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A New Bilaterally Teleoperated Robotic Vehicle Platform with Passivity Control

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***Abstract*— In this paper, a new bilateral teleoperated vehicle testing platform is proposed. In the platform, we apply a new Power-based Time Domain Passivity Control (PTDPC) method in an effort to improve the transparency. The platform is realized where steering angle commands were transmitted from a steering wheel interface to a remote vehicle, and road surface forces are sent back from the vehicle to the steering wheel interface. The communication channel between the steering wheel (master side) and the remote vehicle (slave side) introduces time varying delays in the transmitted signals. To ensure the stability, PTDPCs are applied to each side of the communication channel, which further improve the tracking performance as well and reduce the overall effort required of the human operator. The alternative advantage is the simplicity: the dynamic models of both master and slave side systems are not required to be known. The algorithms, hardware and software realizations are described thoroughly and experimental results are demonstrated to show the effectiveness of the proposed approach as well as the functionality of the platform.**

I. INTRODUCTION

Bilateral Teleoperation is the manipulation of a remote system where master side information from a control device is transmitted to a remote site, and environmental forces are fed back to the human operator. The sensory feedback can improve efficiency in interacting with the remote environment [1] [8]. This has applications for manual tasks that are sufficiently complex to require a human operator, yet are too dangerous or expensive to maintain a human presence.

All bilateral teleoperated systems are comprised of the same basic elements: 1) a human operator; 2) master hardware; 3) communications port; 4) slave hardware; and 5) the remote environment. The master hardware is the device with which the human operator interacts and the slave hardware is the device which operates on the environment.

Bilateral teleoperated systems are prone to instabilities due to various system non-linearities. These include signal quantization, zero-order-hold that occur with digitization, actuator miss-calibration, sensor measurement noise and time delay [3]. Delays as low as 0.1 seconds can destabilize an otherwise stable bilateral teleoperated system [2].

Time delay can be introduced into a communication channel system by increased transmission distances, or from data processing such as network protocols (TCP/IP, UDP, etc.), encryption or data validation. Network delays are not constant and indeed must be considered unbounded and constant damping levels can not be applied to ensure stability, as is the case with constant delay. In a bilateral case with the reflected force measured from a slave side sensor, the system designer must choose a gain for this force that is transmitted to the user. Often with delayed or otherwise unstable systems, this reflection gain must be set unreasonably low [1].

In this paper, a human/vehicle bilateral feedback scenario, where the ground forces are relayed back to the operator, who in turn effects changed in the vehicle steering system is employed. By increasing the stability of a teleoperated system through PTDPC, we can safely increase this reflected force gain and provide the user with better tactile information about the remote environment. This can improve the overall task performance, and decreasing task completion time. The advantage is further demonstrated by the real tele-operated robotic vehicle platform developed in the host lab.

II. POWER-BASED TIME DOMAIN PASSIVITY CONTROL

Power-based Time Domain Passivity Control (PTDPC), falls under the category of "passivity" control methods, which are based on the intuitive concept of energy transfer between systems. Most teleoperation schemes operate using a flow signal that travels from the master side to the slave side, and a reflected effort signal from the slave side to the master side. In a bilateral teleoperated scheme, the flow variable is velocity, v, and the effort variable is force F. Power flow, P, is the cross product of these two signals, $P = F \times v$. PTDPC works by monitoring conjugate signals of force and and velocity that are transmitted between interacting systems. If the power flow is deemed to be excessive, the remote node is deemed to be "active" (instead of passive), and a damping agent is employed to remove excessive power flow from the system (Fig.1).

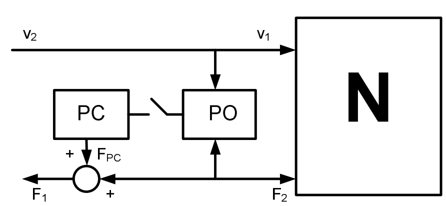

Fig. 1. Impedance Node with Passivity Observer and Passivity Controller

Every component of the teleoperation system together with human operator, master device, communications port, slave device and environment, can be thought of as an element, or sub-system, between which these signals are passed. Each element is deemed to be *passive* if it obeys:

$$P = Fv = \frac{dE}{dt} + P_{diss}, \quad (1)$$

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where E is the low-bounded energy stored within the system and P_{diss} is the (non-negative) energy dissipated from the system by friction or other damping mechanism. This means that all energy entering the system is either stored or dissipated [3]. Integrating Equation (1) gives us:

$$\int_0^t P d\tau = E(t) - E(0) + \int_0^t P_{diss} d\tau \geq -E(0), \quad (2)$$

and if assume the system starts from rest and substitute 0 for $E(0)$, using (1), Equation (2) becomes

$$\int_0^t F v d\tau \geq 0. \quad (3)$$

Equation (3) simply states that the energy entering a passive system must be greater than the energy leaving. The idea behind PTDPC is to monitor this power value in real time and ensure that it never becomes negative by selectively engaging a passivity controller. The metric to determine if a system has become active is termed "Passivity Observer" (PO):

$$P_{obsv} = Fv - \frac{dE}{dt}, \quad (4)$$

where P_{obsv} is the passivity observer. The E in the $\frac{dE}{dt}$ term is the port-side stored energy, which we assume can be modeled. As with the traditional TDPC, if P_{obsv} falls below zero we can determine that the monitored channel has become active, and the passivity controller (PC) is engaged.

If $PO \geq 0$ at any given time, the system connected to the monitored port is dissipating energy and can be considered passive. If the observer falls to a negative value, the PC introduces an adjustable element α which engages to dissipate the excess energy observed (as in Fig.1). The PO monitors exactly how much energy is generated by the unstable port, and this dissipative element removes only the excess amount of energy and is therefore lossless. The PO may also incorporate the environmental energy dissipation if the model is known; more information regarding this may be found in [4].

The PC is designed such that $P_{obsv} + P_{ctr} = 0$ when $P_{obsv} < 0$ where P_{ctr} is the power dissipated by the PC. The dissipation element α is computed as:

1) where $v_1(n) = v_2(n)$ is an input;
2) $F_2(n) = F_E$ where F_E is the environmental force;
3)

$$\alpha(n) = \begin{cases} -P_{obsv}(n)/v_2(n)^2 & \text{if } P_{obsv}(n) < 0 \\ 0 & \text{if } P_{obsv}(n) \geq 0 \end{cases}; \quad (5)$$

4)

$$\begin{aligned} F_1(n) &= F_2 + F_{PC} = F_2 + \alpha v_2(n) \\ &= F_2(n) - P_{obsv}/v_2(n). \end{aligned}$$

F_{PC} is the output of the PC. Similarly, α can be computed for the admittance causality case. The combination of the virtual environment and the passivity controller is passive and stable. Note that the passivity controller must be disabled when $v_2 = 0$ to avoid a singularity, in this case $F_1(n) = F_2(n)$.

III. Application of PTDPC to Bilateral Teleoperation

Passivity schemes can be applied to any network where the transmission variables can be in terms of power or energy. In [5], the author lays out groundwork for applying PTDPC to a bilateral teleoperated system. The commanded master and slave variables are simply delayed output signals from the other side of the communication port. Fig.2 further describes the variable transmitted through the communication port with different channel delays T_{d1} and T_{d2}. Hence we have

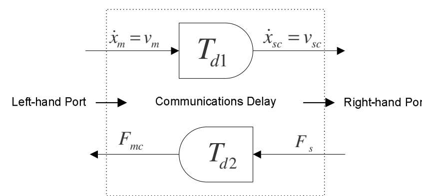

Fig. 2. Communications Channel

$$\dot{x}_{sc}(t) = \dot{x}_m(t - T_{d1}); F_{mc}(t) = F_s(t - T_{d2}), \quad (6)$$

where $x_m(t)$ is the master side position signal and $x_{sc}(t)$ the signal to the slave side, and $F_{mc}(t)$ is the transmitted force from the slave side (e.g. $F_s(t)$).

From [6], a positive constant b is introduced to relate the different units of force and velocity. Using (6), the power flow between systems is then determined by:

$$\begin{aligned} P &= \dot{x}_m(t)F_{mc}(t) - \dot{x}_{sc}(t)F_s(t) \\ &= \frac{1}{2b}F_{mc}^2(t) + \frac{b}{2}\dot{x}_m^2(t) - \frac{1}{2b}(F_{mc} - b\dot{x}_m)^2(t) \\ &\quad + \frac{1}{2b}F_s^2(t) + \frac{b}{2}\dot{x}_{sc}^2(t) - \frac{1}{2b}(F_s + b\dot{x}_{sc})^2(t) \\ &= \frac{1}{b}F_{mc}^2(t) - \frac{1}{2b}(F_{mc} - b\dot{x}_m)^2(t) + b\dot{x}_{sc}^2(t) \\ &\quad - \frac{1}{2b}(F_s + b\dot{x}_{sc})^2(t) + \frac{1}{2b}F_s^2(t) - \frac{1}{2b}F_{mc}^2(t) \\ &\quad + \frac{b}{2}\dot{x}_m^2(t) - \frac{b}{2}\dot{x}_{sc}^2(t), \\ &= \frac{1}{b}F_{mc}^2(t) - \frac{1}{2b}(F_{mc} - b\dot{x}_m)^2(t) + b\dot{x}_{sc}^2(t) \\ &\quad - \frac{1}{2b}(F_s + b\dot{x}_{sc})^2(t) + \frac{d}{dt}\int_{t-T_{d2}}^t \frac{1}{2b}F_s(\tau)^2 \mathrm{d}\tau \\ &\quad + \frac{d}{dt}\int_{t-T_{d1}}^t \frac{b}{2}\dot{x}_m^2(\tau)\mathrm{d}\tau. \\ &= \frac{1}{b}F_{mc}^2(t) - \frac{1}{2b}(F_{mc} - b\dot{x}_m)^2(t) \\ &\quad + b\dot{x}_{sc}^2(t) - \frac{1}{2b}(F_s + b\dot{x}_{sc})^2(t) + \frac{dE}{dt}, \end{aligned}$$

where

$$E = \int_{t-T_{d1}}^t \frac{b}{2}\dot{x}_m^2(\tau)\,\mathrm{d}\tau + \int_{t-T_{d2}}^t \frac{1}{2b}F_s^2(\tau)\,\mathrm{d}\tau, \quad (7)$$

by subtracting Eq.(1) from Eq.(7), we see that the dissipated power in the communication channel is:

$$P_{diss} = \frac{1}{b}F_{mc}^2(t) - \frac{1}{2b}(F_{mc} - bv_m)^2(t) + bv_{sc}^2(t) - \frac{1}{2b}(F_s + bv_{sc})^2(t). \quad (8)$$

For a passive communication system, we require P_{diss} to be positive, and since we cannot communicate the power levels from each side in real time, we must use two sufficiency conditions (master and slave) that depend only on local information at each side: i) master side as,

$$P_{obsv}^m = \frac{1}{b}F_{mc}^2(t) - \frac{1}{2b}(F_{mc} - bv_m)^2(t) \geq 0, \quad (9)$$

and ii) slave side as,

$$P_{obsv}^s = bv_{sc}^2(t) - \frac{1}{2b}(F_s + bv_{sc})^2(t) \geq 0. \quad (10)$$

Thus the right hand side of equations (9) and (10) forms the basis of two passivity observers, one each on the master and slave sides. It is when these values exceed zero that passivity is breached and some method of removing energy from the communication environment is required. Note that these POs do not take into account any modelled power flow from the other side of the communication channel; any *active* behavior is regarded as undesirable and will be addressed by passivity controllers, e.g. two PCs attached at each port are activated when P_{obsv}^m and P_{obsv}^s are less than zero. That is $P_{obsv}^m + P_{ctr}^m = 0$ or $P_{obsv}^s + P_{ctr}^s = 0$ where P_{ctr}^m and P_{ctr}^s are the power dissipation of the PCs.

PTDPC offers a novel solution to theinstabilities due to delay, in that it allows direct limits to the power transmitted to the user. The lack of integration in PTDPC is an additional safety feature, as it is not subject to the same issues related to data loss or reset as traditional TDPC.

IV. Bilaterally Teleoperated Robotic Vehicle Platform

In an effort to fully explore the utility of PTDPC in a real application, a robotic vehicle was outfitted for bilateral teleoperation. As shown in Fig.3, the five components are: 1) the driver or the human operator; 2) the steering wheel interface; 3) the communication port; 4) the vehicle steering mechanism; 5) the road surface. To improve repeatability and to prevent experimental bias, the human operator is replaced by a human operator input model.

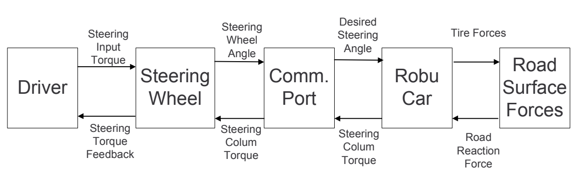

Fig. 3. Five Corresponding Components of a Bilaterally Controlled Robotic Vehicle Teleoperation Scheme

A. Human Operator Input Model

The purpose of bilateral teleoperation is to expand the capabilities of a human operator. Every teleoperation scheme must have some sort of human "driver" directing the operation of the overall system. A human input model was introduce to produce more repeatable test conditions. Fig.4 illustrates the validity of the human input model by comparing it to actual human steering input. A PID controller

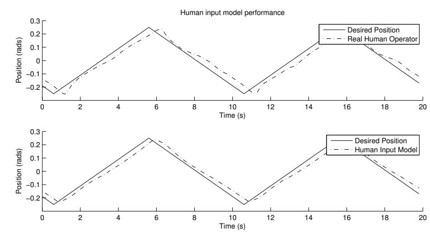

Fig. 4. Performance of a PID Controller vs. an Actual Human Operator

was developed and tuned such that it could respond to road forces, and would control the steering wheel in a method similar to an actual operator. The modeled human force, F_h, represents an additive force input sent to the motor.

$$F_h = K_P(x_{hd} - x_m) + K_I\int_0^t (x_{hd} - x_m)dt + K_D(x_{hd} - x_m)dt,$$

where x_{hd} is the desired human trajectory. For the steering experiments x_{hd} took the form of a sawtooth wave which varied between 0.25 and -0.25 radians. The controller gains were set as follows: $K_P = 5$, $K_D = 0.9$ and $K_I = 1$.

B. Master Hardware: Haptic Steering Wheel Interface

The apparatus used in these experiments was constructed in-house by the lead author, as show in Fig. 5. A haptic steering wheel interface was constructed with two axial bearings to isolate a single moment on the steering wheel. The rotary moment of inertia was calculated to be 0.0286 kg m^2.

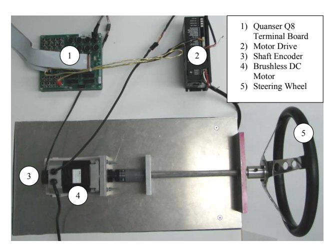

Fig. 5. 1-DOF Haptic Steering Wheel Use for Master Interface

A feedback force on the steering wheel is produced through a direct coupling to a MCG IB34005 brushless DC servo motor with a peak torque of 5.2 Nm. The motor is powered by a BMC12L servo drive, and the command signal is provided by a Quanser Q8 Data Acquisition (DAQ) card .

C. Slave Device: Robotic Vehicle

The RobuCAR, a programmable autonomous vehicle developed by Robosoft, was used as the slave vehicle. The vehicle has four independently driving wheels and independent front and rear steering. For these experiments, the rear steering was disabled and the forward speed for each wheel was equal.

The vehicle measures 2.1 m in length and 1.2 m in width; the total vehicle weight is approximately 500 kg. The maximum turning angle is 0.3 radians and the maximum forward velocity is 5 m/s (18 km/hour). An on-board computer provides the processing and command center for the vehicle.

Like an automobile, the RobuCAR has tie rods which transmit force to each wheel to control the steering. The tie rod in the front left wheel was replaced with a rod that had similar geometry but also contained a TS-250[1] load cell. This load cell measures the axial forces transmitted between the steering servo cam and the wheel. As the tie rod is a rigid body with negligible inertia, the forces on the tie rod can be considered proportional to the road contact forces; which in this case is equal to the actuator force.

D. Communication Channel

Typically, the communication channel is the element responsible for most of the overall system delay and also for the instability in a bilateral teleoperation scheme. In these experiments the communication channel is actually a series of devices and systems through which the information is relayed (Fig.6). Some devices, such as the Quanser DAQ card, are very robust and fast; any delays or data loss can be disregarded. Others, such as Microsoft Robotics Developer Studio (MRDS) service to service communication over the WiFi network, are subject to significant delay and occasionally lose packets of information.

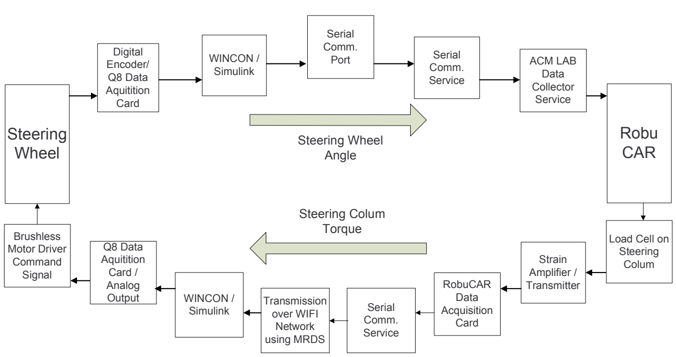

Fig. 6. 15 Steps Process to Send a Position Signal from Master to Slave and Return a Force Signal

The control architecture of this teleoperation scheme takes place on three computers; one each is associated with the master and slave hardware and one with the communication channel. The master-side computer communicates with a Q8 Quanser DAQ card. This computer processes the signals coming from the master hardware in a SIMULINK/WINCON environment. This SIMULINK environment contains a number of different control architectures, including the human operator input model (Fig.4), the master side passivity observer, as in Eq.(9), and the passivity controller. The second computer serves as an intermediary step in the communications signals between the master and slave hardware. The laptop is connected via serial cable to the master PC to connect to the SIMULINK environment housed in the master side computer, and communicates via WiFi to the robotic vehicle. The third computer is a component of the robotic vehicle. This computer commands the movements of the robot and processes signals from its sensors and data acquisition card, including the analog input signal from the wheel force sensor.

V. Bilateral Teleoperation of the Robotic Vehicle with MRDS Software Services

A. MRDS Software Programming Realization

The software programs that operate the RobuCAR are collectively referred to as *RobuBOX*. *RobuBOX* is a series of connecting robotic functions based on MRDS [7]. MRDS is specialized for robotics applications in two aspects: 1) that it is designed to perform as a series of discrete smaller programs, referred to as services; 2) that these services are designed to all run concurrently, as opposed to sequentially.

B. Teleoperation Control with MRDS Software Services

The RobuCAR uses pre-existing operating services (e.g. Cardrive) that handle basic low level functions such as sensor signal processing, obstacle detection and safety control. For these experiments four new services were developed to enable the bilateral teleoperation architecture. Using the MRDS communication protocols, commands from these services are transmitted to the *cardrive* service, which implements the velocity and steering commands. The following is a brief description of the function of each service:

1) Serial Communication Service: The sole purpose of this service is to provide serial communication to another PC. This service executes the serial transmit and receive functions every 100 ms. It transmits one *double*[2] variable and received eight separate bytes which are assembled to create a returning *double* variable.

2) PVS Data Collector Service: The PVS (Position-Velocity-State) Data Collector service collects data about the state of the vehicle. It receives updates from the IO card and the *cardrive* service with information about vehicle telemetry and the state of the IO card. It merges this data into one object called *PVSDataState* and makes this object available to the *DCD Supervisor Service* (DCD is just a name we used). This service executes every 200ms, which is the maximum execution rate as recommended by the robot manufacturer.

3) DCD Supervisor Service: The DCD supervisor executes higher level control regarding robot movement. It

[1]TotalComp TS Series S-TYPE Load cell with 250 lb capacity

[2]double precision floating point variable which occupies 8 bytes of computer memory

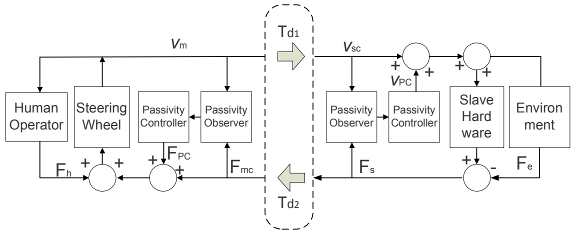

Fig. 7. Implementation of Bilateral Teleoperation System with PTDPC

receives and processes information from the *PVS Data Collector Service*, implements control methods and protocols, and commands the vehicle's velocity and steering angle. The PTDPC algorithm for the slave device is implemented in this service. The DCD Supervisor is associated with a graphic user interface which allows the operator to set the velocity speed and enable or disable the PTDPC. This service also records the slave side robotic telemetry, including vehicle velocity, steering position, commanded position, PO value, wheel force, Vpc value and a time-stamp. The *DCD Supervisor* executes whenever data is available from the *PVS Data Collector Service*.

4) DCD Dispatcher Service: The DCD Dispatcher is a communication service that passes commands from the *DCD Supervisor Service* to low level steering and velocity controllers (motor drivers). The *DCD Dispatcher Service* executes when new velocity and steering commands are made available from the *DCD Supervisor Service*. The *DCD Dispatcher Service* was constructed separately from the DCD supervisor so that different robots may be able to use the *DCD Supervisor Service* simply by changing the *DCD Dispatcher Service*.

C. Implementation of PTDPCs to the Platform

As outlined in the Section III, the master PTDPC controller is built in the same WINCON/SIMULINK environment that interacts with the haptic steering wheel. The slave PTDPC controller is constructed in the DCD supervisor service environment that processes the signals from the steering wheel. Fig.7 shows how the passivity controllers augment the incoming signals on either side of the communications port.

The passivity observer on the master side interacts with impedance causality; it monitors the local velocity signal and the force signal transmitted from the slave side. The master side PC adjusts the force feedback signal to make the system interaction with the master hardware passive.

The slave side interacts with admittance causality and the passivity controller adjusts the velocity signal that is sent to the vehicle steering controller. The passivity controller should correct for some of the undesirable feedback caused by delay.

The master side passivity controller outputs an adjusting force value, F_{PC}:

$$F_{PC} = \begin{cases} -P^m_{obsv}(n)/v_2(n) & \text{if } P^m_{obsv}(n) < 0 \\ 0 & \text{if } P^m_{obsv}(n) \geq 0, \end{cases} \tag{11}$$

where $v_2(n) = v_m(n)$.

The slave side passivity controller outputs an adjusting velocity value, V_{PC}:

$$V_{PC} = \begin{cases} -P^s_{obsv}(n)/F_2(n) & \text{if } P^s_{obsv} < 0 \\ 0 & \text{if } P^s_{obsv} \geq 0, \end{cases} \tag{12}$$

where $F_2(n) = F_s(n)$.

D. Experimental Gains

In the conducted experiments, a gain of $1/270$ lbs of vehicle wheel force per Newton of haptic feedback was chosen. It was found that higher values produced oscillations in the steering position, regardless of whether the PTDPC was applied.

For this experiment, the 'b' value for the slave side passivity observer was set at 5 and the 'b' value for the master side passivity observer was set at a value of 80. These values were set by taking an set of experimental bilateral teleoperation data and mathematically calculating the expected effects of the passivity observer and controller on the system. The values for 'b' were chosen for their levels of activity on the system.

To make the steering gain more in line with a commercial vehicle, the ratio of steering wheel angle to vehicle steering angle was reduced to $2/3$. Additionally, to achieve more effect from the slave side passivity controller, the Vpc term was increased by a factor of two. It was found that this additional contribution from the PC improved the slave side tracking without contributing to instability.

VI. Experimental Results

This experiment is designed to represent a teleoperated robotic vehicle performing normal turns with ideal road conditions. The test took place on a flat, clean floor. The RobuCAR was commanded to move forward with a velocity of 0.2 m/s, and a steering which swerved from left to right. The ideal steering signal was a sawtooth wave that varied between $\pm.25$ radians with a 10 second period. Fig.8 to Fig.9 show the test results with no passivity control.

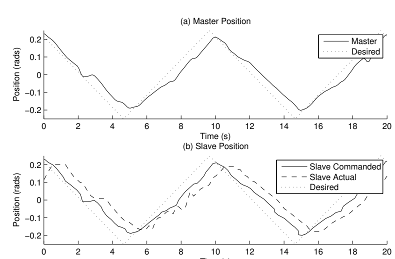

Fig. 8. Turns at Speed without PC: (a) Master steering input and ideal steering path; (b) Slave commanded position, actual position and ideal steering path (from master side)

We can see immediately from Fig.8 that with bilateral teleoperation the master steering input is not as smooth as with open loop control (Fig.4). The feedback forces cause the human operator to veer away from the ideal desired trajectory. We also see the effects of delay both in the transmission of the commanded velocity signal from master to slave, and in the actual response of the robotic vehicle. The total integrated human effort during the test period was 3.45 Nms.

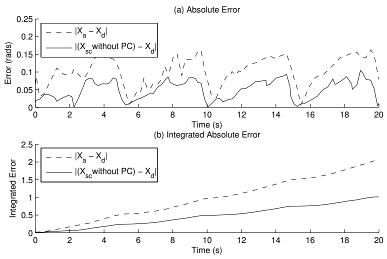

Fig. 9. Turns at Speed without PC: Absolute and integrated absolute error

Fig.9 deals with the performance metrics for the teleoperation system. Fig.9(a) indicates the difference between the slave command signal and the ideal slave position, where x_{sc} is the slave commanded signal, x_d is the ideal slave position and x_a is the actual slave position. This graph also displays the difference between the actual robotic vehicle steering position and the ideal trajectory. The periodic reduction of error corresponds to the reversal of commanded steering angle; at some point the ideal and actual commanded steering values must be identical. The total integrated error between the command signal and the ideal signal in this test is 0.04975 radians seconds.

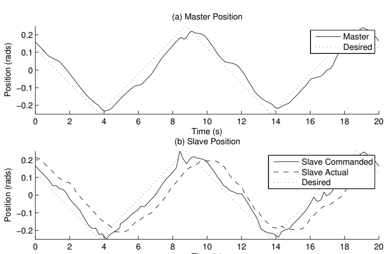

Fig. 10. Turns at Speed with PC: (a) Master steering input and ideal steering path; (b) Slave commanded position, actual position and ideal steering path (from master side)

Fig.10 through Fig.12 show this same test with passivity controllers engaged. The total integrated human effort in this test is 2.96 Nms, which is a reduction from the 3.45 Nms value recorded during the test without passivity control. Another difference is apparent when looking at Fig. 12, which shows the error with and without the passivity controller. The difference between the slave command signal and the ideal steering signal is compared to the slave command signal without passivity control; The total absolute integrated error for the test period is 0.0417 radian seconds with the passivity controller. If we subtract the contribution of the passivity controller to the commanded position, the total absolute integrated error for the test period is 0.04655. This value is is an improvement over the period recorded without passivity control, because the effects of the master side PC also smooth out the overall velocity signal. These tests show that there is performance improvement besides ensuring stability of the whole system by using PTDPC.

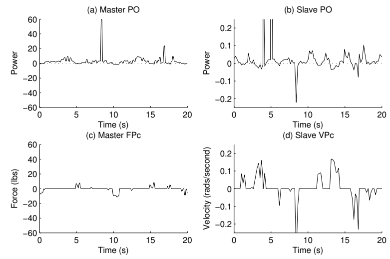

Fig. 11. Turns at Speed with PC: Master and Slave POs and PCs

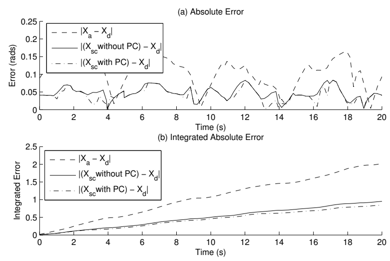

Fig. 12. Turns at Speed with PC: Absolute and integrated absolute error

VII. Conclusions

The work successfully applied the PTDPC approach to the teleoperated robotic vehicle in the authors' host lab. During the left-right turn test, the vehicle steering signal tracking was slightly improved by the application of PTDPC, with the overall human effort decreased by 0.49 Nms. The setup offers a new test platform for future research in the area of teleoperation systems where the system dynamics are not required to be known.

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