Survey of Actuation Technologies for Body-Grounded Exoskeletons

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ABSTRACT

This paper reports on the evaluation of various actuation technologies to be used in a portable exoskeleton for space applications. It is divided into four parts. The first part defines the scope of the project and gives a brief overview of the existing arm exoskeleton devices. The second part is devoted to the description of the three actuation technologies evaluated: DC motors and their combination with other mechanical systems in order to integrate them in a portable haptic device, a brake prototype developed at the ASL using magnetorheological fluid and finally ultrasonic motors. The third part is devoted to the experimental prototyping with the description of the 1 DOF setup built to compare the actuators, and the results obtained for each of them. Finally, the fourth part shows some comparisons between the technologies, related to relevant parameters for portable haptic interfaces.

Keywords: Haptic actuator, MR Brake, Ultrasonic motor, Exoskeleton

1 INTRODUCTION

Future space missions will require a higher level of cooperation between astronauts and robots that could be used as first explorers in hostile environments or as assistants for Extra-Vehicular Activities (EVA). In such situations, the use of a portable device that would procure the robot operator with force-feedback sensations (also called haptic sensations) would highly increase the easiness of the command task. For that purpose, we are currently investigating, in cooperation with ESA, which actuation technologies are most suitable for inclusion into the ESA human arm exoskeleton, that could be used as master in a teleoperation system where the slave would be a maintenance robot located outside the International Space Station (ISS)[11][12][13].

Due to high technological complexity, only a very few prototypes of portable arm exoskeletons have been developed up to now. Moreover, the majority of the existing devices are not well suited for use inside a microgravity environment. Indeed, non body-grounded devices [1][5][15] will produce feedback forces that would rather push away the astronaut than creating confortable haptic sensations. Furthermore, most of the time, existing body-grounded exoskeleton [2][3][6] require complex annex systems that are not suited for space applications.

When developing a portable haptic device, the choice of the actuation technology has a high influence on the quality of the device related to the confort of the operator and the force-feedback performances. Several parameters can be defined to evaluate and compare them: Torque/Mass and Torque/Volume ratios (of major importance when considering portable haptic interfaces), Dynamic Range, Torque rise time (has a direct impact on the system bandwidth, limiting the maximum stiffness that can be represented by the haptic interface), controllability and finally the user safety (especially important when the haptic interface is body grounded and used in a space environment). It should be noticed that the last two above mentioned parameters are more difficult to quantify and only qualitative considerations allow to compare them.

Following a literature study and from our past actuation experiments, we selected three kinds of technologies which could be considered in the ESA exoskeleton development : DC motor, magnetorehological brake and ultrasonic piezoelectric motor. Other type of actuators, like those based on pneumatic and hydraulic principle, where directly eliminated due to their important weakness related to our application (size, risk of leakage,...).

The next sections will describe each of the technologies selected and the experimental 1 DOF setup built to compare them related to the previous criteria and their possibility of use in a teleoperation system.

2 DESCRIPTION OF THE CONSIDERED ACTUATION TECHNOLOGIES

2.1 DC motors and reducers

DC motors are currently, by far, the most used haptic and robotic actuators. They are easy to install (no complex piping, wiring,...), clean (no oil leaks), quiet and easy to control [3]. Force-feedback experiments were conducted on both brushed and brushless DC motors and have shown that a very similar haptic rendering could be obtained with both technologies implemented in our setup. We thus decided to focus our study on brushed DC motors requiring much less complex controllers.

Stand-alone DC motors being very inefficient under haptic working conditions, it is usually preferable, in portable applications, to use a smaller motor in combination with a reducer, even if it will affect the dynamic range and off-state friction of the system.

In order to avoid backlash and high friction inherent to the use of conventional reducers, haptic interfaces usually make use of cable capstan reducers allowing zero-backlash transmissions as well as low friction. It is however obtained at the expense of a slightly lower Torque/Volume ratio. Their working principle is based on a capstan located on the motor shaft wrapped with a cable having its both ends linked to a large diameter wheel (Figure 1). An automatic tensionning system, composed of a spring and a fixed post on the wheel, can also be implemented in order to avoid manual adjustment of the preload after a certain period of time due to creep in the cable.

A good compromise could be the use of a planetary gearbox (presenting limited backlash and a low reduction ratio) before the cable capstan reducer. Such a system would reduce the backlash

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due to the planetary gearbox by a factor equal to the reduction ratio of the cable reducer while having a high global reduction ratio in combination with a smaller volume. Furthermore, as long as the internal friction inside the planetary gearbox is kept small enough, the total friction remains acceptable.

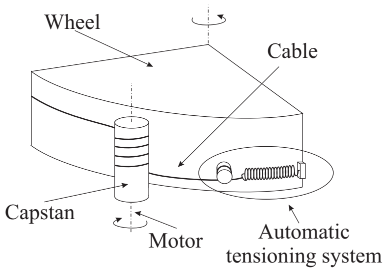

Figure 1: Cable capstan reducer with the automatic tensionning system

Another problem appearing when considering quite heavy and bulky actuators such as DC motors, directly located on the joints axes of a portable haptic interface, is the weight to be supported by the operator. In order to solve this problem, an active gravity compensation can be implemented, requiring more powerful and more bulky motors as well as more complex control strategies. Another solution would be to delocalize the motors from the joints axes (in our case, to locate them in the back of the operator) and to transfer the torque from the motors to the joints by means of a cable transmission, as proposed in [13] and described in more details in [8].

2.2 Magnetorehological Brake

As an alternative to active actuators (such as DC motors), semi-active actuators (such as brakes) can be used leading to a stable behavior of the haptic interface independently of the stiffness of the contact to be represented, a characteristic that can not be achieved with active actuators. This intrinsic stability of semi-active actuators is thus a major advantage regarding to operator safety issues. However, because semi-active actuators are not able to apply power to the operator, their use is limited to applications where only resistive torques (i.e. screwing operations, stiff contacts, springs in their compression phase...) have to be represented. It should also be noticed that such actuators can also be used in combination with active actuators either to introduce damping in the system with the aim to stabilize it or to replace active actuators when very stiff contacts have to be represented.
After a deep analysis of semi-active technologies, it appeared that MR brakes were the best candidates for our application; unfortunately, no commercial brake exhibits dimensions compatible with our application and we thus decided to build our own prototype. The working principle of MR brakes is based on the use of a small quantity of magnetorheological fluid located in the gap between the rotor and the stator of the brake. Such fluid belongs to the group of so called controllable fluids. This means that it exhibits a significant change in its rheological behavior when an external magnetic field is applied to it. Magnetorheological fluids are indeed composed of micron-sized magnetic particles, located inside a liquid carrier, that form chain-like structures when the external field is applied (figure 2), resulting in an increase of the apparent viscosity of the fluid. By increasing the viscosity of the fluid, the friction force applied to the rotor will increase accordingly, resulting in a braking torque at the brake output shaft.

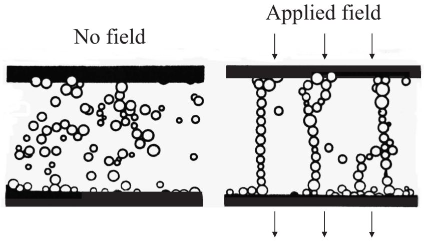

Figure 2: Chain-like structure formation under the applied external field ([10])

2.3 Ultrasonic motor

A third candidate for haptic feedback in portable devices could be ultrasonic motors. Their working principle is based on mechanical vibrations in the ultrasonic range generated by piezoelectric effect [14] (Figure 3). The motor is principally composed of two circular parts. The purpose of the first one, the stator, is to convert electrical energy into mechanical vibrations. A polarized piezoelectric layer allows to generate a propagating wave on the stator. A second layer of bronze teeth amplifies the vibration and generates an elliptical movement. The second part, the rotor, is pressed on the stator. By friction, the propagating wave generates the movement of the rotor. The principal advantage of this kind of motors is their Torque/Mass and Torque/Volume ratios that are theoretically 20 times larger than common DC motor (without amplification system). They are also designed to work at low speed, typical of haptic applications. They however require a specific control approach, based on local force feedback, as they are intrinsically not backdrivable (the rotor is indeed pressed on the stator).

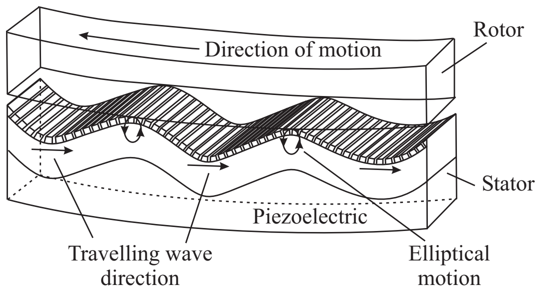

Figure 3: Ultrasonic motor principle

3 Experimental prototyping

3.1 Control Strategies

In parallel to the actuation selection, it is also important to analyze the control strategy to achieve the best results for each actuator. The aim of the control is double: first, it has to guarantee the stability of the teleoperation system within the required bandwidth. This stability is important for the quality of the perception and also the safety of the operator/device. The second purpose is to optimise the performances of the system like its dynamic range, its bandwidth or its transparency.
For the DC case, the intrinsic control of the actuator is very simple as the output torque is proportional to the coil current. We payed then more attention to the teleoperation control strategy, in contrary to the two other technologies where specific control is needed to drive them as haptic devices. We implemented two channels (impedance control) and four channels controllers which corresponds to an exchange of both positions and torques on each

side of the teleoperation system to drive the actuators [7]. At the expense of more sensors in the setup, the last allows better results in terms of transparency and stability.
The MR Brake device needs a specific control to allow correct force feedback. As it can only work as a passive device it will not be able to produce active torques against the operator. To avoid wrong feeling, it has then to be shut down if the movement is opposite to the force command. In order to decrease the sticking phenomenon at the switching, we implemented a stick/slip control method [4],

Slip mode : $(if\ (|\dot{\theta}| \geq \delta\dot{\theta})$

$$\tau_{out} = \begin{cases} -sgn(\dot{\theta})\,|\tau_c| & \text{if } sgn(\dot{\theta}) \neq sgn(\tau_c) \\ 0 & \text{else} \end{cases} \quad (1)$$

Stick mode : $(if\ (|\dot{\theta}| < \delta\dot{\theta})$

$$\tau_{out} = \begin{cases} \tau_c & \text{if } sgn(\tau_H) \neq sgn(\tau_c) \\ 0 & \text{else} \end{cases} \quad (2)$$

with $\dot{\theta}$ the angular velocity, τ_c the torque command and τ_H the measured operator torque.
For the ultrasonic motor, as it is not backdrivable, it has to be actuated to allow free movement of the operator. A local force feedback, with a proportional-integral controller, is used.

3.2 Results

3.2.1 DC motors

Several teleoperation experiments (Master + Slave, both using DC motors equipped with an encoder and home-made torque sensors) have been conducted in order to assess the performances of DC motors for haptic feedback. Various 1DOF mechanical architectures were tested : simple DC + capstan reducer, DC + capstan + gearbox (ratio 1:81) and delocalized DC with bowden cable transmission[13](see figure 6 and 7 in [8]). For each of them two channels and four channels control methods were implemented. During each test, the Master is held by the operator who controls, through it, the Slave that can interact with a real "wall" characterized by a specific stiffness. The Master and Slave positions, the torque felt by the operator at the Master and the Slave contact torque are recorded.
The 2C control allows correct haptic sensation only for the simplest mechanical structure (no gearbox or bowden cables transmission) and for limited wall stiffness. Otherwise, for high stiffness or with the cables, the system can easily present unstable behavior. With the added gearbox, the Master can simply not be moved due to the high internal frictions (unless a specific friction compensation is implemented).
The use of the 4C method leads to an increase of the performances. The two major benefits are the stability improvement and the Master dynamic compensation. The use of the gearbox is now feasible with almost a complete disappearance of frictions and inertias. The controller allows free movement of the operator without high frictions or inertia's at the master side (normally it can't be moved) and stable contact of the slave with a stiff environnement. We however observed a lack of transparency in the force tracking due to dynamical effects in the gearbox. However, it should be noticed that backlash remains (even if slightly reduced) affecting the haptic sensation even if it doesn't affect the system stability. Similar stable results were also achieved with the bowden cable transmission system. They are described in more details in [8].

3.2.2 MR Brake

The MR brake performances were also evaluated using a 1DOF test setup including an optical encoder and a home-made torque sensor. In order to analyse the MR Brake specific behavior as a haptic device, we linked it to a virtual environment represented by a spring. Figure 4 represents several stiffness that can be sensed by the operator when entering in contact with the virtual spring. Before the contact, the intrinsic brake friction can be highlighted. Its value is below the intrinsic friction of the DC case. When entering in contact, the stick/slip method allows to sense the spring stiffness only if the operator velocity is in the direction opposite to the reaction torque. When the operator removes from contact, he can't feel the spring compliance anymore. These results show the ability of the brake to present several stiffness values, however, in practice, the lack of compliance is a little destabilizing.
Despite its high torque/volume and torque/mass ratios (as well as a good dynamic range) measurements have shown that the torque rise time of this first prototype is quite high (around 60ms), having a bad influence on the system bandwidth. This limited response time also restricts high stiffness representations to about 10 Nm/rad. Due to these results we did not conduct any teleoperation experiments and focused our efforts on a new brake prototype with improved time response.

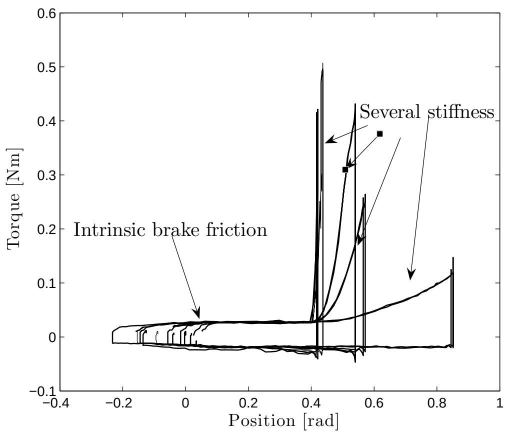

Figure 4: Various stiffness emulated by the MR Brake

3.2.3 Ultrasonic motor

For the ultrasonic motor, we also conducted some tests with virtual springs (figure 5) using a 1DOF setup similar to the one used for the MR brake. With the local force feedback the operator was allowed to drive the ultrasonic motor in free motion almost without perturbation. Only when reversing the movement, some friction sensations appear. We were able to represent various stiffness values (from 0 to 2Nm/rad). The maximum torque deliverable by our motor is not sufficient to simulate harder contact. However, other versions do exist, two times bigger in diameter, which present theoretically enough torque capabilities. Moreover, the motor presents some instabilities in contact and changing behavior with time (temperature, wear) that affects its controllability.

4 Discussion and Conclusion

Figure 6 summarizes the different types of actuators related to the parameters defined in the Introduction. The dynamic range corresponds to the intrinsic value of each actuator. In practice and in the experiments presented before, the controller allows to

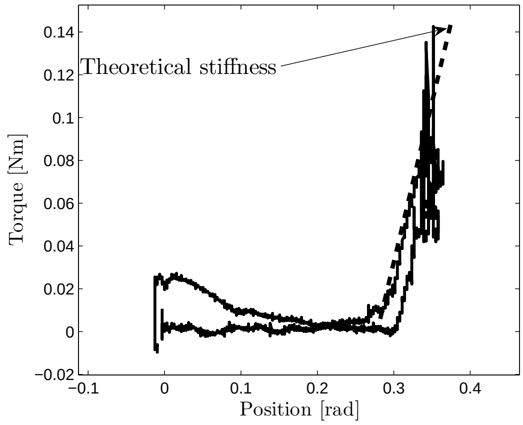

Figure 5: Virtual spring contact with ultrasonic motor

increase this value.
It can be seen that the DC alone presents very bad characteristics for use in a force feedback portable device compared to the other technologies. The DC+gearbox system and the MR brake are comparable and both present satisfying results in terms of haptic rendering. It should however be noticed that the brake presents an advantage relatively to its high intrinsic dynamic range (no need of specific control strategy for friction compensation) and the absence of backlash. Furthermore a new design of the brake should enable to achieve a twice higher maximum torque leading to twice higher torque/volume and torque/mass ratios more suited for direct implementation on the joint than the DC+gearbox. However, due to its limitations (no active compliance, low response time, controllability), it can only be used in applications where only stiff contacts have to be represented. For more complex force feedback, the DC motor will keep the lead. In the same way, if delocalization with bowden cable transmission is considered (leading, however, to a much more complex mechanical design), the possibility for the DC motor to inject energy for friction compensation and the lower necessity of high value parameters (torque/mass,...) support the use of the DC motor. A smaller local joint MR Brake could then still be used as damping device in order to stabilize the system. This approach is still under investigation.
The next step of this project will be the implementation of the actuators inside the ESA arm Exoskeleton to achieve force feedback. According to the results described in this paper, three options could be considered. The first one would be the implementation of DC motors directly on the joints axis. Such solution would only be feasible (without external gravity compensation) under O-G environnement. The second option, more polyvalent but more complex to implement, would be the use of delocalized DC motors with bowden cable transmission ([8]). The third one would be the implementation of stand-alone MR brakes directly on joint axis allowing high torque/mass capabilities but at the expense of limited force feedback capabilities. We excluded the ultrasonic motor from a further implementation due to its lack of controllability.

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REFERENCES

[1] M. Bergamasco. Exoskeleton interface apparatus. In *EU patent wo2004/058458*, July 2004.

[2] A. Bin. Sensory feedback exoskeleton armmaster. In *EU patent wo95/32842*, December 1995.

[3] Grigore Burdea. *Force and Touch Feedback for Virtual Reality*. Wiley-Interscience, 1996.

[4] C. Changhyun, K. Munsang, and S. Jae-Bok. Performance analysis of a 2-link haptic device with electrical brakes. In *11th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems HAPTICS'03*, page 47, 2003.

[5] A. Frisoli, F. Rocchi, S. Marcheschi, A. Dettori, F. Salsedo, and M. Bergamasco. A new force-feedback arm exoskeleton for haptic interaction in virtual environments. In *Proceeding of the 1st World Haptics Conference*, Pisa, March 2005.

[6] M. Kim. Master device having force reflection function. In *US patent 6,301,526*, October 2001.

[7] Dale Lawrence. Stability and transparency in bilateral teleoperation. *IEEE Transactions on Robotics and Automation*, 9(5):624–637, 1993.

[8] P. Letier, A. Schiele, M. Avraam, M. Horodinca, and A. Preumont. Bowden cable actuator for torque-feedback in haptic applications. In *Proceedings of EuroHaptics2006*, Paris, France, July 2006.

[9] S. Marcheschi, A. Frisoli, C. Avizzano, and M. Bergamasco. A method for modeling and control complex tendon transmissions in haptic interfaces. In *Proceedings of the 2005 IEEE International Conference on Robotics and Automation*, pages 1785–1790, Spain, April 2005.

[10] M. Sakaguchi and J. Furusho. Force display system using particle-type electrorheological fluids. In *Proceedings of the Int. Conf. on Robotics and Automation*, Belgium, May 1998.

[11] A. Schiele and F.C.T. van der Helm. Design to improve ergonomics in human machine interaction. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, (in press).

[12] A. Schiele and G. Visentin. Exoskeleton for the human arm, in particular for space applications, us200323844, dec. 2003, european patent application ep 1364755a1, nov. 2003.

[13] A. Schiele and G. Visentin. The esa human arm exoskeleton for space robotics telepresence. In *Proceeding of the 7th International Symposium on Artificial Intelligence, Robotics and Automation in Space*, 2003.

[14] Kenji Uchino. *Piezoelectric Actuators and Ultrasonic Motors*. Harry L. Tuller, Massachusetts Institute of Technology, 1997.

[15] R. Williams, M. Murphy, D. North, J. Berlin, and M. Krier. Kinesthetic force/moment feedback via active exoskeleton. In *Proceeding of the IMAGE conference*, Scottsdale, August 1998.

Parameters	DC Alone	DC+Gearbox (20:1)	MR Brake	USR30	USR60
Max Torque [mNm]	47,3	993,3	910	100	1000
Torque / volume [mNm/m]	949	12570	12633	5781	10709
Torque /mass [mNm/kg]	0.2	2,46	2.6	2	4
Dynamic range	11,8	11,8	58.8	10	100

Figure 6: Summary of actuations technologies