HEXEC: A HAND EXOSKELETON DESIGNED TO BE EMBEDDED IN THE ASTRONAUT’S EVA GLOVE

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ABSTRACT

In the next decades, planetary exploration will play an important role in directing the global technological development and will provide at the same time an extensive application and testing field for many innovative technologies. In support of exploration missions, new space systems shall be developed requiring research on many new technologies involving robotics, automation, bio-engineering, artificial intelligence, and nanotechnology skills. Extravehicular pressurized suits impose severe limits to astronauts’ mobility particularly impacting on dexterity, force, and endurance of the hands. A device able to overcome the hand fatigue during the extra-vehicular activity (EVA) would be a significant improvement allowing optimization of crew productivity. In this paper, a preliminary approach towards a possible technological solution able to reduce the astronaut’s hand fatigue is discussed.

Key words: Hand Exoskeleton; EMG; Lightweight.

1. INTRODUCTION

Extra Vehicular Activities (EVAs) are operations carried out by astronauts in the dangerous environment outside spacecrafts. In the forthcoming years, NASA is planning to increase significantly the number of hours dedicated to EVA operations during space missions [1].

Needing to protect the astronauts from various hazards such [2] as cosmic dust, the vacuum, extreme temperatures, micrometeoroids, and high energy cosmic radiations, spacesuits are composed of a complex and highly technological multilayer structure [3, 4]. This structure, together with the pressurization of the inmost bladder, imposes strong limitations to the astronaut’s mobility during a mission, increasing the stiffness at each articular joint and requiring the astronaut to exert forces greater than normal to perform even the simplest movements.

The problems related to the stiffness of the suit are amplified at the gloves sharply increasing the fatigue of the hands and forcibly limiting the overall duration of EVAs. Figure 1 shows the three separate parts of an EVA glove (i.e. bladder, glove, garment). Several studies have been conducted to determine the influence of the EVA glove on manual capabilities, both in the past [5, 6] and more recently [7, 8]. Six basic hand capabilities have been identified in literature [5]: range of motion, strength, tactility, dexterity, fatigue and comfort. These aspects have been studied in several papers [5, 6, 7, 8] following different approaches.

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.

Our final goal is the development of a prototype of a lightweight hand exoskeleton designed to be embedded in the astronaut’s glove, overcoming the stiffness of the pressurized space suit. The system should be able to provide force, dexterity, and endurance to the hand grip. The exoskeleton will have a multi-finger design; however some fingers may be combined with each other to lighten and simplify the assembly. The architecture and design of the actuation system, which shall mimic the kinematics of the hand joints, will be studied. Soft actuators and artificial muscles will also be considered. The forces...
of the hand will be monitored by an array of thin pressure sensors mounted on the internal side of the glove. Force sensing will be provided by further tactile sensors mounted on the external side of the glove. Microcontrollers using the pressure sensors as input will modulate the power of the motors allowing the astronaut to perform both power and precision grasps.

1.1. Issues and Constraints

The main constraints related to the application scenario are analyzed hereafter.

- **Dimensions and Weight.** The exoskeleton dimensions and weight are a major constraint in the choice of each component, particularly those related to the actuation system and structural materials. Nowadays exoskeletons reported in literature [5, 6, 7, 8] are generally bulky because of their field of application, e.g., rehabilitation and virtual reality, not imposing strong limits. In this project, on the contrary, the glove size is a constraint as the exoskeleton has to be embedded in it. Moreover, low mass and inertia are important requirements in order to facilitate the various manipulation tasks.

- **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 workspace, and hence to the operator’s dexterity. Since the palm should be as free as possible, all systems should be placed 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 as small as possible in order not to impair movements.

- **Degrees of Freedom.** The hand is a very complex organ with 23 degrees of freedom (DoFs) in a significantly reduced space. A 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, and the need to create a device with limited size and weight. Studying the kinematics dependencies of the hand can be used to reduce the active DoFs and general complexity of the system.

- **Comfort, Ergonomy, and Safety.** Last but not least, comfort must guaranteed to the operator. Hitherto, some astronauts have already experienced some physical damage from gloves such as paraesthesia, loss of feeling in fingers, abrasions, loss of nails [9]. Reducing comfort might increase these risks.

2. LITERATURE REVIEW

Even if some hand exoskeletons have been proposed in recent years, bulk and weight issues have not been solved yet. Among the others, a device aimed at preventing the astronaut’s hand fatigue is present in literature [2]; it adopts the strategy of coupling some fingers, in order to reduce the complexity of the system; however, it still presents the aforementioned problems of bulk and weight (see Figure 2).

![Figure 2. The exoskeleton proposed by Shields [2].](image)

A similar approach, even if not conceived for a specific application, is proposed in [9], where the middle, ring and little fingers are coupled together (see Figure 3). Further research activities can be found in the fields of rehabilitation and haptic interaction in virtual environments, like tele-manipulation systems. Preliminary single-finger kinematical schemes [10, 11], as well as two-finger architectures [12] and whole hand exoskeletons [13] have been developed.

However, due to their terrestrial application, they are not performing particularly well in terms of lightness and encumbrance. An exception is the work of Kunii et al. [10], where the exoskeleton connected to the finger is under-actuated, with the adduction-abduction angle as a passive joint while the three flexion–extension joints that connect the phalanges each other are driven through a single motor. Hence, such architecture is more lightweight and simpler than traditional solutions but reduces the controllable DoFs.

3. DESIGN OF THE HAND EXOSKELETON

When designing the hand exoskeleton, among the possible strategies, two possible approaches arise: the former delineates a structure that has its own kinematics and has to comply with the human finger movements. In this approach, it could be said that the structure holds the fingers. In the other approach, the structure is held by the fingers, that impose their own kinematics to the exoskeleton parts. Given that the finger physiological joints are not pure hinges but behave like rolling coupling profiles, then the design of a mechanism which is definitely compliant with the human fingers is very complicated and should be custom-made; thus, at the beginning, the second approach, that also leads to a less bulky and more lightweight solution, has been chosen. Furthermore the first approach would be subject to strong physiological constraints like the presence of the hand.
Sensors and actuators have to meet strong requirements due to their usage in the harsh space environment particularly in terms of temperature and electromagnetic interferences. Other constraints related to the sensors are their size, working space, and energy consumption. One of the problems is that it is difficult to separate external and internal forces with the use of force, pressure, or torque sensors. A possible solution may be related to the use of two separate arrays of sensors. In parallel to this traditional mechanical approach, an innovative way of designing is explored with an Additive Manufacturing (AM) technology particularly suitable for metals and composites: the Direct Metal Laser Sintering (DMLS) [14]. This process will allow the realization of completely new designs in terms of one structure assembly (with kinematics) as well as single lightweight components (like lattice structural parts).

3.1. Sensors and Actuators

Sensors and actuators have to meet strong requirements due to their usage in the harsh space environment particularly in terms of temperature and electromagnetic interferences. Other constraints related to the sensors are their size, working space, and energy consumption. One of the problems is that it is difficult to separate external and internal forces with the use of force, pressure, or torque sensors. A possible solution may be related to the use of two separate arrays of sensors. In [15] we have reviewed several typologies of sensors. Among the different types of sensors, electro-goniometers resulted particularly interesting from the point of view of such an application revealing good precision and repeatability properties. In the same work, also tactile pressure sensors have been deeply investigated and they have been used to evaluate the effects of EVA gloves on human hand fatigue [16]. Next generation sensors, based on new nano structured piezoelectric and piezoresistive materials are currently under development in our center; our goal for the future is to replace commercial sensors with our own custom built devices [17, 18, 19].

Many types of actuators are available, like hydraulic or mesofluidic actuators that use high-pressure fluids, or air muscles that use compressed air. ElectroActive Polymers (EAP), Shape Memory Alloys (SMA), or magnetic-field actuators are other possible solutions. However, due to the constraints of the outer space and the astronaut’s safety, only a few solutions are feasible. For example, no high-pressure fluids are allowed inside the space suit; moreover, energy consumption has to be as low as possible. For this reason, electric brushless motors have, currently, been selected for an exoskeleton test bench; in such a scenario the limitation of size and weight are not relevant. At the same time, alternative solutions are being studied, specifically in the domain of combined use of multiple actuators and by the study of new EAPs.

3.2. Mechanical Structure

Given the high number of constraints, the complexity of the system, and the number of technologies involved, a stepwise approach has been chosen. In particular, while the other technologies (sensors, actuators, etc.) are being studied the mechanical structure will be analyzed with the development of a modular test bench. The test bench is conceived as a modular architecture: different units are assembled together and concur in the testing activity, each of them realizing a module of the whole testing flowchart. Hence, it is referred to as a modular test bench: delaying shape, bulk and weight issues to a later stage allows analyzing the best possible solution for joints, sensors and tendon holes without having to rebuild the structure to test each alternative configuration.

Our first mechanical study concerns a single finger as the index finger, having one side completely free. In this case, the structure of the exoskeleton and the joints may have an asymmetrical design, as they are placed on the accessible side of this finger. The joints are realized through flexible elements like torsional springs; they are not only responsible of achieving the kinematics of the hand as precisely as possible, but also they simulate the presence of the EVA glove on the test bench. In fact, the EVA glove has stiffness properties that tend to keep the astronaut’s hand open; the goal of the exoskeleton is to partially or totally compensate these resisting actions.

To transmit the forces from the brushless motors to the structure, cables have been chosen, in order to keep the whole system as lightweight as possible. Each cable connects a moving part of the exoskeleton, that corresponds to a phalanx, to a motor. However, given that the cables that drive the position of the distal elements pass through holes located on previous phalanges, then an action applied to the cable that controls the last one has a not-negligible influence also on the proximal phalanges. Thus, the tension of the cables cannot be calculated independently and in each position of the hand exoskeleton, each cable has its specific amount of tension that is related to the tension of other cables. An optimization activity has been performed and an optimal solution for the cables of the holes has been found, in order to minimize the magnitude of the force actions required to reach the different exoskeleton configurations inside its workspace. A few example of possible configurations is shown in Figure 4.

Figure 4. The exoskeleton proposed by Fontana [9].
3.3. Innovative Designs through Additive Manufacturing

As stated above, AM involves a new different method of design concept, allowing the creation of complex surfaces and internal features directly when building the part, as no tooling is required. Moreover, the complexity of the part has no much effect on the building times, contrary to the other manufacturing processes. In particular, through DMLS is possible to create metal components for structural applications by scanning powdered materials with a laser beam so as to melt and fuse the material into a solid, the parts being manufactured layer by layer direct from the CAD file data. Many materials have been processed successfully like iron and steels, superalloys, Ti and Ti6Al4V alloy. One materials group of great interest to those developing the DMLS process are the aluminium alloys, which are extensively used in modern manufacturing and which could have the main requirements for structural robotics, like high specific strength and stiffness, high fatigue resistance and a low friction coefficient. What seemed promising was to process an AlSi10Mg alloy (nominally Al, 10 wt% Si, 0.3 wt% Mg): it is often used in casting for parts with complex shapes and subjected to high loads. As a consequence, the first finger prototype parts were realized in this Al alloy through an EOSINT M270 Xtended version machine. At first was fundamental to study and optimize the laser sintering parameters (like layer thickness, hatching distance, laser pulse energy): in particular was very important to evaluate their effect on the microstructural, superficial and mechanical properties of the final components, also considering the relationship with the powder features and the exoskeleton requirements on the basis of the final application and the hand kinematics studies. In a second step, the development of new materials for DMLS, like composites and shape memory alloys, together with new designs, like new ideas for joints and lightweight lattice structures, is now under investigation.

4. EMG AS A CONTROL STRATEGY

As seen in section 3.1 pressure sensors on the inside and on the outside of the glove are hard to discriminate. It is, thus, quite hard to both provide pressure feedback and to control the exoskeleton without adding some sort of alternative control strategy and without impacting too much on the hand sensibility and dexterity. As an alternative technique to pressure sensors, surface electromyography (sEMG) of the forearm has been selected.

Electromyography (EMG) is a technique which evaluates and record the electrical activity produced by skeletal muscles. Analyzing the dynamics of EMG signals of the forearm it is possible to recognize the muscular activation to obtain a precise feedback control system; furthermore, with the same technique it is possible to estimate muscular fatigue, and time to fatigue [20].

Beside the improvement in space exploration, this type of solution (hand exoskeleton + sEMG feedback control) could be effectively applied to other terrestrial scenarios. A broad field of applications is related to elderly care and rehabilitation to recover from the main symptoms associated with progressive disorders, such as bradykinesia, tremor, carpal tunnel syndrome and rigidity, but many other scenarios are foreseeable; in fact, the hand exoskeleton can generally improve the hand dexterity, endurance, and strength.

In the state of the art sEMG electrodes are composed of coupled metallic contacts that have sizes ranging from about 7 to 10 mm. We argue that this spatial resolution is not enough to discern movement of the hand because of the density of different muscles of the forearm. It is, thus, crucial to build smaller electrodes and to organize them into dense sEMG electrode matrices.

Dense sEMG electrode matrices already exist and are currently being studied in few research centers [21]. The state of the art technology of the electrodes and, in particular, the reduced dimension of the metallic contacts, require conductive gels or cremes between the electrode and the skin to reduce the skin-electrode impedance (wet electrodes). Furthermore, very often skin preparation is suggested or even required. To be used extensively, without skin preparation, and for long sessions, wet electrodes cannot be considered as an optimal solution; better dry electrode systems have, therefore, to be investigated. To be effectively developed this kind of system need multiple efforts and an interdisciplinary approach focused on the different aspects that compose the system itself [22]:

- new materials and designs for sEMG electrodes.
- in-situ electronics.
- new dense arrays designs for sEMG electrodes.
- advanced signal analysis technique.
At the Italian Institute of Technology we are pursuing all of these research topics; please refer to [23] for more details.

5. CONCLUSION

The current paper describes the first steps towards a full prototype of a hand exoskeleton to be embedded in the glove of the astronaut’s spacesuit during EVA. Given the strong constraints from the point of view of weight, dimensions, electromagnetic interferences, and so on, then it is critical to analyze the choice of the sensors and actuators, the conception and design of the kinematical structure, as well as the involved technological processes and materials. In order to analyze different configurations, a modular test bench has been built, actually based on traditional motors but with innovative kinematic solutions. In parallel, new solutions as innovative and creative designs of joints and structural parts, as well as lightweight materials formed into complex shapes, are explored thanks to Direct Metal Laser Sintering, a rapid manufacturing technology. Then the possibility to substitute, or merge, traditional control strategies based on pressure sensors with new ones based on EMG technique is also discussed. Future activity will be devoted to develop these concepts and preliminary design stage, in order to build a demonstrator of the hand exoskeleton.

REFERENCES


