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ADVANCED CABLE-DRIVEN SENSING ARTIFICIAL HANDS FOR EXTRA VEHICULAR AND EXPLORATION ACTIVITIES

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INTRODUCTION

At the ARTS Lab of Scuola Superiore Sant'Anna, since 1999 artificial hands for both robotic and prosthetic applications have been studied; thus several approaches have been exploited so far. A bio-inspired under-actuated approach showed the best results and has been developed further in several prototypes. This paper is aimed to suggest the exploitation of these results for extra vehicular and exploration activities.

SSSA ADVANCED PROSTHESES BACKGROUND

In the research and development of artificial hands three main applications can be identified: prosthetics, robotics and devices for augmenting human capabilities. In their work, Scuola Superiore Sant'Anna (SSSA) researchers have been focusing on the first two topics. After a first design approach based on intrinsic micro-actuation [1], it was pointed out that a more bio-inspired, extrinsic actuated approach would be a more suitable solution, especially for prosthetic applications. Hence the research was shifted on underactuated and cable-driven artificial hands. The design approach based on micro-actuators is indeed quite far to offer a real alternative to standard design approach based on traditional electro-magnetic actuators. This is mainly due to the lack of high torque micro-actuators and to the difficulty to implement complex control scheme with a natural interface for controlling all the DOFs. According to [2], a prosthesis has to perform a stable grasp with a wide variety of objects with complex shapes and to adopt simple control scheme. In order to enhance prosthesis flexibility obtained by keeping the *intrinsic* actuation solution, and implementing simple control algorithm, an innovative design approach based on underactuated mechanisms was presented [3] (see fig.1).

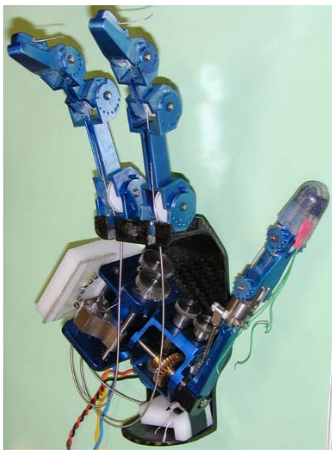

Fig. 1. The RTR2 Hand.

Implementing an underactuated design means the number of degrees of freedom (DoFs) is higher than the number of motors (DoMs), hence the number of components is quite lower than in choosing a micro-actuated approach. Furthermore a lower mechanical complexity gives a big advantage as a lower control burden is required.
As the human fingers are moved by tendons pulled by muscles sited in the forearm, the SSSA cable driven approach was mimicking the human anatomy; hence a new *extrinsic actuated* solution was chosen. One of the advantages is positioning the motors in the arm/previous link (as it happens in the human hand), thus the end effector could be more compact and lighter [4]. These aspects are extremely important in the development of advanced prosthetic hands and humanoid robots. Moreover this underactuated approach provides the hand with an auto-adaptive grasp. When a finger envelopes an unknown object, the differential mechanism distributes the forces automatically in the phalanges and the finger can adapt its shape to the object. Elastic and damping passive elements (e.g. a spring in every underactuated joint) are used in a way antagonistic to the action of the cable. Tuning properly the stiffness of the whole agonistic-antagonistic system is mandatory to get the correct kinematics. It has to be pointed out that only in case of a well-balanced mechanism the auto-adaptive grasp will be effective and more stable; hence the control system will be simpler.

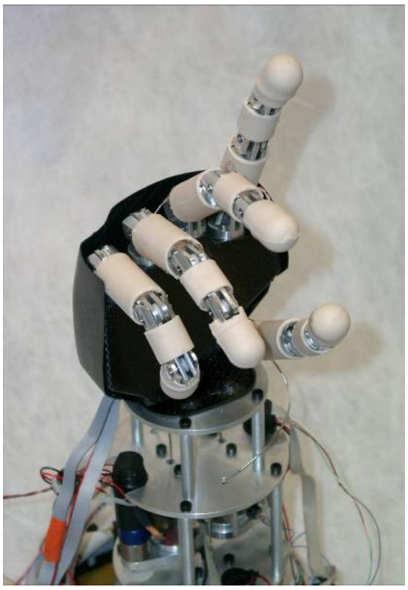

Fig 2. The Cyberhand.

EXTRA VEHICULAR AND EXPLORATION ACTIVITIES: NEW ISSUES AND REQUIREMENTS

Obviously artificial hands for Extra Vehicular Activities (EVAs) and exploration tasks should be provided with different capabilities. Nevertheless the results obtained in the field of advanced prosthetics (CYBERHAND, see fig.2) could be adapted to different requirements and then exploited properly.
Moreover the cable-driven underactuated approach can be justified by the characteristics of a low-gravity environment. A lower inertia reduces the gap in the dynamical behavior between direct actuated and extrinsic cable actuated hands. The extremely compact dimensions and a better portability of the device are an advantage for the operator. Hence it should be pointed out that the extrinsic actuation gives the chance to place all the motor units in the rear of the spacesuit/jetpack. No matter the number and the size of the motors required, their weight will be located with the other high-inertia devices (see fig.3).

Fig 3. Un-tethered extra vehicular activity.

This means that the user's mobility in the environment will not be affected even if high manipulation capabilities (high number of actuators) and high forces exerted (high weight of actuators) are required. It has also to be considered lubrication is critical in spatial applications and it is a huge problem in direct actuated hands. Thus another pro in choosing the cable-driven underactuated approach is the possibility to use auto- lubricating bearings and components in the transmission (e.g. pulleys). Moreover the bio-inspired correlation between human tendons/muscles and cables/actuators results in a quite high compatibility between the human hand and the artificial kinematics. This aspect can result in a broader use of Cyber Gloves and other wearable Human Machine Interface in case of teleoperation of the device.

Nevertheless in this kind of environment several problems are amplified. The low gravity mellows the damping effect of masses thus elasticity of tendons and damping passive elements can oscillate wider and with a different frequency. A tuning of the latter elements can be useful even if it is not enough in case of high precision and repeatability tasks.

A NEW BREED OF SSSA ADVANCED HANDS

In the last year at the ARTS Lab of Scuola Superiore Sant'Anna a new breed of artificial hands has been designed and developed. New ambitious project in Prosthetics (DARPA's Revolutioning Prosthetics Program) and in Cognitive Robotics (FP6-IST-IP ROBOTCUB) required devices provided with hands able to perform high-level exploration and manipulation tasks. To fulfill the requirements a new cable-driven approach has been implemented.

A hybrid solution has been developed with the aim of improving our hands capabilities without losing the advantages of underactuation. Thus new DoFs has been implemented (abduction/adduction of the fingers and the hollowing of the palm) and a system of antagonistic tendons has been studied with the two-folded goal of increasing the DoMs for manipulation tasks and reducing oscillations.

Although, an under-actuated gripper may pretty well accomplish the grasping tasks, such device may not perform manipulation: to meet the manipulation requirements direct driven joints and adequate sensing are mandatory. According to the human hand physiology [5] the PIP joint and the DIP joint are coupled; whereas the MP joint is direct driven and endowed with ad/abduction. Moreover, the little and the ring fingers are designed as fully under-actuated fingers, and coupled together. The latter provide stability during the grasping and the manipulation, and are able to apply force during power grasp, as in the human hand. Two very peculiar DoFs in the human hand are (1) the thumb opposition and (2) the hollowing of the palm. The opposition of the thumb makes the human hand an extraordinary versatile tool, allowing several grasp types and specially the power grasp and the precision grasp. The hollowing of the palm and the abduction of the fingers allows the spherical grasp (for power grasp) or tripod grasp (for precision grasp). The hollowing is also involved in the diagonal palmar grasp (see fig.6).

Eventually, as shown in Fig. 5, the number of DoFs of the *iCub* hand (RobotCub) [6] for each hand is 20:

- 15 flexions of the phalanges
- 1 thumb opposition
- 3 ad/abduction (for little finger, ring finger and index)
- 1 hollowing of the palm (flexing little and ring finger toward the thumb)

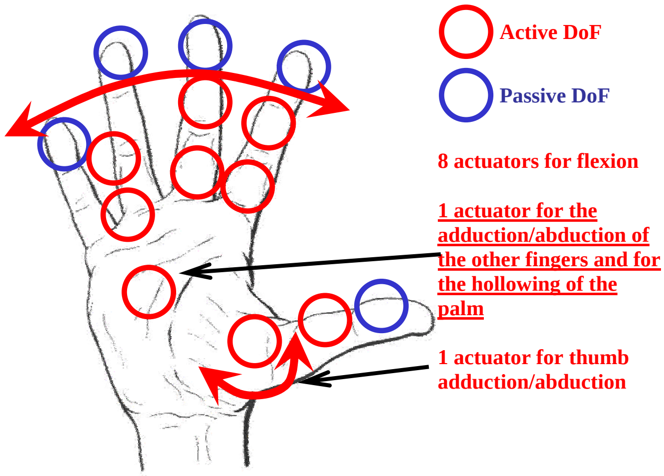

Fig. 4. The selection of DoFs/DoMs in the *iCub* Hand.

According to the exploitation of the under-actuation concept, the number of actuators for each hand is 9, as shown in Fig. 5:

- 3 for MP joints flection of thumb, index and middle finger
- 3 for PIP and DIP (coupled in an unique under-actuated DoM) joints flection of thumb, index and middle finger
- 1 for thumb opposition (the only one located in the palm)
- 1 for flection of fully under-actuated fingers, both the little and the ring finger with a differential mechanism
- 1 for the hollowing of the palm and the abduction of little finger, ring finger and index. We preferred to couple the hollowing and the abduction, because both are involved usefully in the spherical grasp.

The diameter of the pulleys and the stiffness of the springs determine the kinematics of the fingers.

The CAD drawing shows the layout of the robotic hand: the DC motors are placed in the palm for the thumb opposition and hollowing of the palm/finger ad/abduction movements.

The implementation of the hollowing of the palm and of the abduction of the fingers are an important issue to be stretched further. First of all, these movements are all involved in tripod, spherical and diagonal grasps (see Fig. 6); thus the iCub, endowed with thumb opposition movement, will be able to handle a wider range of objects.

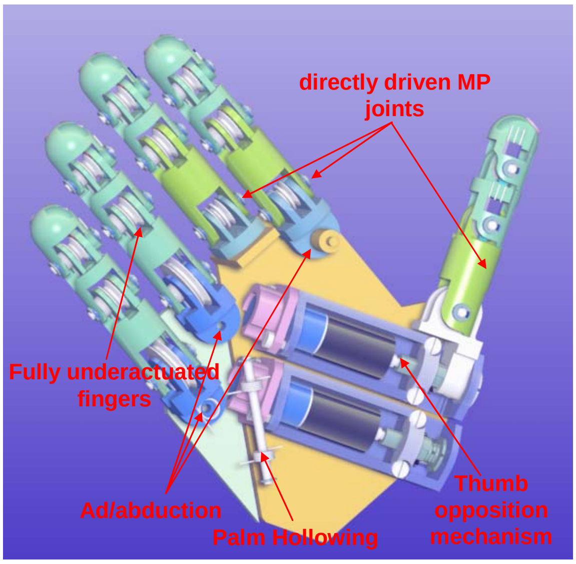

Fig. 5 The CAD drawing of the *iCub* Hand

Moreover the fingers and the palm will adapt to shape of the object in a better way by the means of a pre-shaping control strategy. The contact area will be increased and so the grasp stability.

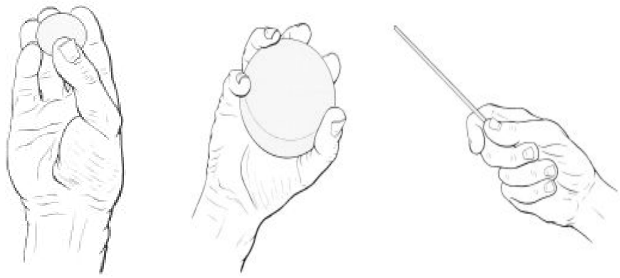

Fig. 6. Three kinds of grasp in which the ab/adduction of the fingers and the hollowing of the palm are involved.

The coupling of the finger abduction and of the hollowing of the palm will permit to control 4 DoFs with only one motor. Torsion springs, the diameter of the pulleys and mechanical stops will set the right kinematics and impose the desired timing between abduction of the fingers and hollowing of the palm. [6].

Thanks to this system and a well-balanced joint pre-tensioning, there is no more need of damping passive elements and moreover the problems given by the tendon elasticity are strongly reduced.
The first experimental results confirm this hybrid approach is successful both for prosthetics and robotic applications. Furthermore an application in extra vehicular and exploration activities is encouraged from both a theoretical and practical point of view.
Anyway, in the development of artificial hands for prosthetic purposes, ARTS Lab is also working on other important field of research as Human Machine Interfaces and bio-inspired sensors. The results obtained in the latter issue demonstrate to be worthy of being stressed further and not only for prosthetic purposes. If we distinguish between proprioception (perception of the internal parameters of the mechatronic system) and exteroception (perception of the external world), in each one of this topics we are developing several innovative solutions.
In the control of the grasping force, a strain-gages based sensor for detecting the tension of tendons has been developed [6] (see fig. 7 and fig. 8)

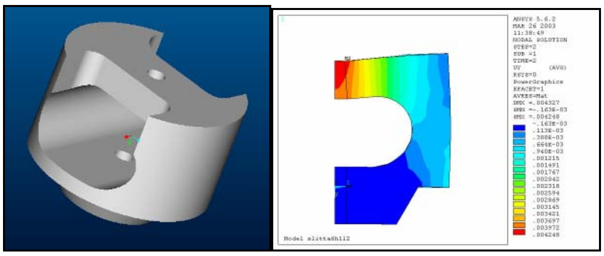

Fig. 7 Mechanical structure of the cable tension sensor and FEM analysis.

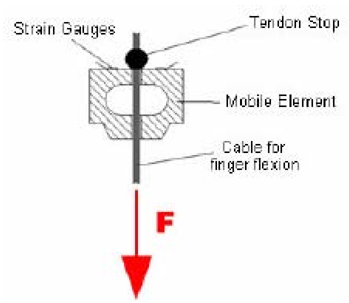

Fig. 8. Cable tension sensor: working principle.

The data obtained in this way have given an important improvement to the control strategy. The reason is the possibility of imposing the force exerted by each finger with a good sensibility; moreover it helps the low level control in redistributing the grasping force automatically in case of unknown external forces applied to the hand [7].
Another innovative research topic is aimed at investigating the response of an array tactile microsensors based on the emulation of natural mechanoreceptors of the human skin. This bio-inspired tactile system is able to detect both normal and shear components of the contact forces and their variations when slippage events occur. Advances in MEMS

technology have offered us the opportunity of developing single high reliability sensors and sensor arrays with small dimensions [8] and [9] (see fig. 9 and fig. 10).
Arrays of microsensors integrated in artificial fingertips could provide local information useful to mimic other functions of the physiological sensory system like, e.g. provide information about local shape at contact point.

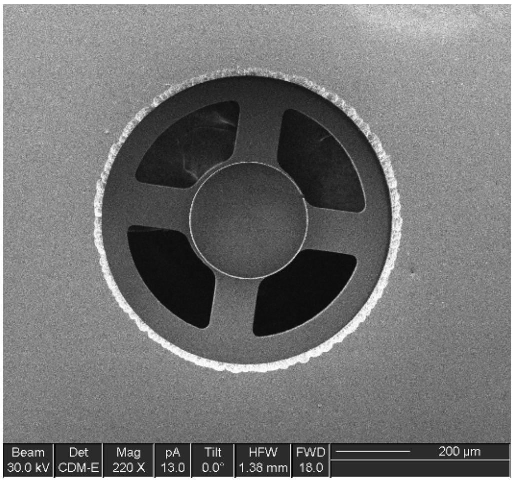

Fig. 9 3D silicon structure of the triaxial force microsensor [8].

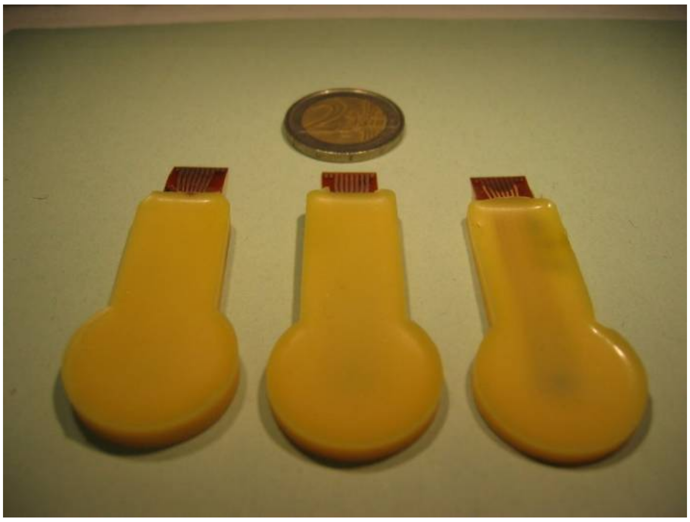
Fig. 10 Three prototypes of the Soft Compliant Tactile Microsensor [9].

CONCLUSIONS

In this paper an advanced under-actuated approach to the design of artificial hands for extra vehicular and exploration activities has been presented. The evolution in the approach to artificial hands at the ARTS Lab of Scuola Superiore Sant'Anna shows the effectiveness of extrinsic under-actuated approach for both prosthetic and robotic devices. Furthermore the advanced sensory system integrated in the mechanical design is basilar in performing grasping and manipulative tasks. Hence few little modifications would be enough to make the new breed of SSSA hands a good solution also for extra vehicular and exploration activities.

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