ABLE, a versatile transparent upper-limb exoskeleton for teleoperation

P. Garrec, Y. Perrot, Y. Méasson, F. Colledani

ABLE, a Versatile Transparent Upper-Limb Exoskeleton for Teleoperation

P. Garrec, Y. Perrot, Y. Méasson, F. Colledani

CEA, LIST, Service de Robotique Interactive
18 route du Panorama, BP6, FONTENAY AUX ROSES, F- 92265 France
Phone : +33 1 46 54 89 94 ; Fax : +33 1 46 54 89 80 ; Email philippe.garrec@cea.fr

I. INTRODUCTION

This paper presents ABLE, an innovative exoskeleton for the upper limb currently under development at CEA-LIST Interactive Robotics Unit (Fig 1). Its distinctive high performance mechanical transmissions – screw and cable patented arrangement [9] – and its integrated architecture makes it the very first of its category. Back-drivable, high efficiency, low inertia actuators provide a high capacity (around 50 N continuous effort at the hand) and hybrid force-position control capability without force sensor. ABLE 4D is currently used in a research project dedicated to rehabilitation (BRAHMA). Only the 4 axis model is described in this paper but a 7 axis version is already planned for 2009. Thanks to the performances obtained with ABLE 4D we are planning to use ABLE 7D for assistance for disabled persons as well as for intuitive teleoperation and haptic applications (VR). Thanks to its particularly simple design industrial versions are foreseen in a near future.

Fig 1. ABLE 4D exoskeleton actuated by screw-and-cable actuators (SCS actuator)

II. THE GENESIS OF ABLE – A SHORT STORY OF THE SCS ACTUATOR

ABLE exoskeleton is directly related to electrical master-slave manipulator (EMSM) teleoperation technology in which our laboratory has played a historical role. Fig 2 shows a quick summary of well-known pioneering machines [8], [11], [12], [13], [14], [15], [16] illustrated with their mechanical solutions.

The first principle has been used by R. Goertz (ANL) in his E1-E4 and Model M. Motor torque is amplified using high-precision spur gears driving the joints either directly (translation joints) or, like the scheme shows, trough transmission cable (for remote rotation joints). The second is due to J. Vertut and is team (CEA) for the MA 23. Motor torque is amplified using block-and-tackle cable (or tape) arrangements which drives a transmission cable (or tape). The last one, the capstan, is known to have been proposed for this function by J. K Salisbury (here the JPL Hand Controller). The cable is wrapped around pulleys to increase the adherence, thus enabling the capstan to transmit more torque with very low tension in the cable resulting in a very low friction threshold. For this reason, this is today the more sensitive device

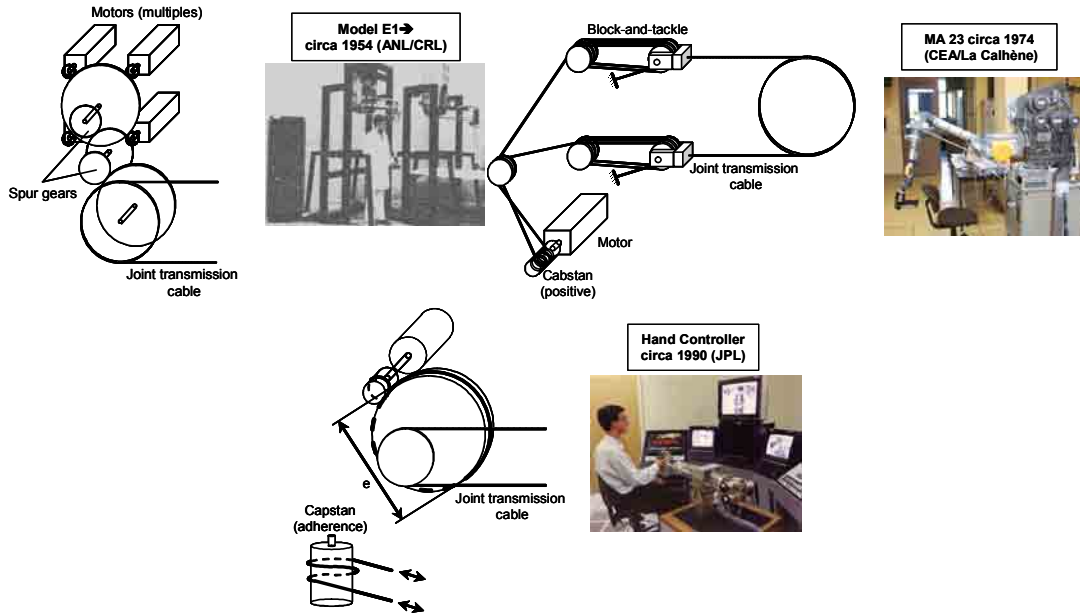for torque amplification and it is most commonly used on haptic devices.

Fig 2. Landmarks in torque amplification for back-drivable electrical master-slave telemanipulator (EMSM)

All of these machines have been mechanically designed to be back-drivable, highly efficient and have low friction threshold (no-load friction reflected on the limb), allowing force feedback without force sensor. This solution provides a high potential of reliability and availability. For example, the Mascot EMSM system [15] used by Oxford Technologies Ltd under the name DEXTER has performed over 7,500hrs of remote handling tasks inside the JET (Joint European Torus, UK) with a system availability above 95% in tough conditions. The central difficulty encountered by designers was to actuate the joints with a linear input-output torque law. All of these solutions – spur gears, block-and-tackle, capstan - have a common drawback that has tended to limit their applications to a broader scale: The motor and the basic mechanism is transversal to the transmission cable making its integration in multi-axis serial manipulators rather difficult. As a consequence, the actuators are generally located at the base, resulting in complex routing and long cable loops for the last axis synonymous with more flexibility and friction.

In the late nineties we were working on the development of a new mechanical concept of transmission for high-fidelity force feedback – the screw-and-cable transmission or SCS for Screw Cable System - to motorize a new master arm that could replace its predecessor – the MA 23 (CEA/La Calhène) [14] – in new force feedback teleoperation systems.

The first prototype (Fig 3) has been presented during the 9th American Nuclear Society Topical Meeting on Robotics and Remote Systems congress in Seattle in 2001 [6].

Fig 3. Left, Virtuose 6D the first 6 axis force feedback master arm powered by screws and cables – Right, V6D 4040 an industrial version produced Haption®

This master arm has been since industrialized and it is now commercialized by Haption® under the name Virtuose 6D 4040 as a general purpose component for teleoperation (http://www.haption.com).

The SCS actuator design has been presented in previous publications [3], [5], [6], [7], [8], [9] but it is important to summarize its basic principles here.
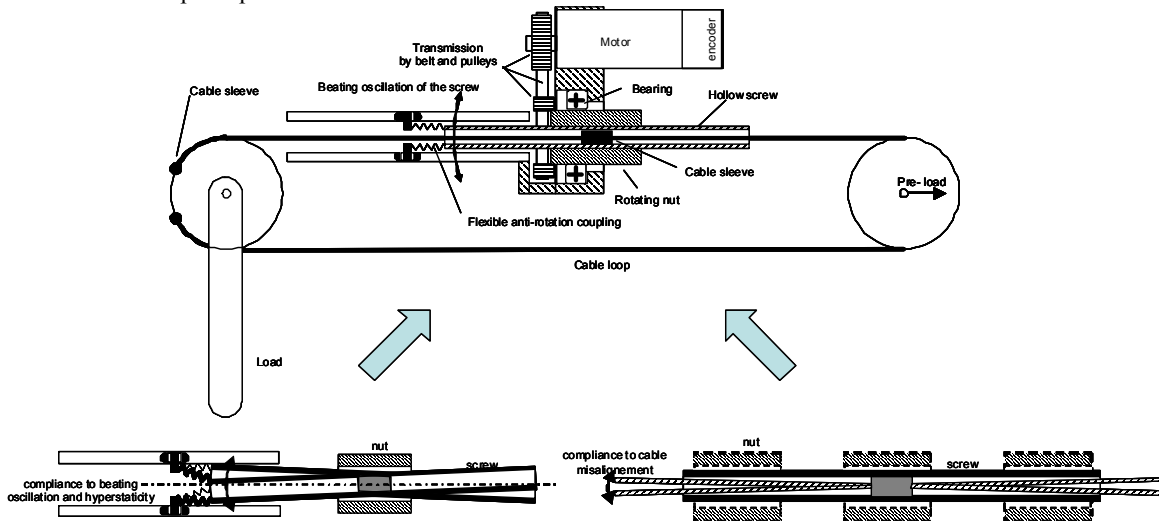

Fig 4. SCS basic principles

On the schemes (Fig 4) we can first see a general view of the actuator. A rotative joint is driven by a standard push-pull cable. On one side, the cable is driven by a ball-screw which translates directly in its nut (the screw is locked in rotation thanks to rollers moving into slots). The nut is rotating in a fixed bearing and is driven by the motor thanks to a belt transmission. Alternatively, a direct-drive pan-cake motor has been used in other applications as it is shown on Fig 5.
The particular patented mounting is detailed underneath. First of all, the ball-screw is free to oscillate thanks to a flexible coupling. These oscillations are known as beating oscillations and are amplified by the deliberate absence of centering device such as a linear bearing. Complementary the screw is bored and the cable passes inside with a radial play and is attached in its center. The scheme shows the various positions of the cable attachment relative to the nut when the screw is translated. This compliant mounting tends to isolate the screw from bending moments and thus guarantees a low and regular friction. The result is a highly linear force transmitter which is also unusually compliant to manufacturing imperfections and structural deformations.

As a summary, the main advantages of the SCS over previous solutions are:

- high force capacity (especially with ball-screws)
- low friction threshold and high backdrivability allow force control without force sensor (reliability, absence of drift and calibration procedure, electromagnetic immunity, simplified wiring)
- motor aligned parallel to cable as opposed to any of the previous solutions in Fig 2: highly compact arrangement to actuate transversally compared to transversal motors or beveled gearboxes
- low inertia and high electrical stiffness
- high tolerance to manufacturing incertitude and to structure flexibility (wide choice of structural material)
- large section cable working at low speed/high force which is synonymous with endurance

Additionally cable transmission provides generic advantages such us: shock absorption, smoothness, high efficiency, and design versatility for intricate routings through joints.

Shortly after completing Virtuose 6D, a specialized slave arm using SCS was also designed for radioactive waste retrieval (STeP: Système de Téléopération en Puits). This manipulator possesses 5 axis of which the first is a vertical translation and a gripper, all force controlled. We expanded upon the same mechanics but this time we opted for direct-drive concentrical motors in order to pack its 6 actuators inside a half-cylinder housing which also integrates

counterweights to compensate the actuator unit's weight on its vertical travel.

If for both Virtuose 6D and STeP the use of SCS led to a spectacular reduction of the mass and volume of their drive units – in comparison with the well-known MA 23 (CEA-La Calhène) for example -, the manipulators themselves were commercially available cable-driven arm structures and the overall architecture of pioneering design was still present.
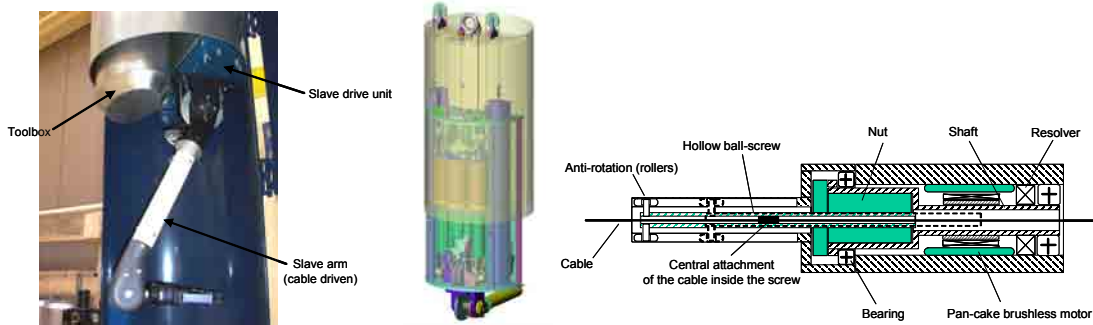

Fig 5. Top, STeP slave arm in a mock-up of a well (CEA-LIST) ; Bottom, Slave drive unit with direct-drive SCS

We soon realized that the SCS concept was not here fully exploited. It was then decided to work on their integration in the moving parts of the arm to offer a new deal to actuate a manipulator and the design of an exoskeleton for the upper limb quickly appeared to be the highest and most exciting challenge due to its broad potential of application.

III. ABLE EXOSKELETON DESIGN

In order to limitate the detrimental effect of an increased moving mass (weight and inertia) due to the integration of the SCS in the limb, it was decided to position the motor close to the upstream articulation of the arm using lightweight shafts to transmit the torque. At the same time, the transmission cable was shortened thus increasing its stiffness and leading to a satisfactory tradeoff (Fig 6).
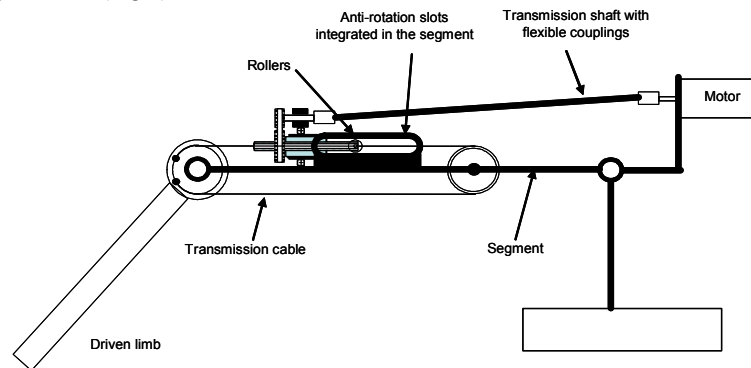

Fig 6. Embedded SCS principle

The second option was to take advantage of the flexibility of the cable to pack two SCS's in the arm module, each of them actuating a transversal axis (shoulder and elbow joint). The overall result is a streamline arm module where the two SCS's perform alike electrical muscles (Fig 7).
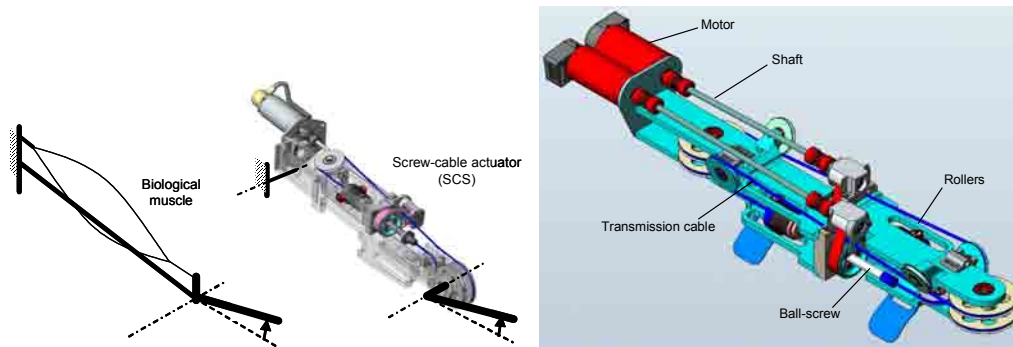
Fig 7. Arm module twin actuators and its analogy with biological muscles

In a second phase we designed the shoulder joint and the back module. The scheme Fig 8 shows the resulting kinematics of the 4 first joints. The shoulder articulation is a spherical articulation made of three orthogonal pivots whose common intersection approximately coincides with the center of the person's shoulder. However, the major difference with previous designs [1], [2], [4], [10] is that the second joint is realized with a circular guide. Such an arrangement is both free of singularity and not invasive.
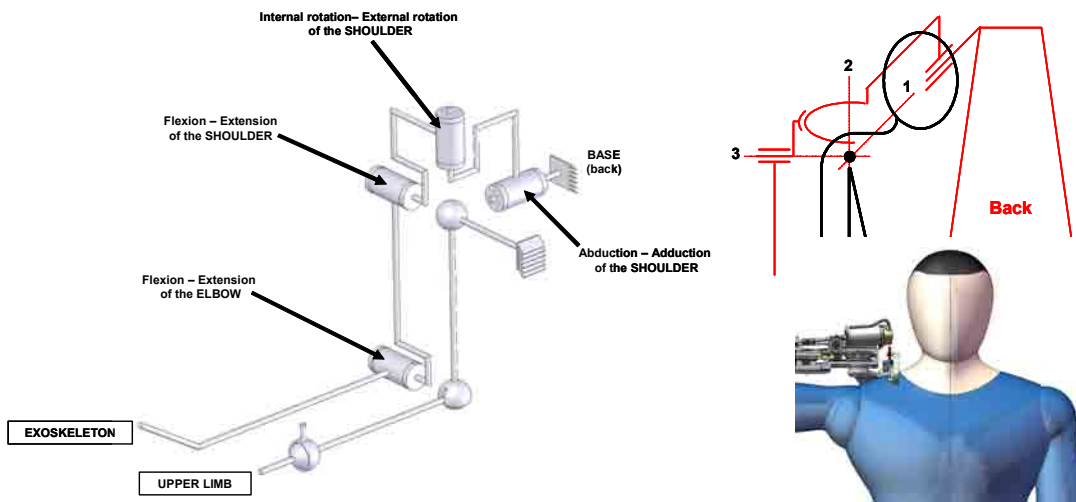

Fig 8. ABLE - 4 axis kinematics

The back module incorporates two SCS which drive the first and second joints whereas the third joint is driven transversally by one of the two embedded SCS of the arm module (Fig 9). The coupling effect between the two first joints is classically compensated by the control.
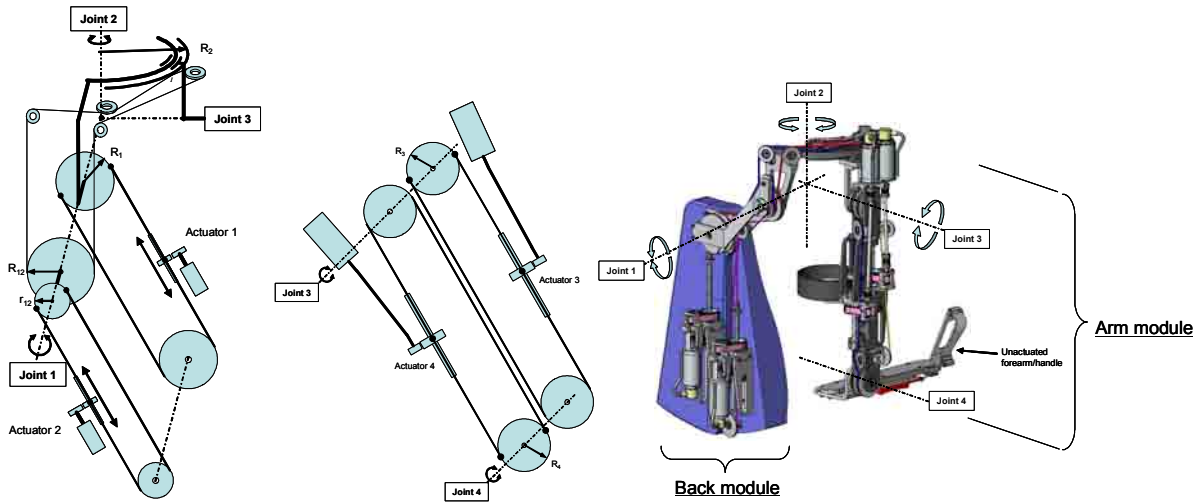
Fig 9. ABLE - 4 axis actuator kinematics: left, back module (Joints 1&2) ; center, arm module (Joints 3&4)

The result is a simple, integrated and morphologically compatible design combined with a distributed actuator mass and volume along the structure. It is important to note that since the two SCS only occupy the half of the back module, it is possible to integrate the motorization of a second exoskeleton without any change of its volume. The table below summarizes the basic specifications of ABLE – 4 axis.

TABLE I - ABLE 4Axis Specifications

JOINT	Axis 1	Axis 2	Axis 3	Axis 4
	Abduction / Adduction	Rotation Internal / External	Flexion / Extension	Flexion / Extension
	SHOULDER			ELBOW
Amplitude	110 °			130 °
Motors	DC Faulhaber type			
Transmission	Ball-screw and cable (SCS)			
Speed (cartesian)	>1m/s			
Joint torque (continuous)	18 Nm	18 Nm	13 Nm	13 Nm
Continuous effort in hand	50 N	50 N	40 N	40 N
No-load friction in hand (approx.)	3 N		2 N	

IV. TRANSPARENT MODE PRINCIPLE

The basic force feedback control principle is the same as with a conventional master arm (master-slave mode or haptic device). The torque of the motor is a combination of gravity compensation torque and a reaction torque proportional to a position error signal. The difference between the awaited position and the measured position is a result from output force exerted (by the operator or by a contact with an object). The proportionality between the position error and the exerted force is directly dependant upon the amount of friction in the transmission as shown on the diagram of Fig 10. At low speed (quasi-static condition), in absence of contact/reaction force the system is moved with a residual effort given by the "y" distance between the red/blue point and the black point.
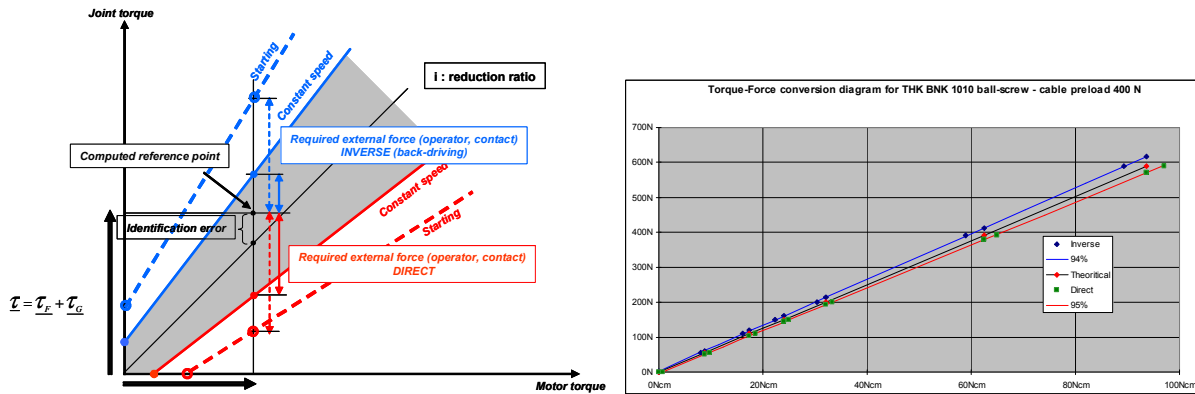
Fig 10. Input-ouput force transmission diagram (in a quasi-static state) : Left, control principle ; Right, a typical SCS diagram

No-load frictions (thresholds) are represented by the dots on "x" and "y" axis. The Direct (red) and Inverse (blue) characteristics correspond to respectively a motor state and a regenerative state. A highly linear transmission requires both a low threshold (compared to the maximum load capacity) and a high efficiency which means that both red and blue slopes should be close to the theoretical one (in black). The maximum efficiency reaches approximately 0,94 in both sense and no-load friction represents approximately 1/1000 of the maximum load capacity of the screw. These values show that in terms of force transmission quality, a SCS can compete with the best existing transmissions.

V. ABLE 7D: TOWARD AN INTUITIVE TELEOPERATION

The development of a lightweight, 3 axis open forearm-wrist, fully actuated with ball-screws is currently undergoing. It will lead to an anthropomorphic, fully open, 7 axis exoskeleton. Thanks to a high transparency and an anthropomorphic architecture, the awaited ABLE 7D (forecasted in 2009) will become a potent master exoskeleton for both teleoperation and haptic VR applications. (Fig 11).
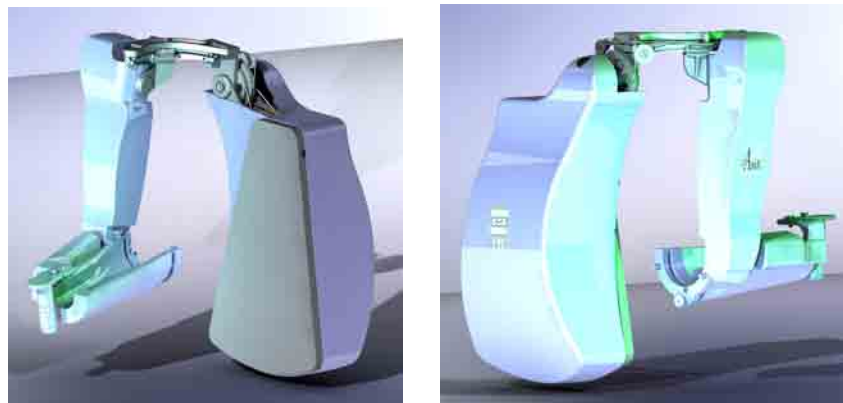

Fig 11. ABLE - 7 axis: an "artist" rendering of a planned version

In teleoperation, VR functions are now becoming a standard efficient addition for training and mission preparation so that a versatile exoskeleton is obviously interesting for users because it reduces investments and maintenance costs.

Technically its advantages are incomparable to existing master arms:

- Intuitive one-hand teleoperation of seven dof slave arms (redundant)
- Intuitive teleoperation of bilateral slave arms (left and right)
- Extension of working time/reduce of fatigue and associated pathologies for the user due to compensation of human weight (at least partially)

However a 7 dof exoskeleton also presents some potential drawbacks in a teleoperation context when compared to a

conventional master arm such as Virtuose 6D 4040 operated with two hands (*Fig 3*).

The single hand teleoperation implied by the exoskeleton - the human wrist being directly coupled to the universal joint of the handle – reduces the amplitude of rotations in comparison with those obtained by the circular motion of a conventional handle when using two hands. Therefore the operator will need to index more frequently which is a detrimental ergonomic factor. This potential problem should be solved to assess the acceptability of an exoskeleton, for example, by the development of appropriate strategies of control regarding rotation management.

Another issue concerns the quality of the coupling between the person and the exoskeleton which is not an issue with a conventional master arm. A satisfactory coupling necessarily implies some adjustment capabilities which in turn complicate the design. Additionally these adjustments are also time consuming factor because it is synonymous of interruption of operations and calibration. These factors must be taken into account when using shifts.

The quality of the technical answer to the above-mentioned issues will decide the success of exoskeleton in teleoperation.

REFERENCES

[1] J.C. Perry, J. Rosen, S. Burns," Upper-Limb Powered Exoskeleton Design",   IEEE/ASME Transactions on Mechatronics, Volume 12, Issue 4, Aug. 2007 Page(s):408 – 417
[2] L. Frisoli, A. Borelli, Montagner, et al,"Arm rehabilitation with a robotic exoskeleleton in Virtual Reality", Proc. of IEEE ICORR 2007, Intern. Conf. on Rehabilitation Robotics
[3] P. Garrec, J.P. Martins, F. Gravez, Y. Perrot, Y. Measson, "A New Force-Feedback, Morphologically Inspired Portable Exoskeleton" Proceedings of 15th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN - 2006), September 2006, Hatfield, UK.
[4] A. Gupta, M.K. O'Malley," Design of a haptic arm exoskeleton for training and rehabilitation", Mechatronics, IEEE/ASME Transactions on Volume 11, Issue 3,   June 2006 Page(s):280 – 289
[5] P. Garrec, J.P. Martins, J.P. Friconneau, "A new Technology for Portable Exoskeletons", AMSE 2004 – Vol. 65 n° 7/8, pp 13-22.
[6] P. Garrec, J.P. Friconneau, F. Louveau," Virtuose 6D: A new force-control master arm using innovative ball-screw actuators", in Proceedings of ISIR 35th International Symposium in Robotics, Paris, March 2004
[7] J.M. Goubot, P. Garrec, "STeP: an innovative teleoperation system for decommissioning operations", Workshop "Decommissioning challenges: An industrial reality ?", French Nuclear Energy Society, 23-28 November 2003, Avignon, France
[8] P. Garrec, "Systèmes mécaniques", in: Coiffet. P et Kheddar A., Téléopération et télérobotique, Ch 2., Hermes, Paris, France, 2002
[9] P. Garrec, French Patent: « Transmission à vis, écrou et câble attaché à la vis » for screw and nut transmission and cable - FR0101630, 2000 (EUR 01938347.0-2421 and US 10/296,740
[10] M. Bergamasco, B. Allotta, L. Bosio, L. Bosio, L. Ferretti, G. Parrini, G. M. Prisco, F. Salsedo, and G. Sartini," An arm exoskeleton system for teleoperation and virtual environments applications", in Proc. IEEE Int. Conf. Robot. Autom., vol. 2, 1994, pp. 1449–1454
[11] Mc Affee et al., USA Patent Number 9,193,963, "Force Reflecting Hand Controller", 1993
[12] J. Vertut, P. Coiffet, Téléopération « Evolution des techniques », vol. 3A, Hermes, Paris France, 1984
[13] G.-W. Köhler,« Manipulator Type Book », Verlag Karl Thiemig, München, 1981
[14] J. Vertut, and al."Bilateral Servo Manipulator MA23 in Direct Mode and Via Optimized Computer Control" 2nd Remotely Manned Syst. Technol.Conf., 1975
[15] Galbiati et al., "A Compact Flexible Servo System for Master Slave Electric Manipulator", 1964
[16] Goertz R. C. et al., "Master-Slave Servo-Manipulator" Model 2", Proc.4th Ann. Conf. Hot Lab. And Equip. 1, 1955