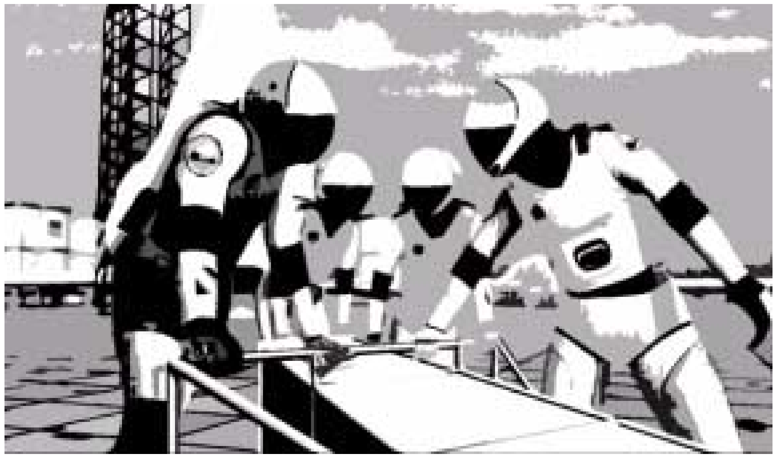


Astronaut Bio-Suit for Exploration Class Missions:

NIAC Phase I Report, 2001

Bradley Pitts, Cam Brensinger, Joseph Saleh, Chris Carr, Patricia Schmidt, Dava Newman

MIT Man-Vehicle Lab
Rm 37-219
77 Massachusetts Ave.
Cambridge, MA 02193

Abstract

A *Bio-Suit System* stands to revolutionize human space exploration by providing enhanced astronaut extravehicular activity (EVA) locomotion and life support based on the concept of providing a *'second skin'* capability for astronaut performance. The novel design concept is realized through symbiotic relationships in the areas of wearable technologies; information systems and evolutionary space systems design; and biomedical breakthroughs in skin replacement and materials. By working at the intersection of engineering; design; medicine; and operations, new emergent capabilities could be achieved. The *Bio-Suit System* would provide life support through mechanical counter-pressure where pressure is applied to the entire body through a tight-fitting suit with a helmet for the head. Wearable technologies will be embedded in the *Bio-Suit* layers and the outer layer might be recyclable. Hence, images of 'spraying on' the inner layer of the *Bio-Suit System* emerge, which offers design advantages for extreme, dusty, planetary environments. Flexible space system design methods are slated to enable adaptation of *Bio-Suit* hardware and software elements in the context of changing mission requirements. Reliability can be assured through dependence of *Bio-Suit* layers acting on local needs and conditions through self-repair at localized sites while preserving overall system integrity. The proposed *Bio-Suit System* contributes to four under-represented NIAC areas, specifically, human space flight, life sciences, information systems and software, and biology. The *Bio-Suit System* is relevant to NASA's strategic plan and stated visionary challenges in the Human Exploration and Development of Space, AeroSpace Technology, and Space Science enterprises.

Contents

1.0 Overview

1.1 Motivation and Objectives

The main objective of the effort was to research and design a revolutionary concept for human exploration missions, namely, the *Bio-Suit System*, which is envisioned as a locomotion enhancing, life support system for astronaut extravehicular activity (EVA) based on the concept of providing a *'second skin'* capability for astronaut performance. The *Bio-Suit System* concept is in stark contrast to the incremental space-suit design approach and improvements witnessed over the history of human spaceflight in both the NASA and Russian programs, including the International Space Station. Pressurized life support would be accomplished through mechanical counter-pressure where pressure is applied directly to the body compared to current spacesuits where the entire suit volume is pressurized, inflating it similar to a balloon and requiring the astronaut to continuously work against the cumbersome pressurized volume.

Mars EVAs can be characterized as planned, unplanned, or contingency (unexpected, but may be required for crew safety). For ISS EVA operations, there are planned and contingency EVAs [17], while on Mars, we can assume that all EVAs beyond the initial steps on the surface will be unpredictable upon mission launch and therefore will fit into the unplanned/contingency framework. EVA tasks or components can be characterized by their criticality, such as whether the accomplishment of a specific task would be safety critical, a requirement for mission success, or a mission enhancement. EVAs vary considerably in complexity: some EVAs require only a standard set of tools and skills, while other EVAs require specialized tools specific to a given task or mission. Finally, very complex EVAs may require both specialized tools and a "significant extension of capabilities" including scaling/ repelling cliffs and demanding geologic traverses.

Detailed objectives for the *Bio-Suit System* Phase I effort include providing: 1) a novel design concept through symbiotic relationships in the areas of wearable technologies; information systems and evolutionary systems design; and medical breakthroughs in technology and 2) a synergistic multidisciplinary approach combining expertise from the fields of engineering; design; medicine; and space operations.

Imagine astronauts on Mars utilizing the *Bio-Suit System* for their search to find the definitive proof of life, which requires them to repel cliffs; perform geology in extreme environments where Olympus Mons and Valles Marineris dwarf Mount Everest and Grand Canyon terrains; and continuously work in extreme temperature and storm conditions.

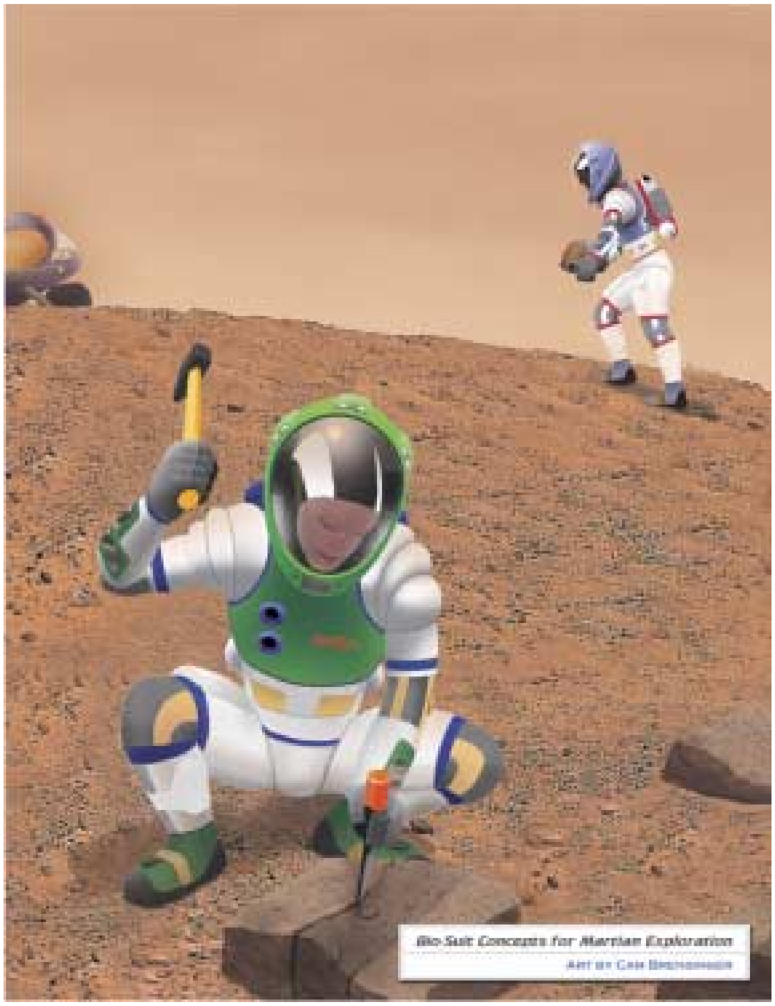


Figure 1.1. A vision of geology work on the surface of Mars while wearing the Bio-Suit.

1.2 Past and Current Research

1.2.1 Current Suit Mobility

1.2.1.1 Forces required to operate the current suit. [35]

The EMU space suit, which is currently used for NASA EVA's, has both hard fiberglass and soft fabric components. Mobility features, such as pleats that open as joints bend and rotational bearings, are built into all modern space suits. Without these mobility features, a person in a space suit would be virtually immobile. Even though space suits are designed to allow mobility, they restrict the wearer's motion in significant and complicated ways.[18]

Limited space suit joint torque-angle data has been reported in the literature. Studies that used human subjects wearing space suits reported higher torques than studies that measured torques on joints of empty, pressurized space suits. Higher torques with human subjects may be expected because contact between the space suit and the wearer's body affects the deformed shape of the space suit, but it is unclear whether the discrepancy in experimental results is due to shortcomings in experimental methods or actual differences in observed torques.[1, 11, 27, 28]

1.2.1.2 Investigating possible space suit models:

Membrane versus Beam model analysis points to the advantages a mechanical counter pressure (MCP) space suit offers. Since the first EVA's were performed by Alexei Leonov and Ed White in 1965, the capabilities of astronauts to do useful work outside of their spacecraft have steadily increased. Likewise, our understanding of EVA astronauts' capabilities and limitations have also progressed through in-flight experience, experimentation in neutral buoyancy facilities and parabolic flight, and engineering tests of space suits and EVA tools.

The most important aspect of an EVA astronaut's capabilities is the ability to move his or her body while wearing the space suit. In every EVA scenario, astronauts physically manipulate objects to accomplish tasks. Two factors make these physical interactions strikingly different from those performed on the ground. First, the microgravity environment requires an astronaut to restrain his or her body in order to exert forces and moments on another object, and second, space suits constrain astronauts' body motions in significant and complicated ways. Clearly, for planetary exploration applications, limited mobility is the overriding concern.

Physical models, in contrast to mathematical models, can lead to insights into the physical processes that govern space suit mobility, and therefore inform us as to where major advancements are needed and can be found. Two physical models of the bending characteristics of inflated cylinders may be relevant to current space suit joints. The beam model treats the inflated cylinder as a beam with a fabric wall that stretches, maintaining a constant internal volume. In this model, the mobility of the space suit joint is determined by elastic behavior of the fabric wall.[21-24] The membrane model treats the fabric shell as an inextensible membrane. Bending deflections of the cylinder result in shape and volume changes. The work required to bend the joint is entirely due to compression of the gas inside the tube [12, 13] Differences in torque predictions between the beam model and the membrane model illustrate the relative importance of elasticity and gas compression in space suit joint mobility.

The beam model and membrane model represent opposite extremes of the processes governing space suit joint mobility. According to the beam model, bending moments only stretch the space suit fabric; according to the membrane model, bending moments only compress the gas inside the space suit.

Experimental data shows that the beam model is inconsistent with current elbow and knee joints, both in the bending moment magnitudes predicted and the trend in bending moment with increasing deflection. Other physical processes, including fabric bunching, sideways compression of the space suit arm or leg, and friction between fabric layers, which were not included in the membrane model, likely play an important role in determining the torque needed to bend the space suit joints at high bending angles.

The results of this analysis indicate that elastic deformations of the space suit fabric do not contribute significantly to the torque needed to bend the elbow and knee joints near the equilibrium angle, and the mobility of the EMU elbow and knee joints near their equilibrium angles is not sensitive to changes in the material properties of the fabric. The membrane model predicts that only internal pressurization and joint geometry determine mobility. This data suggests that increasing mobility can be achieved by lowering/eliminating the pressurized volume of a space suit as could be accomplished with mechanical counterpressure. In the case of MCP, however, the designer is forced to deal with the implications of the beam model since all the bending properties will be determined by the material properties.

1.2.2 Advanced Suits

Advancements have been made in pressurized suit technology, through the drive to maintain constant joint volume while bending. One design option to achieve constant volume is to fabricate hard (metal/composite components) suits such as the AX-5 high pressure, zero prebreathe suit developed at NASA Ames Research Center in the 1980s. Due to their rigid exoskeleton approach, hard suits maintain a constant volume as the astronaut bends the joints. Although this minimizes the torque required to bend the joints, it makes the suits heavy and potentially uncomfortable to wear. Typically hard suits require additional internal padding for astronauts in order to reduce the risk of injury due to contact with the hard interior of the suit. Designers should note that the commercial deep sea diving community has developed hard, pod-like suits and used them successfully. The current Mark III advanced, high pressure hybrid fabric/hard suit developed at NASA Johnson Space Center offers improved mobility over the Shuttle/ISS EMUs.

1.2.3 Mechanical Counter Pressure (MCP)

1.2.3.1 Initial development: The Webb suit [3]

In 1971, James F. Annis and Paul Webb published a report of their Mechanical Counter Pressure (MCP) suit known as the “Space Activity Suit” (SAS).

They were able to develop a prototype suit made up of six layers of elastic material that created the MCP, which was accompanied by a full bubble helmet. “The ultimate goal of the SAS [was] to improve the range of activity and decrease the energy cost of work associated with wearing conventional gas filled pressure suits.”

Webb states the motivations for a MCP suit, which still apply today and into the future. Besides the improved energy cost, a MCP suit “should be safer and more reliable than full pressure suits since suit rupture would not mean loss of life supporting gas pressure.” If designed properly, a small tear in a MCP suit would only expose a local body region to reduced pressures. This exposure would cause the wearer discomfort, and possibly pain, but would allow them to return to safety without major injury.

In addition to safety concerns, Webb also notes that the life support system of a MCP suit could be greatly simplified from existing versions due to the fact that the body can enable “physiologically controlled cooling” by means of sweating. This assumes that the suit is porous (as was Webb’s), allowing sweat to evaporate through the second skin. The Space Activity Suit directly exposed areas of skin no larger than $1mm^2$ to vacuum (5 mmHg, 0.1 psia, 0.7 kPa) without problems. There were no signs of excessive fluid loss, or freezing of the skin. This also demonstrated that, at such a scale, the skin withstood the tensile loads.

Without the need for thermal control, the life support system would become a tank of oxygen with pressure regulators and a carbon dioxide scrubber. A MCP suit might also be an order of magnitude less expensive because it could be less bulky and lighter than current garments thus taking up less payload resources.

Though strongly articulating the benefits of a MCP approach, Webb was also able to demonstrate the major challenges of such a system. Through a series of demonstration tests, the SAS was effective to breathing pressures of 24 kPa (170 mmHg, 3.3 psi) within the laboratory environment (101 kPa, 14.7 psi, 1 atm). Major issues encountered included don/doff time and swelling/edema in parts of the body. Webb specifically notes that “the most difficult areas to pressurize occur where the limbs join the torso.” In order to prevent blood pooling, the pressure across these regions needed to remain smooth.

Despite the physiological problems encountered, Webb’s research suggested that, “energy cost of activity, and mobility and dexterity of subjects is the SAS, were found to be superior to those in comparable tests on subjects in [gas pressurized suits].” They also suggested that every problem encountered was primarily mechanical in nature, and could be solved by the development of new materials and tailoring techniques. Simplifying the donning process was specifically noted as a critical area of future research.

1.2.3.2 Research into a MCP glove: Clapp [8]

In 1983, W. Mitchell Clapp published an article on his development of a MCP glove that he called the "Skinsuit Glove." His motivations were similar to Webb's, but he focused on the glove as an area where more mobility/dexterity and tactile feedback was required to enhance space operations. After developing a prototype, he tested the glove against a bear hand, and an Apollo A7L-B glove (a pressurized glove) in the areas of mobility/dexterity, strength/fatigue, aeromedical effects, and tactile feedback.

Clapp claimed that "the skinsuit glove showed a sizable mobility and dexterity advantage over the A7L-B glove. There was also less strength degradation with fatigue. Tactile feedback was considerably higher in the skinsuit glove as well." Although subjects were only subjected to thirty minutes of partial vacuum exposure (23 kPa, 3.5 psi, 176 mmHg), Clapp stated that "only a minor swelling of the hand occurred." He noted that "small amounts of edema fluid, accompanied by a slight swelling, were... observed, mainly in the palm, but also in the wrist and web of the thumb." Although he was probably correct in stating that these effects, after thirty minutes of exposure, did not pose a risk, it seems reasonable to assume that after an eight hour EVA these problems might have grown in complexity and severity.

Clapp concluded that his glove achieved improved mobility, tactile feedback, and fatigue characteristics over the A7L-B glove. The mobility and tactile feedback results were explained by the use of stretchy, lightweight material. While addressing the aeromedical issues, Clapp notes that the palm of the hand swelled "only a very small amount." He suggested that this swelling was due to the concavity of the region and "could probably be prevented by inserting a small foam pad between the glove and the palm where the fabric gaps across."

After developing the Skinsuit Glove, it was suggested that future research focus on the effects of enhanced tactile feedback on learning and on comparing the MCP glove to the (then new) EMU glove design. He hypothesized that due to the increased tactile feedback, the Skinsuit Glove would be able to reduce the time needed to learn EVA tasks. Seeing as the EMU glove design focussed on improved glove mobility, he suggested comparing the effectiveness of both designs against each other.

1.2.4 Integrating Wearable Computing into EVA [5]

Wearable computing has the potential to enhance astronaut safety and performance by providing new or redundant support mechanisms for astronauts during extravehicular activity (EVA). Current predictions from the National Aeronautics and Space Administration (NASA) EVA Project Office estimate

168 days devoted to EVA for assembly and maintenance during the construction of the International Space Station (ISS)[2]. Future terrestrial missions will most likely require more EVA hours than the sum total of the entire history of EVA experience.

1.2.4.1 Space Suits as Wearable Computers

In a sense, the EMU and ORLAN suits already meet one definition of a wearable computer [30]: They are portable while operational, capable of hands-free use, able to sense characteristics of the environment (at least the internal environment), are always on (during EVAs), and augment human capabilities.

A suit-external independent electronic cuff checklist, developed to serve as a limited mechanism for astronauts to reference procedures or contingency procedures, was flown as a space flight experiment. Despite the success of this project, a wrist mounted paper checklists still serves as the primary written procedural reference during EVA.

1.2.4.2 Limitations of EVA addressed by information technology

Major limitations during EVA include the need to cope with sensory degradation, the limited duration of EVAs, limited mobility, dexterity, force application, and endurance of suited astronauts, operations time and resource overhead requirements, working volume and access limitations, and hazards to crewmembers. [25]

A system capable of mitigating some of these limitations might therefore (1) sense characteristics of the external environment and communicate those characteristics to the astronaut; (2) extend or augment the senses or capabilities of the astronaut; (3) enhance the efficiency with which tasks can be carried out, and (4) minimize any negative impacts on operations time and resource overhead.

The existing systems provide only limited capabilities of information transfer to or from an astronaut during EVA. The primary method of information transfer during EVA has been two-way voice communication over UHF. Life support parameters from the EMU are also sent over the UHF communication system to the Shuttle or ISS and from there via downlink to the MCC. An EMU TV camera has also been used to provide video coverage of EMU worksites.

1.3 “Requirements” for the *Bio-Suit* MCP Concept

1.3.1 Strategy: Why MCP?

As suggested by Paul Webb, Mitchell Clapp and others, Mechanical Counterpressure suits have the possibility of greatly improving space suits in performance. While discussing the need to provide pressure to an EVA astronaut others have suggested that “the penalty for using gas pressurized systems is high system weight.” [19] Thus, MCP provides a possible solution to minimizing weight and improving other performance metrics such as flexibility/mobility, don/doff time, system bulk, tactile feedback, and possibly system cost.

As pointed out by Clapp, “the human skin is almost an ideal pressure suit. Having a high tensile strength, almost no gas permeability, and very good water retention characteristics, the skin requires only an applied pressure equal to the pressure of the breathing gas to function normally.” Given the performance characteristics of our biologically grown skin, it seems reasonable to envision a second skin capable of augmenting our biological skin to the point where it can withstand the absence of a pressurized environment.

If designed properly, Webb showed that a MCP suit could expose regions of skin no larger than 1 mm^2 to vacuum. There are two major advantages suggested by this result. Firstly, this result suggests the improved safety of a MCP suit design. Especially on planetary surfaces where the astronaut will be exposed to highly abrasive environments and activities, tears become an issue of increasing concern. In a gas pressurized suit, a small tear not only means the possibility of loosing pressure but also oxygen. In an MCP suit, however, this would not be the case. Webb’s result suggests that should a small hole appear in a MCP suit, the user would be unharmed. There would be no loss of breathable oxygen, and the skin would not suffer any damage. Should the hole be larger than 1 mm^2, the wearer would still have sufficient time to return to a pressurized environment due to the fact that the effects of the reduced pressure would be highly localized.

The second advantage suggested by Webb’s result is that of thermal cooling. In gas pressurized suits, the materials must clearly be impermeable to air in order to maintain the pressure required. This causes thermal issues due to the fact that our normal mode of thermal control, evaporation of sweat, cannot be implemented. This motivated the need for thermal garments such as the Liquid Cooling and Ventilation Garment (LCVG) which complicates the life support system. In a MCP suit such as the Space Activity Suit, however, this issue is resolved by using air-permeable fabric. By allowing the skin to be exposed to vacuum, Webb allowed the body to utilize its own cooling mechanisms. “Without the need for a convective gas cooling system or liquid cooling garment, the life support system becomes essentially a tank of oxygen with pressure regulators. In addition to being less bulky and heavy, [MCP suits] would be much less costly to produce than current garments.”

Beyond the findings and projections of past suits, MCP suits provide the possibility to be donned and doffed easily, enabling the astronaut to explore much like we do on earth: by slipping into protective clothing rather than strapping on a space craft. Although this capability of MCP suits has yet to be demonstrated, it is a clear goal of the Bio-Suit effort. Not only would decreased don/doff time increase the productivity on the surface of planetary bodies, but it would also lower the psychological and physical barriers between Intravehicular Activity (IVA) and EVA. Thus it would change the exploration paradigm from “spam in a can” to an individual interacting with and inhabiting an extra-terrestrial environment. This would allow her/him to truly explore the three dimensional space of the environment in ways that only the human body can.

1.3.2 Locomotion and Mobility

Clearly if terrestrial environments are to be explored and useful geology work is to be done, locomotion is a top priority. Since the Apollo era no space suit has been designed for walking and the Apollo suits left great room for improvement. In an environment such as Mars, astronauts will need the ability to traverse loose terrain, steep grades, and possibly scale, if not repel, down cliff sides. These activities place unheard-of requirements on advanced suits in the areas of mobility and dexterity. Due to the activities mentioned above as well as the evaluation of samples and the maintenance of equipment, manual dexterity will be a high priority as well.

1.3.3 Pressure Variations

As demonstrated by both Webb and Clapp’s prototypes, pressure variations within the MCP garment must be kept to a minimum. From their reports, it seems that body regions with concavities and joints will pose the greatest challenge in this area. Neither study investigated the pressure tolerances the body is able to handle without physiological or physical damage.

1.3.4 Wearable Computing [5]

Maintaining and promoting safety is the primary EVA wearable computer system priority: First do no harm. Second, it is critical that the system is both comfortable and easy to use. Third, the system should greatly improve existing operational processes.

For components inside the gas pressurized helmet, safety considerations include operation of electronics in a 100% oxygen atmosphere, out-gassing off-gassing issues, thermal restrictions, and the severe space constraints. Components outside this pressurized volume will have stringent requirements as well due to the fact that they will be exposed to abrasive dust, wind, and other environmental conditions.

Achieving comfort and ease of use requires an innovative user interface (both displays and controls) and form factor. For an in-suit wearable, comfort dictates that the computer be body-conformable and maintains a comfortable surface temperature. Ease of use requirements imply that the user should interact with the computer in a way that is natural to the EVA environment and requires little mobility on the part of the astronaut. Voice control is one option, but is an unlikely candidate because of the potential for interference with existing audio communications, especially given the central role that these communications have played throughout the history of EVA. A solution that requires no movement on the part of an astronaut, and only indirectly may involve audio communication, is remote control of information delivery to the EVA astronaut by IVA crewmembers IVA crewmembers follow EVA progress very closely, and could direct specific information to an EVA astronaut either by prearranged understanding or at the request of the EVA astronaut.

Locating and positioning a visual display is also a significant challenge. Currently, there are many objects inside the suit near the eyes and face including the communications carrier assembly (CCA, or CommCap, which is basically a pair of headphones and redundant noise canceling microphones), a drink bag, food stick, and a valsalva device (used for equalizing pressure in the ear canals during suit pressure changes). This limits the space that can be allocated to a suit-internal display. Implementing an effective suit-external display would also be a significant challenge because of positioning and illumination requirements. An external fixed position display does not allow the display to move along with head movements of the astronaut, while an internal display embedded in a pair of standard EVA glasses (with proper prescription for a specific astronaut, or a blank prescription for astronauts who do not require glasses) enables a display to occupy a constant solid angle relative to the head of the astronaut. This could be accomplished using an eyeglass or clip-on micro-display. The varying lighting conditions external to the suit, and the visors used to limit light entry into the helmet, further complicate the development of an external visual display.

Operational simplicity in the donning, utilization, doffing, and maintenance of a wearable computer system for EVA is imperative. Integrating the operational procedures of the wearable computer system into preexisting EVA procedures drives what hardware interconnect configurations are desirable. If a suit-internal wearable computer is used exclusively for EVA (as opposed to a dual use system for both IVA and EVA) the wearable computer system CPU could be stowed attached to an undergarment so that donning of the wearable computer would be accomplished by simply putting on the undergarment. Similar considerations might apply for other components of the system.

Operational simplicity during EVA requires careful choice of audio or tactile controls. Traditional hand-based user interface tools may be extremely challenging and generally undesirable due to the physical exertion requirements of moving stiff space suit gloves. Internal tactile controls, or simple external controls (such as buttons or switches) are possible, but must be evaluated with respect to the burden they impose on the astronaut. External tools also pose system integration challenges such as crossing the suit pressure barrier. External tools could also act as additional wireless network clients – this, however, increases the checkout and maintenance burden by requiring battery change-outs or tool recharging, and may also complicate software development.

Voice communications have played, and will continue to play an integral role during EVAs. In addition, IVA crewmembers and MCC flight controllers are often focused on supporting EVA astronauts during EVAs. As such, audio requests for information delivery fit naturally within the current operations framework and allow for a natural language interface not yet possible through voice recognition systems.

An external visual display (and the apparatus required to secure its position) may obscure a central portion of the astronaut's field of view and work envelope. An internal display may present similar difficulties unless a see-through display is available. A near-eye micro-display integrated into a pair of standard EVA glasses could provide an adequate visual display that could be turned off or adjusted to prevent visual conflicts between the display and the physical environment. It would also be easier to ensure that a suit-internal display would be readable in a variety of external lighting conditions.

Operational life specifications require that non-suit EVA hardware be designed for up to 100 space shuttle missions (for Space Shuttle specific equipment) and up to 10-year on-orbit durations (with required maintenance). Space suit operational life requirements are suit dependent: EMUs are designed for single-mission, multiple-EVA usage followed by refurbishment prior to re-flight. For a mission to Mars, EVA hours are likely to exceed the sum total of past history EVA hours, without access to ground based maintenance facilities. This fact combined with the harsh external environment will place unheard of lifetime and maintenance requirements on a Mars suit. Similarly, operational life requirements for a wearable computer system have yet to be defined.

2.0 MCP Concepts

2.1 Introduction

2.1.1 Explanation of the Portfolio Style

The following pages contain illustrations and explanations of mechanical counterpressure suit design concepts. Central to each concept is ease of donning/doffing and design flexibility. Beyond explaining the concepts, a brief explanation of the technologies used and their application is also included. Each page also contains a list of resources that the Bio-Suit design group found useful and include for future research contacts.

2.1.2 Design Tree Branches. Distributed vs Local

While exploring different design strategies for the Bio-Suit, two main branches emerged. Initially it was thought that the best strategy would be to distribute the use of advanced technologies throughout the suit, making every square centimeter of the suit an active component. This strategy lead to designs such as the shape memory alloy (SMA) mesh suit. Upon further investigation, however, it seemed that a more efficient use of the technologies could be achieved by using advanced technologies locally. Thus, each technology was used in a highly defined region for maximum benefit. By acting in a localized manner, these technologies were able to produce distributed effects. This strategy led to designs such as the SMA Band Suit concept.

2.1.3 Material Technologies

Creating the ability for the suit to shrink around the wearer seemed to be the most straight forward approach to achieving a MCP suit that would be easily donable/doffable. To this end, technologies with the capability of actively changing their strain properties were investigated. Past research suggests that strains of two hundred percent or more might be needed to produce adequate MCP, thus Shape Memory Alloys and “smart gels” were investigated.

Shape Memory Alloys (SMA) are a group of metal alloys that exhibit different sets of physical properties depending on their temperature. In the martensite phase, when the alloy is cool, it becomes soft and ductile and can be easily deformed. If it is heated, it will transform to the austensite phase, where it reverts to its original shape. SMAs are capable of generating large forces it they encounter resistance in the martensitic transformation. SMAs can be heated with an electrical current, they produce large repeatable strokes, and they are proven to be biocompatible.

Polyelectrolyte gels are molecular networks within a solvent, usually water. These gels have the ability to contract or swell, often greater than a factor of 100, under various stimuli such as change in temperature, electricity, or pH.

The phase change occurs almost instantaneously and can be very sensitive to the change. Polyacrylonitrile (PAN) and polyvinylalcohol (PVA) are two common gels stimulated by pH and electricity, respectively. Currently, PAN is being used to create artificial muscle through pH changes. The PAN fibers can contract anywhere from one-half to one-tenth their original length and can support four kilograms per square centimeter. Development in this field has led to several successful demonstrations of the feasibility of gel based actuation including a multi-fingered hand (Karauchi, et. Al., 1991), artificial fish (Kurauchi, et. Al., 1991) and artificial muscle (Brock, Lee, Segalman, Witkowski, 1994; Shahinpoor and Mojarrad, 1994).

The design concepts that follow envision utilizing these technologies together or alone.

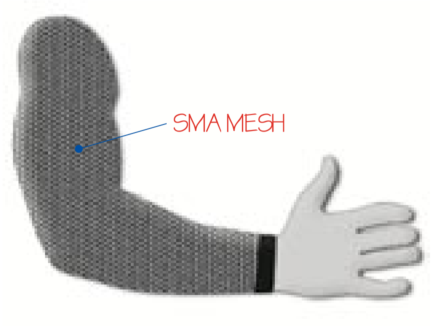
2.2 Distributed Technologies

2.2.1 Electric Alloy Mesh Suit Concept

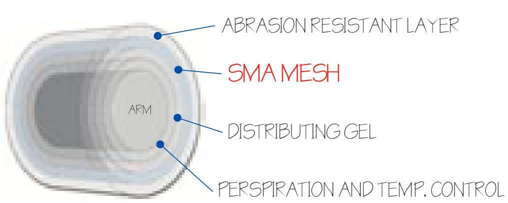
2.2.2 Thermal Gel Suit Concept

2.2.3 Electric Gel Suit Concept

Electric Alloy Mesh Concept



EAMS Concept (glove not shown).



EAMS Layers (not proportional).

Electric Alloy Mesh Suit (EAMS) uses a seamless Shape Memory Alloy mesh to generate voltage controlled mechanical counter-pressure. Pressure is distributed by a viscous thermal regulating gel layer. The gel layer moderates the high temperature of the SMA later and protects the body against impacts the skin directly, wicking away perspiration and absorbing body heat.

Technology: Shape Memory Alloys (SMA) are a group of metal alloys that exhibit different sets of physical properties depending on their temperature. In the martensite phase, when the alloy is cool, it becomes soft and ductile and can be easily deformed. If it is heated, it will transform to the austensite phase, where it reverts to its original shape. SMAs are capable of generating large forces it they encounter resistance in the martensitic transformation. SMAs can be heated with an electrical current, they produce large repeatable strokes, and they are proven to be biocompatible.

Application: Counter-pressure must be applied to the body to simulate the correct atmospheric pressure. Small braces or clasps can line along the seams of the organic or synthetic second skin material. To seal the body and provide a uniform distribution of pressure, the bands can be constricted to draw the material together. SMA technology can be used create a constricting clasp.

Resources:
TiNi Alloy Company
1619 Neptune Drive
San Leandro, CA 94577
(510) 483-9676

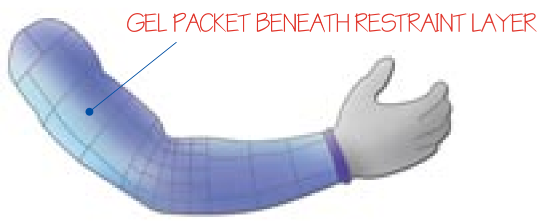
Shape Memory Applications, Inc.
2380 Owen Street
Santa Clara, CA 95054
(408) 727-2221

Thermal Gel Suit Concept

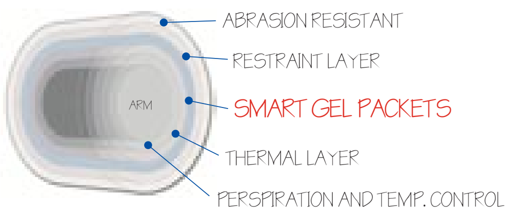
Thermal Gel Suit (TGS) uses “smart” polymer gels which expand at a threshold temperature to create mechanical counter-pressure. The smart gel is trapped in a quilted layer beneath a stretchless restraint layer. The suit is donned in a relatively cool environment, with ambient temperature well below the gel’s threshold. Once on the astronaut, the TGS can be heated momentarily above the threshold temperature to stimulate expansion. The restraint layer prevents outward expansion of the gel, directing the pressure inwards against the body. The cold temperatures on Mars and In Space, preserve the gel’s expansion. Further development of this concept should involve actively controlling the volume of the restraint layer to regulate and properly distribute mechanical counter-pressure.

Technology: Polyelectrolyte gels are molecular networks within a solvent, usually water. These gels have the ability to contract or swell, often greater than a factor of 100, under various stimuli such as change in temperature, electricity, or pH. The phase change occurs almost instantaneously and can be very sensitive to the change. Currently, PAN is being used to create artificial muscle through pH changes. N-isopropylacrylamide (NIPA) has been used and been shown to contact and dilate when stimulated with temperature. Research has been conducted by Tanaka, 1978; Ilavsky, 1982; Hirotsu 1987; and Matsuo 1988.

Application: One class of intelligent gels is hydrogels and they exhibit reversible expansion when subjected to a temperature change. The temperature change would be provided by either body heat or atmospheric temperature. Stimulation through body heat would require close monitoring whereas atmospheric temperature would never reach body temperature thereby avoiding the possibility of reaching the phase change. The gel recovers very rapidly and can be reused multiple times.



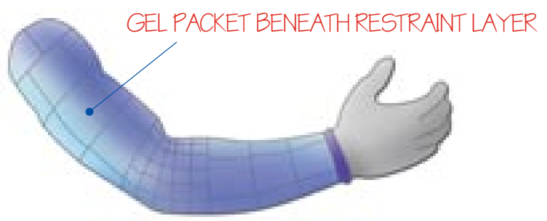
Quilted Smart Gel (glove not shown).



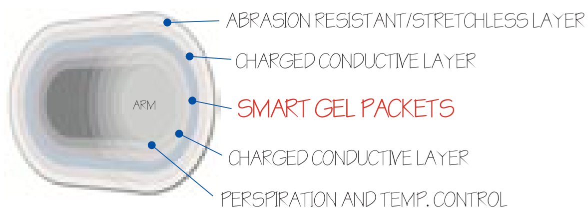
TGS Layers (not proportional).

Resources:
Lee, Woojin “Polymer Gel Based Actuator: Dynamic model of gel for real time control” May, 1996.

GelSciences
213 Burlington Road
Bedford, MA 01730
(617) 276-1700



Quilted Smart Gel (glove not shown).



EGS Layers (not proportional).

Electric Gel Suit Concept

Electric Gel Suit (EGS) uses "smart" polymer gels which expand in an electric field to create mechanical counter-pressure. The smart gel is trapped in a quilted layer, between metallized fabric layers, beneath a stretchless restraint layer. Opposite charges applied to the metallized layers produces a small electric field sufficient to stimulated the expanding smart gel. The restraint layer prevents outward expansion of the gel, directing the pressure inwards against the body. Further development of this concept should involve actively controlling the volume of the restraint layer to regulate and properly distribute mechanical counter-pressure.

Technology: Polyelectrolyte gels are molecular networks within a solvent, usually water. These gels have the ability to contract or swell, often greater than a factor of 100, under various stimuli such as change in temperature, electricity, or pH. The phase change occurs almost instantaneously and can be very sensitive to the change. Polyacrylonitrile (PAN) and polyvinylalcohol (PVA) are two common gels stimulated by pH and electricity, respectively. Currently, PAN is being used to create artificial muscle through pH changes. The PAN fibers can contract to anywhere from one-half to one-tenth their original length and can support four kilograms per square centimeter. Development in this field has led to several successful demonstrations of the feasibility of gel based actuation including a multi-fingered hand (Karauchi, et al., 1991), artificial fish (Kurauchi, et. Al., 1991) and artificial muscle (Brock, Lee, Segalman, Witkowski, 1994; Shahinpoor and Mojarrad, 1994).

Application: The dielectric elastomer gels, also known as electrostrictive polymers, are one class of intelligent gels and exhibit reversible expansion when subjected to an electric field. The electric current would be provided by two conductive layers with the gel inserted in between. The gel recovers very rapidly and can be reused multiple times. Advancements in battery technology may make this a feasible option for the Bio-Suit.

Resources:

C J Whiting, A M Voice "Mechanical Properties of Polyelectrolyte Gels under Electric Field" http://irc.leeds.ac.uk/irc/events/poster99/cjw.html

David Brock
Artificial Intelligence Laboratory
Massachusetts Institute of Technology
NE43-835A
545 Technology Square
Cambridge, MA 02139
dlb@ai.mit.edu
(617) 258-0234

Mo Shahinpoor
Department of Mechanical Engineering, University of New Mexico
Director of Artificial Muscle Research Institute (AMRI)
Director of Intelligent Materials, Structures and Systems Laboratory
shah@unm.edu
(505) 277-3966

GelSciences
213 Burlington Road
Bedford, MA 01730
(617) 276-1700

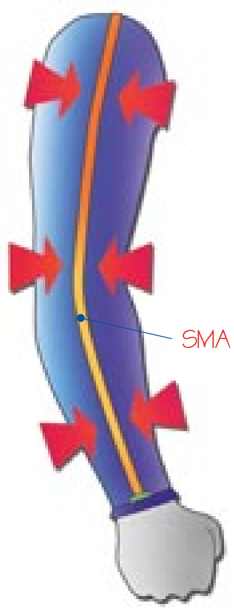
Sandia National Laboratories
Technical Contact: Walter Witkowski, Org. 9234
P.O. Box 5800
Albuquerque, NM 87185-0439

2.3 Localized Technologies

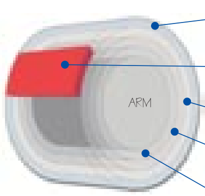
2.3.1 Stretch Alloy Band Suit Concept

2.3.2 Electric Alloy Zipper Suit Concept

2.3.3 Electric Alloy Remote Zipper Suit Concept



SMA Band Contracts Fabric



SABS Layers (not proportional).

Stretch Alloy Band Suit Concept

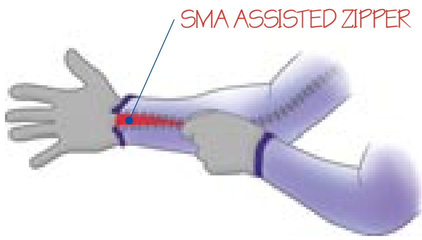
The Stretch Alloy Band Suit (SABS) uses the super elastic properties of SMAs in their austenitic phase to allow the suit's volume to expand enough for donning. Charge is then applied to the SMA band which pulls together the seam of the uni-directional stretch fabric layer (SFL). As the UDSFL constricts it applies a voltage regulated mechanical counter-pressure. The UDSFL is able to stretch longitudinally in order to allow flexion at the joints.

Technology: Shape Memory Alloys (SMA) are a group of metal alloys that exhibit different sets of physical properties depending on their temperature. In the martensite phase, when the alloy is cool, it becomes soft and ductile and can be easily deformed. If it is heated, it will transform to the austensite phase, where it reverts to its original shape. SMAs are capable of generating large forces it they encounter resistance in the martensitic transformation. SMAs can be heated with an electrical current, they produce large repeatable strokes, and they are proven to be biocompatible.

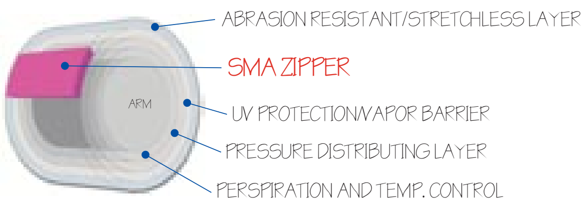
Application: Counter-pressure must be applied to the body to simulate the correct atmospheric pressure. Small braces or clasps can line along the seams of the organic or synthetic second skin material. To seal the body and provide a uniform distribution of pressure, the bands can be constricted to draw the material together. SMA technology can be used create a constricting clasp.

Resources:
TiNi Alloy Company
1619 Neptune Drive
San Leandro, CA 94577
(510) 483-9676

Shape Memory Applications, Inc.
2380 Owen Street
Santa Clara, CA 95054
(408) 727-2221



EAZS Concept (glove not shown).



EAZS Layers (not proportional).

Electric Alloy Remote Zipper Suit Concept

The Electric Alloy Zipper Suits (EAZS) uses shape memory alloy strips to aid and control the application of mechanical counter pressure while manually zipping together seams in the Uni-Directional Stretch Fabric Layer (UDSFL). SMA strips permanently connect the seams of the UDSFL, but relax when voltage is not applied to allow the seam to expand for suit donning. During the zipping operation, voltage to the SMA is controlled to provide the correct mechanical counter-pressure.

Technology: Shape Memory Alloys (SMA) are a group of metal alloys that exhibit different sets of physical properties depending on their temperature. In the martensite phase, when the alloy is cool, it becomes soft and ductile and can be easily deformed. If it is heated, it will transform to the austensite phase, where it reverts to its original shape. SMAs are capable of generating large forces it they encounter resistance in the martensitic transformation. SMAs can be heated with an electrical current, they produce large repeatable strokes, and they are proven to be biocompatible.

Application: Using SMA technology, an interlocking mesh of SMA can be used to create a seam for and constrict the mechanical counter-pressure layer. The interlocking mesh resembles that of a zipper. The mesh is interlocked manually as if it were a zipper. The SMA is then stimulated by a temperature change, possibly by a trip set off when the seam is fully closed.

Resources:
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1619 Neptune Drive
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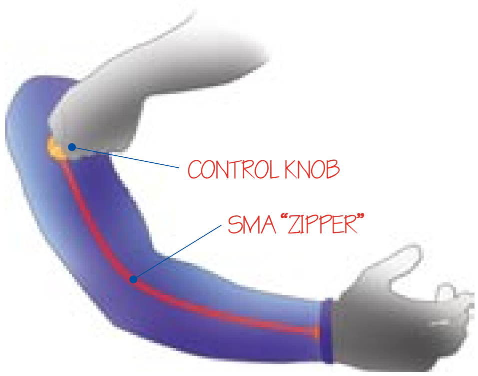
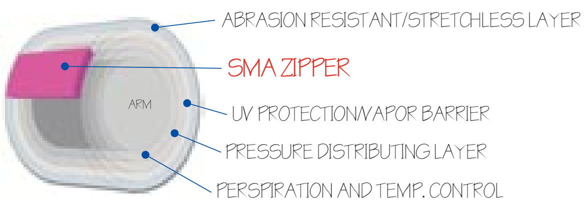
Shape Memory Applications, Inc.
2380 Owen Street
Santa Clara, CA 95054
(408) 727-2221



SMA Remote Zipper Concept (glove not shown).



EARZS Layers (not proportional).

Electric Alloy Remote Zipper Suit Concept

The Electric Alloy Remote Zipper Suit (EARZS) uses the same principle as the EAZS concept, but instead of being zipped manually, the UDSFL is tightened all at once by digital controls at the shoulders. This system assures uniformity of mechanical counter-pressure and ease of operation. Because it is digitally controlled, if necessary it is able to automatically adjust mechanical counter-pressure during EVA.

Technology: Shape Memory Alloys (SMA) are a group of metal alloys that exhibit different sets of physical properties depending on their temperature. In the martensite phase, when the alloy is cool, it becomes soft and ductile and can be easily deformed. If it is heated, it will transform to the austensite phase, where it reverts to its original shape. SMAs are capable of generating large forces it they encounter resistance in the martensitic transformation. SMAs can be heated with an electrical current, they produce large repeatable strokes, and they are proven to be biocompatible.

Application: Using SMA technology, an interlocking mesh of SMA can be used to create a seam for and constrict the mechanical counter-pressure layer. The interlocking mesh resembles that of a zipper. The mesh is interlocked using a remote device that stimulates the SMA with heat. The seam is then formed.

Resources:
TiNi Alloy Company
1619 Neptune Drive
San Leandro, CA 94577
(510) 483-9676

Shape Memory Applications, Inc.
2380 Owen Street
Santa Clara, CA 95054
(408) 727-2221

2.4 Additional Considerations

Beyond providing counterpressure to the skin there are many other issues facing advanced suit development. These include, but are not limited to, thermal considerations, atmosphere generation and maintenance, and radiation protection. The Bio-Suit project focussed mainly on pressure generation at this level, but also developed some thermal concepts illustrated in the following section. These concepts explore overall strategies for maintaining a comfortable operating temperature for the astronaut, but do not explore their feasibility. They represent strategies produced while brainstorming as opposed to technically evaluated concepts.

2.4.1 Thermal Concepts

2.4.1.1 Absorb Concept

2.4.1.2 Vent Concept

2.4.1.3 Transport Concept

Absorb Concept

Thermal Control, Absorb Concept

The Absorb concept for thermal control collects perspiration in a removable component within the suit. One version of the concept involves collecting perspiration in a highly absorptive fabric layer similar to long underwear. Another concept involves collecting perspiration in desiccant packs at critical locations. These packs could then be removed and disposed of, or recharged for future reuse. A vapor barrier layer above the absorption layer prevents contamination of outer layers.

Technology: A semi-permeable membrane is a material that is selective in what molecules pass through. Perspiration, consisting of water, salts, urea, and skin oils, must be transported away from the skin surface to provide a more comfortable environment. Organic biomaterials such as Integra Dermal Regenerate Template or Advanced Tissue Sciences Dermagraft move moisture away from the skin. By channeling the perspiration away from the skin, the body can maintain homeostasis under an artificial atmosphere.

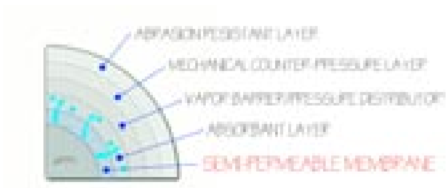
Application of Technology in Design: The semi-permeable layer is used to draw the perspiration away from the skin. The waste is then obtained within a layer of the suit. Collagen matrices are bioabsorbable and may have the potential to wick away perspiration. Collagens, usually made of either animal or human cells, are now also being produced with synthetic materials. This capability will allow for ease of manufacturing in space. Since the layer is organic, it can be thrown out and recycled.
Resources:

Advanced Tissue Sciences
10933 North Torrey Pines Rd.
La Jolla, CA 92037-1005
(619) 450-5730

Integra LifeSciences
105 Morgan Lane
Plainsboro, NJ 08536
(609) 275-0500

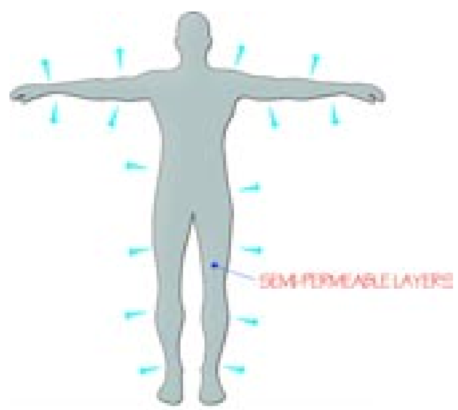
OsteoBiologics, Inc.
12500 Network, Suite 112
San Antonio, TX 78249
(210) 690-2131

TEI Biosciences Inc.
7 Elkins St.
Boston, MA 02127
(617) 268-1616



Absorb Layers (not proportional).

Thermal Control, Vent Concept



Vent-to-Atmosphere Concept

The Vent-to-Atmosphere (VTA) concept controls perspiration by venting moisture directly to the outside environment. A selective, semi-permeable organic layer closest to the skin allows perspiration to pass through at a moderate rate. Subsequent layers of the suit, including the mechanical counter-pressure layer, are also semi-permeable. The openings in the membranes are large enough to allow the suit to breath, but small enough to prevent unwanted fluid loss. The selectivity of the organic layer insures that only perspiration is taken away from the body.

Technology: Semi-permeable membrane is a material that is selective in what molecules pass through. Perspiration, consisting of water, salts, urea, and skin oils, must be transported away from the skin surface to provide a more comfortable environment. Synthetic materials such as Gore-Tex move moisture away from the skin. By channeling the perspiration away from the skin, the body can maintain homeostasis under an artificial atmosphere.

Application of Technology in Design: Through the use of semi-permeable materials, perspiration can be directed out to the atmosphere. This eliminates any need for collecting the waste products. However, all layers must be porous and semi-permeable. Such a specification for all materials will severely limit the possibility of materials. The semi-permeable layer(s) must be insulating and provide adequate mechanical counter-pressure in a Mars atmosphere.

Resources:
Advanced Tissue Sciences
10933 North Torrey Pines Rd.
La Jolla, CA 92037-1005
(619) 450-5730

Integra LifeSciences
105 Morgan Lane
Plainsboro, NJ 08536
(609) 275-0500

OsteoBiologics, Inc.
12500 Network, Suite 112
San Antonio, TX 78249
(210) 690-2131

TEI Biosciences Inc.
7 Elkins St.
Boston, MA 02127

VTA Layers (not proportional).

Transport to Remote Collection Concept

Thermal Control, Transport Concept

The Transport concept for thermal control uses a layer of tiny tubes to channel perspiration away from the body to a remote collection point. These tubes might be manufactured or perhaps organic such as the aquaporin network in plant membranes. A partial vacuum at the collection end might move perspiration through the tubes, or perhaps work will be done by tiny piezoelectric pumps powered by energy harvested from body motion. A semi-permeable layer beneath the transport layer will assure that only perspiration is removed from the skin surface. A vapor barrier layer above the transport layer prevents contamination of outer layers.

Technology: Water crosses cell membranes either by diffusion through the lipid bilayer or through tiny water channels called aquaporins. Though researchers do not yet have a clear understanding of the structural equivalent of these channels, they are known to exist in several different types of tissues. Their potential or known functions vary depending on the tissue type and the stage of tissue development. They help maintain fluid balance in the lenses of our eyes, they are used for osmotic protection in red blood cells and they help reabsorb water in the collecting ducts of the kidneys.

Application of Technology in Design: With the current biotechnology, skin and nerve regeneration has been achieved. The synthesis of more complicated tissues and organs are in progress. By manipulating the genetic structure of the aquaporins, it may be possible to generate a channeling system that can remove perspiration, not just water, from the surface of the skin to central collection chambers.

Resources:
Advanced Tissue Sciences
10933 North Torrey Pines Rd.
La Jolla, CA 92037-1005
(619) 450-5730

Integra LifeSciences
105 Morgan Lane
Plainsboro, NJ 08536
(609) 275-0500

OsteoBiologics, Inc.
12500 Network, Suite 112
San Antonio, TX 78249
(210) 690-2131

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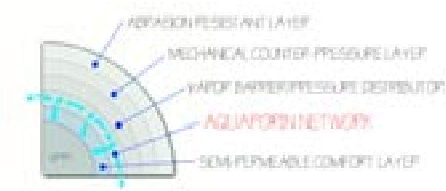


Transport Layers (not proportional).

2.5 Limitations

Due to the long term projections of this report, and the rapid advancement of material technologies, the Bio-Suit Phase I represented here does not include numerical analysis of the concepts envisioned. This phase of the effort was approached as a concept development exercise that would serve to free thoughts from the constraints of tradition and currently actualized systems. Because of this, strategies to provide the required skin pressure were investigated without modeling and analysis, which will take place in the near future. This study encompassed many meetings with developers of the technologies mentioned which allowed us to get a sense of the state of the relative arts and their applicability to the needs of the Bio-Suit system. This enabled us to gage whether or not such technologies could truly advance the capabilities of space suits, or whether they might complicate issues. This feedback permitted us to revise design concepts and pursue solutions to these high level issues.

This effort was also limited by its focus on space suit pressure issues. In environments such as Mars or the Moon, radiation, temperature control, maintenance/repair, and other life support features will clearly be a major concern. As these issues are already being investigated by other researchers, it was decided that the Bio-Suit project would focus on revolutionary pressure and mobility issues. As shown by previous research, the limited mobility of current suits originate from pressure issues, thus in order to facilitate the type of activities required on future exploration class missions this area must be greatly advanced or else be a limiting factor for exploration possibilities.

2.6 Summary

The MCP and thermal concepts illustrated here represent a small glimpse of future possibilities. The Bio-Suit design group feels that the technologies investigated have the possibility of revolutionizing the way extra-terrestrial terrain is explored by allowing the explorer a true sense of freedom. This freedom is realized from the moment of donning and throughout the EVA by facilitating actions that were previously thought impossible in these extreme environments.

Each design concept was conceived to allow the explorer the same ease of donning as we experience with clothes. Conceptually this is achieved by having a suit that shrinks around the wearer once it is donned. In each concept, the wearer would slip into the MCP garment as if it were a pair of long underwear. Once the wearer was ready, the suit would slowly shrink to the point where adequate MCP was achieved. Once properly “pressurized,” the suit would minimally restrict movement if at all.

Designs such as the EARZS allow tweaking of the suit tension at local points on the body. These concepts would allow the wearer to “resize” their suit real-time, thus facilitating maximum comfort. In addition, these concepts would accommodate changes of the body during the mission due to things such as muscle atrophy, weight gain, or spinal elongation.

Future work will explore a proof of concept prototype and further investigation into the applicability of each concept. Once numeric requirements can be determined, such as percent strain and number of cycles, each technology can be critically reevaluated. This will lead to new design concepts as well as furthering the existing concepts.

3.0 Revolutionary Visions: Fly-throughs and Illustrations

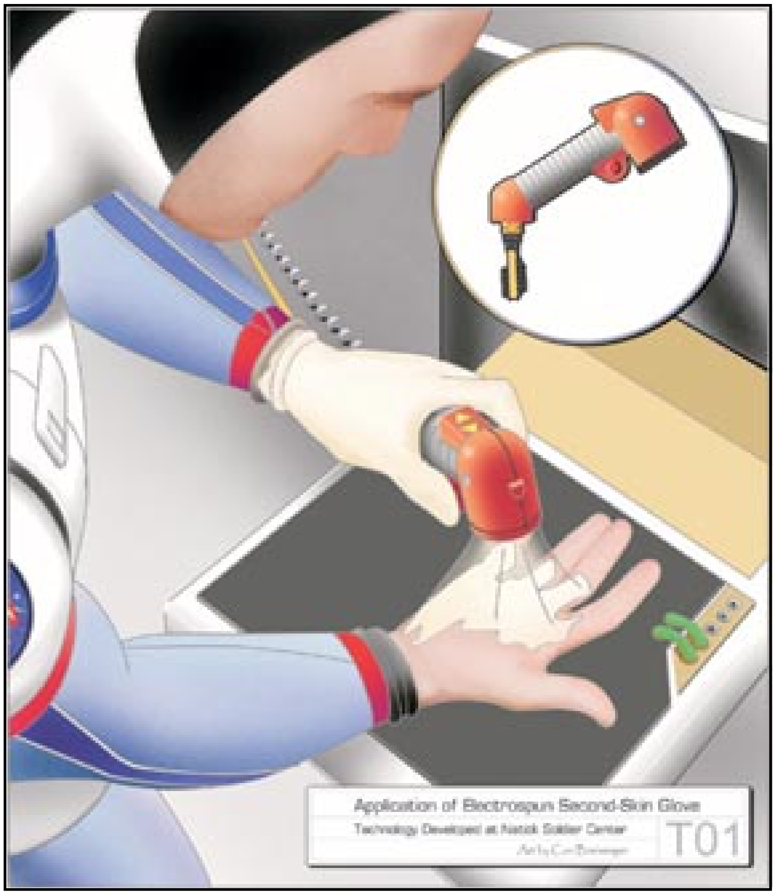
3.1 Advanced Technologies

3.1.1 Electrospinlacing

Electrospinlacing involves charging and projecting tiny fibers of polymer. Versions of this process can involve projecting directly onto the skin, or projecting elastic or semi permeable materials. The electrospinlacing hardware can be consolidated into a small unit, but the current limitation for any size unit is the rate at which material can be spun. For now, high volume can be achieved with multiple jets. In the future, the airborne fibers may be accelerated by an electrical field. It is important to note that electrospinlacing is a solvent based system. Its practicality for space use might involve questions about power consumption and necessity of dangerous chemicals. As this is a nacient technology, however, we did not see this a limitation.

3.1.2 Melt blowing

Melt blowing is another projecting process which involves liquefying polymer and blowing it onto surfaces. It does not produce fibrous material, but is good for creating thin elastic layers. Both electrospinlacing and melt blowing, but especially the latter, have been used in limited applications, commercially.



Electrospinlacing is a process where a multi-filament fiber of polymer is sprayed onto a grounded surface, which is achieved by charging a suspended drop of polymer with tens of thousands of volts. At a characteristic voltage the droplet forms a Taylor cone, and a fine jet of polymer releases from the surface in response to the tensile forces generated by interaction of an applied electric field with the electrical charge carried by the jet. The projected polymer can be collected as a continuous web of fibers in a range of thicknesses. Application can be made directly to the skin as shown, or to advanced 3D forms from laser scans. Wearable computers, smart gels and conductive materials could be embedded between polymer layers in future space suit applications. Electrostrictive gel is used to create a seamless mechanical counter-pressure (MCP) layer. A simple hand-held spray device is used for self application.

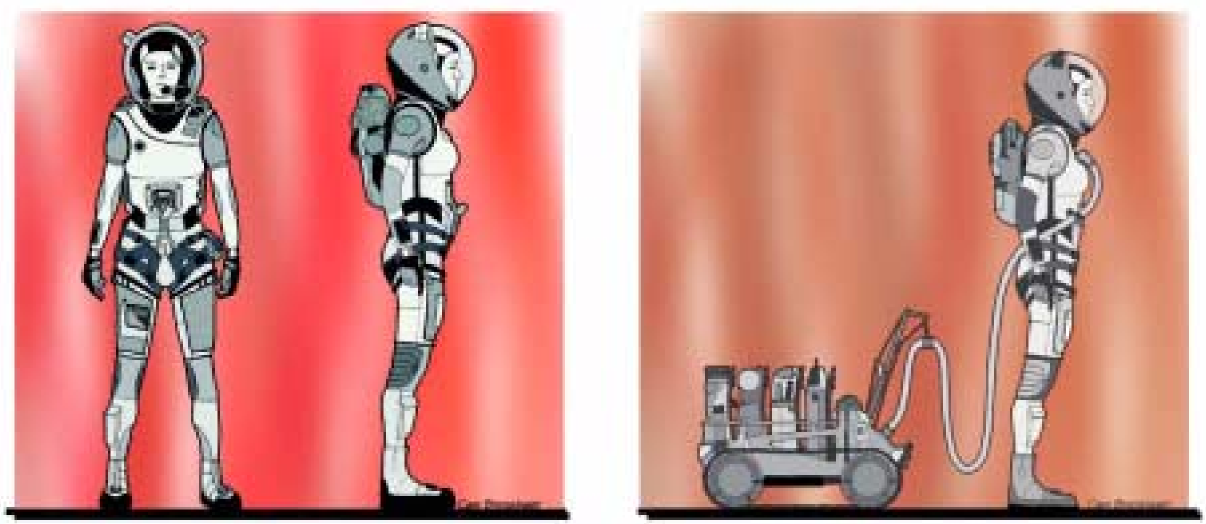
Melt blowing involves liquefying polymer and blowing it onto surfaces. It does not produce such fibrous material as electrospinlacing, but is good for creating thin elastic layers. Both melt blowing and electrospinlacing processes, but especially melt blowing, have been used in limited applications, commercially. Application can be made directly to the skin as shown above, or to advanced 3D forms generated by laser scanning. Wearable computers, smart gels and conductive materials could be embedded between polymer layers. In the above illustration, melt blown gel is used to create a seamless MCP layer over the entire body. A shower-like spray device is used for self application.

3.1.3 Artificial Skin

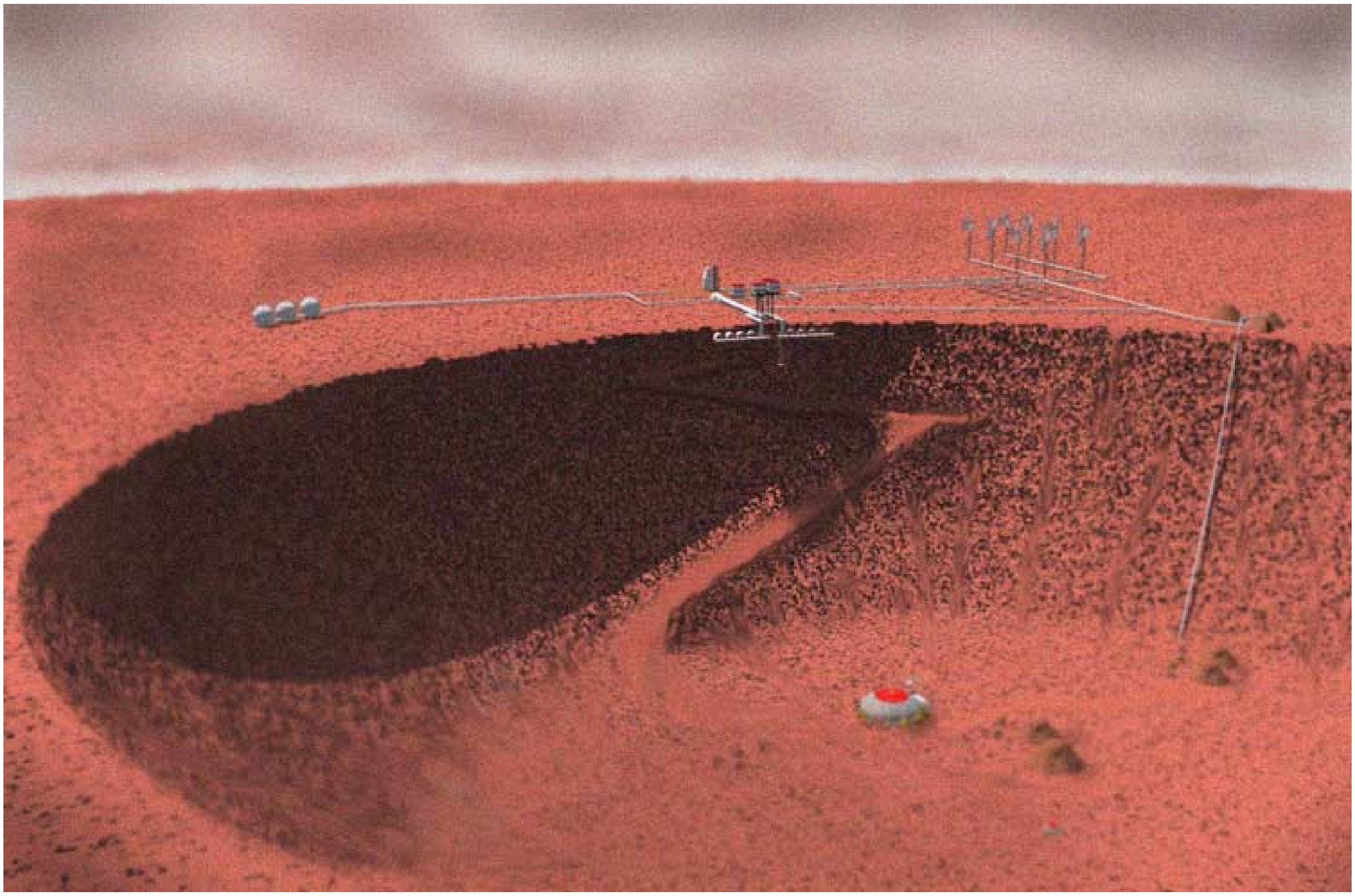
Research in the area of artificial skin has progressed to the point where synthetic and organic materials are being used to treat burn victims regularly. Initially we envisioned that these materials could be customized to meet the requirements of the Bio-Suit system, thereby truly actualizing the second skin capability. Our research showed, however, that the artificial skin being used today is used as a bandage more than a prosthetic skin. The artificial skin acts as a barrier against infection while providing a structure within which the new skin can grow. Thus, at this level of development, artificial skin technologies serve more as a point of interest than a truly applicable technology.

Perhaps, in the future, however, the technology will advance to the point where we could actually grow the Bio-Suit second-skin from organic material. Another concept that presents itself is that of a supporting matrix that skin can grow into. Just like other composite materials, this matrix would be capable of restraining the skin when exposed to reduced pressure. In this approach the human skin itself is augmented without needing a second layer. This has many implications that were not explored, but provides an alternate view of a space suit.

3.2 Visualizations

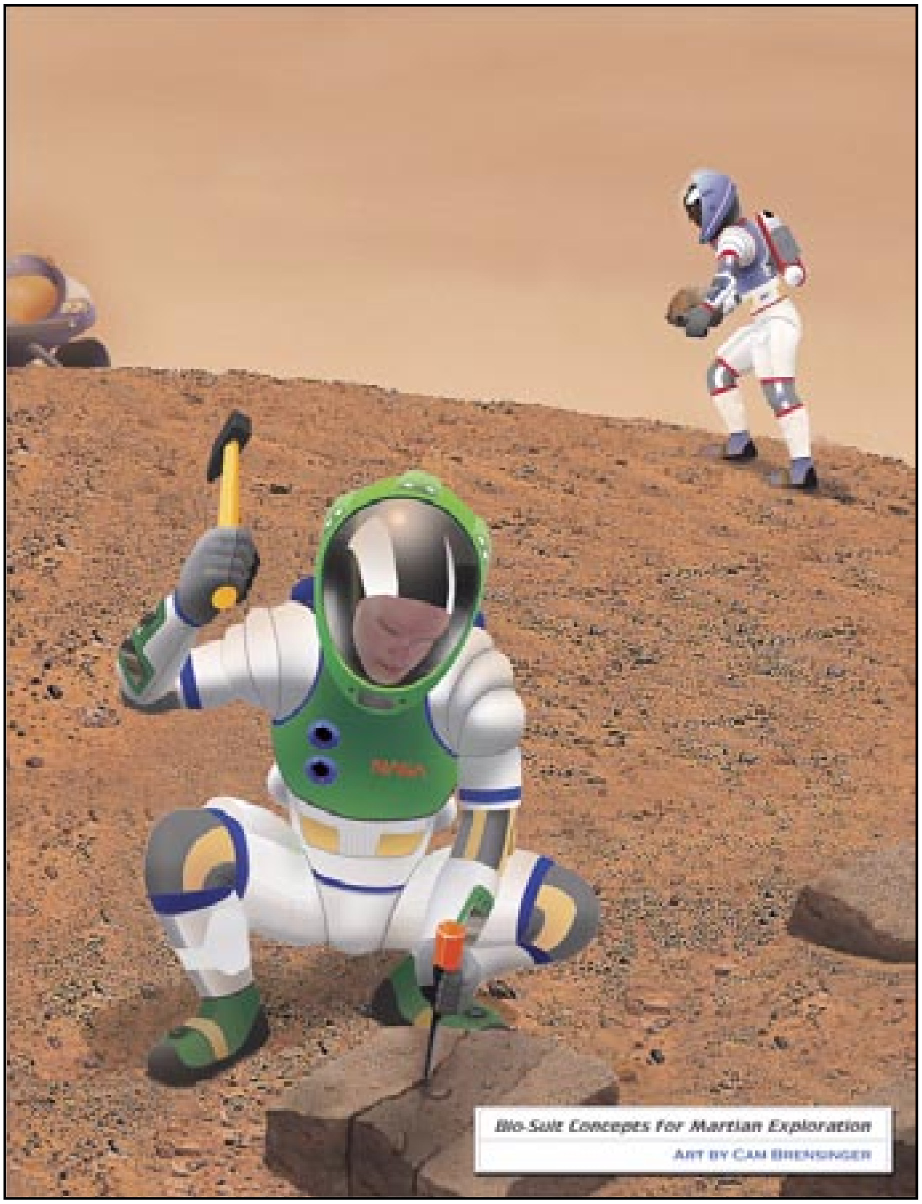


These images depict an astronaut wearing a mechanical counter-pressure (MCP) suit outfitted for extreme Martian exploration (left) and long-duration missions (right). A 'skin suit' layer is complemented with climbing gear, communications, biosensors, and wearable computers for duty that requires high-slope traverses, repelling, and investigating craters (left). A modular design is shown (right) with an umbilical for life support to replenish and recharge oxygen canisters to increase EVA duration and lighten the load on the crew-member. This *little red wagon scenario* offers some advantages over conventional backpack portable life support systems, such as, increased mobility, dexterity, and comfort for exploration. Wearable computers, smart gels and conductive materials could be embedded in the second skin bio-suit design.



A vision of a future Mars colony situated on a crater rim. Depicted components of the colony include a nuclear power station, a crator rim laboratory outpost, a wind power generation station, and a crator floor laboratory outpost. In a colony such as this, EVA is as common as stepping outside to go for a walk, or to check on the status of hardware. It is in an environment such as this that the Bio-Suit concept enables the user complete integration with her environment. As is depicted in other visualizations, the Bio-Suit allows colonizers the ability to scale the windmills for maintenance and repair, finalize and agreement with a hand shake, and work as a team to install the latest piece of station hardware. By facilitating such personal interactions during EVA, the Bio-Suit enables revolutions in the current exploration paradigm.

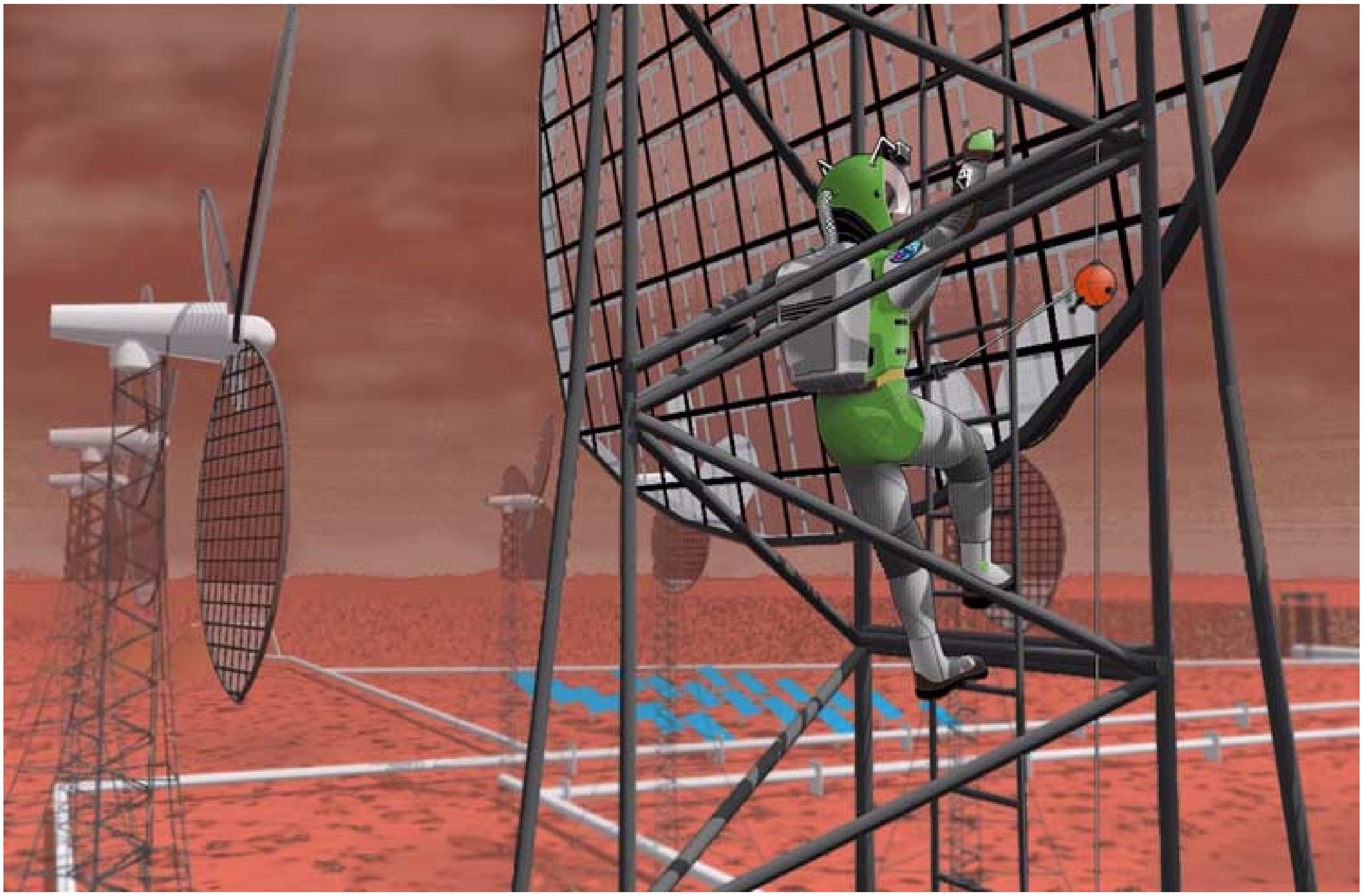
An astronaut on Mars donning the comfortable elastic bio-suit layer (1). The hard torso shell (4) is donned next and seals with couplings at the hips and shoulders. The hard backpack, or portable life support system, (5) atttaches mechanically to the hard torso shell, and provides gas counter pressure. Gas pressure flows freely into the helmet (2) and down tubes on the elastic bio-suit layer to the gloves and boots (3). The bio-suit layer is lightweight and easy to don and doff. It is custom fitted to each astronaut using a laser scanning/electrospinlacing process (Natick Soldier Center). Remaining suit elements are simple, functional, interchangeable and easy to maintain and repair.



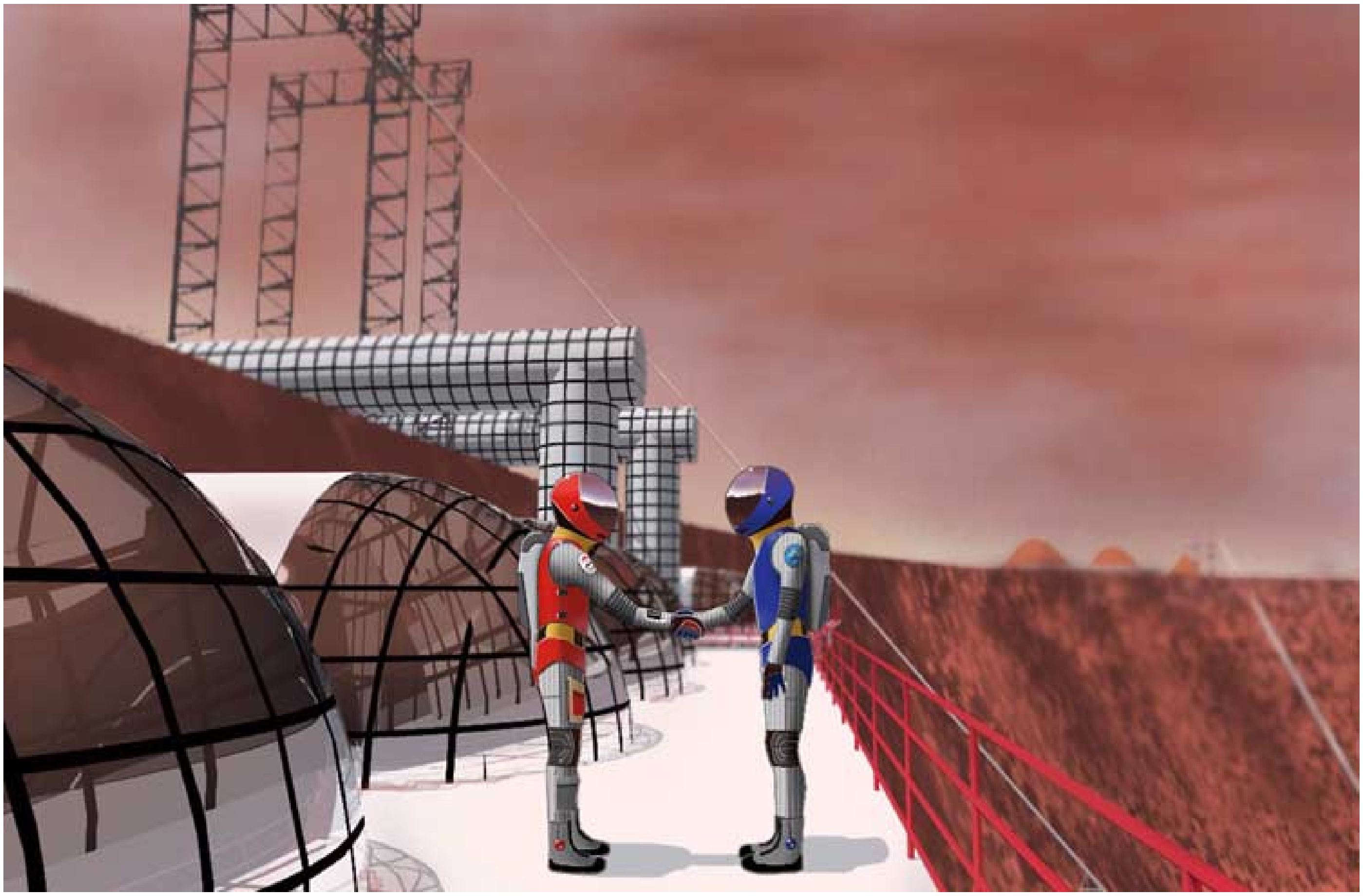
In this version, the Bio-Suit concept is shown with integrated hard torso and mid-section, wearable computers, muscle augmentation and a high visibility helmet. Ball joints, protected beneath a soft dust proof shell, allow a safe and flexible transition from mechanical counter-pressure (MCP) sleeves to the hard upper torso. Extremely abrasion and temperature resistant Kevlar/Zylon skin-suit sections protect the knees and elbows. Smart fabric sections at the calves and forearms actively suppliment counter-pressure to reduce muscle fatigue. Elbows and knees have soft gel polymer bands that comfortably augment articulation. The MCP layer is concealed beneath the white, UV protective stretchy dust proof layer. Hands and feet also receive MCP, covered by lightweight protective boots and gloves. The entire outermost dust proof layer is lightweight and washable. Suits are colored for easy astronaut identification.

A vision of a drilling for core samples on the floor of a Martian crator. In situations such as this, the Bio-Suit allows for unimpeded interaction with drilling equipment and fellow researchers. Due to the increased dexterity of the researcher, made possible by the Bio-Suit design, testing equipment can be as small and manageable as we expect on Earth. No longer are oversized components required to facilitate the bulk and limited mobility of space suits. In this vision, equipment is sized comparable to Earth bound equipment because the Bio-Suit is no more cumbersome than the average set of clothes.

A vision of teamwork taking place within the Martian colony. While moving precision instruments, individuals need to be able to communicate easily between each other and react quickly to changing situations. Because activities such as this become a standard occurrence time cannot be spared to plan procedures around cumbersome equipment. The Bio-Suit is designed to facilitate work in much the same way as we work here on Earth allowing tasks such as this to become "pick-up" activities requiring little to no pre-planing or task simulation.



Maintenance of a windmill within the Martian colony. Harvesting power from the Martian environment will be key to the success of Martian outposts such as this. In this vision we imagine windmills as one component of the power generation hardware. Here an individual scales a windmill for regular maintenance tasks. Activities such as this push conventional space suit design to the limit, but this task feels natural while wearing the Bio-Suit. This is because of its low bulk and MCP technologies which facilitate full range of motion as well as tactile feedback from the environment. Also, integrated into the Bio-Suit are components that allow attachment of such safety devices such as the Martian prussic (shown) or other scaling/repelling equipment. This facilitates the large range of activities required of the explorers on the surface of Mars.



A vision of a personal interaction on the rim of a Martian crator made possible by the Bio-Suit. In order to promote the type of research required of a Martian colony, personal interactions must be facilitated. Here we see two researchers finalizing an agreement in much the same way we would on Earth. Due to the low profile of the Bio-Suit and the increased mobility and tactile sense, interactions such as a handshake become possible and pleasurable. This demonstrates how the physical design of a space suit can directly impact he daily experiences of the wearer on a utilitarian, psychological, and emotional level, thereby promoting overall heath and happyness. Clearly on a long term mission these issues will be paramount.

4.0 Space Systems Flexibility

Another aspect of the Bio-Suit design effort included an investigation into systems lifetime design and flexibility. This was especially appropriate due to the long-term view of the NIAC mission. When contemplating future space missions 10 to 40 years hence issues of technology obsolescence must be addressed. Similarly, once designs become operational, we envision an evolving system capable of adapting to accommodate future demands/requirements in a timely and cost-effective manner.

4.1 Systems' Lifetime Design [32]

What drives a product's design lifetime? How do designers, managers, and/or customers decide on a system's lifetime requirement, and what is the rationale for specifying this requirement? Questions regarding the design lifetime requirement of complex engineering systems can be grouped into three categories:

1.What limits the design lifetime? How far can designers push the system's design lifetime? What is the lifetime "boundary" and why can't it be extended?

2. How do the different subsystems scale with the design lifetime requirement, and what is the total system cost profile as a function of this requirement?

3. What does (or should) the customer ask the contractor to provide for a design lifetime, and why?

According to Wertz and Larson (1999), the design lifetime requirement, in the case of satellite systems, is "assigned rather arbitrarily" with an understanding of the technical limitations and an intuition regarding the economical impacts associated with designing for longer lifetimes. But what are the economic impacts associated with a system's design lifetime? Can we formally capture them and quantify them? Is there an optimal design lifetime for a satellite that maximizes some economic metric? What characteristics of the system's environment, if any, should be taken into account, in order to select an optimal design lifetime? These are some of the questions that were addressed as part of the Bio-Suit effort. The purpose was to provide a formal process for specifying space system design lifetime.

Through the use of mathematical models and an understanding of systems design, an augmented perspective on system architecture was proposed that compliments the traditional views on system architecture. This investigation proposed a view of systems architecture in terms of the flow of service (or utility) that the system would provide over its design lifetime. It suggested that lifetime is a fundamental component of system architecture although one cannot see or touch it. A framework was then developed that identified optimal design lifetimes for complex systems in general, and space systems in particular, based on this augmented perspective of system architecture. It was found that an optimal design lifetime for space systems exists, and that it changes substantially with the expected Time to Obsolescence of the system. The analysis proved that it is essential for a system architect to match the design lifetime with the dynamical characteristics of the environment the system is/will be operating in. It also showed that as the uncertainty in the dynamical characteristics of the environment the system is operating in increases, the value of having the option to upgrade, modify, or extend the lifetime of a system at a later point in time increases depending on how events unfold.

Four major results were obtained relating to system lifetime design. These results were demonstrated through mathematical models illustrated graphically. The results and their respective implications are summarized in the table below.

Results	Implications
An optimal design lifetime exists.	Even if it is technically feasible to design a spacecraft for a longer lifetime, it is not necessarily in the best interest of a customer to do so.
The optimal design lifetime increases as the expected revenues per day increase.	The more a customer expects to generate revenues from a system, the longer he or she would want the system to remain operational.
A minimum design lifetime exists for the system to become profitable, and it decreases as the expected revenues per day decrease.	A minimum revenue per day must be guaranteed for the system to be profitable. In order to decrease the minimum design lifetime for the system to be profitable, and consequently the time to break even, more revenues per day must be sought.
An optimal design lifetime can exist for which the system is not profitable.	Even if a system is fielded with the knowledge that it will not be profitable, it still can be designed for a period of time such that the losses are minimized (as opposed to maximizing its profits).

4.1.1 Flexibility in Systems Design [31, 33, 34]

In addition to exploring the design of system lifetime, flexibility was investigated as a means of extending system lifetime in environments of rapid change. Flexibility was defined as the ability of a system to respond to changes in its initial objectives and requirements, occurring after the system has be fielded, in a timely and cost-effective manner. The concept behind basing space system designs on flexibility is to achieve truly evolvable hardware and software systems. In the case of future terrestrial exploration, uncertainty, and therefore change, will be an inevitable occurrence, therefore requiring system flexibility. Similarly, due to the long development times and mission durations involved, these missions will have to maintain the ability to keep up with the fast pace of technology turnover. If an outpost is set up on Mars, for example, the systems cannot be outdated upon launch, landing, or even within the first decade of operations. Therefore, systems flexibility is a design component that must be addressed. We argue that flexibility reduces a design's exposure to uncertainty, and provides a solution for mitigating market risk as well as risk associated with technology obsolescence.

Extending a system's design lifetime has several side effects: Fielded systems with long design lifetimes can become obsolete, technically and commercially, before the end of their mission. In many cases, such as projected exploration class missions, the initial circumstances from which the original system requirements were derived change or are modified during the system's operational lifetime. In these high-value assets, it is desirable to have systems that are flexible and can adapt to new or emergent missions and roles, instead of fielding new ones.

Flexibility is thus a key property that should be embedded in high-value assets, particularly as they are being designed for increasingly longer design lifetime. But how can one design for flexibility? What are the design practices for embedding flexibility in design? What are the trade-offs associated with designing for flexibility (value of flexibility, cost penalty, performance penalty, etc.)?

Flexibility has become in recent years a key concept in many fields, particularly in most design endeavors. Indeed, for a multitude of disciplines, such as urban planning [26], architecture [14], finance [4], manufacturing [29], software design [16] and others, flexibility is hailed as critical. However, few attempts have been made to formally and unambiguously define it. Intuitively, flexibility is understood as the ability to respond to change. Although essential, this feature nevertheless fails to distinguish it from other properties such as robustness. Furthermore, the literature on design is replete with terms related to a system's ability to handle change, such as adaptability, changeability, agility, elasticity, etc. But when one seeks to grasp their concrete content, such terms often fail. So what are the characteristic features of flexibility? How can one formally define it and quantify it?

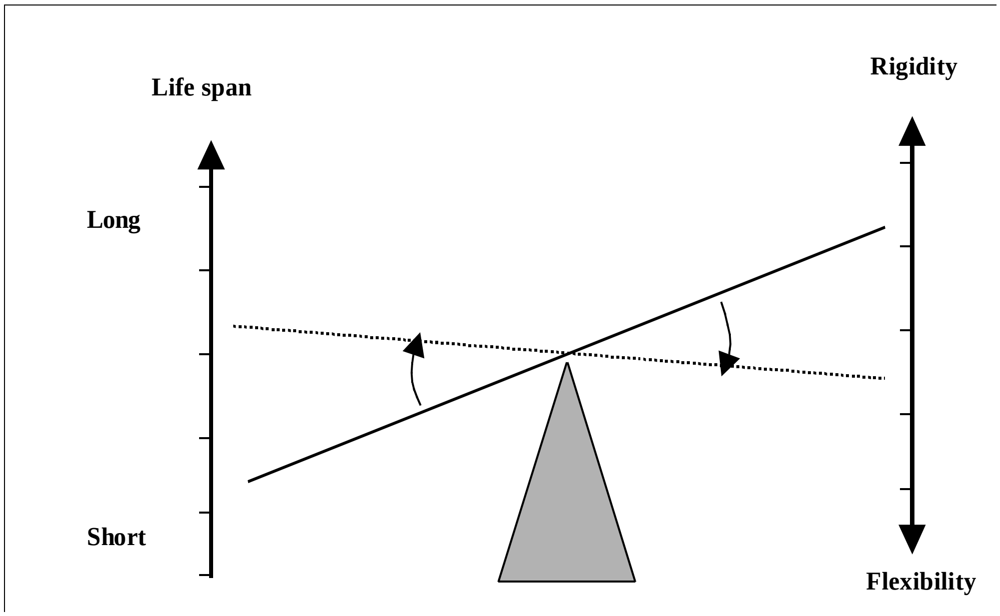


Figure 4.1. Simple model relating a system's (living or inert) life span and its flexibility, which will loosely be defined for the time being as the ability of a system to handle changes.

Current research that has addressed the issue of achieving flexibility in the multidisciplinary design [6, 7, 20] have dealt with different ways of specifying requirements and handling their dynamics or changes occurring prior to T_{ops}. This is the time period with which "flexibility in the design process" is concerned. Process flexibility include activities, methods and tools devised to mitigate the risks—cost, schedule, and performance—resulting from requirement changes occurring before fielding a system.

This is not the focus of this work. We were mainly concerned with changes occurring after T_{ops}. But what are these changes about? Changes can occur in the system's environment (political, cultural, organizational, physical, etc.), in the system itself (e.g., wear and tear), or in its requirements—capabilities and attributes—resulting from changing customer needs.

A corollary of our definition of flexibility is that a flexible system can be modified in a timely and cost-effective way in order to satisfy different requirements at different points in time. These requirements, or requirement changes, as well as the time of occurrences of these changes, can be known or unknown a priori.

As stated previously, the distinction between the two concepts, robustness and flexibility, is a subject rich with ambiguity. Any attempt to define flexibility should address this issue. Flexibility, as defined herein, implies the ability of a design to satisfy **changing requirements** after the system has been fielded, whereas robustness involves satisfying a **fixed set of requirements** despite changes in the system's environment or within the system itself. The relation between flexibility and robustness of a design as a function of the system's objectives and environment is graphically illustrated in Figure 4.2.

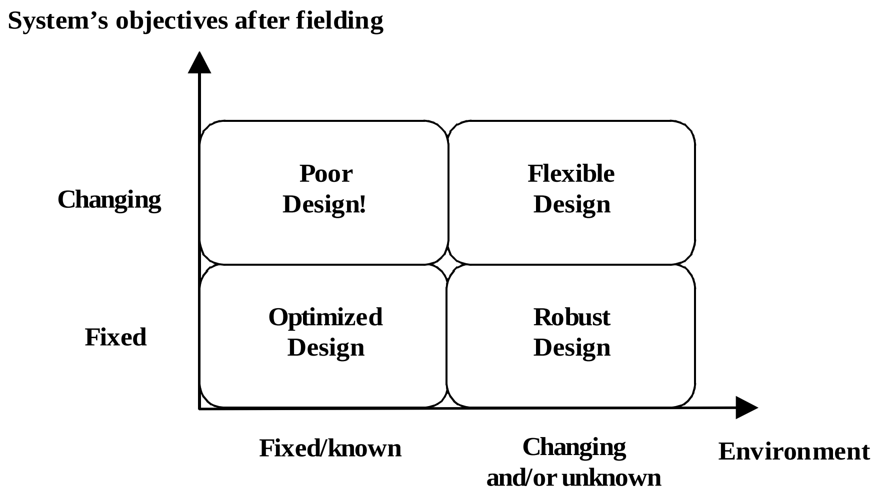


Figure 4.2. Flexibility and Robustness as a function of the system's objectives and environment.

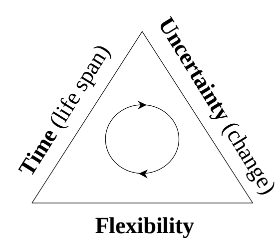


Figure 4.3. The Trilogy: Time, Uncertainty, and Flexibility. Systems that have a longer life span are the ones that are capable of coping with uncertainty and changes in their environment (analyst's perspective). Conversely, if a system is to be designed for an extended design lifetime, the ability to cope with uncertainty and changes has to be embedded in the system (designer's perspective).

The study on system flexibility lead to an exploration of many case studies and how they relate to flexibility. This report captures the first phase of this investigation: answering the question, "Why or when is flexibility needed in system design?" Clearly a thorough investigation into flexibility must answer this question as well as others, including: How can one design for flexibility? and What are the trade-offs associated with designing for flexibility? These are topics that are part of an ongoing investigation.

5.0 Summary

5.1 Review

5.1.1 Brainstorming and concept development/visualization were used to explore the possibilities of truly advanced space suit concepts.

The Bio-Suit design effort encompassed a range of investigations including future space suit concepts and system lifetime/flexibility issues. These investigations lead to the development of several future suit concepts as well as a formal means of determining optimal systems lifetime. In order to accomplish this many technologies were investigated and many connections were made in industry and acedemia. In addition, many visualization techniques were used in order to convey the concepts developed and their future requirements.

In the first section of this report we evaluated the past and current state of space suit development. This included an analysis of current space suit mobility as well as past efforts to achieve mechanical counterpressure suits. This effort demonstrated the potential inherent in MCP as well as its challenges.

The second section of the report explored technologies that could enable the realization of MCP suits. Central to this endeavor was the notion of easily donable/doffable space suits. These concepts were communicated in a number of illustrations as well as textual descriptions of the technologies and their applications.

In the Visions section, far term possibilities were explored conceptually such as Martian settlements and advanced technologies such as electrospinlacing. These provided a storyline that was capable of guiding our design process.

Finally, space system lifetime and flexibility were addressed as key parameters in exploration class mission design. Analytical models were developed to determine optimal system design lifetime as well as evaluate the flexibility of systems.

5.2 Future Work

Although this report represents the end of the NIAC Phase I funding period, work on these concepts continues. Now that some key technologies have been investigated and their application has been envisioned, it is clear that a more thorough analysis must take place. This, along with conceptual analysis and prototyping are proposed future work.

5.2.1 Suiting for Transgression

5.2.1.1 Revisiting the motivations and potentials in space exploration

As stated in the proposal and this Phase I final report, “the proposed Bio-Suit System could revolutionize human space exploration.” In order to truly revolutionize and not just advance space exploration, however, the motivations and potentials within the action must be re-examined. We must look at our political, philosophical, and spiritual goals and design to achieve these. Why do we see these activities as important? How do they impact culture and society? What is their meaning on a daily basis? How can answers to these and other questions inform and shape our designs? This will be a central component of future research.

5.2.1.2 Cyborgology

As we answer these questions and investigate new technologies and strategies, such as that of a “second-skin,” science fiction notions start to immerge. One of these notions, that of the cyborg, has been with us since the beginning of the space age and has become an area of serious anthropological research, known as cyborgology.

In 1960, Clynes and Kline developed notions of actively pushing evolution to the point where humans could inhabit extreme environments without aid. They made the analogy of a fish walking on dry land and noted that it would be foolish for the fish to carry a small bubble of water onto land. Instead they suggested the fish should evolve to a point where it could comfortably walk on land without needing a bubble of water. Criticizing attempts at space suit design they stated that “artificial atmospheres encapsulated in some sort of enclosure constitute only temporizing, and dangerous temporizing at that, since we place ourselves in the same position as a fish taking a small quantity of water along with him to live on land. The bubble all to easily bursts.”[9]

As a solution, the notion of “cyborg” was introduced. “The cyborg deliberately incorporates exogenous components extending the self-regulatory control function of the organism in order to adapt to new environments.” These components can be internal or external such as a membrane that augments the skins capabilities. Clearly the notion of a second skin or a Bio-Suit start to approach these notions.

If space exploration is going to transgress existing possibilities via the Bio-Suit effort, anthropological issues must be investigated and addressed through the design of such a system. We must re-evaluate the roll of the astronaut as an explorer and as a representative of our species on earth. We must carefully design the physical, psychological, and cultural environment that future explorers inhabit during these explorations and truly understand what we are trying to gain from the experience. Currently the priorities of NASA state spiritual goals (inspiration, etc.) as a tersiary concern. Can or should this be the case if we decide to spend the money necessary to explore far away places such as Mars?

5.2.2 Prototyping.

In addition to exploring some of the philosophy behind space exploration and the Bio-Suit effort, further technology development will take place. As noted throughout this report, central to the success of MCP as a design strategy is the reduction of don/doff time of past MCP efforts. This will be pursued by prototyping an MCP suit for a section of a human leg.

In order to incrementally gain the experience necessary to prototype a full MCP suit, we will first investigate the knee region of a human leg. This region provides several types of learning opportunities. First there are the trunk sections of this region which provide both regular sections, which are almost circular like the thigh, and irregular sections, such as the calf, with the sharp curves of the shin. Second, this area contains a simple one degree of freedom joint that imposes challenges of its own, such as the concavities that develop upon flexing of the local muscles. In addition, the sizing challenges are present due to the narrow regions, such as the ankle, that lie beyond wider regions, such as the heel, during the donning process.

In order to build up to this large degree of complexity, work will begin with simple, regular, extruded sections, such as a cylinder, and attempt to produce even mechanical counterpressure. Once this is achieved with easy don/doff characteristics, such as shrinking, more complicated sections can be attempted, until finally the demands of a three dimensional, true human leg can be met.

Once this level of development has been reached, facilities such as the NASA Robot Space Suit Tester (RSST), affectionately known as M. Tallchief, currently on loan to MIT can be used to evaluate the prototype against a bare human leg and the capabilities of current, pressurized, space suits. Both human and robotic testing will allow subjective and analytical torque measurements to be taken so that a full evaluation of the prototype can be performed.

5.2.3 Continued Effort in Wearable Computing [5]

In addition to pursuing the MCP aspects of the Bio-Suit system, wearable computing will also be investigated. Research is currently in place to develop a wearable computing system for EVA astronauts at the International Space Station (ISS). This will serve as a testing ground for future wearable computing concepts and implementation methods.

Requirements suggest that a suit-internal wearable computer system would be potentially more advantageous than a suit-external wearable computer system because of display positioning issues, the challenges of connections across the suit-pressure barrier, the less stringent environmental extremes within the suit, and the flexibility for an suit-internal design to evolve into a dual use EVA/IVA design at some point in the future. A suit-internal design does suffer from a lack of access during EVA: safety is the primary concern here that will need to be addressed as the design evolves. Admittedly, a suit-internal wireless system might require multiple antennas (because of potential blockage), and would increase astronaut non-ionizing radiation exposure and complicate donning and doffing procedures.

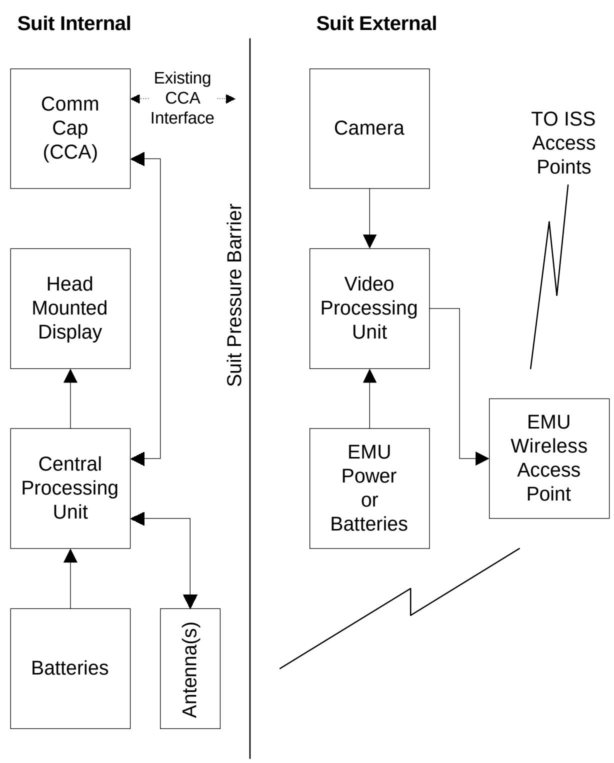


Figure 4. A possible wearable computing prototype.

Figure 4 illustrates one possible prototype system under consideration that would utilize a suit-internal wearable computer system with a suit-external wireless access point and helmet mounted video camera and encoder. A low power CPU core and batteries would be packaged in a body conformal form factor (potentially in the abdominal area or in the small of the back). Potentially, something not too dissimilar from StrongARM™ technology found in recent commercial products could be used. A near-eye display could be integrated into a standard pair of EVA glasses: this might be not unlike the current VGA-resolution embedded-glasses display prototypes produced by MicroOptical Corporation. Cabling could be routed through the LCVG so that it would not interfere with existing donning and doffing procedures. The audio and display cabling might also be physically integrated with the CommCap (CCA) cabling to simplify donning and doffing procedures.

The research project to develop this system is ongoing. While a preliminary concept for a prototype system has been developed, we are still in the process of trying to understand how our proposed wearable computer system can best support astronaut safety and performance during EVA. Over the next couple of months we will further refine our wearable computer system prototype design, with significant input from astronauts and other stakeholders. Over the next year we seek to deploy a prototype system for test and evaluation.

5.2.3.1 Design Recommendations: Wearable Computing

We propose that an initial wearable computer prototype for the EMU should be an information delivery system, requiring minimal input or control by the EVA astronaut, and allowing information to be delivered remotely by an intravehicular activity (IVA) crewmember, or by the MCC. This approach offers significant benefits to EVA astronauts while minimizing any operational impacts of the system in terms of time and complexity. Incremental addition of capabilities could then be pursued commensurate with training and experience. Furthermore, the wearable computer system would function as an element for mission enhancement: not required for any EVA tasks, but used to support well-defined tasks at varying levels of complexity. It would serve to augment existing systems, not to replace them.

Carr et. al's design approach relies heavily on near-term operational simplicity. This is consistent with the recommendations of Conners et al. [9] for future EVA system development based on interviews with the lunar surface astronauts. The astronauts recommended that future information displays should be simple and relevant to the current task, and desired safety related status information on a call-up basis. They were also supportive of visual displays for supporting operational tasks, and felt that both visual and aural communication links would be valuable.

5.2.4 Assisted Locomotion

In addition to the work described in this Phase I report, another pertinent research effort ongoing by the investigators includes development of human augmentation systems. Currently, a system is being developed that will augment the human ankle by means of a prosthetic shoe. This shoe is actuated about the major flexion/extension axis and is being developed for biomedical purposes with future space systems as a future application. Plans include extending this prosthetic's capabilities and addressing other joints incrementally.

The Bio-Suit project critically re-examines future space exploration through revolutionary, advanced space suit technology. This is accomplished by designing to augment the biological skin of the astronaut, thereby enhancing mobility, comfort, and symbiotic integration between space suit and wearer. Technologies investigated included shape memory alloys, 'smart' polymer gels, electrospinlacing, and melt blowing, all of which are currently actualized in laboratory settings or in commercial applications. These provided the means to build on past explorations of Mechanical Counter Pressure (MCP). MCP design concepts were framed by the focus on achieving the same ease of donning/doffing that we experience with clothes. This provides a means to remove physical, temporal, and psychological barriers to EVA activities and unlocks the true potentials of working within an extraterrestrial environment. Electrospinlacing and melt blowing further this push by providing the means to actualize 'science-fiction' notions of spraying on a space suit and embedding wearable computing devices within seamless layers. In all of these concepts, the life support system is assumed to be a bubble helmet with an advanced portable life support system backpack. Additional investigation includes, research into wearable computing, which holds the potential to augment an astronaut's communication and mental abilities; assisted locomotion, which provides a means to enhance her musculoskeletal capabilities; and space systems flexibility, providing a means to augment the capabilities of the suit, hab, and other systems. In order to communicate our visions, illustrations are provided which follow a storyline that shapes the design effort. As this work carries forward, the Bio-Suit project will re-contextualize future exploration endeavors thereby laying the groundwork for a revolution in the exploration paradigm.

6.0 Appendix

6.1 References

Preliminary Considerations for Wearable Computing in Support of Astronaut Extravehicular Activity

Christopher E. Carr[1], Steven J. Schwartz[2], and Dava J. Newman[3]
MIT Department of Aeronautics and Astronautics[1,3], MIT Media Laboratory[2]
chrisc@mit.edu, schwartz@media.mit.edu, dnewman@mit.edu

Abstract

Preliminary considerations for a wearable computer system for astronauts on International Space Station (ISS) during extravehicular activity (EVA) are discussed. The proposed system acts as a client on a wireless network external to the ISS, and provides text, graphics, audio, and video to astronauts using a near-eye display. Primary design considerations include astronaut safety, comfort, ease of use, operational simplicity, and cost. Requirements are highlighted for electrical design, in-suit thermal issues, the space environment, and EVA displays and controls. A suit-internal wearable computer system prototype is proposed. Suit-external components include a camera, video processor, and wireless access point, which provides access for both the suit-internal wearable and other potential wireless EVA tools. Future plans include development and testing of the prototype system.

1. Introduction

Wearable computing has the potential to enhance astronaut safety and performance by providing new or redundant support mechanisms for astronauts during extravehicular activity (EVA). Current predictions from the National Aeronautics and Space Administration (NASA) EVA Project Office estimate 168 days devoted to EVA for assembly and maintenance during the construction of the International Space Station (ISS) [1]. Wearable computing technologies are ideally suited for use during EVA because EVAs generally consist of well defined, tightly scripted tasks. Even in off-nominal situations, many tasks may be carefully scripted or follow contingency procedures. The requirements for a wearable computing system for EVA are constrained and bounded by a well-defined set of existing operational and engineering requirements.

The authors are currently engaged in a research project with the goal of developing a wearable computer prototype for use initially with the NASA space suit (the Extravehicular Mobility Unit, or EMU) and potentially the Russian Space Agency (RSA) space suit (the ORLAN suit). The system would provide text, graphics, audio, and video to an astronaut via a near-eye display while acting as a client on a wireless network external to the ISS. Figure 1 illustrates conceptual opportunities for visual information delivery during EVA as an astronaut might see them on a near-eye display.

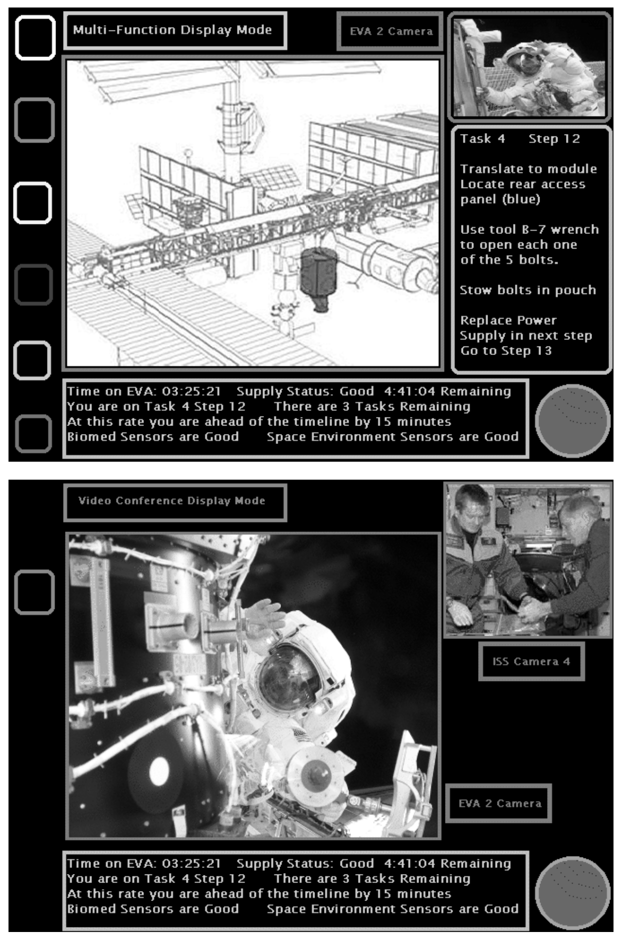


Figure 1 – Visual Information Delivery during EVA

The displayed information (along with audio capability) might be used to guide astronauts through a series of detailed procedures or provide timing, status, and safety information. Video-over-IP and voice-over-IP services could enable real-time videoconferencing between EVA astronauts and other crewmembers, or between astronauts and the Mission Control Center (MCC). Updated procedures, schematics, or images could be "uploaded" to the wearable computer and/or displayed on the heads-up display upon request.

This paper highlights important considerations in the development of a wearable computer system for use with the EMU.

2. Background

2.1 Types of EVAs

EVAs can be grossly characterized as planned, unplanned, or contingency (unexpected, but may be required for crew safety). For ISS EVA operations, there are planned and contingency EVAs [5]. Different flight rules apply for each type of EVA. EVA tasks or components can be characterized by their criticality, such as whether the accomplishment of a specific task would be safety critical, a requirement for mission success, or a mission enhancement. EVAs vary considerably in complexity: some EVAs require only a standard set of tools and skills, while other EVAs require specialized tools specific to a given task or mission. Finally, very complex EVAs may require both specialized tools and a "significant extension of capabilities" including challenging "access (or restraint) problems, or require extended duration or unrestrained translation such as with a propulsion maneuvering unit."[6]

2.2 Origins of the EMU and ORLAN suits

The EMU design has its roots in the space suits of the Apollo program, when an integrated portable life support system (PLSS) was developed to enhance mobility for surface exploration. Previous designs, used during the Gemini program, had provided life support function using a life-support tether. Development of the current-day EMU started in 1973, and it was first used on orbit in 1983. Evolutionary improvements have resulted in the suit that is currently used. The Russian ORLAN suit has evolved from the Salyut-Soyuz program, and has an integrated portable life support system.

2.3 Space Suits as Wearable Computers

In a sense, the EMU and ORLAN suits already meet one definition of a wearable computer[7]: They are portable while operational, capable of hands-free use, able to sense characteristics of the environment (at least the internal environment), are always on (during EVAs), and augment human capabilities.

The display and control module (DCM) of the EMU provides an alphanumeric display of life support status and allows the astronaut to control features of the life support system.

A suit-external independent electronic cuff checklist, developed to serve as a limited mechanism for astronauts to reference procedures or contingency procedures, was flown as a space flight experiment. Despite the success of this project, a wrist mounted paper checklists still serves as the primary written procedural reference during EVA.

2.4 Limitations of Extravehicular Activity

Major limitations during EVA include the need to cope with sensory degradation, the limited duration of EVAs, limited mobility, dexterity, force application, and endurance of suited astronauts, operations time and resource overhead requirements, working volume and access limitations, and hazards to crewmembers [6].

A system capable of mitigating some of these limitations might therefore (1) sense characteristics of the external environment and communicate those characteristics to the astronaut; (2) extend or augment the senses or capabilities of the astronaut; (3) enhance the efficiency with which tasks can be carried out, and (4) minimize any negative impacts on operations time and resource overhead.

The existing systems provide only limited capabilities of information transfer to or from an astronaut during EVA. The primary method of information transfer during EVA has been two-way voice communication over UHF. Life support parameters from the EMU are also sent over the UHF communication system to the Shuttle or ISS and from there via downlink to the MCC. An EMU TV camera has also been used to provide video coverage of EMU worksites. Figure 2 illustrates one of the limitations of the existing communications system:

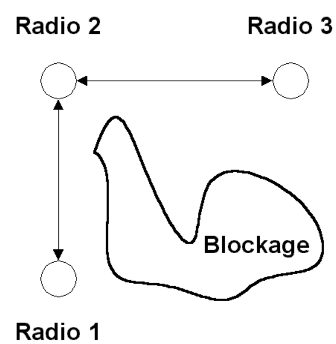


Figure 2 - Blockage scenario (redrawn from Extravehicular Activities Space-To-Space Communication System Training Workbook, p. 2-6)

Because of blockage, Radios 1 and 3 are unable to communicate with each other, although each can communicate with Radio 2. Radios 1 and 3 can have audio contact with each other only indirectly: the user of Radio 2 must relay audio messages.

Augmenting the existing time division multiple access (TDMA) UHF system with a wireless network would greatly enhance the ability to deliver information to astronauts during EVA. This information might be in the form of text, graphics, audio, or video and could provide up to date procedures or enable real-time bi-directional videoconferencing. Making wireless access points available at a number of points external to the ISS could eliminate the blockage scenarios possible in the current system by bridging external wireless LANs using the internal ISS network.

3. Design Considerations

3.1 Design Approach

We propose that an initial wearable computer prototype for the EMU should be an information delivery system, requiring minimal input or control by the EVA astronaut, and allowing information to be delivered remotely by an intravehicular activity (IVA) crewmember, or by the MCC. This approach offers significant benefits to EVA astronauts while minimizing any operational impacts of the system in terms of time and complexity. Incremental addition of capabilities could then be pursued commensurate with training and experience. Furthermore, the wearable computer system would function as an element for mission enhancement: not required for any EVA tasks, but used to support well-defined tasks at varying levels of complexity. It would serve to augment existing systems, not to replace them.

Our design approach relies heavily on near-term operational simplicity. This is consistent with the recommendations of Conners et al. [2] for future EVA system development based on interviews with the lunar surface astronauts. The astronauts recommended that future information displays should be simple and relevant to the current task, and desired safety related status information on a call-up basis. They were also supportive of visual displays for supporting operational tasks, and felt that both visual and aural communication links would be valuable.

3.2 Design Goals and Challenges

Maintaining and promoting safety is the primary EVA wearable computer system priority: First do no harm. Second, it is critical that the system is both comfortable and easy to use. Third, the system should have minimal negative impact on existing operational processes. Fourth, the system should be based on existing technologies and should require minimal modifications to existing flight hardware.

3.2.1 Safety

For components inside the suit, safety considerations include operation of electronics in a 100% oxygen atmosphere, out-gassing off-gassing issues, thermal restrictions, and the severe space constraints imposed by the close-fitting hard upper torso of the suit. Components outside the suit may have fewer environmental constraints, but must withstand the harsh environment of extreme temperatures and vacuum, and, to a much lesser degree, exposure to elemental oxygen, plasma, and micrometeoroids. Safety considerations will be addressed further in the technical requirements section.

3.2.2 Comfort and Ease of Use

Achieving comfort and ease of use requires an innovative user interface (both displays and controls) and form factor. For an in-suit wearable, comfort dictates that the computer be body-conformable and maintains a comfortable surface temperature. Ease of use requirements imply that the user should interact with the computer in a way that is natural to the EVA environment and requires little mobility on the part of the astronaut. Voice control is one option, but is an unlikely candidate because of the potential for interference with existing audio communications, especially given the central role that these communications have played throughout the history of EVA. A solution that requires no movement on the part of an astronaut, and only indirectly may involve audio communication, is remote control of information delivery to the EVA astronaut by IVA crewmembers or the MCC. IVA crewmembers and MCC flight controllers follow EVA progress very closely, and could direct specific information to an EVA astronaut either by prearranged understanding or at the request of the EVA astronaut.

Locating and positioning a visual display is also a significant challenge. There are many objects inside the suit near the eyes and face including the communications carrier assembly (CCA, or CommCap, which is basically a pair of headphones and redundant noise canceling microphones), a drink bag, food stick, and a valsalva device (used for equalizing pressure in the ear canals during suit pressure changes). This limits the space that can be allocated to a suit-internal display. Implementing an effective suit-external display would also be a significant challenge because of positioning and illumination requirements. An external fixed position display does not allow the display to move along with head movements of the astronaut, while an internal display embedded in a pair of standard EVA glasses (with proper prescription for a specific astronaut, or a blank prescription for astronauts who do not require glasses) enables a display to occupy a constant solid angle relative to the head of the astronaut. This could be accomplished using an eyeglass or clip-on micro-display. The varying lighting conditions external to the suit, and the visors used to limit light entry into the helmet, further complicate the development of an external visual display.

3.2.3 Operational Simplicity

Operational simplicity in the donning, utilization, doffing, and maintenance of a wearable computer system for EVA is imperative. Integrating the operational procedures of the wearable computer system into preexisting EVA procedures drives what hardware interconnect configurations are desirable. If a suit-internal wearable computer is used exclusively for EVA (as opposed to a dual use system for both IVA and EVA) the wearable computer system CPU could be stowed attached to the liquid cooling and ventilation garment or LCVG (which regulates internal suit temperature during EVA and assists in circulation of breathing gases) so that donning of the wearable computer would be accomplished by simply putting on the LCVG. Similar considerations might apply for other components of the system.

Operational simplicity during EVA requires careful choice of audio or tactile controls. Traditional hand-based user interface tools may be extremely challenging and generally undesirable due to the physical exertion requirements of moving stiff space suit gloves. Internal tactile controls, or simple external controls (such as buttons or switches) are possible, but must be evaluated with respect to the burden they impose on the astronaut. External tools also pose system integration challenges such as crossing the suit pressure barrier. External tools could also act as additional wireless network clients – this, however, increases the checkout and maintenance burden by requiring battery change-outs or tool recharging, and may also complicate software development.

Voice communications have played, and will continue to play an integral role during EVAs. In addition, IVA crewmembers and MCC flight controllers are often focused on supporting EVA astronauts during EVAs. As such, audio requests for information delivery fit naturally within the current operations framework and allow for a natural language interface not yet possible through voice recognition systems.

3.2.4 Cost

A reasonable delivery cost estimate for the flight version of an EMU might be between $10-20 million. The ORLAN suit is significantly less expensive and is designed to support a higher number of sequential EVAs, but supports a lower number of lifetime EVAs because it lacks a refurbishment capability. Changes to existing hardware are both prohibitive in cost and in risk: any changes must undergo lengthy evaluation especially when such changes may involve any risk to human life. Reducing programmatic risk will therefore tend to reduce development and certification costs. The major limitation this imposes upon a wearable computer system for EVA is a minimization of physical connections across the pressure barrier of the suit. This implies that it is necessary to carefully segment the wearable computer system into suit-internal and suit-external components.

4. Technical requirements

This section highlights some of the existing NASA requirements for EVA systems and outlines their relevance to the development of a wearable computer system for EVA. Prototype development need not produce a wearable computer system that meets all of these requirements. However, the prototype system should be consistent with the design implications of the flight system technical requirements.

4.1 Applicable NASA Requirements Documents

NASA's extensive experience with human space flight systems has resulted in an extensive set of guidelines and requirements for human space flight systems called the Man-Systems Integration Standards[6]. However, for EVA, a more detailed, definitive, and up-to-date source of requirements has been developed by the NASA Johnson Space Center EVA Project Office: the *EVA Hardware Generic Design Requirements Document*[4] is designed to assist project implementation from "concept through development, fabrication, and certification" and is consistent with EVA requirements for both the Space Shuttle and International Space Station programs. Both references are considered for the wearable computing system to assist EVA.

4.2 General Electrical Design

For fire safety in the oxygen-enriched interior of the space suit, currents are limited to 0.5 Amps at a (maximum ground level) operation pressure of 130 kPa (20 psia, due to atmospheric pressure and standard suit differential pressure operations). Current limiting circuit protection devices are also mandatory to preclude fire, smoke, explosion, or arc-over. The NASA standards (JSC-26626A and NASA-STD-3000) recommend against mating or de-mating powered connectors, and require that connectors have key and positive-locking mechanisms, and protective caps when connectors are uncovered. Electronics must be designed to survive in the ionizing radiation environment of low earth orbit. Batteries must be two-failure tolerant to catastrophic events, and are typically lot-checked to achieve well-matched cell capacities. Keep-out zones need to be developed near non-ionizing radiation sources such as transmitters. Existing translation paths incorporate knowledge about recognized dangers, including intentional transmitters.

Current limitations suggest that a low power CPU core will be required for an suit-internal wearable, and that careful power design will be required to ensure all currents are less than 0.5 amps. Compatibility of existing wearable computing technologies with the low-earth-orbit ionizing radiation environment needs to be evaluated. Few space qualified battery technologies can be packaged in a body conformal profile – lithium polymer batteries show great promise but have not yet been flown in space. Finally, the low power requirements for relatively short-range wireless networking should pose little direct risk of exposing crew members to non-ionizing radiation.

4.3 In-Suit Thermal Requirements

In suit surface temperature (or "internal touch temperature") must be between 10° and 43° C. An internal wearable computer tends to reduce the maximum metabolic heat removal capability of the LCVG because the LCVG would need to remove both excess body heat and waste heat from the wearable computer system. However, since the use of the Apollo-era LCVG, cooling has not been a limiting factor in meeting metabolic load requirements. Currently the EMU must support sixty minutes at a metabolic load of 293 watts, and a sustained minimum metabolic load of 73 watts[6].

Our present design criteria of < 15 watts should not have a significant effect on the ability of the LCVG to adequately cool an astronaut in the EMU. The flat profile required because of in-suit volume limitations will provide a large surface area for cooling of the CPU (a primary generator of waste heat) and may even enhance astronaut comfort: The external ISS EVA environment is, on average, significantly colder than the Space Shuttle EVA environment. In addition, the space station will not be rotated to provide optimum sunlight conditions for temperature regulation during EVA (as is often done during Shuttle operations).

4.4 Space Environment

Extreme non-operating temperatures for EVA in the ISS space environment range from -157°C to 149°C while operating temperatures range from -129°C to 121°C. External pressures can range from a surface maximum of 15.23 psia to $1x10^{-10}$ torr in the near vacuum of low earth orbit. Equipment in a suit or an airlock may also need to survive emergency pressurization or depressurization at rates of 0.76 psi/sec and –0.3 psi/sec respectively. Equipment in the space environment will also face high levels of solar ultraviolet exposure, natural and induced plasmas, corona, and atomic oxygen ($5.0x10^{21}$ atoms/cm^2/year). Collisions with micrometeoroids and debris ranging in mass from 1g to 10^{-12}g are also possible.

Design criteria for suit-external wearable components are clearly extreme, and constitute a major reason to design a suit-internal wearable, even given the challenges associated with that option.

4.5 Controls and Displays

Suit-external controls and displays must be located in specific work envelopes defined by NASA standards [6]. These work envelopes are cylindrical boundaries within the EVA astronaut field of view, which is shown in Figure 3. Work envelopes related to space suit joint torque constraints, perhaps more functionally relevant than the existing NASA standard, can also be constructed [8].

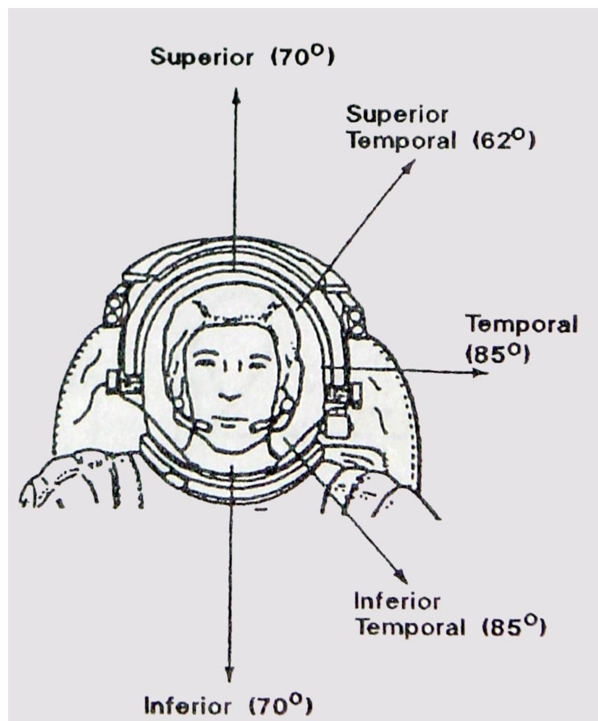


Figure 3 - EMU Field of View (from NASA Man-Systems Integration Standards, page 14-20)

Standard worksite tools can be used to help position tools within these work envelopes. Controls and displays should also be reachable from a neutral body position, compatible with the bulky EMU gloves, and should have a maximum finger actuation force of 9 to 44 N or a maximum required torque of 3.4 Nm (this torque includes only the torque required to manipulate a worksite tool and does not account for the torque required to hold a given body position within the space suit). Battery powered tools should be designed for battery replacement capability at the EVA worksite and should have charge status indicators.

An external visual display (and the apparatus required to secure its position) may obscure a central portion of the astronaut's field of view and work envelope. An internal display may present similar difficulties unless a see-through display is available. A near-eye micro-display integrated into a pair of standard EVA glasses could provide an adequate visual display that could be turned off or adjusted to prevent visual conflicts between the display and the physical environment. It would also be easier to ensure that a suit-internal display would be readable in a variety of external lighting conditions.

A camera and video processor mounted on the helmet of the EMU could provide perspective to the ground of the EVA worksite. Currently, an EMU helmet-mounted camera (EMU TV) can provide a one-way EMU-ISS video link. Views captured by the EMU TV are therefore limited by the position and orientation of the space suit, and no video images can be provided to an astronaut during EVA. A wireless remote camera system could be used to extend the senses of the astronaut or ground crew to locations that are difficult to see because of scale or reach: this new EVA tool might be called something like a "wireless camera on a stick" and could complement free-flying micro-satellite-type video cameras that have recently been proposed and demonstrated such as the NASA Johnson Space Center "Aircam."

4.6 Operational Life

Operational life specifications require that non-suit EVA hardware be designed for up to 100 space shuttle missions (for Space Shuttle specific equipment) and up to 10-year on-orbit durations (with required maintenance). Space suit operational life requirements are suit dependent: EMUs are designed for single-mission, multiple-EVA usage followed by refurbishment prior to re-flight. Operational life requirements for a wearable computer system have yet to be defined.

5. Prototype Development

The above requirements suggest that a suit-internal wearable computer system would be potentially more advantageous than a suit-external wearable computer system because of display positioning issues, the challenges of connections across the suit-pressure barrier, the less stringent environmental extremes within the suit, and the flexibility for an suit-internal design to evolve into a dual use EVA/IVA design at some point in the future. A suit-internal design does suffer from a lack of access during EVA: safety is the primary concern here that will need to be addressed as the design evolves. Admittedly, a suit-internal wireless system might require multiple antennas (because of potential blockage), and would increase astronaut non-ionizing radiation exposure and complicate donning and doffing procedures.

Figure 4 illustrates one possible prototype system under consideration that would utilize a suit-internal wearable computer system with a suit-external wireless access point and helmet mounted video camera and encoder. A low power CPU core and batteries would be packaged in a body conformal form factor (potentially in the abdominal area or in the small of the back). Potentially, something not too dissimilar from StrongARM™ technology found in recent commercial products could be used. A near-eye display could be integrated into a standard pair of EVA glasses: this might be not unlike the current VGA-resolution embedded-glasses display prototypes produced by MicroOptical Corporation. Cabling could be routed through the LCVG so that it would not interfere with existing donning and doffing procedures. The audio and display cabling might also be physically integrated with the CommCap (CCA) cabling to simplify donning and doffing procedures.

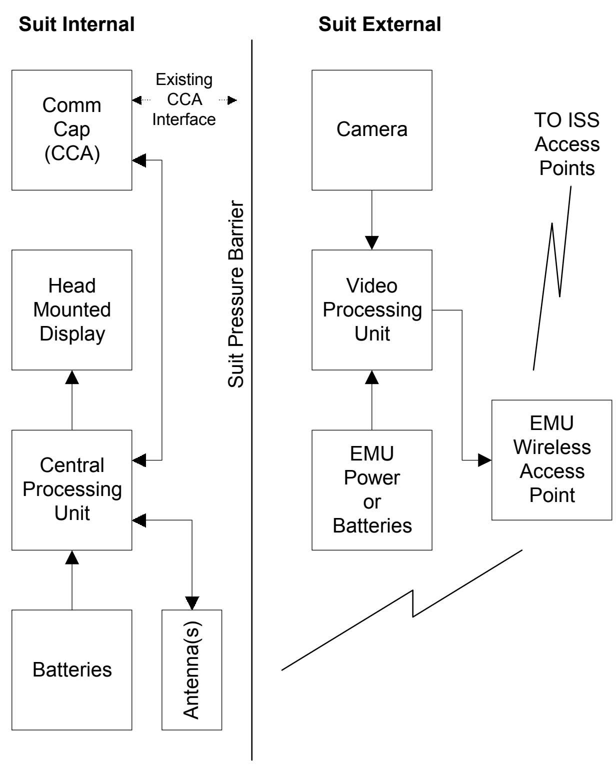


Figure 4 - Potential Prototype Block Diagram

Significant functional integration of the wearable computer system with the existing CommCap (CCA) would raise the criticality of the wearable computer system: it may be desirable to physically but not functionally couple the wearable computer system with the CommCap (CCA). Modifying the existing CommCap design slightly to include an additional independent audio in/out capability would allow for functional independence between the existing audio system and the wearable computer audio system.

The suit external camera system would be similar in function to the current helmet mounted EMU TV, but it would also serve as an wireless access point for the suit-internal wearable computer system and possibly for other wireless EVA tools such as the "camera on a stick" to which we have previously referred.

6. Conclusions & Future Directions

The research project to develop this system is still ongoing. While a preliminary concept for a prototype system has been developed, we are still in the process of trying to understand how our proposed wearable computer system can best support astronaut safety and performance during EVA. Over the next couple of months we will further refine our wearable computer system prototype design, with significant input from astronauts and other stakeholders. Over the next year we seek to deploy a prototype system for test and evaluation.

7. Acknowledgements

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8. Glossary of Terms

CCA	Communications Carrier Assembly
CPU	Central Processing Unit
DCM	Display and Control Module
EMU	Extravehicular Mobility Unit
EVA	Extravehicular Activity
IP	Internet Protocol
ISS	International Space Station
IVA	Intravehicular Activity
LCVG	Liquid Cooling and Ventilation Garment
MCC	Mission Control Center
NASA	National Aeronautics and Space Administration
RSA	Russian Space Agency
TDMA	Time Division Multiple Access
VGA	Video Graphics Adapter
UHF	Ultra-High Frequency

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An Investigation of Space Suit Mobility With Applications to EVA Operations

Thesis Summary
Patricia Schmidt
August 1, 2001

1.0 Introduction

Since the first EVA's were performed by Alexei Leonov and Ed White in 1965, the capabilities of astronauts to do useful work outside of their spacecraft have steadily increased. Likewise, our understanding of EVA astronauts' capabilities and limitations have also progressed through inflight experience, experimentation in neutral buoyancy facilities and parabolic flight, and engineering tests of space suits and EVA tools. The purpose of this thesis is to further advance the current understanding of astronauts' capabilities and limitations in space-suited EVA.

The most important aspect of an EVA astronaut's capabilities is the ability to move his or her body while wearing the space suit. In every EVA scenario, astronauts physically manipulate objects to accomplish tasks. Two factors make these physical interactions strikingly different from those performed on the ground. First, the microgravity environment requires an astronaut to restrain his or her body in order to exert forces and moments on another object, and second, space suits constrain astronauts' body motions in significant and complicated ways.

Historically, feasible limits on planned EVA activities have been determined based on ground experimentation and in-flight experience. Data have been obtained experimentally on operational performance metrics such as joint ranges of motion, the volume in space that a space-suited astronaut can reach, known as the reach envelope, the subset of the reach envelope in which a space-suited astronaut can comfortably work, known as the work envelope, and the strength of a suited astronaut. These performance measures are related to each other through the constitutive and compatibility relations that govern the space suit's behavior, but isolated experimental data does not allow one performance measure to be predicted from another or the same performance measure to be generalized to a different person or situation.

The primary aim of this thesis is to advance the current understanding of astronauts' capabilities and limitations in space-suited EVA by developing models of the constitutive and compatibility relations of a space suit, based on experimental data, and utilizing these fundamental relations to estimate a human factors performance metric for space suited EVA work. The three specific objectives are to:

1. Compile a detailed database of torques required to bend the joints of a space suit, using realistic, multi-joint human motions.
2. Develop a mathematical model of the constitutive relations between space suit joint torques and joint angular positions, based on experimental data and compare other investigators' physics-based models to experimental data.
3. Estimate the work envelope of a space suited astronaut, using the constitutive and compatibility relations of the space suit.

The body of work that makes up this thesis includes experimentation, empirical and physics-based modeling, and model applications. A detailed space suit joint torque-angle database was compiled with a novel experimental approach that used space-suited human test subjects to generate realistic, multi-joint motions and an instrumented robot to measure the torques required to accomplish these motions in a space suit. Based on the experimental data, a mathematical model is developed to predict joint torque from the joint angle history. Two physics-based models of pressurized fabric cylinder bending are compared to experimental data, yielding design insights. The mathematical model is applied to EVA operations in an inverse kinematic analysis coupled to the space suit model to calculate the volume in which space-suited astronauts can work with their hands, demonstrating that operational human factors metrics can be predicted from fundamental space suit information.

2.0 Literature Review

The EMU space suit, which is currently used for NASA EVA's, has both hard fiberglass and soft fabric components. Mobility features, such as pleats that open as joints bend and rotational bearings, are built into all modern space suits. Without these mobility features, a person in a space suit would be virtually immobile. Even though space suits are designed to allow mobility, they restrict the wearer's motion in significant and complicated ways.[14]

Limited space suit joint torque-angle data has been reported in the literature. Studies that used human subjects wearing space suits reported higher torques than studies that measured torques on joints of empty, pressurized space suits. Higher torques with human subjects may be expected because contact between the space suit and the wearer's body affects the deformed shape of the space suit, but it is unclear whether the discrepancy in experimental results is due to shortcomings in experimental methods or actual differences in observed torques.[2, 4, 21, 22]

This thesis uses several mathematical and physical modeling techniques which were originally developed for other applications but are relevant to modeling the torque-angle characteristics of space suit joints. Mathematical modeling techniques allow torques to be predicted from angle histories with accuracy, but, since they do not incorporate physical principles, they do not contribute insights for designing space suit joints with better mobility characteristics. Three mathematical techniques for modeling hysteretic systems, the Krasnoselski-Pokrovski model[15], the Preisach model,[20] and the Tao and Kokotovic model[24], which were originally used for modeling magnetization and shape memory alloy actuators, were evaluated for possible use. The Preisach model was chosen because it can produce output curves similar in shape to the space suit torque vs. angle curves and its identification process is relatively simple.

Physical models, in contrast to mathematical models, can lead to insights into the physical processes that govern space suit mobility. Two physical models of the bending characteristics of inflated cylinders may be relevant to space suit joints. The beam model treats the inflated cylinder as a beam with a fabric wall that stretches, maintaining a constant internal volume. The mobility of the space suit joint is determined by elastic behavior of the fabric wall.[16-19] The membrane model treats the fabric shell as an inextensible membrane. Bending deflections of the cylinder result in shape and volume changes. The work required to bend the joint is entirely due to compression of the gas inside the tube [6,7] Differences in torque predictions between the beam model and the membrane model illustrate the relative importance of elasticity and gas compression in space suit joint mobility.

One application of space suit joint mobility models is in calculating human factors performance metrics, including the one-handed space suited work envelope, which indicates the volume within which a space-suited astronaut can comfortably work with one hand. The current NASA space-suited work envelope[1], which is used in planning EVA's, differs qualitatively from other work envelopes found in the literature.[23] A recently-developed computational technique allows suited work envelopes to be calculated using mathematical models of the torque-angle characteristics and kinematics of a space suit.[13, 10-12]

3.0 Space suit mobility database

The objective of the experimental portion of this thesis was to obtain a quantitative database of joint angles and torques required to move a space suit's joints, under realistic conditions. The impossibility of directly measuring joint torques in space-suited human test subjects necessitated an indirect measurement approach, using both human subjects and an instrumented robot to obtain torque data.

The human test subjects carried out arm and leg motions both wearing the space suit and not wearing the space suit, supplying realistic joint angle trajectories for each of 20 motions, listed in Table 1. The joint angle trajectories produced by the human subjects were then used as command inputs for the robot, so that the robot imitated the humans' motions while torques were measured at each of the robot's joints. Torques on the robot's joints due to the weight of the robot and space suit were subtracted, resulting in a consistent set of joint angle and torque data, with angles accurate to approximately 2 deg-5 deg and torques accurate to approximately 0.1 Nm. An example of the joint torque-angle data for the elbow flexion motion is shown in Figure 1 and torque-angle data for shoulder flexion is shown in Figure 2.

TABLE 1. Arm and leg motions used in experiment

Simple Motions	Complex Motions
Shoulder flexion	Arm swing forward-backward
Shoulder abduction	Arm swing side to side
Humerus rotation	Leg swing forward backward
Elbow flexion	Leg swing side to side
Hip flexion	Overhead reach
Hip abduction	Cross-body reach
Thigh rotation	Low reach
Knee flexion	Locomotion over 12 cm step
Ankle rotation	Locomotion on treadmill
Ankle flexion	
Ankle inversion	

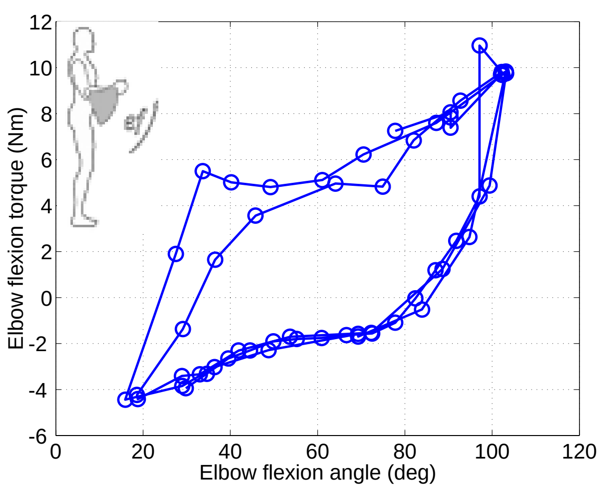

FIGURE 1. Elbow flexion torque vs. angle.

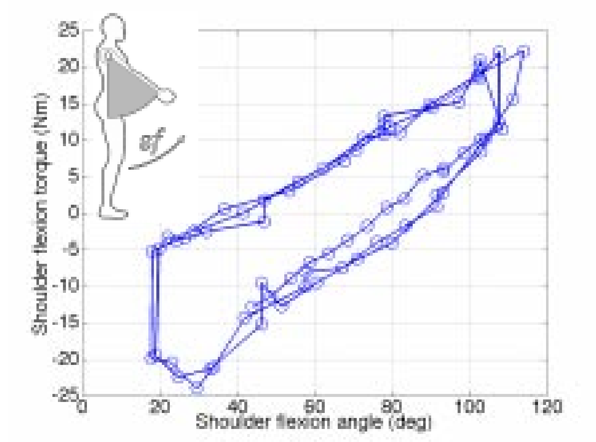

FIGURE 2. Shoulder flexion torque vs. angle.

Angle ranges for which angle and torque data was obtained are shown in Figure 3. The gray rectangles in Figure 3 indicate the range of motion that was specified for the design of the EMU, or the robot's range of motion for the humerus rotation, ankle rotation and ankle inversion joints, where the EMU range of motion was unspecified.

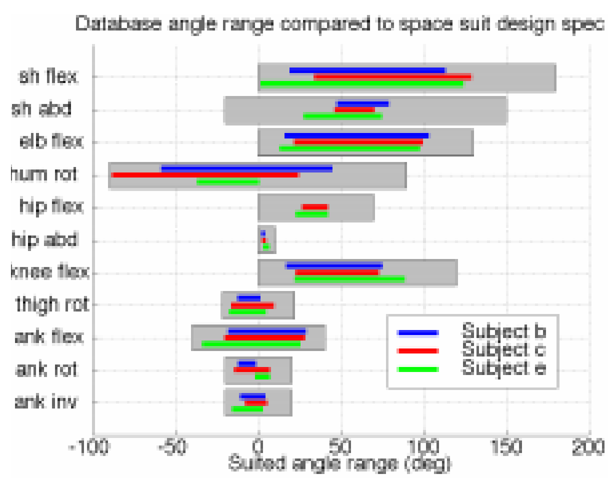

FIGURE 3. Angle range of space suit database.

The database compiled in this work is more extensive than any other published space suit torque-angle database, covering 11 joints over a large range of angles. Realistic, three-dimensional human-generated motions were used for data collection. Because torque data was collected by the robot as a surrogate for a human occupant of the space suit, the torques measured in this study are more representative of realistic conditions than data from previous studies that measured joint stiffnesses for empty, pressurized space suits. The space suit torque-angle database serves as a basis for developing and validating both mathematical and physical models of space suit joint mobility characteristics.

4.0 Modeling

The space suit torque-angle database described in Section 3.0 presents a unique opportunity to develop models of space suit mobility and verify them against experimental data. Models of space suit mobility are useful in two applications: numerically predicting the torque required to bend a space suit's joints and understanding the physical processes that determine how mobile a space suit's joints are. These two applications require two different modeling approaches: first, a descriptive mathematical modeling technique based on experimental data and second, a theoretical model based on physical principles. Section 4.0 describes two modeling efforts: a mathematical model based on empirical data that predicts the torque required to bend the space suit's joints and a comparison between two physics-based models of bending pressurized cylinders and the space suit torque angle database compiled in Section 3.0. The opportunity to validate the mathematical and physical models against experimental data is a unique aspect of this thesis.

4.1 Mathematical modeling

The Preisach model The Preisach hysteresis model reproduces a hysteresis curve by summing contributions from the simplest possible hysteresis transducers. The primitive hysteresis transducer, $\hat{\gamma}(\alpha, \beta)$, has an output value equal to either +1 or -1. For increasing inputs, the output switches from -1 to +1 at an input value of α, and for decreasing inputs, the output switches from +1 to -1 at an output value of β.

To construct more complicated hysteresis transducers with continuous, non-unity outputs, the Preisach model uses a weighted sum of simple hysteresis operators. The weighting function $\mu(\alpha,\beta)$ is defined as a function of the combination of upward and downward switching values, α, β, of the hysteresis transducer. The Preisach function, $\mu(\alpha,\beta)$, is defined for all $\alpha > \beta$, $-\alpha_0 < \alpha < \alpha_0$, and $-\alpha_0 < \beta < \alpha_0$, forming a triangle in α–β space.

Construction of the output of the composite hysteresis transducer is done by integrating the individual $\hat{\gamma}_{\alpha,\beta}$ values, as shown in Equation 1.

$$f(t) = \iint_{(\alpha > \beta)} \mu(\alpha, \beta)\hat{\gamma}_{\alpha,\beta}u(t)\,d\alpha\, d\beta \qquad \text{Eq 1}$$

Calculation of *f(t)* is aided by a graphical representation of the α-β space. The weighting function $\mu(\alpha,\beta)$ is defined over the triangle that is bounded by the $\alpha=\beta$ line and the maximum values of α and β, α_0 and β_0, which are defined by the saturation limits of the output. To obtain *f(t)*, Equation 1 is integrated over this triangle.

To perform the integration in Equation 1,the triangle may be subdivided into two sets:

- Region S+, where corresponding $\hat{\gamma}_{\alpha,\beta}$ operators are "up", or equal to +1
- Region S-, where corresponding $\hat{\gamma}_{\alpha,\beta}$ operators are "down", or equal to -1

Substituting +1 for $\hat{\gamma}_{\alpha,\beta}$ in the S^+ region and -1 for $\hat{\gamma}_{\alpha,\beta}$ in the S^- region, Equation 1 simplifies to

$$f(t) = \iint_{S^+} \mu(\alpha, \beta)\,d\alpha\, d\beta - \iint_{S^-} \mu(\alpha, \beta)\,d\alpha\, d\beta . \qquad \text{Eq 2}$$

Equation 2 can be integrated if the boundary between the S^+ and S^- regions is known. The input history is stored by drawing the boundary between the S^+ and S^- regions. The boundary is drawn by constructing line segments in a staircase pattern within the triangle based on the value of the input *u(t)* and whether the input is increasing or decreasing. The boundary is drawn according to the following rules:

1. The boundary starts on the $\alpha=\alpha_0$ segment if the initial input is descending and the $\beta=-\alpha_0$ segment if the initial input is ascending.
2. Subsequent boundary segments are drawn horizontally or vertically depending on whether *u(t)* is increasing or decreasing:
   - Increasing *u(t)*: horizontal line segment at $\alpha=u$
   - Decreasing *u(t)*: vertical line segment at $\beta=u$
3. A boundary segment is obsolete if its α value is less than the α value of a later segment having the same β value or if its β value is less than the β value of a later segment that has the same α value.
4. The last line segment ends on the $\alpha=\beta$ line.

An exploration of the Preisach hysteresis model focused on four of the important features of the outer hysteresis curve shape: number of loops, direction of loops, separation between increasing and decreasing curves and *dT/du*, resulting in several important insights. The proper choice of $\mu(\alpha,\beta)$ can produce single or multiple hysteresis loops, in either clockwise or counterclockwise directions. The separation between increasing and decreasing curves can be written as an integral of $\mu(\alpha,\beta)$ over a region in the top left corner of the $\alpha-\beta$ space. Thus, high amplitudes of $\mu(\alpha,\beta)$ in the top left corner of the $\alpha-\beta$ space, where α is near α_0 and β is near $-\alpha_0$, result in large separations between the increasing and decreasing output curves.

Model identification The model identification process for the Preisach model involves calculating the weighting function $\mu(\alpha,\beta)$ from experimental data. The central premise of the Preisach model identification methods is that the difference between two output values is equal to the integral of $\mu(\alpha,\beta)$ over a region whose bounds are known from the input history. Calculating the integrated $\mu(\alpha,\beta)$ for a sufficient number of regions allows the Preisach model to be implemented to predict the hysteretic system's output as a function of its input and input history. The following derivation shows how the integral of $\mu(\alpha,\beta)$ over a region with known bounds can be calculated from the difference between two output values.

The input to the hysteresis transducer begins below the low input limit, $-\alpha_0$, and increases to a value u_1, which is below the high input limit. The corresponding output, when $u=u_1$, is $T=T_1$. In the α-β plane, the S^+/S^- boundary lies at $\alpha=u_1$. The input then decreases from $u=u_1$ to $u=u_2$, and a vertical segment is added to the S^+/S^- boundary at $\beta=u_2$. The output when $u=u_2$ is $T=T_2$.

According to Equation 2, the output $T(u)$ is equal to the integral of $\mu(\alpha,\beta)$ over the S^+ region minus the integral of $\mu(\alpha,\beta)$ over the S^- region. Using Equation 2 to calculate the difference between T_1 and T_2 results in the following expression for the output difference, in terms of the S^+ and S^- regions at $u=u_1$ and $u=u_2$.

$$T_1 - T_2 = T_{max} - 2\int_{S^-_1}\int \mu(\alpha,\beta)\,d\alpha\,d\beta + -\left[T_{max} - 2\int_{S^-_2}\int \mu(\alpha,\beta)\,d\alpha\,d\beta\right] \quad \text{Eq 3}$$

$$T_1 - T_2 = 2\int_{S^-_2 - S^-_1}\int \mu(\alpha,\beta)\,d\alpha\,d\beta$$

The difference between integration areas, S^-_2-S^-_1, for $u=u_2$ and $u=u_1$, is a triangle that has vertices at (u_1,u_2), (u_1, u_1) and (u_2, u_2). When the input decreases from u_1 to u_2, the difference in output values is equal to the integral of $\mu(\alpha,\beta)$ over the triangle.

Numerical Implementation To determine $\mu(\alpha,\beta)$ from output differences, Mayergoyz[20] suggests differentiating the output data twice with respect to the input. Taking two derivatives of measured data values would amplify random noise to unacceptable levels, so the method that Mayergoyz[20] recommends is not practical.

An alternative Preisach model identification scheme, developed by Doong and Mayergoyz[5] and further explained by Ge and Jouaneh[8], is based on the same premise, but avoids differentiating data in the identification step and double integrations in the implementation step. This method avoids differentiation and integration by calculating the integral of $\mu(\alpha,\beta)$ over a collection of triangles in $\alpha-\beta$ space from output differences, then uses sums and differences of the triangle integrals to construct the output for any input history.

According to Equation 3, the integral of $\mu(\alpha,\beta)$ over a triangle bounded by the $\alpha=\beta$ line and the $\alpha=u_1$, $\beta=u_2$ point is equal to T_1-T_2, as long as the input increased from its lower limit to u_1, then reversed direction and decreased to u_2, with no other direction reversals. This relationship allows the integral of $\mu(\alpha,\beta)$ to be calculated based on the appropriate output differences for triangles bounded by the $\alpha=\beta$ line and any point inside the large triangle over which $\mu(\alpha,\beta)$ is defined. The quantity $X(\alpha_1,\beta_1)$ is defined as the integral of $\mu(\alpha,\beta)$ over a triangle bounded by α_1, β_1 and the $\alpha=\beta$ line. If u increases from its low limit, reverses direction at $u=\alpha_1$, then decreases to β_1, $X(\alpha_1,\beta_1)$ is given by

$$X(\alpha_1,\beta_1) = (T(u=\alpha_1) - T(u=\beta_1))$$

$$X(\alpha_1,\beta_1) = 2\int_{\beta_1}^{\alpha_1}\int_{\beta}^{\alpha_1} \mu(\alpha,\beta)\,d\alpha\,d\beta \quad \text{Eq 4}$$

If $X(\alpha,\beta)$ is known for all $-\alpha_0<\alpha<\alpha_0$, $-\alpha_0<\beta<\alpha_0$, $\alpha>\beta$, then $X(\alpha,\beta)$ values can be added and subtracted to construct any Preisach model output, provided that the boundary between S^+ and S^- is drawn according to the rules described above. The integral of $\mu(\alpha,\beta)$ over S^+ is given by:

$$T = -X(\alpha_0, -\alpha_0) + \sum_{i=1}^{n} -1^{n+1} X(\alpha_i, \beta_i) \quad \text{Eq 5}$$

Error Analysis Because the hysteresis model coefficients are determined from experimental data, random errors in the experimental data lead to random errors in the model output whose statistical properties can be predicted. The error analysis provides a method for generating confidence intervals for the Preisach model output if the model is identified and implemented according to the Doong and Mayergoyz[5] method.

According to Equation 5, the Preisach model output is the sum of positive and negative $X(\alpha,\beta)$ values at the vertices of the S^+/S^- contour. Assuming that the errors in the experimental torque and angle data that was used to calculate $X(\alpha,\beta)$ are random, white noise, errors in $X(\alpha,\beta)$ should be uncorrelated with errors in X at other values of α and β. Thus, the variance of the model output T is equal to the sum of the variances of the individual $X(\alpha,\beta)$ values that were summed to obtain T.

Summing the variances of the X values at the n S^+/S^- boundary vertices results in the variance of the model output T. The variance of the measured torque is σ^2_T and the variance of the measured angle is σ^2_A.

$$var(T) = (2n)\sigma_T^2 + \sigma_A^2 \sum_{i=1}^{n} \left(\frac{\partial X_i}{\partial \alpha_i} + \frac{\partial X_i}{\partial \beta_i} \right)^2 \qquad \text{Eq 6}$$

The hysteresis models were implemented for each joint and compared to experimental torque-angle data for motions that were generated by space-suited human subjects, as described in Section 3.0. Joint angle data from the human subjects was used as an input for the hysteresis model, which generated a torque prediction as well as a 95% confidence interval on the prediction. The experimental joint torque data is compared to the model predictions and confidence intervals for the elbow in Figure 4 and for the knee in Figure 5.

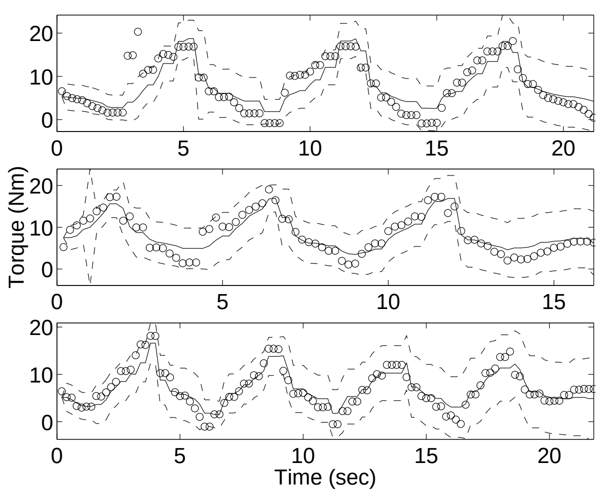

FIGURE 4. Elbow flexion torque compared to hysteresis model prediction for subjects B (top), C (middle), and E (bottom).

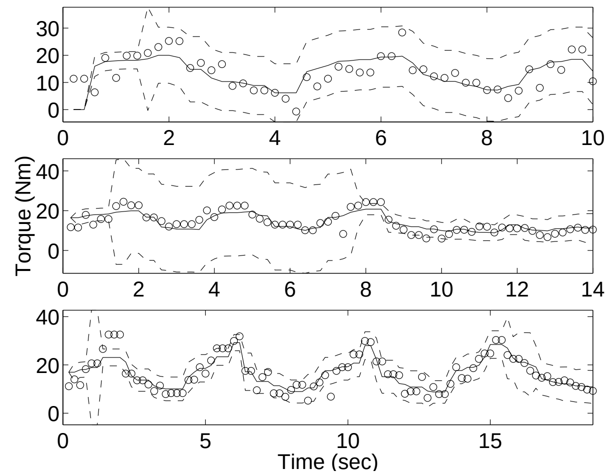

FIGURE 5. Knee flexion torque compared to hysteresis model prediction for subjects B (top), C (middle), and E(bottom).

The Preisach model outputs match well with data for elbow flexion, hip abduction and knee flexion, with $R^2>0.6$ for these joints. The error estimates generated appear to be a reliable, or at least conservative, estimate of the error standard deviations.

The Preisach hysteresis model is a useful tool for predicting the torque needed to bend space suit joints as a function of time for complicated angle trajectories. The ability to reproduce realistic space suit torques dynamically makes the Preisach model well-suited for use in dynamic simulation of EVA tasks. The experimental data reported in Chapter 3 as well as other investigators' data indicate that the torque-angle relationship for space suit joints is markedly hysteretic. Consequently, reproducing dynamic behavior of space suit joints requires a model that captures hysteresis; other modeling techniques such as linear regressions on angle and angular velocity will not accurately predict the effects of the angle history on the torque required to bend the space suit's joints.

The Preisach hysteresis model has some limitations in modeling space suit joints, however. To identify the model coefficients, it is necessary to vary the input between several distinct minima and maxima. Because of this, the model identification process is not well-suited to human-generated motions, although characteristics of human-generated motions, such as range and speed, can be incorporated into the input data for realism. Another limitation of the Preisach model is that the maximum input and output are set when the model coefficients are identified. When the model is implemented later, if the input exceeds the previously-set maximum, the output saturates and errors between the model prediction and actual torques may become large. Modeling the hysteretic characteristics of space suit joints is essential for making accurate predictions of the torques required to bend the space suit joints in dynamic situations. This work demonstrates that the Preisach hysteresis model accurately reproduces torques needed to bend space suit joints.

4.2 Physics-based modeling

Beam model The beam model, which was developed by Comer and Levy[3] and extended by Main, Peterson, and Strauss[16-19], treats a pressurized cylinder as a long, slender member, loaded in a single plane, whose behavior is governed by elasticity and buckling phenomena. The central idea of the beam model is that fabric can sustain only extensional stresses; when the fabric wall of the beam is compressed, it wrinkles and does not contribute to the stiffness of the beam. The beam model predicts the extent of the wrinkled portion of the beam and integrates the extensional stress resultants over the tensioned, unwrinkled, portion of the beam to obtain a moment-curvature relationship for the pressurized beam.[3, 16, 19] Stress resultants are normalized by the thickness of the fabric, and expressed in terms of load per unit length in units of N/m, because fabric stress-strain behavior is not highly correlated with fabric thickness.

The applied loads and the constitutive relations of fabric, which relate stresses and strains and are given in Equation 7, determine the extent of wrinkling in the fabric. In general, fabric is assumed to be orthotropic, with Poisson ratio ν and different moduli, E_H and E_L in the hoop and longitudinal directions.

$$\varepsilon_L = \frac{\sigma_L}{E_L} - \frac{\upsilon\sigma_H}{E_L} \qquad \varepsilon_H = \frac{\sigma_H}{E_H} - \frac{\upsilon\sigma_L}{E_L} \qquad \text{Eq 7}$$

The beam model predicts that the fabric wall of the beam wrinkles when the local longitudinal strain, ε_L, becomes negative. Equation 7 shows that the cross-coupling component in the constitutive relations makes the fabric wrinkle at positive values of longitudinal stress, σ_L, when the hoop stress, σ_H, is positive. The hoop loading due to pressurization thus makes the fabric wrinkle at lower applied loads as the beam is bent. The longitudinal stress at which wrinkling occurs is given by:

$$\sigma_L = \upsilon pr \qquad \text{Eq 8}$$

When the fabric is wrinkled, its stress resultant is considered to be zero, because it cannot resist compressive loads. The longitudinal stress is maximum on the outside of the bend and decreases linearly until it reaches the wrinkling limit, then the wrinkling condition sets it equal to zero.

To determine the curvature of the beam, it is first necessary to find the extent of the wrinkled region, using the relation between applied moment, M, internal pressure, p, and beam radius. A polar coordinate frame is defined with $\theta=0$ on the inside of the bend, at the center of the wrinkled region and $\theta=\theta_0$ at the edge of the wrinkled region. The value of θ_0 is given by Equation 9.

$$\frac{M}{pr^3} = \frac{\frac{\pi}{2}[(\pi-\theta_0) + \sin\theta_0\cos\theta_0] +}{\sin\theta_0 + (\pi-\theta_0)\cos\theta_0} \qquad \text{Eq 9}$$
$$\frac{-\upsilon[(\pi-\theta_0)^2 - (\pi-\theta_0)\sin\theta_0\cos\theta_0 - (2\sin\theta_0)^2]}{\sin\theta_0 + (\pi-\theta_0)\cos\theta_0}$$

The θ_0 that is calculated by solving Equation 9 numerically for specified M/pr^3 can then be substituted into Equation 10 to obtain the curvature resulting from the applied moment.

$$K = \frac{M - 2\upsilon pr^3\sin\theta_0}{Er^3[(\pi-\theta_0) + \sin\theta_0\cos\theta_0]} \qquad \text{Eq 10}$$

In contrast to the beam model, the membrane model treats the fabric cylinder wall as an inextensible material that transmits forces only along its surface and only in tension. Bending deflections of the structure result in changes in its cylinder's cross-sectional shape and the volume that it encloses. The cross-sectional shape of the fabric tube is determined by the assumptions of inextensibility and exclusively tensile loading. These assumptions result in reliable approximations of the tube's shape, even when deflections are large.

Membrane model The membrane model uses a variational principle to relate applied bending moment, force applied at the tube's ends, and the bending angle of the pressurized fabric tube. The potential energy of a tube with volume V, internal pressure p, end force Q, bending moment M, bending angle ϕ and linear displacement δ is given by:

$$\Pi = -pV - Q\delta - M\phi \qquad \text{Eq 11}$$

When the system is at equilibrium, the potential energy is minimized. For the case of pure bending, $Q=0$ and $\delta=0$. The moment-angle relationship that minimizes the potential energy is calculated by holding the bending moment, M, fixed and differentiating the potential energy, *Π*, with respect to the bending angle ϕ. When $\frac{d\Pi}{d\phi} = 0$, the potential energy is minimized.

$$\frac{d\Pi}{d\phi} = -p\frac{dV}{d\phi} - M = 0$$
$$\Rightarrow M = -p\frac{dV}{d\phi} \qquad \text{Eq 12}$$

Equation 12 shows that the equilibrium bending moment-bending angle relationship is set by the relationship between the internal volume of the tube and the bending angle. The assumptions of inextensibility and tensile loading set the shape of the tube as a function of bending angle. Based on the four principles of membrane shape listed in Reference [7], the shape of the bent tube can be determined. The geometry of a bent pressurized tube is shown in Figure 6. For a tube of radius *R*, the radius of the bent outer surface of the tube is *2R*. The inner surface at the bend folds inward, towards the center of the tube, forming a kink in the tube wall. Away from the kinked region, the tube is straight. Points P and S, which lie on the tube wall, are defined to aid in calculating the tube's cross-sectional area. Point P is located on the kink at the inside of the bend, and point S is the corresponding point on the outside of the bend. Point P and point S are the same distance away from the end of the tube. θ is the angle between a line drawn from the inside of the bend to point S and another line that is normal to the straight sides of the tube. The length of the bent portion of the tube on the outer edge is $4R\phi$.

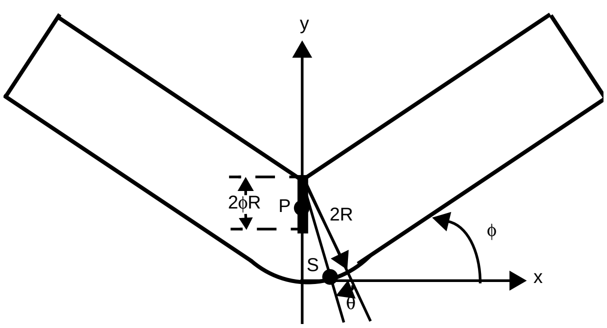

FIGURE 6. Bent tube shape, according to membrane model.

The locations of points P and S are defined as follows.

$$x_P = 0$$
$$y_P = 2R(1+\theta)$$
$$x_S = 2R(1-\cos(\phi-\theta)) \qquad \text{Eq 13}$$
$$y_S = 2R\sin(\phi-\theta)$$

The distance between points P and S, which can be calculated from Equation 13, and continuity of slope between the rectangular portion and the circular portion of the cross-section allow the cross-sectional area to be calculated as a function of θ. The cross-sectional area of the tube is given by Equation 14, as a function of *H,* the distance between points P and S.

$$A(\theta) = \pi\left(R^2 - \left(R - \frac{H(\theta)}{2}\right)^2\right) \qquad \text{Eq 14}$$

The cross-sectional area is integrated over the length of the tube to obtain the bent tube volume. The moment-bending angle relation is obtained by differentiating the volume numerically with respect to ϕ, according to Equation 12.

A comparison of the torque-angle predictions of the beam model, membrane model and experimental data from the knee joint is shown in Figure 7. The membrane model agrees with experimental data within 30 degrees of the knee joint's equilibrium angle, while the beam model's torque predictions do not agree with the experimental data.

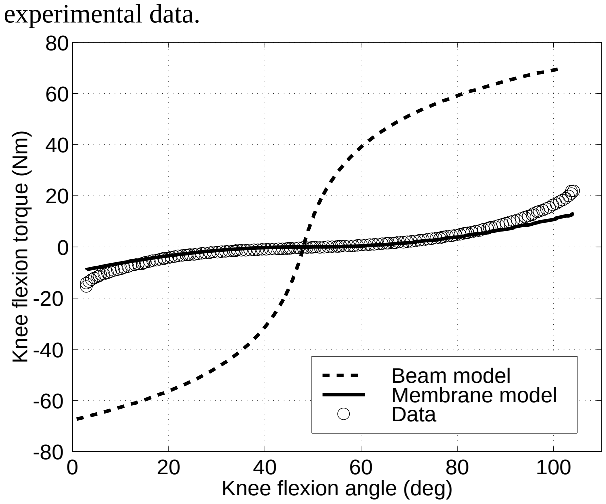

FIGURE 7. Comparison between beam model, membrane model and experimental data for knee joint.

The beam model and membrane model represent opposite extremes of the processes governing space suit joint mobility. The beam model assumes that the space suit joint torque-angle relationship is determined solely by elastic deformations of the fabric wall of the space suit, with no changes in the internal volume of the space suit segment. The membrane model makes the opposite assumptions: that the space suit fabric does not stretch, although the cross-sectional shape deforms, resulting in reduction in internal volume as the joint is bent. According to the beam model, bending moments only stretch the space suit fabric; according to the membrane model, bending moments only compress the gas inside the space suit.

It is reasonable to expect that the actual behavior of a space suit falls between these two extremes, that both elasticity and volume changes determine space suit joint mobility. Comparing these two approximate models to experimental data illustrates where on the continuum between elasticity and volume change the space suit joint behavior falls and indicates whether the space suit behavior can be approximated by one model or the other.

The beam model is inconsistent with experimental data for the elbow and knee joints, both in the bending moment magnitudes predicted and the trend in bending moment with increasing deflection. The beam model predicts bending moments for the elbow and knee joints that exceed the experimental data by at least a factor of 5. In addition, the beam model predicts a decreasing slope of the moment-angle curve as bending angle increases, while the data shows a increasing slope with increasing bending angle.

The shape of the torque-angle curves generated by the membrane model is consistent with the experimental data, because the model's torque-angle curves are flat near the equilibrium position of the joint and increase in slope as deflection increases. The membrane model follows the experimental data over a bending angle range approximately 30-50 degrees from the equilibrium angle, for the elbow and knee joints. Outside of this range, the amplitude of the experimental torque data is greater than the membrane model's predictions. Although the membrane model can predict the torque needed to bend the joints over about half of the available range of motion, the model's underprediction of torques near the extremes of the angle range prevent it from being used to predict a joint's angular range of motion. Other physical processes, including fabric bunching, sideways compression of the space suit arm or leg, and friction between fabric layers, which were not included in the membrane model, likely play an important role in determining the torque needed to bend the space suit joints at high bending angles.

The results of this analysis indicate that elastic deformations of the space suit fabric do not contribute significantly to the torque needed to bend the elbow and knee joints near the equilibrium angle, and the mobility of the EMU elbow and knee joints near their equilibrium angles is not sensitive to changes in the material properties of the fabric. The membrane model predicts that only internal pressurization and joint geometry determine mobility.

5.0 The work envelope: Applying space suit modeling to EVA operations

A reach envelope is the region in three-dimensional space that a person can reach. The work envelope is a subset of the reach envelope, representing the volume in which a person can comfortably work. Reach and work envelopes depend on the size and flexibility of the individual. A standard practice is to size workspaces to accommodate the reach and work envelopes of individuals at the extremes of the expected size range, for example, 5th percentile females and 95th percentile males.[23] Most work envelopes are determined experimentally, by measuring how far people of different sizes can reach and obtaining subjective information about the difficulty of working with the hands in different locations. An alternative approach to reach envelope analysis has been developed recently, which uses robot kinematic analysis methods to determine the boundaries within which a person can reach with prescribed limits on joint ranges of motion.[10-13, 25]

A new work envelope analysis method, which combines inverse kinematics and the space suit model, enables the work envelope of a space-suited person to be assessed in greater detail and with more generality than the current, experimental, methods allow. For any proposed hand position, the inverse kinematics analysis determines the arm configurations that place the hand on target. Based on the arm joint angles, the joint torques required to hold a specific arm position are determined by the space suit model. Knowledge of joint torques as a function of hand position allows a detailed analysis of worksite placement: areas requiring excessive torques at any joint can be eliminated from the feasible work space, while areas that are particularly easy to reach can be preferred. Furthermore, the inverse kinematics method allows the work envelope analysis to be customized for individuals of different sizes. Work envelope analysis represents one area in which fundamental models of space suit mechanics are useful in predicting and understanding a large-scale EVA human factors performance metric.

Three criteria determine whether a proposed hand position is in the work envelope: torques needed to hold the required arm configuration, visibility, and the shape of the resulting work envelope boundaries. The shape of the work envelope is considered because highly convoluted work envelope boundaries are difficult to use, since they are excessively sensitive to the relative positions of the EVA astronaut and the worksite. However, adding the shape criterion overconstrains the problem; as a result, a single torque limit cannot be enforced uniformly. To deal with this issue, a smoothing algorithm is used to systematically trade off the joint torque and work envelope shape criteria.

The volume surrounding the astronaut is evaluated point-by-point to determine whether each point in a three-dimensional mesh is inside or outside of the work envelope. Points are placed in three categories, based on their visibility and the joint torques required to place the hand on that point. Points that are not visible, or require more than 30% of the maximum torque from any joint go into the “always exclude” category. Points that are visible and require no more than 15% of the maximum torque from all joints go into the “always include” category. The remaining points, which are visible and require torques between 15% and 30% of the maximum torques from some joints, go into the “possibly include” category. The smoothing algorithm then draws the work envelope boundaries to include all of the “always include” points, none of the “always exclude” points, and then draws a limited number of points from the “possibly include” category to smooth the shape of the work envelope.

The arm model chosen for the inverse kinematics calculations is a simplified approximation of the complex mechanics of the human arm. The number and type of articulations of the model arm were chosen to coincide with the joints included in the space suit model and to limit the kinematic redundancy of the model arm. The model arm includes four joints: shoulder flexion, shoulder abduction, humerus rotation, and elbow flexion. A wrist joint is not included in the model.

Results of the work envelope analysis are shown in Figure 8 and Figure 9. Figure 8 shows the boundaries of the region in the smoothed work envelope. Figure 9 shows a horizontal slice through the work envelope 19 cm below the shoulder, indicating the smoothed work envelope boundaries and the reach difficulty metric. Dark areas are easy to reach, while white areas are difficult to reach.

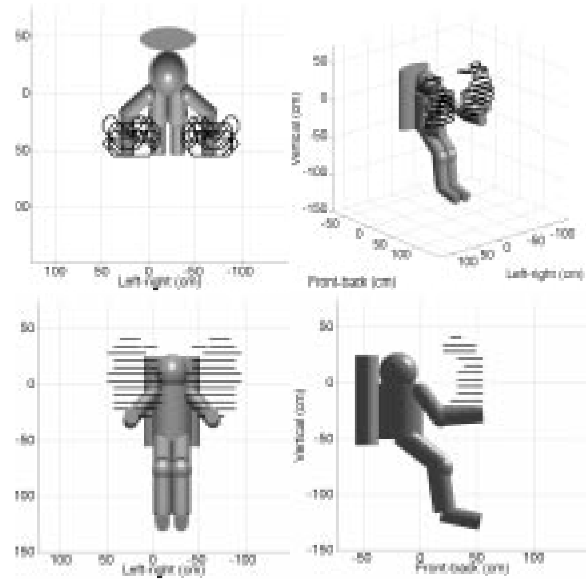

FIGURE 8. Smoothed work envelope boundaries for female, 50th percentile size, 95th percentile strength

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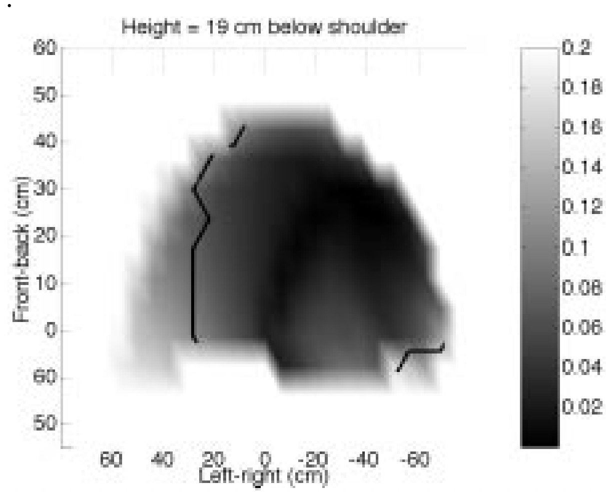

FIGURE 9. Horizontal slice through work envelope, showing reach difficulty metric and work envelope boundary.

All of the work envelope criteria listed above contribute to the size and shape of the work envelope. Because multiple constraints set the boundaries of the work envelope, it is informative to determine which constraints affect the outcome of the work envelope analysis and which constraints do not. The combination of space suit joint stiffness and human strength limits sets the range of motion for each joint. The joint ranges of motion, combined with the lengths of the arm segments, determine the region that a person can reach.

Looking at the effects of increasing torque limits for individual joints indicates which joints limit the overall size of the work envelope and where each joint's limits bound the work envelope. Individual joints were analyzed using the female, 50th percentile size, 95th percentile strength case. The baseline case uses torque limits of 30% of the maximum strength for all joints. Eight variations on the baseline case were analyzed. In each variation, the positive or negative torque limit for one joint was increased from 30% of the strength limit to 50% of the strength limit. The work envelope volume in the baseline case and the six variations, normalized by the volume of a hemisphere with radius equal to the total arm length, are shown in Figure 10. The largest gain in work envelope volume is associated with an increase in the negative shoulder abduction torque limit. Increasing the negative shoulder flexion limit also increases the work envelope volume somewhat, while positive shoulder flexion and positive and negative elbow flexion do not limit the work envelope volume.

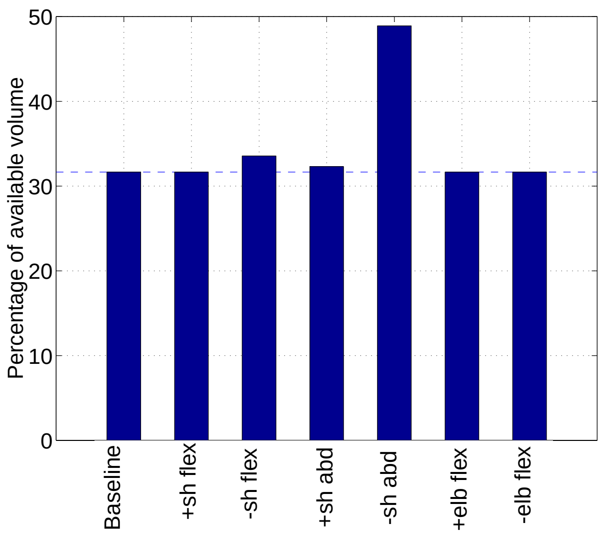

FIGURE 10. Percentage of available volume occupied by work envelope when torque limits are increased from 30% to 50% for single joints.

6.0 Summary of contributions

This thesis advances current knowledge of astronauts' capabilities and limitations in space-suited EVA in three areas: by gathering data on the torques needed to bend space suit joints, developing both mathematical and physics-based models relating joint torques to angles, and using the joint torque-angle data to predict and analyze the work envelope of a space suited astronaut.

The space suit torque-angle database compiled in this thesis is more extensive in the number of joints and angular range than any other published space suit mobility data set. Furthermore, the data was collected under realistic conditions, using joint angle trajectories that were generated by space-suited human subjects and torques measured using an instrumented robot as a surrogate for a person in the space suit. This database provides the basis for developing and validating models of space suit mobility.

The modeling work in this thesis contributes both numerical predictions of the torques needed to bend the space suit joints and insight into the physical processes that govern space suit joint mobility. Preisach hysteresis model coefficients were identified from experimental space suit torque-angle data and a new method was developed for estimating the variance of the error in the Preisach model's torque predictions. The Preisach model was then used to generate numerical predictions of the torque needed to bend the space suit joint as a function of time. The physics-based modeling work compared two approximate models which describe pressurized fabric cylinder bending to experimental data. The beam model assumes that space suit joint bending occurs through elastic deformations of the space suit fabric, while the membrane model assumes that space suit fabric never stretches. The experimental data agrees most closely with the membrane model, indicating that elasticity is not an important contribution to space suit joint bending performance and efforts to improve space suit joint mobility should focus on geometrical aspects of joint design, rather than the material properties of the fabric.

The work envelope analysis demonstrates the usefulness of modeling space suit mobility in predicting a global human factors metric. The work envelope prediction method developed in this thesis is rapid and easily reconfigurable for people of different sizes and strengths. It generates not only boundaries on acceptable work sites, but also predicts the locations of desirable work sites. A sensitivity analysis on the work envelope revealed that improvements in shoulder mobility and upward and downward visibility would be most effective in enlarging the space suited astronaut's work envelope.

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Title: Advanced Crew Escape Suit
From: Aerospace Engineering September 1995

Author:

Summary
The Advanced Crew Escape (ACE) Suit was designed to be a quick don/doff suit for emergency situations. An earlier suit was the S1-32 Launch Entry Suit (LES). Since then, the S1035 ACE has been designed with some added improvements. Though the suit is still a full volume pressure suit, some of the material layers and connecting mechanisms may be of use in the new bio-suit system. One of the major goals was to reduce bulk and weight. A lighter ventilation system was put in place. The separate restrain layer was removed by incorporating the restraint into the nomex fabric while still providing adequate knee mobility. There were some trade-offs for heavier materials to provide additional comfort. Breathable material was used as opposed to the urethane-coated nylons making the suit heavier. However, the thermal load was reduced, keeping the astronaut cooler and more comfortable. The focus was on the improvements to the self don/doff. The major improvements dealt with a the use of a multi-function pressure locking mechanism and improved locking glove mechanism that could be initiated with either bare or gloved hands. David Clark Company, Inc. was contracted by NASA to design the ACE.

Relevance to Bio-Suit
Though the suit is not made for EVA purposes, there were efforts in designing a thinner and lighter suit. Some of the innovative design incorporating don/doff mechanisms, materials and fabrics could be used or improved given the most recent technology in the Bio-Suit. There were no details on any of the new incorporated technologies. No information could be obtained by Daniel Barry and John Bassick of David Clark Company since the company was contracted by NASA. For detailed information on the suits, NASA Scientific and Technical Information Center should be contacted directly.

References
David Clark Company
360 Franklin St
Box 15054
Worcester, MA 01615-0054
(508) 751-5800

Title: “*Aspen Systems takes a giant step toward commercialization of Aerogels- Thermal Insulation for the Space Age*”
From: News from Aspen Systems, February 1, 2001

Summary

Aspen Systems has developed a high speed, low cost, manufacturing process for aerogels for which Aspen received the prestigious SBIR Technology of the Year Award in Manufacturing/Materials in November 1999. The ability to produce low cost aerogels gives rise to the potential of commercial use and incorporation into products. The flexible Aerogel Blanket is a fabric that acts as insulation. Currently, NASA is funding a project to develop advanced Space Suit Insulation using the Flexible Aerogel Insulation. Spaceloft and Aerotex are potential next generation clothing insulation material.

Relevance to Bio-Suit

The use of aerogel may be useful in insulating the astronaut and can be incorporated into many different materials. Aerogels can be used in a wide range from –273 to 550 degrees Celsius. Due to the aerogel’s hydrophobicity, the material is a good impermeable encapsulation. This may be useful to protect sensors and other electronics from perspiration. In addition, the aerogel can protect the astronaut from materials such as SMAs that must be heated to extremely high temperatures to actuate.

Reference:

Aspen Systems
184 Cedar Hill Street
Marlborough, MA 01752
www.aspensystems.com
www.aerogel.com

Title: Medicine on Mars
From:

Author: Jerome Groopman

Summary

This article raises questions about the medical complications of going to Mars. Long-term exposure to cosmic radiation and zero-gravity, medical emergencies in space, and psychological effects all pose as real problems to the point of jeopardizing the Mars mission. Of the 279 astronauts that participated in space missions between 1988 and 1995, only three of them returned without getting any illness. The loss of gravity can create vertigo, space sickness, dehydration due to the pooling of blood, anemia, and deterioration of the musculoskeletal system. It is estimated that the probability of breaking a bone in space will be between 20-30%. After returning to the Earth's atmosphere, rehabilitation is needed to regain balance, health, fitness and general strength. Though Mars has only _ G, this will still be a significant force to an astronaut that has been in flight for six months. Artificial gravity chairs are under development to reverse or inhibit the zero-g effects. The question is whether or not the brain can adapt to a dual readaptation- that is can the brain adjust quickly to both a zero-g and gravity environment. Another problem is radiation in which Earth is protected by a magnetic field. Genetic mutation in the body, surrounding bacteria and viruses have the potential to cause cancer, dangerous defects, or change into virulent pathogens, respectively. The chances of getting cancer during a voyage to Mars could be as high as 40%, a level illegal for NASA to send astronauts to Mars. Complications in space surgery arise due to issues such as blood aerolization, weightlessness of the surgical tools, and the lack of communication between Mars and Earth. Invasive surgery and virtual mentors with aided robotics are under development to aid the in-flight surgeon. Pyschological well-being will also be a challenge. Between working with an international space crew, loss of circadian rhythm and restful REM sleep, confined space, home sickness, anxiety and depression are all likely scenarios. Again, due to transmission difficulties, psychiatric help will not be possible from Earth.

Relevance to Bio-Suit

Of the medical issues that arise in space exploration, only radiation and compression can be addressed by the suit. Materials that are resistant to UV and cosmic rays can be applied to the suit to protect the astronaut from radiation. Lead is one source of protection. However, lead is also relatively heavy and will be an issue during EVA on Mars. NASA is currently searching for ways to protect the astronauts. Due to the weightlessness of space, the blood that is normally pooled in the legs and lower torso rushes to the head and upper body. Continual compression in the upper torso may help alleviate some of the dehydration caused by zero-g. However, G-suits and a water and salt tablet regiment have not been very successful. The compression of the suit will only replace the G-suit and will most likely not prove to be any better. The Bio-Suit was not meant to tackle these issues of space flight. However, new technologies may be incorporated into the suit if the mechanisms are small enough.

6.2 Meetings

Natick Soldier Center
Dr. Dava Newman, Cam Brensinger and George Hanson met with group at Natick Monday, August 6 2001 at 8am.

Meeting organized by Rita Gonzalez, Director National Protection Center; Lynn Valcourt, NPC; David Querim, Sr. Technology Program Manager, NPC.

The Soldier Center is a division of the Army Materials command, comprised mostly of scientists and located in Natick, Massachusetts. They are concerned with technologies pertaining to what a soldier might carry, consume or wear. They have partners in other military organizations, NASA, government and business. John Hines, NASA ARC, facilitated the meeting between NSC and MIT. NSC works in conjunction with ARIEM and NCTRF to provide the technology demanded by the US Army.

NPCs design approach is systems integration. They try to avoid a "christmas tree" approach where items are simply hung on the soldier. They are concerned with making battle gear as lightweight, efficient, effective and economical as possible.

NPC clearly faces many of the same issues in their design of soldier equipment as the Bio-Suit group faces in its design for Mars. Both are concerned with human survival in extreme environments.

The first of two technologies Natick demonstrated for us was the use of gel polymers in a Navy Seal single piece combat suit. The suit uses the polymers to change breathability depending on temperature so that the same suit can be comfortably worn on land and in water for a reasonable range of temperatures. The minimum temperature resistance is limited by the thickness of the polyurethane. As well, the suit is impermeable to dust particles. Dr. Quoc Truong also showed us a few examples of chemical/biological protection two piece suits. Apparently, this technology was developed with Mitsubishi Corp. Both suits had limited breathability despite being impervious to toxic chemicals. This is achieved by carefully engineering the semi-permeable membrane. Other forms of chemical protection were also discussed as well. Carbon spheres could be used in place of the charcoal based materials, reducing the weight by 50%. There are efforts in designing biological chemical layers that decontaminate the suit automatically.

A side project from the Navy Seal Amphibious Suit was a three layer laminate material under joint development between Malden Mills and Mitsubishi Corp. The material had excellent thermal retention properties, was breathable, elastic and stretched in two directions.

Dr. Heidi Gibson demonstrated the second applied technology: electrospinlacing. We will be receiving technical papers to explain the process in detail, but basically it involves charging and projecting tiny fibers of polymer. Versions of this process can involve projecting directly onto the skin, or projecting elastic or semi permeable materials. The electrospinlacing hardware can be consolidated into a small unit, but the current limitation for any size unit is the rate at which material can be spun. For now, high volume can be achieved with multiple jets. In the future, the airborne fibers may be accelerated by an electrical field. Melt blowing is another projecting process. Melt blowing involves liquefying polymer and blowing it onto surfaces. It does not produce such fibrous material, but is good for creating thin elastic layers. Both processes, but especially melt blowing, have been used in limited applications, commercially. It is important to note that electrospinlacing is a solvent based system. Its practicality for space use might involve questions about power consumption and necessity of dangerous chemicals. Some references in academia were brought up regarding these technologies. North Carolina State University has demonstrated 3D melt blowing capabilities. University of Tennessee has been working with Natick on the electrospinlacing technology, however a 3D application has not been achieved yet. Thus far, only one company is currently using electrospinlacing technology. Most companies do not have the necessary equipment. As well the learning curve is very high. The final deterrent is EPA restrictions. In the near future, carbon nanotubes and conductive polymers will be incorporated into the electrospun fabric.

Other technologies, which we discussed briefly, and need to pursue with Natick include closure systems. Apparently Natick has much to offer in terms of innovative zippers and fasteners. One such observed zipper was from the chemical protection suit. The zipper was lined on either side with a rubber strip. This rubber was on both halves of the zipper so that when closed, the two rubber strips came in contact with each other providing a seal to protect the zipper. However, bubbles have been found within the seal.

Harvesting and reusing moisture is also something being considered for soldier systems which could apply to space suit technology. Dust control is of concern to the military because it can be a mode of transport for biological/chemical weapons. Of course, it is of great concern to Mars suit design. Woven technologies and integration of wearable computing and conductive layers is something Natick is working on. Lastly, refrigeration at a very small scale using electronic chips within fabric layers has been studied at Natick and could benefit thermal control for space suits.

Dr. John Madden, Mechanical Engineering Department, MIT
Meeting with Cam Brensinger and George Hanson on 8/8/01

Summary
Dr. Madden is currently working with conductive polymers but has done some work with SMAs. The speed of the conductive polymers are limited by the diffusion rate so the smaller the cross sectional area, the faster the polymer will react to the stimuli. Currently, the polymer creates 35 MPa of force and has 10x the strength of skeletal muscle. His lab will be conducting studies on the life span of the conductive polymer. He estimates that there will be roughly 1,000,000 cycles but the polymer will be running off of a battery so the polymer will not generate a lot of force. Another current project that Dr. Madden is working on is molecular actuators with Swager in the Chem. Dept. at MIT. They are sacrificing force ofr displacement. The strain could potentially reach up to 20%, a value similar to muscle. But regardless, this technology looks promising and may have serious potential in the future. Dr. Madden also mentioned of some other projects that may be of interest. Kornbluh at SRI is working on dielectric elastomers. I had read some about this material. The major problem is that it requires a lot of voltage but Bar-Cohen (JPL) feels that they are the closest to having a practical material. As well, a new circuit has been designed to use low current and generate a high voltage. Another project of interest is under Dubowsky of MIT (Mech E. Dept). They are also being funded by NIAC for a multi-limbed robot that will be used on Mars. A student working under Dubowsky is (Andres) is looking at dielastic elastomers so he could be a good starting point for that field of polymers. Finally, he mentioned that Bob Hanley was working with magnetic SMAs a few years back so he might be another contact.

References:

Dr. Steven Dubowsky
Professor of Mechanical Engineering, MIT
dubowsky@mit.edu
617-253-2144

Dr. John Madden
Postdoctorate Associate of the Mechanical Engineering Department, MIT
Bioinstrumentation Laboratory
jmadden@mit.edu
617-253-4423

Dr. Timothy Swager
Professor of Chemistry, MIT
tswager@mit.edu
617-253-9671

Jessica Banks, Graduate Student, MIT
Artificial Intelligence Laboratory

Meeting with Cam Brensinger and George Hanson on 8/23

Summary

Jessica Banks's research initially proposed a design for a robotic finger using a Shape Memory Alloy platform. As her work progressed, her interests turned toward detection of multi-point, 3-dimensional force application on the periphery of the robot so the SMAs were replaced with small DC motors. Integration of tactile perception is a key component in rendering systems which organically interact with the world. Such behavior is characterized by compliant performance that is initiative of internal and responsive to external force application in a dynamic environment. The tactile sensor currently under research is an optical transducer technology whereby localized changes in light intensity within an illuminated foam substrate correspond to the distribution and magnitude of forces applied to the sensor surface plane. This enables high resolution, multi-point force feedback for tasks such as grasping, pushing, and investigating. The goal is to approach a primitive correlate of human skin. Future work will involve an engineered analogue of the human hand along with the control architecture to support dextrous manipulation.

Relevance to Bio-Suit

The robotic finger is a step in human assisted motion. This technology may be one way to keep the hand from fatiguing so quickly due to the cumbersome glove. Though SMAs were not used, it may be possible to incorporate them at a later date. With the increased experimentation with gels, this may also be a possibility. The force sensor could also be useful in aiding the astronaut to gain a better sense of touch. Again, currently due to the glove, it is difficult to gauge the force being applied to tools as well as feeling texture of objects. Using the force sensor in conjunction with a tactile feedback system similar to Yoseph Bar-Cohen's feedback system using electrorheological polymers would greatly aid in the senses of the astronaut. Fiber optics are used which are flexible and light enough that the sensors could be directly incorporated into the suit without hindering its motion. However, fiber optics can get very expensive.

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Jessica Lauren Banks, jessical@ai.mit.edu
MIT Artificial Intelligence Laboratory
200 Technology Square, Room 937
Cambridge, MA 02139
(617) 253-7471

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