

A SYSTEM FOR SPACE-TO-GROUND MULTI-DOF BILATERAL TELEOPERATION

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ABSTRACT

The goal of this work is to introduce a complete direct teleoperation system which can be used to execute 6-DOF tasks with force-feedback over an uncertain delayed communication link. The system implementation is based on the Sensoric Arm Master portable exoskeleton as the master device commanding an impedance-controlled Kuka Lightweight manipulator over mobile internet connection which approximates the behaviour of a direct S-band link connection to the ISS. The bilateral control is implemented using the 4-channel architecture with time-domain passivity control to ensure stability independently of the communication network characteristics. Video and data communication between the master and the slave side occurs over a bandwidth limited mobile Internet connection with an average 100 ms delay and 17% data loss. To handle the network limitations, video is compressed to keep the bandwidth usage to 96kbits/s. The results for a contact task with different environments show that the system remains stable at all time and that soft environments are accurately rendered but limited transparency is achieved for hard and rigid environments. In free-air, since weight and friction of the master device are not compensated, the operator feels forces up to 10N which deviate from transparency.

Key words: Bilateral teleoperation; Time-delay systems; Human-robot interaction.

1. INTRODUCTION

Robots are particularly well suited for executing tasks that occur in locations that are too dangerous for or inaccessible by human operators. However, for robot manipulators executing complex activities in unknown, unstructured environments - despite the recent increases in computation power - human input is still required for task planning and execution. To execute meaningful tasks remotely, the operator has to be able to simultaneously control multiple degrees-of-freedom of a slave robot and to efficiently receive information from the remote site. In these cases, haptic feedback has been shown to improve the operator task execution performance [She92]. Such

bilateral teleoperation systems can be used for applications in space exploration [SH11], nuclear material handling [She92] and robotic surgery [GSJ00].

In the particular case of space-ground teleoperation, which is the main focus of this research, the available transmission links have limited bandwidths and variable delays in the order of tens or hundreds of milliseconds with data loss up to 30%. These characteristics place constraints both on data transmission, in particular for video [KS13], and on the performance in terms of the achievable transparency [Law93] and stability [AS89]. Due to these constraints, teleoperation in space environments has so far been limited to teleoperation without force-feedback relying in local autonomy [HBDH94] and bilateral teleoperation of two degrees-of-freedom devices with limited force-feedback performance [PRLH06]. The ongoing Multi-Purpose End-to-End Robotic Operation Network (METERON) project, aims at demonstrating technologies which can be used for teleoperation in future exploration missions.

The goal of the work presented in this paper is to introduce a complete direct teleoperation system which can be used to execute 6-DOF tasks with force-feedback over an uncertain delayed communication link. For this purpose the portable 7-DOF SAM exoskeleton is used as the master device and a 7-DOF Kuka Lightweight robot is used as the slave manipulator. Communication occurs over the Internet using a GSM connection on the master side and a land-line connection on the slave side. This situation is analogous to the one corresponding to communications from space to ground over a direct S-band link [Sch11] and is used to prove the feasibility of the technology.

2. SYSTEM DESCRIPTION

The bilateral teleoperation system used in this work consists of a master side composed of the 7 DOF SAM exoskeleton arm master and a tablet computer running the GUI. The slave side consists of a 7 DOF Kuka Lightweight robot equipped with a Robotiq Gripper and an ATI force-torque sensor. A separate camera system is mounted on a pan-and-tilt unit for visual feedback from the slave side. The communication between the master and the slave side occurs over the internet using a land-

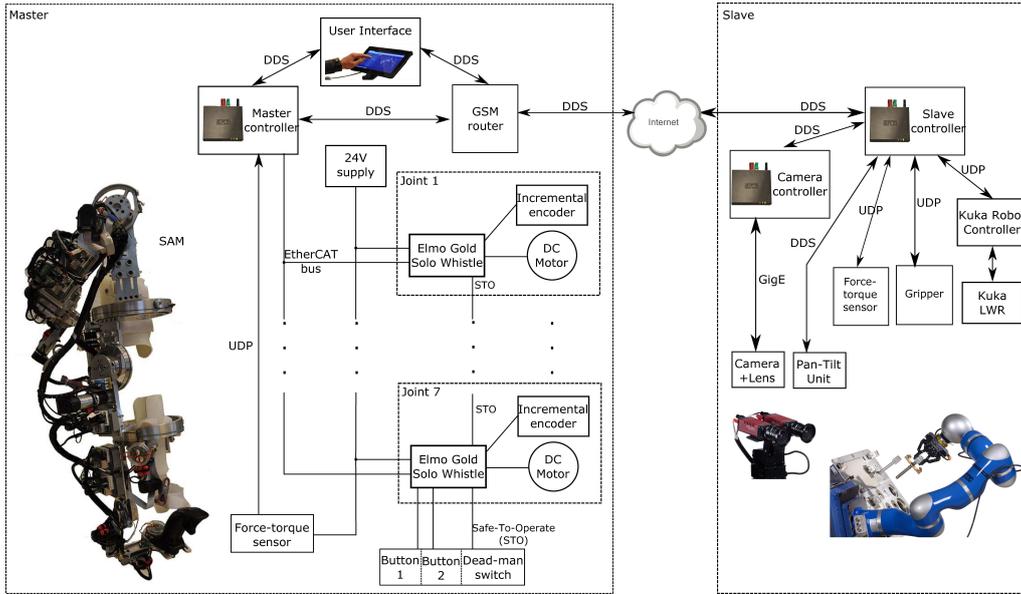


Figure 1. System architecture diagram

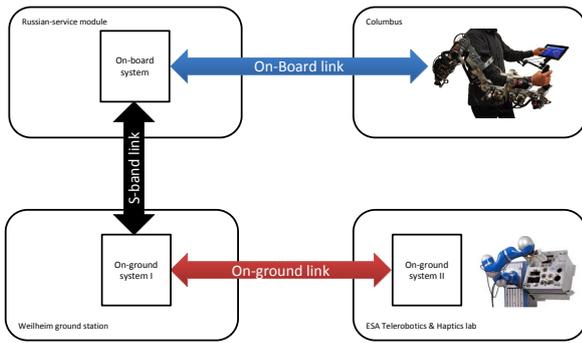


Figure 2. Bilateral teleoperation system with exoskeleton on the ISS commanding a Kuka Lightweight Robot (LWR) on the ground over a direct S-Band Link

based connection on the slave side and a mobile WAN router on the master side. The system architecture is depicted in Figure 1. This system is an analog for a future bilateral teleoperation experiment which will make use of a direct S-Band link, as shown on Figure 2. The remaining of this section explains each of the components of this architecture in detail.

Communication between the master and slave occurs over the Internet with a Conel LR7 GSM router on the master side and a regular high-speed internet connection on the slave side. To connect the GSM router to the slave network a Virtual Private Network (VPN) connection is established. To minimise the complexity of interconnecting systems with different addresses and to ensure that the received messages fulfil the required quality-of-service (QoS), the RTI Data Distribution Service (DDS) middleware [PC03] is used. All communication in this work makes use of best effort transmission (UDP) with

no deadline for message arrival and reading always the most recent packet. This type of QoS ensures the most consistent behaviour for real-time systems when using unreliable communication channels such as the Internet. The connection shows an average round-trip time-delay of approximately 100 ms and a data loss of 17%. These characteristics can vary depending on the network usage and the amount of data transmitted over the link; however, they were observed to be the most typical characteristics of the link during the experiments.

2.1. Master side

The portable Sensoric Arm Master (SAM) is a 7-DOF serial arm exoskeleton with each joint equipped with an incremental encoder and DC motors that are current-controlled locally using commercially available ELMO servo drives. A master control PC executes the control algorithm and the communication with the local joint controllers is done via an EtherCAT communication bus at 1 kHz. Table 1 shows the maximum torques provided for each joint. To measure the end-effector force and torques between the operator and the exoskeleton an ATI Gamma 6 DOF force-torque sensor with a resolution of 0.01 N and 0.0005 Nm is mounted at the base of the joystick handle. The force-torque sensor readouts are sampled via UDP a frequency equal to that of the EtherCAT network. As a safety mechanism, a dead-man switch is present on the operator joystick and the drive electronics hardware is only enabled when this button is pressed by the user. More detailed information on the system implementation can be found in [RSDE⁺14].

Higher-level control of the system, such as start and stop commands or joint calibration, is performed using a Graphical User Interface (GUI) by the operator on a

Table 1. SAM exoskeleton maximum torque per joint

| Joint | Max. torque (Nm) |
|-------|------------------|
| 1 | 4.4 |
| 2 | 4.4 |
| 3 | 6 |
| 4 | 3.6 |
| 5 | 2.2 |
| 6 | 0.4 |
| 7 | 0.4 |

10inch diameter Dell Latitude touch screen tablet computer running Windows 8.1. Visual feedback from the remote location to the operator is provided using the same interface. Both video and command communication with the remaining components of the system make use of the Data Distribution Service (DDS) communication middleware. The software receives DDS packages with H.264 network abstraction layer (NAL) units as the payload which is pushed into an H.264 decoder on the tablet. As soon as enough NAL units to decode a video frame arrive, the data is decoded and drawn on the screen. The encoding and displaying of one frame takes approximately 8ms. Swipe functions from the touch interface can be used to send pan and tilt commands to the remote pan and tilt unit. With a 2 finger pinching motion the zoom of the camera can be altered. Figure 3 shows an example of the calibration screen and camera view on the GUI running on the tablet.



(a) Calibration interface

Figure 3. Screen captures of the calibration screen and camera view on the Graphical User Interface running on the tablet. The calibration views also shows the joint numbers for the master device. The camera image shows the robot manipulator and the taskboard and peg used when executing peg-in-a-hole type of tasks.

2.2. Slave side

The Kuka Lightweight Robot (LWR), used as the slave device in this setup, is a commercially available 7 DOF lightweight robot which can be used directly in impedance-control mode. The Cartesian impedance can be configured in values ranging, approximately, from 200 N/m to 2000 N/m for translations and 2Nm/deg and 500 Nm/deg for rotations. The damping can be configured at the joint level between $0.1 \text{ Nm} \cdot \text{rad}^{-1} \cdot \text{s}$ and $2 \text{ Nm} \cdot \text{rad}^{-1} \cdot \text{s}$. An ATI Gamma 6 DOF force-torque sensor with a resolution of 0.01 N and 0.0005 Nm is mounted on the robot tool to measure the actual contact forces and torques. Both the master and slave force torque sensor

are set to 0 when the operation is started. The manipulator is controlled using the Kuka Fast Research Interface (FRI) [SSB10] at a frequency of 1 kHz. Using this interface it is possible to control both the tool Cartesian pose and forces/torques as well as the Cartesian stiffness and damping of the manipulator.

An Allied Vision Technology Prosilica GX2000C colour camera with an attached motorised zoom (8 mm to 48 mm) lens is used for capturing motion pictures. The camera is connected via a GigE vision interface to an encoding computer. As soon as a raw frame from the camera arrives at the camera controller it is resized to 352x288, transformed to monochrome and encoded with an H.264 encoder. In [KS13] a description is given on how the encoder parameters for a packeted network should be set. The encoder packs the data into NAL units which are sent via DDS to the slave. The encoder is set to use 84kbit/s on average, has a hypothetical reference decoder (HRD) set to 100ms, uses only 1 slice per frame and sends a P-slice every 4s. A P-slice is a slice of a frame which can be decoded without dependency on previous frames. The exposing of a frame takes 40ms and the encoding approximately 16ms. The HRD ensures a maximum delay for a bandwidth limited transport with the consequence of quality reduction of the P-slices.

3. CONTROL ALGORITHMS

For the bilateral teleoperation control, the 4-channel architecture is implemented. To ensure that the system remains stable at all times, the 4-channel time-domain passivity control presented by the authors in [RS14] is used. These controllers are expected to provide a high-level of transparency while making the system remain stable at all times, independently of the communication channel characteristics. This section details the implementation of the 4-channel architecture and the time-domain passivity controller used in this work.

3.1. 4-channel bilateral teleoperation control

The bilateral teleoperation control is designed using the 4-channel architecture [Law93] implemented on all the Cartesian degrees-of-freedom of the system. Using this architecture, the master sends both the position and orientation commands, as well as the actual force and torque exerted by the operator, to the impedance-controlled slave manipulator. The measured force and pose of the slave manipulator are sent back to the master device and used to compute the amount of force/torque that is rendered by the master device to the operator. The complete teleoperation control architecture is shown in Figure 4.

The master joint torques resulting from the force-feedback commands can be calculated at each instant using the principle of virtual work as

which can make it potentially unstable. To ensure stability, this excess energy has to be dissipated by means of a passivity controller. As shown by the authors in [RS14], it is sufficient to place passivity controllers on the master and slave output sides of the TDPN, since the voltage sources are assumed ideal, meaning they can both generate and absorb an infinite amount of energy.

In multi-dof systems excess energy can be dissipated in different manners. For example, the energy could be dissipated in the Cartesian direction with higher velocity, in the motion nullspace or equally distributed in every direction. The method used in this paper consists of dissipating the energy equally in every direction. The effects of uniformly distributing the energy is expected to minimise the effects on task performance execution. Taking the master side as an example, the force output of the series passivity controller for each Cartesian direction can be computed as

$$f_{M_i}^{PC}(n) = \begin{cases} \frac{(E_M^{\text{out}}(n) - E_M^{\text{in}}(n-T))/d}{\Delta T \cdot v_{m_i}^2(n)} & \text{if } E_M^{\text{out}}(n) > E_M^{\text{in}}(n-T) \text{ and } v_{m_i}(n) \neq 0 \\ 0 & \text{otherwise,} \end{cases} \quad (8)$$

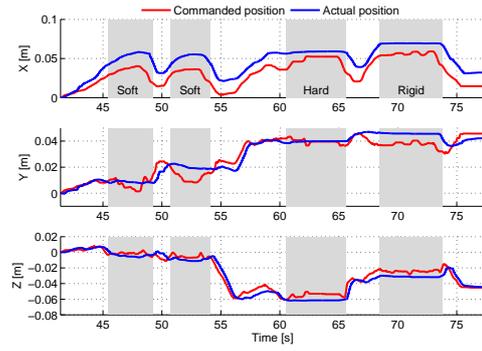
where d is the number of directions in which energy is to be dissipated, and where the subscript i is the actual direction for which the dissipation element is being calculated. Using the proposed combination of passivity observers and controllers, the multi-dof 4-channel can be made passive when time-delay is present on the communication channel.

4. RESULTS

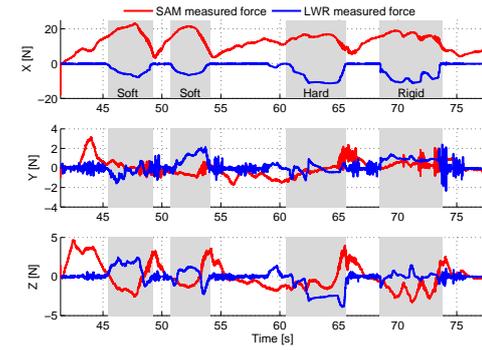
This section shows the performance of the complete bilateral teleoperation system when using the SAM exoskeleton to command the LWR, both in free-air and contact. The experimental scenario is a contact task with different environments in which the operator is instructed to drive the slave manipulator into contact with three surfaces of different stiffness, keeping in contact with each for a couple of seconds. The surfaces used are soft foam, hard foam and a rigid metal plate.

The behaviour of the system during the contact task with passivity control is shown in Figure 5. The results show that the system allows probing of all three environments without the existence of involuntary oscillations. From Figure 6 it can be observed that the passivity controller acts with small force commands just after contact with the environment is established, and acts with forces of up to 1.5 N on the master side and 2 N on the slave side when contact with the environment is released.

Table 2 shows the measured stiffness on the slave side and rendered stiffness of the environment computed from the ratio between the distance from the environment start



(a) Position response



(b) Force response

Figure 5. System position and force response as viewed from the master side during the contact task using time-domain passivity control. Contact with the environment occurs mainly in the X direction. The areas marked in grey correspond to moments in which the slave is in contact with the environment.

and the measured force, averaged throughout the entire contact duration.

Table 2. Comparison between actual environment stiffness and reflected stiffness to the operator

| Environment | Measured stiffness [N/m] | Reflected stiffness [N/m] |
|-------------|--------------------------|---------------------------|
| Soft | 450 | 620 |
| Hard | 3700 | 1600 |
| Rigid | 10750 | 4500 |

5. DISCUSSION

Using the presented teleoperation system, it is possible to execute 6-DOF tasks in bilateral teleoperation over a mobile internet network with variable time-delay. In terms of transparency for translational motion, the system provides a ratio between the measured and reflected environment of 1 for soft environments, a ratio of 0.5 for hard environments and a ratio of 0.2 for rigid environments.

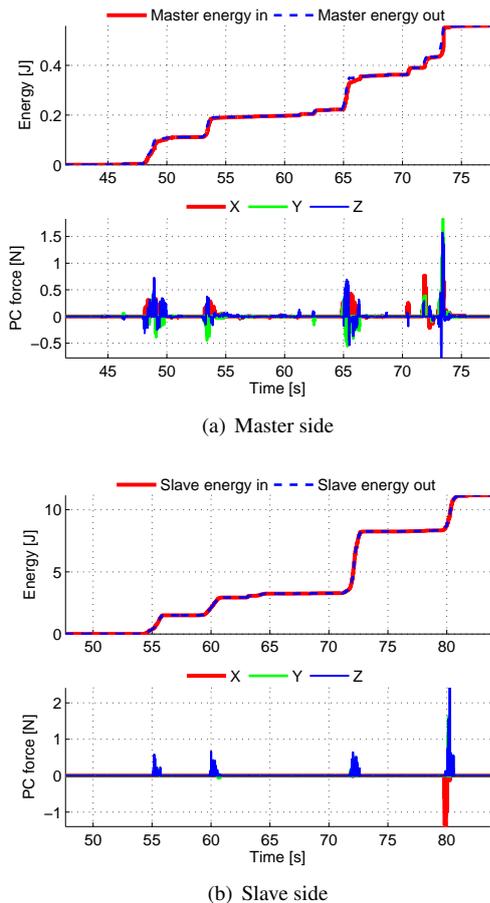


Figure 6. Master and slave time-domain passivity control response during the contact task

For rigid environments, the currently used DC motors do not provide enough torque to render higher stiffness to the operator. Despite the reduced transparency, the stiffness rendered to the operator by the master device is different for each of the three environments. In free-air motion, since the effects of friction and gravity are not compensated, the operator has to interact with forces different from 0. While these forces are within an acceptable range for human operators, long-term operations can be limited by these effects due to fatigue.

For rotational motions, the system transparency has not been measured; however, the gains of the control parameters have to be reduced due to the uncompensated effects of the gripper inertial forces. If the tuning rules for perfect transparency are followed, the system becomes unstable even in situations without time-delay. In the future, an inertial estimator should be used to avoid these effects and allow an increase of the gain parameters. The low-pass filter used to remove the vibration effects of the slave manipulator is also required to ensure that the operator can interact with the system without feeling these vibrations, which can be otherwise clearly perceived.

In terms of stability, the passivity controller ensures that the system remains stable at all times as shown in the re-

sults reported in Figure 5. To ensure stability of the system, the passivity controller issues force commands that prevent unstable oscillation from occurring. As observed in Figure 6, the passivity controller force commands result in high frequency noise, however no influence on operator motion is observed. Without time-domain passivity control, the system is not usable since involuntary oscillations are introduced when the slave is in contact with the remote environment.

Since the bandwidth for video transmission is limited to 90kbit/s, the video sent to the operator is black and white, and the quality, when objects move in the image is seriously reduced due to the compression algorithm characteristics. The ability to change the zoom and control the pan-and-tilt of the camera is very useful for observing different details of the taskboard during operations. This gives the operator the possibility of having a broader view during large range motions and a detailed image of the place in which more precise tasks need to be executed. During this experiment, different camera placements were tried which, combined with the kinematic mapping between the master and the slave, seemed to influence the performance of the operator during the experiment. A more detailed analysis of these effects should be completed to determine the ideal camera placement to maximise the task performance.

6. CONCLUSION

The teleoperation system presented in this paper allows the execution of contact tasks in bilateral teleoperation over a mobile Internet communication network with variable time-delays whilst maintaining system stability. Despite the existence of a delay, the operator can feel an impedance transmitted through the master device which allows distinction between stiffness values of different environments. In free-air motion, since the device is not capable of compensating its own weight and no friction compensation was implemented, the operator feels a force of up to 10N which does not prevent task execution but can reduce the amount of time the system can be used due to fatigue.

The combined force-feedback with the low bandwidth video transmission makes this system usable also in real-life situations in which high-speed cable internet connections are not available. Using this system it should be possible to investigate the relationships between transparency, video quality and master/slave mapping with the operator task performance in order to determine the best conditions for executing tasks remotely in an intuitive and efficient manner.

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