Bowden Cable Actuator for Torque-Feedback in Haptic Applications

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ABSTRACT

This paper introduces a novel type of actuator for force-reflection to haptic master interfaces. The actuator is based on a DC motor that is relocated from the mechanism joint by means of bowden cable transmissions. After an introduction and formulation of the project goals, the paper highlights some important bowden cable transmission characteristics that influence the design of the necessary hardware. Next, a hardware prototype is presented that has been built to analyze the transmission characteristics of the bowden cable transmissions between actuator and robotic joint. The prototype was used next to investigate achievable actuator performance in force-feedback control with a slave. Results are presented, which show good performance and contact stability in a 4 channel control scheme. The actuator has low movement resistance in free motion and can reflect high torques during hard contact situations with a slave.

Keywords: Bowden Cable, Haptic Actuator, Exoskeleton

1 INTRODUCTION

Future human missions or permanent presence in space without doubt require robotic support. The European Space Agency started developing a humanoid servicing robot for the International Space Station (ISS), called Eurobot. In a first instance, Eurobot shall support astronauts during extra-vehicular activities (EVA). Two main control modes are foreseen therefore; autonomous control and master-slave manual control.

For the manual control of the anthropomorphic arms of Eurobot, an exoskeleton type man-machine interface is currently being developed at ESTEC. The exoskeleton shall provide force-feedback to the human operator inside the ISS. The mechanical design of the exoskeleton features ergonomic properties and has already been previously published in [10] and [9]. It offers a great dexterity of movements to the operator while being worn, which is enabled by its ergonomic kinematic structure [8].

For creation of a good quality force-feedback with the exoskeleton under micro-gravity conditions, it is adequate to integrate actuators, e.g. DC motors, directly into its mechanical structure. Their mass and inertia is anticipated to only modestly reduce force-feedback performance under weightlessness. On earth, however, directly integrated actuators would need to compensate the weight of the structure and of their own, which makes it difficult to achieve good haptic performance. Provision of a high power output in the entire workspace at a reasonably low system mass is difficult to achieve by this approach. In order to fight their own weight, the size of motors must increase, escalating the required power from joint to joint and resulting in a significant increase of total exoskeleton mass and inertia. Eventually, a similar compact and enhanced kinematic design approach than for the 0-g version is infeasible, if gravity force cannot be compensated by external mechanisms or if the motors are not extremely lightweight and power-dense.

One way to arrive at a power dense actuation (as seen from the exoskeleton) is relocation of the power delivering actuator units, by means of hydraulic, pneumatic or cable transmissions. This way, mass and inertia of the movable system can be minimized, thus, allowing an ergonomic kinematic design similar than for a reduced-G exoskeleton.

Moreover, a good actuator relocation and transmission system can also provide benefit to other robotics developments, where the ratio of workspace over mass must be large and where a high power output near the workspace limits is desirable.

This is why an investigation was launched, to search possible solutions for relocating motors away from robotic joints. Hydraulic transmissions, as well as pneumatic transmissions were discarded rather quickly, because their complexity is relatively high at low performance, and furthermore, application within a space system would be impracticable. For the exoskeleton, a cable-based transmission system seems most suited, which is why this option was studied in more detail.

Cable transmissions can be established in two different kinds, either by routing the cable over a set of pulleys such as in [13] and [4] or by employing a bowden cable system, in which the cable is guided inside a flexible sleeve. Because the first option leads to a rather extensive increase of mechanical complexity, the bowden cable approach was chosen by ESA for further investigation and laboratory prototyping. The use of bowden cables for force-reflective display design was previously reported in [3] and [11]. While the use of such an actuator for the ESA Exoskeleton was already postulated in [10] and [9], this paper introduces a more rigorous investigation of the time-dependent transmission behavior of such cable systems. Their influence on haptic performance in a teleoperation system with master and slave is presented in this paper, as well as the investigation of the control laws to be used in order to achieve correct force feedback.

While the first development of a prototype set-up and proof of the overall actuation concept was done at ESA, it was decided to develop a second, improved version of the hardware at ULB. This new set-up allowed to achieve the results presented about haptic performance in this paper.

2 SPECIFICS IN BOWDEN CABLE TRANSMISSIONS

2.1 Application

In a bowden cable transmission, a cable is guided inside a flexible sheath. For remote actuation of a robotic joint, force is delivered to the remote joint by mechanical displacement between the cable

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and the outer sheath. To implement a remote-actuated rotary joint, a pull-pull configuration as illustrated in Figure 1 is optimal.

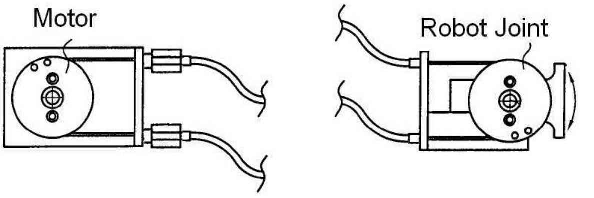

Figure 1: Principle of bowden cable actuation

The robotic joint can be actuated in both directions by respective rotation of the motor. A pre-loading unit, located somewhere along the transmission can be used to tension the cable-loop with respect to the sheaths and external mechanical structure, if desired.

2.2 Specific Characteristics

Losses and inefficiencies of the bowden transmission are mainly due to complex and non-linear friction phenomena. Coulomb friction, viscous friction, stiction and stick-slip, can all be present in bowden cable transmission systems. In the following, it is discussed how to optimize the mechanical set-up for reduction of those effects.

The main parameters influencing performance of the transmission are normal forces on the cable (influenced by cable tension or pre-load), friction coefficients resulting from material pairs and velocity of the cable inside the external sleeve. Furthermore, cable and sleeve stiffness play an important role regarding stick-slip behavior and thus, mechanical bandwidth of the transmission.

It is important to notice, that some of these primary parameters are depending furthermore on the geometric configuration of the bowden transmission. Basic friction effects have been described by models that are available in literature. However, understanding of the particular influence of cable geometry on the friction characteristic of a bowden cable is not so common and is therefore summarized hereafter.

The main geometric parameter influencing friction between the outer housing and the inner cable is the total wrap angle of the cable system. Theoretically, the friction losses of bowden cables are similar to those occurring when sliding a cable over a stationary cylinder at constant velocity, as indicated in Figure 2.

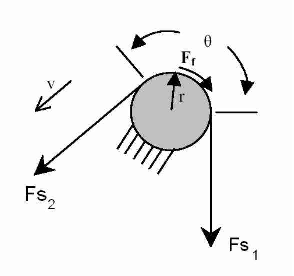

Figure 2: Force balance of cable routed around stationary cylinder

The force transmission efficiency can thus be approximated by Eq. 1.

$$\frac{Fs_1}{Fs_2} \cong \frac{1}{e^{\mu\theta}} = e^{-\mu\theta} \tag{1}$$

μ is the coefficient of sliding friction and θ, the wrap angle of the cable around the cylinder. In a bowden system, T is the sum of all bending-angles along the transmission. In Figure 3, theoretical force transmission efficiencies are shown in dependence of the wrap angle, for different friction coefficients between cable and the sheaths. Practical measurement results of different material pairs and lubrications are presented in [7] and [2]. As Eq.1 indicates, the bending radius does not influence the cable friction. In fact, the only effect of very small deflection radii is increased wear of the cable, which negatively influences the friction coefficient over time. Manufactures of bowden cable systems therefore recommended us to use minimal deflection radii r_m according to Eq. 2.

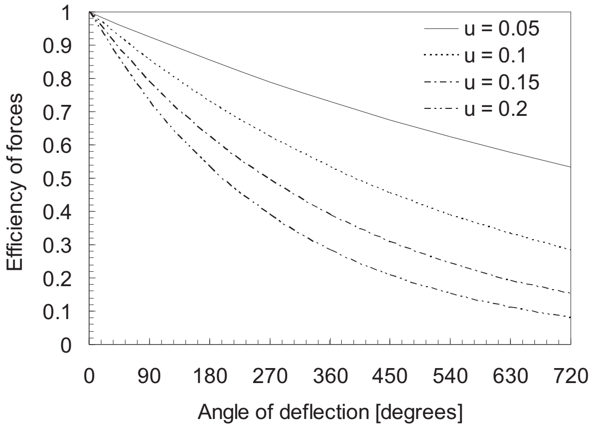

Figure 3: Theoretical force transmission efficiency in a bowden cable system

$$r_m \geq 20.D_{Cable} \tag{2}$$

In this rule of thumb, D_{Cable} represents the external diameter of the cable inside the sleeve.

However, in a real bowden cable system, changing wrap angle changes cable pre-load in addition and therefore has a bigger effect on force transmission efficiency. The pre-load changes during bending can be explained as follows: The external casing often comprises of a spiral of flat steel-band or a linear arrangement of steel bands forming a tube. Those deform elastically during bending, like when bending a spiral spring. During bending, the centerline of this tube extends longer, which stretches and pre-loads the cable inside. Figure 4 shows the measured stretch $DeltaL$ of a cable inside a bowden cable system under load - for different wrapping angles. These measurements have been recorded with the first setup being developed at ESA. It can be seen that if the wrapping angle is increased under constant load, the pre-load of the bowden cable assembly increases, resulting in increased stretch of the cable.

Cable pre-load influences the amount of friction loss directly, by increasing normal forces between cable and sleeve surfaces. This means that if the geometric configuration of the Cable System changes under constant load, also the force transmission efficiency will change. In order to minimize this effect, cables as well as sleeves should be a stiff as possible. For the sleeves, a longitudinal construction of flat-band steel is therefore preferable to spiral-spring type constructions.

As can be seen furthermore in Figure 4, stiffness of the cable is mostly non-linear over the load range. The question arises, whether to operate a bowden cable system better at low force transmission (e.g. Figure 4 (b)) or better at high force transmission regime (e.g.

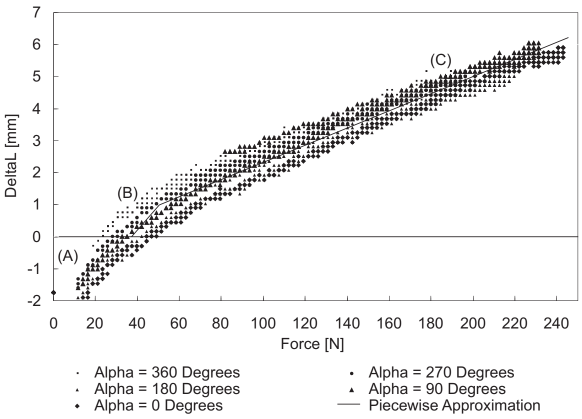

Figure 4: Preload dependance on wrapping angle

Figure 4 (c)) for haptic applications. Up to now, similar configurations of bowden cables were used only in highly pre-loaded conditions [12]. This linearizes the cable stiffness but creates relatively high friction levels. The approach works fine for position control applications, if large motors are used to overcome the frictional force.

In principle, a low pre-load should be better for haptic applications, because friction in the system is lower. As a consequence, the torque dynamic range can be higher, leading to a better haptic rendering capability. However, if pre-load is too low, the cable can detach from the pulleys, which introduces slack into the system (Figure 4 (a) - negative stretch). In order to avoid slack of the cable, stiff spiral springs can be inserted in series with the sleeve and the motor casing. The springs will counteract the effect of loosening from the pulleys and yet ensure constant pre-load of the system independent from the wrapping angle.

Another dominant effect occurring in bowden cable transmissions is stick-slip. During movement, stick-slip causes vibration that is characterized by a sawtooth displacement over time evolution. The motion is governed by a static friction force in the stick phase and a viscous friction force in the slip phase. As the presence of vibrations can be highly detrimental to the mechanical bandwidth and torque dynamic range of the system, stick-slip has to be minimized. Following solutions exist :

- Use friction couples whose coefficient of friction increases with speed. (When the coefficient of friction increases with the speed, the phenomenon will not occur, because a static equilibrium between the driving force and the friction force will be ensured.) Few material pairs offer this characteristic. The most common is PTFE on PTFE.
- Use friction couples with a very small friction coefficient in general.
- Use cables and sleeves with high stiffness.
- Keep the load small or reduce the tension in the cable by other means.

We chose to prototype an improved version of the haptic master actuator operating with small motors in a low pre-loaded condition. The following paragraphs describe the design of the hardware prototypes and preliminary results that have been achieved in friction characterization and force feedback performance.

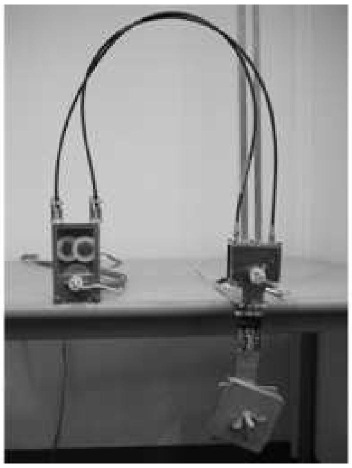

Figure 5: Overview of first bowden cable actuator, developed at ESA, for force feedback to ESA exoskeleton

3 PROTOTYPE DESIGN

3.1 Mechanical Setup

A first prototype developed at ESA proofed the concept and feasibility of remote actuation for an exoskeleton. A picture of it is shown in Figure 5.

This set-up was used to determine the optimal architecture for a bowden cable system that can be used in a master device for force-feedback applications. The design was altered several times, before arriving at its final hardware and sensor architecture. This set-up was used to confirm the need for a torque sensor at the joint-side and the springs between cables and the sleeves. In order to perform focused investigations on influence of mechanical imperfections to the system and to analyze performance in a haptic control loop with a real slave, it was decided to develop a second prototype in cooperation with ULB. The second prototype is explained below. It has an improved mechanical design and added features such as an adjustable backlash unit and a backlash-free cable-capstan reducer.

The master prototype is built from two devices linked by the cables: the motor joint and the robot joint (Figure 6). The first consists of a brushed DC motor and a cable capstan reducer (with ratio 10:1). This type of reducer allows zero backlash and extremely high efficiency at the expense of a low torque/volume ratio. The robot joint consists of a bar, representing an articulation of the exoskeleton.

As the cables can only transmit traction forces, they are attached to the joints with 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 friction-free (low-friction) operation. The pretension is obtained by a spring system which can be locked by a solid part to conduct experiments also with stiffer transmissions.

Each side of the master is equipped with a 500 pulses per revolution encoder and a self-made strain gage based torque sensor (Figure 7) to allow studying the cable behavior (friction,. . .). With a diameter of 42 mm they reach a maximum torque of 2.5 Nm with a resolution below 1 mNm. The Slave prototype consists of a brushed DC motor with planetary gearbox (ratio 66:1) and 100 pulses per revolution encoder. A bar equipped with a strain gage force sensor is attached to the gearbox output-shaft. The whole slave setup can be located next to a stiff wall in order to conduct telemanipulated contact experiments.

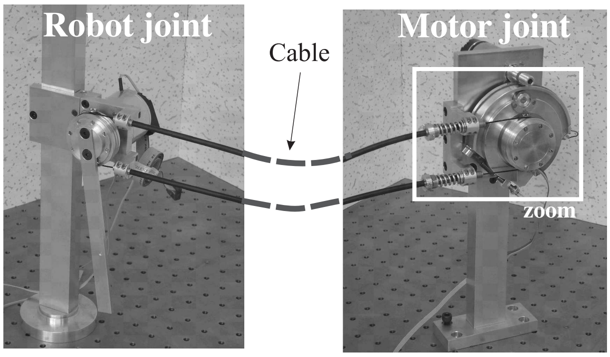

Figure 6: Second bowden cable actuator Master prototype, developed at ULB

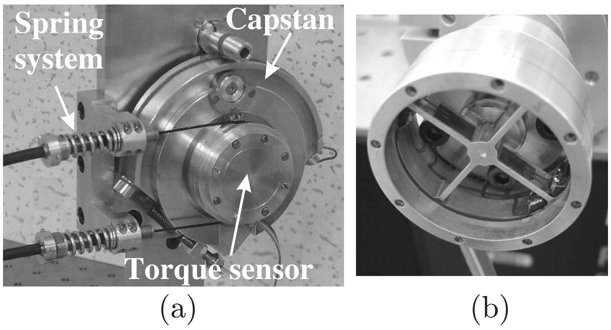

Figure 7: (a) Zoom Motor joint, (b) Home made torque sensor

3.2 Controller

The master and the slave are linked by a dSpace DSP control board (ds1103) that interfaces the sensors and current amplifiers. The updating rate is fixed for all the experiments at 1kHz.

3.2.1 Friction Compensation

The first purpose of the setup is to analyze the behavior of the cable transmission alone, related to its intrinsic friction and the way to decrease it.

A first approach has been to consider a Karnopp friction model to make feedforward compensation [5]. Its principle is to implement a Coulomb or Viscous model with a dead zone in the low velocities to avoid oscillations and instabilities. The feed-forward command, sent to the actuator (DC motor), is given by,

$$F_{comp} = \begin{cases} F_{cst} & \text{if } V > \delta v \\ -F_{cst} & \text{if } V < \delta v \\ 0 & \text{else} \end{cases} \tag{3}$$

with F_{cst} the Coulomb force model (constant as the operator works always with limited speed), V the rotational speed at the joint and dv the dead zone limit. A variant of this strategy is to implement a linear variation of the compensation force in the dead zone.

Another approach that has been studied is the use of active feedforward compensation by using the measured torque to create the command in the dead zone. At the expense of an additional torque sensor, it leads to better results as shown in section 4.

3.2.2 Force-feedback with slave

The second purpose of the system is to show the feasibility to use bowden cable transmission for force feedback teleoperation. The motor controller structure, chosen here, is a 4 channel (4C) type similar to that proposed by Lawrence [6]. The principle, illustrated in Figure 8, is to exchange both torque and position between master and slave to command the opposite side. The position information is compared to the local value through a PD (proportional-derivative) controller, Cm and Cs. 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}. The position and the torque command are then added to create the actuator set-point.

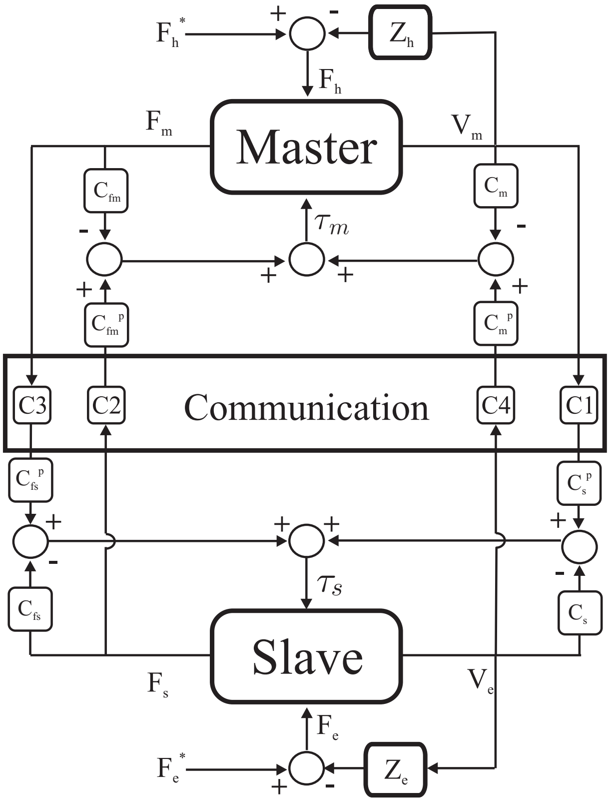

Figure 8: Controller structure for force-feedback between master and slave joint (C_1 to C_4 for communication channels (scaling, delays), C_m and C_s for position master and slave controllers, C_{fm} and C_{fs} for force controllers, Z_h and Z_e for operator and environnent impedance)

4 RESULTS

4.1 Friction Compensation

Depending on the initial preload in the cable, the user will experience friction by moving the master bar of the robot joint. Figure 9 is showing the measured torques on each side of the bowden cables, with in dashed the robot joint measurement and in plain the signal on the motor side. The difference between them is the torque due to the friction between the cables and the sleeves.

Figure 10 represents the case with the Karnopp friction model compensation. Decrease of the average value of the sensed friction can be obtained. However, sticking phenomenon appears when reversing the bar movement. To avoid this effect, the dead zone width has to be defined as narrow as possible. At the same time, to achieve enough compensation, the constant compensation torque (F_{cst}) has to be as high as possible. However, a too narrow dead zone compared to the compensation torque will lead to oscillations and instabilities. By using a linear evolution of the compensation torque in

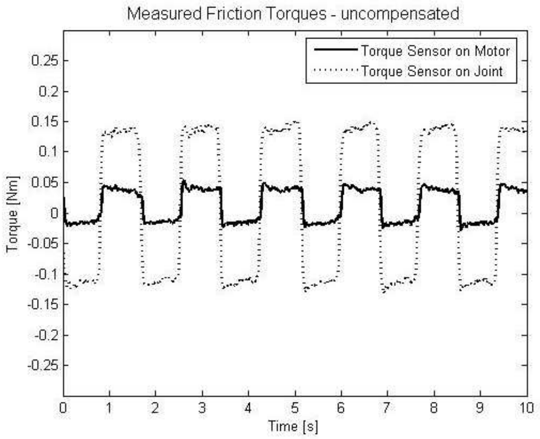

Figure 9: Torque sensors measurement, in free motion, without compensation

the dead zone, F_{cst} can be increase to a higher value, but the sticking effect remains. The fact that a torque is now generated by the actuator can be highlight by comparing Figure 9 and 10 related to the 180 phase shift between the two torque signals.

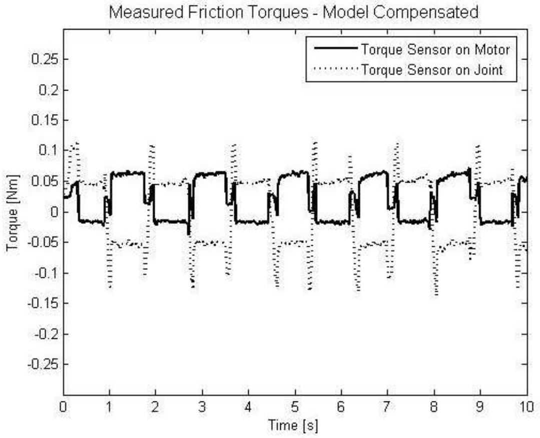

Figure 10: Torque sensors measurement, in free motion, after compensation with Karnopp friction model and feedforward compensation

By using the robot joint measured torque, active compensation can be implemented in the dead zone with a sort of local force feedback. Depending on the feedback gain value, several level of compensation can still be obtained, but here the sticking effect disappears. The best result is obtained when a large dead zone (bigger than the velocity capabilities of the operator) is used, which is equivalent to always use the active compensation (Figure 11). The use of high proportional or integral gain (in the feedback loop) is limited by instabilities due to the dynamics and flexibility of the cables.

4.2 Teleoperation Force Feedback Analysis

Teleoperation experiments were done with the bowden cable actuated master commanding the slave system in free motion or touching hard-contact surfaces. The choice of a 4 channel control architecture comes from the weakness of simple 2 channel approaches such as for instance direct force feedback. With direct force-feedback alone (impedance control) we were unable to exhibit stable behavior when the slave experienced a hard contact.

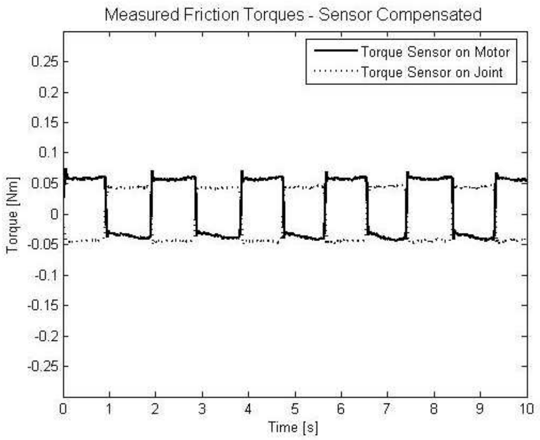

Figure 11: Torque sensors measurement, in free motion, after active feedforward compensation of measured torques on robot joint side

Figure 12 to 14 show the results using the 4C with open loop force controller, in free motion during the first 2 seconds, and then in contact with a steel surface (considered as hard). The solid line corresponds to the robot joint at the master (in dashed in Figure 9).

In free motion, it can be see in Figure 13 that a residual torque of about 0.1 Nm remains. This value is situated between the values obtained for the cases with and without compensation. It is important to notice that here, there is no any local force control at the master. The 4C controller is responsible of this effect.

In contact, a good transparency (limited position and torque tracking error) and stable behavior are reached. The maximum contact stiffness that can be replicated with the bowden cable actuator is in the order of 8.6 Nm/rad (Figure 14). In this case, the springs were clamped, this value can then be attributed to several factors as the flexibility of the cables, the control architecture and the flexibility of the slave bar. When the preload springs are used, to avoid friction variation with the wrapping angle, this stiffness will be mainly limited by the spring stiffness.

Similar experiments were also conducted with additional local force feedback control, which corresponds to the actieve approach for the friction compensation. Although almost similar results to the one represented in Figure 12were achieved in free motion, the contact with the surface is more unstable and the position tracking is less accurate than what was obtained in the first 4C case.

In general, in all the experiment, the feeling of the actuator is good, compared to tests without cable transmissions.

5 SUMMARY AND CONCLUSIONS

A study of the specificities of bowden cable transmissions has shown the advantage of a low pre-load condition of the cables for a good haptic rendering in terms of friction. That let to the development of a new 1 DOF setup. Several experiments have shown the possibility to compensate for the friction inside the cables. The best results are obtained by the use of active compensation. We have also shown the ability of the DC + bowden cable system to realize, in a 4 channels configuration, correct stable haptic rendering with real slave contacting hard surface.

The purpose of the system is to actuate the ESA exoskeleton in space environnement. The advantage of the actuators delocalization by the bowden cable transmission is to decrease the inertia of the movable system. On earth, it will also decrease the mass and

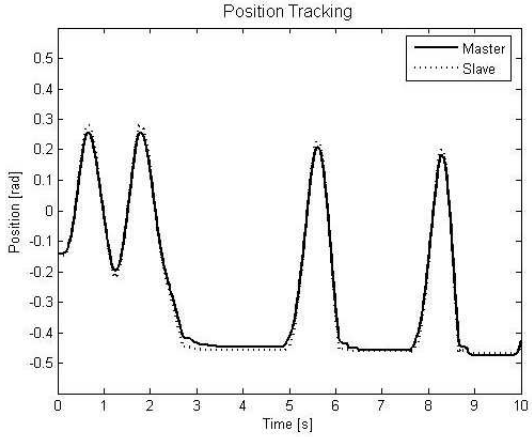

Figure 12: Position tracking between bowden cable actuated master and real slave in free motion and in contact

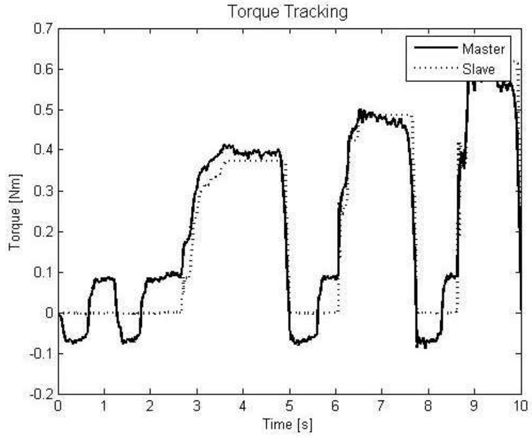

Figure 13: Contact force of slave and bowden cable actuated master in three contact situations

allow the use of bigger actuators, relocated on the back of the operator. Such bigger actuators also allow gravity compensation of the movable part of the system.

The use of springs to guaranty a constant pre-load related to the wrapping angle decreases the maximum stiffness that can be presented by the master device. It can also lead to the apparition of some oscillations when contacting hard surfaces. The results shown in this article were obtained when the springs were clamped. Further tests have to be conducted to analyse the effect, in low pre-load, of the wrapping angle on the quality of the force feedback in this clamped configuration. It is also envisaged to investigate the use of high-preload conditions, where the relative variation of the preload with the wrapping angle is less, related to the performances of haptic feedback.

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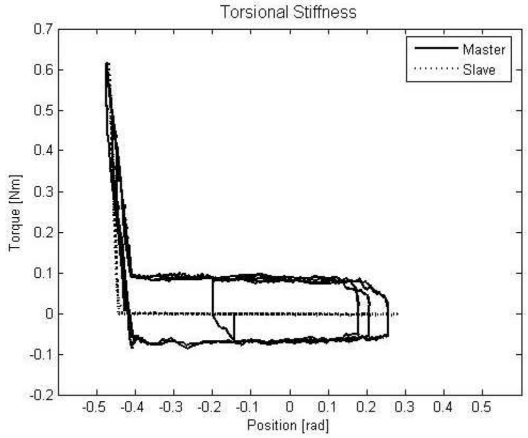

Figure 14: Contact stiffness of slave and bowden cable actuated master in hard contacts

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