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EXOSTATION : Haptic Exoskeleton Based Control Station

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Abstract— **EXOSTATION is a project aiming at building a complete haptic control station, which allows the operator wearing an exoskeleton-based haptic interface for the human arm to remotely control a virtual slave robot.**
This paper briefly describes the various components : the Sensoric Arm Master (SAM), a portable haptic exoskeleton, the Exoskeleton COntroller (ECO), the slave simulator, simulating an anthropomorphic manipulator and a 3D visualisation client. Several teleoperation control strategies (impedance, hybrid control, 3-channel) have been tested and compared in order to evaluate their performances. The last has shown the best behavior in term of haptic feedback. Finally, a focus is made on the application, and how various manipulation and operation tasks can be performed to assess the system's performances (contact wall, objects manipulation, screwing). Users who tested the system were very impressed by the easiness of operation with the exoskeleton and felt the advantages of a force feedback information.

I. INTRODUCTION

EXOSTATION is a project aiming at building a complete haptic control station, which allows the operator wearing an exoskeleton-based haptic interface for the human arm to remotely control a virtual slave robot.

There is a wide range of applications for this kind of system, from virtual reality in the domain of virtual training to the teleoperation of real robot in the field of remote maintenance, exploration in severe environment and space exploration. Indeed, in future space missions, robots could be used as first explorers in hostile environment [2] 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 provide 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 [11]. The EXOSTATION project was launched to implement a force feedback exoskeleton master arm to control this robot in its master-slave manual control mode.

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The project has been divided into several phases due to technological complexity. In phase 1, a fully integrated 1-DOF haptic chain representing one joint (master and slave) has been developed to validate all components and their integration [7]. In phase 2, a complete 7-DOF haptic control chain has been built, including the exoskeleton master arm controlling a simulated slave robotic arm.

This paper introduces the various components of the system developed in phase 2 as well as the control strategies adopted. Then a focus is made on the application, and how various manipulation and operation tasks can be performed to assess the system's performances.

II. SYSTEM OVERVIEW

The purpose of the EXOSTATION setup is to allow an operator wearing an exoskeleton-based haptic interface for the human arm to remotely control a virtual slave robot. It is composed of four main components, described in the following sections (Fig. 1):

A. Sensoric Arm master (SAM)

SAM is a portable arm exoskeleton, used as a master haptic interface. The use of a fully portable device can be advantageous for space applications either in the case of 0-G environment to avoid reaction forces from the external structure or in the case of planetary exploration as the system is easily transportable. Moreover, an arm exoskeleton structure allows more intuitive manipulations with anthropomorphic slave robot arm than desktop haptic devices.

SAM has a kinematic structure, isomorphic to the human arm. It has 7 Degrees Of Freedom (DOF) from the shoulder to the wrist, with adaptable length links to allow a correct alignment with the human joints. A specific kinematics structure is implemented to avoid internal singularities inside the workspace [9]. The total weight of the system is 7kg, mainly composed of the aluminum structure and the actuators.

Based on the results of a previous study where several actuation technologies were compared [4], each joint is composed of a brushed DC motor coupled with a cable capstan and gearbox for a permanent output torque comprised between 10 Nm and 1 Nm depending on the joint. 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.

Position and torque information are measured on each joint, respectively by an incremental encoder and an integrated

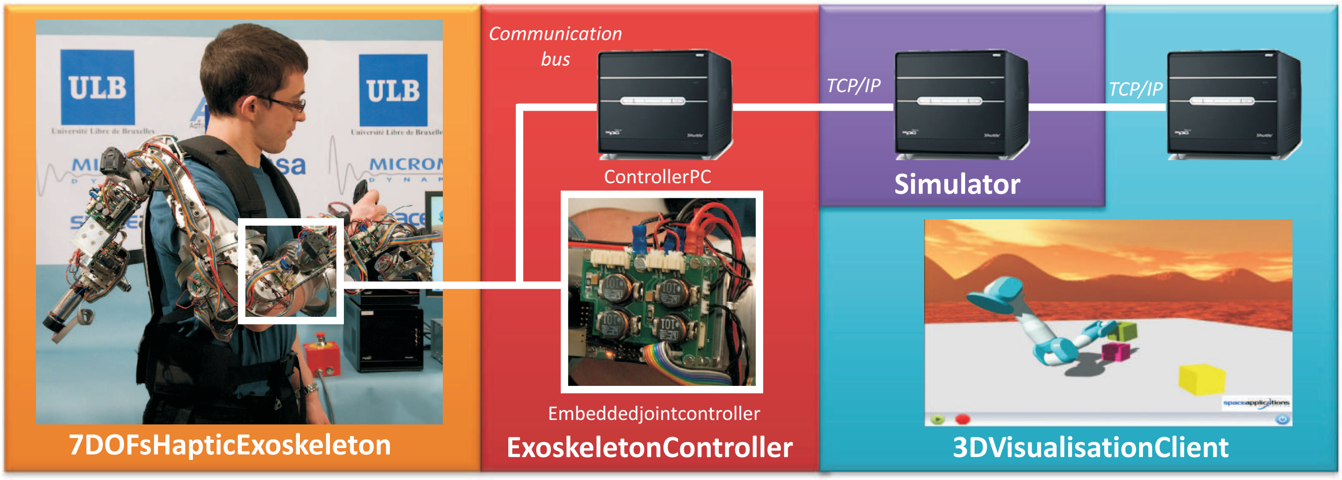

Fig. 1. Components of the EXOSTATION haptic control station

torque sensor based on strain gages located inside the capstan reducer.
The exoskeleton is attached to the user through three fixations, at the back, on the upper and lower arm. At the end tip, the operator holds a joystick implementing button interfaces to control the operations. More technical details can be found in [5], dedicated specifically to the SAM exoskeleton.

B. Exoskeleton Controller

The hardware of ECO (Exoskeleton COntroller) is divided in two parts 1. Firstly, a PC running QNX real-time operating system implements the control strategies of the haptic teleoperation chain. It insures also the communication transfers at a 500 Hz sampling rate, needed for haptic rendering. Secondly, small electronic boards are mounted locally on SAM. Their purpose is to drive individually the joints of the exoskeleton with onboard PWM current amplifiers, encoder and torque sensor interfaces. All these elements are interconnected through a lightweight, multipoint network composed of a control and power bus. That allows limiting the number of wires routed to the main PC controller.

C. Slave Simulator

The Slave Simulator is a multithreaded application which simulated an anthropomorphic 7DOFs robot and its interactions with virtual environments [6]. The physics engine is built on top of ODE [8] and simulates the collision detection, the dynamics and kinematics of the robot.
It is a modular application in which the robot, the environments and all the control parameters are defined into Python [10] scripts which proved to be very efficient during final tests on the system. Thanks to the scripting technology, tuning the control parameters and switching from one control strategy to the other as well as creating new environments is very easy.
The Simulator runs a Debian GNU/Linux. Although this operating system is not real time, the simulation is precisely synchronized by ECO to keep up with the 500 Hz frequency of the haptic loop.

D. 3D Visualization Client

The 3D Visualization Client allows visualizing in real time the state of the virtual world and supports the various states of the system (calibration, simulation monitoring).
It is not part of the haptic chain and remotely connects to the Slave Simulator. There is no hard-coded information in the Visualization client and all needed data is sent at runtime. This way no world-dependent visual information is stored; it allows more flexibility in the system.
The rendering is done in OpenGL 2.1 and features shadows to improve depth perception. An audio feedback is also provided when a contact occurs to enhance the haptic sensation.

III. Master-Slave Control

A. State Machine of the system

Figure 2 depicts the states of the system. Initially, SAM is unpowered and mechanical adjustments can be performed to adapt the operator morphology before further operation. During the calibration each joint of SAM is calibrated to ensure a correspondence between the real master position/orientation and the one given by the kinematic model. In the No Simulation state the system is waiting for a simulation to be loaded. When done controller parameters are sent and the haptic loop is running. In the Inactive State, the system waits for the operator to be ready.
Before going in the *In Control* state, the slave robot and SAM will usually not be in the same position. This can lead to high commanded torques when the actuators are turned on. For this reason, in *Active State*, a joint position correspondence is obtained. SAM will be driven to the Slave robot's position. The operator can then pass safely to the

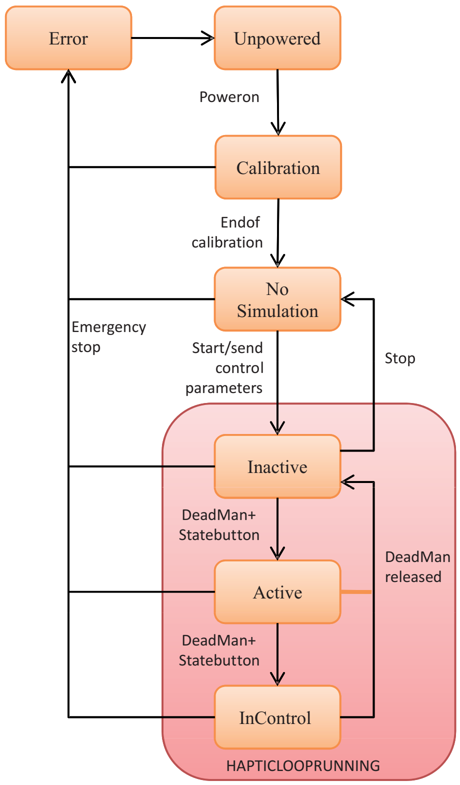

Fig. 2. State diagram of the EXOSTATION system

In Control state where he can control the slave robot. SAM renders to its wearer the forces felt by the Slave Robot.
When the haptic loop is running, the operator has to hold a dead man switch that will stop the control if released. An emergency stop can also be triggered that will unpower the system.

B. Active state - Matching control

As mentioned earlier, before starting haptic feedback, the exoskeleton has to take the position of the slave robot in the joint space. To insure smooth motion, a trajectory of the third degree, between the initial position and the position of the slave robot, is defined in time for each joint:

$$\theta_t = a_0 + a_1 t + a_2 t^2 + a_3 t^3 \tag{1}$$

with the ai computed from the conditions of limits (starting and ending positions) and the desired average motion velocity. At each time step, a proportional/derivative position controller is used to compute the command torque sent to each joint, based on the difference with the actual joint position. For security purposes, if this command reaches a too high value (e.g. when the operator prevents the motion), the update-time of the trajectory is paused until the master joint catch up the trajectory set-point.
Fig.3 depicts the evolution of the joints position of the exoskeleton during an *Active State*. Each joint reaches the corresponding slave joint position (all equal to zero, for the basic Slave configuration) in a specific amount of time,

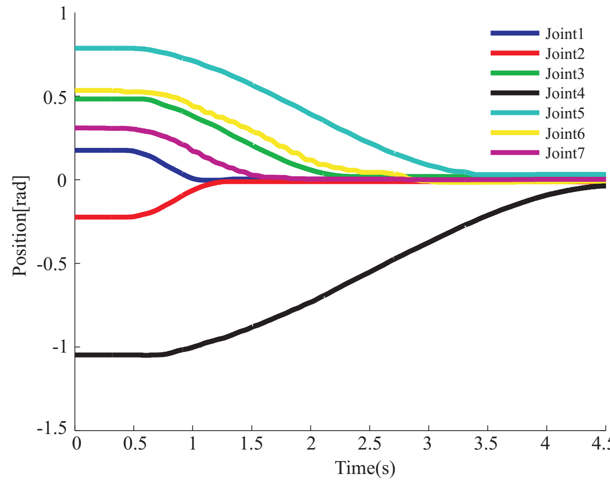

Fig. 3. Evolution of the joint position during a typical *Active State*

defined by the initial distance. Initial null speed conditions have been chosen to obtain smooth start and stop motion. Once the final point is reached, the controller is used to keep the operator in position.

C. In Control - Haptic feedback

In the *Control State*, the operator teleoperates the slave robot arm. At the same time, the interaction forces between the robot and its environment are transmitted to the user by the exoskeleton actuators. Fig. 4 depicts the control strategy implemented in the system. It is based on a joint to joint approach allowed by the existence of a similar kinematic structure between the exoskeleton and the slave robot arm (comparable to the PA-10 from Mitsubishi). Individual control loops are implemented between SAM joints and their corresponding Slave joints. Three different control methods have been implemented and tested to perform the tasks:

1) Impedance control: This is the simpler control method. A proportional/derivative controller, C_s, is used to command each slave joint position, based on the comparison between the position of the Master and Slave, θ_{mi} and θ_{si}. The contact interaction forces (end-tip or structure) between the Slave robot and its environment are translated in joint torque information, τ_{ei}, through the Slave Jacobian. They are transmitted in open-loop to the Master actuation, with the possible application of an amplification gain. Based on the master position, a gravity torque, G, can be added to the actuation to help the user to carry the exoskeleton (the weight of the moving part is transmitted to the back of the operator).
The main advantage of this strategy is its simplicity of implementation as only position sensors are required on the Master device. However, the main drawback is the limited torque tracking, between both sides, in free motion or in contact as the Master works in open loop.

2) Hybrid torque control: The second strategy implements a local torque controller on the Master joint to improve

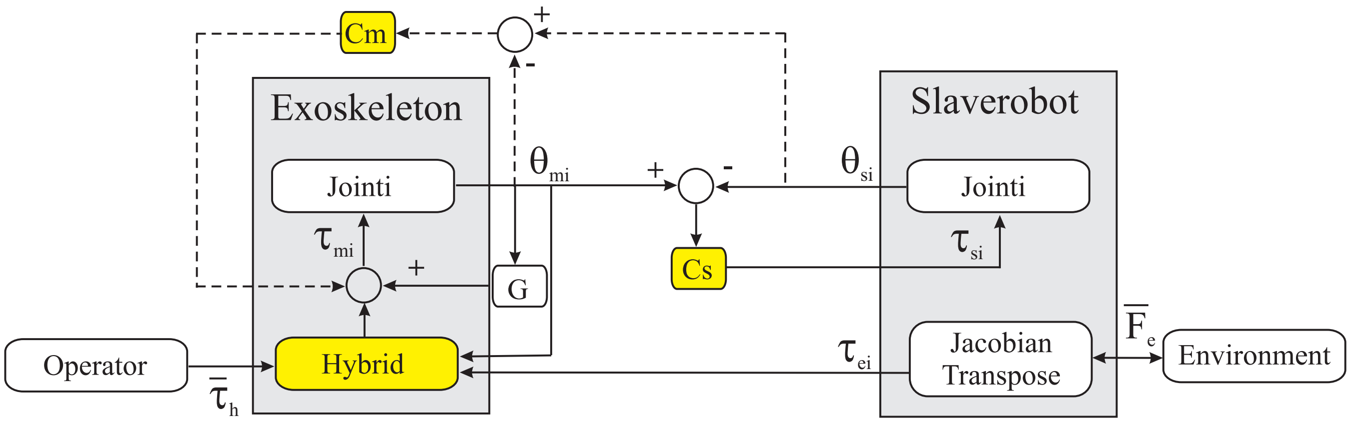

Fig. 4. Joint to joint control algorithm implemented in the EXOSTATION demonstrator, hybrid torque controller and the 3C control upgrade (dashed line)

the torque tracking with the Slave torque set-point. This controller is based on the approach proposed in [1], called hybrid control. The principle is to use either a proportional torque regulator or a feedforward model based friction compensator, depending on the joint velocity. The first is used for the low velocity range and the second for the high. To insure a smooth transition, each part is amplified by the gain of a low pass or high pass filter based on the velocity information. The Master command torque is given by,

$$\tau_{mi} = \tau_{ei} + K(\tau_{ei} - \tau_{hi})\frac{\beta}{\beta + \left|\dot{\theta}_{mi}\right|} + Model\frac{\left|\dot{\theta}_{mi}\right|}{\alpha + \left|\dot{\theta}_{mi}\right|} \quad (2)$$

with K the proportional feedback gain, τ_{hi} the measured master joint torque and $Model$ a model of the friction of the joint. A simple static + viscous friction model has been implemented.
Although this strategy presents to the user a better dynamic behavior and better contact torque tracking, the decreasing of the remaining friction limits the stability of the system and the range of contact impedance that can be rendered.

3) 3-channel control: The 3-channel control implements the previous hybrid torque control with the addition of a new channel of communication. The slave joint position is sent back to the master position controller, C_m (dashed lines in Fig. 4). The master command torque is then computed by the addition of the position and torque channels. This controller is inspired from [12] where the coupling of an impedance and a position/position controller has shown an increasing of the performances compared to a simple impedance approach.
It is well known that a 2-channel position/position controller is more stable than the impedance controller. But, at the same time it increases the free motion dynamic of the master (more friction). By coupling it to the previous hybrid torque controller, the purpose is to increase the global stability while limiting this free motion dynamic.

D. Results and comparison

In [6], preliminary results regarding the exoskeleton's control have been shown. In the following section, results regarding the integrated haptic control station are presented. Fig. 5 represents the torque felt by the user during a contact wall experiment for the three control methods. The arm is placed in a right angle configuration and the operator moves his arm, in a flexion/extension motion of the shoulder, to touch an horizontal wall in front of the head. Only the three main joints implied in the contact (that present the higher level of torque) are represented for clarity : the shoulder and elbow extension/flexion (joint 2 and 4) and the wrist abduction (joint 6). The wall stiffness is 200 N/m which corresponds to a *soft* wall.
With open-loop impedance control, poor torque tracking is observed in contact (1). As presented before, the actuation system is composed of the coupling between a capstan reducer and a gearbox (2 stages). This last component introduces some friction that have been shown to be variable depending on the output torque [3]. Although the friction without load is acceptable in order to move the system freely (2), when contacting a soft wall, it leads to important differences between the command set-point (from the Slave) and the real output torque (1). The same phenomenon happens when implementing gravity compensation, leading to the blocking of the system for some configuration. The fourth joint presents the same problem but not the sixth. This is due to the use of a one-stage gearbox that seems to be less sensitive to this phenomenon.
By using the hybrid torque controller, the quality of the torque tracking is increased in contact and also in free motion (3). Also, with gravity compensation, no more blocking of the system was observed. The drawback of this method is the decreasing of the stability margin in *hard* contact when increasing the gains. With the parameters used to produce Fig.5, the limit stiffness rendering was 1200 N/m for the hybrid control, which is insufficient for hard contact rendering. This low value can also been explained by the

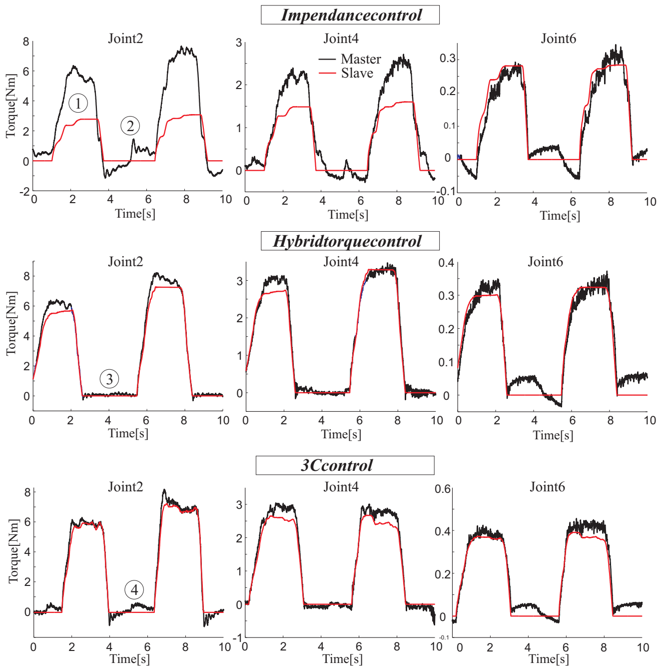

Fig. 5. Joint 2 (shoulder flexion/extension) friction experienced by the operator during free arm motion

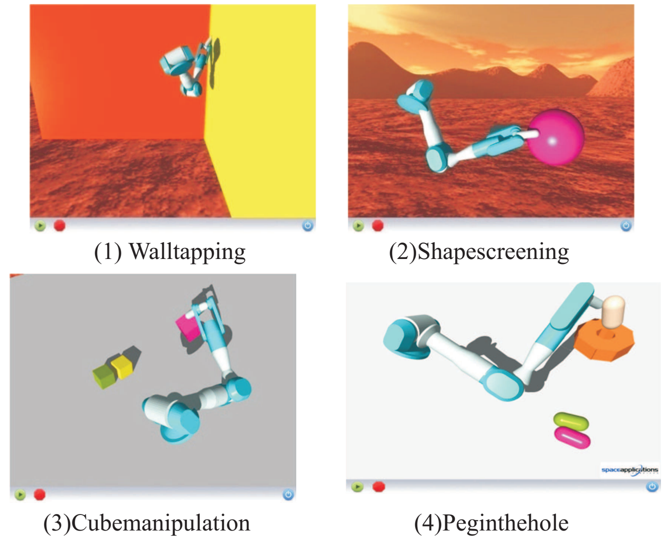

Fig. 6. 3D visualisation of typical scenarios with the EXOSTATION system

low haptic rate (500 Hz) limited by the physics engine simulating the Slave robot. Experiments with a simpler virtual reality and a 1 KHz rate presented a better stability behavior.

The use of the third control method, with the Master position loop, allows at the same time to keep a good torque tracking and a better stability margin. Stiffness of 2500 N/m could be achieved. Only a small amount of friction can be observed in free motion (4). In the 3rd case, the sixth joint implements the simple impedance control as the performances are sufficient.

IV. APPLICATIONS

Demonstration scenarios have been implemented in Python scripts to assess the performances of the system (Fig. 6). The selected activities have been chosen to reflect common situations met in robotic manipulation applications. For each of them, the stiffness of the virtual bodies can be modified to show the ability of the system to render various levels of stiffness.

In the *Wall Tapping* scenarios (1), the operator can feel the presence of a wall in various directions with tapping motion. This scenario has been used for the tests presented earlier. The multi-point contact rendering also allows to touch the wall with the elbow (or other inner part of the arm). That represents a big advantage of this structure against end-tip haptic interfaces as the operator experiences a better world immersion.

In the *Shape Screening* environment (2), the operator can feel the presence of volumes, as sphere, cubes, meshes in his workspace.

Some robotic manipulation imply a constraint motion on the robot (sliders, screws,...). Scenarios have been implemented to reflect these behaviors. The *Sliding Knob* object constraints the operator to a linear motion. *Screws* are implemented and render a various friction depending on the rotation between the end-effector of the slave robot and the screw.

Manipulation tasks can also be performed using the system. Virtual objects can be grasped by the operator and he can interact with the environment, for example to build structures (3). The haptic feedback allows manipulating the objects more intuitively and also limiting the contacts forces between them. If only a visual feedback is used, and no specific controller is implemented, the high position gains of the Slave controller can destroy the environnement or the robot itself. A specific manipulation task is the *Peg in the Hole* (4). Although this scenario is more challenging in term of computation load and stability, we succeeded to present a good behavior to the operator. Without visual feedback, it is fairly easy to find the hole and align the peg.

V. CONCLUSIONS AND FUTURE WORKS

This paper has presented the EXOSTATION project, a complete 7-DOF haptic control chain, developed in the frame of an ESA project. The main components of the system and the control strategies have been introduced. Important characteristics are the portability and the backdrivability achieved with the exoskeleton, the onboard electronic and the bus connection allowing a limitation of the global wiring, the scripting technology for an easy modification of the control methods and the virtual world description and the complete dynamic simulation of a 7-DOF anthropomorphic robot.

The 3C control method has shown the best behavior when contacting soft wall under gravity compensation. The complexity of its implementation isn't trivial (sensors,

gains,...). If only hard contact is needed and no gravity compensation implemented, the simple impedance control can already give very nice sensations to the user.
The system succeeded to simulate real life applications as contacts, manipulation of objects, screwing,... through the use of an anthropomorphic arm robot. Users who tested the system were very impressed by the easiness of operation with the exoskeleton and felt the advantages of a force feedback information.

In the future, improvements of the system are foreseen. The 500 Hz haptic rate has shown some limitation in term of stability (hybrid control). Effort has to be done to improve this rate, in a global manner or locally on the Master Device. Another control strategy could also be implemented to allow teleoperation of a real anthropomorphic Slave and extend to other Slave kinematics by 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.

VI. ACKNOWLEDGMENTS

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