Bowden Cable Actuator for Force-Feedback Exoskeletons

Conference Paper · November 2006

DOI: 10.1109/IROS.2006.281712 · Source: IEEE Xplore

4 authors, including:

André Schiele
Delft University of Technology

Frans CT van der Helm
Delft University of Technology

Bowden Cable Actuator for Force-Feedback Exoskeletons

Andre Schiele
Automation and Robotics Laboratory
European Space Agency
Noordwijk, Netherlands
Andre.Schiele@esa.int

Pierre Letier
Active Structures Laboratory
Université Libre de Bruxelles
Brussels, Belgium

Richard van der Linde,
Frans van der Helm
Dept. of Biomechanical Engineering
Delft University of Technology
Delft, Netherlands

***Abstract* - This paper introduces a novel type of actuator that is investigated by ESA for force-reflection to a wearable exoskeleton. The actuator consists of a DC motor that is relocated from the joint by means of Bowden cable transmissions. The actuator shall support the development of truly ergonomic and compact wearable man-machine interfaces.**

Important Bowden cable transmission characteristics are discussed, which dictate a specific hardware design for such an actuator. A first prototype is shown, which was used to analyze these basic characteristics of the transmissions and to proof the overall actuation concept. A second, improved prototype is introduced, which is currently used to investigate the achievable performance as a master actuator in a master-slave control with force-feedback. Initial experimental results are presented, which show good actuator performance in a 4 channel control scheme with a slave joint. The actuator features low movement resistance in free motion and can reflect high torques during hard contact situations. High contact stability can be achieved. The actuator seems therefore well suited to be implemented into the ESA exoskeleton for space-robotic telemanipulation.

Index Terms – Exoskeleton. Bowden cable. Actuator. Ergonomic kinematics.

I. INTRODUCTION

Future human missions or permanent presence in space will require substantial robotic support. The European Space Agency (ESA) started developing a humanoid servicing robot for the International Space Station (ISS), called Eurobot [1]. Eurobot shall support astronauts during extra-vehicular activities (EVA). Two main control modes are foreseen therefore; autonomous control and manual control in a master-slave type architecture. For the manual control of the seven degrees of freedom (d.o.f.) arms of Eurobot, an exoskeleton man-machine interface is currently being developed at ESA [2] [3] [4]. The exoskeleton shall provide force-feedback from Eurobot to the arms of human operators located inside the ISS. In order to provide high comfort during long-duration operations, special attention was paid to ergonomic design of the exoskeleton. The device offers a great dexterity of movement to the operators while being worn and needs no adjustments to different individuals. This is achieved by its novel ergonomic kinematic design presented in [5].

For creation of a good quality force-feedback with the exoskeleton under micro-gravity conditions, several actuation options exist. It could be adequate to integrate actuators, e.g. DC motors with reducers, directly into its mechanical structure. Their mass 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 force-feedback performance. Provision of a high power output in the entire workspace at a reasonably low system mass is difficult to achieve. 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 impracticable, if gravity force cannot be compensated by external mechanisms or if the motors are not extremely lightweight and power-dense. One solution to the problem of power dense actuation for wearable interfaces can be the relocation of all actuators to the static base of the system. This way, mass and inertia of the movable part can be significantly reduced, thus, allowing an ergonomic kinematic design similar than for a reduced-G exoskeleton also on ground.

In space, actuator relocation could lead to less inertia felt by the operators during telemanipulation, as well as to a more compact design of the wearable device. This is why we decided to investigate possible solutions allowing actuator relocation.

Actuator relocation could be achieved by means of hydraulic, pneumatic or cable transmissions. Hydraulic transmissions, as well as pneumatic transmissions were discarded rather quickly, however, because their complexity is relatively high at low performance in force-feedback applications. For the ESA exoskeleton, therefore, a cable-based transmission system seemed most suitable.

Cable transmissions can be established in two different manners, either by routing cables over a set of pulleys such as implemented in [6] and [7] 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 detailed study. The use of Bowden cables for force-reflective display design was previously reported in [8] and [9]. The use of such an actuator type for the ESA Exoskeleton was already postulated in [2] and [3].

However, to the current knowledge of the authors, this paper presents for the first time an investigation of the transmission behavior of Bowden cables and their influence on haptic performance in a force-feedback control.

In the first part, this paper discusses the specific transmission characteristics of Bowden cables and their influence on the required hardware architecture of the actuator. The characteristics were investigated with a first prototype at ESA and TU Delft. The design of a second, improved version of the first prototype is shown next, which was developed to investigate actuator performance in force-feedback control. It was built in cooperation with the University of Brussels.

II. Geometric Characteristics of Bowden Cable Transmissions

A. Implementation

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 and the outer sheath. To implement a remote-actuated rotary joint, a pull-pull configuration as illustrated in Fig. 1 is optimal. The cables are fixed to pulleys at both sides. The robotic joint can be actuated in both directions by respective rotation of the motor. A preloading unit, located somewhere along the transmission can be used to tension the cable-loop with respect to the sheaths.

B. Specific Bowden System Characteristics

Losses and inefficiencies of Bowden transmissions are 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.

The primary parameters influencing efficiency of the transmission are normal forces on the cable (induced by cable tension or preload), 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 characteristic for Bowden transmissions that those primary parameters depend furthermore on the geometric configuration of the cable system. 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 treated 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 *v*, as illustrated in Fig. 2. The force transmission efficiency F_{S1}/F_{S2} can thus be approximated as in

$$F_{S1} / F_{S2} \cong 1 / e^{\mu\Theta} = e^{-\mu\Theta}. \tag{1}$$

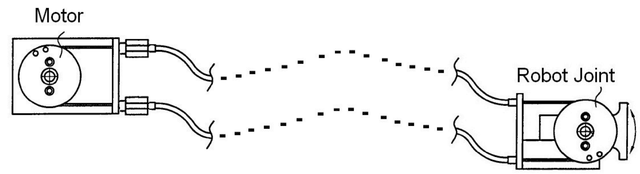

Fig. 1: Concept illustration of Bowden cable actuation to a robotic joint. The robotic joint represents one joint of a wearable structure such as an exoskeleton. The motors can be located e.g. on the back of the operator.

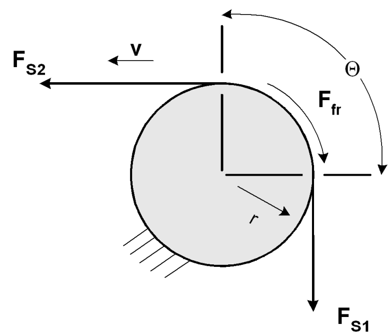

Fig. 2: Friction inside a Bowden cable is similar to friction of a cable routed around a stationary cylinder. Theta represents the sum of all bending angles of the transmission, from motor to joint, and is called wrap angle.

In (1), μ is the coefficient of sliding friction and Θ, the wrap angle of the cable around the cylinder. In a Bowden system, Θ is the sum of all bending-angles along the transmission. In Fig. 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 [10] and [11].

As indicated in (1), the bending radius should not influence the cable friction. According to cable manufacturers, the only effect of very small deflection radii is increased wear of the cable, which negatively influences the friction coefficient over time. Therefore, they recommended having minimal deflection radii r_m of

$$r_m \geq 20 \cdot D_{Cable}, \tag{2}$$

with D_{Cable} being the external diameter of the cable inside the sleeve.

However, in a real Bowden cable system, changing wrap angle also changes cable preload and therefore has a bigger effect on force transmission efficiency as shown in theory. The preload changes during bending can be explained as follows: The external casing often comprises of a spiraled 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 center-line of this tube extends longer, which stretches and preloads the cable inside.

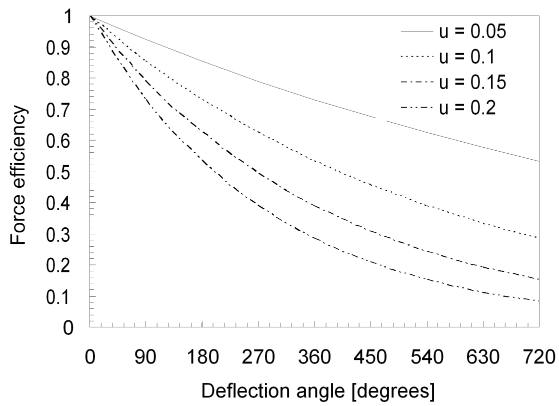

Fig. 3: Theoretical efficiencies of force transmission in a Bowden cable system. Curves are presented for various friction coefficients.

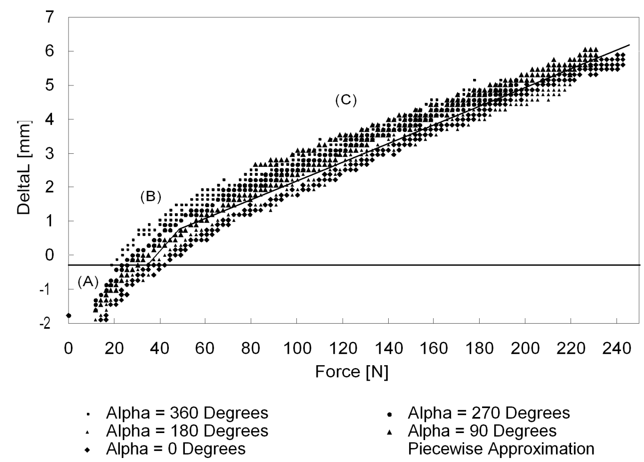

Fig. 4: Measured cable stretch *DeltaL* in function of actuator force. The influence of wrapping angle *Alpha* on cable stretch is shown at different actuator loads. Measurements were done with the first actuator prototype.

Fig. 4 shows the measured stretch *DeltaL* of a cable inside a Bowden cable system under load, for different wrap angles. It can be seen that if the wrap angle is increased under constant load, the preload of the Bowden cable assembly increases, resulting in increased stretch of the cable.

Cable preload 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 must be as stiff as possible. This is important for implementation of force control to the actuator joint. For the sleeves, linear constructions have higher stiffness than spiral-spring type constructions and are therefore preferred. Fig. 4 furthermore shows that stiffness of the cable is not linear over the load range.

The question arises, whether to operate a Bowden cable system better with low loading (i.e. Fig. 4(B)) or better with high loads (i.e. Fig. 4 (C)) for force-feedback applications. Up to now, similar configurations of Bowden cables were only used in highly loaded conditions for joint actuation [12]. Operation at exclusively high load linearizes the cable stiffness; however, has the negative effect of creating high friction. The approach works fine for position control applications, if large motors can be used to overcome the frictional force. In principle, a low load is better for haptic applications, because friction in the system is lower. As a consequence, the torque dynamic range can be higher, which can lead to a better haptic rendering capability. Furthermore, smaller motors can be used, to keep the system mass within acceptable limits. However, if cable preload is too low, the cable can detach from the pulleys, which introduces slack into the system. This effect is apparent in the experimental results presented in Fig. 4 (A), as negative stretch *DeltaL*. In order to avoid such slack of the cable, stiff spiral springs were inserted in series with the sleeve and the robotic joint structure in the first prototype. These springs counteract the effect of slack at low loading, if they are slightly tensioned. Furthermore, the springs reduce the influence of the wrap angle to the cable preload. It is important to dimension the spring stiffness appropriately. If they are too soft, they significantly limit the contact stiffness that the actuator can create in a force-feedback application. A cable transmission model was developed at the TU Delft, which allows performing such optimizations.

Another effect that has to be considered in the hardware configuration of a Bowden cable actuator is stick-slip. During movement, stick-slip causes vibration that is characterized by a saw-tooth 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 were found out to reduce stick-slip and to improve the Bowden cable transmission characteristics:

- *Use of 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 poly-tetra-flour-ethylene (PTFE) on PTFE. The actuator uses therefore PTFE coated steel cables in combination with a PTFE liner inside the sleeve.
- *Use friction couples with a very small friction coefficient in general.* PTFE on PTFE is well suited.
- *Use cables and sleeves with high stiffness.* Therefore, it is optimal to use pre-stretched 7 x 19 cable construction with a Kevlar reinforced linear shell-type external sleeve. The 7 x 19 cable construction ensures good flexibility of the cable at high stiffness.
- *Use the actuator in a low preload condition.*

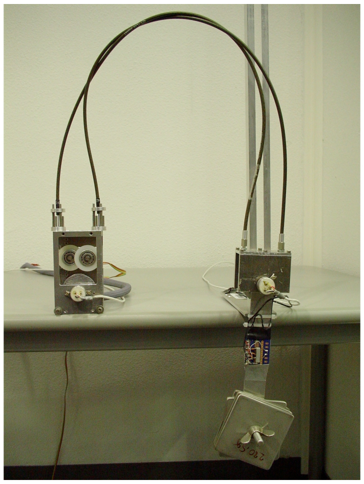

Fig. 5: First Bowden cable actuator developed at ESA. The prototype was used to investigate the basic cable transmission characteristics.

The investigations presented above were performed with the first prototype shown in Fig. 5. The prototype consists of a DC motor with gearbox, encoder, potentiometer and differential tendon force sensor on the actuator side, and one torque sensor, potentiometer and load bar at the joint side. The load torque sensor is integrated into the pulley spokes on the robotic joint (not visible in Fig. 5). Different masses can be attached to the load bar, to simulate actuator loading. This set-up was used to proof the overall concept of Bowden cable actuation. However, its hardware has undergone too many changes during the development, which is why we decided to build a second, better constructed prototype for carrying out the master-slave control experiments. The second prototype includes all elements that were found necessary for a good Bowden cable actuator.

III. Bowden Cable Transmissions in Force Feedback

A. *Mechanical Set-up*

Similar to the first set-up, the second prototype is built from two devices linked by the cables: the motor joint (Fig. 6, right) and the robot joint (Fig. 6, left). The motor joint consists of a brushed DC motor with a cable capstan reducer (reduction ratio of 10:1). This type of reducer allows zero backlash and extremely high efficiency (≈ 99%) at the expense of a low torque to volume ratio. In order to investigate influence of backlash to the actuator at a later stage, an adjustable backlash unit is included in the motor-side of the prototype. The robot joint consists of a bar, representing an articulation of the exoskeleton. The cables are attached to the joints in a pull-pull configuration, just like before. They consist of PTFE-coated steel cables sliding in slightly preloaded, low weight, Kevlar-reinforced cable housings. The sleeves also contain the inner Teflon-coated liner. The pretension is obtained by a spring system, which can be locked to conduct experiments also under high preload conditions later on. Each side of the master contains 500 pulses per revolution encoders. A torque sensor is included in each pulley.

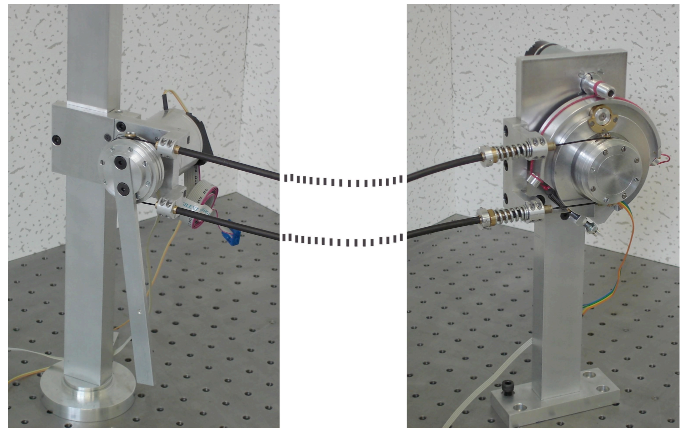

Fig. 6: Motor joint (right) and robot joint (left) of the second prototype developed to investigate force-feedback performance with a slave joint.

With a diameter of 42 mm they reach a maximum torque of 2.5 Nm with a resolution bellow 1 mNm. The two torque sensors will allow studying the cable friction behavior between the two joints, in various configurations, more deeply in the future. In addition, we developed a simple joint representing a joint of the slave robot. This slave joint prototype was used during the force-feedback experiments shown below. The slave joint consists of a simple brushed DC motor with planetary gearbox (reduction ratio of 81:1) and a 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 steel wall to conduct contact experiments in a one d.o.f master-slave set-up with the cable actuator as a master.

B. *Controller*

A dSpace DSP control board (Ds 1103) interfaces sensors and current amplifiers of both, master and slave. The control updating rate is fixed for all the experiments at 1 kHz. As mentioned already above, the primary purpose of this system is to show the feasibility to use Bowden cable transmissions for force feedback telemanipulation within the ESA exoskeleton. The chosen motor controller structure is shown in Fig. 7.

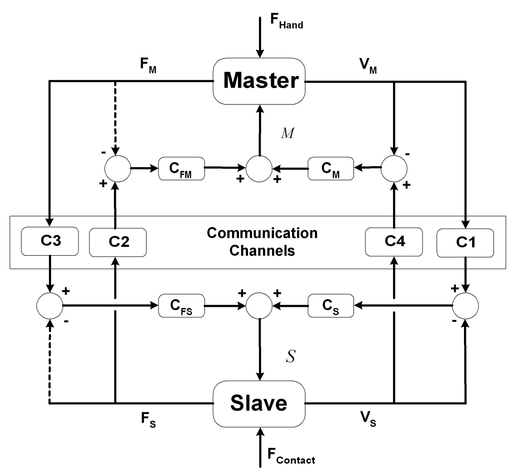

Fig. 7: Structure of the 4 channel controller that was used for the force-feedback experiments carried out with the Bowden cable actuated master.

The controller is a 4 channel (4C) type, similar to that proposed by Lawrence [13]. The control principle consists of exchanging torque and position information between master and slave for command of the opposite side. The position information is compared to the local values through proportional-derivative (PD) controllers, represented by C_m and C_s. The torque commands can be used in open loop or through proportional-integral (PI) controllers, represented by C_{fm} and C_{fs}. The position and the torque commands are then added to create the actuator set-points. Torque commands on the master side are acquired from the torque sensor on the robotic joint side of the master.

C. *Force-feedback Performance Experiments*

Telemanipulation experiments are currently being carried out with the Bowden cable actuated master commanding the slave system in free motion and in hard-contact situations. The results presented below are an extract from the ongoing experiments with the system. The choice of the 4C control architecture is a consequence from poor results that we have achieved with conventional 2 channel control approaches (i.e. direct force feedback). With direct force-feedback, we were unable to exhibit stable behavior when the slave experienced a hard contact.

Fig. 8 to Fig. 10 show results attained by using the 4C controller with open loop force control during the experiments. The robot joint of the master was moved by the operator hand to command the slave remotely. Free motion took place during the first seconds of the experiment. After about 2.8 seconds, the slave was rotated far enough to contact the steel surface next to it. The solid line in all graphs corresponds to recordings of the cable actuator (i.e. the master), whereas the dashed line represents recordings of the slave. It can be seen in Fig. 9 that a residual torque of about 0.1 Nm remains during free motion. It is important to notice that, for these results, no local friction compensation is used on the master side. The reduction of free motion resistance is done by the 4C controller only. In hard contact, Fig. 8 and Fig. 9 show very small position and torque tracking errors, which proofs good actuator transparency and a stable behavior. The maximum contact stiffness that can be replicated with the Bowden cable actuator is illustrated in Fig. 10. The stiffness is in the order of 8.6 Nm/rad. For this measurement set, the springs between the sleeves and the joint structure were clamped, to see the maximum attainable stiffness of the actuator. When the springs are used, to avoid friction variation with the wrapping angle, the actuator stiffness is limited to the spring stiffness. In Fig. 10, the stiffness is only limited by the flexibility of the cable system, the control architecture and the flexibility of the slave bar.

Similar experiments were also conducted with additional local force feedback control, aiming at reducing free motion resistance even further. Although almost similar results to the ones presented in Fig. 8 were achieved in free motion, contact of the slave with the surface caused more unstable behavior of the master. The position tracking error was bigger.

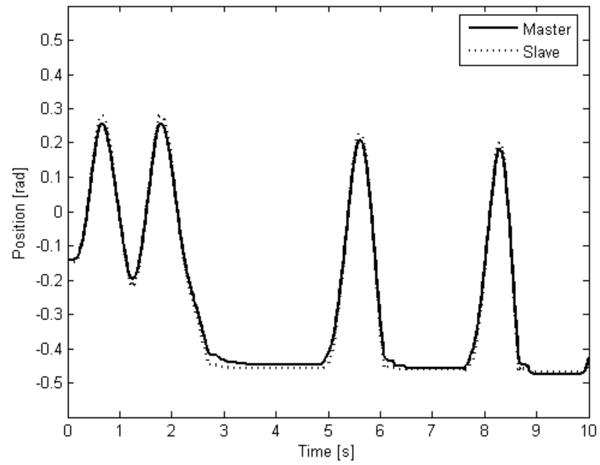

Fig. 8: Experimental results from master-slave control with Bowden cable actuator. Position tracking capability.

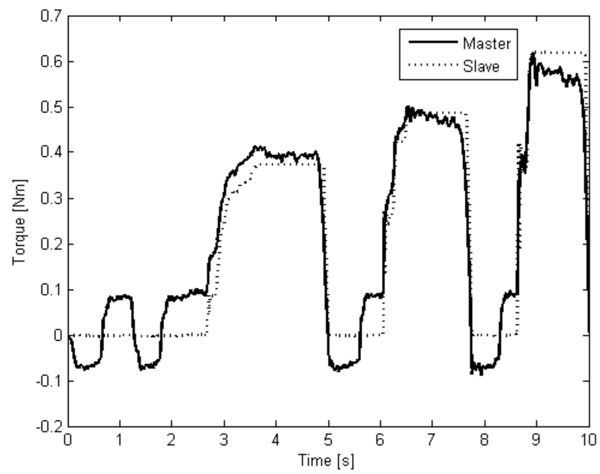

Fig. 9: Experimental result from master slave control with Bowden cable actuator. Torque tracking capability in contact situation.

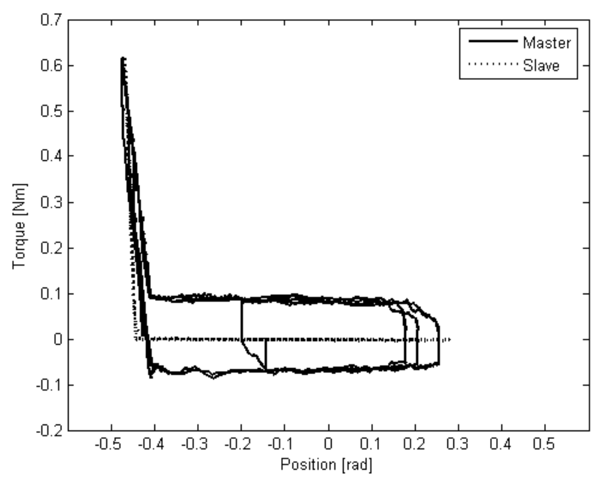

Fig. 10: Experiment results from master-slave control with Bowden cable actuator. Contact stiffness of master actuator and slave in hard contact situation.

In general, the feeling of the actuator in free motion and in contact situations is very good when used with a 4C controller without local force feedback.

The results shown above confirm the possibility to use the actuator for the ESA exoskeleton in a space application.

IV. Future Work

The experimental results shown above have proven suitability of the actuator to work in a low load condition. This condition resembles use inside a micro gravitational environment. The next step will be to investigate how the actuator will perform in a force-feedback control under higher load conditions. In order to analyze whether the actuator will be truly usable on ground, we need to conduct force-feedback experiments with additional masses attached to the robot joint of the master actuator. Those experiments will allow investigation of actuator performance when additional weight compensation of adjoining mechanical linkages is simulated. While these tests had been carried out with the initial prototype, they have not been confirmed with the new hardware set-up yet.

Furthermore, the high load experiments will have to be repeated under varying wrapping angles of the Bowden cable system. The compensation springs of the new set-up must then be used to compensate for varying preload of the Bowden actuator.

Only when these two additional experiment sessions have been successfully conducted, we can truly be sure that the developed actuator is usable also on ground. In a positive case, the presented actuator could provide a great benefit to many terrestrial robotic applications. In principle, all robots requiring a large workspace at a low system mass could make use of such an actuator. In particular, this actuator would be suitable for the vast range of wearable and non-wearable haptic devices, which suffer from the same lack of power dense actuation.

V. Conclusions

Geometric specificities of Bowden cable transmissions are presented, that have been analyzed during experiments with a first Bowden cable actuator prototype.

A suitable hardware configuration is shown, to implement remote actuation to a robotic joint via Bowden cable transmissions.

Furthermore, the capability is demonstrated to use a Bowden cable actuator for haptic applications in a low load configuration, with good force-feedback performance and contact stability in hard contact situations with a slave.

We have demonstrated that our Bowden cable actuator can, already now, be successfully used for actuation of the ESA human arm exoskeleton in space.

The Bowden cable actuator can help to increase compactness of wearable human machine interfaces, by shifting design complexity from the movable part of the system, to the stationary one. By enabling compactness, the actuator opens the way to a more advanced kinematic design of the devices, which can enable better comfort and ergonomic properties during human-machine interaction.

References

[1] P. Schoonejans, R. Stott, F. Didot, A. Allegra, E. Pensavale, C. Heemskerk, “Eurobot: EVA-assistant robot for ISS, Moon and Mars”, Proceedings of 8th ESA Workshop on Advanced Space Technologies for Robotics and Automation, ASTRA, Noordwijk, November 2004.

[2] A. Schiele, G. Visentin, “The ESA human arm exoskeleton for space robotics telepresence, Proceedings of the 7th International Symposium on Artificial Intelligence, Robotics and Automation in Space, iSAIRAS, Nara, May 2003.

[3] A. Schiele, G. Visentin, “Exosquelette pour bras humain, notamment pour des applications spatialles”, European Patent Application, EP 1364755, 2003.

[4] A. Schiele, G. Visentin, “Exoskeleton for the human arm, in particular for space applications”, U.S. Patent, US 2003223844, Dec. 2003.

[5] A. Schiele, F.C.T. van der Helm, “Kinematic design to improve ergonomics in human machine interaction”, IEEE Transactions on Neural Systems and Rehabilitation Engineering, in press.

[6] R. L. Williams, M. A. Murphy, D. North, J. Berlin, M. Krier, “Kinesthetic force/moment feedback via active exoskeleton”, Proceedings of IMAGE Conference, pages RL-1 – RL-7, Scottsdale, Arizona, August 98.

[7] A. Frisoli, F. Rocchi, S. Marcheschi, A. Dettori, F. Salsedo, M. Bergamasco, “A new force-feedback arm exoskeleton for haptic interaction in virtual environments”, Proceedings of the first World Haptics Conference, pages 195 – 201, Pisa, March 05.

[8] Immersion Corporation, “The cybergrasp”, web: www.immersion.com/3d/products/cyber_force.php, 2004.

[9] S.L. Springer, N.J. Ferrier, “Design and control of a force reflecting haptic interface for teleoperational grasping”, ASME Journal of Mechanical Design, Vol. 124, pp. 177 – 283, 2002.

[10] G. Ognar, “Entwicklung eines bowdenzug pruefstands fuer tribologische untersuchungen and bowdenzuegen”, Ph.D. Thesis, Technical University of Vienna, 1994.

[11] L. B. Carlson, B. D. Veatch, D. D. Frey, “Efficiency of prosthetic cable and housing”, Journal of Prosthetics and Orthotics, Vol. 7, No. 3, pages 96 ff., 1995.

[12] J. F. Venneman, R. Ekkelenkamp, R. Kruidhof, F. C. T. van der Helm, H. van der Koij, “Design of a series elastic- and bowdencable based actuation system for use as torque actuator in exoskeleton-type training”, proceedings of IEEE 9th International Conference on Rehabilitation Robotics, pages 496 – 499, Chicago, 2005.

[13] D. Lawrence, “Stability and transparency in bilateral teleoperation”, IEEE Transactions on Robotics and Automation, 9(5), pages 624 – 637, 1993.