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Development of a Space Suit Soft Upper Torso Mobility/Sizing Actuation System

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ABSTRACT

ILC Dover Inc. was awarded a three-year NRA grant for the development of innovative spacesuit pressure garment technology that will enable safer, more reliable, and effective manned exploration of the space frontier.

Figure 1: Spacesuit Hammering Motion (NASA Artist Concept)

The research is focusing on the development of a high performance mobility/sizing actuation system. This technology has application in two areas (1) a spacesuit soft upper torso (SUT) pressure garment for joint interface geometry repositioning to improve specific joint motion, hammering (Figure 1) vs. hand over hand translation (Figure 2), etc., and (2) as a suit sizing mechanism to allow easier suit entry and more accurate suit fit with few torso sizes than the existing EMU. This advanced soft upper torso will support NASA's Advanced EMU Evolutionary Concept of a two-size fit all upper torso for replacement of the current EMU hard upper torso (HUT). A diagram of the proposed project plan is shown in Figure 3.

The research began with a system requirement analysis to identify and categorize actuation system requirements for a multitude of applications (International Space Station, Mars, etc.). An actuation study has also been conducted to identify potential actuators that provide acceptable force and response times, and have limited power requirements. Methods for force multiplication will be researched for application to improve actuation range of motion with reduced power consumption. The actuators will be used to position the SUT shoulder joint interface angles in a designated location and remain there until task completion. The joint interface will then be held in this position until it is again activated. The control mechanism will also be modeled and developed. Attention will be given to developing a fail-safe design that provides redundant function in the event of a loss of power or function.

The SUT development will include the creation of an algorithm for the conversion of scan or manual human anthropometric data into optimal SUT shape including optimal interface ring positions. The SUT will incorporate the mobility/sizing actuation technology in the form of a system of rapidly sizable structural tendons and softgoods that govern interface angles and allow for compact packaging of the upper torso.

Figure 2: Spacesuit Hand Over Hand

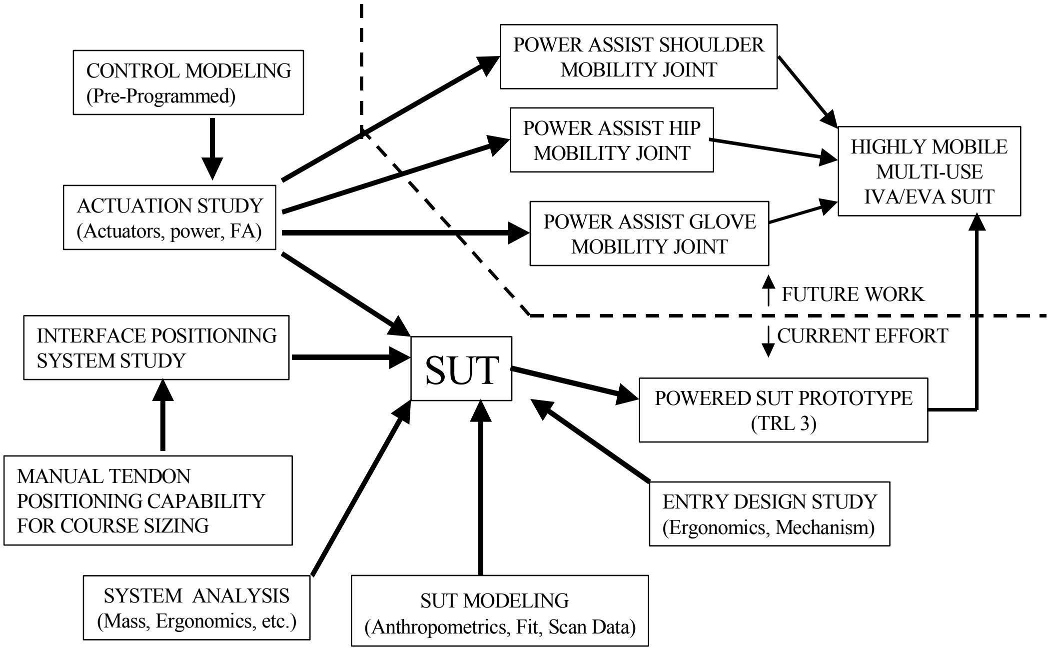


Figure 3: Project Plan Summary

INTRODUCTION

The current Shuttle Extravehicular Mobility Unit (EMU) hard upper torso (HUT) has performed well since its first use in 1980 but it is heavy, uncomfortable, costly, and fits a limited crew population due to the system being limited to three sizes. The original EMU upper torso design (Pivoted HUT) included soft bellows in the scye openings which were required to facilitate donning and doffing while providing acceptable scye positions once pressurized in the suit. The bellows had a limited life and therefore the design was changed in 1990 in favor of fixed scye plane openings (Planar HUT) (Figure 4). In order to facilitate donning and doffing, the scye diameter and angles had to be altered. This resulted in a HUT design with reduced mobility because the scye planes are not positioned in the optimum locations for performing work once pressurized in the suit.

The current upper torso system is also extremely costly due to its labor intensive fabrication process. The manufacturing and support cost limits the current EMU system to only three sizes of HUT that reduces user fit and therefore task efficiency, and in some cases excludes population from service. Previous research has shown that the minimum number of HUTs required to properly fit the astronaut population is 4, and 5 or more sizes are desirable. Further system inefficiencies are observed with the current EMU HUT regarding mass, stowage volume and relationships to launch cost.

A soft upper torso (SUT) system provides many benefits over a hard upper torso (HUT). These benefits include lower mass, smaller packing volume, and lower manufacturing and maintenance cost. Another benefit is that it provides the inherent ability to change the shape of the SUT while the spacesuit is pressurized, given an appropriate actuation and control system. A breakthrough technology is required to provide an upper torso design that will fit a broader range of anthropometric sizes as well as provide a means for adjusting critical features of the upper torso in real time to allow the crewmember to demonstrate greater task efficiency with less fatigue. The mobility/sizing actuation system will be integrated into a soft upper torso pressure garment providing a dramatic leap in crewmember performance and comfort.

Figure 4: EMU Planar HUT

This paper will focus on the research performed to date. This research includes the system requirement study, actuation study, electronic textile control study, SUT Modeling, prototype development and testing, and a SUT sizing analysis.

REQUIREMENTS STUDY

The development of a high performance mobility sizing and actuation system requires a comprehensive system analysis to identify key system needs and interface requirements. The development of system requirements will continue through the duration of this research. At this time, a limited number of requirements have been defined allow the development of system concepts and provide a basis for initial SUT mockup testing.

Suit operating pressure is one of the most important system requirements because is affects all aspects of the design. This requirement defines the structural loads that the upper torso will experience. The loads in turn will have a significant effect on the upper torso material selection and actuator force requirements. The suit operating pressure was chosen to be 4.3 psid. This is the operating pressure for the current Shuttle EMU and will therefore provide a basis for spacesuit performance comparison at a later point in this research.

Other higher order system requirements are listed below.

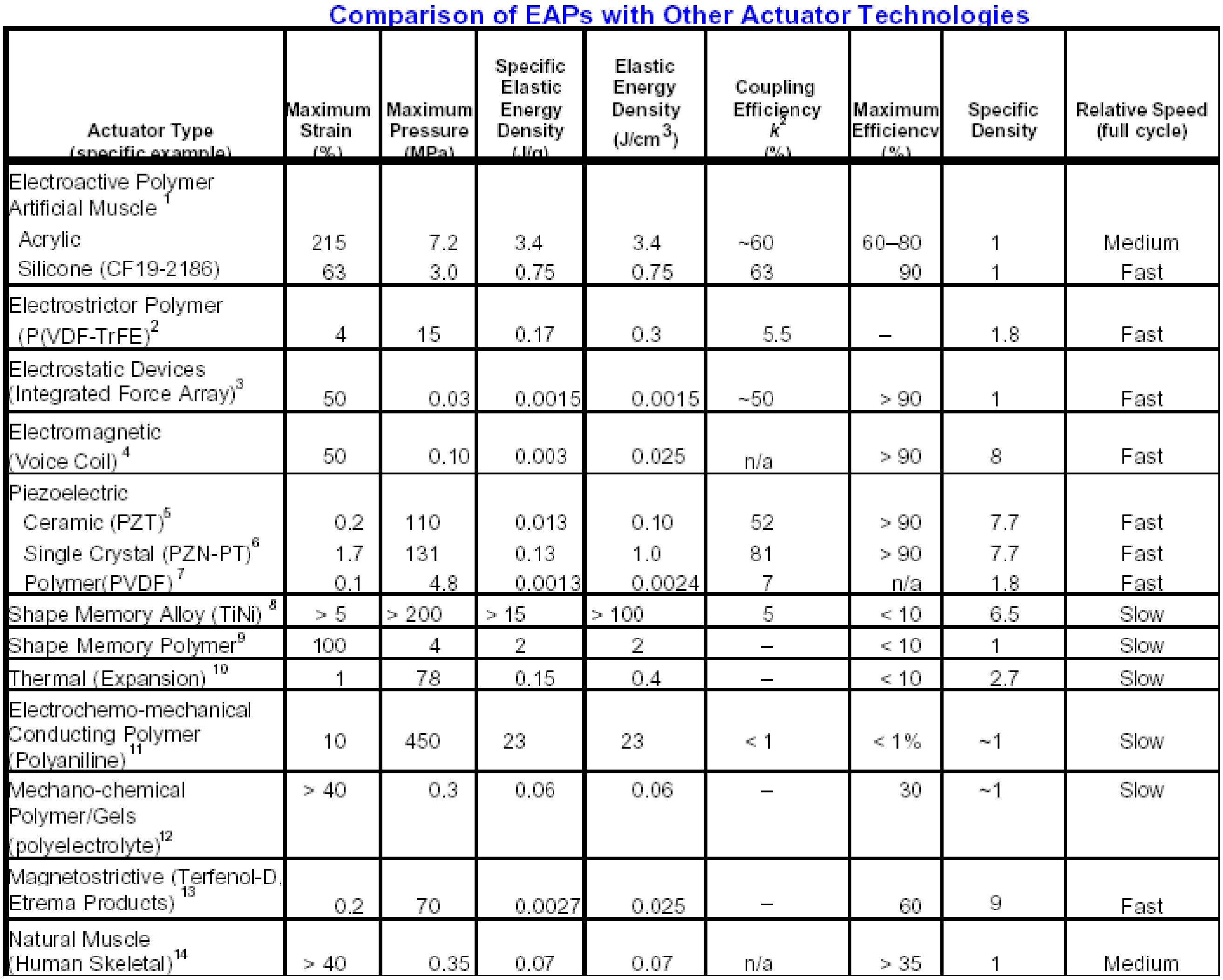
- Real-time shoulder plane repositioning at 4.3 psid
- Total upper torso system weight of 40 lbs (Including helmet, arm assys., and suit closure hardware)
- 2 SUT sizes fits 5% female to 95% male
- No impact to crewmember downward visibility due to actuator size
- 8 hour operation between battery recharge
- Fail safe design with no loss of mission capability

ACTUATION STUDY

The actuation study began with an examination of the current state of the art in actuator technology. This includes pneumatics, hydraulics, synthetic muscles, piezoelectric actuators, shape memory materials, and electrical motor driven devices such as ball screws. These technologies have been compared based on their size, weight, response time, actuation system force requirements, actuator power requirements, and reliability (Table 1). An ideal actuator for use on a spacesuit will be small, lightweight, and robust. The actuation forces required for application in a shape changing SUT are significant but force multiplier technologies will also be investigated which may reduce the force requirements on the actuator, and thus power required. Actuator response time is a significant issue in the development of a strength- augmented mobility joint but it is less critical for application to SUT shape changing.

Figure 5: Fluidic Muscle Actuator

One example of a synthetic muscle that could be utilized in the upper torso actuation system is a “fluidic muscle.” This revolutionary actuator technology has no piston. The pneumatic principle of the muscle is a tube that contracts in length with increasing internal pressure. The technology consists of a fluidically pressure-tight flexible tube and a sheath made of non-elastic fibers in a diamond pattern. As the pressure medium flows into the tube, the fluidic muscle increases in circumference and decreases in length. The lattice pattern limits this reduction in length as a function of increasing internal pressure until a neutral angle is reached. The result is a stroke of up to 25% of the initial length and up to 10 times more power than a conventional pneumatic drive and only 40% of the energy consumption for a given power output. This technology could be developed for application on the upper torso repositioning and sizing system, and could also be applied later to strength



Comparison of EAPs with Other Actuator Technologies

Actuator Type (specific example)	Maximum Strain (%)	Maximum Pressure (MPa)	Specific Elastic Energy Density (J/g)	Elastic Energy Density (J/cm^3)	Coupling Efficiency k^2 (%)	Maximum Efficiency (%)	Specific Density	Relative Speed (full cycle)
Electroactive Polymer Artificial Muscle[1]								
Acrylic	215	7.2	3.4	3.4	~60	60–80	1	Medium
Silicone (CF19-2186)	63	3.0	0.75	0.75	63	90	1	Fast
Electrostrictor Polymer (P(VDF-TrFE)[2]	4	15	0.17	0.3	5.5	–	1.8	Fast
Electrostatic Devices (Integrated Force Array)[3]	50	0.03	0.0015	0.0015	~50	> 90	1	Fast
Electromagnetic (Voice Coil)[4]	50	0.10	0.003	0.025	n/a	> 90	8	Fast
Piezoelectric								
Ceramic (PZT)[5]	0.2	110	0.013	0.10	52	> 90	7.7	Fast
Single Crystal (PZN-PT)[6]	1.7	131	0.13	1.0	81	> 90	7.7	Fast
Polymer(PVDF)[7]	0.1	4.8	0.0013	0.0024	7	n/a	1.8	Fast
Shape Memory Alloy (TiNi)[8]	> 5	> 200	> 15	> 100	5	< 10	6.5	Slow
Shape Memory Polymer[9]	100	4	2	2	–	< 10	1	Slow
Thermal (Expansion)[10]	1	78	0.15	0.4	–	< 10	2.7	Slow
Electrochemo-mechanical Conducting Polymer (Polyaniline)[11]	10	450	23	23	< 1	< 1%	~1	Slow
Mechano-chemical Polymer/Gels (polyelectrolyte)[12]	> 40	0.3	0.06	0.06	–	30	~1	Slow
Magnetostrictive (Terfenol-D, Etrema Products)[13]	0.2	70	0.0027	0.025	–	60	9	Fast
Natural Muscle (Human Skeletal)[14]	> 40	0.35	0.07	0.07	n/a	> 35	1	Medium

Table 1: Actuator Technology Comparison

augmented mobility joints due to its enormous initial force delivery, acceleration, and frequency. The lightweight fluidic muscle is ideal for mobility joint applications that include high operating frequencies and highly dynamic motions. It is also important to note that the fluidic muscle technology exhibits acceleration characteristics that are entirely free of stick or slip. Fluidic muscles are also unaffected by dirt, dust, sand and many other forms of contamination. Figure 5 shows an example of a commercially available fluidic muscle for use in stamping machines where the fluidic muscle is routinely actuated 420 cycles per minute.

Force multiplier technologies such as a simple block and tackle arrangement or reduction gearing will be investigated as part of the actuation study. Some type of force multiplier will most likely be employed due to the significant forces that will be required to alter the shape of a SUT pressurized to 4.3 psi. An actuator technology such as a powered ball screw may have an inherent force multiplication due to the screw pitch or gearing used to drive the ball screw. A force multiplier will also aid in reducing actuator power requirements, and provide a zero-power, while in position, capability.

ELECTRONIC TEXTILE CONTROL STUDY

Future control interfaces on spacesuits will have to be an integral part of the suit. This will require future interfaces to be lightweight, low profile, and robust. Work has begun on determining electronic textile technologies for controlling the actuation system. The control system will allow the crewmember to have real-time control of the position of the SUT scye planes. The system envisioned will allow the crewmember to choose from several specific scye plane breadths for improved upper torso fit and comfort. Several task-specific scye plane angles can also be chosen to improve crewmember efficiency when performing specific tasks. Figures 6 and 7 show examples of a low profile electronic textile switch technology that is currently being evaluated in ILC Dover's Advanced EVA Prototype Spacesuit (I-Suit) for actuation of helmet lights and remote control of a vehicle. The best location for the system controls will also be investigated. This investigation will evaluate arm reach and visibility for several different existing suit systems.

Figure 6: Low Profile Fabric Switch

Figure 7: Low Profile Fabric Switch

SUT MODELING

As part of the SUT Modeling effort, concepts are being developed for control of the scye planes for repositioning and sizing. All concepts will include a method for managing the SUT restraint fabric and bladder. The management includes control of excess fabric and interface plane stability during and after repositioning. As the interface planes are moved, the SUT surface will either contract or expand. The excess fabric associated with a contraction may have to be managed. This could be accomplished in a manner similar to how a convoluted mobility joint would be patterned. If the SUT was comprised of mobility joint panels located at key areas where scye plane movement is to take place, the load requirement on the actuation system could be reduced. The incorporation of mobility joint panels will also provide a means to control the stability of the interface plane by tailoring the mobility panels to the specific loading conditions in each area applied.

The initial approach was to evaluate the need for mobility panels. A basic patterning method was chosen and a 3D model of an initial SUT was developed (Figure 8). This first prototype SUT was used to understand inflated fabric behavior, sizing limits, and force required to move the scye planes. If testing shows the SUT fabric contracts and expands in a consistent predictable manor, the SUT fabrication can be greatly simplified. This initial mockup was also used to determine the limits of resizing within one SUT size. This first mockup utilized a manual sizing and repositioning system. The manual system consisted of cable and pulley arrangement that was used to quantify the loads required to manipulate the interface planes. The results of the mockup testing aided in the definition of actuator type and size.

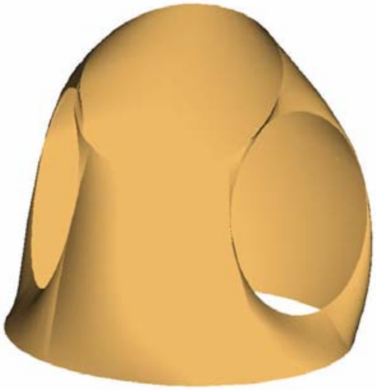


Figure 8: SUT 3D Computer Model

PROTOTYPE DEVELOPMENT AND TESTING

Once the first SUT surface model was developed as seen in figure 8, two-dimensional patterns were developed by dividing the surfaces and unfolding them from the model. The patterns were laser cut and used to fabricate the first prototype SUT including patterned restraint and bladder layers. The prototype SUT pressurized to 4.3 psid can be seen in Figure 9. The prototype testing is being used to characterize the behavior of the inflatable as its shape is manipulated. It is also being used to define the forces required to reposition the scye planes. Load versus deflection data has been gathered at varying pressures with an electronic load cell and data acquisition software. Figure 10 shows a view of the backside of the SUT, pressurized to 4.3 psid, with load cell installed. The force data gathered is being used to size actuators that will be installed on the prototype SUT in the future. The data gathered is also being used at a more basic level to better understand the effective radius for the complex SUT shape. The effective radius is defined as the average radius dimension that defines the pressurized loads in the SUT. This data is critical to determining required fabric and seam strengths. Table 2 shows a small sample of the data gathered to date.

Figure 9: SUT Prototype at 4.3 psid

Figure 10: SUT at 4.3 psid with Load Cell

SUT SIZING ANALYSIS AND ALGORITHM

A study of the correlation coefficients between various anthropometric measurements reveals the need for individual adjustment in order to achieve optimal fit. Previous Shuttle HUT developments used basic anthropometric data and trial and error to determine HUT dimensions. While this method ultimately provided reasonably good HUT definition, it is very labor intensive and costly. As part of this research effort, work has begun on the development of a SUT sizing algorithm that will utilize laser scanned anthropometric data to define the SUT shape and size.

The sizing analysis began with laser scanning the prototype SUT shown in previous figures. The SUT was scanned with the scye planes at three different breadth positions. The scans included the full out position, 50% reduction in scye breadth, and full in position (Figures 11). The position chosen for this analysis is the 50% position as it has already been established as a comfortable and highly mobile position for the scan subject. The next step was to laser scan a subject with significant space suit experience (Figure 12) The subject has been initially scanned with his arms down by his side and then with his arms perpendicular to his torso.

Through an iterative process of pressurized suit evaluations and manipulation of the 3D body scan in the 3D SUT model, an algorithm defining optimum fit based on comfort and performance will be established. This method will also allow for determining the limits of the upper torso sizing with regards to suit comfort and the subject's mobility.

CONCLUSION

The current focus on future planetary exploration is showing the need for improvements in EVA spacesuit performance. Soon, the Shuttle EMU will have been in service for 25 years. The EMU has and continues to perform well in sustaining zero gravity operations. The EMU was designed primarily for satellite servicing and deployment and the most recent version for space station assembly.

The Shuttle EMU was originally design to have 5 sizes of hard upper torso each having a flexible bellows that would pivot to aid donning and doffing. The number of HUT sizes was reduced initially to 4 then to 2 and now back to 3. In the early 1990s, the HUT design was also changes to eliminate the bellows in an effort to improve the reliability of the HUT. The result of these changes is

Smallest Bearing Center to Center Breadth			Largest Bearing Center to Center Breadth		
Pressure (PSI)	Force* (lbs)	Effective Radius (in)	Pressure (PSI)	Force* (lbs)	Effective Radius (in)
1	31	7.7	1	32.5	7.9
2	57.5	7.4	2	52	7.0
3	76.5	7.0	3	66	6.5
4	97	6.8			
	Average	**7.2**		Average	**7.1**
* Force measure with an electronic strain gage					

Table 2: Force Data from Pressurize Prototype SUT

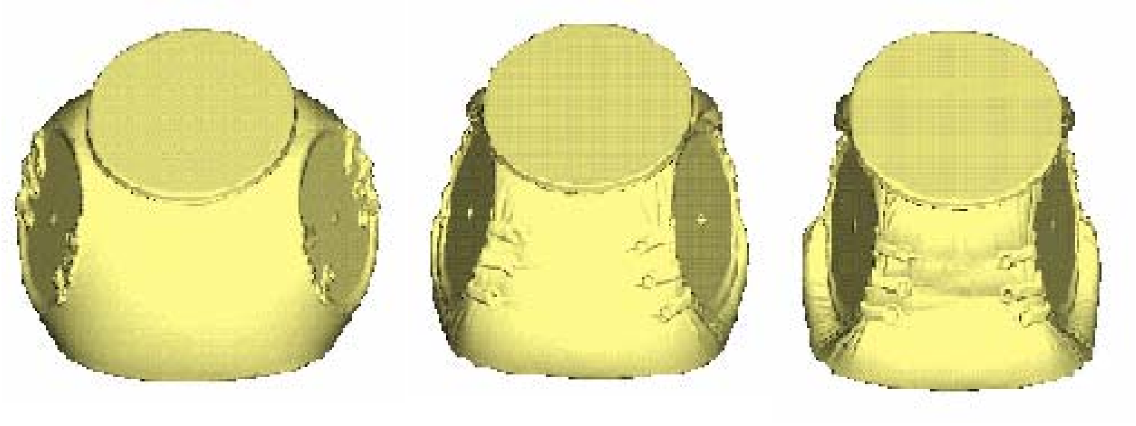


Figure 11: Prototype SUT Laser Scan Surface Models

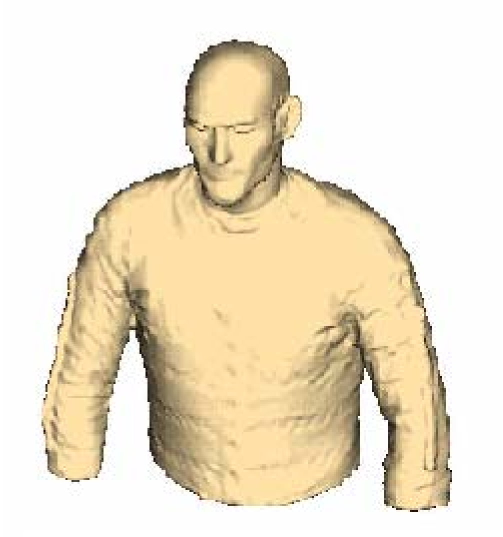


Figure 12: Subject Laser Scan

a HUT system that is not well received by many current crewmembers. This research focuses on an effort to push the state of the art in space suit upper torso design. It will provide future astronauts with a more comfortable easier to don and doff upper torso system that fits a broader population well with fewer sizes and also provides real-time improvement to mobility.

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ACRONYMS

EMU: Extra-Vehicular Mobility Unit

HUT: Hard Upper Torso

SUT: Soft Upper Torso

ISS: International Space Station