Hard Suits/Soft Suits: Revisiting Technologies and Applications for a New Space Era

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Abstract

For three decades, two major types of pressure suits were developed in parallel for potential flight applications. Suits flown through Apollo were "soft suits", where the pressure garment was exactly that: a multilayer fabric garment that provided wearer motion while retaining atmospheric pressure for life support. Never flown, "hard suits" were rigid metal suits providing body articulation via multiple sealed rotary bearings around the body. This system produced a true constant-volume suit, eliminating the primary source of joint forces driving to a "neutral" position and creating the need for continual application of torque by the wearer. Hard suits were more flexible with lower biomechanical loads on the wearer than soft suits, but had operational implications due to their mass and limited ability to stow in restricted volumes. The shuttle extravehicular mobility unit (EMU) was a "hybrid" design, adopting a rigid upper torso as a convenient mounting point for the portable life support system, helmet, and fabric limb assemblies.

This paper does not rehash the competitive aspect of "hard" vs. "soft" suits, but looks at the technologies, capabilities, and limitations of each in the context of upcoming space operations focused on planetary exploration. Over the next decades, there are potential requirements for extravehicular activities (EVAs) in various microgravity conditions, including geostationary orbit and at microgravity bodies such as asteroids, comets, or the moons of Mars. There are also potential requirements for extensive EVA exploration tasks on the lunar surface and Mars. The paper examines the requirements for each of these locations and their associated environments, including on human protection from radiation, micrometeoroids and orbital debris, shifting structures on low-gravity bodies, and dust intrusion and fall protection on the moon and Mars. Duration is also a critical issue: missions to Mars could involve surface stay times of up to 15 months, which could translate to hundreds of EVAs per crew in a highly challenging environment. As humans move farther away from Earth for longer durations, without the feasibility of logistics resupply, the need to maintain, repair, and replace suit components will become paramount for crew productivity and safety.

Given mission requirements and logistics challenges, the paper examines current and upcoming fabrication technologies to assess their potential impact on EVA systems design and operations. While the access to Earth or shorter duration missions may favor the use of a fabric-based solution, the specialized equipment and high levels of required technical skills make this design difficult to maintain and repair on extended missions. One potential mitigation for this is the use of state-of-the-art fabrication techniques, such as additive manufacturing, in conjunction with wider use of hard-suit components. Recent self-funded research at the University of Maryland has demonstrated the ability to use fused deposition manufacturing to produce components of a four-roll elbow assembly, including a single-build monolithic construction of an elbow bearing. The paper examines potential automated fabrication technologies to produce suit replacement components on need, and compares that scenario to the challenge of providing sufficient logistics to ensure adequate spares in all potentially replaceable suit components throughout the extent of an extended-duration surface stay, or in the eventual implementation of a permanently inhabited base on the moon, Mars, or both.

I. Introduction

Looking ahead, human missions to the Moon, or even Mars, will demand EVA capabilities of a different order of magnitude than ISS assembly and maintenance. Missions to the Moon will be costly enough that crew on an eventual lunar base would be likely to stay for at least the six months of a standard ISS expedition, or more likely a

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year given the significantly greater effort and cost of performing a crew rotation at the lunar surface. While current speculations about a permanently crewed Martian base in a "one-way" human mission is unlikely to be undertaken in the foreseeable future, even a "simple" minimum-energy human mission could involve as much as 15 months stay time at Mars. Unlike the International Space Station (ISS), where the great majority of both scientific and operational tasks are internal to the habitat, for both the Moon and Mars the purpose of being there is to explore: extended surface traverses, detailed geological surveys, and direct human involvement in surveying and sampling as far from the landing site as technology will allow.

Figure 1 shows what was referred to as the "wall of EVA": an order of magnitude increase in EVA required for the assembly and operation of ISS. As Figure 2 clearly demonstrates, the EVA "wall" itself is dwarfed by the potential EVA requirements of a extended lunar or Mars exploration mission.[1] In such an operating environment, issues of suit components breaking down (or just wearing out) will be critical to crew safety and mission success. If a minimum-energy Mars mission followed the shuttle policy of allowing EVAs only on alternating days, and assuming one day off per week, an average crew member might perform 192 EVAs during their surface stay, which (again assuming six hours per EVA) would put well over 1100 hours on their suit system. Clearly, in these future scenarios, suits will need extensive maintenance and spares, without the ability for convenient replacement parts to be routinely shipped from Earth. To avoid the requirement of the equivalent of multiple suits worth of spares are carried for each EVA crew, the ability to fabricate suit components on need will be an enabling technology for future space missions beyond Earth orbit.

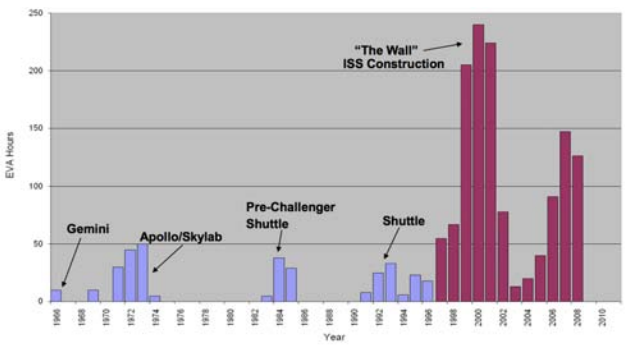

Figure 1. "EVA Wall" - predicted requirements for ISS[1]

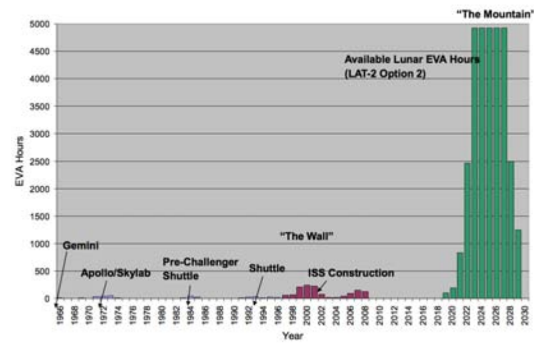

Figure 2. "EVA Mountain" - requirements for lunar exploration[1]

The fiftieth anniversary of the first extravehicular activity recently passed. All of the thousands of hours of EVA experience which has been accumulated since that time has been obtained using space suits based on *soft goods*; carefully tailored fabrics to provide the essential elements of gas retention, force restraint, shape and flexibility control, and thermal/micrometeoroid protection. Although all space suits are extremely high-tech devices, critical components of soft suits still require artisans, as a small number of highly trained craftspeople use sewing technologies little changed from the 19th century, in conjunction with state-of-the-art systems such as computer-controlled fabric cutters and radio-frequency heat sealing machines, to create 21st century space garments.

This approach has worked well to date. Throughout the Gemini, Apollo, Skylab, and Space Shuttle programs, missions were bounded in duration, and EVA requirements were small in terms of number of sorties per mission. In the first phase of the International Space Station, EVAs were frequently coordinated with shuttle missions to take advantage of the simplified logistics and to allow the use of "fresh" suits launched with the shuttle. Things have become more complicated logistically with the retirement of the shuttle, but a few ISS EVAs per year are easily accommodated with suits stored on the station, along with the use of routine cargo flights to bring up replacement parts following failures or when reaching end of certified life on-orbit. If allowable landed payload mass and volume permits suits can be returned to Earth at their end-of-life; more typically they are disposed of by destructive reentry in one-way cargo vehicles, along with the rest of the trash.

These workarounds will fail, however, when contemplating human exploration of Mars, or even extended-duration missions to the lunar surface. In this category of mission, the crews will be in an exploration mode, where EVAs are desirable on a routine rather than infrequent basis. Resupply will be either rare or infeasible, so maintaining EVA capability for all of the crew (which will be a crew safety imperative) will require either extensive spares or more easily repaired suit components. With increased distance and frequency, EVAs will be more dependent on crew skills and judgement, and less amenable to task-specific training and tightly scripted operations monitored from Earth in real time.

A nominal low-energy mission to Mars will involve surface stay times on the order of 400 days. Even with the 30-day surface interval of a "sprint" mission, the crew will be strongly motivated to spend most of their days on the surface of Mars exploring, rather than staying inside while robots explore in their place. This will place more wear and tear on the suits than have ever been seen since the Apollo lunar missions, which maxed out at 3 surface EVAs per crew. Suit elements will be subject to abrasion, textile failures, and environmental degradation from dust, ultraviolet light, and extreme temperatures. Fabric elements are particularly susceptible to abrasion from repeated rubbing against environmental elements, suit structures, or even just other areas of fabric. While some of the suit elements can be designed for in situ servicing, it is unlikely that the limited size of planetary exploration crews will allow the inclusion of a highly skilled textile fabrication specialist to maintain the soft goods elements of the suits, and to fabricate new components as necessary.

In parallel with the soft suits used to date in space, "hard" suits were also developed throughout the early phases of the space program. By using rigid suit segments, along with low-friction joints such as sealed rotary bearings, hard suits have been developed which rival conventional soft or hybrid suits in most performance metrics. For this analysis, they offer the potential to leverage the new, growing field of additive manufacturing to allow in situ suit fabrication, while eliminating or, at least, minimizing the fabric elements which require additional specialized skills and equipment.

II. Hard Suit Background

It has been remarked that the early pressure suits were built by companies familiar with diving suits, and based on similar technologies with airtight fabrics and heavy helmets (Figure 3). It is perhaps lesser known that early diving suits also examined the use of rigid metal structural elements for atmospheric diving suits, which maintain surface pressure even at depth. The earliest known version of such a hard-shelled atmospheric diving suit was built by the Carmagnolle brothers in 1882 (Figure 4). While never actually successful as a diving system, in many ways this suit presaged the design elements of successful hard space suits a century later.

Figure 3. Wiley Post's pressure suit - 1935 (Smithsonian Institution)

Figure 4. Carmagnolle brothers atmospheric diving suit - 1882 (French Maritime Museum)

Both soft and hard suits were developed and tested during World War II to protect air crews at increasingly higher cruise altitudes. Development continued through multiple designs throughout the subsequent decades and into the first years of human space flight. Soft suits were initially used in space flight, based primarily on commonality to previously flown high-altitude systems, as well as lighter weights and smaller stowage volumes. Soft suits were used exclusively in space until the start of the Space Shuttle program, although hard suits were seriously considered for both later (canceled) Apollo lunar missions and the DOD-controlled Manned Orbiting Laboratory program. The shuttle suit itself, which became the eponymous "extravehicular mobility unit" or EMU, was a hybrid suit, featuring a hard upper torso (HUT) with preintegrated portable life support system (PLSS), and using soft goods for the arms and lower torso assembly. This suit started flying with the Space Shuttle in 1981, and is still used exclusively in the US segment of ISS 34 years later.

It is not really feasible to devote this paper to a review of hard suit development, although that paper (or, more likely, book) would be fascinating and a needed contribution. Developments in both types of suits from the early days of the human space program through the start of the space station program produced multiple designs and prototypes which exhibited fundamental feasibility, along with some intriguing insights into the strengths and weaknesses of each approach. All of this reached a nexus a quarter of a century ago, which is the "jumping-off" point for this investigation.

In 1990 the space station was beginning development in earnest, and serious consideration was being paid to the question of what the ideal space station suit would be. Although space suit development funding was not as readily available as in the early days of human space flight, two suits could be identified as the most highly developed examples of their design. The Mark III hybrid suit (Figure 5) was developed by the NASA Johnson Space Center, incorporating a hard upper torso and hip assembly. Three-roll bearing arrangements were used to provide thigh mobility, and rolling convolutes were used with soft goods for shoulder motion. Representing hard suits was the AX-5 (Figure 6), developed at the NASA Ames Research Center as an all-hard suit, exclusively using rotary joints and wedge-shaped suit elements to provide joint mobility. Both suits were designed to operate at 8.3 psi, which would allow direct EVA operations from space station without denitrogenation beyond that inherent in suit checkout and airlock depressurization. In response to the perceived "wall of EVA" referenced in Figure 1, the Johnson Space Center undertook a head-to-head evaluation of both suits, as well as the current shuttle EMU of that time as a control, with an eye to selecting the suit system to be developed for operational use on the space station.

The focus of that study, to decide which suit was to be developed as the standard space station pressure suit, turned out to be a moot point: budget pressures from all sides led to the decision to just continue to use the shuttle EMU as the station suit./citemcmann The testing revealed a number of interesting results, including areas of clear advantage for the AX-5, along with a subjective crew preference expressed for the soft good joints in the knees and elbows. Documentation of the results was limited, but some available documents[3,4] provide some details of the testing approach and results. These results will be highly informative for further discussions in this paper.

III. Future Issues with Present Suit Technologies

As previously discussed, potential futures in human space flight will place demands on extravehicular systems as far beyond space station as ISS was beyond Apollo or the early shuttle program. Even a single sortie mission to Mars could involve thousands of hours of EVA time in an environment of temperature extremes, abrasive regolith, and wear and tear over dozens or hundreds of EVA sorties. It is useful to consider scenarios where EVA demands far exceed those experienced to date, but where there is no recurring logistics support to provide spare parts or replacement suits. In each category, we will examine the implications on current suit technologies, and then consider if hard suits would provide a potential benefit.

A. Environmental Protection

Several potential future destinations for human space flight will involve regions with far more environmental hazards than the relatively safety of low Earth orbit. Recent studies of potential human/robotic servicing activities in geostationary orbit, for instance, detail the long-term health limitations of more than a few hours of EVA in GEO using current suits.[5] Small asteroids, recently selected as a near-term focus of human space exploration, may well be an aggregate of loose materials bound together only by mutual gravitational attraction; this raises the potential for metastable states where relatively minor physical interactions could create major motions of the surface materials, which could threaten the crew with crushing forces or entrapment.

1. Dust Mitigation

One environmental hazard which everyone agrees will be pre-eminent is that of ambient dust. Regolith on the moon or Mars will be kicked up by crew activities (as well as by the wind on Mars), and will tend to accumulate on the

Figure 5. Mark III pressure suit (NASA Johnson Space Center) **Figure 6. AX-5 pressure suit (NASA Ames Research Center)**

suits. Significant concern has been expressed on the physiological effects of these dust particles when aspirated, due primarily to carrying the dust into the pressurized volumes via airlock transits. This has been one of the overriding arguments in favor of suit ports, which leave the suit outside while allowing crew ingress and egress. At some point, however, all suits will have to be brought bodily into the habitat, if only to replace the gloves, and probably for routine maintenance activities.

Dust capture by a suit is a function of the surface topology, texture, and material. Soft suits are at a disadvantage, since surface structures (wrinkles, folds, etc.) are natural sites to capture loose materials such as dust. The weave of the fabric used for the surface layer is also an excellent dust capture mechanism, at a smaller scale than the lay of the fabric itself. Surface coatings (Teflon impregnation in beta cloth, for instance) can reduce the adhesion of dust particles to the surface itself, but will not compensate for the inherent texture of the fabric layer. Surfaces of hard suits, on the other hand, are usually designed to be featureless and can be arbitrarily smooth, whether in the manufacturing process or by smoothing and polishing afterwards, as well as using surface coatings to fill voids and reduce adhesion.

Bearings are a critical issue for all suits due to dust intrusion. The Apollo crews remarked on a noticeable deterioration of smoothness and required friction in the wrist bearings, after only three surface EVAs. Hard suits, being dependent on bearings in all degrees of freedom, will be particularly susceptible to this issue, although all soft suits mobile enough for use will have some bearings, at least in the shoulders and wrists. The fixed structure around hard suit bearings would allow the use of exterior elastomeric dust seals, or the potential use of labyrinth seals to prevent dust from reaching the bearing surfaces altogether.

2. Micrometeoroids and Orbital Debris

The NASA goal for micrometeoroid and orbital debris (MMOD) susceptibility for space suits is to have a penetration be a once-in-2000-year event, based on an assumed number of hours of EVA exposure per year. The AX-5 met this criteria, as did the hard upper torsos on the Mk.III and shuttle EMU suits. The fabric arms and legs do not meet this criteria, but could with the addition of additional layers of MMOD shielding, such as tungsten-loaded silicon fabric layers.[3] More recently, NASA has defined the goal of having a probability of no penetration (PNP) of a space suit thermal/micrometeoroid garment (TMG) layer of 0.91 over 5400 crew-hours of EVA;[11] this works out to a 99.99% chance of no penetration on any given six-hour EVA. One experimental study of a revised TMG to improve MMOD resistance increased the mass of an EMU leg segment by 48%, and increased the joint torques by 37%.[12]

3. Crush Hazards

Crush hazards are rare, as potential sources of crushing (such as modules on ISS being mated together) are done without crew in the immediate vicinity. In a more deterministic environment such as ISS, procedures are the best protection for EVA crew from hazards such as being caught between two large masses on a collision course.

On planetary surfaces, external events are less controllable via procedures. Geologists get their best data from vertical surfaces and other regions which explore different strata in the crust; these regions are highly susceptible to avalanche, and scree surfaces build up at the lower approaches to such vertical faces due to rocks and boulders coming loose and falling to the ground. Climbing over such scree is always hazardous to geologists, as their weight can initiate redistribution of loose elements, and the possibility of having rocks capture part of the person's body is ever-present.

Both types of suits are somewhat resistant to crush hazards, as the internal pressure provides a preset tension to the surface which must be overcome before the suit material can be pushed in to contact and ultimately injure the wearer's tissues. The difference is that the hard suit has inherent compression strength from the structure, in addition to the internal pressure reinforcement; as such, hard suits would be more protective against crush damage to the wearer than a soft suit would be. It should be noted in fairness that an external crush load sufficient to deform a hard suit element, such as an ankle wedge, to injure the wearer would at a minimum create a real problem to get the suit off of the victim after they are returned to the habitat, and could potentially be more susceptible to a full fracture (and loss of atmosphere) from that level of damage than a multi-layer fabric suit might be.

4. Radiation

At our current level of understanding, no isolated pressure suit system would offer significant diminishment of galactic cosmic rays (GCRs). Mass requirements for significant GCR shielding would be on the order of meters of material, which clearly eliminates GCR shielding from being a consideration in any anthropomorphic suit.

Solar particles are easier to shield, and under circumstances of a coronal mass ejection could be potentially lethal to an EVA crew. While it would impractical to shield the suit against the peak of a solar flare, suits could add mass shielding to reduce the radiation dosage per unit time. This is especially important in regions of continually heightened solar particle radiation, such as the van Allen radiation belts around the Earth, which overlaps into geostationary orbit. As discussed under MMOD protection, additional layers of material to enhance particle radiation protection will impede motion of fabric joints, reducing range of motion and increasing the actuation forces to the wearer. Hard suits typically start out with higher areal masses than a soft suit, and additional mass added to increase shielding will not impede motion of the rotary joints, as long as it does not add sufficient bulk to reduce the range of motion from self-collision.

5. Solar Exposure

Even on Earth, significant deterioration occurs in many materials from prolonged solar exposure. Ultraviolet illumination attacks the molecular bonds, and fabric is particularly susceptible to this attack. It has been speculated, for instance, that the American flags placed on the moon during the six successful Apollo lunar landing missions were bleached white within weeks, and long ago all traces of the fabric would be gone as the materials were effectively dissolved by prolonged exposure to UV rays unfiltered by the atmosphere of Earth. While this is not an issue for short-stay missions, long-term exploration or settlement would produce much higher levels of exposure, particularly if suit ports were adopted as the standard for pressurized cabin ingress and egress. Even early simulations, such as the NASA Space Exploration Vehicles used for the Desert RATS simulations, adopted deployable fabric covers over the suits in the suit ports to shield against both sun and dust.

Hard suits would primarily be affected by long-term solar exposure via deterioration in the surface coatings, with implications for thermal loads on the portable life support system (PLSS). Metal hard suit structures would not be affected within any imaginable lifetime; polymer suits would be affected, but the thicknesses of the elements would be sized for pressure and crew-induced loads, and would be significantly thicker than any single layer of a fabric suit. It is unclear at what time frame this effect would be significant; while each layer of a soft suit would be more immediately affected, the number of layers which have to deteriorate to significantly compromise the integrity of the suit would be a function of exact design and specific locations of interest.

B. Maintenance, Replacement, and Logistics

Suits have long been described as human-shaped, articulated spacecraft. As such, it is not surprising that they are susceptible to wear and tear with frequent use, and the need to repair, reconfigure, and ultimately replace suits in a scenario of routine EVA operations. This is especially true in planetary exploration, where the demands on the suits are enhanced by terrain, dust, temperature extremes, and force-intensive tasks such as geological exploration.

1. Reconfiguration and Sizing

Originally, all space suits were custom-fit to each crew. Soft suits were resized by lacings at the extremities of the limbs, to allow the crew to change the arm and leg lengths as designed within a range of a few centimeters. The EMU introduced a modularity to the suit system, with each flight suit "built to order" based on an individual's measurements for each shuttle flight. This assembly from modular components was a highly involved operation, and was not initially user-modifiable on-orbit other than laces at the wrist and ankles. Even during the shuttle program the concept of "one crew, one suit" was abandoned, as EVA-intensive flights had more than two crew, and frequently HUT/PLSS assemblies were shared between crew on alternate days. EMUs used on the ISS have been modified to incorporate hard elements in the limbs which facilitate modular resizing upon need, whether to accommodate different wearers or just adjust for crew preference in arm or leg lengths.

The AX-5 used various-length sizing inserts to adapt the suit to the wearer. A range of lengths in sizing inserts for the upper and lower legs and arms, as well as the torso itself, allowed a close fit across a range of sizes in potential wearers. These insets incorporated O-ring seals, and used Ortmann wire couplers to make the connection. Both could be affected by dust intrusion in the seams between the inserts.

Perhaps one of the most serious problems with resizing any suit is the inter-scye joint system, which should ideally correspond to the distance between shoulder sockets in the wearer's skeletal system. Soft suits offer the potential to change this distance on a soft torso to improve suit fit in this critical dimension; research at UMd and elsewhere have examined the possibility of active real-time resizing of the shoulder joint placement not just for each test subject, but for different ranges of motion needed for different tasks.[7]

Since designing a hard torso with reconfigurable shoulder bearings would be quite challenging, it is likely that this issue will be best resolved with a range of torso sizes, which utilize interchangeable components for limbs and other suit components. This will be facilitated by technology for in-situ production of hard suit torsos, along with 3D scanners and biomechanical models to allow the automated design of torsos tailored to each individual if EVA operational patterns make that desirable.

2. Logistics Scenarios

There are now more than 15 years of experience in permanent inhabitation of the International Space Station. With the current six-person crew, cargo resupply missions are flown to ISS 6-7 times per year, in addition to four crew rotation flights per year with some limited capacity for low-volume, high-priority cargo. At a gross level, any critical component on ISS could be resupplied in a few weeks, and a life-threatening contingency can always be remedied by having the crew evacuate and return to Earth in a few hours.

On the other hand, even a lunar base would only have windows for ideal crew or cargo transfer on a monthly schedule, and the funding limitations for near-term exploration would limit logistics flights to no more than 1-2 per year. While a three-day return trajectory to Earth is generally available, from the specific view of this paper getting crew safely to the ascent/return vehicle(s) is dependent on the availability of a functioning space suit. Rather than wait two transport cycles to get a replacement suit to the lunar surface to allow the suitless crew to return to the ascent vehicle for evacuation, there is a clear need for sufficient capability to repair or replace suits for any credible likelihood of suit malfunctions.

This need is exacerbated in the case of a Mars base. Here, return to Earth could require as much as a year, and opportunities for resupply are at best on the 26-month synodic period between Earth and Mars. In general, a “rush shipment” to a Mars settlement will be delivered in three years, including cargo planning and preparation, waiting for a launch window, and the eight months or so of coasting between Earth and Mars. In this scenario, there needs to be either a number of replacement suits for each crew member (or for each subgroup of crew members with similar sizes), or the capacity to rebuild suits from scratch from an extensive supply of spare parts (as was done on the ground for EMUs for each shuttle mission), or the ability to fabricate, test, and qualify suit components from common feedstocks. While a formal logistics analysis would be a logical next step in this area, the attraction of some limited number of common materials which can be autonomously fabricated into the required components in-situ would seem to offer maximum flexibility with minimum logistics overhead.

C. Crew Capabilities and Demands

Ultimately, the utility and acceptability of a space suit is dependent on two questions: what capabilities does the suit provide to the wearer? and what demands does the suit place on the wearer?

1. Reach Envelopes

EVA is used for a simple reason: getting a human’s eyes and hands on the task are the most effective way to accomplish it. Modern hemispherical helmets, as used in both the Mk.III and AX-5, are noted for providing excellent sight lines for the wearer. The key, however, is the reach access from the suit, particularly the highly restricted volume where both hands can reach simultaneously.

The critical results of one set of comparative suit tests are shown below. Figure 7 shows the reachable area in a plane perpendicular to the body as a function of distance from the body. The AX-5 has superior reach across the gamut from closest to farthest reaches, and in the mid-range the reachable planar area exceeds that of the two soft suits tested by as much as 75%. Of even greater interest, however, is the two-handed reach envelope, shown in Figure 8. This is the volume in which most tasks are accomplished, as it is highly preferable where possible to use both hands in performing a dexterous task. Again, the AX-5 was superior across the board, and in the middle distances had more than a 2:1 advantage in reachable area over the EMU and Mk.III. It is tempting to attribute this to the four-roll segmented shoulders, as compared to the rolling convolutes in the other two suits, however, this test was a ”whole-body” reach test performed in neutral buoyancy, and there would have been a serious advantage to the enhanced lower-body mobility of the AX-5 in this test protocol. As a result, no single factor can be clearly identified as the source of the difference in reach envelope. One recommendation of the testing was to investigate the use of the AX-5 type rotary wedge elements in the Mk.III suit as an experiment in hybridization of the technology;[3] no publications have been located to date indicating that this test was ever performed.

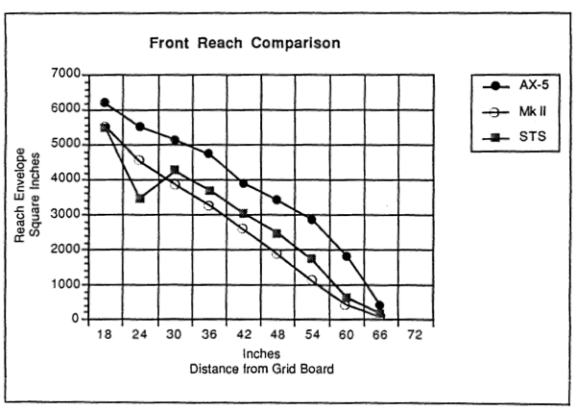

Figure 7. Extent of forward reach limits in test suits[3]

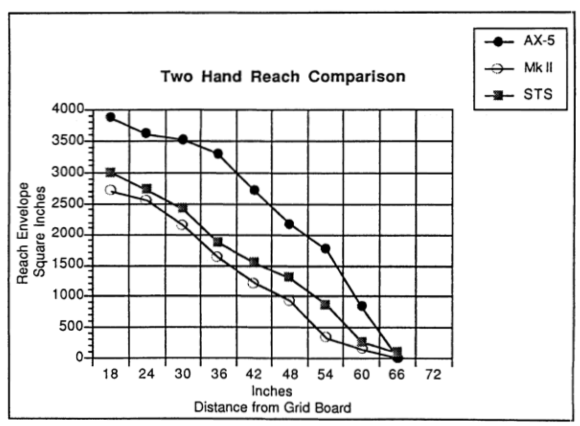

Figure 8. Extent of two-hand reach envelope in test suits[3]

2. Physiological Workloads

There are a number of sources which produce forces internal to a suit, which must in turn be overcome by the wearer. These include pressure work, joint friction, and bearing friction. The pressure envelope of a suit forms a quasi-static envelope surrounding the air and human body inside the suit. Any changes in gas volume require work, as per the classic formulation $\int PdV$. Even if the suit pressure is kept absolutely invariant, work is still required to move if the suit changes volume. Fabric joints require crew forces to make the convolutes move over each other, due to friction between the layers moving in opposite directions. Bearings have their own friction sources from the ball motions as well as sliding on the required seals in a pressure suit.

A representative set of joint torques, in this case for the elbow, are shown in Figure 9. There are three significant issues in these comparative graphs: the maximum torques, the forms of the torques, and the internal areas of the hysteresis representing different torques in opposite directions. On the face of it, the AX-5 hard suit is clearly superior in this aspect, as all motion in the suit is due to rotary joints. The rigid segments produce a true constant-volume joint, so operationally any changes in suit volume are due to changes in the wearer's volume as they move. (It should be noted that these tests were performed with external measurements of motion in a pressurized, but unoccupied, suit arm.) Joint torques for the hard suit are near zero for most of the range of motion, and at the ends of the range of motion are an order of magnitude less than the two soft suit arms tested.

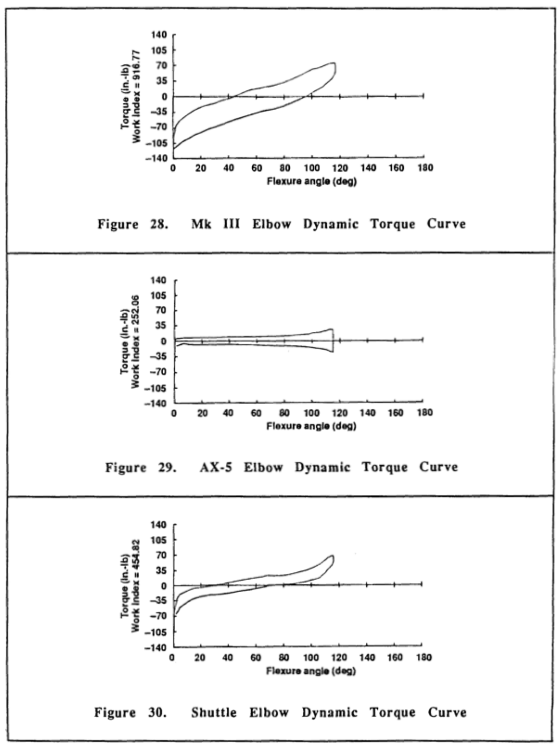

Figure 28. Mk III Elbow Dynamic Torque Curve

Figure 29. AX-5 Elbow Dynamic Torque Curve

Figure 30. Shuttle Elbow Dynamic Torque Curve

Figure 9. Torques in elbow motion for suits under test[3]

The shape of the torque curves provides insight into the torques required for the wearer. At the ends of the range, the soft suits have non-zero torque requirements; this indicates a steady pressure to return to the regions where the joint exhibits zero torque requirements. This is the source of the "set point" in most suits, as the residual torques at the joints seek to restore them to the limited region where they can exist at zero torque compensation. Holding suit joints outside the nominal set range is a source of an ongoing force requirement for the wearer. The rotary joints of the hard suit, by comparison, are stable without force at any angle, removing the need for the wearer to compensate for joint restrictions to hold an arbitrary position.

The last element of the curves is the area within the traces, which represent the hysteresis between extension and flexion. Over the course of a single bidirectional actuation, the area within the curves represent work done by the wearer on the suit, which is energy exerted by the wearer that adds to their metabolic workload over repeated motions throughout the EVA. Again, the low area of the hysteresis curve for the AX-5 represents lower demands on the operator, definitive at least for this particular joint.

It should be noted that the equivocal nature of much of the comparative data would be resolved if the tests could be rerun in the present day. Modern bioinstrumentatipn systems allow real-time measurement of metabolic workload[8] and full-body joint angles[9] in a nonintrusive form factor inside a pressurized suit. Advances in soft suit joints over the past twenty-five years would also influence the trades between the suits. Unfortunately, no functional hard-suit system exists to allow an updated comparative investigation.

3. Articulation, Weight, and Volume

There are two issues which have traditionally been counted as negatives for hard suits: weight of the suit, and "programming" of the joints. Programming (joint torques requiring indirect motions to minimize forces) are also present in some suits such as the shoulders of the EMU, due to the arrangement of the scye and upper arm bearings, but is noticeable through all of the limbs of a fully rotary hard suit. Programming appears to be a personal preference issue; some learn to deal with it, others object to not always being able to take the shortest path from the current position to the desired one.

Weight and volume have always been the "Achilles heel" of the hard suit. Hard suits have traditionally been made out of metal, with individual components "hogged out" of full billets of aluminum using contour milling on 4- or 5-axis mills. When complete, the suits are significantly heavier than the corresponding hybrid or soft suit.[a] Similarly, the fixed components do not allow the suit to be compactly stowed, at least not without substantial disassembly. Early programs such as Apollo and Skylab had severe mass and volume limits, and hard suits traded badly against soft suits in these critical parameters.

Technologies such as advanced 3D manufacturing and materials could ameliorate the disadvantage of hard suits, at least in as much as weight is concerned. If it is possible to fabricate hard suit components from space-rateable polymers rather than metal, the mass of the suit could be reduced by as much as a factor of two. Even if metal components are still required, the ability to use additive manufacturing to place the material exactly where required for operational loads (as opposed to thicknesses required to withstand contour milling loads) would allow thinner and lighter suits. Design for reconfigurability, such as the sizing ring inserts of the AX-5, would allow the suits to be shipped as cargo in more efficient volumes than a complete human-shaped suit, and then be assembled prior to planetary use.

IV. Future Suit Fabrication

Based on the discussions to this point, there is a real potential for the use of hard suit technologies, along with additive manufacturing and other rapid prototyping techniques, to support extensive EVA operations and logistics on long-duration human exploration and settlement of the moon and Mars. To assess the feasibility of this approach, two critical questions need to be answered:

- Is it possible to fabricate all or, at least, significant portions of hard suits using additive manufacturing?
- Will hard suits be suitable for planetary surface exploration, since no hard suit development or testing to date has focused on walking or similar tasks in a gravitational field?

To find the answers to these questions, the University of Maryland has made some modest first steps, and laid out a plan for further near-term research initiatives.

Under (severely limited) internal funding, the University of Maryland has initiated an effort to examine the feasibility of using modern 3D printing and other rapid prototyping technologies for the production of a hard suit. To date, this effort has been limited to fabrication systems currently in place at UMd and within budget limitations, primarily fused deposition printing using ABS and PLA filament materials.

A. Bearing Fabrication Test

Since the critical element of hard suits are the rotating bearings, the logical first step was to examine the possibility of producing a bearing using fused deposition techniques. The initial prototype was a bearing appropriate for an elbow or knee joint, with an internal diameter of six inches and incorporating races and ball separator for 0.25 inch balls.

[a]Actually, it is difficult to get numerical values for the masses of the AX-5 and Mk.III - or, rather, it is too easy to find such numbers, generally in wild disagreement with other cited weights and without references as to original source. Rather than propagate inaccurate mass values, the authors continue to search for verifiable mass estimates for each suit.

The first prototype of a complete bearing assembly is shown in Figure 10. This bearing was printed fully assembled in ABS as a single print operation, on a UPRINT FDM printer made by Stratasys. Following evaluation, the assembly was taken apart, as shown in Figure 11. The bearing assembly consisted of inner and outer races, a bearing separator, and 42 balls, all made in place from ABS. The UPRINT printer also used support material from a separate extruder, which was dissolved in a water bath to remove the support material.

Figure 10. Test bearing manufactured assembled by fused deposition

Figure 11. Components of 3D printed bearing disassembled

As a first prototype, this unit was considered a success. The greatest drawback to the fabrication of a complete bearing assembly was that the balls had to be printed undersized (0.240 inches diameter instead of the nominal 0.250 inches) in order to have the balls separate from the races when the support material is dissolved away. While the bearing rotated at low friction, the undersized balls created a very "loose" bearing assembly, which also had noticeable variations in friction due to imperfect ball fabrication.

To address the shortcomings of this system, the bearing was reassembled, using stock 0.250 inch stainless steel balls in place of the fabricated ABS balls (Figure 12). These balls were selected as the design fit to the bearing races, and produced a much smoother rotary motion, due both to the close tolerance fit to the races and the more spherical surface of the stainless steel balls.

As the second step in this testing, a 30^o wedge element (for an elbow assembly) was designed and fabricated, using the same race designs from the prototype bearing. By removing the balls, the outer race from the bearing was attached to the male end of the arm wedge (Figure 13). The rotary joint was reassembled by inserting balls into the races one by one, with a fabricated cover closing off the race access when the bearings are all assembled. This element had similar rotation properties to the simple bearing, and was used to validate form and fit to potential test subjects for the planned arm fabrication and testing.

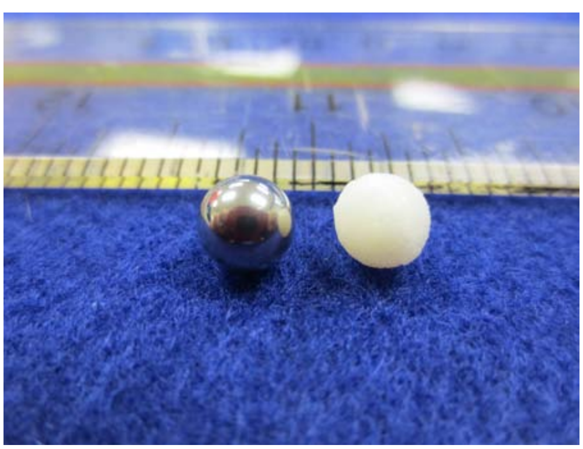

Figure 12. Prototype bearing balls: in-place fabricated (right); commercial stainless steel balls (left)

Figure 13. Partial assembly of elbow joint consisting of bearing and 30^o wedge element

B. Planetary Surface Operations Tests

A problem with FDM is that the material is generally porous, and as such cannot hold gas pressure. Other 3D printing techniques, such as stereo lithography or laser sintering, can produce fully filled parts which can be pressurized. At the same time, there is immediate utility for 3D printed hard suits, even without being airtight. The University of Maryland has been producing a series of soft suit simulators, designed for operation in field simulations of planetary surface EVAs (Figure 14. These suits, which are not pressurized but replicate the bulk and restrictions of a pressure suit via fabric tailoring, increase the fidelity of analog field tests without the safety and support requirements of pressurized suits.[10] These suits have also been used for neutral buoyancy simulation of microgravity EVAs (Figure 15).

Figure 14. MX-C suit simulators in use at the HI-SEAS analog site in Hawaii

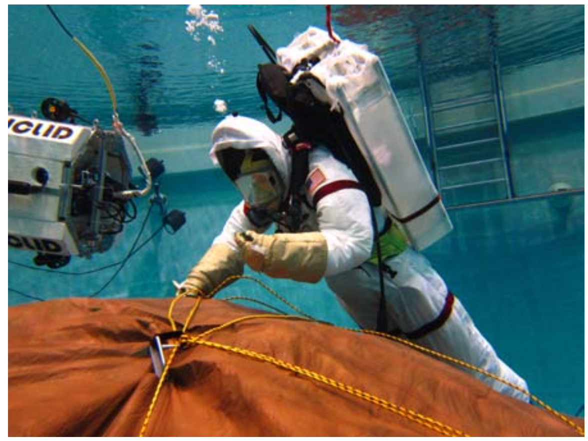

Figure 15. MX-B suit simulator in the UMd Neutral Buoyancy Research Facility investigating asteroid EVA translation aids

Over the next year, the UMd Space Systems Laboratory hopes to produce the prototype of a hard suit simulator for assessment and field testing at the HI-SEAS habitat in Hawaii. Hard suit simulators will be subject to the crew-induced loads common to space suits, without the pressure loads; the use of a prototype suit on an extended mission simulation such as HI-SEAS will provide extensive data and important lessons on wear and tear on the suit. Most importantly, the development of a hard suit simulator will allow addressing a critical unresolved issue at low cost: is a hard suit feasible for routine surface EVAs in noticeable gravity fields such as on the moon and Mars? The hard suit will also simplify some of the issues the HI-SEAS crews have had with the MX-series of simulators, such as resizing and ventilation runs. The HI-SEAS habitat also has a 3D printer, and there will be the potential for the crew to print some of their own components if needed due to failure, wear, or crew-inspired redesigns.

It should be pointed out that common plastics used in consumer-grade fuse deposition machines is not at all suitable for hard suit use, except in two very important categories of cost (about $20/kg) and availability of suitable printers. Since the bearing loads are insufficient to take pressure loads, there has been little incentive to attempt to verify structural parameters of the prototype bearing system. Flight-rated polymers and 3D printed metals are currently 1-2 orders of magnitude more expensive than ABS/PLA, which puts even prototype components out of reach for unfunded projects. The goal of the current program is to continue to explore designs and basic functionality with the low-cost systems, as a way of developing the necessary knowledge base to transition to a funded research program.

In line with this, the SSL has also planned out a series of tests to evaluate the use of 3D printed parts on an operational hard suit. Given sufficient funding, sample elbow assemblies would be fabricated with a variety of materials and methods. For example, Windform XT^{TM} is typical of a series of thermoplastics which do not outgas and have wider working temperature limits and strength characteristics than more typical 3D printing materials. Alternatively, a wide variety of metals can be used for 3D printing structures using methods such as direct laser sintering. Each rotary joint will require seals to prevent air leakage; a number of elastomers are currently available for 3D printing, and tests of these will be performed in parallel to downselect elastomer materials and fabrication methods for seals to be incorporated in the test assemblies. As funding permits, sample of flight-rated materials would be formed into elbow assemblies, and operated pressurized in the SSL thermal vacuum chamber to assess leak rates and operations in varying thermal environments. Between these tests of flight-rated pressurizeable components and the fully integrated hard suit simulators in field evaluation, the SSL aims to develop a knowledge base adequate to permit the fabrication of a complete pressurizeable hard suit based on maximum use of 3D printing technologies.

V. Conclusions

After the comparative assessment of the Mk.III and the AX-5, hard suit research essentially came to a halt. There was a prolonged period when other budget priorities limited all suit research, and attention was focused on soft and hybrid suits suitable (like the A7L-B) for near-term lunar exploration. Current suit development is focused on launch and entry suits for new vehicles, with scars to enable some of the suit elements to be adapted to microgravity EVA operations, or ultimately planetary surface suits. A decision was recently announced that when NASA performs the Asteroid Redirect Mission component with astronauts performing sampling in 2021 or so in lunar orbit, they will be wearing shuttle EMUs.

It is always difficult to overlook the limitations and problems of the next program, or even just the next mission, for issues enabling longer-term visions of human space exploration. Beyond expressed desire from many quarters to push for a human Mars mission, other groups are looking beyond to extended exploration of the moon and Mars, with stay times long enough the categorization of the crew living volume will transition from “vehicle” to “habitat” to “settlement”. The challenges of sustainable EVA capabilities over multi-month, or multi-year, or even multi-decade programs is substantial. This paper has attempted to lay out some meager near-term steps to reassess conventional wisdom in suit design, to maximize sustainability for future human explorations.

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