

# Haptics force feedback based on current control loop for remote manipulation

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**Abstract – This paper presents the development of a force control loop in a teleoperation system with master and slave robotic devices.**

**The force control based on current control loop has been applied to a teleoperation open platform consisting on electric master device, hydraulic slave robot and equipment for data acquisition and control programming.**

**This force control loop is applied in each master joint using a custom designed electronic board with current sensors for closing the control loop. This board gives information about the current consumption and the direction of rotation of each motor drive.**

**For maintaining the correct relationship between current and torque in each motor some experiments were performed to obtain the curves with an force/torque sensor from ATI.**

**Finally, an inexpensive force control is obtained in the master device, providing an accurate haptic feedback for the operator.**

## I. INTRODUCTION

Haptic devices are mechatronic systems which allow interacting with virtual or remote environments by perceiving forces to the user [1].

The man-machine interaction required for handling tasks generally used in teleoperation can be improved with the application of devices that interact with touch sense. A haptic interface is a bidirectional mechatronic device that allows the user of a teleoperated system to have a perception of the applied forces and a much more natural management of devices with greater precision in delicate operations system. This paper aims to design and implement a master-slave force control in a robot system with force feedback.

In the past three decades, research in force control has significantly advanced due to the great interest of robotic systems to provide information and sensory abilities [2] [3]. These abilities cover audio or visual feedback or even touch and force senses too, enabling autonomous operation also in unstructured environments.

From initial researches in the area of teleoperation using feedback force was designed to assist the human operator to manipulate objects in a remote environment with a slave manipulator. Recently cooperative robotic systems using multiple manipulators supporting one another to perform the tasks have been implemented [4] [5] [6].

The force control plays an important role in the performance and versatility of robotic systems in complex environments providing them with an intelligent response in situations where there is no visibility and allowing human-robot interaction [7].

Controlling the physical interactions between the robot and its environment is crucial for the execution of tasks where the end effector of the robot has to perform tasks [8] or manipulate objects on a surface. Other applications where force control is required assembly or machining operations. A complete classification of tasks that require force control, including non-industrial applications, it is virtually impossible due to the large number of these existing, well not this classification would be necessary to develop a strategy to control the interaction with the atmosphere [11] [12].

Designing an electronic board for measuring current in the master motors is one of the contributions of this work to acquire the reflection of forces on the master system. The master system is operated by two-phase ac motors in each of its degrees of freedom. The AC signals are generated through a board data acquisition real-time controller (PXI) and subsequently amplified in a power amplifier to supply the necessary current to the motors [9].

This paper describes the design of an inexpensive force control in a bilateral system using a current loop approximation. In this manner we avoid needing force/torque sensors in each master device joint; it also includes the design and implementation of an electronics board with current sensors to analyze the waves that command each joint drive.

The main contribution of this paper concerns the design of scalable control from the current control to the force

control for being also extensive to other types of control. The solution implemented in both hardware and software define the force control for a bilateral teleoperation force feedback system [10].

This solution offers a significantly low-cost solution and precise enough for telemanipulation haptic devices, in comparison with the use of several expensive force/torque sensors in each master Degrees of Freedom (DoF) with the consequent increment of undesirable weights and inertias that affect directly to the operator perception and immersion.

## II. TELEOPERATION OPEN PLATFORM

As a first approach, it is necessary to define the UPM teleoperation open platform in which the control has been implemented. As shown in Figure 1, this robotic teleoperation consists on following parts:

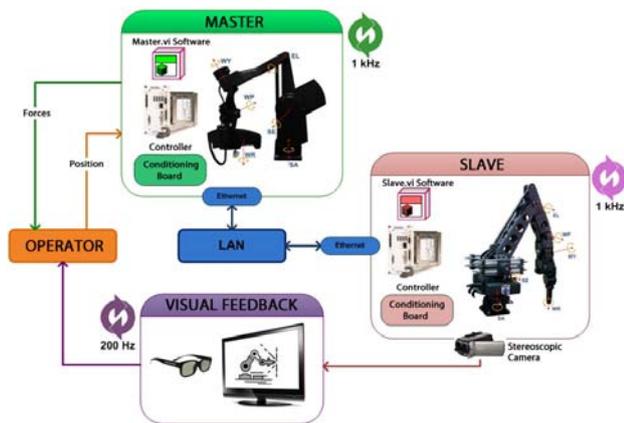


Fig. 1. Diagram of teleoperation open platform used in UPM telemanipulation laboratory.

- Two hydraulic manipulator with 6 DoF from Kraft Telerobotics ® with a gripper end effector. Figure 2(left).
- Two real-time controllers NI PXIe-1078
- Two master robots of six DoF each. Figure 2(right).

The control architecture has been designed to share all information between the master and slave systems through Internet. In this platform teleoperation information between master and slave is shared over a local network (LAN).

The real-time controller master system receives measurements of the position and pressure in the hydraulic actuators and sends real-time controller of the master device [13]. The master controller reads the current position of the joints and calculates the desired position and orientation of the slave, and sends them to the master device. The slave controller uses this information to close the loops control at each joint position.

The network protocol used for this teleoperation system was UDP (User Datagram Protocol). UDP uses a simple transmission model with a minimum resources

consumption [14]. UDP ensures the received packet belongs to robot last known state without waiting for data queues (these queues may lead to instability if the delay is large enough to produce a mismatch between master and slave). Therefore, this protocol helps maintaining the stability of the system in real time, as even with packet losses it will try to reach the last known value avoiding to get stuck with a big buffer, that may produce instabilities, when using other communication protocols.

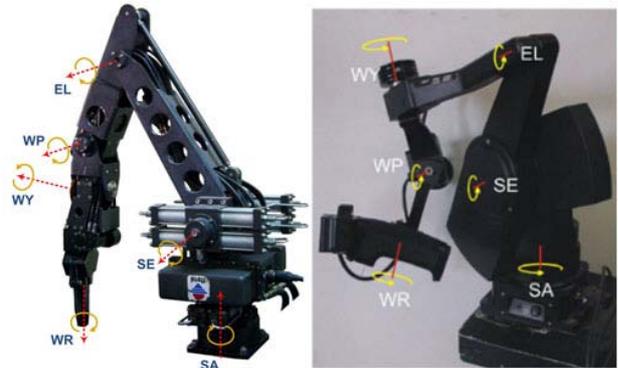


Fig. 2. Both, slave (left) and master (right) robots from KRAFT Telerobotics, and their joint correlation.

## III. FORCE FEEDBACK CONTROL

In this section the force control based on the current loop is described. For this, it is important to take into account the control requirements for this kind of teleoperation systems:

### A. Control system requirements

The developed system should have haptic feedback in the master device so the feedback provided to the user is the result of physical interaction with the remote environment [16].

The user experiences the information in a coherent visual and tactile feedback: Focusing in the touch sense, the force feedback requires high update rate to provide not only a realistic sensation but also to ensure stability. It is considered that a refresh in real time at least 1 KHz is necessary to achieve an acceptable haptic sensation [15]. Nevertheless, delays in the transmission of forces can cause instabilities in haptic system not being considered in the design stage. For this reason, all the hardware and software added to the system has to meet this real time requirement [17].

The realism of the interaction between operator and remote environment is influenced by the transparency of the system. If the teleoperation system would be ideally transparent such that operators would feel as if they interact directly with the remote or virtual task [19]. In fact, a system is considered transparent if the master and slave's position and force responses are identical respectively, no matter what the object dynamics are [20],

or even, a transparent system requires that the impedance transmitted to or “felt” by the operator equals the environmental impedance the human operator is interacting with [21].

But achieving perfect transparency, means that haptic devices should have neither inertia nor friction, and infinite bandwidth. Unfortunately, these features are unachievable and compromise each other. Because of this, the teleoperated system transparency is highly influenced by the bilateral control algorithm, so that a mandatory requirement of a functional remote handling system is to ensure system stability for all circumstances that may be encountered during the operation.

To satisfy these requirements, a network architecture that processes signals and perform the calculations necessary to control real-time system. This control architecture allows simultaneous connection of systems on the LAN or even the Internet, which is ideal to allow an open architecture that allows developers to develop and test your applications or control strategies [18].

#### B. Force Control based on Current Control

For a real-time teleoperation system with force feedback it is mandatory to have some kind of force reflection, to make the operator feel the remote environment.

The best way to implement this is adding force/torque sensors in all the joints, but this solution is expensive and introduces bad effects on the operation perception and maneuverability since weights and inertias due to sensors decrease the master device performance.

Other option less precise is to measure the current of motors to calculate consumption and estimate the torque in each joint by using the motor characteristic curves which correlate this to variables [24] [25] [26] [27]. This solution applied to our telemanipulation open platform makes necessary to measure 2 current waves for each motor to estimate torque and also the turning direction of the motor [28] [29] [30].

The slave controller system takes measurements of the force applied at each of the joints by means of pressure transducers installed in the interior of the hydraulic actuators. Information regarding pressure sensors is available in shared variables via Ethernet via UDP protocol.

In order to reflect and control the forces exerted on the master device, a electronic board with current sensors has been designed and integrated in the system.

#### C. Current Sensor Board

The design of the board includes signal conditioning in order to convert the sinusoidal current flowing through the motor in a DC voltage to be read easily by the PXI real-time controller.

Designing a board for measuring current in the master motors is one of the contributions, as mentioned

previously, the master system is operated by two-phase Alternate Current motors in each of its degrees of freedom. The torque and velocity of the motor are directly lead by the amplitude of the voltage set in the PXI outputs, and also relevant the load and the current consumed. The direction of rotation depends on the phase between both waves that could be  $+90^\circ/-90^\circ$ .

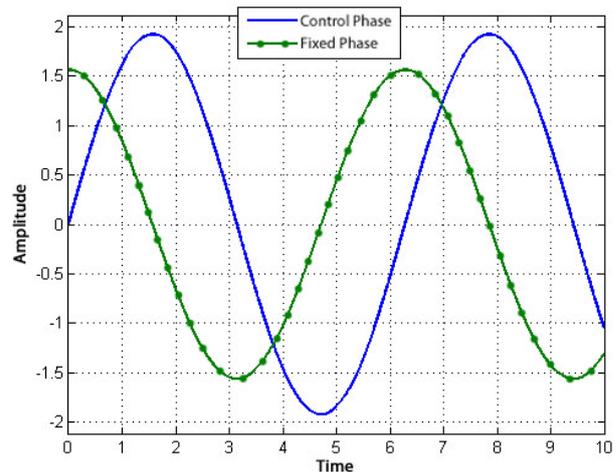


Fig. 3. Voltage waves (measured in Volts) used to control one master joint motor.

The AC current waves signals are measured through current sensors board data acquisition real-time controller (PXI) and subsequently amplified in a power amplifier to supply the necessary current to the motors.

Because the master device is equipped with two-phase AC motors that rotate in one direction or another depending on the offset of the input signals, torque is proportional to the amplitude of the current [3].

The electronic boards reads the RMS effective value of the current, giving a DC value form  $-10V$  to  $+10V$ . The positive or negative indicates the forward or backwards turning.

#### D. LabView implemented control

Finally, once the boards have been integrated in the system, the control loop has been made in LabView running in real time inside the masters PXI Controller.

For this control some signal conditioning were needed since the values from the sensor board has a high frequency noise, and also an amplified white noise near the zero value while motors are not moving, even receiving current values in the zero flat initial part of the torque curve. Because of this some filters were added before the PID control.

The PID control for Current Loop resulted to be just a PI, with a very low integral action for the offset correction.

The conversion from Current Loop to Force Loop was performed through the curves extracted from the Torque

test, by adding programmed equations blocks directly in the Current control Loop.

#### IV. TESTS

Some experimental test have been performed in order to obtain trustable motor models and good force feedback control based on current loop control:

##### A. Current Loop

Some test were performed measuring the current and applying the PID control. For several ranges of input values, external forces were applied to the master.

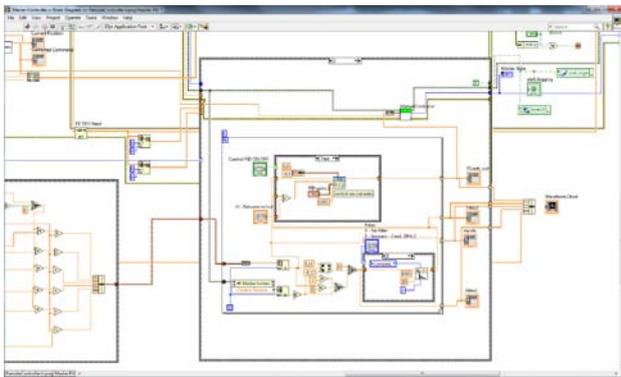


Fig. 4. Screenshot of the control implemented in LabView.

The PID performed a good control by maintaining the current value stabilized in the current work setpoint: the Proportional gain and the Derivative control action were set to have the fastest response without overshooting, and some Integral action was required to avoid steady-state error. The stabilization time was finally set to 2 ms in each motor, this delay does not introduce any instability in this 1kHz system.

Five PID values were calculated per master device, since all motors have different characteristic curves even being very similar and also the differences of the measuring electronic equipment in each joint: PID values are slightly different in each joint. This means that the calibration of the control loop for the sensor boards has to be independently calculated in each motor joint.

##### B. Motor Characterization Curves

As mentioned in previous section it is necessary to extract the curves from the motors for make a correct relationship between Current Control Loop and Force Control Loop.

A setup was performed at this stage to find the relationship between the current flowing through the motor and the torque exerted by the motor shaft. The setup uses a ATI @ SI-130 force sensor (see Figure 5). This sensor allows measurement of force and torque in six axes with its cell multi-axis load. The sensor has a system of intelligent data acquisition which can be

accessed via an Ethernet/DeviceNet interface. It can handle forces about 130N in all axis that is enough for our purposes. The force is directly related to the torque divided by the distance to the SA axis.

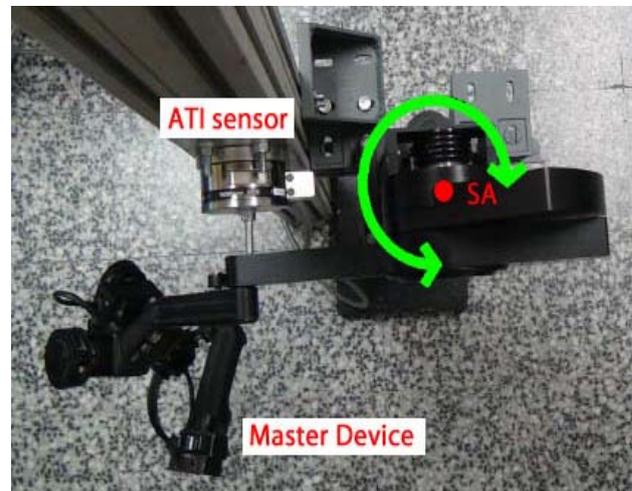


Fig. 5. Set-up for obtaining the Voltage-Torque- Current curves for SA joint.

Obtaining squared curve model between the current input and the torque in the output is the way to obtain directly the torque from the current measurement. Of course, each motor has its own model, so they have to be calculated independently for each joint.

In Figure 5 it is shown the set-up for measuring torques in one of the master joints. Figure 6 shows the curves of current and force obtained from this test in the SA motor. In this example both curves present a stabilization area over 1000 ms, due to the maximum limit of current sensors. There is also some oscillation in the force curve because of the electronics from KRAFT Telerobotics that build the current waves to control the motors as their boards do not make a linear conversion of the amplitude.

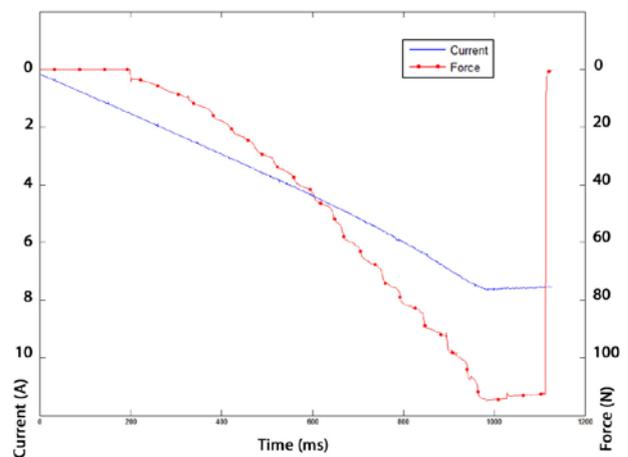


Fig. 6. Current and torque relationship in SA joint.

### C. Force Control Loop

The development of the force control loop only needs to add the current-torque model obtained in the previous step within the current loop for each of the motors. In this way we can establish a setpoint control in torque by controlling current through the sensor boards.

The way to do this is to introduce models into the software Labview control just before control loop to transform setpoint units, and the corresponding inverse function in closed loop. From outside it works as a force control loop, as we set a torque for the motor (the force depends on the distance from the applied torque axis) and we compare the torque transformed from the current measurement. But internally it still has the current loop and the transformations from the characteristic curves model of the motor.

## V. EVALUATION

Finally some tests were performed measuring the force with the ATI sensor and applying different external stimulus to the device, while setting different torque setpoints.

The results were a correct control with very slightly and assumable error between the force estimation and the values measured with the ATI sensor. This is mainly due to the different electronic components used that introduce some errors because of the resolution and also that they do not have a perfect linear response.

Adding also the oscillation due to the current wave generator boards from KRAFT that motors use, all these effects produces some oscillating error between the torque measured in ATI sensor and the calculated torque through the current feedback. This error is always less than 5% of the mean torque value: this means that for example handling 100N there is a maximum error of 5N, although human being could perceive this variation, it is not very significant [22] [23], it could be considered as negligible in most teleoperation applications; but may be this solution would not be suitable for applications with very accurate and dexterous teleoperation requirements.

For general purpose force control we can conclude that the PID control applied to force feedback is successfully implemented, having a good response and stabilization to the force/torque setpoint values, without adding weight in each actuated joint due to expensive force/torque sensors required for the force/torque control loop.

## VI. CONCLUSION

In this paper, the implementation of a force feedback control in a robotic master used for teleoperation has been presented.

A electronic board has designed for measuring the currents of each joint in order to close control loops. This board gives information about the current consumption and the direction of rotation in each motor drive.

The force control based on current control loop has

been developed, correctly calibrated and been integrated into a teleoperation open platform.

The PID control applied to force feedback is successfully implemented, having a good response and stabilization to the force setpoint values.

This inexpensive force control provides an good haptic feedback for the operator, but it is not suitable for applications requiring less than 5% error in the force loop control.

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