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EXOSTATION PHASE A: A 1-DOF HAPTIC DEMONSTRATOR

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ABSTRACT

EXOSTATION is an ESA project aimed at developing an arm-exoskeleton force-feedback device, to be worn by an astronaut in microgravity, supporting the telemanipulation of anthropomorphic robotic arms.

Within the frame of the first phase of the project, a fully integrated haptic demonstrator has been developed. The main idea was to build a complete 1-DOF (Degree-of-Freedom) haptic chain, as a proof of concept for the individual components, as well as to assess the correct behaviour of the selected integrated structure. This integrated structure would be the basis of the second phase of the EXOSTATION project, dedicated to the development of a multi-DOF wrist exoskeleton to be interfaced with the ESA upper-arm EXOSKELETON currently under development at ESTEC.

1. INTRODUCTION

In future space missions robots could be used as first explorers in hostile environments or as assistants for Extra-Vehicular Activities (EVA). This will require a higher level of cooperation between astronauts and robots. For this, the use of a portable device that would procure the robot operator with force-feedback sensations (also called haptic sensations) would highly increase the easiness of the command task.

In this context, ESA has launched the development of a humanoid servicing robot, called EUROBOT. Two control modes are foreseen to drive this robot: autonomous control and master-slave manual control. For this last purpose, an arm-exoskeleton has been developed at ESTEC [1][2][3]. However, up to now, this exoskeleton did not provide force-feedback to the operator. The EXOSTATION project was launched to implement a complete telemanipulation system, including a force feedback exoskeleton master arm and a slave 3D simulation-visualization. Due to technological complexity, it was decided to divide the project in two phases, the first one being dedicated to the development of a fully integrated 1-DOF haptic chain (*Phase A Demonstrator*) as proof of concept for each component and their integration.

The haptic chain is composed of four main components that will be described in more details in this paper (Fig. 1).

The first component is the Master Joint, which is a 1-DOF actuated master mechanical interface representing one joint of the exoskeleton. When developing a portable haptic device, the choice of the actuation technology has a high influence on the quality of the device, especially on the comfort of the operator and on the force-feedback performances. Several actuation technologies have been studied in the first phase of the project in order to find the best fit for the targeted application. The results of this comparative study have been reported in [4] and [5]. Based on these results, only brushed DC motors have been selected for implementation in the Phase A Demonstrator. However, three different motor configurations, described in more details in section 2, have been tested.

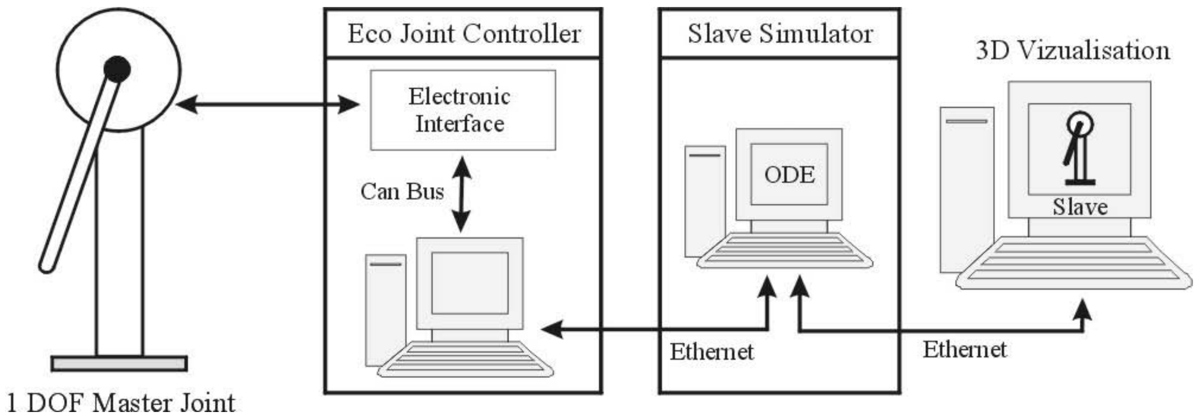

Fig. 1 Phase A Demonstrator haptic chain

The second component, the ECO Joint Controller is a PC-based controller running on QNX, connecting the Master Joint (via a CAN bus) to the third component, the Slave Simulator, using a TCP/IP communication protocol. It also involves several integrated circuits such as a torque sensor interface, an encoder interface, an actuator interface and a CAN interface.

The third component of the haptic chain is the above-mentioned Slave Simulator running on a conventional Linux PC, simulating on top of ODE [6] a 1-DOF actuated slave arm colliding against a virtual wall, and implementing the slave side of the haptic control loop. This simulation represents one joint of the future slave robot (such as EUROBOT) to be remotely controlled by the exoskeleton.

The final component is a 3D Visualisation Client based on OpenGL, which allows visualizing the state of the slave arm in 3D.

This demonstrator was used to perform haptic experiments with several control strategies depending on the actuator choice. The main results are presented below. The paper will end with the perspectives for the second phase of the project.

2. PHASE A DEMONSTRATOR DESCRIPTION

A. Master Joint

To represent one joint of the exoskeleton in the Phase A Demonstrator, a 1-DOF actuated arm has been developed. The set-up is based on DC motor technology (Fig. 2). DC motors are currently, by far, the most used haptic and robotic actuators. They are easy to install (no complex piping, wiring, etc.), clean (no oil leaks), quiet and easy to control [7]. The Master joint is basically composed of a Maxon A-MAX 32 linked to a cable capstan reducer (ratio 1:10). This type of reduction system, commonly used in haptic technologies, allows zero-backlash transmissions as well as low friction compared to common reducers, like planetary gearboxes. However, the size of the capstan is directly proportional to the coefficient of reduction, limiting its use for high reduction ratios. The Master joint is equipped with a 500 pulses per revolution encoder and a home-made strain gauge based torque sensor, both connected to the electronic interface of the ECO Joint Controller.

Based on this basic joint, three Master configurations were tested.

The first configuration, considered as the ideal case, is the basic joint itself, allowing no backlash and limited frictions.

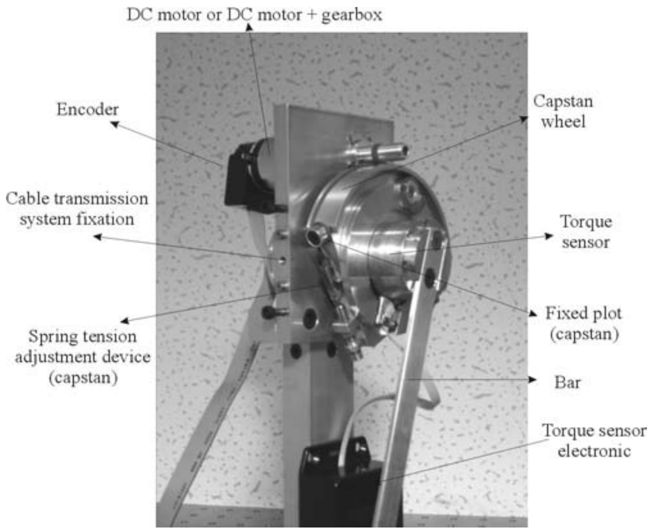

Fig. 2 Basic Master Joint based on DC motor or DC motor + gearbox

In order to increase the maximum output torque (required for exoskeleton applications), in the second configuration, a planetary gearbox is placed before the capstan reducer. Such a system allows for reducing the backlash inherent to the planetary gearbox by a factor equal to the reduction ratio of the capstan, while having a high global reduction ratio in combination with a smaller volume.

Another problem appearing when considering DC motors directly located on the joints axes of a portable haptic interface, is the weight to be supported by the operator. An idea is to delocalize the actuators to the back of the operator and to transfer the torque from the motors to the joints by means of a bowden cable transmission, as proposed in [2] and described in more details in [5]. This strategy is implemented in the third configuration (Fig. 3). The basic Master Joint (Motor Joint) is linked to the Robot Joint held by the operator, by means of cables. As the cables can only transmit traction forces, they are attached to the joints in a pull-pull configuration. They consist of steel Teflon-coated cables sliding in preloaded, low weight, Kevlar reinforced cable housings. These also present an inner Teflon coated surface for optimal low-friction operation. The pretension is obtained by a spring system that can be locked by a solid part to also enable experiments with stiffer transmissions.

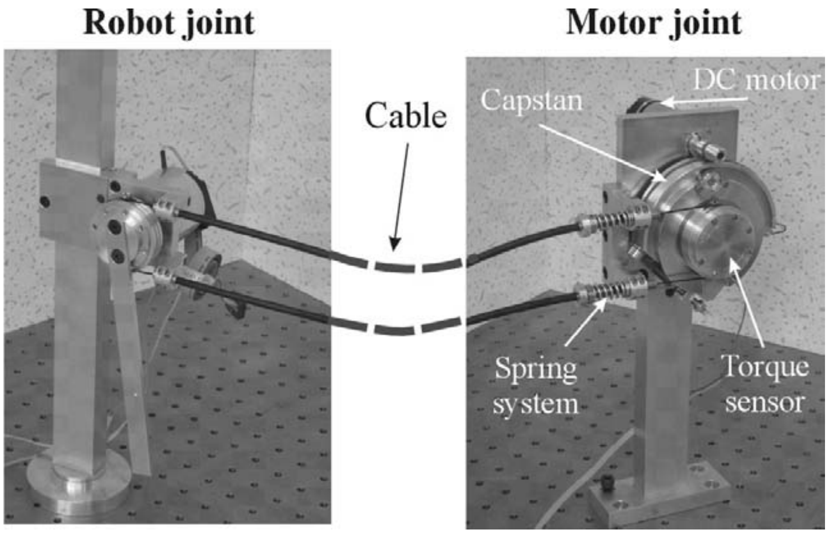

Fig. 3 Bowden cable Master Joint configuration

B. ECO Joint Controller

Several control strategies have been tested on the Phase A Demonstrator in order to compare them based on performance and stability criterions. We implemented two channels (impedance control) and four channels controllers. At the expense of more sensors in the set-up, the last allows for better results in terms of transparency and stability. The principle, illustrated in Fig. 4, is to exchange both torque (F_m and F_s) and position (V_m and V_s) between master and slave to command the opposite side. The position information is compared to the local value through a PD controller (proportional/derivative), C_m and C_s. The torque command can be used in open loop (not compared to the local signal) or through a PI block (proportional-integral), C_{fm} and C_{fs} (see dashed arrows). The position and the torque command are then added to create the actuator set-point. Depending on the type of Master Joint considered, some strategies could not be implemented. Indeed, due to high intrinsic friction in the DC motor + reducer case, the 2C control does not allow for free motion of the master and this control strategy could thus not be used.

These control strategies are implemented by the ECO controller (upper part of Fig. 4) that must exhibit hard real-time performances in terms of processing and data exchange with both Joint Controller and Slave Simulator. ECO is implemented on a PC running the real-time QNX™ Operating System (Fig. 5). This allows for a quasi-deterministic behaviour even though the TCP/IP protocol is used for communicating with the Slave Simulator. Sampling frequencies up to 1 kHz have been achieved with relatively slow hardware (i.e., 1 GHz CPU and 100 Mbit Ethernet).

Beside good general hardware performances, the main requirements regarding the joint controller were compactness and wiring/harness size reduction as several Joint Controllers are expected to drive the set of joints of a complete exoskeleton. Physically those will be located either on the exoskeleton itself and/or on the user's back. Hence they must be small enough to fit, while retaining full capabilities. PWM-type motor drives have been selected as these allow for reduced-size implementation with high efficiency as compared to bulky, low-efficiency (i.e., heat-dissipating) linear drivers. A dedicated EMI output filter has been designed to avoid interference with low-level sensor signals. A "smart" embedded torque sensor signal conditioning has been designed as well to fit within the torque sensor itself and to interface with the Joint Controller through only 2 wires with very good EMI rejection properties.

Finally the Joint Controller functions are implemented on a DSP/Microcontroller TMS320F2812 optimised for Motor applications. Beside the DSP core, several interfaces (i.e., ADC, PWM signal generator, encoder management, CAN interface, etc.) are present on the same chip, which makes it possible for the Joint Controller to fit on a few square centimetre circuit.

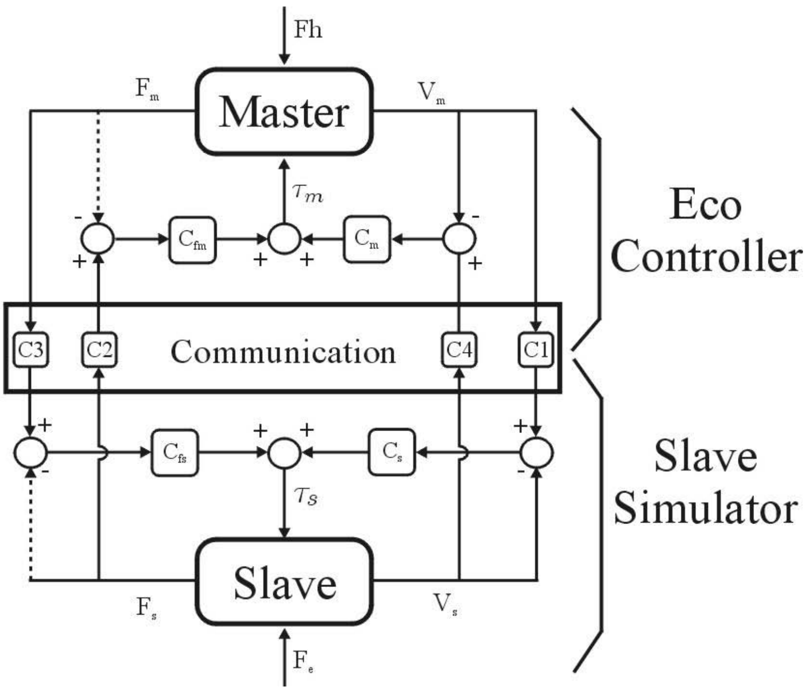

Fig. 4 4C controller structure for force-feedback between master and slave joint

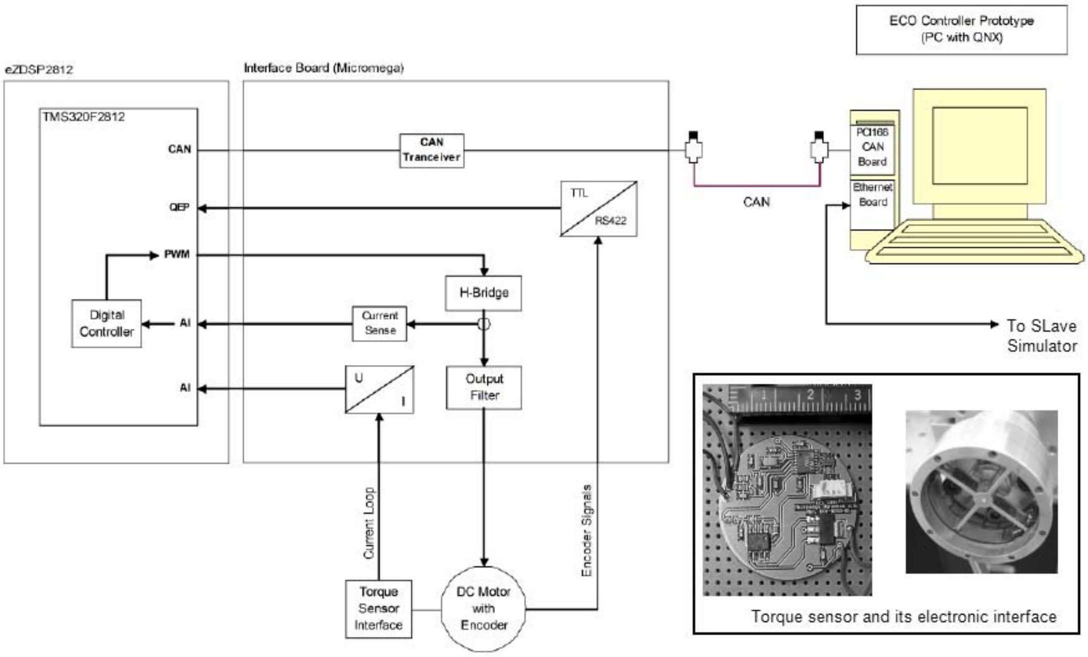

Fig. 5 ECO Controller and electronic interfaces

C. Slave Simulator

The simulation part of the Phase A Slave Simulator is layered on top of ODE 0.5. The simulator does the collision detection between the virtual slave and its virtual environment (i.e., a wall), and handles the dynamics and kinematics of the slave. The properties of the collision between the slave and the virtual wall can be configured. This includes the spring constant and the damping constant, describing how much force is applied on the slave when it collides with the wall. Although irrelevant for a 1-DOF robot, the collisions of the slave with itself can already be correctly handled.

While ODE provides the low-level functionalities for implementing the dynamics and kinematics simulation, as well as the collision detection, it is still up to the simulator to implement most of the medium-level and high-level logic, such as the collision handling and the simulation of the slave sensors. The development of the latter proved to be trickier than expected, as ODE does not directly provide sensors functionalities.

The simulator also implements the slave side of the haptic loop, and as such simulates the controller and the motor of the slave robot. The motor is modelled such that the real torque output is computed from the given electrical current, the current motor speed, and a linear friction factor (associated with the motor speed).

The Phase A Slave Simulator runs on an Intel Pentium 4 1.6 GHz, 256 MB of RAM, using Debian GNU/Linux. Because Linux is not a real-time operating system, the simulation is synchronized by ECO to keep up with the 500 Hz frequency of the haptic loop with the highest possible time precision.

To minimise the latencies and the possibility of real-time failures on the haptic loop, the Slave Simulator multithreads all the communication channels, and features two separate 100 Mbps Ethernet network cards: one for communicating with ECO, and one for communicating with the 3D Visualisation Client.

The haptic loop section between ECO and the Slave Simulator is implemented via TCP/IP. While other alternatives were evaluated such as UDP, TCP/IP was chosen because it is only marginally slower (i.e., latencies) while guaranteeing data and order coherency, allowing us to focus more on the haptic loop rather than on the network protocol. Some care must be however taken with TCP/IP when working at high frequencies. If not correctly handled, the Nagle algorithm and the delayed ACK mechanism implemented in most TCP/IP stacks can incur serious delays ranging from a few milliseconds to hundreds of milliseconds.

D. 3D Visualisation Client

The 3D Visualisation Client is not part of the haptic loop, but allows one to visualise the state of the slave arm in 3D (OpenGL is used for rendering the 3D objects) (Fig. 6). It also allows for remotely controlling the simulator such as changing configuration parameters, stopping, and restarting the simulation.

Among typical 3D rendering features, volumetric shadows were implemented to improve the impression of depth and the judgment of the distance separating the slave from the wall.

3. RESULTS

Experiments were conducted on each Master configuration. In each case, the Master device commands the virtual slave, described before, contacting a virtual wall. Several levels of stiffness were given to the wall: 0 (free motion), 500 N/m (soft contact) and 5000 N/m (hard contact). Most of the experiments were conducted with a sampling frequency of 500 Hz.

With the Basic Master 2C and 4C control strategies were implemented. Already with the 2C approach stable distinguishable stiffness could be sensed. However, lower gains were used in the controllers for stability purposes, leading to some position tracking errors in contact. The use of the four channels allows for reducing this error thanks to a better stability robustness compared to feedback gains.

With the Master Joint implementing a planetary gearbox, due to a too high gearbox reduction ratio (1:66) the intrinsic dynamic of the Master becomes too high in terms of frictions and inertias. This hampers free motion of the operator. As a consequence of that, a local force control and/or a 4C approach has to be used to at least allow for this motion. Moreover, we showed that in contact a simultaneous use of the 4C and a local force feedback at the master is necessary to avoid instabilities. With this kind of controller, we achieved a good feeling for the operator in free motion as well as good stiffness discrimination. However, we highlighted a problem linked to the saturation of the motor's amplifiers. In free motion, as the rotation speed of the motor is multiplied by the gear ratio, the back EMF produced is higher and can saturate the power stage amplifier. The amplifier can thus not inject the required current to achieve the expected friction compensation. This leads to an increase of the force sensed by the operator in free motion. In order to avoid that, higher voltages or lower gear ratios have to be used.

As for the Basic Master, the two control strategies have been analysed for the bowden cable delocalised Master Configuration. We achieved similar results when contacting the virtual wall. However, in free motion, the intrinsic torque friction of the Master is higher than for the Basic Master (around 200 mNm). This value depends on the initial preload of the cable, which has to be high enough to guarantee the position and torque transmission. The force feedback

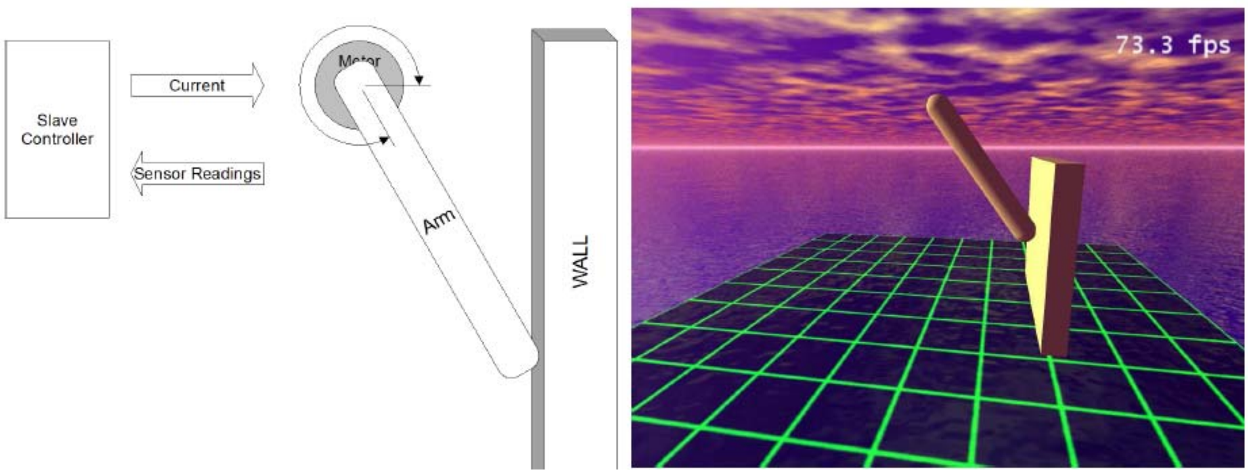

Fig. 6 Slave Simulator principle and 3D Visualisation Client output

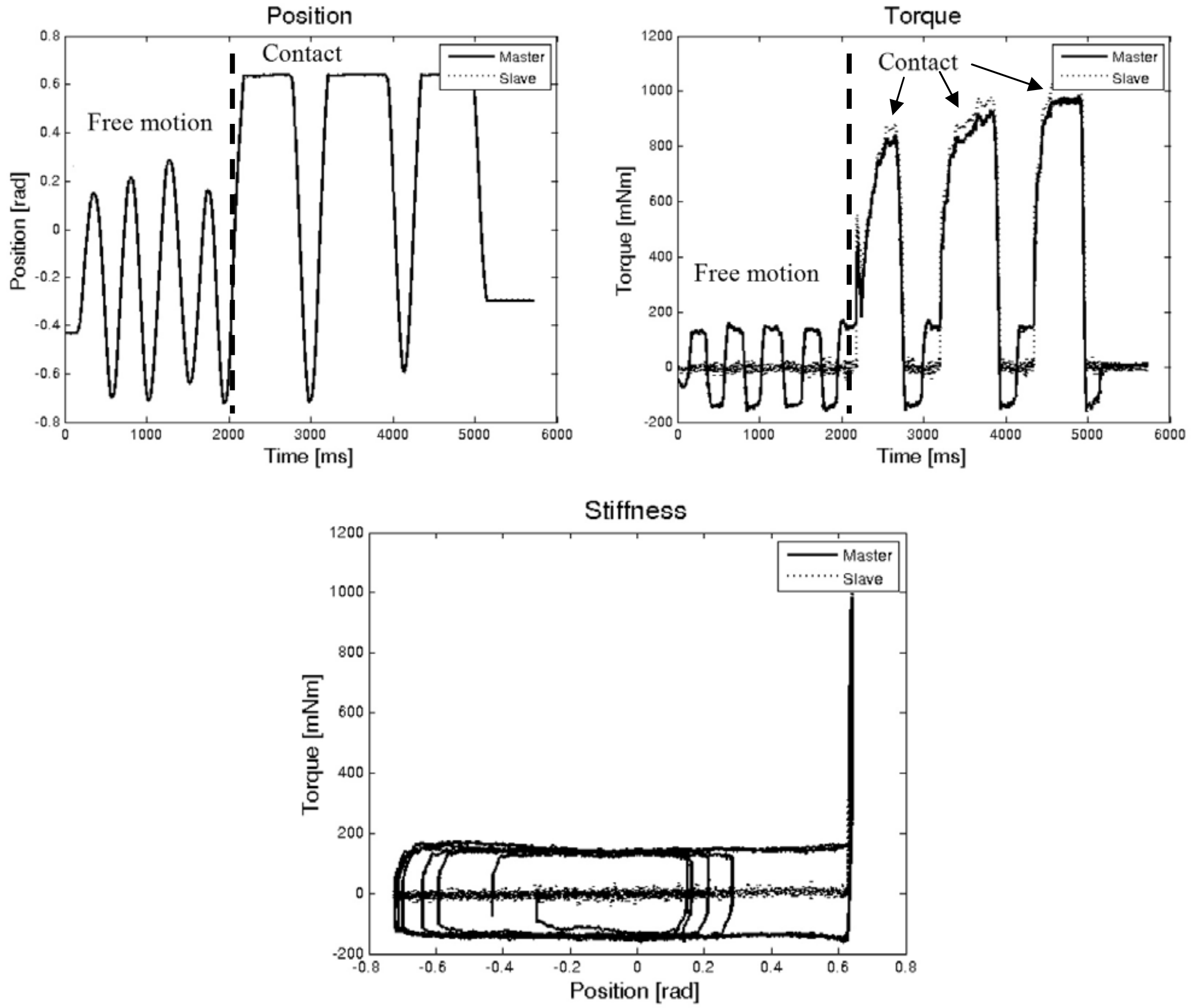

Fig. 7 Teleoperation results with bowden Cable Master Joint and 4C control

gain at the master side had to be modified to comply with the new hardware and to achieve proper torque tracking between Master and Slave. With the 2C control strategy, we observed a position tracking error in contact similar to what we previously obtained with the Basic Master set-up, but combined with more instability. Fig. 8 presents the results obtained when contacting a virtual hard wall with the 4C control strategy implemented. Three graphs are presented. For each of them, the Master and the Slave measurements are plotted. The first graph gives the position as a function of time, the second graph gives the torque measured by the sensor, and the third shows the stiffness experienced on each side of the teleportation system (ratio between position and torque). We can highlight good tracking in terms of position, torque and stiffness during contact. In free motion, during the first 2 seconds, we still have some additional friction due to the presence of the cables, which did not appear in to the basic case.

4. FUTURE

A second phase of the EXOSTATION project is expected to be initiated soon. Phase B would see the design and development of a prototype 3-DOF wrist exoskeleton ("EXOWRIST") for robotic control. The proposed EXOWRIST features force-feedback through 3-DOF actuation at a control loop frequency of 500 Hz, and includes a complete virtual test environment with a EUROBOT-like slave robot. The virtual environment is foreseen to include auditive feedback of contacts, to enhance the haptic sensation.

The EXOWRIST concepts and technology build upon the experience gathered in Phase A. Extra efforts are foreseen at the level of scalability, ease of use and stability. The EXOWRIST is designed to be integrated with an arm exoskeleton currently under development at ESTEC.

5. CONCLUSION

For all Phase A Demonstrator set-ups, we succeeded to achieve good force feedback and we validated the concept of a complete teleoperation system composed of a real Master and a simulated virtual slave. While ODE has limitations (especially when using non-parametric collision models, or when using complex joint-structures), we have shown that it is a suitable open-source solution for handling haptic-related physics simulations in a research-oriented environment.

Moreover, we have shown that it was possible to have the ECO Joint Controller, the Simulator, and the 3D Visualisation Client respectively running on different computers and operating systems, communicating via common network devices and protocols, while maintaining a high and stable frequency (500 Hz).

As far as pure haptic performances are concerned, for the Basic Master configuration the system is more stable in contact than with a real slave (experiments with real slave devices were conducted in parallel to this study). The behaviour, related to the choice of the gains, is however similar. If the required sensors are present, the use of the 4C control has shown its advantages over a 2C DFF approach (position tracking and stability).
In the case of the Master with gearbox configuration, we have highlighted some limitations of the use of a high gear ratio. Of course, the one used in this case is extremely large for haptic experiments. However, we believe that the simultaneous use of the capstan and a gearbox is clearly advantageous (decrease of the backlash, limited friction, etc.). Depending on the required output torque, a good ratio could be between 2 and 20. Also a smaller capstan could also be used to decrease weight and volume. Finally, we have shown bowden cable capabilities in terms of haptic feedback, their main advantage being the ease of motor delocalisation. However, this system is clearly more difficult to implement (e.g. manufacturing, maintenance, etc.) and can present more variable performances with time (e.g., modification of the tension, wear).

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