A PRELIMINARY STUDY TOWARDS AN EVA GLOVE EXOSKELETON

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ABSTRACT

This paper investigates the key factors associated with the realization of a hand exoskeleton to be embedded in an astronaut's EVA glove, in order to overcome the stiffness of the pressurized space suit. An overview is provided, laying the ground for the forthcoming prototype study, design and construction, by presenting the main constraints related to the realization of a hand exoskeleton for EVA suits and a preliminary concept analysis of possible solutions in terms of mechanical structure, actuators and sensors. The future exoskeleton will be a complex mechatronic system detecting the operator's movement through sensors, processing the acquired data and generating the motion through its actuation system.

1. INTRODUCTION

Extra Vehicular Activities (EVAs) are operations performed by astronauts away from Earth and outside spacecrafts. To allow the astronaut to operate in such harsh conditions, they are equipped with spacesuits composed of a complex and highly technological multilayer structure [1]. The suit must also protect the astronaut from the vacuum outside, so it must be internally pressurized. All those factors impose strong limitations to the astronaut's mobility during a mission, increasing the stiffness of each joint and requiring the astronaut to exert greater-than-normal forces to perform even the simplest movements. Therefore, gloves are probably the most critical part of the space suit because almost all operations require the use of hands. The hand is a complex system composed of 23 degrees of freedom in a significantly reduced space, driven by small muscles that must perform several repetitive movements. In fact, one of the main problems limiting the overall duration of a spacewalk is the astronaut`s hand fatigue. A device able to overcome (or prevent) hand fatigue during EVA would be a significant improvement for the astronauts, allowing them to accomplish their tasks more efficiently, more comfortably and for a longer time. In the forthcoming years, NASA is planning to increase significantly the number of hours dedicated to EVA operations during space missions [2], as shown very clearly in Fig. 1. Therefore, it is easy to understand the importance of this kind of device. Our study is a preliminary approach towards a possible technological solution able to reduce the fatigue of the astronaut's hand avoiding interference with its natural movements. Our final goal is the realization of a prototype of a lightweight hand exoskeleton to be embedded in the astronaut's gloved hand, in order to overcome the stiffness of the pressurized suit. The high complexity of the human hand, in terms of degrees of freedom and working space, and the extreme environment in which the exoskeleton will have to work both create a series of different constraints increasing the complexity of the project.

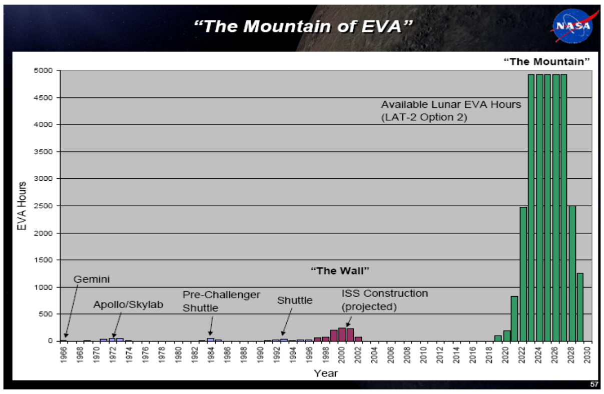

Figure 1. "The mountain of EVA" [2]

2. APPLICATION ENVIRONMENT: ISSUES AND CONSTRAINTS

Various typologies of devices can be realized in order to reach the goal previously described. The possible alternatives of installing an exoskeleton outside the EVA glove instead of inside it, or of realizing a robotic hand instead of an exoskeleton would change

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completely the constraints and the issues related to the realization of this project. The decision to realize the exoskeleton embedded inside the EVA glove changes the application environment of this project from the space to the glove. This means that some problems and constraints related to the space environment, for example radiation and cosmic dust, became less incisive, because they are screened by the protective multilayer system, while other issues related to dimensions and working space arise. Below, the main constraints related to the application scenario are analyzed.

2.1. Dimension and Weight

The exoskeleton dimensions and weight are a major constraint on the choice of each component, particularly those related to the actuation system and structural materials. Nowadays exoskeletons found in literature [3]-[6] or commercially available are generally bulky because they are built for tasks, such as rehabilitation or virtual reality, that don't impose strong size limits, especially on the back side of the hand. In this project, on the contrary, the glove is a size limit if we want to embed the exoskeleton in it. Otherwise, we would need to redesign completely the glove itself, which could be a possible further step of this project in case the exoskeleton would become a necessary part of the astronaut's equipment. Moreover, low mass and inertia are important requirements in order to facilitate the various manipulation tasks.

2.2. Working Space and Self Interference

A critical point in the development of an exoskeleton for an EVA glove is the necessity to avoid excessive restrictions to the work space, and hence to the operator's dexterity. Considering only the structure that the exoskeleton must have, first of all the palm should be as free as possible, so it is strongly preferable to place all the systems within a small space on the back of the hand in order to avoid limiting the ability to grasp and handle objects. Furthermore the lateral thickness at each finger must be very small in order to allow all movements related to the fingers abduction. All those represent limiting factors on the structure and the technologies that can be used.

2.3. Degrees of Freedom

The hand is a very complex limb with 23 degrees of freedom in a significantly reduced space. It is difficult to reproduce faithfully every single possible movement with a robotic structure, especially under the constraints related to weight, size and dimensions analyzed above. Another big challenge arises considering the first joint of the thumb that causes the displacement of a great portion of the palm. Therefore, there are two opposite requirements: the desire to ensure high dexterity to the operator, creating a structure with many joints, in order to reproduce the motion of the hand, and the need to create a device with limited size and weight. A compromise should be found, since it is hardly possible to actuate and sense 23 DoFs in an appropriate way, and conversely it would be useless to create a basic device with few degrees of freedom that will not help the operator. Studying the various kinds of movements that the hand can perform during various typical tasks the number of active DoFs of the exoskeleton can be reduced by appropriate kinematic dependencies and by the use of passive joints.

2.4. Space Environment

Space is a highly dynamic environment that poses threats [7] related to several different aspects. This must be taken into account when choosing the various components and material of an exoskeleton. The glove and the suit in general, guarantee a certain level of protection from certain effects trough a multilayer system. Despite the protective layers, some problems related to the space environment still persist such as cosmic dust, electromagnetic interferences, high temperature variations, micro-meteoroids.

Cosmic dust is a type of dust composed by particles which are molecules up to 0.1 µm in size. These dust particles might also penetrate through the seals of space suits causing many problems related to the astronaut's health or to the mechanical parts.

Electromagnetic interference is an effect due to many causes in the space. Solar activity, high energy particles, electromagnetic radiation, space plasma can degrade or damage the devices and also cause background noise possibly leading to permanent damage and component failure. Sensors in particular are very sensitive because a high level of background noise can make the data useless.

Micro-meteoroids are small particles that can be made of various kinds of material travelling with high relative velocity trough space: this element can be dangerous upon direct impact.

Finally, an indirect effect of the space scenario are the strict requirements in terms of energy consumption, it is very important in fact that the exoskeleton uses as little energy as possible in order to increase autonomy and to allow using smaller batteries.

2.5. Comfort

Last but not least is the comfort factor that the glove must guarantee to the operator. It is supposed that the astronaut will have to withstand a high amount of hours in EVA. Today some astronauts have already experienced some physical damage from gloves such as parastesia, loss of feeling in fingers, abrasions, loss of nails [8]. Therefore it is important that the comfort level guaranteed by the exoskeleton is as high as possible because otherwise is would be dumb to reduce fatigue

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while increasing the risk of hand injuries.

3. PRELIMINARY DESIGN CONCEPTS

The first step to focus on in order to create a hand exoskeleton is a detailed analysis of the static and dynamic characteristics of the hand and the effect that the glove has on the activities of the hand. The main problem related to the hand is due to the large number of degrees of freedom and the relatively high variation in the characteristics in terms of strength, size and dexterity between different individuals.

3.1. Analysis of finger/hand geometry

Despite variations in size, the hand can be uniquely described by a kinematic chain whose joints are placed in the same position as the various articulations and whose links appear to be the bones [9]-[10].

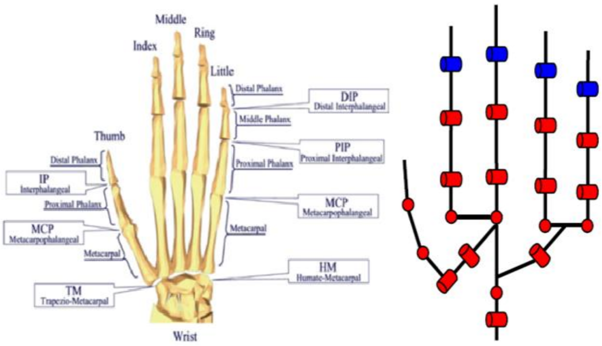

Figure 2. Kinematic structure of the hand

Each finger, excluding the thumb, can be modelled as a kinematic chain composed of four links, three of which have joints with almost parallel axes (MCP, PIP, DIP), involved in flexion and extension movements, and one perpendicular to them involved in the movement of abduction. The thumb is much more complex because his movements involve strongly also the metacarpal bone. The scheme of the correspondence between hand anatomy and its kinematic structure is presented in Fig. 2. Analyzing the hand in depth it can be observed that there are some "pseudo kinematic constraints" between certain degrees of freedom due in part to the arrangement of tendons and in parts to the tissues of the hand: for instance, even though the little finger and the ring one can move independently, large movements of one force a movement of the other. Another example is represented by PIP and DIP joints that, unless forced to do otherwise, move naturally with a ratio of about 2/3 between the relative angles.

All the joints of the hand rotate around axes passing through the finger. Therefore, in order to replicate finger motion trough a mechanical exoskeleton without interference, it is necessary to ensure that the physiological and the mechanical axis coincide as shown in Fig. 3. This is made harder by the necessity to have a very small lateral thickness.

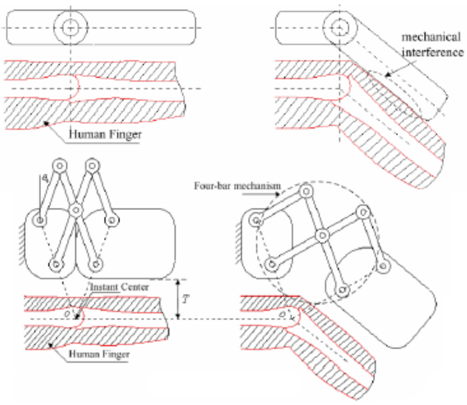

Figure 3. The problem of joint axes

3.2. Analysis of forces and velocities

While the analysis of the geometry is needed for the development of an appropriate structure, the analysis of forces and velocities is required in order to dimension properly sensors and actuators. It is necessary to know the respective ranges because over dimensioning the devices directly implies having larger masses and weights, while under dimensioning them means not being able to follow all natural capabilities of the fingers. In literature there are several studies on forces and velocities of the hand. Conversely, a quantitative analysis of the stiffness of the EVA glove and thus of the forces the EVA glove applies on the astronaut's hand is not available. This figure is very important because EVA-related fatigue is a direct consequence of the stiffness of the EVA glove; resisting forces from the glove also provide a design indication for the force range that the exoskeleton must be able to provide. In this regard, a preliminary analysis is being performed at Italian Institute of Technology using an unpressurized Russian Orlan EVA glove.

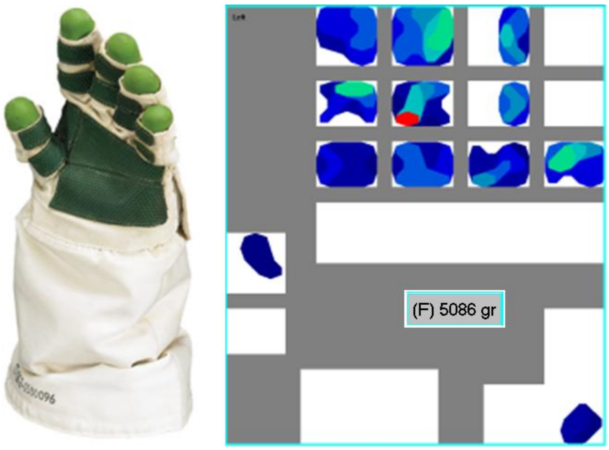

Figure 4. Orlan EVA glove (left) and its effect on the sphere grip test (right)

Trough a distributed sensor system properly positioned on the hand of an operator, the pressure acting on the

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hand with and without glove is recorded. The integral of the pressure on the surface of the hand provide a first quantitative idea of the value of the interested dimension. In the Fig. 4 are shown the Russian Orlan EVA glove on the right and its maximum effect during a sphere grip test.
The results of that study will be presented in another article.

4. GENERAL CONCEPTS FOR EXOSKELETON DESIGN

The preliminary analysis carried out permits to depict the specifications of each element composing the exoskeleton and to get a first idea about possible strategies. An exoskeleton is a complex mechatronic system: here we will focus on its structure, actuation and sensorization.

4.1. Structure

The structure is the part of the system that should provide support, aid and guidance to the fingers, ensuring the correct kinematics, so to achieve the right implementation of the transmission of the movements from the actuators. Moreover, the choice of an appropriate and well designed structure will allow simple integration between sensor and actuation components. The analysis of a possible geometry is a very important step to optimize the weight and strength. Whereas an extremely lightweight structure seems to be an advantage, we have also to consider that the structure has to address correctly forces and torques to avoid to stress the operator's articulations. The choice of the right material, the number of active and passive degrees of freedom, the decision on how to overcome the problem of the axes of rotation and the choice of how to transmit the forces from the actuators, all those are constraints and specifications that determine the type of structure that it is to be realized. In the Fig. 5. are shown two different kind on exoskeleton structures. The structure on the left use the four bar mechanism to move the joints and the structure on the right use the cable mechanism.

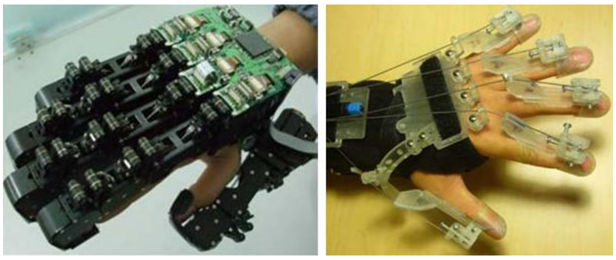

Figure 5. Two different exoskeleton structures: Four bar mechanism (left) [11] and Cable mechanism (right)

4.2. Actuators

The actuators are those elements that generate the movement of links around joints, from command signals coming from the control unit. The actuation part is a critical point in the project; in fact, usually, the size of an actuator is strictly related to the power and to the torque that it is able to generate. The specifications of speed, from the study of the hand, and of forces, from the study of EVA glove effects, provide a first idea about the kind of actuators to be used. There are numerous types of actuators based on different technologies: using high-pressure fluids such as hydraulic or mesofluidic ones, using compressed air, as pneumatic muscles, relying on magnetic fields and many others. Despite the wide variety of available technologies, the solutions that might be used in our project are very few due to many factors. First of all the space environment described previously, then there are factors related to the safety of the astronauts (for example high pressure liquids or gases cannot be used inside a space suit), finally there are constraints in terms of energy consumption, robustness against magnetic fields, dimensions and weight.

4.3. 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 torques and/or forces and the relative positions of the various joints of the fingers. There are many types of sensors that differ in the technology they use: piezo-resistive, load cells, capacitive. Even in this case, the constraints are related to the problems of energy consumption, electromagnetic robustness, size and weight. The positioning of sensors is an additional issue, for example pressure sensors positioned on the outside of the glove also allows a kind of tactile feedback of the object to be manipulated, ensuring an improvement in performance and partly overcoming the loss of sensitivity caused by wearing an EVA glove. An interesting possibility is guaranteed by electro-miographical (EMG) sensors, measuring directly the user's muscular electrical potentials. Those are electrical pulses travelling from the brain to the muscles trough the nerves and conveying contraction commands. A great advantage of using EMG sensors is that the signals they detect are proportional to the force that the human being desires to apply trough his muscles. This kind of sensor can be used as a force sensor with the great advantage of being placed not on the hand but on the forearm, where most of the finger-actuating muscles reside.

5. PRELIMINARY CONTROL CONCEPTS

The latter elements interact with each other by means of the control system. The sensors detect the desired quantities, then their signals are processed by the control system, which decides how to act on the

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structure by means of the actuators. A simple control strategy would be to use tracking control: the astronaut transmits their will to perform a given movement by acting on the structure. This is detected by pressure sensors, and then the control issues the appropriate commands to the actuators to follow and assist the desired astronaut's movement and bring back the sensor reading to a predefined value just above zero (or proportional to the forces from the environment). Using a couple of sensors for each degree of freedom (one inside and one outside the exoskeleton) would also allow to distinguish free motion (where only the signal of the internal sensor changes) from a grasp situation (in which both the internal and the external sensor will be loaded).

6. CONCLUSIONS

In this paper we have summarizes the preliminary analysis done in order to study and verify the feasibility of a hand exoskeleton designed to be embedded in an astronaut's glove in order to overcome its stiffness. When all the preliminary analysis is finished, a prototype will be developed and realized. As a first step, the idea is to proceed with the design of a single finger prototype. The structure, the sensors and the actuators used in the design of the finger will then be redesigned on the base of the results obtained and integrated in a wider project, taking into account the constraints and limitations described in the present paper. Finally the complete exoskeleton hand prototype will be realized.

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