EXOSTATION: 7-DOF HAPTIC EXOSKELETON AND VIRTUAL SLAVE ROBOT SIMULATOR

Pierre Letier (1), More Avraam(1), Samuel Veillerette(1), Mihaita Horodinca (1), Elvina Motard(2), Jean-Philippe Verschueren(3), Andre Schiele(4), André Preumont(1), Michel Ilzkovitz(2)

(1)*Active Structures Laboratory*
Université Libre de Bruxelles
50, Av. F.D. Roosevelt, 1050 Brussels, Belgium
Email : scmero@ulb.ac.be

(2) *Space Application Services*
Leuvensesteenweg 325
B-1932 Zaventem, Belgium
Email : elvina.motard@spaceapplications.com

(3) *Micromega Dynamics*
Parc Scientifique du Sart Tilman
Rue des Chasseurs Ardennais
B-4031 Angleur, Belgium
Email : info@micromega-dynamics.com

(4) *European Space Agency*
Automation and Robotics Laboratory
P.O. Box 299, 2200 AG Noordwijk, The Netherlands
Email : andre.schiele@esa.int

ABSTRACT

EXOSTATION is an ESA-funded project aiming at developing a complete haptic control chain. The demonstrator is composed of a 7-DOF portable arm exoskeleton master, controlling an anthropomorphic slave robot interacting with its working environment. This system is meant to be used in telemanipulation and telepresence modes (master/slave control), making it usable in many applications including space exploration missions (planetary surface exploration and surface habitat construction), medicine, CBRNE crisis management (interventions requiring precise remote manipulation or performed in unstructured environment), industrial environments (remote maintenance).

1. INTRODUCTION

In a lot of applications, the use of a force feedback device can improve the performances and the efficiency of the user. These range from virtual reality in the domain of virtual training to the teleoperation of real slave robot in the field of remote maintenance, telemanipulation in severe environments (CBRNE crisis management) and space exploration.
EXOSTATION is an ESA-funded project aiming at developing a complete teleoperated haptic control chain. This system allows the operator who is wearing an exoskeleton haptic device to remotely control a slave robot. The slave is following every movement done by the operator and the exoskeleton procures him force-feedback sensations. These haptic sensations add the sense of touch and increase the easiness and quality of the control.

The global system is composed of four main components (Fig. 1). The first component is a 7-DOF exoskeleton, known as the Sensoric Arm Master (SAM), playing the role of the master robot in the haptic loop. The second component is the exoskeleton controller (ECO) composed of the master controller and local integrated joint controllers. These implement the real-time control strategies and manage the communication links with the slave robot simulator. The system also includes a virtual reality training environment composed of a Slave Simulator and a Visualisation Client. The Slave Simulator is a modular application simulating, on top of ODE (Open Dynamics Engine) [1] a 7-DOF actuated slave arm, cinematically equivalent to SAM. The 3D Visualisation Client, based on OpenGL, allows one to several users to visualize the state of the slave arm and provides a GUI to remotely control the simulator.

The developments presented here are based on results obtained in a previous study dedicated to the development of a fully integrated 1-DOF haptic chain representing one joint (master and slave) of the global telemanipulation system [2]. This paper describes in more details the components of the EXOSTATION system and gives some results obtained with the haptic chain.

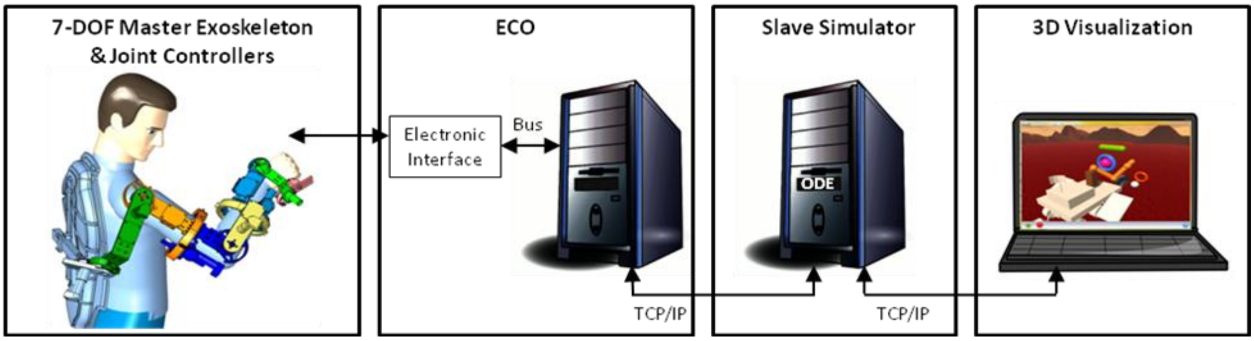

Fig. 1 : EXOSTATION system overview

2. GLOBAL SYSTEM DESCRIPTION

A. SAM Exoskeleton Master Haptic device

For the applications cited before, the use of a fully portable exoskeleton can improve the immersion of the operator during manipulation, as the operator does not have to be linked to a fixed base. However most of the exoskeletons developed until now are ground based [3][6]. This is due to the use of a heavy structure and big DC-based actuators to allow high torque level compared to the human arm joints capabilities. Only a few fully portable devices have been reported in the literature. In [7] water cooling is used to allow higher level of current and torque for a given actuator size. In [8], it was proposed to delocalize the actuators, with bowden-cables, in the back of the operator to reduce the weight carried by the arm. In [9] and [10], the DC actuation is replaced by pneumatic muscle actuators with a better power/weight ratio allowing a low system weight. However, these concepts bring more complexity due to the requirement of annex systems or cable routing. In [11] electric brakes are implemented, making the device light and compact. However the use of brakes can limit the type of sensations that the operator can feel, as the reaction forces from springs. The development of SAM is based on the assumption that the feedback force required to produce a haptic sensation is much smaller than the user capabilities [12]. Based on this principle, the SAM specifications, in terms of achievable joint torque, were selected to be around 1/20th of maximum human capabilities [4][13]. It allows designing a lighter and simpler system with integrated DC actuation.

SAM consists of a serial kinematics, isomorphic to the human arm (Fig. 2). There are 7 actuated DOF from the shoulder to the wrist, which corresponds to the minimum number of joint allowing full immersion of the operator. The exoskeleton can be adapted to the morphology of the user by a set of 5 sliders located in the various Aluminum links. A specific kinematics structure is implemented to maximize the workspace, compared to the normal human workspace and to avoid internal singularities [13].The current weight of the device is 6.5 kg, mainly from the actuators. Most of the mass is located near the shoulder.

Based on the results of a previous study where several actuation technologies were compared [14], each joint is composed of a brushed DC motor coupled with a cable capstan and gearbox with reduction ratio between 3 and 23 depending on the joint. The capstan type reducer, often used in haptic devices, allows zero-backlash transmission as well as low friction at the expense of a low torque/volume ratio. The diameter of the wheel is proportional to the reduction ratio. At the opposite, gearbox presents a good compactness but with a higher level of friction and some backlash. The purpose of combining the two types of reducers is to achieve a high enough torque combined with high compactness, low friction and low backlash transmission. The target was taken to be 1/20 of the maximum human torques [4][5]. A provision for friction compensation was added to joint 3 an 5, because of the special feature of the open bearings that integrates seals for dust protection.

Position and torque measurement are provided at each joint, respectively by an incremental encoder and an integrated torque sensor based on strain gages located inside the capstan reducer (Fig. 2).

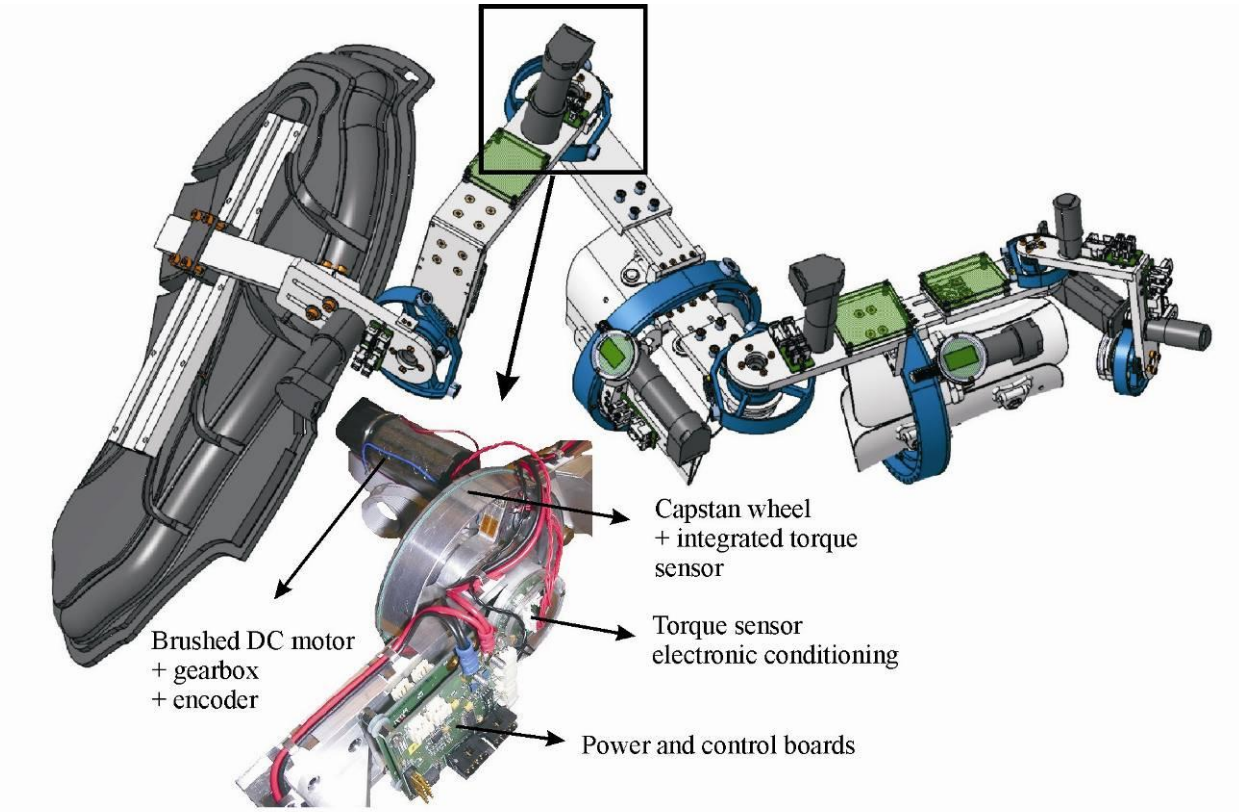

Fig. 2 : SAM design and joint 2 description

B. ECO Joint Controller

The control architecture is implemented using a PC-based real-time controller (ECO) and a set of small factor Joint Controllers directly mounted on SAM, close to each mechanical joint to be controlled (Fig. 3). All those devices are connected on a lightweight, multipoint, half-duplex, twisted-pair network, which allows them to communicate with each other in real time and at a fixed sampling rate (500 Hz). The ECO computer is connected to the network trough the Joint Dispatcher, which is implemented as a PCI plug-in board. It dispatches global requests into individual requests for each joint, collects individual answers and merges them into a global answer. Each Joint Controller and the Joint Dispatcher are built around a Microcontroller from Texas Instruments' F281x family. Joint Controllers are small factor, compact electronic boards (60x50x5mm) located on SAM. Each joint Controller is able to drive two joints (optimum performance-to-size ratio). Features of joint controllers are:

- Pulse Width Modulation (PWM) interface to the motor (H-bridge configuration) with embedded digital control.
- Quadrature Encoder Pulse (QEP) interface
- Potentiometer interface
- Torque sensor interface, consisting of a 2-wire 4-20mA current loop.
- High-speed, low overhead communication with ECO.

Preliminary tests have demonstrated that a 500 Hz sampling rate can be achieved with a basic network speed of 3.5 Mbits/s for communicating between ECO and Joint Controllers.

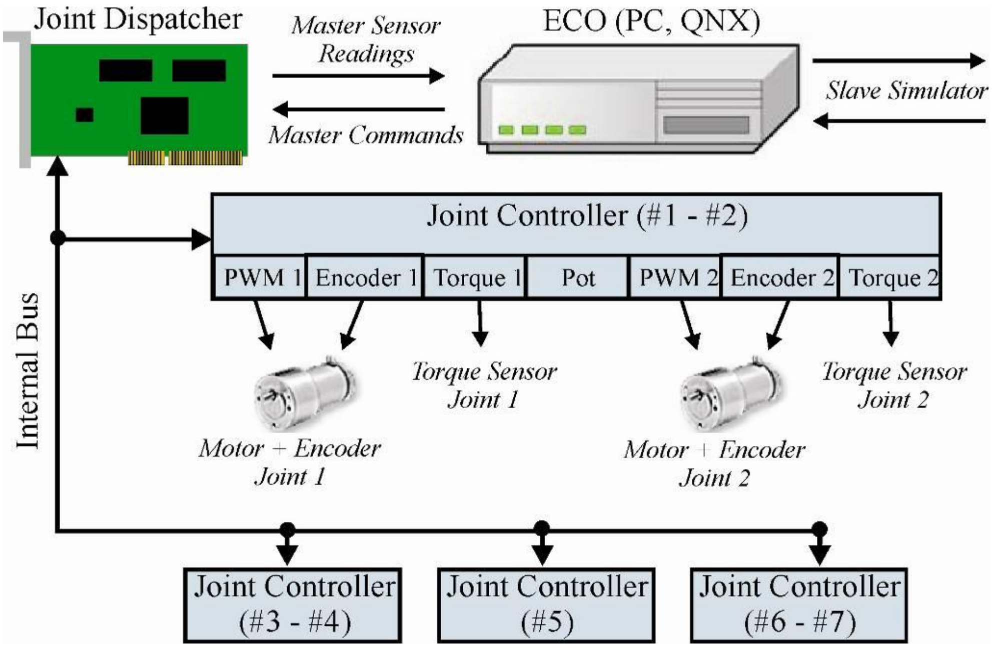

Fig. 3 : ECO controller architecture

The controller strategy, implemented in ECO, is based on a joint to joint approach. Each joint of SAM controls individually the corresponding joint of the slave robot by exchanging the information of position and torque, in both directions, between the master and the slave at a 500 Hz sampling rate. On each side local position and torque control create the joint actuation command. At this moment, only impedance strategy has been implemented (master sends position and receives torque command). The disadvantage of this strategy is that, without specific local control, the operator is sensitive to the backdrivability of the mechanical system (frictions and inertias). A local control is thus implemented on each joint to reduce friction in free air motion and at the same time to increase the fidelity and stabilise the arm in contact. The local joint controller used is called “Hybrid controller” [15]. It consists in the coupling of a torque feedback controller and a feedforward model compensator. More detailed information can be found in [13].

C. Slave Simulator

The Slave Simulator is a modular application that simulates a 7-DOF virtual robot slave, its controller and the interactions with its workspace (a virtual world). When a collision occurs between the slave and its environment, the corresponding dynamics and kinematics response is computed.
The physics engine (collision detection and dynamics/kinematics) is built on top of ODE [1]. The slave robot is controlled by direct kinematics, with its 7 DOF corresponding to the seven joints of SAM.
The Slave Simulator features a scripting technology that allows the users to describe the virtual worlds and the slave robot in Python. When a simulation starts with a given virtual world and a slave, the corresponding code is executed by the Slave Simulator. This allows more flexibility when using the system. The user can have a set of different virtual worlds and/or slave and can easily modify them (the elements of the environments, the contact parameters, the shape of the elements of the slave,…).
Lots of scenarios can thus be imagined, typically to prepare real missions. In the scope of this project, common scenarios such as wall tapping, shape screening, sliding knob, screwing operation and peg in the hole have been implemented to demonstrate and measure the capabilities of the system in terms of capacity to render various stiffnesses, forces and frictions.

The simulation runs at the same frequency as the remaining haptic loop (i.e. 500Hz). The Slave Simulator runs on a Core 2 Duo 3.0 GHz with a Debian GNU/Linux. Although the operating system is not real time, the simulation is precisely synchronized by ECO to keep up with the 500Hz frequency of the haptic loop.

The simulator is a multithread application (Fig. 4). Several threads are dedicated to the communication with the different sub-systems. The physics simulation is run on a separated thread to allow more time to the simulation to proceed.

The communication with ECO is based on the TCP/IP protocol and on a request-response scheme. Indeed, TCP/IP implementations give better performance when used in a request-response fashion (~0.2ms of delay, versus ~20ms of delay given by a server broadcast solution).

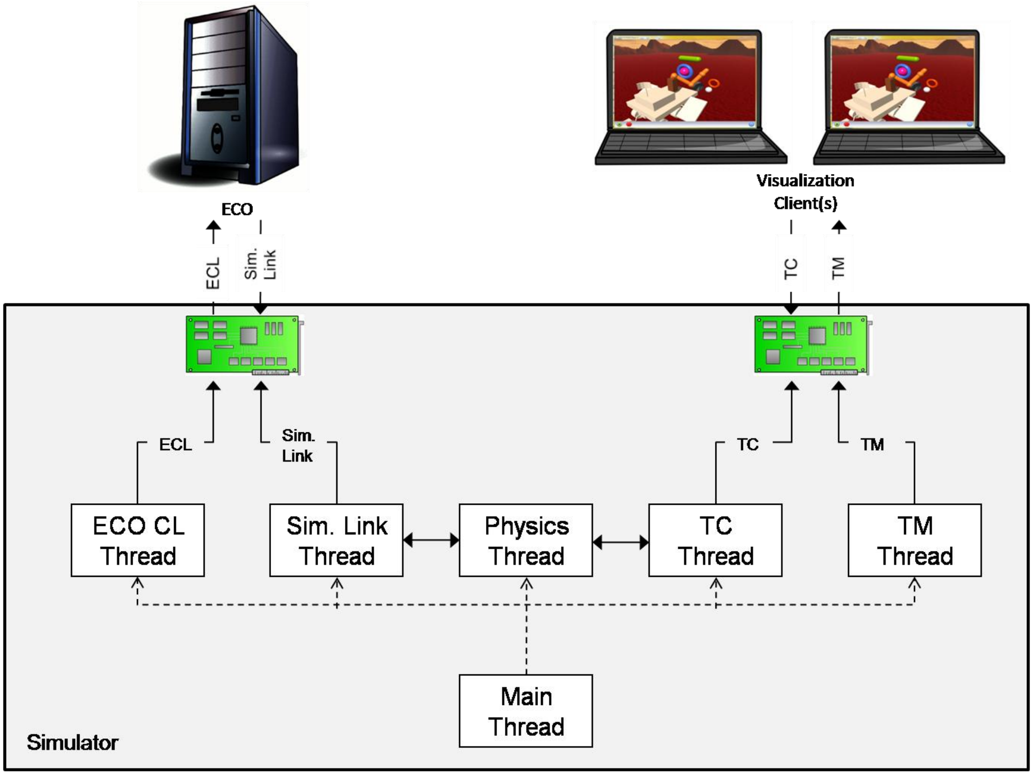

Fig. 4 : Simulator architecture

D. 3D Visualisation Client

The 3D Visualisation Client is a remote application which is not part of the haptic chain, but connects to the Slave Simulator to allow visualizing in real time the state of the slave and its working environment. Several clients can connect to the Simulator, allowing several users to visualize the state of the simulation at the same time. Thus a HMD (Head Mounted Display) could also be used.

It is a totally independent application and it doesn't have any hard-coded information about the system. The visual description of the slave robot and its environment is automatically sent by the Slave Simulator to the 3D Visualisation Client when a simulation is started. Then telemetry updates are sent upon request of the 3D Visualisation Client (The communication between the Slave Simulator and the 3D Visualisation Client is based on a Client/Server architecture).

The GUI allows the user to switch between the different states of the system and thus allows starting and stopping the simulation, browsing a list of available virtual worlds and it supports the calibration of SAM joints. It can also remotely stop the Slave Simulator.

The 3D rendering is done in OpenGL 2.1 and features the shadows (using shadow mapping) of the slave robot to improve depth perception. An audio feedback is also provided to enhance the haptic sensation when a contact occurs.

Figure 5 shows the GUI provided by the 3D Visualisation Client, and the display of different slaves and scenarios (screwing operation, peg in the hole, wall tapping).

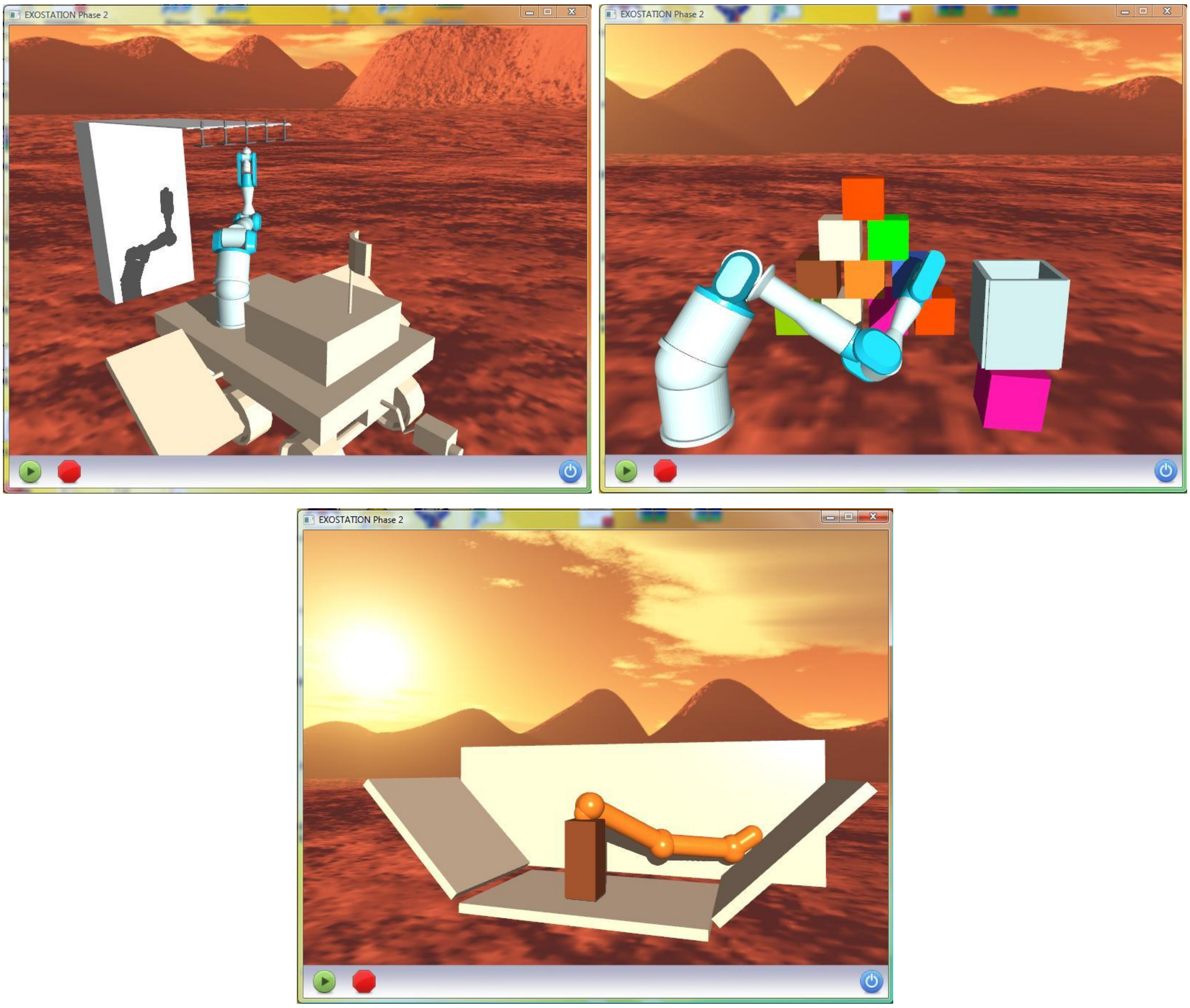

Fig. 5 : 3D Visualisation client

3. RESULTS

The complete 7-DOF SAM is represented in Fig. 6 . Preliminary tests have been conducted on a simplified VR (without a complete virtual slave robot representation) in order to show the capabilities of the master device in terms of haptic rendering and sensation.

Firstly, several geometrical forms could be presented to the operator. Fig. 7(a) represents the position of the operator when he was asked to follow a sphere in space (projection in XZ plane). We can see a good matching between the real position and the virtual object. Secondly, the friction compensation algorithm was evaluated in free air motion (no contact force from the slave side) or in contact for joint 2. Fig. 7(b) illustrates the use of the hybrid controller on joint 2 when contacting a soft wall. Without local torque control, we can highlight at the beginning some friction in free air motion and after a mismatch between the torque set-point and the measured one during the contact. Although the open loop gain is well fitted, this problem comes from sticking phenomenon inside the gearbox when the motor produces high torque with a low velocity. That blocks the position of the user who can apply higher torque without moving deeper in the wall and thus without set-point modification. On the other hand, with hybrid control, the friction sensed by the user is decreased and at the same time a better correspondence between the torques in contact is obtained. According to the application, friction can be added or removed through the model part of the hybrid control. If higher stiffness has to be simulated, adding friction when a contact is detected can help to stabilize the system.

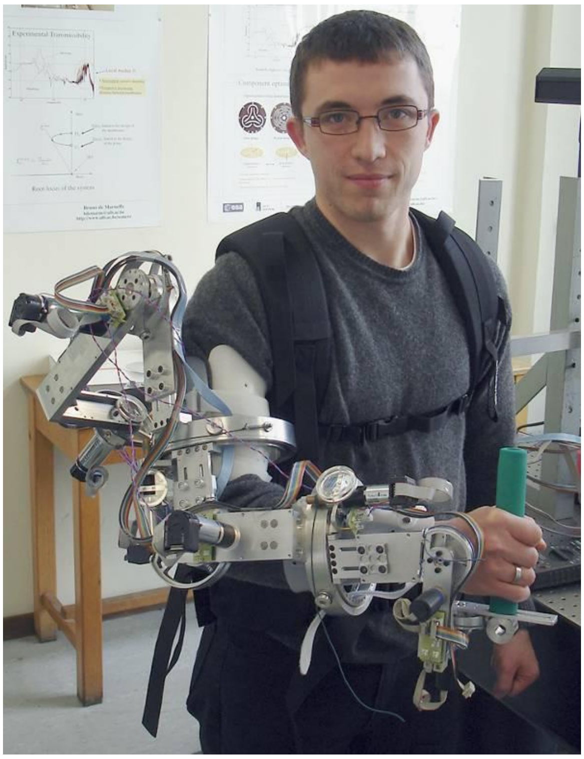

Fig. 6 : 7 DOF SAM exoskeleton prototype

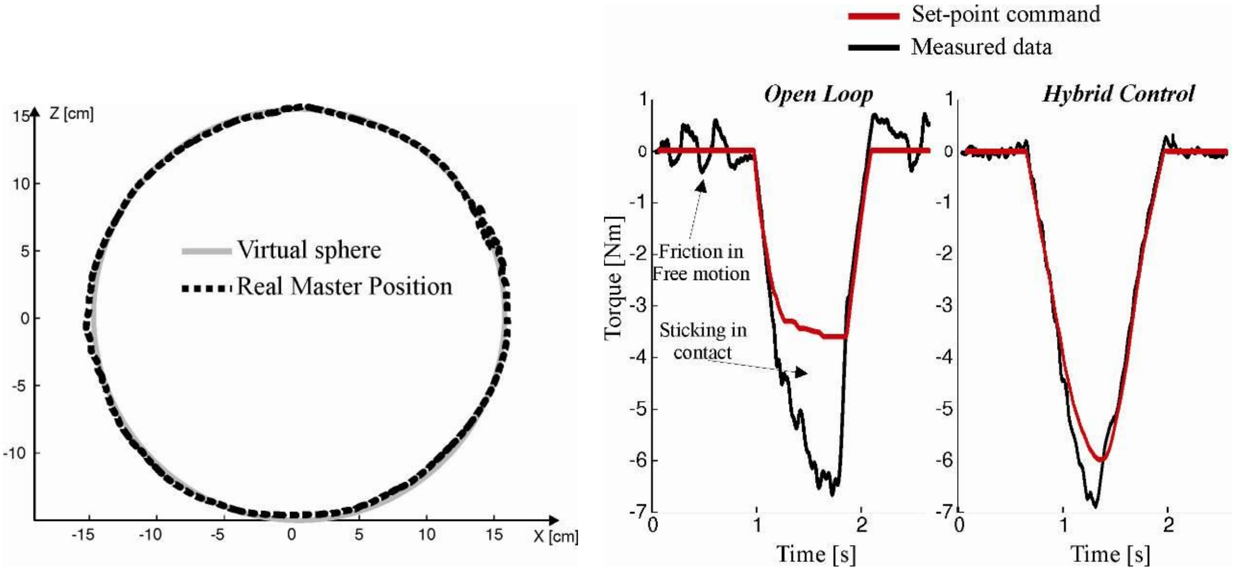

Fig. 7 : Shape rendering (a) and contact (b) experiments with SAM exoskeleton.

5. CONCLUSION

This paper has introduced and described the major components of the complete 7-DOF haptic control chain under development in the frame of the EXOSTATION project. Tests have been conducted on both hardware and software. It has been shown that the exoskeleton is able to provide high quality 3D haptic rendering when interacting with a Virtual Reality. The ECO controller has shown its possibility to control simultaneously the 7 joints with a 500 Hz rate. Tests on the Slave simulator have shown the ability to command a virtual multi-DOF robotic arm and compute dynamics associated with collisions from various virtual worlds defined in Python scripts.

The integration of the whole haptic control chain and experiments are currently conducted in order to assess the global system performance through several scenarios. Once the system performances will be assessed, another control strategy could be implemented to allow teleoperation of a real anthropomorphic slave, using inverse kinematics control. The Virtual Reality tools could also be upgraded to establish a high quality visual feeling, using a head mounted display, to move forward from teleoperation to telepresence.

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