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Title:

ADAH PROJECT – EXECUTIVE SUMMARY

To be distributed to:	Frederic Didot (ESA technical officer)

Authors:	Maria Chiara Carrozza Luca Barboni Stefano Roccella Fabrizio Vecchi

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ABSTRACT

By 2025 an international human mission to Mars may be a reality. Over the next 20 years robotic missions will prepare for human missions, by collecting as much scientific data as possible without requiring human scientists missions in-situ. Robotics technologies will play an essential role in both unmanned and human exploration missions for supporting human EVA by providing intelligent cognitive and manipulative aids.

The objective of the ADAH project is to study a robotic system able to support the astronaut while he/she is performing EVA grasping and manipulation tasks, which are currently done by the astronaut wearing a space suit.

Scientific studies demonstrated that space gloves reduce basic hand grip strength, and hand performance decreases by increasing pressure differential. Compared to bare hand capabilities, there is a 30÷75% reduction in power grip and in key and palmar pinch maximal strength when gloves are donned and therefore the EVA work productivity are affected by early forearm and hand fatigue.

In order to address these problem two types of robotic systems can be exploited corresponding to two different concepts: 1) *Functional support*: A robotic system can support and even augment grasping and manipulation capabilities of the astronaut in performing EVA task. 2) *Functional replacement*: A robotic hand and a manipulator replace the astronaut hand/arm in doing the EVA tasks, and the astronaut teleoperates the artificial hand from a pressurised module.

The ADAH project studied the two system concepts intended to solve the problem of supporting/replacing astronaut's hand, by focusing the efforts on the development of an exoskeleton that can be used for supporting the space gloved hand (*Functional support*) to enhance his/her resistance to fatigue. As an alternative, a slight modified exoskeleton can be exploited as a master interface for teleoperating from a pressurized module and external artificial hand (*Functional replacement)*.

The ADAH project analysed the feasibility of different engineering solutions from the simplest, consisting in a human power extender without sensory feedback, to the more complex resulting in a master exoskeleton to provide tactile feedback to the astronaut hand.

The ADAH project conceived and analysed some feasible different scenarios corresponding to the two configurations described above. The trade off analyses of the EVA and IVA concepts defined during the ADAH project have selected two systems which are proposed to be furtherly investigated in the eventual next phase:

- carbon fibre exoskeleton "only pull";

- IVA exoskeleton with "simple"haptic feedback.

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No ESA Study Contract will be accepted unless this sheet is inserted at the beginning of each volume of the Report.

ESA CONTRACT NO:	SUBJECT:	Name of Contractor:
16224/02/NL/PA	**ASTRONAUT DEXTEROUS ARTIFICIAL HAND**	**Scuola Superiore Sant'Anna**

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Names of Authors: **M.C. Carrozza (SSSA), F. Vecchi (SSSA), S. Roccella (SSSA) and L. Barboni (SSSA)**

**NAME OF ESA STUDY MANAGER:	** ESA BUDGET HEADING	
F. Didot Div: **Mechanical Systems** Directorate: **Technical & Operational Support**		

SUMMARY

1 Introduction

1.1 Scope

By 2025 an international human mission to Mars may be a reality. Over the next 20 years robotic missions will prepare for human missions, by collecting as much scientific data as possible without requiring human scientists missions in-situ.

It is expected that robotics technologies will play an essential role in both unmanned and human exploration missions for the following functions:

- docking, berthing, assembly, inspection, maintenance and servicing of orbital and surface infrastructure;
- mobility on, beneath and above the surface of planets or moons;
- automation of scientific and technological investigations (including the deployment/positioning of instruments, the handling of tools for grinding/polishing/picking up samples, and the logistics transfer of specimen;
- automation of in-situ resource development and management (including logistics transport, excavation, mining, processing, refining, manufacturing, structure fabrication, plant cultivation and trash management around surface bases);
- support to human EVA by providing intelligent cognitive and manipulative aids.

In this work, the expertise of ARTS Lab on engineering problems solving by exploiting robotics and biomechatronics have addressed the problem of augmenting the performance and the safety of astronauts during Extra Vehicular Activities (EVA).

1.2 Objectives

The aim of this project is to study a robotic system able to support the astronaut while he/she is performing manipulation tasks, which are currently done during EVA.

In order to address this problem two types of robotic systems can be exploited corresponding to two different concepts:

1. *Functional support*: A robotic system can support and even augment grasping and manipulation capabilities of the astronaut in performing EVA task;
2. *Functional replacement*: A robotic hand and a manipulator replace the astronaut hand/arm in doing the EVA tasks, and the astronaut teleoperates the artificial hand from a pressurised module.

In this framework, the objectives of the ADAH project are:

- to identify the applicative scenarios and the reference tasks for the ADAH system;
- to define its basic requirements;
- to define some feasible concepts of the ADAH system.

1.3 Problem definition

The human hand has three main functions: grasping, manipulating and explorating. Thanks to these basic functions, the human hand is able to accomplish complex tasks offering a broad range of different and complementary capabilities like dexterity, accuracy, and tactile sensitivity. This project addresses the problems occurring when the human hand wears protective gloves, and its resulting performance is affected because hands functions are impaired.

This is a well-known problem that has attracted the attention of several research studies aimed at functional assessment of the human hand while wearing commercial gloves. Few of these studies have analysed the space gloves worn by astronauts, which affect their hand capabilities.

The first phase of the ADAH project has been devoted at analysing the state of the art of the scientific literature on the problems occurring when the hand wears the space suit glove. In this case, even very simple grasping tasks may result very difficult and exhausting, and the safety and quality of the task performed may be compromised. Starting from these evident but qualitative observations, it is possible to address the problem by identifying the specific tasks to be performed, the types of grasps involved, the finger kinematics and the muscles subject to early fatigue.

In summary the most salient findings of these studies are [1]-[5],[7]:

- Gloves reduce basic hand grip strength, and the pressure differential reduces it further; performance decreases by increasing pressure differential;
- Compared to bare hand capabilities, there is a 30÷75% reduction in power grip and in key and palmar pinch maximal strength when gloves are donned, whereas the maximal tip pinch strength results comparable to or better than the bare hand performances (approximately -10÷+20%);
- The EVA work productivity can be affected by early forearm and hand fatigue.

The fatigue is a complex, integrated phenomenon involving three domains: physiological, subjective, and performance. All three of these domains were experimentally assessed during grasping tasks in bare hand, gloved-hand, and pressurised glove conditions [2]. Tests results showed the occurrence of early electrophysiological fatigue in FDS muscle while the ECU muscle was more enduring during gloved work (one explanation for this effect is that the stiffness of the glove may act as a 'wrist-splint' replacing the need for the ECU to support the wrist). During power grasp tasks, the fatigue sensation occurs after 50÷925 sec. compromising the execution of the work [6].

A synthesis of the state of the art analysis is reported in the Technical Note ADAH-TN-SSSA-01 (Technological assessment of the ADAH concepts).

1.4 Applicative scenarios and configurations of the ADAH system

The first statement of the ADAH project is that a robotic system can solve the problem in two ways: the first is based on functional replacement of the astronaut hand with an artificial hand teleoperated by him/her by an appropriate interface (exoskeleton), and the second is based on functional enhancement i.e. a robotic exoskeleton (worn by the astronaut) can amplify the force exerted by the gloved hand.

These solutions correspond to two possible scenarios which have been analysed and compared:

EVA scenario – The objective is the functional augmentation of EVA grasp capability (less fatigue during EVA and more power grasps).

The system is composed of:

1) the astronaut hand;

2) the space suit glove;

3) an exoskeleton inside or outside the glove.

The exoskeleton should enhance the grasping force without limiting the astronaut dexterity.

IVA scenario – The objective is the functional enhancement of astronaut EVA by means of the teleoperation of a manipulator with an appropriate end effector.

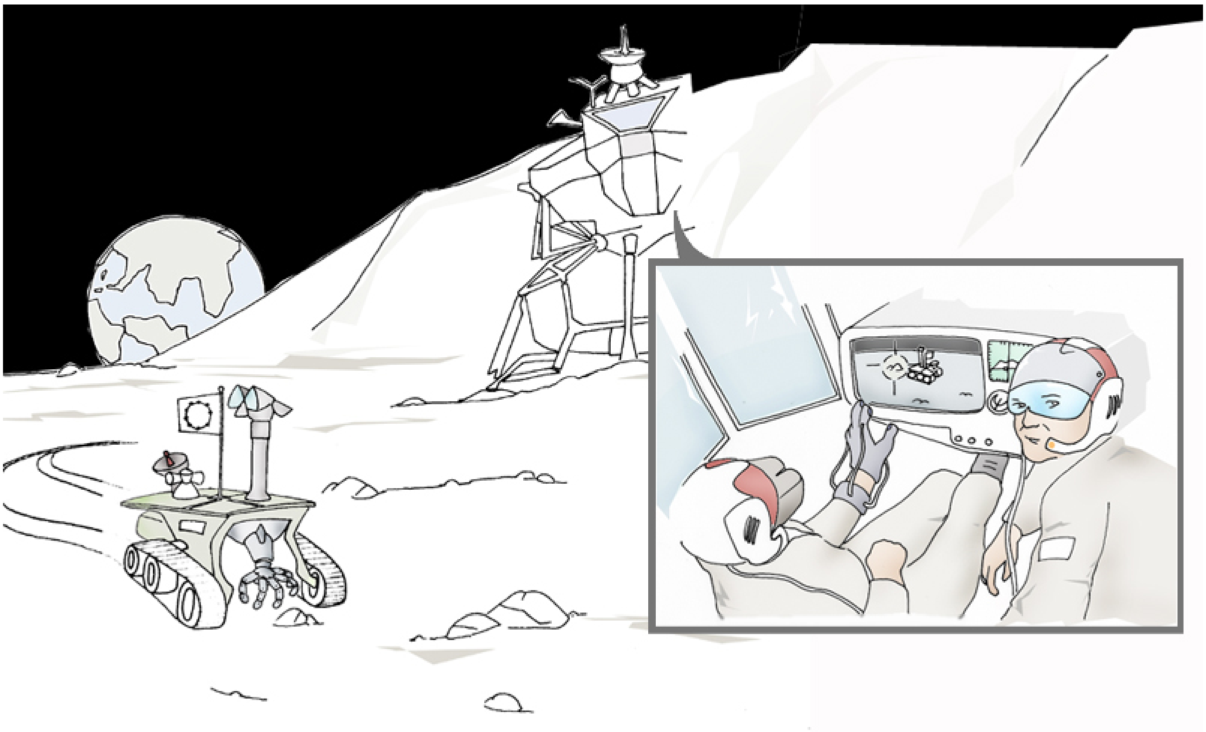

Figure 1: Conceptual scheme of the master-slave system for EVA. The advanced robotic hand is performing exploration missions. The astronaut teleoperates the exploration task by means of a specific human/machine interface.

This application is promising in order to:

1) allow the crew to perform very dexterous activities using a robotic system at no risk (i.e., maintenance and repair activities outside the pressurised module);

2) provide a good tactile feedback of rocks characteristics without direct manipulation/contamination risk;

3) reduce risk for Mars "contamination" by avoiding EVA sorties;

4) support of the crew fit during long journey providing several physical training programs.

The system is composed of:

1) the astronaut hand (inside the pressurised module);

2) the Human Machine Interface (the master device that is the interface for the human operator);

3) a manipulator (the slave device).

The feasibility study did not consider the artificial hand and manipulator concepts. The attention has been focused on the Human/Machine Interface.

1.5 State of the art

The second phase of the ADAH project analysed the state of the art of robotic systems intended to solve the problem by pursuing the EVA approach (functional enhancement) or the IVA approach (functional replacement). In this section the main results of state of the art analysis are summarised (See Technical Note ADAH-TN-SSSA-01 for a complete report).

1.5.1 POWERED EXOSKELETONS FOR SPACE APPLICATIONS

1.5.1.1 Powered (Space) glove

The University of Maryland Space Systems Laboratory together with the space suit manufacturer ILC Dover, Inc. have developed a unique, self-contained "power-assist" actuation system which facilitates gloved motion of the major hand joint, the metacarpophalangeal (see Figure 2). The new actuator sits unobtrusively on the dorsal side of the glove, and provides torque to counterbalance those induced by the pressurized glove, enabling near "nude-body" hand mobility with reduced arm fatigue [8].

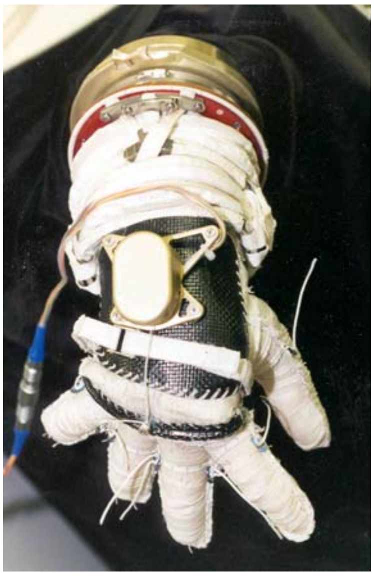

Figure 2: Power glove.

1.5.1.2 Actuator for flexing a resilient covering

This system provides a power assisted actuator assembly for flexing restraints in response to movement of an underlying member or a controller [10]. The actuator assembly comprises part of a glove, such as the 3000 series glove used astronauts during an EVA (see Figure 3 and Figure 4). The actuator control is preferably provided by a sensor positioned to detect movement of the human joint inside the glove being actuated.

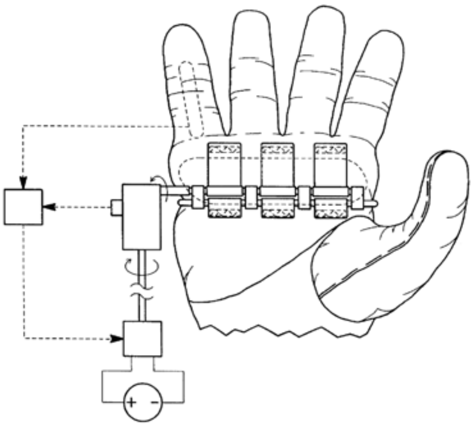

Figure 3: partial schematic front view of a retracting panel actuator.

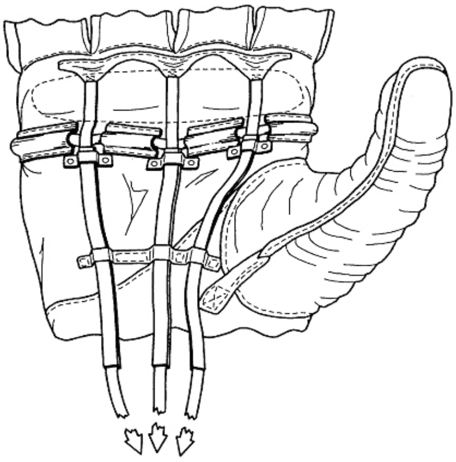

Figure 4: alternative retracting panel actuator using a cord sheath assembly.

1.5.1.3 SkilMate finger for EVA gloves

Yamada et al proposed a SkilMate Hand for space EVA gloves which has both a tactile media and a power assist devices [11]. It is a power assist device which compensates the bending moment exerted at a human finger joint utilizing an ultrasonic motor (see Figure 5). They also propose to introduce a tactile media device which is composed of a slip sensor element on the outer side and a vibrotactile display element on the inner side of a skilMate Hand.

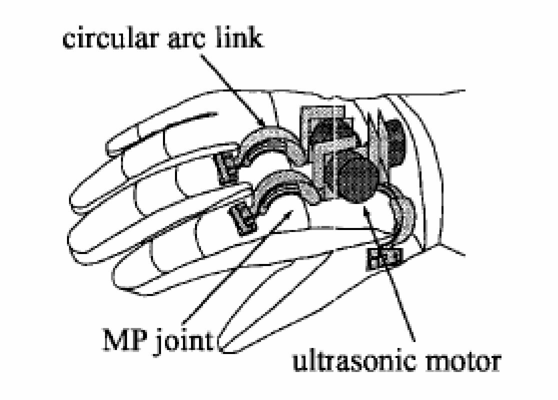

Figure 5: structure of the power assist device.

1.5.1.4 Anthropomorphic hand exoskeleton

A three-fingered exoskeleton prototype is described in [9]. The three-fingered design allows independent movement of the index finger and middle finger, and combines the ring and little finger. Each exoskeleton finger reproduces the movement of the wearers' metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joint (see Figure 6). A separate drive and sensor system is used for each finger so that they may operate independently. The fingers are enclosed in the exoskeleton by semicircular brackets that are mounted on the exoskeleton fingers.

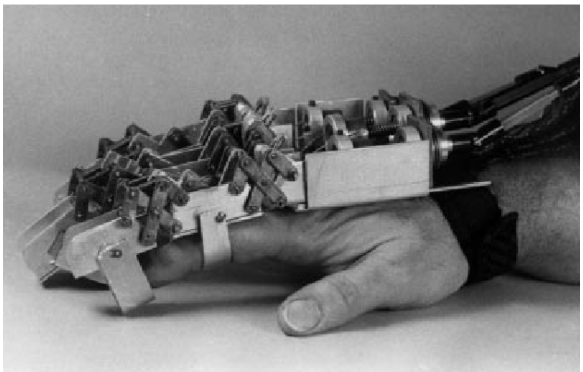

Figure 6: Anthropomorphic hand exoskeleton

1.5.2 HAPTIC INTERFACES FOR TELEOPERATION

Several haptic interfaces for teleoperation have been developed [12]. They use pneumatic micro-cylinders to provide force feedback to the operator [13], or use parallel-link mechanisms spanning the length of each finger to sense the finger position and to provide force feedback [14],[16], or use resistive bend sensors to measure the deflection of each finger and small vibrotactile stimulators on each finger and the palm to provide tactile feedback [15]. The analysed haptic interfaces for teleoperation are quite cumbersome to put on and take off and requires some adjustment to fit the hand properly. Although their light-weight, they are not very stable on the hand when the whole hand is shaken or moved rapidly. Finally, they have not been designed for space applications.

1.5.3 ROBOTIC HAND FOR SPACE APPLICATIONS

Several artificial hands have been developed for space and other applications. The analysis of the state of the art has demonstrated that at present robotic hands are far to reproduce the same capabilities of the human hand, but recently robotic hands technology is evolving fastly showing promising results.

1.5.3.1 Laval hands

Several underactuated hands have been proposed by researchers for solving the problem of hand adaptability [19],[20]. Among them the Laval hand is one of the most advanced, it is a 10-DOF hand showed in Figure 7 [17],[18]. It is actuated only by two externally mounted DC motors. The driving is achieved through a complex differential gear mechanism. The 10-DOF robotic hand is constructed in collaboration with the Canadian Space Agency. Its design is covered by a pending US patent as well as a European patent. The current version is adapted as an end-effector to the SPDM of the Canadian Space Arm (Canadarm, a.k.a. SSRMS/SPDM) for the International Space Station.

Figure 7: the new version of the underactuated 10-DOF Laval Robotic Hand.

1.5.3.2 Robonaut hand

The Robonaut is one of the first hand under development for space EVA use characterised by the size and capability close to a suited astronaut's hand [21]-[24]. The Robonaut Hand is showed in Figure 8 and it has a total of 14 degrees of freedom. It consists of: a forearm which houses the motors and drive electronics; a two degree of freedom wrist; a five finger, twelve degree of freedom hand. Overall the hand is equipped with forty-three sensors not including tactile sensing. Each joint is equipped with embedded absolute position sensors and each motor is equipped with incremental encoders.

The hand itself is broken down into two sections:

- a dexterous work set which is used for manipulation;
- a grasping set which allows the hand to maintain a stable grasp while manipulating or actuating a given object.

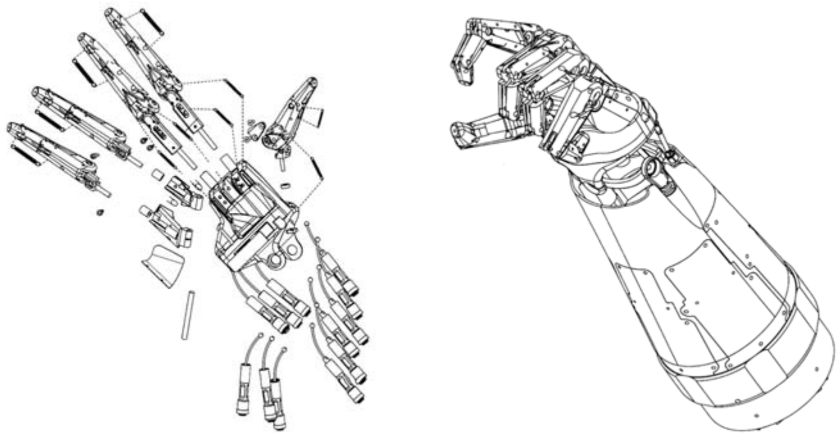

Figure 8: Robonaut hand.

1.5.3.3 DLR II hand

The main design goals of the DLR hand are the maximum performance to improve autonomous grasping and to introduce also some fine manipulation possibilities. Another important characteristic is that the actuators and electronics are all integrated on board (see Figure 9). For this reason the size of DLR hand is approaching the size of a human hand (approximately 1.5 times). The fingers and base joints of Hand II have been developed as an open skeleton structure. The main target developing Hand II has been the improvement of the grasping performance in case of power- and precision-grasps. The three independent joints of each finger are equipped with appropriate brushless dc-motors actuators. The actuation system in the medial joint is designed to meet the conditions in the base joint when the finger is in stretched position and can apply a force of up to 30 N on the fingertip. Each joint is equipped with strain gauges based joint torque sensors and specially designed potentiometers based on conductive plastic. Moreover each finger integrates 6 temperature sensors [25],[26] are fundamental to outline and compare hand performance and characteristics.

Figure 9: DLR II hand.

1.5.3.4 Comparative analysis

The following table reports a summary of the most critical parameters of the artificial hands reported in the robotics literature. It is very difficult to compare different design and technologies, and according to the authors experience and knowledge the parameters reported are most useful to outline hand performance and characteristics.

HANDS	n° fingers	Size Hand/Human Hand	DOF	n° actuators	weight [Kg]	force [N]
Human hand	5	1	22	38 ext+int	about 0,4	>300
Salisbury hand	3	1,2+control	9	12 ext	1,1 (+5,5drive assembly)	44
Utah/MIT hand	4	2+control	16	32 ext		31
DIST hand	4	1,5+control	16	20 ext	1	
Sugiuchi hand	5		17			
Anthrobot hand	5	1+control	20	16 ext	4,5	
SDSU hand	5	1+control	15	6 ext	2	15 (finger tip)
NTU hand	5		17	int	1,57	
Shadow hand	4	1,2+control	21	ext	between 5 and 10	
BUAA hand	4	1+control	16	int	1,4	
Goldfinger hand	4	1,5+control	12	est	2,27	
BarrettHand	3	1,2	8	4 int	1,18	20 (finger tip)
Laval hands 1	3	2	12	6 ext	9	687
Laval hands 2	3	1,5	10	2 ext		
DLP Mechanical Prehensor	3	1	8	0		
Gifu hand II	5	1,5+control	20	16 int		4,9
Robonaut hand	5	1,2+control	12 (+2wrist)	12 (+2) ext		
DLR II hand	4	1,5+control	13	13 int		30 (finger tip)
RTR II hand	3	1	9	2 int	0,32	16

2 Materials and Methods

2.1 Identification of the system requirements

In the following some specific requirements for the ADAH system are deduced from a critical analysis of the EVA tasks to be performed:

- **Analysis of the grasps performed during EVA tasks.** The number of occurrences for a type of grasp i.e. how often each grasp is used (i.e. how many CATs and interface use that specific grasp) is fundamental for addressing a specific system design [28]. From the summary shown in Figure 10 , it turns out that most (53%) of the grasps are cylindrical. Cylindrical grasps are divided in large diameter, small diameter and medium wrap.

Category	Occurences	% of Tools
Basic Grasp		
Power	71	29%
Precision	92	38%
Precision/Power	79	33%
Specific Grasp		
1-finger	61	25%
2-finger	92	38%
3-finger	2	1%
4-finger	1	< 1%
Adducted thumb	17	7%
Disk (Power)	17	7%
Disk (Precision)	13	5%
Large diameter	14	6%
Lateral pinch	24	10%
Light tool	25	10%
Medium wrap	49	20%
Small diameter	64	26%
Sphere (Power)	1	< 1%
Sphere (Precision)	1	< 1%

Figure 10: occurrences for type of grasps during EVA [28].

- **Analysis of grip strength during EVA.** Compared to bare hand capabilities, there is a 30÷75% reduction in power grip and in key and palmar pinch maximal strength where gloves are donned. The maximal tip pinch strength results comparable to or better than the bare hand performances (approximately -10÷+20%).
- **Occurrence of early electrophysiological fatigue**. The results showed the presence of early electrophysiological fatigue in FDS muscle during cylindrical grasps.
- **Requirements for the ADAH systems:** The EVA configuration has to enhance grasping capabilities of the astronaut without affecting his/her dexterity in reaching the object to manipulate. The configuration IVA has to enable the exchange of sensory-motor information between the astronaut hand and the external end-effector. Tactile feedback and exteroceptive sensing ability can enhance the quality and effectiveness of the teleoperation task.

According to the requirements summarised above, the feasibility of an exoskeleton to be worn inside the space suit glove, or outside (if compatible with the task and the working space) has been investigated. The exoskeleton should support and help the astronaut during the EVA, enhancing his/her resistance to fatigue. The ADAH project should consider the feasibility of different solutions from the simplest consisting in a human power extender without sensory feedback, to the more complex consisting in an exoskeleton providing tactile feedback.

The Human/Machine Interface of the IVA scenario can be an exoskeleton similar to that studied in EVA scenario. The differences are that the EVA exoskeleton is mainly a force amplifier while the IVA exoskeleton is mainly an haptic interface integrating cognitive force feedback.

We have conceived some feasible different scenarios corresponding to the two configurations described above. **The trade off analyses of the EVA and IVA concepts defined during the ADAH project have selected two systems which are proposed to be furtherly investigated in the next phase:**

1) **EVA carbon fibre exoskeleton "only pull";**
2) **IVA exoskeleton with "simple" haptic feedback.**

2.2 EVA carbon fibre exoskeleton "only pull"

According to experimental results, force reduction and early fatigue affect flexion movements of all the fingers while thumb performance are not reduced [2],[7]. Therefore the power extensor concepts is focused on the function of supporting fingers flexion without acting on the thumb.

This version of the ADAH system exploits a flexible and lightweight mechanical structure made of carbon fibres that is flexed by pulling tendons running along the internal part of the fingers. The fingers joints are compliant joints without moving parts and they can be made by appropriately machining a flexible hinge. In particular, the joints corresponding to the hand MP joints are purposely made for facilitating fingers movements without impairing their adduction/abduction. The exoskeleton is intended to be worn externally to the space suit glove as shown in the schematic drawing in Figure 11.

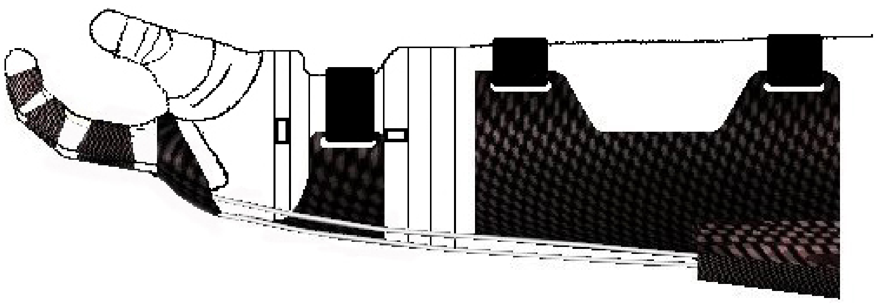

Figure 11: ADAH exoskeleton "only pull" worn by astronaut

The Figure 12 shows a slightly different version of the exoskeleton where the cables are collected inside only one larger Bowden cable running from the forearm to the palm. The four conducts where the cables run from the dorsal to the palm volar side are shown.

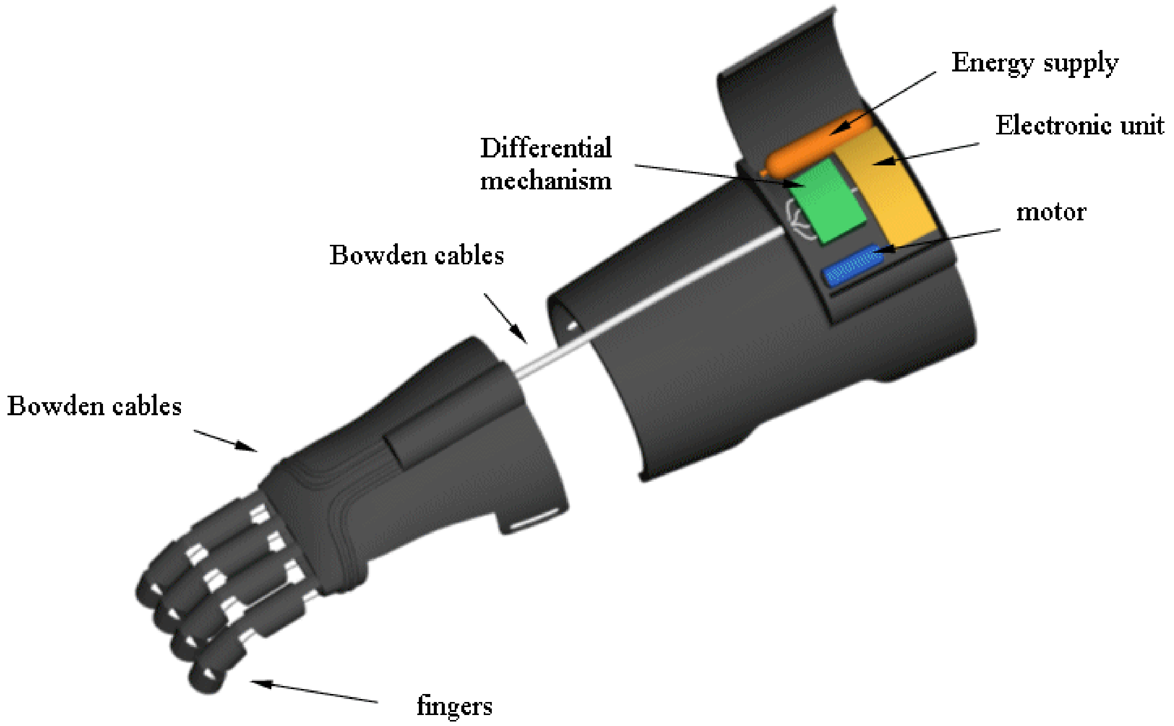

Figure 12: *ADAH exoskeleton "only pull"* with a single Bowden cable.

The exoskeleton only "covers" four fingers made of carbon fibres composite material. Each finger is composed of a tubular structure with flexible joints which are located in the dorsal part of the structure. A cable runs in a conduit along the volar side of the phalanges and it is fixed to the distal phalange. The cable acts like the human tendon: the cable pulling acts on finger flexion. The Figure 13 shows a 3D model of the finger (note that the fingertip of the ADAH exoskeleton will be machined in order to allow the direct contact of the space suit glove fingertip with the objects).

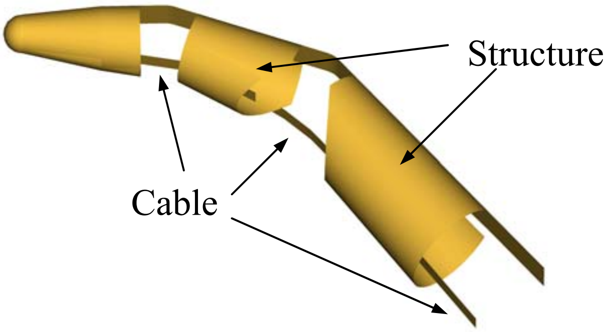

Figure 13: View of the structure model of the finger exoskeleton (Pro Engineer 2000i).

A preliminary FEM analysis (ANSYS 5.6) of the finger has been carried out (see Figure 14), by simulating an external load of 10 N applied on the fingertip; the analysis has shown that the composite material with carbon fibres can be used for the prototype implementation.

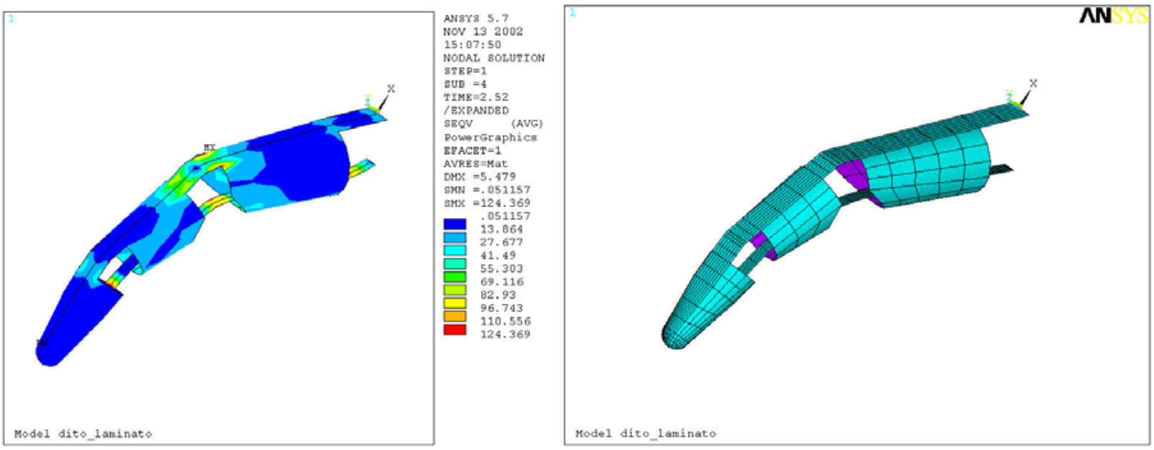

Figure 14: FEM Analysis of the finger structure (ANSYS 5.6).

A simple finger prototype has been fabricated in order to test the manufacturing process (see Figure 15) and the operability of the exoskeleton in terms of movements impairments and force required for flexing the fingers (see Figure 16).

Figure 15: finger prototype before and after the cuts.

Figure 16: finger prototype worn by a human hand.

As an alternative for finger structure, every finger exoskeletons can be replaced by three rings, one for every phalange. The idea is to fix three rings on each finger (see Figure 17), one for phalange, and to use a cable linked to the distal tip ring to close the hand. The cable passes inside a hole in the volar part of the rings and acts as the human tendon of the fingers flexion muscles. As for the previous concept, the finger extension is helped by the effect of the pressured space suit glove. It is not necessary to build a set of finger structures because only one size of "adaptable ring" is sufficient to personalise the structure according to the space suit glove sizes and. Finally, the rings maximise the contact surface between the space suit glove and the object

The cables used to flex the fingers are connected to the differential system and they are passed trough the rings of the fingers (in specific small channels), and they are fixed to the distal ring. Figure 17 shows two 3D models (Pro Engineer 2000i) of finger exoskeleton with rings, one using belt and one using steel cable, and the position of the rings on the phalanges.

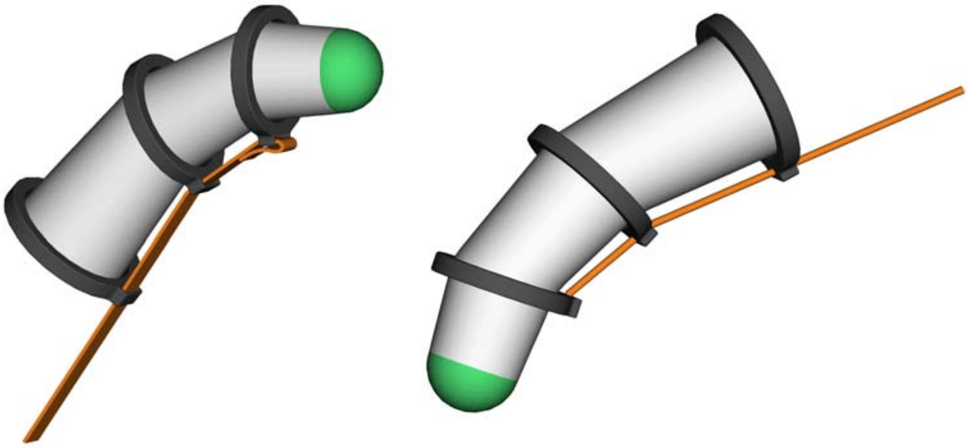

Figure 17: Views of the finger exoskeleton based on rings (Pro Engineer 2000i)

2.2.1 ACTUATION SYSTEM

The fingers flexion can be actuated by four actuators, one for each cable. This solution requires enough space in the forearm for linear motors housings. The simplest solution can exploit only one actuator which acts simultaneously on four fingers. In order to obtain an adaptive flexion with only one actuator it is possible to exploit an underactuated system that is based on a differential mechanism as illustrated in the following section. The differential mechanism provides an adaptive grasps but it requires an actuator with a longer stroke that can be obtained by means of an **electric DC motor** with suitable gears reduction. In summary, a possible solution is an actuators system composed of one single DC motor, a gear reduction and a specific differential system in order to obtain an underactuated mechanism (twelve degrees of freedom actuated by one motor) characterised by an high grasping adaptability and a simple control interface.

It is also possible to exploit a different actuator principle, as for example **pneumatic** pistons. In this case a pressure tank must be used to actuate a limited number of grasp cycles. Once finished, a new tank should be used.

A trade off among different motor solutions has been done. The result is that the pneumatic solution is not the ideal solution essentially for its following drawbacks:

- difficult to control;
- low energy storage capacity;
- difficult to replace the pressure tank;
- the performance decreases after some working cycles;
- more cumbersome than the electric actuation.

2.2.2 CONTROL SYSTEM

Two control strategies has been identified:

1. Control strategy #1

   In this case, a completely automatic solution has been envisaged. The ADAH system will be automatically switched on and off after appropriate time intervals.

2. Control strategy #2

   In this case, the control system can be divided into two separate modules:

(1) the High Level Controller (HLC) which has to identify the task (i.e., grasping or releasing tasks) that the astronaut is willing to carry out and how he/she would like to do that (i.e., which level of force must be produced);

(2) the Low Level Controller (LLC) which has to actuate the different "artificial muscles" in order to achieve the selected movement.

Two main different control strategies for the implementation of the HLC can be envisaged:

(a) processing of the kinematic information recorded from wrist and hand joints - short-term solution (this approach is based on the consideration that during grasping the extension and the flexion of the wrist are correlated to the closing and opening of the hand, respectively. For this reason a sensor on the wrist can allow the implementation of this natural control strategy);

(b) processing of the information coming from physiological signals (EMG or EEG) – long-term solution (The information extracted from physiological signals such as electromyographic (EMG) or electroencephalographic (EEG) signals can be used to obtain the information to implement the HLC).

2.2.3 Reliability and Safety

The exoskeleton works in contact with the external side of the space suit glove, wrist and forearm. It is important to limit the friction between parts in contact. Simple cables or belts must be covered with ducts of appropriate low friction material, and the palm and the forearm must be firmly fixed to the suit glove and forearm by means of Velcro belt. Moreover, the exoskeleton design must avoid sharp edges. The resin used in the composite material avoids the contact between the carbon fibres and the space suit.

In case of breaking of the:

- **actuation** or **transmission** system:
    1. the clutch mechanism can be used to disconnect the actuation system in order to give to the astronaut the possibility to finish the mission without the help of the exoskeleton. In this eventuality, the resistance of the exoskeleton has been estimated very small because it is limited to the resistance of the fingers joints;
    2. a better solution is to put a redundant actuation and transmission system in order to increase system success;
- **structural** system: the exoskeleton does not keep its whole functionality, but the astronaut can finish the mission with a reduced help or without the help of the exoskeleton.

2.3 IVA exoskeleton with "simple" haptic feedback

It is assumed that a dexterous, multi d.o.f., sensorised artificial hand is available.

The haptic feedback is a combination of tactile feedback and force feedback [29]:

Tactile feedback: sensation applied to the skin, typically in response to contact or other actions in a virtual word (e.g., initial contact, object fine geometry, surface rugosity and temperature, and slippage).Tactile feedback can be used to produce a symbol, like Braille, or simply a sensation that indicates some conditions.

Force feedback: sensation of weight or resistance in a virtual world. Force feedback requires a device which produces a force on the body equivalent (or scaled) to that of a real object.

The exoskeletons will be worn by the nude arm of the astronaut inside the pressurised module (see Figure 16).

In order to limit the movements impairment generated by the donned exoskeleton, its structure must be light and slim, and the actuators and the processing electronics must be located as proximally as possible.

The exoskeleton must establish a sensory-motor correspondence with the artificial hand that is supposed to be anthropomorphic with five fingers. As a consequence the exoskeleton must include a structure for the thumb and thus the ADAH IVA concepts have a thumb exoskeleton that allows its flexion/extension and adduction/abduction movements (see Figure 18). Moreover, the exoskeleton joints should not impair the natural adduction/abduction movements of the fingers.

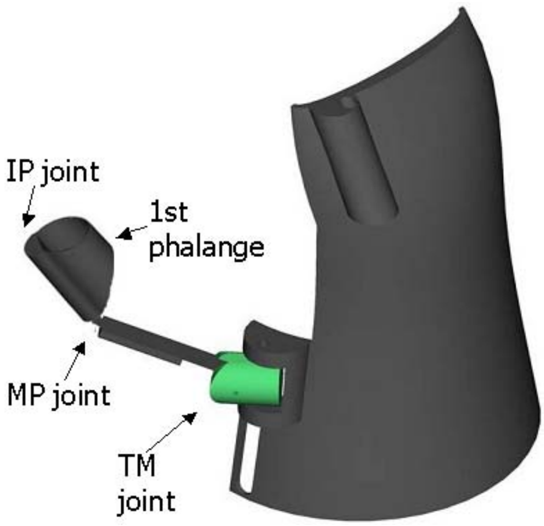

Figure 18: exoskeleton palm with thumb

The other parts of the exoskeleton structure (fingers, palm and forearm) are similar to those of the EVA exoskeleton "only push" where the screws and lead screws are replaced by a specific joint angle sensor. Nine linear position sensors will be located at the exoskeleton dorsal part in order to measure:

- four MP angular displacements (index, middle, ring, little);
- four PIP angular displacements (index, middle, ring, little);
- one IP angular displacements (thumb).

An additional couple of joint angle sensors will be integrated in the TM joint in order to measure:

- the thumb adduction/abduction;
- the thumb opposition.

The nine pistons of the joint angle sensors are connected to nine tendons which are pull by nine DC motors (see Figure 19).

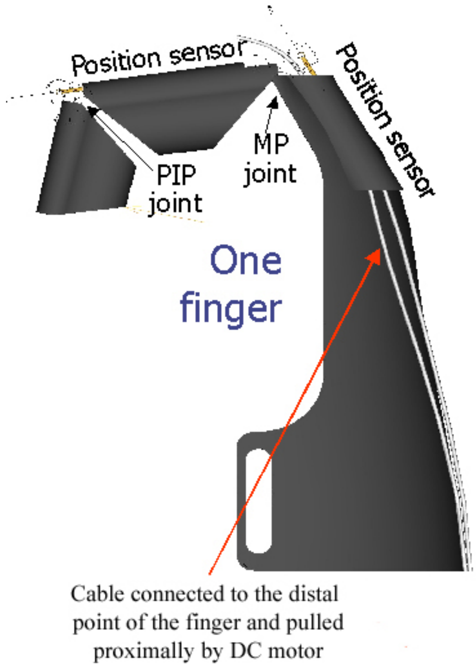

Figure 19: Schematic view of the IVA exoskeleton showing the cables providing a "simple" haptic feedback

The **Tactile feedback** is obtained as follow:

- Tactile sensors located on the end effector detect the contact;
- The corresponding tendon is actuated;
- The operator feels the change of resistance as the resistance of the rigid object contacted.

The **Force feedback** is obtained as follow:

- The tension of the exoskeleton cables is proportional to the forces detected by the end-effector;
- The operator feels a resistance opposing to fingers flexion.

The human senses tactile and proprioceptive stimuli much faster than he/she can respond to them. In other words, the input (or sensing) bandwidth is much larger than output (or control) bandwidth [30]. The output loop, which corresponds to the ability of the hand and fingers to exert forces, has a 5 to 10 Hz bandwidth. By comparison, the proprioceptive sensing has a bandwidth of 20 to 30 Hz, and tactile sensing has 0 to 400 Hz bandwidth. In order to obtain a stable teleoperated grasp, the expected bandwidth of the force feedback of the IVA concepts is of 20 to 30 Hz (according to studies performed by Howe and Kontarinis [31], a force feedback bandwidth of 8 Hz is sufficient) and the expected control bandwidth is of 5 to 10 Hz. **The resulting max time delay of the system (the time between the detection of the forces on the object and the modification of the slave configuration) is of 325 msec.**

2.4 Adaptability to different hand morphology and size

The exoskeleton must be worn by astronaut with different hand size and it is important that:

1. it is necessary to build a set of fingers for fitting different fingers/hands size because the exoskeleton finger hinges must accurately correspond to the Astronaut's finger joint;

2. the exoskeleton palm can be built according to the 4 standard sizes of the space suit gloves which can be selected in accordance with the Astronaut's palm circumference and length;
3. concerning the exoskeleton forearm, a unique size should be sufficient for every suit size.

In any case, the 3D virtual model of the astronaut hand (for example obtained by means of a 3D laser scanner) is sufficient to manufacture a personalised exoskeleton structure in carbon fibre composite material.

2.5 List of materials

A possible first selection of materials is given in the following table:

Type & Usage	Commercial identification	Chemical nature	Example of available manufacturer
Aluminium	Al 7075 T73	Al, Zn 5.6%, Mg 2.5%, Cu 1.6%, Cr 0.3%	ALCOA
Steel (springs)	AISI 302	Fe, C 0.07%, Cr 18%, Ni 8%	Trafilerie Brambilla
Steel (general structural parts, cables, …)	AISI 316	C 0.08%, Cr 16-18%, Ni 10-14%, Mo 2-3%, Si 1%, Mn 2%, P 0.045%, S 0.03%	
Epoxy-carbon fibre	AS4C193PW 8552 (CF)	Carbon fibre with epoxy resin	HEXCEL (HERCULES)
Plastic Bearings	Vespel SP3	Polymide plus MoS_2	DUPONT
General Plastic Parts	ULTEM		
Teflon Tapes	Teflon ®		DUPONT
Kevlar tapes	Kevlar ®		DUPONT

Table 1: First selection of materials for use in space applications

Concerning the actuators, particular attention should be paid to the rotating DC motors: brushless motors are preferable, even if also other types could be used after a positive design evaluation on the aspects related with the use of brushes (materials, EMC, …).

Moreover, lubricant shall be of dry type to avoid problems with vacuum.

3 Conclusions

The objective of the ADAH project was to study a robotic system able to support the astronaut while he/she is performing EVA grasping and manipulation tasks, which are currently done by the astronaut wearing a space suit.

The analysis of the scientific literature demonstrated that space gloves reduce basic hand grip strength, and hand performance decreases by increasing pressure differential. Compared to bare hand capabilities, there is a 30¸75% reduction in power grip and in key and palmar pinch maximal strength when gloves are donned and therefore the EVA work productivity are affected by early forearm and hand fatigue.

Two types of robotic systems have been investigated in order to solve the problem:

1) Functional support: A robotic system to support and to augment grasping and manipulation capabilities of the astronaut in performing EVA task.

2) Functional replacement: A robotic hand and a manipulator which replace the astronaut hand/arm in doing the EVA tasks. The astronaut teleoperates the artificial hand from a pressurised module.

The ADAH project studied the two system concepts intended to solve the problem of supporting/replacing astronaut's hand, by focusing the efforts on the development of an exoskeleton that can be used for supporting the space gloved hand (Functional support) by enhancing his/her resistance to fatigue. As an alternative a slight modified exoskeleton can be exploited for teleoperating from a pressurized module and external artificial hand (Functional replacement).

The ADAH project analysed the feasibility of different engineering solutions from the simplest consisting in a human power extender without sensory feedback, to the more complex consisting in a master exoskeleton providing tactile feedback to the astronaut hand.

The ADAH project conceived and analysed some different feasible systems corresponding to the two configurations described above.

The architecture of the two systems have been studied according to a biomechatronic approach aimed at developing a system really usable and useful for the astronaut hand. The different system modules have been studied and engineering solutions for the mechanical structure, actuator system, transmission mechanism and sensors have been proposed, according to the system requirements identified in the first part of the project.

Finally, the trade off analysis of the EVA and IVA concepts have selected two systems which are proposed to be further investigated in the eventual next phase:

- EVA carbon fibre exoskeleton "only pull";
- IVA exoskeleton with "simple" haptic feedback.

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