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DESIGN OF A HAND EXOSKELETON FOR SPACE EXTRAVEHICULAR ACTIVITIES

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ABSTRACT

Due to the bulk and stiffness of the astronauts' glove, so called Extravehicular Activity (EVA) glove, many problems occur during their missions outside the spacecraft i.e. fatigue, dexterity reduction, decrease of possible EVA hours, etc. [1, 2]. To solve these problems a hand exoskeleton which can be embedded inside the astronauts' glove has been proposed as a solution to help them to move their fingers more easily.

In this work all the steps that were taken towards the design of a preliminary version of the hand exoskeleton are explained in detail. The paper starts with a brief survey on related literature, followed by an analysis of three main research subjects for the design and realization of the hand exoskeleton: sensors, actuators and structure. In particular, different kinds of sensors and actuators are evaluated and advantages and disadvantages of each one are investigated. Then the main reasons to choose a specific type of sensor or actuator are described in detail. Regarding the structure, different possible solutions converging towards an optimal design for this application have been evaluated. Moreover, the use of some springs in the structure to simulate the stiffness of the EVA glove is proposed in order to be able to test the device in a condition similar to its final application. A brief description about the kinematic modeling and simulation of the structure in order to find the optimum location of the transmission cables and their tension forces is explained.

KEYWORDS

EVA (Extravehicular Activity) Glove, Hand Exoskeleton, Robotic Hand

INTRODUCTION

During the past few years, the total time of Extravehicular Activity (EVA) performed by astronauts has increased significantly [3]. Bulk and stiffness of a pressurized EVA spacesuit glove are the major causes of astronauts' fatigue, thus reducing the duration of EVAs [4, 5]. This has led NASA to organize a specific plan to improve EVA gloves in order to overcome the bulk and stiffness of the gloves and reduce fatigue effects on the astronaut's hands. To fulfill this demand a hand exoskeleton which can be embedded inside the astronaut's glove has been proposed as a solution. Our work starts with a comprehensive survey on literature and the outcome of this investigation convinces us that at present, it is very difficult to create an ideal hand exoskeleton that can be embedded completely inside the astronauts' glove, due to strong technological limitations. The main problem is the size and power of the existing electric motors or actuators in the market since there is not much room inside the astronauts' glove. Although, many new actuators and piezomotors have been produced recently which may solve bulk issues, but on the other hand they do not provide enough power to move the structure of the hand exoskeleton that should overcome the stiffness of the EVA glove. Moreover, the complication of the human hand and the number of its degrees of freedom along with the space limitation between fingers have led us to change our approach from creating a complete hand exoskeleton to a preliminary test bench for the index finger that can simulate, to some extent, the behavior of a hand exoskeleton.

LITERATURE REVIEW

The most similar research paper to this project is the work by Shields et al [6]. In their research a hand exoskeleton has been proposed to prevent astronaut hand fatigue. Although, they have tried to create a suitable device for this application, as it can be seen in Figure 1, the above mentioned problems prevented them to arrive to a light weight and small structure.

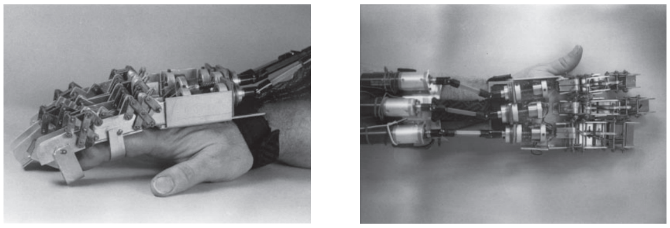


FIGURE 1- PHOTOGRAPH OF THE EXOSKELETON IN ITS EXTENDED POSITION AND FROM THE TOP VIEW

Related research activities can be usually found under two titles of Hand Exoskeleton and Robotic Hand, dealing with rehabilitation and humanoid robotics, respectively.

Among papers with a hand exoskeleton approach, we can refer to Fontana's work of 2009 that can be seen in Figure 2 [7]. His hand exoskeleton, which is a high performance portable one, allows exerting controlled forces on the fingertip of the index and thumb of the operator.

In 1997, University of Tokyo developed the so called Sensor Gloves II which is a 20 degrees of freedom (DOFs) haptic interface. It can be viewed in Figure 3. Each of its joints is driven by an actuator through wire transmission. The joint angles are measured by rotary encoders and the torques of human fingers by strain-gauges as the stress of links [8].

A more complex exoskeleton which has been designed especially for rehabilitation purposes is called HANDEXOS. It has been shown in Figure 4. Its design activates almost all the DOFs of the human finger with a natural Range of Motion (ROM), and it achieves requirements such as low restraint, light weight, comfort and good wearability [9].

Other two examples of hand exoskeleton for rehabilitation of human fingers are the works of Wege [10] and Hasegawa [11]. The first one (Figure 5) was specifically designed to accomplish requirements of medical applications. For research on control algorithms and rehabilitation programs a prototype supporting all four DOFs of one finger was built. The second one (Figure 6) has three active joints for an index finger, three active joints for combination of a middle finger, a ring finger and a little finger and two active joints for a thumb.

In addition to the hand exoskeleton, several robotic hands have also been designed in different research centers. Sheffield Hand with 12 DOFs and a life-like movement as a replica of the human arm (Figure 7), Shadow Hand with 24 DOFs and 40 air muscles with integrated sensing and position control that allows precise control (Figure 8), Zurich/Tokyo Hand which is a 13 DOFs prosthetic robotic hand inspired by the muscle tendon system of the human hand and equipped with different types of sensors (Figure 9), RAPHaEL Air Powered Hand with elastic ligaments which powered by a compressor air tank at 60 psi and a novel accordion type tube actuator (Figure 10), Touch Bionics i-LIMB Hand, Honda Hand, Robonaut Hand and Utah/MIT Hand, are just some of the developed robotic hands of different research centers in the world.

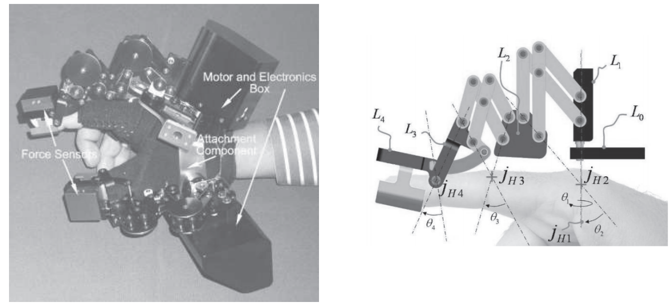


FIGURE 2- PICTURE OF THE HAND EXOSKELETON REALIZED BY FONTANA ET AL.

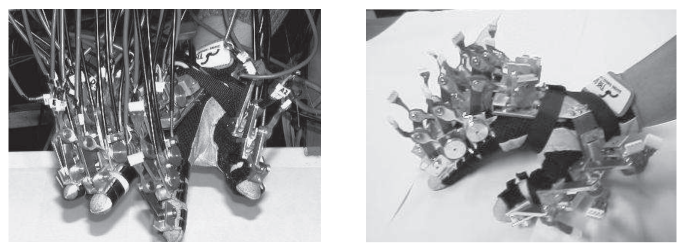


FIGURE 3- PICTURE OF SENSOR GLOVES II WITH AND WITHOUT WIRES

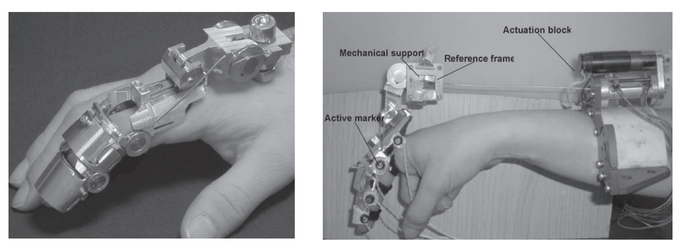


FIGURE 4- OVERVIEW OF THE HANDEXOS INDEX FINGER MODULE WITH AND WITHOUT THE ACTUATION BLOCK

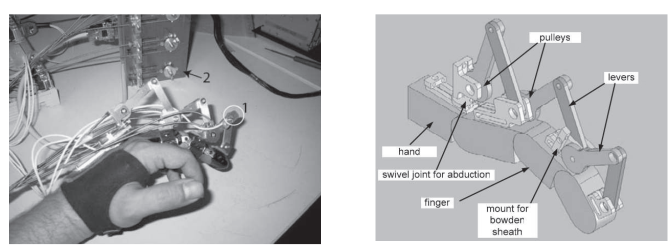


FIGURE 5- WEGE HAND EXOSKELETON FOR REHABILITATION. (1) HALL SENSOR TO MEASURE FINGER JOINTS ANGLE, (2) ACTUATOR UNIT

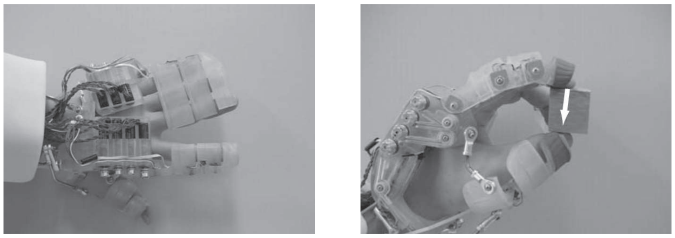


FIGURE 6- FIVE-FINGERED ASSISTIVE HAND DEVELOPED BY HASEGAWA ET AL.

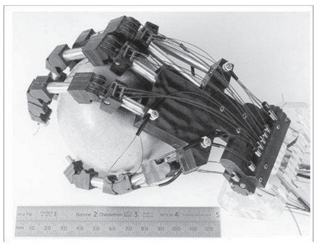


FIGURE 7- SHEFFIELD HAND

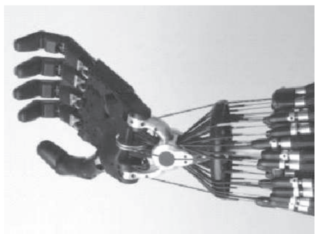


FIGURE 8- SHADOW HAND

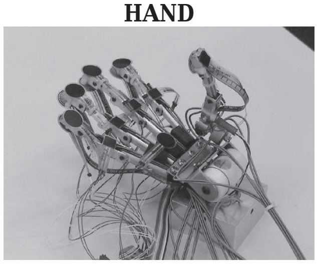


FIGURE 9- ZURICH/TOKYO HAND

FIGURE 10- RAPHAEL AIR POWERED HAND

Considering all these hand exoskeletons and robotic hands, it can be found out that none of them has a structure light enough to be embedded inside an EVA glove; even if they can be created in small scale, they will not be powerful enough. Therefore, the need for a specific research for such an application is necessary in research centers.

ACQUIRING PRELIMINARY DATA

The first step in the design of our hand exoskeleton was to discover the amount of forces that the exoskeleton actuators have to exert in order to overcome the EVA glove stiffness. Therefore, we started the work with an evaluation of the EVA glove stiffness. To have a general view about the effects of the EVA glove on the human hand fatigue and strength, we specified four tasks and asked some subjects to repeat these tasks several times, with and without the EVA glove, as far as they cannot continue to do them correctly anymore. The tasks and the test setup are shown in Figure 11 and the result of the test is presented in Figure 12. It can be seen that except for the 2-finger pinch, for all the other tasks the number of cycles decreases when wearing an EVA glove. To know the amount of the power of our hand exoskeleton in order to compensate this reduction or even increase it, we used a kind of distributed sensor which covering all the phalanges of the fingers and the palm. An EVA glove was worn over this distributed sensor (Figure 13). A test protocol was defined and the subject was asked to follow it in order to measure the total exerted force from EVA glove on subject's hand. The test protocol consisted in opening and closing the fingers in four steps. We have described the details of these tests in a previous paper [12].With

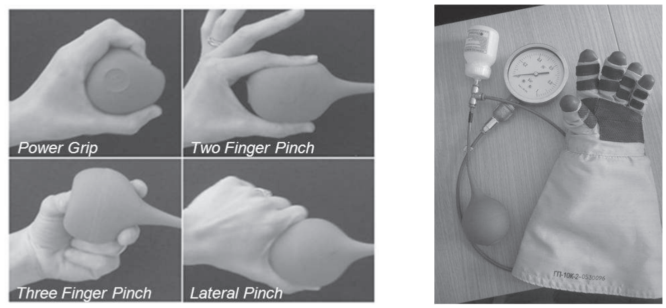


FIGURE 11- FOUR CHOSEN TASKS FOR THE TESTS AND TEST SETUP

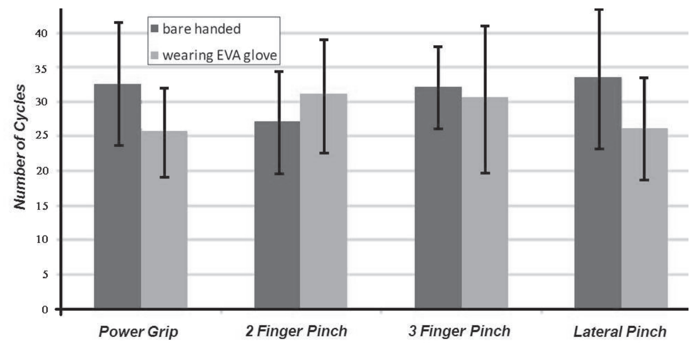


FIGURE 12- EFFECTS OF THE EVA GLOVE ON NUMBER OF EXECUTED CYCLES FOR EACH TASK

FIGURE 13- THE DISTRIBUTED SENSOR AND THE TEST SETUP

this test we extracted the exerted force from EVA glove on each phalange of the subject's fingers and also the Center of Force (COF) for each phalange (Figure 14), that made us capable to calculate the mean torque value for each phalange (Figure 15).

These preliminary data show us the range of forces of each phalange in order to select the proper sensors. Moreover, selecting the suitable actuators or motors is highly related to the amount of torque that we got from this test.

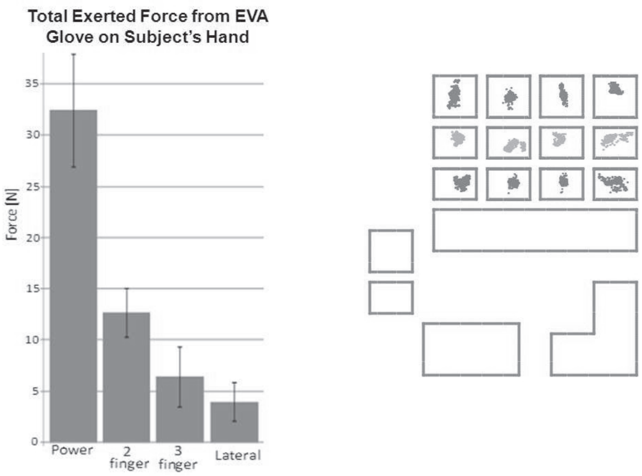


FIGURE 14- THE TOTAL EXERTED FORCE FROM EVA GLOVE ON SUBJECT'S HAND AND CENTER OF FORCE (COF) OF EACH PHALANGES

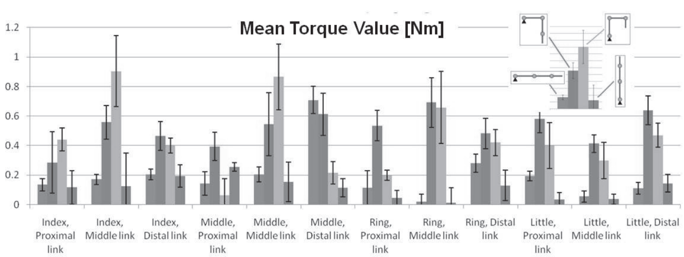


FIGURE 15- THE MEAN TORQUE VALUE CALCULATED FOR EACH PHALANGE

SENSORS

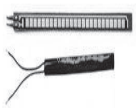
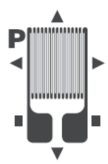
The most important parameters which have to be controlled in a hand exoskeleton are the position of the fingers and their applied force/torque. Different principles can be used to control the position and movement of the finger's phalanges and the applied force. There are many types of sensors which have been designed for this purpose. For example, Wege used a type of force sensors which are integrated into the device to measure force exchanged between human and exoskeleton [13]. This allows the human to control the movements of the hand exoskeleton. His control method also used the electromyography (EMG) sensors to generate a trajectory for the movement of the hand exoskeleton phalanges.

Schabowsky used a digital optical encoder with resolution of 0.002 degrees which is attached to the end of the motor of the hand exoskeleton for position sensing [14]. For finger flexion/extension torque measurement a torque sensor is placed between the motor and the linkage. Furthermore, the Hall sensors, optical encoders and force sensors are used in the exoskeleton to measure joint angles, angles of motor axes and the force between human and construction, respectively. Surface EMG sensors on the forearm are the other used sensors in his system.

Nowadays various kinds of sensors exist in the market for different applications in robots and exoskeletons and it is possible to find a suitable sensor for each specific need. Due to many limitations imposed by the space environment in our case, we cannot use all types of sensors in our exoskeleton. Some related constraints to the choice of sensors are the size, the working space, the energy consumption and the effects of space environment in terms of noise, temperature and electromagnetic interference. Table 1 presents a range of different sensors which have been evaluated to determine their suitability for our application.

TABLE 1- SOME OF THE SENSORS WHICH HAVE BEEN EVALUATED TO SPECIFY THEIR SUITABILITY

SENSOR	BRIEF DESCRIPTION
Electro-goniometer 	Electro-goniometer is a kind of position sensor with different working principles. It can use potentiometers, strain gauges, light or accelerometers to measure the angles. However, potentiometers which must be placed directly on the joint and accelerometers which are based on gravity are not suitable choices for our exoskeleton. The strain gauge type looks like a flexible spring in which the strain gauge mechanism is housed inside a spring and changes its resistance proportionally to the imposed angle.
Flexible Stretch Sensor 	Flexible Stretch Sensor can be used both as a position or a force sensor. It changes its resistance when bended or stretched. It is fully customizable in terms of dimensions, and as it can be both a position and a force sensor, represents a versatile solution for different applications. It is not suitable for our exoskeleton since as a force sensor there are more precise and smaller sensors than stretch sensor and as a position sensor it is proper for measuring just inline displacement.

Bend/Flex Sensor 	It is basically a position sensor and its technology is based on resistive carbon elements. When the substrate is bent, the sensor produces a resistance output correlated to the bend radius. The smaller the radius, the higher the resistance value. It can be created in one or two directional type and is available in various resistance ranges. It seems to be a suitable and cheap choice for the hand exoskeleton applications.
Strain Gauge 	A strain gage is a sensor whose resistance varies with applied force; It converts force, pressure, tension, weight, etc. into a change in electrical resistance. Strain gauges are available in lots of sizes and shapes. The strain gauge is the fundamental sensing element for many types of sensors, including pressure sensors, load cells, torque sensors, position sensors, etc. It seems to be a suitable and cheap choice for the hand exoskeleton applications.
EMG Sensor 	The EMG sensor measures the electro-physiological signals coming from the brain to the muscles. These signals are proportional to the force that the human body wants to apply through its muscles. This sensor can be used like a force sensor and must be placed on the forearm. Its disadvantage is that it has to be attached exactly in a right place on the forearm. Moreover, interaction of various muscle signals makes the separation of the signals difficult.
Finger Tactile Pressure Sensor 	It uses capacitive principals to detect the force. Tactile sensors are devices which indicate contact between themselves and some other solid object. This kind of sensors can be touch sensor, which are used just to detect the contact between two objects, or force sensor, which also indicate the magnitude of the contact force between the two objects. Tactile sensor seems to be proper for exoskeleton application.
Piezoresistive Force Sensor 	Piezoelectric sensor is a device that changes the electrical resistance when a mechanical stress is applied. 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. This kind of sensors seems to be the best choice for measuring the pressure between the fingers and exoskeleton structure.

In order to make the correct design choice about the sensors, we managed to test the more promising ones, from our application point of view. For example, we performed the characterization of the Electro-goniometers, through a dedicated test bench that is shown in Figure 16. The results of the tests confirm that the behavior of Electro-goniometers is very precise when a single test was repeated 9 times, once when the angle changes from -20 to 110 and once when it changes from 110 to -20 (Figure 17). Moreover, we did some other tests

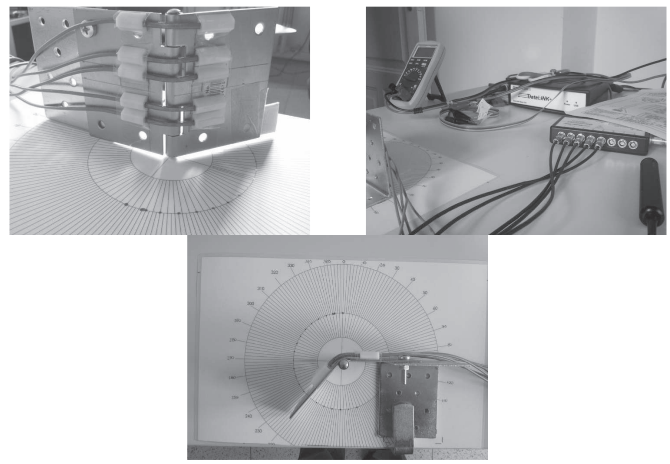


FIGURE 16- TEST SETUP AND CHARACTERIZATION OF THE ELECTRO-GONIOMETERS

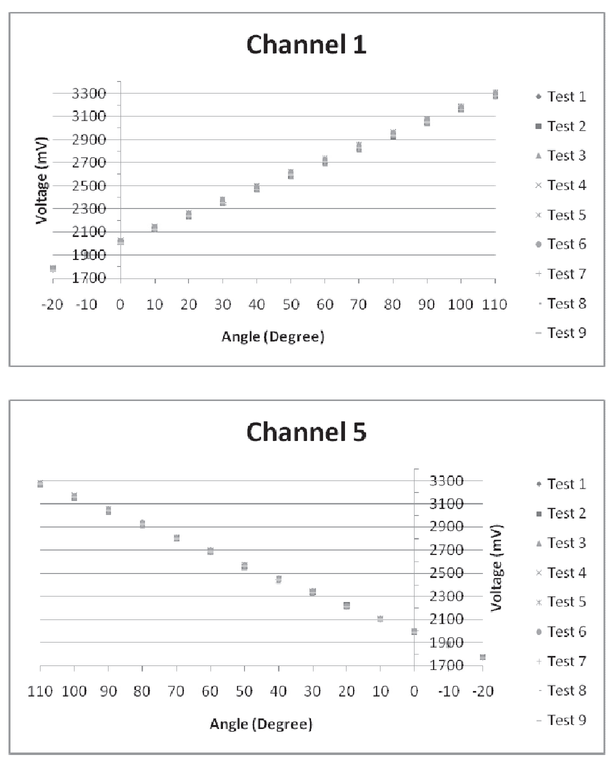


FIGURE 17- TEST RESULTS SHOW THE PRECISE BEHAVIOUR OF THE ELECTRO-GONIOMETERS

while grasping an object with the tactile pressure sensors which had already been used to evaluate the effects of EVA gloves on human hand fatigue to know more about the behavior of this kind of sensors, (Figure 13). A problem in using of these sensors is that almost all the force or torque sensors measure both external and internal forces and it is difficult to separate these two of each other.

ACTUATORS

Numerous types of actuators with different technologies can be found in literature. Some of them use high-pressure fluids like hydraulic or mesofluidic actuators; some others use compressed air, like air muscles. There are some actuators which use Electroactive Polymers and some which use Shape Memory Alloys (SMA) or those which rely on magnetic fields.

Despite this wide variety of technologies, the solutions that can be used in practice are very few due to many factors. First and foremost, there is the space environment in terms of noise, temperature and electromagnetic interference; furthermore, there are some factors related to the safety of astronauts. For example, high pressure liquid or gas cannot be used inside a space suit. Finally, there are some constraints in terms of energy consumption and magnetic fields. Therefore, we have to consider the more traditional electric motors such as brushless or stepper motors which have the disadvantage of being bulky.

We use the brushless motors and since we need a place to locate them on the structure, we changed our approach from a real hand exoskeleton to a test bench to be able to continue the construction of the exoskeleton.

STRUCTURE

Different aspects should be taken into account to design the structure. Overall shape of the structure is an important point that cannot be finalized before many other issues.

As the final goal of this exoskeleton is to compensate the stiffness of the EVA gloves, a possible option consists in a passive exoskeleton in which there is not any kind of external actuators. Since EVA gloves are pressurized, it is easy for the astronauts to open their fingers while the effort is needed to close them. Therefore a structure that uses some springs to apply an amount of counter-force equal to what is applied by the glove on human hand could be a choice. This is not a proper solution because in each position of the fingers, the springs apply a fixed amount of force to the phalanges regardless of the intention of the astronauts. Springs apply force to close the fingers even if the astronaut wants to open his fingers.

Hence, an active exoskeleton has been chosen; then, the force transmission method from the brushless motors to the structure has to be considered. Two alternative methods are possible: a bar mechanism or a cable one. The bar mechanism needs more space and is heavier, while the cable mechanism has the disadvantage of single direction actuation. Since EVA glove applies an opening force to the fingers, just a single direction actuation to close the fingers seems to be enough for this stage. Therefore, we chose the cable mechanism to transmit forces from brushless motors to the structure.

There are several kinds of cables or strings which can be used for this transmission. Bowden cables are one of the most popular kinds for this goal. There are also some robots that use steel wires and some others that use polymer fibers. But in order to choose the best solution the particular needs and limitations have to be considered. Due to the small dimensions in our application, a small bending radius is required. Moreover, cable elongation should be as low as possible; otherwise it will be very difficult to control the system. Furthermore, they should be strong enough to be able to handle the desired force and also thin enough to pass through the designed canals. The possibility of making knots can be also important. To reduce friction between the cable and the canals a cable with a circular cross section and a special polymer coating is preferred. Given all these constraints we decided to use a kind of coated braid line made of Gel-spun Polyethylene Microfibers. The 0.45 mm-diameter line guarantees a tension up to 620N, which is enough for the current application.

Another issue is the kinematics of the structure. Two kinds of structure can be designed according to this subject; 1- A structure that has its own kinematics and has to be compliant with the human fingers as much as possible. In this approach the structure holds the fingers. 2- Some supporting pieces which are placed on the fingers and use fingers kinematics. In this approach the fingers hold the structure. According to our research, as the center of rotation of the phalange of the fingers is not a fixed point, design of a mechanism which is definitely compliant with the human fingers is very complicated and, even if possible, the structure has to be custom made for each person who wants to use it. Therefore we decided to choose the second approach which can also be less bulky and more light weight. A comprehensive study about the kinematics of the fingers was performed and the results were used in the following steps to simulate the behavior of the exoskeleton. The details about the kinematics of the hand were published in another paper [15].

The need to perform some tests on the exoskeleton in a condition similar to its final application made us to add some springs to our structure in order to simulate the effects of EVA glove on the hand. In fact, these springs applies a counter-force similar to the EVA glove to open the structure. To specify the stiffness of the springs, we used the acquired data from our tests on the EVA glove which was explained before.

In order to be able to select suitable brushless motors, it is necessary to know the tension forces of the cables in different positions of the exoskeleton. As three brushless motors are considered for three phalanges of the index finger, three cables are needed to transmit the forces to the structure. Moreover, since the related cable of each phalange passes through holes which are located on previous phalanges, if a pulling force applies to the cables of distal or middle phalange, an other-than-zero force is also applied from the same cable to the previous phalanges. This means that the tensions of the cables cannot be calculated separately 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. To calculate the maximum tension of each cable the kinematical and dynamical equations were studied and implemented in a MATLAB routine to simulate the behavior of the exoskeleton. An optimization activity, in order to find the best position of the holes that make the cables to pass inside each body of the exoskeleton, has also been performed, through the simulation of the system with the same MATLAB code. The details of this optimization and the resulting estimation will be exposed in a future paper.

From the beginning many configurations for the test bench were proposed. Some of them did not satisfy some of the above mentioned requirements and have not been considered in the following steps (Figure 18).

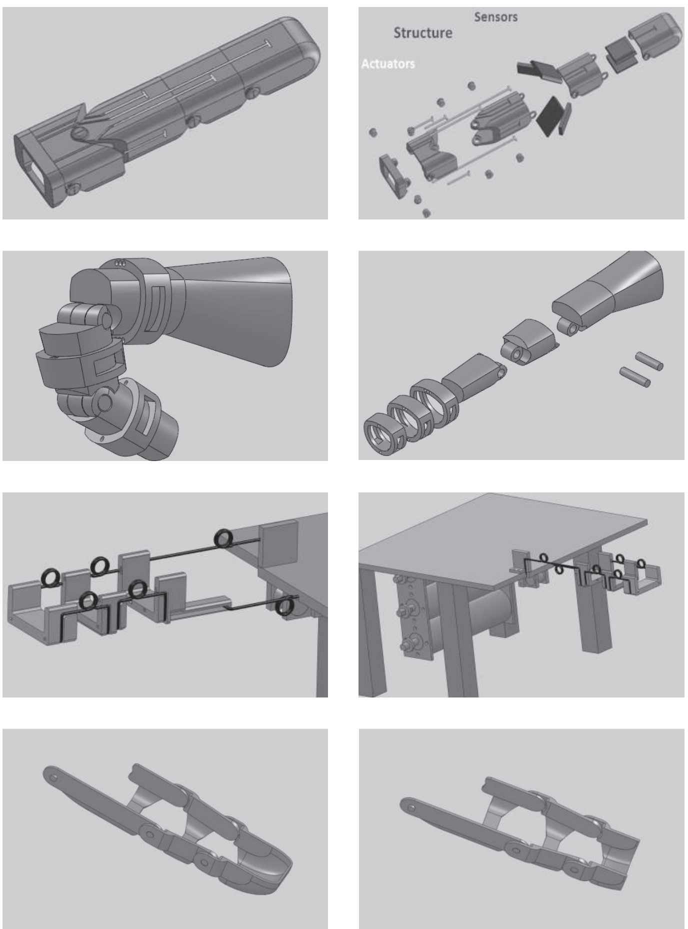


FIGURE 18- SOME OF THE PROPOSED CONFIGURATION FOR THE FIRST TEST BENCH

After considering all the above issues and many others like the required manufacturing equipments, the material of the structure, risk of any damage to the user and etc., we decided about the overall shape of the structure which can be seen in Figure 19.

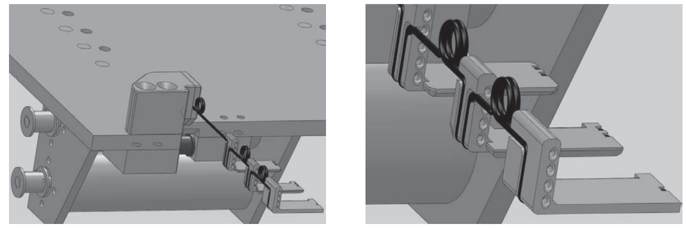


FIGURE 19- THE OVERALL SHAPE OF THE TEST BENCH

CONCLUSION

In this paper three major issues in design of a hand exoskeleton were described: sensors, actuators and structure. For each issue all the performed works were explained. Advantages and disadvantages of different kinds of sensors and actuators were evaluated and the reasons to choose a specific type of sensor or actuator were described in detail. Different possible solutions regarding the structure and the solutions for existing constraints were presented. What we have done during this research project can be used as a guideline for all other similar projects in the field of hand exoskeleton.

NOMENCLATURE

EVA (Extravehicular Activity)
DOF (Degree of Freedom)
ROM (Range of Motion)
COF (Center of Force)
EMG (Electromyography)
SMA (Shape Memory Alloy)

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