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Towards a Hand Exoskeleton for a Smart EVA Glove

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Abstract — **In this paper we investigate the key factors associated with the realization of a hand exoskeleton that could be embedded in an astronaut glove for EVA (Extra Vehicular Activities). Such a project poses several and varied problems, mainly due to the complex structure of the human hand and to the extreme environment in which the glove operates. This work provides an overview of existing exoskeletons and their related technologies and lays the ground for the forthcoming prototype realization, by presenting a preliminary analysis of possible solutions in terms of mechanical structure, actuators and sensors.**

I. Introduction

EXTRA vehicular activities (EVA) are operations done by an astronaut away from the Earth, and outside of a spacecraft. The term most commonly applies to an EVA made outside a craft orbiting around Earth, a spacewalk, but also to an EVA made on the surface of the Moon, a moonwalk. EVA is a highly expensive and risky activity, therefore it is mandatory to complement EVA with robotics support as much as possible.

A spacesuit today is composed by a complex and highly technological multilayer structure realized to protect the astronaut from various factors, such as hostile cosmic radiation, especially infrared and ultraviolet unfiltered for lack of atmosphere, wide range of temperatures, presence of small particles of dust or micrometeoroids. The suit must also be able to protect the astronaut from the vacuum outside, that is close to zero pressure condition. So the suit must be internally pressurized through inflated air. All these factors, while protecting the human being from a hostile environment, impose strong limitations on the mobility and dexterity of the astronaut during a mission. Both the multilayer system and the presence of pressurized air, in fact, contribute to increase the stiffness of each joint, requiring from the astronaut a greater than normal force to perform even the simplest movement.

Gloves in particular, that are essential for the work of the astronaut, are thinner than the others parts of the space suit, and are manufactured to ensure comfort during the missions. Externally they have one layer of rubber to increase grip, and some hook placed on the back for handling tools. Because of the prolonged manual activity, the gloves are often subjected to wear, which may result in cuts or tears, causing the depressurization of the suit.

Gloves are thus probably the most critical part of the space suit because practically all operations require the use of hands. The hand is a complex system composed of over 20 degrees of freedom, driven by small muscles that must perform several repetitive movements. The problems regarding the stiffness are then amplified greatly when referred to hand movements. So one of the main problems limiting the overall duration of a spacewalk is the astronaut`s fatigue.

In forthcoming years NASA plans to significantly increase the number of hours dedicated to EVA operations during the space missions.

It is easy to understand how a device able to overcome the hand fatigue during the extra-vehicular activity (EVA) would be a significant improvement for the astronauts, allowing them to accomplish their tasks in a more efficient way, for longer time and with more comfort.

II. The Goal of the Project

Our study is directed to the development of a prototype of a lightweight hand exoskeleton designed to be embedded in the gloved hand of an astronaut, in order to overcome the stiffness of the pressurized space suit.

The exoskeleton we have in mind is a complex mechatronic system that must detect the operator intention to move through sensors, process the data acquired and then generate the motion through the actuation system. So the structure of the exoskeleton should be built to avoid changing the kinematics of the part of the body where it has to be placed.

In literature there are many examples of exoskeletons for various applications [1]–[4], such as in orthotics field or for virtual reality, but the space environment presents a series of problems that are hard to overcome. Some rare examples of a space suit exoskeleton application are present in literature, such as EVA suit motorized wrist joint by Sheperd et al. [5] or the three DoF Exoskeleton, proposed by Shields et al. [6].

In this paper we try to analyze the main constraints related to the ambitious realization of a hand exoskeleton for helping astronaut in EVA, and we try to propose some possible solution to overcome these limits for the envisaged

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prototype realization.

III. Main Constraints

A. Dimensions and Weight

The exoskeleton size and weight are vitally important. Low mass and inertia are important requirements, in order to facilitate manipulation tasks. Moreover the desire to integrate our device in a space suit imposes strict limits on its possible size, unlike what happens with exoskeletons made for rehabilitation or virtual reality, that are usually relatively large, with bulky motors and actuators, as shown in Figure 1 and Figure 2, since physical dimensions are not an obstacle in these endeavours. Dimension and weight thus put a first major constraint on the choice of components, particularly those relating to the actuation system and the material of the structure.

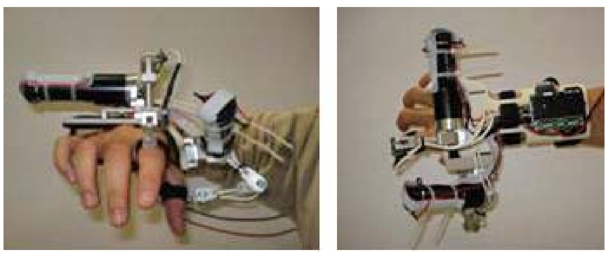


Fig.1. IIT Exoskeleton Hand [7]

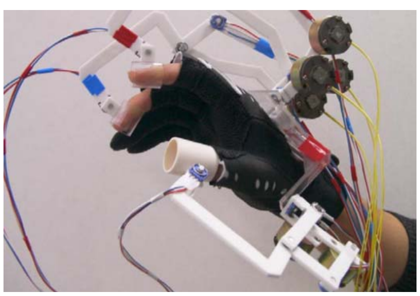


Fig.2. Multi-fingered master hand [8]

B. Working Space

A critical point in the development of our project is the necessity to avoid excessive restrictions of the working space, and hence the dexterity of the operator. Considering only the structure, firstly the palm should be as free as possible, trying to place all the systems on the back of the hand to avoid to limit the ability of grasping and handling. Furthermore the lateral thickness of each finger must be very small in order to allow movement related to the abduction DoF. All these represent limiting factors on the structure and technologies that can be used.

C. Degrees of Freedom

The hand is a very complex limb with 23 DOF in a significantly reduced space, as shown in Figure 3, and it is difficult to reproduce faithfully especially under the constraints related to weight, size and dimensions analyzed above. Another big challenge is provided by the first joint of the thumb that causes the displacement of great part of the palm.

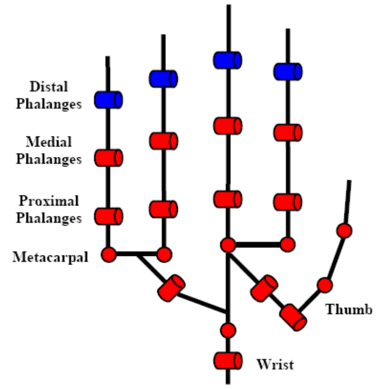


Fig.3. The 23 DoF of human Hand [9]

There are then two opposite requirements: the desire to ensure a high degree of dexterity to operator, placing many joint in order to reproduce the actual motion of the hand, and the need to create an object with reduced size and weight. A compromise should be found, since it is unthinkable to be able to actuate and detect signals of 23 DoF in an appropriate way, and at the same time it would be useless to create a simple device with few degrees of freedom that will not help the operator.

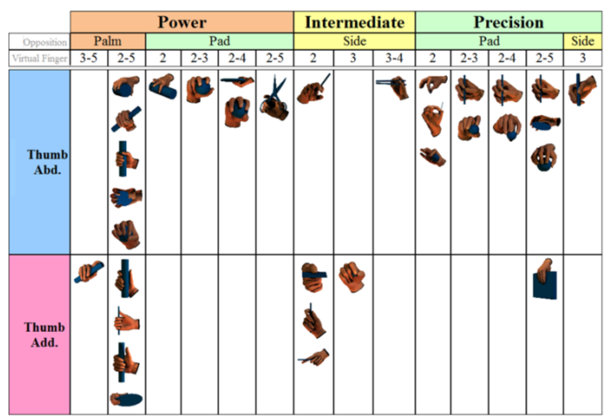


Fig.4. Position of the hand during some works [10]

Concerning this, a research on the various movements that the hand can perform during various type of works has been made, as reported in Figure 4, observing that practically all movements are linked to eight types of fundamental grips, as described in the scheme of Figure 5.

D. The joints

Another critical point for the development of a hand exoskeleton is that the phalanges of the operator`s finger rotate around a centre of rotation located inside the finger. To replicate the motion of the operator`s finger, avoiding mechanical interference between the human finger and the exoskeleton, the position of the two centres of rotation has to be the same. As stated before, the actuation system cannot be placed directly on the joint due to the size problems, hence it is better to place it on the back of the hand.

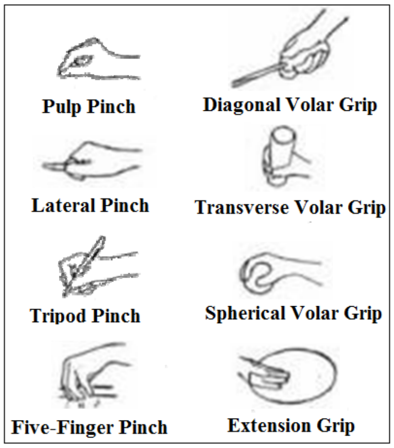


Fig.5. The eight type of grips [11]

In Figure 6 an example of an exoskeleton using a structure called four bar mechanism, designed to mimic human finger kinematics, is reported. This solution rotates around an instantaneous centre that corresponds with the one of the wearer`s finger.

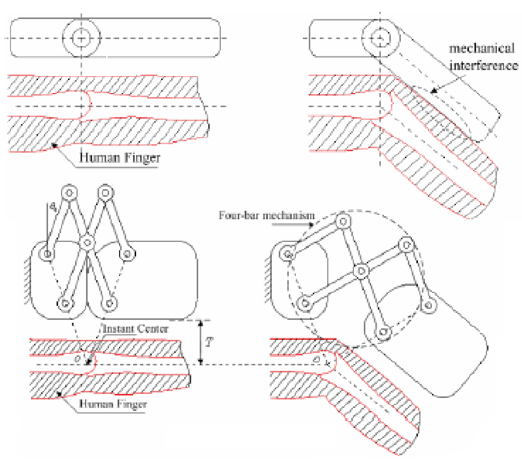


Fig.6. The joint problem and the four bar mechanism [12]

E. Space environment

Space is a highly dynamic environment that imposes different threats due to many aspects [13], such as:

1) Solar Activity: the Sun is the source of electromagnetic radiation, solar winds and plasma. Cosmic rays and high energy solar particles are scattered by solar wind and interact with Earth atmosphere to produce high energy particles. Solar eruptions consist of two main phenomena`s: Coronal Mass Ejections and Solar Flares. The first are eruptions of magnetized plasma, expanding outwards sun`s corona, while the latter are sudden and rapid releases of magnetic energy in the solar atmosphere. These events release high doses of radiations, causing degradations or damage to the devices, and also high background radiation noise.

2) Geomagnetic storms: the geomagnetic storms are disturbances inside magnetosphere associated with solar eruptions. The shock wave due to the solar wind pressure can cause damage such as electronic component failure.

3) High energy particles: the high energy charged particles generated by Sun or coming from outside the solar system can cause electronic components and structural materials degradation. Sensors are very sensitive because these particles cause high radiations and high level of background noise which can make the data useless.

4) Electromagnetic radiations: the visible and IR regions of electromagnetic radiation cause thermal effects that can change the temperature in a wide range of values, causing thermal stress on material and thermal drift of the sensors. UV, X-ray and γ ray cause ionization and generation of secondary particles in the material that can cause degradation or damage in the material.

5) Space plasma: the space plasma can generate electrical phenomena such as surface charging, arc or coronal discharge and induced electric current. The induced potential in the low temperature region and solar wind ranges between few volts to few tens of volts, while it is could reach few several tens of volts in the high temperature region.

6) Micrometeoroids: micrometeoroids, called also micrometeorites, are small particles that can be made of rock, metal or both, that travel with high relative velocity trough the space. Because to their relative velocities these elements could be dangerous in direct impacts.

7) Space Debris: space debris are man-made object in orbit around Earth coming from previous space missions, like entire satellites, rocket stages, explosion fragments and other things. Usually Space debris are slower than micrometeoroids but other parameters can affect the amount of damage caused, for example size, shape and type of material.

There are thus many different problems to take in account when choosing the various components and materials. However is not necessary that each element must be able to withstand all these conditions, since in a multilayer structure there are some protective screens and guards that can be placed to protect the device.

F. User`s Comfort

Last thing but equally important thing to keep into proper consideration is the comfort factor that the glove must guarantee to the operator. It is supposed that the astronaut will have to withstand a high number of hours during his EVA. It is important that comfort is as high as possible.

IV. Possible Solutions

A. Structure

The structure is the part of the system that should support the sensors and ensure the correct kinematics, so to achieve a correct implementation of the transmission of the movements from the actuators. The choice of an appropriate and well designed structure will allow simple integration between the sensor and actuation parts. The analysis of a possible geometry is a very important step for having the minimum weight and maximum strength. If an extremely lightweight structure seems to be an advantage, we have also to consider that the structure has to address correctly forces and moments to avoid to stress the operator's articulations. Different kinds of structures have been proposed in literature, and below there are the two that we considered the most suitable for our project.

1) Four bar mechanism: the four bar mechanism allows to rotate around an instantaneous centre that coincide with the operator`s finger centre joint. Because of the parallelogram structure of the mechanism, the instant centre of rotation remains fixed during all movements (see Figure 6). This means that the exoskeleton that uses this strategy should be customized to the wearer hand. One advantage of this structure is that practically all elements are located on the back of the hand and does not hinder the work space of the operator. This solution however has the disadvantage of being quite bulky, as shown in Figure 7.

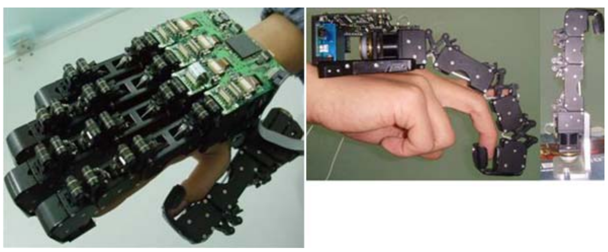


Fig.7. Example of four bar mechanism [12]

2) Cable mechanism: an example is reported in Figure 8; in this kind of structures, the movement is done through cables connected to motors that apply the desired torque on the joints. The advantage is that this technique does not involve a massive structure on the hand and that the engines that generate the actuation can be placed in less binding areas such as the forearm. A disadvantage of this structure is that the cables work only in traction and so it is necessary to place a couple of cables for each degree of freedom, one for the flexion and one for the extension of the finger.

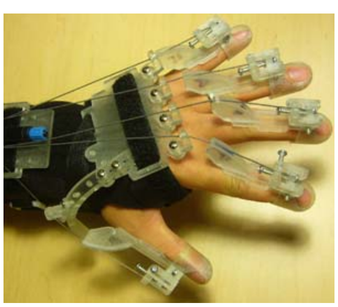


Fig.8. Example of cable mechanism [14]

A particularly relevant version of this mechanism is called tendon mechanism, shown in Figure 9. This reproduces the structure of the extensor mechanism of the human hand. The extensor mechanism is a web-like structure composed of tendons and ligaments that rides on the dorsal side of the finger and connects the controlling muscles of that finger to the three bones. Through this structure we can obtain all the natural finger positions. It is extremely light and small, the actuation is connected by cable to the lower end of the finger so the actuators can be placed in a less critical zone in terms of space and weight.

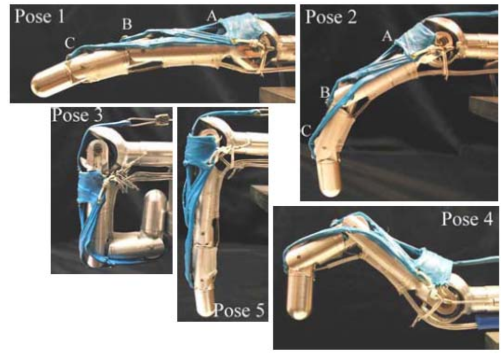
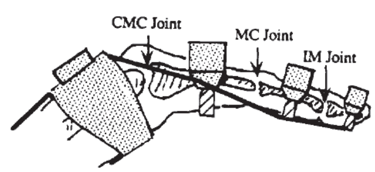


Fig.9. Example of tendon mechanism [16]

B. Actuators

The actuators are those elements that generate the movement of joints from a command signals that usually come from the control unit. The actuation part is probably the critical point of the project: in fact usually the size of a motor or, more in general, of an actuator, is proportional to the power that it must be able to generate, and then, to the torque it must be able to provide.

First of all we noted that there is no real specification about the strength that different connections should be able to generate. The exoskeleton must help the astronaut in daily work, but in what percentage it has to contribute is not known. It's a good assumption to think that the glove should be able to generate forces at least comparable with the human forces. The table reported in Figure 10 [16] shows the forces that a human being is able to generate. These forces, obviously, are quite indicative because the strength depends on many factors such as age, sex, training and many others.



FORCE OF THE FINGER JOINTS

Motions	Force (N)
Finger CMC Joint	3,92
Finger MC and IM Joints	8,82
Lateral Motion of Thumb	7,84
Thumb CMC Joint	6,86
Thumb MC and IM Joints	5,39

Figure 10: Table for values of the finger joint force [16]

In literature there are numerous types of actuators based on different technologies, those that use high-pressure fluid such as hydraulic or mesofluidic, those that use compressed air, as air muscles, those that rely on magnetic fields, and many others. Despite this wide variety of technologies, the solutions that could be used in practice are very few due to many factors. First the space environment described previously; then there are factors related to the safety of the astronauts (for example high pressure liquid or gas cannot be used inside a space suit), and finally there are constraints in terms of energy consumption and magnetic fields.

Therefore we have to consider the more traditional electric motors such as brushless or stepper which have the disadvantage of being bulky.

Otherwise an interesting solution is offered by piezoelectric motors. A piezoelectric motor (see Figure 11) is a small size electric motor based upon the change in shape of a piezo material when an electric field is applied. The geometries of piezoelectric motors are various depending on the location and number of piezoelectric elements inside the motor. In Figure 11 is illustrated a sequence that shows one possible movement of a piezo motor is reported.

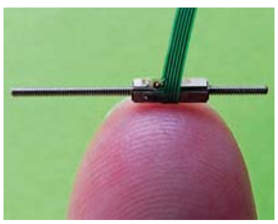


Fig.11. Piezo motor [17]

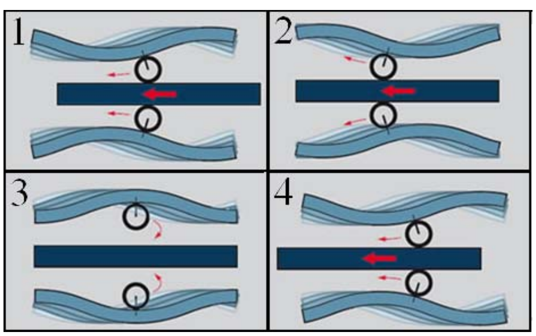


Fig.12. A possible kind of movement of a piezo motor [17]

Despite their small dimensions piezoelectric motors could generate high forces. The growth and forming of piezoelectric crystals today is a well known process, producing very uniform and consistent distortion for a given potential difference. This fact, combined with the minute scale of the distortions, gives the piezoelectric motor the ability to make very fine steps. The high response rate and fast distortion of the crystals also allows the steps to be made at very high frequencies, upwards of 5 MHz, giving linear speed up to 800 mm/s. A great advantage of piezo motors is that they can be Normally locked or Normally free. When no power is applied to a Normally Locked motor, the spindle or carriage does not move under external force. For a Normally Free motor, the spindle or carriage moves freely under an external force; however, if both locking groups are powered at rest, a Normally Free motor can resist to an external force without providing any motion force.

C. Sensors

The sensors allow the perception of quantities of interest based on which the control actions will be generated. The quantities of interest involved in the development of a hand exoskeleton are the torque and the relative positions of the various joints of the fingers. As analyzed above, the constraints related to the choice of sensors are the size, the working space, the consumption and the effects of space environment in terms of noise and temperature. These latter problems can be reduced partially by an appropriate coating. There are currently various force and position sensors available on the market, but not all of them are suitable for our purpose. Below are reported the solutions that are considered interesting for our project.

1) *Electro-goniometer*: an electro-goniometer is an electronic device made to measure angle (see Figure 13). There are some different kinds of electro-goniometers that use different angle sensors, such as potentiometers, strain gauges or accelerometers. However potentiometers and accelerometers are not useful in our context because the former need to be placed directly on the joint, and the latter cannot be used in the space environment. The strain gauge electro-goniometers look like a flexible spring. The strain gauge mechanism is housed inside the spring and changes his resistance proportionally to the angle imposed. It is a lightweight solution, easy to apply on the hand. Thanks to the measurements trough Wheatstone bridge this sensor is also able to reject effects due to temperature fluctuations.

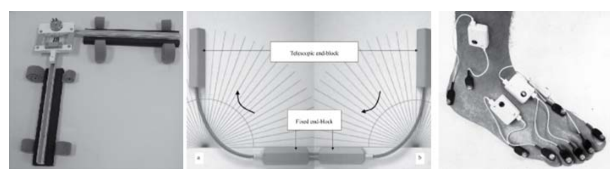


Fig.13. Electro-goniometer sensor [18]

2) *Stretch/Bend sensor*: stretch and bend sensor are sensors that change their resistance when stretched or bended. They are fully customizable in terms of dimensions, and so they represent a versatile solution. This kind of sensors can also measure resistance trough Wheatstone bridge.

3) *EMG Sensor*: EMG sensors are electrical devices that measure the electro-miographical signals. EMG signals are electrical pulse that comes from the brain to the muscle trough the nerves. A great advantage is that the EMG signals are proportional to the force that the human being wants to apply trough his muscles. This sensor can be used like a force sensor with the great advantage of being placed not on the hand but on the forearm.

4) *Piezoresistive Sensor*: piezoelectric sensors are devices that change the electrical resistance when a mechanical stress is applied. The sensing material in a

piezoresistive sensor is a diaphragm formed on a silicon substrate, which bends on applied force or pressure. A deformation occurs in crystal lattice of diaphragm caused by bending; this deformation causes a change in the band structure of the material that can increase or decrease the resistance.

V. FUTURE ACTIVITIES

This paper summarizes the preliminary analysis performed in order to study and verify the feasibility of a hand exoskeleton that could be embedded in an astronaut glove.

As a first step the idea is to proceed with the development of a prototype of a single finger, based on the structures, the sensors and the actuators analyzed in this paper and commercially available. The sensors, actuators, structure and materials will then be redesigned on the basis of results obtained from first feedback implementation, in order to obtain the most suitable solution for our project.

Possible further applications include the use of such a smart-glove as a human-machine interface in which the hand can interact with the operator both in the form of sensor and in the form of actuator. The use of the hand as a sensor requires the placement of sensors to detect all the movements, or at least those deemed important. In this way the exoskeleton can be used like a very complex joystick with which the operator can tele-operate machinery or perform simulations simply moving his fingers. The use of the hand as an actuator means that the object to be caught imposes a force on the operator's hand, similar to what happens with those used for physiotherapy. This force can also generate a friction, simulating a kind of tactile feedback of the object or simulation that is being manipulated. The coexistence of both mechanisms would allow the operator to manipulate imposing a force control on the object or run simulations in very immersive virtual reality environments.

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