8). Wave variables were introduced for a variety of master/slave scenarios with widely varying time delay (9). Passive control formulations were developed to stabilize interaction with virtual environments in the presence of time delay (10). None of the investigations we encountered, however, considered time-delay compensation in the context of multiple haptic displays.

OPERATING MODES

The robot testbed has two operating modes: tele-assessment and cooperative rehabilitation. In Tele-Assessment Mode, the clinician attempts to evaluate various properties of the patient's arm through bilateral manipulation over the internet. In Cooperative Rehabilitation Mode, the patient and therapist cooperatively manipulate common objects over the internet by moving their robot handles to accomplish a therapeutic task. Both modes are described in detail below.

Tele-Assessment Mode

In this mode, the robot handle that is grasped by the subject mirrors the movements made by the clinician's robot and

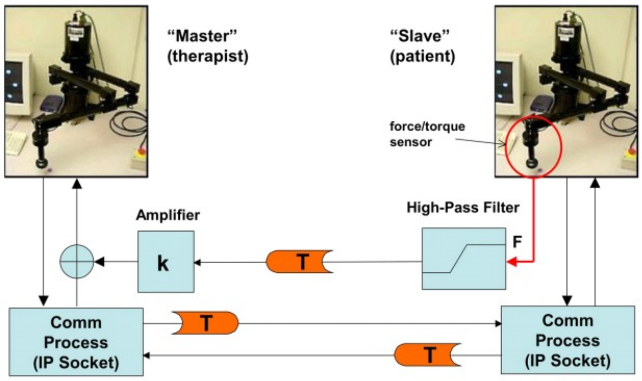

Fig. 2: Bilateral Tele-Assessment Mode Architecture.

vice versa. A force sensor on the patient's robot relays the forces exerted by the subject back to the clinician's robot, where the force pattern will be 'displayed' on the haptic interface. This position-based 'force-reflection' is commonly used today in robot-assisted surgery.

The system block diagram for assessment mode in Figure 2 is similar to the bilateral force feedback architecture used in master/slave teleoperation. Both the master and slave are under Cartesian proportional-derivative (PD) control: the position of the master becomes the desired position of the slave, and the position of the slave becomes the desired position of the master (the same holds for velocity). The position and velocity data for each robot are '*packetized*', sent across the internet using an internet socket, and picked up by a communication process at the other side, where they are unpacked and used by the local controller.

As the PD controller filters out from the patient's arm the high-frequency content that might be useful for patient assessment, a force-sensor capable of picking up high frequency phenomena, such as hand tremor, was used to augment the haptic display. The force sensor output is high-pass filtered and transferred alongside the position/velocity data to the therapist's robot, where the output is amplified by a gain k and added to the PD control input. The high pass filter is necessary to remove bias readings that are normally present in the force sensor, which would otherwise cause a position offset (11).

Cooperative Rehabilitation Mode

The control architecture for the cooperative task is shown in Figure 3. In this scenario, both therapist and patient robots are considered *masters* that are independently interacting with the virtual object, which is considered the *slave*. The virtual object generator (VOG) applies the sensed 'interaction' forces from the masters and then calculates the resultant motion of the object. The motion of the object at each 'contact' point is then transmitted back to each master where it is tracked by a controller.

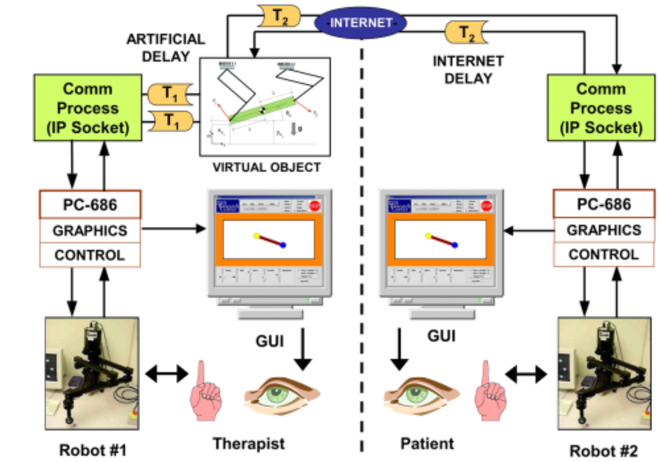

Fig. 3: Hardware configuration for Cooperative Rehabilitation Mode.

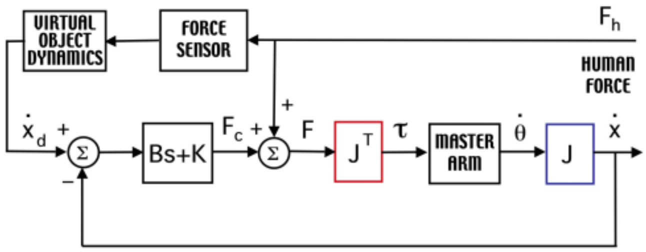

Fig. 4: Admittance controller block diagram.

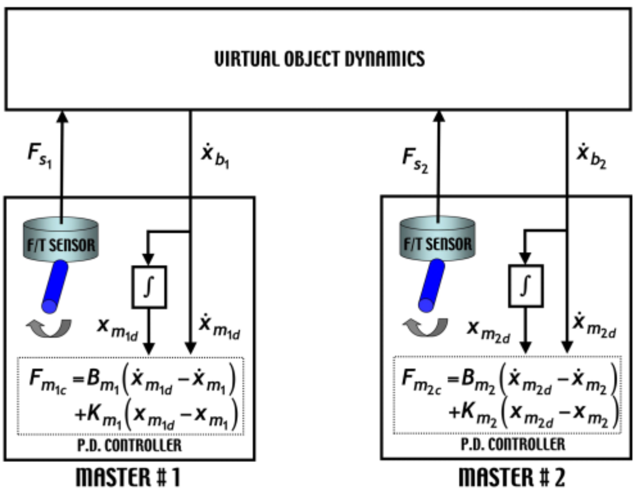

Fig. 5: Cooperative Rehabilitation Mode architecture using admittance control.

The virtual object dynamics are calculated via a separate process on one of the master arm computers. T_1 and T_2 are the time delays caused by either internet transit or computational processing. If the object dynamics are calculated on the master 1 computer, then T_1 is primarily the computational delay for the VOG process (essentially zero), and T_2 is the internet time delay for a signal to reach master 1 from master 2. To maintain a truly cooperative task, however, the two time delays should be matched. Therefore, an artificial time delay based on a moving average of the internet time delay is applied to the master control computer hosting the virtual object process (master 1 in this case).

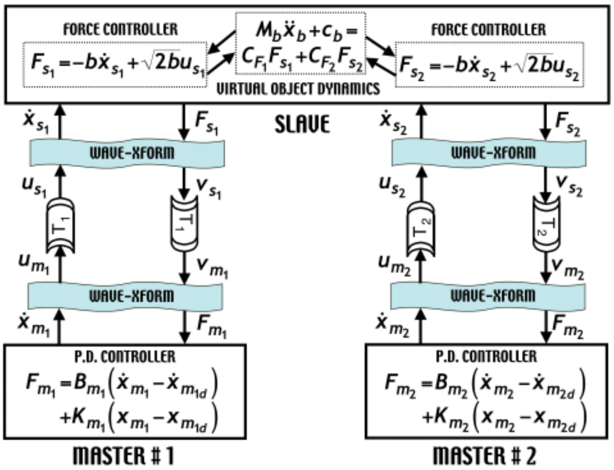

Fig. 6: Wave variable control architecture.

HAPTIC CONTROL-TIME DELAY COMPENSATION

In both operating modes, the core of the haptic controller is a Cartesian PD controller that servos on the position and velocity of the handle

$$F_c = B_m(\dot{x}_{md} - \dot{x}_m) + K_m(x_{md} - x_m) \tag{1}$$

where x_m is the position of the handle, F_c is the commanded Cartesian force, and B_m and K_m are diagonal damping and stiffness gains, respectively. For the cooperative mode, an additional force loop wraps around the servo loop as shown in Figure 4 to provide compliance (12). For the cooperative mode realization shown in Figure 5, the 'sensed' human forces applied at each handle are used as the force inputs to the virtual object dynamics to generate the motion command inputs to each master.

The haptic controller works well for the interconnected robot configurations shown in Figures 2 and 3, as long as the roundtrip time delay is under about 100 msec. As the time delay begins to exceed 100 msec, the passivity of the controller becomes severely compromised and can drive the system unstable. To restore passivity in the system, compensation using wave variables emerged as the most natural approach for performing cooperative tasks over the internet (13).

The wave variable architecture for the cooperative mode is shown in Figure 6. The strategy is similar for tele-assessment mode except that the second master, rather than the virtual object, is the slave. Instead of using the sensed force to impart force commands to the slave, force and velocity data are used by the master to generate an impedance 'wave' command that is transmitted and decoded by the slave side into a force command for cooperative rehabilitation mode or a velocity command for tele-assessment mode. Part of the incoming wave is subsequently reflected back to the master. How much of the wave is reflected depends upon the impedance of the slave; a yielding environment will not reflect the incoming wave as greatly as a rigid wall. The wave impedance b is a tuning parameter used to tradeoff speed and force; a high b produces an inertially dominant system, and a low b presents a more rigid interface (14).

Each force to be 'applied' to the slave is computed from the transmitted wave variable from the master using

$$F_s = -b\dot{x}_s + \sqrt{2bu_s} \tag{2}$$

where the incoming wave to the slave $u_s(t)$ is the delayed output wave from the master, $u_m(t-T_{delay})$. After the virtual object dynamics are computed, the virtual object generator emits its outgoing wave variable using

$$v_s = \frac{b\dot{x}_s - F_s}{\sqrt{2b}} \tag{3}$$

where the incoming wave to the master $v_m(t)$ is the delayed output wave from the slave, $v_s(t-T_{delay})$.

The desired master velocity, dx_{md}/dt, is computed from the master force F_m and return wave variable v_m as follows. The outgoing wave from the master is

$$u_m = \frac{b\dot{x}_{md} + F_m}{\sqrt{2b}} \tag{4}$$

If the master force command F_c is used to compute the master force in Eq (4), then $F_c=-F_m$ and Eq (1) and Eq (4) form a recursive loop (9). Substituting eq (1) into Eq (4) and solving for dx_{md}/dt gives

$$\dot{x}_{md} = \frac{\sqrt{2bv_m} + B_m\dot{x}_m + K_m(x_m - x_{md})}{B_m + b}$$
$$x_{md} = \int_0^t \dot{x}_{md}(\tau)d\tau \tag{5}$$

Note that the wave impedance for both masters was chosen to be identical since the time delays were matched and the devices were the same. The effect of an increase in time delay on the wave variable implementation is to decrease the system's natural frequency. The 'communications stiffness' K_{comm} is given by b/T_{delay}, thus the wave impedance should be increased in proportion to the time delay to maintain system bandwidth (9). However, the time delay also introduces an apparent mass proportional to delay, $M_{comm}=bT_{delay}$, which produces a heavier feel at the handle as the time delay (or wave impedance) increases. Thus, a tradeoff exists in wave impedance between maintaining high system bandwidth and low inertia at the handle.

Fig. 7: Detecting the edge of a spiral notebook during a tele-assessment test.

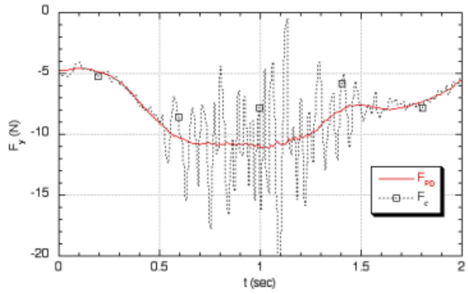

Fig. 8: Total force command (F_c) and PD component (F_{PD}) in x-direction for gain of k=5.

EXPERIMENTAL RESULTS

The control station and haptic controller operate on an AMD XP1800 PC with an Athlon 686 processor running at 1533 MHz. The control process was implemented in RT-Linux and uses approximately 1.2% of the CPU time at a rate of 200 Hz. Fast internet communication between robots was achieved using UDP protocol, which enabled transfer rates of 100 Hz for 16 byte datasets. A 3rd-order Butterworth filter with a 5 Hz cutoff was used for the high-pass filter in the assessment tests (15). The time delay for the therapist's computer, T_1, was set equal to the internet time delay T_2 in the rehabilitation tests to maintain symmetry between the VOG and each robot.

Tele-assessment

As a demonstration of the utility of the high bandwidth force feedback in assessment mode, an experiment was conducted in which an operator used the master robot to move the slave robot along the vertical edge of a spiral bound notebook as shown in Figure 7. The operator tried to maintain a constant normal force as the handle moved along the edge. Figure 8 shows the total force command for the master robot in the x-direction, F_c, superposed on just the PD control input force for a force gain of k = 5. The ripple in F_c was due to the force sensor picking up the 'tremor' caused by the spiral edge; this detection was totally missed by the PD controller, which only had a bandwidth of 5 Hz.

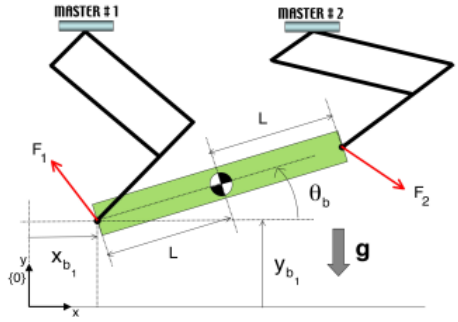

Fig. 9: Haptic master interaction with virtual beam.

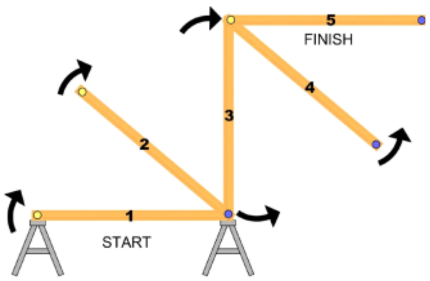

Fig. 10: Maneuver performed in the beam test.

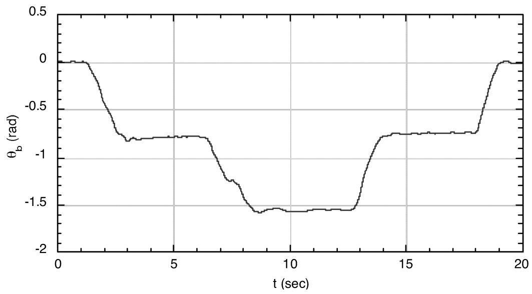

Fig. 11: Beam angle versus time under admittance control with no time delay.

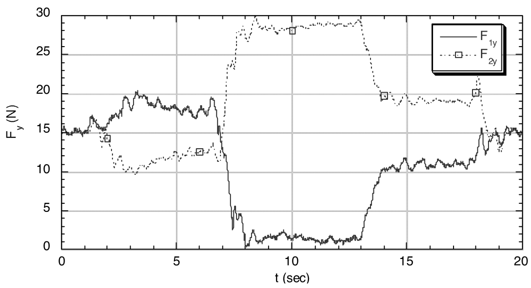

Fig. 12: Vertical force applied under admittance control and no time delay.

Cooperative rehabilitation

An example of a cooperative rehabilitation task is depicted in Figure 9. The patient and therapist 'pick up' opposite ends of a virtual beam by grasping the robot handle. The mass, length, and inertia of the beam can be adjusted to correspond to real-life objects using a Graphical User Interface (GUI) on the therapist's computer. The gravity vector points in the sagittal plane of the operator so that s/he is pushing away when lifting the beam (toward the screen in Figure 1). As the object is 'lifted', the side that is lower will begin to feel more of the weight, thus urging the participants to maintain the beam in a horizontal position. Additionally, if one side tugs on the object, then the other side feels it encouraging a cooperative strategy to lift the object.

The VOG calculates the dynamics of the virtual object being manipulated by the master arms. The center of mass of the beam is chosen to be at the geometric center, and the beam is assumed to be a uniform slender rod so that the inertia about its center of mass is given by $i_b = m_b L^2/3$. The orientation of the beam with respect to the x_0-axis is given by θ_b and the total length of the beam is 2L. The resulting beam dynamics are given by

$$M_b(x_b)\ddot{x}_b + c_b(x_b,\dot{x}_b) = C_{F_1}F_1 + C_{F2}F_2 + m_b a_g \tag{6}$$

where the gravitational acceleration vector is $a_g = [0\ -g\ 0]^T$. The complete dynamics for Eq (6) can be found in Carignan and Olsson (16).

Three sets of experiments were performed to illustrate the cooperative beam manipulation task over the internet: admittance control with negligible delay, wave variable control for an actual internet test, and wave variable control for simulated internet roundtrip time delays of 0.5 and 1 sec. In all tests, the master controller had a bandwidth of 30 rad/sec and was critically damped yielding gains of $K_m = 900$ N/m and $B_m = 60$ N/m/s. The beam parameters were $m_b = 10$ kg, $L = 0.15$ m, and $i_b = 0.075$ kg-m^2. A reduced gravitational acceleration of $g = 3$ m/s^2 was used in order not to exceed the force capacity of the robot.

In the first set of tests, the robots were co-located at the ISIS Center and the admittance control scheme of Figure 5 was used. The control and communication rates were 200 Hz, and the time delay within our own IP domain was only 0.15 msec. The beam starts out horizontally and then it is lifted by the haptic master on the left until it reaches the vertical position (see Figure 10). Then the second haptic master raises the right side of the beam until it is again horizontal. The plot of the beam angle θ_b versus time is shown in Figure 11.

The plots of the commanded vertical forces on the beam (sensed master forces) are shown in Figure 12. F_y for haptic master 1 goes to 0 N when the beam reaches a vertical position while haptic master 2 sustains the full load of the beam. After master 2 raises its side of the beam, the force becomes equally distributed again. The desired versus actual velocities for master 1 (not shown) indicate very good tracking by the PD controller. These plots for the zero time delay case represent the best possible performance for the cooperative task.

In the second set of tests, the wave variable control scheme of Figure 6 was used. The controller rate was

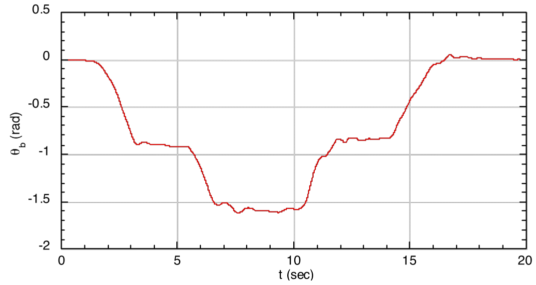

Fig. 13: Beam angle for Internet test (b=40).

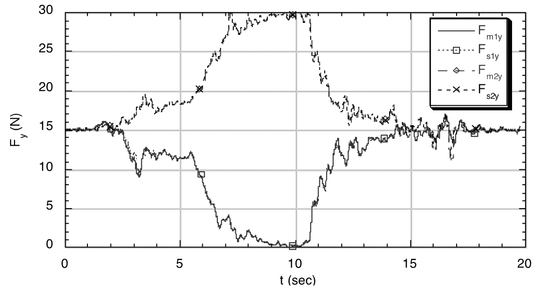

Fig. 14: Vertical force command for Internet test (b=40).

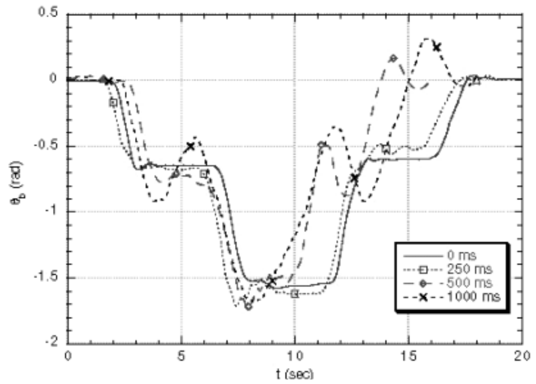

Fig. 15: Beam angle for time delays of 0, 0.25, 0.5 and 1 sec (m_b = 10 kg).

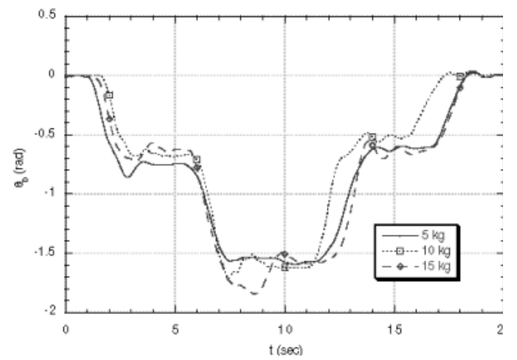

Fig. 16: Beam angle for masses of 5, 10, and 15 kg (T_{delay} = 0.25 sec).

decreased to 100 Hz due to the bandwidth limitation of the communication process, and the wave impedance parameter b was set to 40 to compensate for the additional delay. The roundtrip internet time delay between Washington, DC and Cambridge, Massachusetts for this test varied between 35 and 110 msec and averaged about 50 msec. A 10 sec window was used to compute a moving average for the artificial delay T_1 to be applied to master 1.

The beam was manipulated in the same manner as before yielding the beam angle θ_b shown in Figure 13. The commanded master and slave forces in the y-direction for the two haptic masters, shown in Figure 14, look remarkably remarkably similar to the zero-delay test. F_y for both masters starts out equal and then goes to zero for master 1 when the beam reaches a vertical position and master 2 sustains the full load of the beam.

Constant roundtrip time delays of 0.25, 0.5, and 1 sec were simulated to demonstrate the feasibility of the wave variable approach for longer time delays, and the results are overlaid in Figure 15. The decrease in system stiffness with increasing delay is evidenced by the lower frequency oscillations in the beam angle. In addition, the communications mass at the handle increases from about 0.5 kg for a 50 ms roundtrip delay to 10 kg and 20 kg for roundtrip delays of 0.5 and 1 sec, respectively. The heavier feel of the handle made it even more difficult for the operator to control, contributing further to the degradation.

Increasing the modeled physical mass of the beam has a similar effect to increasing the time delay under wave variable control. Figure 16 shows the beam angle during the same maneuver for masses of 5, 10, and 15 kg. As expected, it becomes increasingly difficult for the operator to manipulate the beam as the mass increases, resulting in large overshoots in the desired position.

CONCLUSIONS

The internet experiments conducted thus far indicate the feasibility of conducting both remote assessment and cooperative rehabilitation over the internet using robotic devices. During a cooperative internet task between robots spaced 500 miles apart, time-delays of up to 110 ms produced borderline instability without compensation. Under wave variable control, however, the system was robust to time-delays, and there was an almost imperceptible increase in the apparent mass of the handle. Packet loss was found to be less than 1% at transfer rates of 100 Hz when using UDP transmission.

Current work is focused on generating new cooperative tasks for stroke rehabilitation such as tandem canoeing over the Internet. The head-mounted display and tracker shown in Figure 1 are being integrated into the system to allow for more realistic simulations using 3D graphics rendered on stereographic head mounted display. Coordination of the haptic and visual feedback in the simulator (stereopsis) is an area of ongoing research, as are strategies for dealing with packet loss during less reliable transmission.

ACKNOWLEDGMENTS

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