NASA Innovative Advanced Concepts (NIAC)
Phase I Final Report:

The Spacesuit Digital Thread: 4.0 Manufacture of Custom High Performance Spacesuits for the Exploration of Mars

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1.0 EXECUTIVE SUMMARY

Imagine that at some point in the future, one could stand in a human full body scanner, be scanned from head to foot, and then a few days later, would be issued an EVA space suit which had been digitally evaluated for fit, performance, and comfort. Figure 1 illustrates this concept.

Fig. 1: A DT concept from Step 1: a digital body scan, to Final Step: a customized pressure suit which has been digitally modelled for performance and mobility prior to manufacture (*virtual twin*), and then is continually monitored and optimized after manufacture via a *digital twin*.

This Phase I NIAC project sought to investigate the **feasibility** of just such as concept for improving the design, performance and "fit" of Mars exploration spacesuits by *manufacturing* "custom" suits**,** utilizing the Digital Thread (DT), which integrates digital technologies, such as 3D/AM printing, full body IR/Photogrammetric scanning, digital twins, CADs, model-based engineering, human factors, and robotic/automated 3D garment manufacturing. The DT strategy can further address mission architectural components such as launch mass, resupply, and in-situ repair.

Mars explorers should expect to launch with both IVA and EVA suits which fit, are reliable, are functional, and, if designed effectively, more cost effective. Mars missions are expected to be EVA intensive, yet EVA spacesuits have been largely manufactured in siloed environments, not optimized to human anthropometrics, have caused injuries, and still require significant manual labor to manufacture. This study evaluated the feasibility (1) to digitally design, model, manufacture, and "track" "custom" EVA spacesuits through their entire life cycle, and (2) to manufacture those spacesuits with new 4.0 digital engineering systems with the goal of reducing costs and delivery schedule. Although all current components for the DT were considered for this feasibility study, there were three low TRL (< 2) DT components that were explored more deeply: *(1) Finite Element Modelling (FEA) of the soft fabric pressurized parts of EVA suits in order to predict mobility of a particular design on a digital scanned human, (2) 3D/AM production of customized pressure bladders, and (3) Digital Human Modelling (DHM) with current commercial models.* Additionally, the team met with a commercial 3D knitting company which fabricates both standard size and custom garments and fabric systems for a large range of industries, including Aerospace. All four of these technologies are proposed for further development and the study concluded that the DT concept is feasible for manufacturing EVA space suits, with further technology development. However, it should be noted that, although robotic assembly of the suits, especially the soft fabric components, is also a low TRL manufacturing capability, it is currently benefitting from investment in the public market place, so was not part of this study.

Although this feasibility study is focused on a Human Mission to Mars in the time frame of ~2035 – 2039, if successful, this manufacturing strategy may also be extensible to future long duration Lunar Exploration Missions (Artemis) where there may also limited resupply and return capability; to future commercial spaceflight crewmembers and passengers who will likely expect cost effective rapidly delivered protective garments; and to any application where humans must be protected from extreme environments with anthropometric enclosures. The applications range from first responders to members of our military services, to those exposed to adverse chemical or biological environments where fit and leakage can be a life or death situation (*e.g. a suit in the closet*). These garments must fit humans with a large range of anthropometrics, provide mobility, be functional, and keep the wearer safe.

The recently awarded xEVAS contracts to Axiom Space and Collins Aerospace for the development of new EVA suits for International Space Station (ISS) and the Lunar/Artemis missions could provide a platform for evaluation of DT technologies so that lessons learned are captured prior to the application to the manufacture of Mars exploration suits. This potential extensibility is conceptualized in the NASA chart shown in Figure 2, as presented by the NASA Space Technology Mission Directorate at the 2022 IEEE Aerospace Conference in Big Sky, Montana. Although the Martian atmosphere and gravity levels will likely dictate a different suit design, the implementation of DT systems and strategies in current programs will benefit later system development.

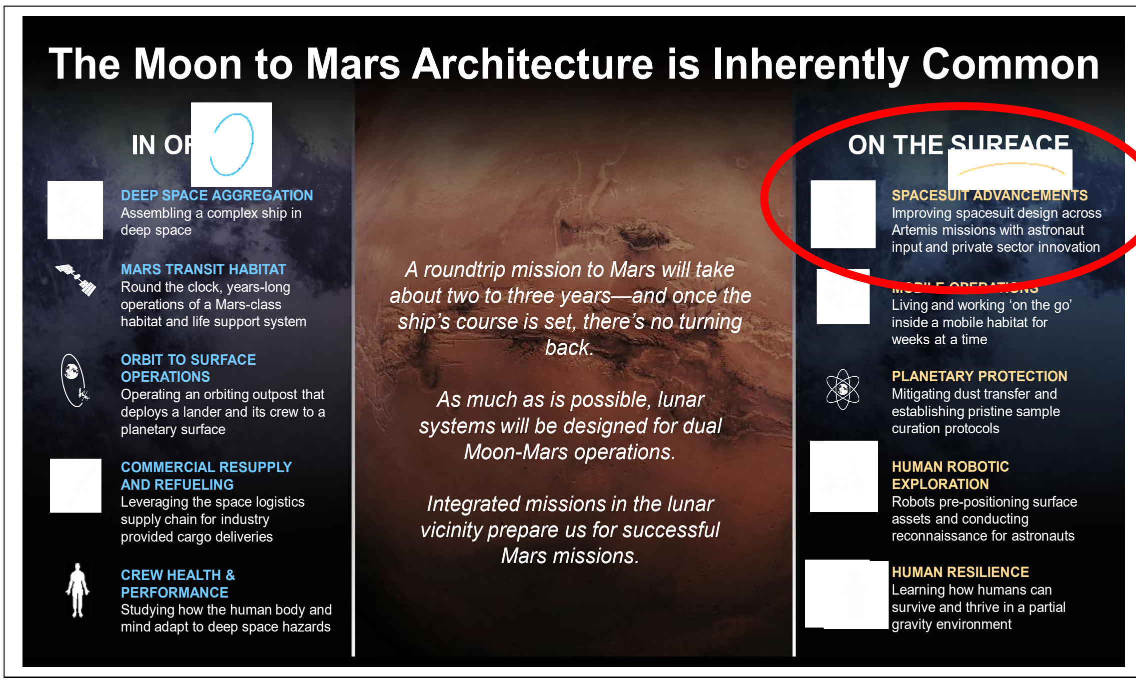

Fig. 2: Moon to Mars Architecture Commonality Chart presented by the NASA Space Technology Mission Directorate at the 2022 IEEE Aerospace Conference in Big Sky, Montana. Note the inclusion of Spacesuit Advancements as a Key Component of Surface Operations on both the Moon and Mars.

2.0 KEY ACRONYMS, DEFINITIONS, AND CONCEPTS

Table I: Key Acronyms

DRM	Design Reference Mission	IVA	Intravehicular Activity
LEO	Low Earth Orbit	TRL	Technology Readiness Level
FEA	Finite Element Analysis	EMU	SS/ISS EVA Mobility Unit
DHM	Digital Human Modeling	PLSS	Portable Life Support System
CONOPS	Concept of Operations	HUT	Hard Upper Torso
3D	Three Dimensional	SSA	Space Suit Assembly
AM	Additive Manufacturing (e.g. 3D)	A7LB	Apollo EVA Suit
EVA	Extravehicular Activity	TMG	Thermal Micrometeoroid Garment
LCVG	Liquid Cooling and Ventilation Garment	LTA	Lower Torso Assembly
ISS	International Space Station		

The following Concepts are provided in order to establish a common vocabulary, and because some have varying meanings within the engineering community. For the purpose of this report, we are using the following definitions unless elaborating text is also used.

Bioastronautics: Bioastronautics is the area of science and technology at the boundary of life science and space technology… Bioastronautics encompasses the provision of an artificial environment supporting the astronaut's health and function – inside or outside of a spacecraft. (Young and Sutton, 2021)

Manufacturing 4.0: Often referred to as the 4th Industrial Revolution. Digitization and automation are considered the "game changers" to enable 4.0

Digital Thread: Defined as "the use of digital tools and representations for design, evaluation, and life cycle management. First used in the Global Horizons 2013 report by the USFA Global Science and Technology Vision Task Force.

Digital Twin: Following the design of a system, using multi-physical simulations with data analytics in a fully virtual environment, the Digital Twin to create new insights by examining "what if" scenarios and predicting future performance.

Virtual Twin: A relatively new concept - begins at the start of design, allowing virtual design change iterations in order to assess performance before generation of engineering drawings and parts. Powered by computational power and simulation platforms. (Dr. R. Byron Pipes, Purdue University, 2020)

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5.0 INTRODUCTION

5.1 Background: The Driving Imperative

The planned Mars architectures for placing humans on the surface in the 2030's envisions nearly daily spacewalks in EVA suits. EVA suits are considered to be anthropometrically shaped "space ships" which must protect the crew from the extreme environments of space, while at the same time, providing the mobility required to effectively perform both engineering and scientific exploration tasks outside of the habitat or the spacecraft. Because EVA suits are pressurized, even fabric portions become relatively rigid. The current EMU operates at a delta pressure (DP) equal to ~4.3 psid. Future suit concepts are considering increasing this DP to approximately 8 psid, nearly doubling the apparent rigidity of the fabric portions of the suit. This rigidity impacts mobility and increases energy costs. Poorly fitting suits will add to the human energy expenditure costs and decrease mobility, and can even impact safety in time critical situations.

Soft fabric "custom" suits were manufactured for all early spaceflight crewmembers (Mercury, Gemini, Apollo and Skylab) prior to the Space Shuttle Program. Apollo era crewmembers reported to be very satisfied with their custom suits on the Lunar surface, including those on the last mission, Apollo 17. For a variety of reasons, this strategy was changed to support the Space Shuttle Program with a "modular" plug and play suit, the Extravehicular Mobility Unit (EMU). The initial inventory included 5 Hard Upper Torso (HUT) chest sizes, 1 size helmet, adjustable arm and leg lengths but only two diameters, two size boots with adjustable inserts, and custom gloves. A total of 18 suits were built to support nearly 200 astronauts. This inventory was originally designed to the Space Shuttle crew selection anthropometric standards, advertised as "5th percentile Asian Female to 95th percentile Caucasian Male. However, not all selected and trained astronauts could fit into or function in the suit, and many crewmembers experienced shoulder injuries, pressure points, finger nail loss, and nearly a 50% loss of effective strength due to the pressure resistance of the suit. A return to custom EVA suits seems warranted.

But, how to do this in a rapid cost-effective manner? Is it possible to utilize current scanning technologies, human factor studies, physiological data, additive manufacturing, robotics, and modern digital design and analysis tools? The primary aim of this feasibility project was to answer those questions by determining how the "Digital Thread" manufacturing process, which is being deployed in other non-human manufacturing spheres as the 4.0 Manufacturing revolution, can be used to develop a digital manufacturing stream which will provide any sized or shaped crewmember (or future tourist) with an optimized EVA space suit.

5.2 Background: Mars Design Reference Mission

This study supported the NASA Strategic Plan, NASA Taxonomy TX06, and the Mars Design Reference Architecture, 5.0 with Annex #2. It also supported *STMD Strategic Goal:* "LIVE (*Sustainable Living and Working Farther From Earth), specifically, human spaceflight exploration for routine crewed operations beyond low Earth orbit, sustainable human presence on the Moon, and Sustainable Human Presence on **Mars***."

This research also supports a more recently proposed architecture presented by the Space Technology Directorate at the 2022 IEEE Aerospace Conference: The Strategic Analysis Cycle (SAC) 21, which proposes a shorter stay on the surface with two crew members (Figure 3).

SAC 21:

- Two crew land/live in pressurized rover
- Provides habitation and mobility for 30 days
- Supports science and exploration operations

Figure 3: Strategic Analysis Cycle (SAC) 21: Reference First Human Mars Mission Concept as Presented at the IEEE Aerospace Conference, 10 March 2022 by NASA: G. Chavers, S. Creech, K. Chojnacki and M. Rucker

Planning for this shorter surface mission of about 30 days is still a 700 day mission. (HEOMD-415) The following web sites were provided by NASA at the March 2022 IEEE Aerospace meeting describing this shorter surface stay mission CONOPS.

1.0 HEOMD-007: HEOMD Strategic Campaign Operations Plan for Exploration: Sept 28, 2022
https://ntrs.nasa.gov/citations/20210022080

2.0 HEOMD-415: Reference Surface Activities for Crewed Mars Mission Systems and Utilization:
https://ntrs.nasa.gov/citations/20220001816 (June 2022)

3.0 Moon to Mars (M2M) Habitation Considerations - A Snap Shot as of January 2022:
https://ntrs.nasa.gov/citations/20220000524

SAC 21 assumes the following: (1) 4 crew, with 2 remaining in Mars orbit while 2 explore the Mars Surface, (2) Crew will be in Cis-Lunar, Deep Space, and 5 Sol Mars Orbit, (3) Opportunity for 2039 (4) Crew is away from Earth ~2.5 years (5) Crew remains on Mars for 30 Sols; (6) Cargo is pre-Deployed and (7) Crewed Surface Exploration Phase is “Light Exploration Footprint”.

This study assumes the worst-case mission scenario – longest duration and frequent surface EVAs. Even though the shorter SAC surface sprint mission is being studied by NASA, planning for the worst case seems a prudent strategy. Experience suggests that if a shorter mission is planned, unplanned failures and delays could put the crew into a contingency position

Whichever DRM is finally executed, **Mars explorers** should expect to launch with both Intravehicular (IVA) and EVA suits which fit, are reliable, and are functional while providing maximum mobility, and be more cost effective than current suits. Planetary exploration to the Moon and Mars, and beyond, will require an increased number of planetary EVA’s, and this will require new and innovative approaches to design and manufacture of spacesuits which will fit a diversely shaped population. Optimizing EVA suits should receive as much attention as the launch system to reach the destination, since a significant portion of mission success will be defined by the crew on the surface, just as it was for Apollo. What will change between the different architectures (long and short stays) are assumptions of resupply and potential failures/repairs while on the surface.

5.3 Background: Assumptions and Approach at Study initiation:

Pressurized suits have been a component of both aviation and spaceflight since humans first explored altitudes which didn't support human physiology. Suits may be divided into two broad categories: those which remain inside the vehicle for intra-vehicular activity (IVA) in the event of vehicle de-pressurization, and those that are used outside a pressurized vehicle, extravehicular Activity Suits (EVA), either in LEO or on a planetary surface. The difference between the two environments influence the final design, with the most complicated design being the EVA suit with its multiple suit layers (hard and fabric) and independent life support system (the Portable Life Support System, PLSS). EVA environments include reduced pressure, large thermal extremes (e.g. +-250 deg. F), Micrometeoroids, and solar radiation.

5.3.1 Custom Vs Modular EVA Suits*:*

At the beginning of human spaceflight in both the US and the Soviet Union, all pressurized suits were custom fabricated to the individual. This was true for the Mercury, Gemini, Apollo and Skylab programs. In fact, each Apollo astronaut had three custom suits: one for flight, one for training and a backup [6]. The Apollo A7LB received high marks from crew members, including Dr. Harrison Schmidt, a geologist who was on the last mission to the Moon, Apollo 17. In the decision to fabricate custom suits, engineers followed the long-tested adage of engineering to relate ***form, fit and function*** (or human performance***)***

Apollo engineers also considered the entire mission architecture, underscoring that mission success was not only depended upon the design of the launch system to reach the destination, but that it was also dependent upon the astronaut successfully achieving operational and science objectives. Therefore, the "Spacesuit", a human anthropometrically shaped spacecraft, was designed for easy of mobility, with minimized mass, for durability, to protect against the extreme environments, to provide life support, and to avoid injuring the crewmember.

In an ideal world, the spacesuit should be "transparent" to the operations of the astronaut. The Apollo approach was considered successful by the crews, but altered for the Space Shuttle and ISS programs. This change in design approach has often been attributed to a cost analyses based on an expected increase in the number of astronauts to support the Space Shuttle program, however, retired NASA managers have stated that no such analyses was presented. Even though the astronaut office leadership argued in favor of keeping the Apollo AL7B Spacesuit approach, which had matured considerably in support of both Apollo and the follow-on Skylab program, the design strategy was changed by program engineering to accommodate a "modular" approach, with the largest anthropometric size change being the addition of taller male astronauts (95% Caucasian Male).

The Extravehicular Mobility Unit Hard Upper Torso, the EMU HUT, was initially available in 5 standard chest sizes, which were later reduced to 3, and intended to fit the 5th percentile Asian female to the 95th percentile Caucasian male . Arm and leg lengths were altered by "inserts", with only 2 available diameters. The helmets were one size (95th % Caucasian male) driven by the radius of the neck ring, and the gloves were customized for assigned EVA crewmembers (but not for contingency crew). Unfortunately, this "plug and play" approach to spacesuit design resulted in ill-fitting suits for most astronauts, which adversely impacted mobility, increased energy expenditures, caused shoulder and finger injuries, and eventually did not fit approximately 40% of the women who had already flown on the Space Shuttle, but were then precluded from flying on the ISS because of the requirement that all ISS crewmembers be EVA certified.

5.3.2 Technology Gaps and HRP Risks

Even after 40 years of operation, many EVA EMU technology gaps persist Gaps and risks for EVA suit fit and function have been captured in a number of NASA documents, as early as 2012 when the first Roadmap was reviewed by the National Academies. Our proposal addressed three EVA technology gaps (Table 1) in the NASA Technology Roadmap and 2020 NASA Technology Taxonomy: TA 7.3.1 (EVA Mobility); TX 11.2.3 (Human-System Performance Modeling) and TX 6.2.1 (Develop systems that enable astronauts to perform work outside of a spacecraft's habitable environment.)

Table II: EVA technology gaps in the 2015 NASA Technology Roadmap and 2020 NASA Technology Taxonomy

Gap #	Gap Name	Gap Description
TA 7.3.1	EVA Mobility	Enable safe and efficient EVA operations in micro or low gravity
TX 11.2.3	Human-System Performance Modeling	Ensure that new and relevant human-related technologies are infused into all vehicle and habitat designs and associated operational concepts
TX 6.2.1	Pressure Garment Development	Develop systems that enable astronauts to perform work outside of a spacecraft's habitable environment

The NASA Human Research Program (HRP) integrated health and EVA suit fit gaps, are shown in Fig. 4. Note that several organizations in NASA would be required to share funding for closing the gaps.

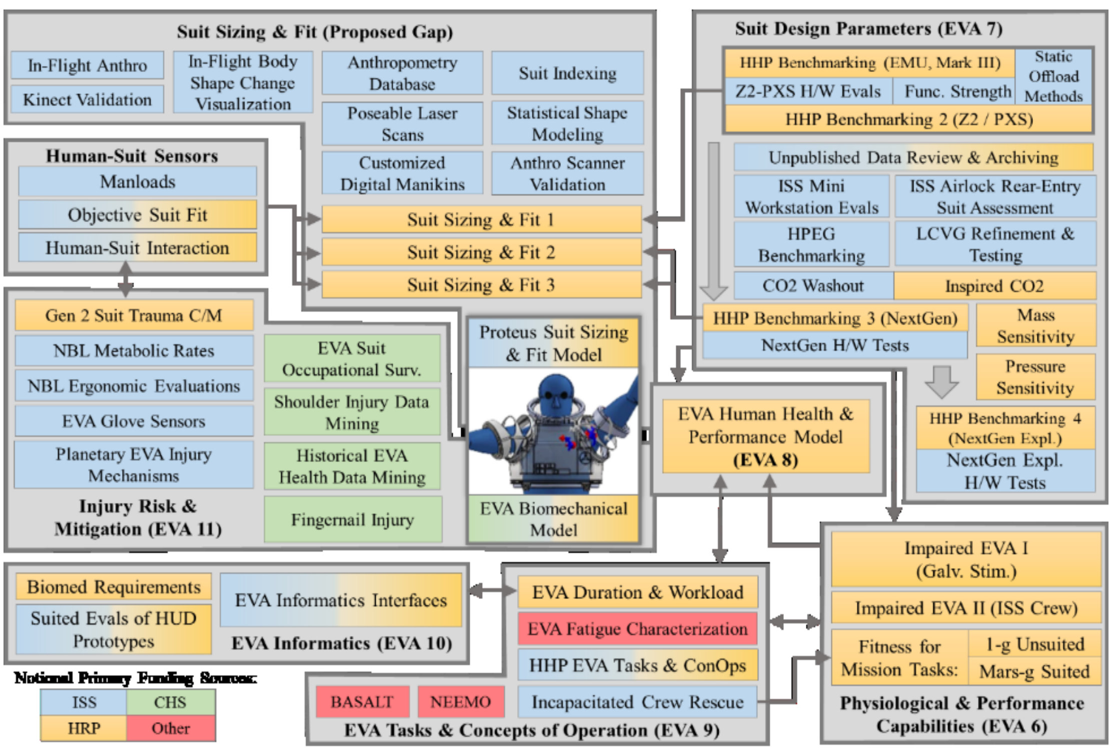


Figure 4: Organization of the NASA Integrated EVA Human Research Plan into groupings of proposed tasks that map to proposed HRP Gaps (Credit NASA HRP)

5.3.3 Thoughts on the new xEMU EVA Suit Initiative:

NASA recently developed the xEMU (Right on Figure 5 and Figure 6) for the Artemis Missions, now transferred to xEVAS Contractor, Axiom Space, for construction and optimization. The xEMU is not a custom suit. Similar to the EMU, the xEMU is "customizable" by changing arm and leg lengths and moving shoulder bearings in and out, but arm and leg diameters remain constant, there are limitations to the lower body/hip fit and the rear entry with helmet and PLSS access door appear to be one size. Based on past history with the EMU, it is postulated that the *one size* PLSS door access will likely drive suit dimensions in the chest and waist area which will probably be detrimental to the female population. .It demonstrated flexibility improvements when first unveiled at NASA headquarters, but it is not yet clear that it has been tested to a wide anthropometric population. It's success across the anthropometric range, including mobility, fit, and lack of injury, is yet to be demonstrated. While our team is hopeful that a standard size suit (or two) will fit the advertised selection criteria of 1% Female to 99% Male, "fit" may

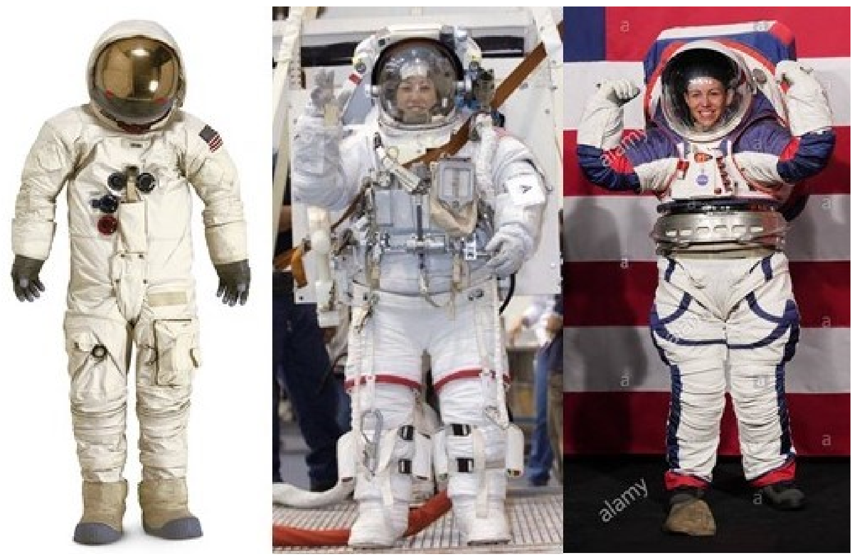


Fig. 5. (L) Armstrong Soft Apollo A7LB (M) Asian Female in Modular Hard/Soft ISS EMU (R) Caucasian Female in Rear Entry Hard/Soft Lunar xEMU *(not to same scale)*

Fig. 6. NASA illustrations of xEMU with One Size PLSS. (NASA)

not translate well to mobility and energy expenditures, especially in the $1/6^{th}$ g environment of the Moon, where the combined xEMU and PLSS are substantially heavier that the prior A7LB EVA suits.

It is interesting to note that with respect to IVA pressure suits, Boeing, SpaceX and the Orion Program have returned to manufacturing primarily custom suits for Intravehicular Activity (IVA), (Figure 7), understanding the need to maximize mission success with "form, fit, and function (or performance)" when those suits are pressurized.

Fig. 7. First SpaceX Crew in Custom IVA Pressure Suits (NASA).

In summary, with the renewal of planetary exploration to the Moon and Mars, and beyond, which will require an increased number of planetary EVA's, new and innovative approaches are required to design and manufacture reliable, mobile, cost effective spacesuits which will fit a diversely shaped population. Properly fitting and functioning EVA suits will be directly related to mission success, including the scientific return on Mars surface exploration. In an emergency, they are also related to "Safety". We believe that a return to custom suits will be the best solution for the future.

5.4 The Digital Thread (DT) Technology Development Concept

The Digital Thread Technology Development Concept is the opportunity to innovate EVA space suit manufacturing in order to produce a new generation of spacesuits, which address all of the deficiencies described in this report. DT reflects a "science fiction" vision of a space explorer stepping into a full body human scanning chamber, and then receiving a "Spacesuit" the next day. While this may appear improbable at the present time, pushing the envelope with an "out of the box" defined schedule will help to move the DT 4.0 manufacturing technology forward. Digital Thread manufacturing has the potential to bring this vision to reality. Twenty years ago, this concept was still within the realm of science fiction. However, DT is now being deployed in the Aeronautics and other industries, and new companies are providing DT services. This is supported

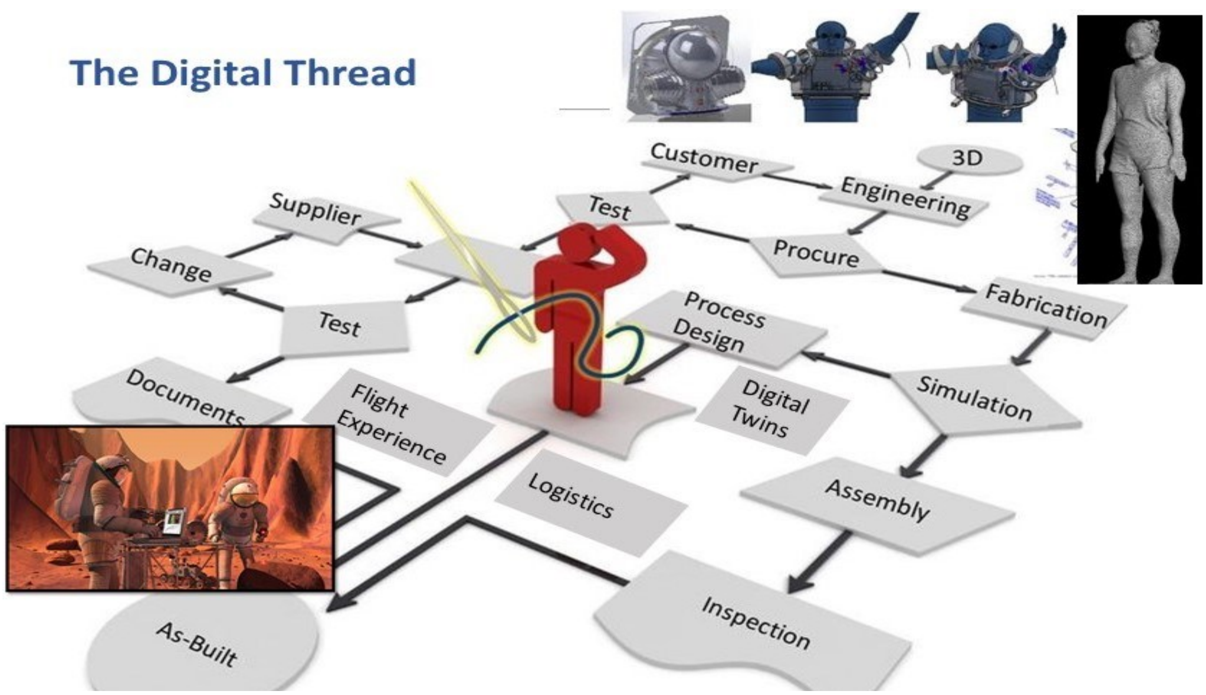


Fig. 8: Notional Spacesuit DT: From Human Scans and Suit CADs to Integrated Spacesuit.

by a series of supporting technologies, such as 3D printing/Additive Manufacturing (AM), Human Systems Modelling (HSM) model-based systems engineering, and IR, Laser, and Photogrammetric full body scanning. These have matured to the point where this integrated digital manufacturing system for spacesuits could be envisioned to be implemented in the next 10-20 years. Figure 8 illustrates a DT starting point for the EVA suit which is explored in this report. Note that the beginning state can either be a modular hard system such as the existing EMU/HUT or start with a human scan for a custom suit, such as the Apollo A7LB. The DT steps which follow are not new, although linking them together through common software platforms is a current challenge for most companies. Although DT is being deployed in the Aeronautics Industry, the garment industry is still in its infancy for translating a 3D digital scan into a finished garment. Some of challenge lies in modelling mobility and performance in pressurized deformable fabrics which still are an integral component of EVA suits and the robotic manufacture of deformable fabrics. Spacesuits are also significantly more complicated than the conventional garment or spacecraft because of the requirements for mobility, pressurization, life support and protection from extreme environments (e.g. thermal extremes, UV radiation, micrometeoroids).

However, DT is also the opportunity to address a number of current EVA suit deficiencies, such as fit (e.g. not fitting females below the 40^{th} percentile), mobility, bodily injuries (requiring shoulder surgeries), excess energy expenditures and repair complexities. The DT could also allow manufacturers to more completely address full mission architectural components such as launch mass, resupply, and in-situ repair. The implementation of Digital Twins after manufacture is complete will allow for tracking performance and failures, which could be used for design optimization in the next iteration of the suit, and could be supplied to the crew for in situ support.

5.5 NIAC Phase I Feasibility Study Requirements and Report Structure:

This NIAC Phase I feasibility study executed the following tasks in Table 2 as were proposed. The results and data described in each task are intended to provide the decision bases for the following task. For example, Task 1 allowed us to develop a better understanding of the basic components of each of the two primary suits under study, the Apoll0o A7LB and the STS/ISS EMU. Task 2 provided a benchmarking of available DT components; Task 3 provided the basis for identifying the feasibility of applying a DT architecture to manufacture of the EVA suit, with a focus on the low TRL components; Task 4 provided the basis for discussing trade studies on what could be repaired or replaced in situ on Mars based on the original manufacturing process and Task 5 is a final feasibility assessment of a Preliminary DT architecture.

Table III: Phase I NIAC Feasibility Tasks

TASK	EVA SUIT DT Feasibility Tasks
1.	Deep Dive Comparative Analysis of Historical EVA Suits - Page
2.	Benchmark commercially available Digital Thread (DT) Software Tools—Page
3.	Assess feasibility of mapping EVA suit manufacturing to existing DT Tools –Page
4.	Integrate the Mars CONOPS and Design Reference Missions to DT Trade Space-- Page
5.	Assess Feasibility of a Preliminary DT Architecture—Page

6.0 RESULTS OF TASK 1 – DEEP DIVE COMPARATIVE ANALYSIS OF HISTORICAL EVA SUITs

6.1 EVA Suit Common Components Overview:

Over the last 60 years, the NASA Program manufactured 3 primary EVA suits: the **Apollo A7LB** (planetary and orbital), the Space **Shuttle/ISS EMU** (orbital only), and the pending **xEMU** for the Artemis Lunar program (Figure 9). The differences in these suits provide an opportunity to evaluate different designs and different manufacturing methods mapped onto a DT architecture considering two significant variables: 1) fit/sizing (custom vs modular) and 2) Hard vs Soft component designs, and the percentage of each.

Fig. 9. The Customized "soft" *Apollo* EVA Suit with separate pressure garment (accessed through a front zipper); the *Shuttle/ISS* EMU accessed through a waist bearing, and the *Artemis* one piece suit accessed through the back.

All EVA suit designs can be considered to have three unique garment parts separate from the Portable Life Support System, PLSS, whether custom or modular. Collectively, for the current EVA EMU these 3 parts constitute 14 layers separated into the following segments:

A. Liquid Cooling and Ventilation Garment (LCVG – 3 layers) Figure 10;

B. (The Pressure Bladder/Restraint System – 2 layers) referred to as the Pressure Garment Assembly, PGA

C. A Thermal Micrometeoroid Garment, TMG - 9 layers.

Customized Liquid Cooling and Ventilation Garment (LCVG). The custom Liquid Cooling and Ventilation Garment (LCVG) consists of two layers of fabric with an integrated tubular water circulation and air circulation systems – often referred to as 3 layers. The LCVG was invented in the UK by the Royal Air Force and later adopted by NASA and the Air Force. It has changed little over the last 60 years. (Figure 10)

Fig. 10: Custom Liquid Cooling and Ventilation Garment, LCVG (NASA)

As is discussed in following sections, although the Space Shuttle EMU was not customized, the LCVG, by necessity had to be modified from several standard sizes in order to ensure that the water-cooling tubes contact the astronaut's skin. The ability to use the LCVG to cool the astronaut during peak metabolic activity is a fundamental requirement for design and health. The heat absorbed by the circulating water is eventually rejected through a sublimator to vacuum on the Portable Life Support System (PLSS) attached to the back of the EVA suit. During Apollo and Skylab, the LCVG was customized to the astronaut during the normal EVA suit customization process.

6.2 The Apollo A7LB EVA Suit

Figure 11 illustrates the Primary Components of the Apollo A7LB which was flown on the later Apollo missions and on Skylab (The A7LB underwent several iterations until the final flights of Apollo and Skylab.) The LCVG is labelled as "Cooling Garment". The A7LB was a one -piece custom suit closed by means of a zipper from crotch to the back. Figure 12 further illustrates the

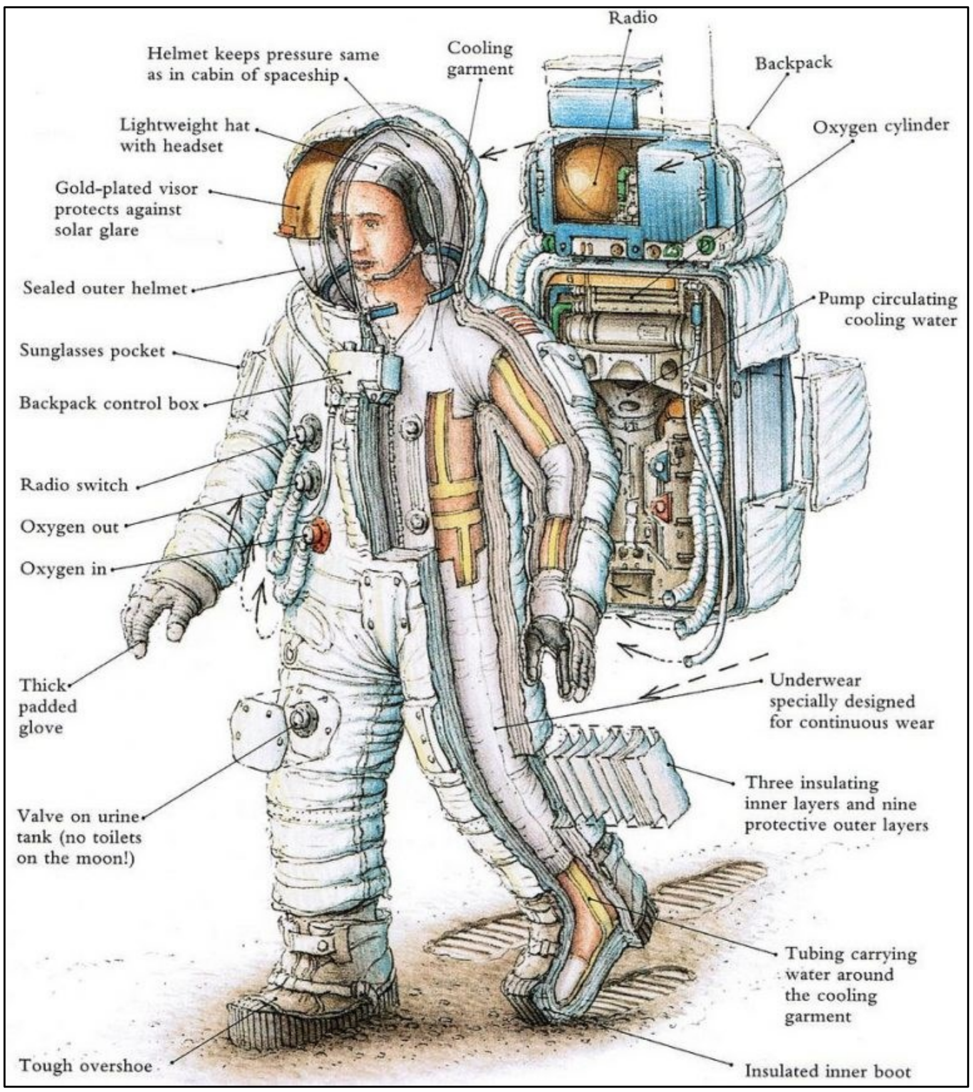


Figure 11; Apollo A7LB EVA Suit Components with PLSS Credit NASA suit parts from Astronaut Neil Armstrong's Apollo 11 suit, now in preservation at the Smithsonian Institute in Washington DC. Note that most of the suit is multi-layer woven fabric.

Fig. 12: Apollo A7LB Suit: customized to Neil Armstrong. Credit: NASA

The external physical design of the A7LB is pictured in Figs. 13A and 13B. Figure 13A shows the Apollo A7LB worn on Apollo 15 and Figure 13B shows the suit worn on Skylab 2. While the suits were largely similar, the Apollo suit was connected to the PLSS for life support and independent surface operations, while the Skylab suits were connected by umbilical to the Skylab space station. Both suits were customized and performed with no anomalies or failures. Figure 14 shows the Pressure Garment Assembly beneath the TMG. Note the design of the arms on either side of the elbow. This design is significantly different from that of the Space Shuttle EMU arms. A7LBs were designed to allow the arm to hang straight and were manufactured of a multilayered circumferential convolute material which functioned both as the bladder and the restraint. The primary customization occurred with the pressure and restraint layers.

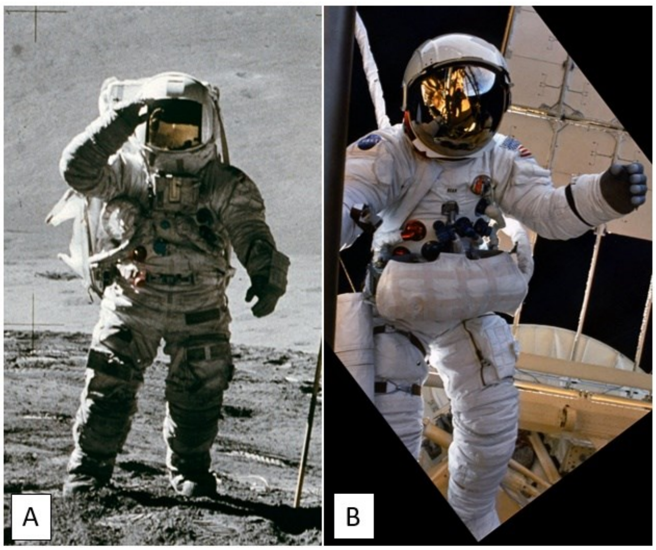


Fig. 13 A) Apollo A7LB suit worn on Apollo 15, B) Skylab A7LB suit worn on Skylab 2, Credit NASA

Fig.14 Apollo Pressure Garment beneath the TMG layers. Credit NASA

6.3 The Space Shuttle and ISS EMU EVA Suit:

As described previously, the EMU is a modular design with a waist connection vs a zipper. This full suit is shown in Fig 15. Note that placed on the front of the suit is both the “Display and Control Module, DCM” and a portable and removable “Mini work station”. Attached to the back is the PLSS. The mini work station contains storage for tools and consumables used in repair and maintenance. Since this is a standard size, the presence of this hardware can impact reach and mobility on some crew members. Also note the attachment at the waist of the safety tether at a D ring below the waist bearing. One of the reach requirements is that the crew member be able to connect and disconnect the safety tether, largely by “feel” since it cannot be seen from the helmet and the design of the suit restricts bending at the waist.

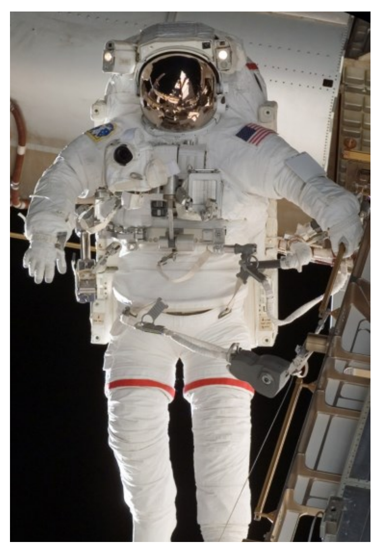


Fig 15. EMU on ISS. Credit NASA

While the A7LB was primarily a one-piece custom suit, the EMU was modular with the two largest components being the Hard Upper Torso, HUT, and the Lower Torso Assembly, LTA. (Figure 16). Figure 17 illustrates the individual components of the EMU, in similar fashion as Fig. 12 for the A7LB.

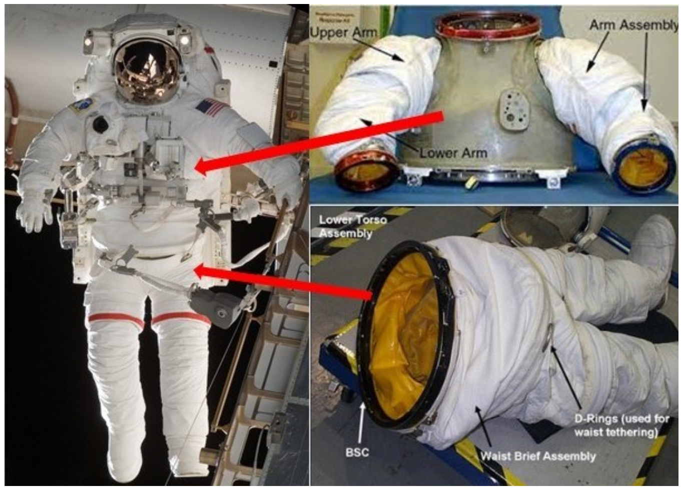


Fig. 16: (L) Full image of EMU on the ISS, (Top R) The HUT with the inflatable modular arm assemblies and Bottom R, the LTA with inflatable leg assemblies – note the metal waist disconnect ring. (NASA)

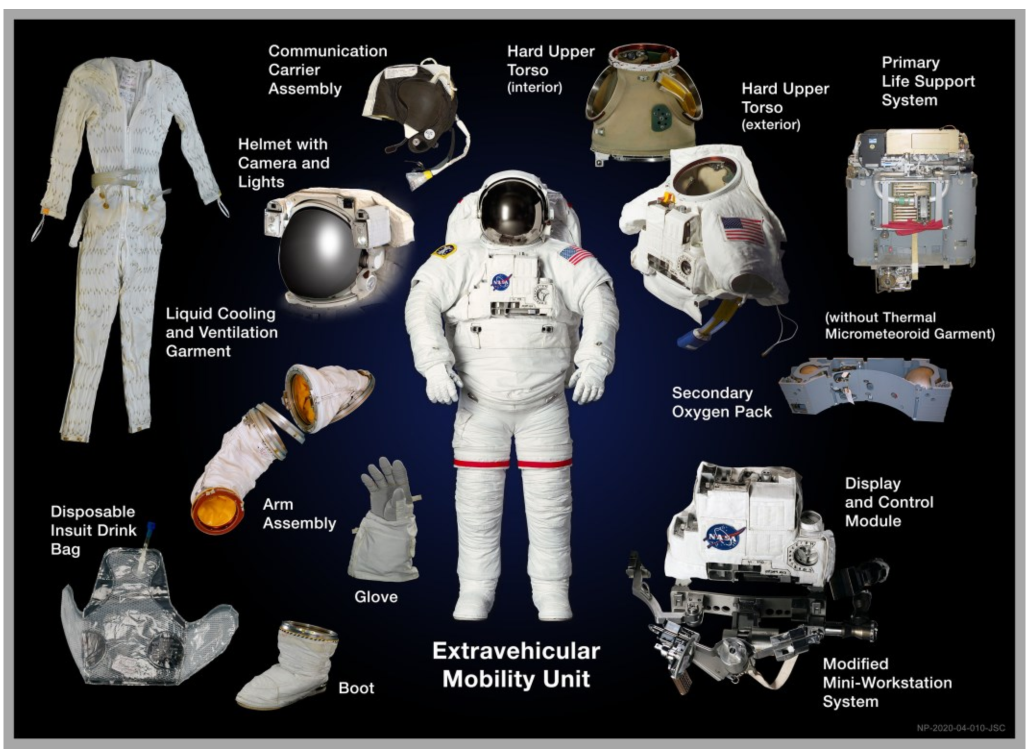


Fig 17. Components of the Extravehicular Mobility Unit (EMU) used for EVA. Includes the LCVG and the PLSS. (NASA)

While the lower body is mult-layer flexible fabrics and Mylar films, (although rigid once under pressure), the top is a "Hard Upper Torso, HUT", currently only available in three sizes (Fig 18).

The HUT is manufactured from fiberglass composite and the original sizing was derived from a data base for males. As a result, the shoulder breadth is typically too large for most females. Design is also complicated by the fact that the neck ring and helmet are one size: 3 sigma Male.

Fig. 18. EMU Hard Upper Torso (HUT)

6.4 EVA Gloves: EVA gloves (Figure 19) have been issued to crewmembers as both "best fit" from prior flights and as customized. Customization has been largely allocated to assigned EVA crewmembers who didn't have a good fit with the existing inventory. However, when budgets were tight, customization was offered only to assigned EVA crewmembers, while those who were Space Shuttle contingency crewmembers were issued "best fit" gloves from inventory. Well fitting EVA gloves remain a challenge from since the Apollo program. In many cases, nearly 50% of effective strength and energy is lost to simply deflecting the pressurized layers of the glove. Glove fit and mobility could remain an on-going challenge.

Fig. 19 EMU EVA Phase VI Gloves: formed bladder, restraint layer and thermal micrometeoroid garment.

6.5 EMU Soft Fabric layers.

The EMU Arm: The pressurized EMU arm cross section is shown with all three major multi-layered components illustrated in Fig. 20. Specific Materials are shown in Table III and Fig. 21.   Note: the manufacturing methods and specific compositions are proprietary to ILC although they are discussed in Section 8.

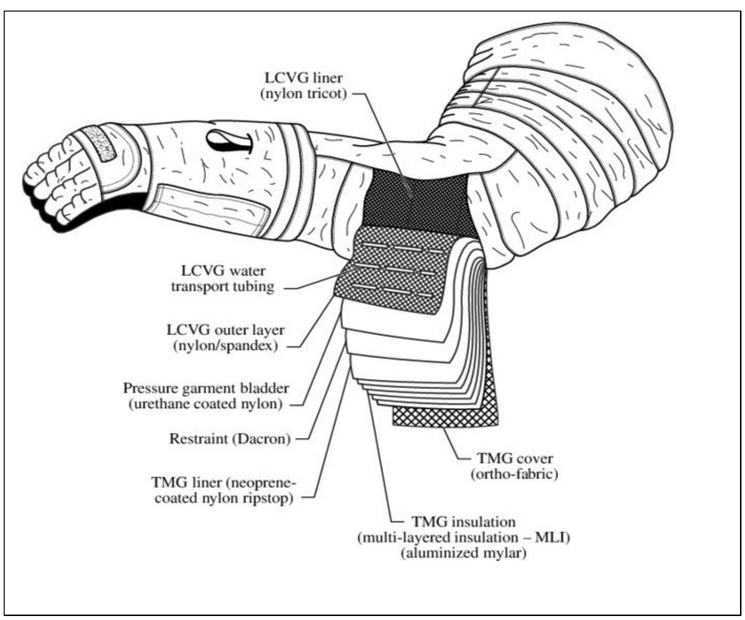


Fig. 20: Cross section of 14-layer EMU space suit arm,

1. LCVG – Liquid Cooling and Ventilation Garment;

2. TMG – Thermal Micrometeoroid Garment.;

3. MLI = Multi-layered insulation (aluminized Mylar)

Table. IV: EMU Arm Materials- 14 Layers

1	LCVG Liner	Tricot
2	LCVG	Water Tubing
3	LCVT Outer Layer	Nylon/Spandex
4	PGA Bladder	Urethane Coated Nylon
5	PGA Restraint Layer	Dacron
6	TMG Liner	Neoprene Coated Nylon Ripstop
7	TMG Insulation	Aluminized Mylar Laminated with Dacron
8	TMG Insulation	Aluminized Mylar Laminated with Dacron
9	TMG Insulation	Aluminized Mylar Laminated with Dacron
10	TMG Insulation	Aluminized Mylar Laminated with Dacron
11	TMG Insulation	Aluminized Mylar Laminated with Dacron
12	TMG Insulation	Aluminized Mylar Laminated with Dacron
13	TMG Insulation	Aluminized Mylar separated with Dacron
14	TMG Cover	Ortho-Fabric – Blend of Gore-Tex, Kevlar, and Nomex

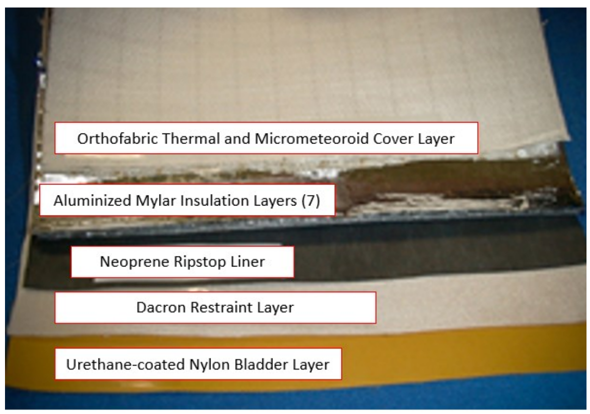


Fig. 21: Images of materials used in the EMU EVA suit. Note: the Urethane coated Nylon bladder for the primary suit is “yellow”, but the color of the EVA glove bladder is now “green”.

6.6 Methodology for EVA Suit Sizing:

The Space Shuttle Program was the first human program in the US to depart from custom pressure suits and EVA suits. The sizing strategy and anthropometric selection criteria are summarized in Table V.

Table: V: EVA Suit Sizing Strategy by Program

Program	IVA and EVA Suit Sizing Strategy	Suit Nomenclature	Astronaut Selection Anthropometrics
Mercury*	Custom	Modified US Navy	Smallest Possible
Gemini	Custom	G-2C	Smallest Possible
Apollo	Custom	A7L and A7LB	Smallest Possible
Skylab	Custom	A7LB	Smallest Possible
Space Shuttle	Modular	EMU Pivot and Planar	5^{th} % Asian F to 95% Caucasion Male
International Space Station (ISS)	Modular	EMU Pivot and Planar	Initially Space Shuttle, then Reduced to 95^{th} % M – 40% F

** According to Chief Engineer Dr. Max Faget, who designed the Mercury capsule, once the program had selected astronauts for "skill", he assessed for mass and volume. At the beginning of the Mercury program, the size of the astronaut was in the trade study for vehicle launch mass, habitable volume and consumables.*

6.6.1 Apollo A7LB Measurements, Fit Checks and Delivery: (Ref: Ayrey 2020)

The Apollo suits were tailored for each crewmember who received three suits: prime, back-up and training. It was considered by the Apollo astronauts to be a successful suit and there were no inflight failures during the whole of the Apollo program. Capt. John Young referred to the A7LB as "comfy" and Mike Collins stated in his book, *Carrying the Fire*, "By the end of Apollo, astronauts were spending long hours in lunar EVA with no apparent discomfort, a fact beyond our wildest expectations during 1965 when we got our first look at the lunar EVA hardware." The time from planning to final acceptance of an Apollo suit was approximately 120 calendar days. The **build process itself was 40 days**.

Apollo Suit Fit Process: (Figures 22 and 23)

1.0 Crew Selection
2.0 Report to ILC for measurements - 66 specific measurements, from head circumference to width of foot. Process took from 1 to 2 hours.
3.0 After dimensions were delivered to ILC, engineers would review what size components would be needed to assembly a complete suit
    3.1 There were some basic sizes for the arms and legs, but the torso was patterned from the dimensions of each astronaut, since this was considered a critical element of suit sizing.
    3.2 The pressure boots were chosen based on shoe size.
    3.3 Gloves were made from molds based on very precise measurements of a hand cast.
4.0 Fit checks were scheduled near completion date and took a full day.
5.0 Following fit check, any cable modifications were adjusted that day
6.0 Repeat of fit check for about 2 hours

Fig, 22: A7LB Pressurized Suit Fit Check at ILC (photo 17-72-H-314 from NASA)

Fig. 23: Gene Cernan Fit Check in A7LB at ILC (photo 17-72H-253)

6.6.2 Space Shuttle/International Space Station EMU Fit checks for Hard Upper Torso (HUT) and other components

The EMU processing contractor provided NASA with space suit sizing services for flight and training. They sized crewmembers for EMU suits by first recording 21 different linear and circumferential body measurements and 16 hand measurements. A description of each measurement and ranges from 5th percentile Japanese female to 95th percentile American male are shown in Table VI.

Table VI: EMU Sizing Measurements

ID#	Body Measurement	Minimum Bound (cm/inches)	Maximum Bound (cm/inches)
122	Bideltoid breadth	40.31 (15.87)	59.19 (22.91)
223	Chest breadth	26.80 (10.55)	42.19 (16.61)
230	Chest circumference	85.01 (33.47)	114.91 (45.24)
249	Crotch height	71.91 (28.31)	91.21 (35.91)
416	Hand circumference	19.02 (7.49)	24.51 (9.65)
420	Hand length	16.51 (6.50)	21.59 (8.50)
427	Head breadth	14.20 (5.59)	17.91 (7.05)
441	Head length	18.49 (7.28)	22.63 (8.91)
457	Hip breadth	31.60 (12.44)	41.58 (16.37)
747	Shoulder circumference	93.29 (36.73)	132.00 (51.97)
805	Stature	163.50 (64.37)	188.70 (74.29)
873	Tibiale height	42.90 (16.89)	56.90 (22.40)
916	Vertical trunk circumference	152.50 (60.00)	195.91 (77.13)
SSA 01	Expanded chest depth	23.11 (9.10)	28.80 (11.34)
SSA 02	Vertical trunk diameter	59.79 (23.54)	77.50 (30.51)
SSA 03	Mid shoulder height (standing)	135.81 (53.47)	160.40 (63.15)
SSA 04	Shoe size	16.51 (6-1/2)	33.02 (13.00)
SSA 05	Forearm circumference	18.01 (7.09)	32.26 (12.70)
SSA 06	Inter-wrist	124.69 (49.09)	155.30 (61.14)
SSA 07	Inter-elbow	79.20 (31.18)	104.50 (41.14)
SSA 08	Inter-fingertip (span)	157.81 (62.13)	195.58 (77.00)

Early methods of taking these measurements involved using a handheld tape or caliper but recent technology developments have enabled the NASA JSC Anthropometry and Biomechanics Facility, ABF, to utilize 3dMD and Vitus full-body 3D scanners and anthropometry analysis software to perform these measurements and archive them for future analysis. Using these measurements as inputs, technicians use a custom algorithm for EMU sizing to predict *preliminary* suit component sizes *that combine* to make a full suit for each crewmember. Suit engineers in the engineering organization use this information to assemble the modular suit components and to perform a 1g standing fit check with the crewmember. (Figure 24) This normally takes about two hours.

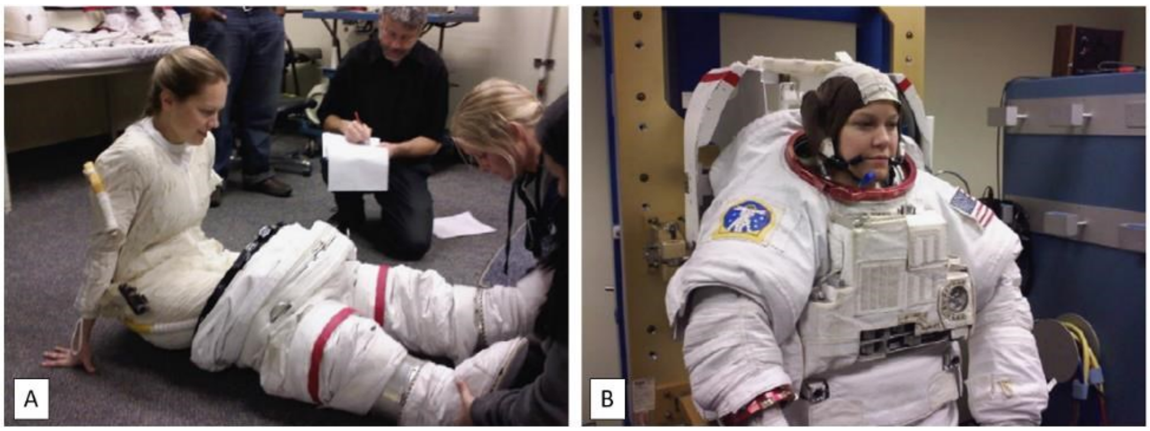


Figure 24: EMU fit checks for donning A) the Lower Torso Assembly, LTA and B) Hard Upper Torso, HUT

Once the crewmember is satisfied with the fit in 1 g, suit engineers assemble a training suit for use in the water training facility, the Neutral Buoyancy Laboratory, NBL. (Fig. 25)

Fig, 25, ISS Crewmember in NBL for EMU suit fit checks (NASA)

If this configuration is suitable during training, suit engineers also assemble a flight suit, and the crewmember will "checkout" this suit during chamber testing. It is not unusual for a crewmember to request multiple changes to suit sizing following an NBL "training run". During NBL training, NBL suit engineers collect data, make sizing changes, and suggest options to solve comfort/sizing issues reported by the crewmember. Results are documented and used to update contractor data bases, glove sizing sheets, and comfort pad selection sheets. NOTE: According to conversations with NASA ABF, there is a disconnect in the feedback loop such that any sizing adjustments NBL suit engineers may make after the initial ABF assessment are not fully communicated back to ABF. Access to this information would help to inform and update the ABF initial fit assessment database and algorithm and provide a more efficient sizing process. Figure 21 shows the flowchart of the entire preliminary fit assessment procedure for the EMU space suit system.

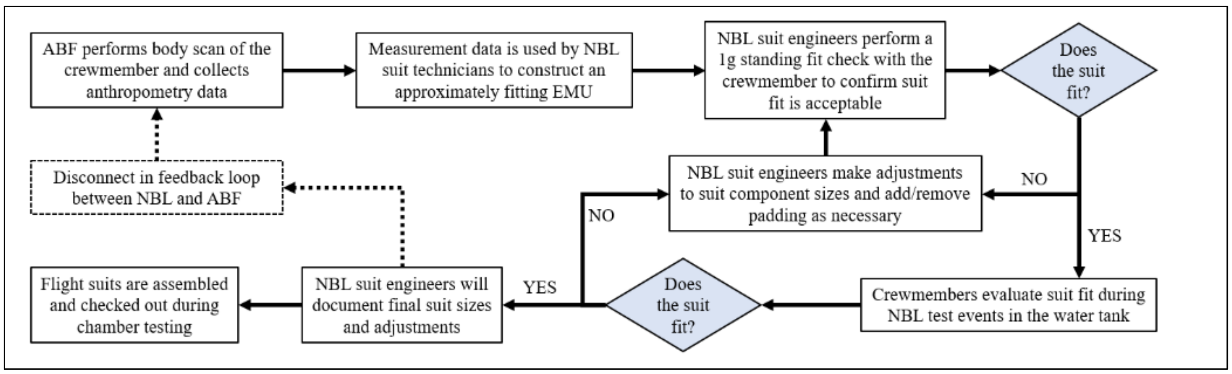


Fig 26: Flowchart describing the preliminary fit assessment of the EMU Space Suit System for NASA astronauts

The disadvantage of this process is that it actually decreased the number of crewmembers who could achieve optimal fit in the suits and broadened the acceptable margin of fitting error experienced for those that were in-between sizes. Subsequently, this impacted performance in the early NBL assessments, (performance in the NBL was considered a filter for assignment to EVA, even if the suit was poorly fitted) and this then reduced the percentage of the astronaut office that could participate in EVA tasks. Poorly fitting suits made completing these tasks harder for many that did not fit the suit perfectly, and contributed to a series of shoulder injuries (and surgeries) encountered during training and flight.

Part of the complexity of fitting space suits to humans arises from the subjective feedback required by the occupant to ensure the best achievable fit while standing in a 1g environment. Thomas and McMann summarize other technical challenges involved with spacesuits: "Space pressure suits require greater consideration for pressurized fit and use. Development is very dynamic, and minor changes can have surprising results. Complex shapes and effects from pressure load make the use of structural fabrics a 'black art.' Unlike most other engineering applications, there are effectively no textbooks with empirical tables to allow the selecting of materials, system architectures, and volumetric/mass attributes to effectively design, certify, and produce an effective spacesuit system for an application with minimal development. Thus, spacesuit design and development are very iterative processes."

6.6.3 Impact of EMU HUT Size reductions to Crew Selection and Operations:

The following set of EVA suit program decisions illustrates the disadvantages of not having custom suits, or not investing "up front" in properly fitting protective equipment for already trained crewmembers. When the NASA suit development program changed the HUT design to what was termed a "Planar" HUT from the "Pivot" HUT in order to provide more arm mobility in fewer HUT sizes, this resulted in design impact to the Small HUT, which had already flown. The Display and Controls Module, DCM, was now too large for the HUT chest area. As a result, a redesign effort was initiated to reduce the "footprint" of the DCM. However, in 2002, the Space Shuttle program decided to terminate production of the Small Planar EMU HUT because of costs (~$2M) required to decrease the size of the DCM.

This essentially decreased the EMU fleet to two sizes: Large and Medium, from the original five sizes, although the XL was eventually added back to the inventory. The small Pivot EMU (original design) had already been successfully worn by two women in the Astronaut Corps, one during the Space Telescope repair mission. This illustrates the engineering axion of being careful of "unintended consequences" Although reducing the number of EMU sizes in 2002 had limited impact on most of the females and smaller males since only two crew members from a crew of up to 7 on every Space Shuttle flight were required to be EVA trained. Thus, the remaining "small" astronauts -- Pilots, Mission Specialists, Remote Manipulator Operations, etc. – could still be assigned to flight. However, it had a significantly adverse impact on the astronaut office, when the Shuttle program was cancelled in 2011. From that point forward, all astronauts had to be EVA trained in order to assigned to International Space Station (ISS) Crews. Subsequent to the budget decision and cancellation of the Shuttle Program, this impacted about 40% of the female astronauts and there was a significant departure of highly trained crewmembers from the astronaut office through retirements and agency reassignments. This decision was made just prior to a decision to cancel a new Small EMU suit development program. In order to help inform the analyses of and future suit fit decisions, a discussion of development and cancellation of the new Small EMU follows:

The Small EMU Development Program was initiated in 1999 by EVA Project Office at NASA-JSC. The purpose of this initiative was to investigate potential modifications to the Enhanced EMU suit design in order to accommodate a wider range of anthropometric profiles and to improve fit and mobility for all astronauts. The fundamental objective of the project was to develop an EMU with improved fit, reach and visibility for crewmembers at the lower range of anthropometric accommodation (primarily small female crewmembers).

Note that "small" can be misleading for those at the higher limit of being defined as small. One of the astronauts fitting a Small HUT was a 75th percentile female in height. Therefore, a crucial factor in this effort was the identification of critical anthropometric measurements for suit fit and operability by EVA/EMU subject matter experts. Seven body dimensions were selected as the most significant determinants of proper suit fit to ensure adequate operation of the EMU, as well as EVA task performance.

Those seven critical dimensions are shown in Table VII along with de-identified subject data. Percentiles for chest breadth, bi-deltoid breadth, chest circumference, shoulder circumference, and stature were derived from AMRL-TR-70-5. Cited percentiles for lower arm length and arm span reference NATICK/TR-89/044. Note the significant variability of the measurement percentiles, indicative of the lack of correlation between key anthropometric measurements (e.g., a 5th-% stature subject was 77th-% chest breadth and 37th-% shoulder circumference).

Table VII: Percentile of key anthropometric dimensions for space suit sizing

Subject	Chest breadth	Bi-deltoid breadth	Chest Circ.	Shoulder Circ.	Stature	Lower arm length	Arm span
A	77	26	12	37	5	20	16
B	39	7	4	3	40	40	34
C	45	4	31	7	56	10	16
D	15	30	6	10	66	40	35
E	49	50	14	47	23	21	24
F	84	45	23	7	91	87	74
G	67	65	64	17	74	60	43
H	76	27	64	64	53	12	13
I	60	35	46	37	16	12	13
J	88	27	73	17	73	40	51
K	57	24	80	77	43	9	7
L	81	20	36	23	89	38	29
M	33	80	69	39	74	34	34
N	84	55	39	47	76	8	11
O	61	89	47	67	37	58	43
P	80	82	47	25	47	35	63
Q	97	86	93	92	56	40	33

Eight modular EMU sub-components were identified as potential candidates for modification to increase the range of accommodation, particularly for small crewmembers: Planar Hard Upper Torso (HUT); Canted Waist Mobility Joint; Advanced Soft Shoulder Mobility Joint; Dual Seal Arm Bearing; Elbow Mobility Joint; Liquid Cooling and Ventilation Garment; Boot Sizing Insert; and Helmet.

It was also determined that modifications to the pressure suit itself would be sufficient to address concerns with actuation and visibility of the Display and Control Module (DCM). Since the DCM contains all of the electronics and software to operate the pressure suit subsystems, modifications can be extremely costly and the process to certify new configurations of critical life support hardware for spaceflight can be lengthy.

One significant finding of preliminary human-in-the-loop (HITL) testing of engineering prototypes was that substantial reduction of the upper arm segment length negatively impacted the reach and mobility of smaller crewmembers. An extremely short upper arm segment causes the subject's arm to be slightly rotated up and away from the torso, thus restricting downward and cross-reach. Further, although there is not an absolute positive correlation between size and strength. Modifications that reduced the strength required to actuate suit joints, particularly in the shoulder and arm, were found to significantly enhance the performance and capability of smaller crewmembers. This was accomplished by using the large-size shoulder bearing in combination with a new, small size arm bearing. Two design concepts for the shoulder mobility joint and one new elbow joint were developed and tested with astronaut subjects. Shoulder joint concept 1 (Figure 27) incorporated an unsymmetrical flat patterned gored joint with a wedge element at the shoulder

Fig 27. Small EMU shoulder mobility joint, Concept 1

Fig 28. Small EMU shoulder mobility

bearing. Shoulder joint concept 2 (Figure 28) used a symmetrical flat patterned toroidal convolute shoulder joint. Both concepts incorporated a new flat patterned gored elbow joint designed to provide more distributed flex points on the front of the elbow. This design allows greater tolerance in the placement of the subject's elbow placement. Subject evaluations revealed that Shoulder Concept 1 provided the greatest cross and downward reach capability while Shoulder Concept 2 provided the best mobility of the shoulder joint while requiring the lowest torque to affect joint motion.

Design features such as smaller diameter joints also improved smaller crewmember's capabilities by matching the center of rotation of the suit's joints with the corresponding human joint center of rotation in critical areas such as the shoulder. This improvement enables smaller astronauts to be more productive by reducing the amount of effort it takes to move the pressurized suit mobility joints and also mitigates fatigue over the course of a multi-hour EVA.

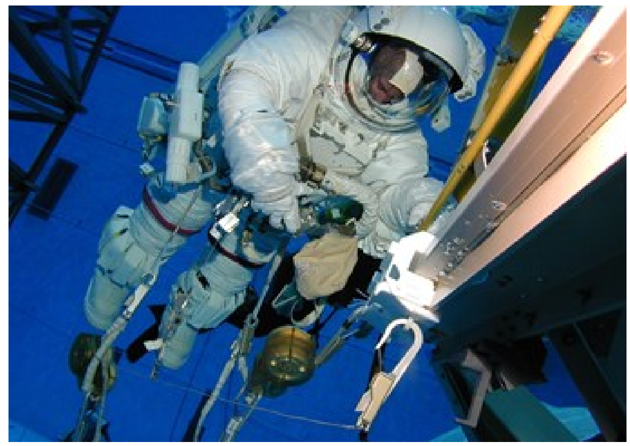


Fig. 29 Small EMU Neutral Buoyancy Lab (NBL) Testing with subject Astronaut N. Currie

Of the 109 active, U.S. astronauts at the time of this study (2003), 16 were deemed to anthropometrically fit in a Small EMU. The Small EMU HUT suit was built and tested in the NBL (Figure 29). However, the Small EMU was never adopted by the International Space Station Program. Most of the proposed modular components to accommodate small crewmembers were unique designs resulting in a space suit that would be incompatible with the other existing EMU sizes in the inventory. EMU redundancy was usually gained by having an additional space suit available that can be reconfigured with the subassemblies from the failed suit. There have been several occasions during orbital operations during which a space suit has experienced mechanical malfunctions and the crew has been able to quickly reconfigure and resize the spare unit in order to continue EVA operations. Thus, the uniqueness of the Small EMU presented significant logistical challenges, especially for operations on the International Space Station. Ultimately, the lack of a correctly sized EMU to enable satisfactory performance of physically demanding EVA tasks, led to ISS expedition crew assignment restrictions for this cadre of "small", depending upon which measurement is used, exclusively female, astronauts during the initial years of ISS operations.

As noted previously, "small" is determined by which measurement is used. Small was also relative to the original HUT anthropometrics, which were based primarily on male chest dimensions. Figure 30, a chart presented to the students at Purdue during NIAC Phase I illustrates this conundrum when attempting to build modular EVA suits to "standard" humans. The measurements were taken from active female astronauts who had already flown. The question is: *Which one of these subjects is the 5th percentile female?*

Subject #	Chest breadth	Bi-deltoid breadth	Chest Circ.	Shoulder Circ.	Lower arm	Arm span	Stature
1	77	28	12	37	20	16	5
2	39	7	4	3	40	34	40
3	45	4	31	7	10	16	56
4	15	30	6	10	40	35	66
5	49	50	14	47	21	24	23
6	84	45	23	7	87	74	91
7	67	65	64	17	60	43	74
8	76	27	64	64	12	13	53
9	57	24	80	77	9	7	43
10	81	20	36	23	38	29	89
11	84	55	39	47	8	11	76
12	61	89	47	67	58	43	37
13	80	82	47	25	35	63	47
14	25	27	11	1	40	44	54
15	12	NA	4	NA	NA	<1	<1
16	20	2	30	2	<1	<1	<1
17	74	55	93	96	5	8	9
18	54	17	2	3	24	25	45
19	98	93	74	79	3	4	20
20	40	30	7	23	47	70	91
21	86	60	80	77	17	14	35
22	44	69	34	14	7	2	28
inimum Di	10.24	14.63	31.5	36.75	15.25	58	57.87
aximum D	12.88	17.88	39	43.25	18.5	74	67.13

NOTE: 1) Percentiles are from AMRL-TR-70-5
2) Span and Lower arm length percentiles are from NATICK/TR-89/044

Fig. 30. List of 22 Female Astronauts who were not assigned to EVA for lack of properly fitting EVA suit and the variation in percentile measurements. Chart prepared by Dr. Currie-Gregg when at NASA JSC

6.7 Relative Costs and Delivery Schedules:

6.7.1 Apollo A7LB:

Historical costs and schedules were benchmarked based on available data and as documented by Ayrey (Lunar Outfitters: Making the Apollo Space Suit) in order to estimate a figure of merit improvement of the DT. **The cost of the A7LB at time of manufacture and escalated to present day was approximately $1M from time of first fitting until delivery to the crew member approximately 6 months after the first fit check at ILC.**

A detailed cost analysis of the Apollo/Skylab Suit Program was provided by ILC to NASA on April 30, 1974 under Contract NAS- 9-6100. (Document SES-074-101). “Apollo/Skylab Suit Program Management Systems Study”, Volume II Cost Analysis. The following figures are copied from that report. The contract performance was divided into four phases; (1) Apollo 7 through 14; (2) Apollo 15 through 17; (3) Skylab, and (4) ASTP (Apollo Soyuz Test Program). The contract functions were Production, Development, Mission Support, Program management, Field Support, Retrofit and Repair and Spares. In June 1966, NASA awarded ILC contract NAS 9-6100 “Apollo EMU garment CEI Program Phases II and III. Schedule 1 included the design, fabrication, and delivery of garment CEIs of the Apollo EMU. Schedule II provided for filed support and sustaining engineering at the field sites and the contractor’s facility. The initial procurement value for schedule I was $13,426,000 which closed out at $25,990,183. (1966 – 1970) This contract delivered 25 A6L and 90 A7L suits. Schedule II was established with contract value of $747,158. (June 1966-December 1969) but closed out at $5,740,888. A schedule III was issued for support at MSFC, but not included in this report. Schedule IV was issued in 1969 for the initial delivery of 6 A7L and 30 A7LB suits. Skylab added another program procurement for 57 A7LB PGAs, and extended the contract to December 31, 1973. Schedule IV had a final cost of $28,771,407. With the deletion of Apollo 18 and 19, the addition of spares, and additional 9 suits for ASTP, ILC delivered 201 pressure garment assemblies and associated spares, provided management, design and mission support engineering for all aspects of the program, and support field operations.

They reported that during Apollo 7-14, they delivered a suit every three days and later, 1 suit every five days as the pace slowed. Materials costs were reported to be approximately 10%. Total Program Cost is reported as $62,626,000. Figure 31 shows the Total Costs by function for

SUMMARY - MAJOR FUNCTIONS ALL PHASES

BY COST ELEMENT

	Production	Development	Mission Support	Program Mgmt.	Field Support	Retrofit & Repair	Spares	Total
Labor	4,096	3,494	2,252	2,868	5,505	296	210	18,721
Material	7,940	614	34	717	37	230	1,369	10,941
Other Direct	812	311	40	1,187	574	4	2	2,930
ST	12,848	4,419	2,326	4,772	6,116	530	1,581	32,592
Burden	4,671	4,086	2,517	3,265	1,414	344	239	16,536
G & A	2,981	1,438	975	1,400	1,511	170	300	8,775
ST	20,500	9,943	5,818	9,437	9,041	1,044	2,120	57,903
Fee	1,674	791	499	781	720	87	171	4,723
TOTAL	22,174	10,734	6,317	10,218	9,761	1,131	2,291	62,626

Fig, 31. The Apollo EVA Space suit costs through 7 performance areas. (SES-074-101)

all phases. Figure 32 illustrates costs of suits as by function and phase. Note the production costs by suit, which varied from ~$126,270 during Apollo 7 -14; to $108,825 during Apollo 15-17; to $68,972 during Skylab and then $83,111 to support ASTP. Escalating costs to 2023, the Apollo 7-14 suits would cost approximately $1M for production, while the Apollo 15-17 Suits would cost ~$855,000. The Skylab suits would have cost approximately $546,000, a reduction of more than 50% from the first suits. While there are many other variables to consider in this initial assessment, it does illustrate that “mass” production will eventually reduce individual costs, even for custom EVA suits.

TOTAL COSTS BY MAJOR FUNCTION BY PHASE (IN 000's)

	Apollo 7-14	Apollo 15-17	Skylab	ASTP	Total
No. of Suits	115	40	37	9	201
Functions					
Production	14,521	4,353	2,552	748	22,174
Development	6,341	3,347	1,046	-	10,734
Mission Support	1,002	3,150	1,542	623	6,317
Program Management	5,030	3,716	1,229	243	10,218
Field Support	2,951	4,727	1,175	908	9,761
Retrofit and Repair	206	820	105	-	1,131
Spares	1,680	487	94	30	2,291
TOTAL	31,731	20,600	7,743	2,552	62,626

Fig, 32. The Apollo EVA Space suit costs (201 suits) through 4 phases and 7 performance areas. (SES-074-101)

6.7.2 Space Shuttle/ISS EMU Costs and Delivery Schedules

Figure 33 illustrates the ROM cost of the current Space Shuttle/ISS EMU as currently understood by our team. It should be noted, that there are multiple vendors which are integrated together, and there is still considerable "manual labor" involved in the soft goods manufacture.

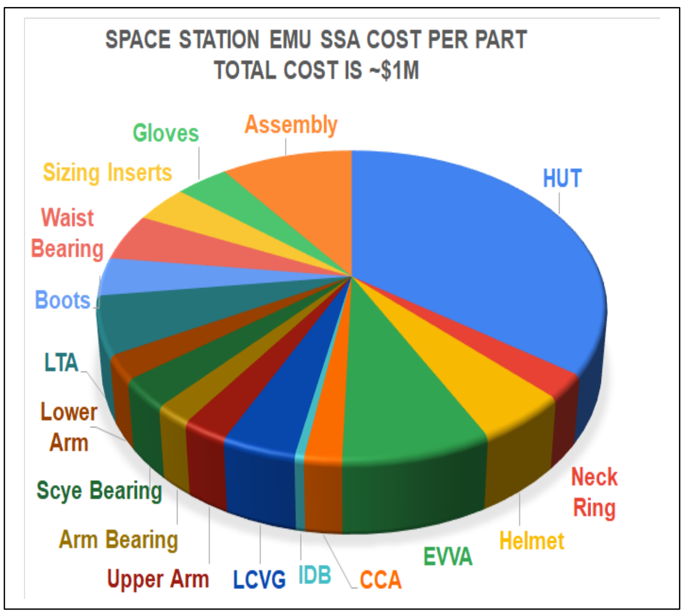


Fig. 33. An estimate of the cost of each ISS EMU Pressure Garment (exclusive of the PLSS).

Current challenges are skilled manufacturing personnel and supply chain materials.

Composition of fabrics are Nylon Tricot, Spandex, Urethane Coated Nylon, Dacron, Neoprene Coated Nylon, Mylar, Gortex, Kevlar, and Nomex.

Acronym Definitions of EVA EMU suit components- HUT: Hard Upper Torso; LCVG: Liquid Cooling and Ventilation Garment; LTA: Lower Torso Assembly; CCA: Communications Carrier Assembly; EVVA: Helmet/Extravehicular Visor Assembly

With respect to delivery times, the metric for delivery was different between the A7LB and the EMU. Delivery for the A7LB occurred following the last fit check of the crewmember at ILC which was approximately 6 months. For the EMU, delivery meant a "ship set" of hardware/soft goods was delivered to NASA, which was verbally estimated at 6 months but the suit had not yet been fit to a crewmember. After receival at NASA JSC, a suit was then assembled for a crewmember based on measurements, a 1g fit check was completed, and then performance was evaluated in the Neutral Buoyancy Laboratory. This was an iterative process which could add several months to a final "fit" depending upon availability of the NBL.

6.8 Summary of Findings:

Finding 1: The decision to migrate from Apollo/Skylab custom A7LB suits to the current modular EMU's used on the Space Station and the ISS was not made on the basis of either cost or schedule considerations for larger astronaut classes, but based on an interest in trying a new engineering approach. There were concerns regarding the zipper materials and reliability of the vendor for future deliveries.

Finding 2: When factoring in Measures of Performance (MOP) such as mobility, fit, injury history, maintenance, mass, volume, component failure history, complexity, sparing, etc., the A7LB custom suit approach should be considered a more viable investment for future missions to Mars.

Finding 3: When comparing the two suits for cost and delivery schedule:

(1) The Apollo suits cost about $1M (escalated to 2023 dollars) at the start of the production program for 201 custom suits. At the conclusion of the program, suits were costing about $500K in 2023 dollars. Suits could be produced in 40 days at ILC ready for crew training. With the PLSS, they weighed about 180 lbs on Earth.

(2) The EMUs were estimated to cost $1M per ship set, but not dedicated to any particular crew member. However, public information on the cost of delivering 18 EMUs (of which 11 may remain) varies from $15M - $22M. Delivery was estimated at 6 months (180 days) per ship set. Additional time was required for crewmember measurements, 1g fit checks and training runs in the NBL to evaluate fit. The added time was highly variable. Total reported weight has varied with design changes, but is estimated at about $320 lb.

(3) For comparison, the xEMU with PLSS (under development) was estimated to weigh about 404 lbs before it was transferred to the xEVAS.

Finding 4: The A7LB suit was primarily a pressurized soft multilayered fabric custom system with fewer mechanical and hard components than the EMU. (Less complexity can be related to higher reliability and simplification of resupply and repair.) There were no failures on any of its missions.

Finding 5: Given the option between custom suits and modular suits, both past crews and current crews favor customization. Proper fit is particularly relevant to fitting a diverse population of male and females, of different ethnicities, ranging from 1st percentile to 99th percentile.

7.0 RESULTS OF TASK 2; BENCHMARK COMMERCIALLY AVAILABLE DIGITAL THREAD SOFTWARE TOOLS

7.1 Evolution of the DT:

A historical knowledge review of the Digital Thread/Digital Twin is well summarized by Dr. Edward M. Kraft, USAF, in his 2016 paper "The US Air Force Digital Thread/Digital Twin – Life Cycle Integration and use of Computational and Experimental Knowledge". AIAA SciTech, January 2016). " *In conjunction with these new policies, the United States Air Force is developing and applying a Digital Thread/Digital Twin analytical framework to provide engineering analysis capabilities and support to decision making over the entire lifecycle of air vehicles. The Digital Thread/Digital Twin merges physics-based modeling and experimental data to generate an authoritative digital representation of the system at each phase of the acquisition and sustainment process of a weapon system."*

Dr. Kraft stated that the evolution and intersections of computational fluid dynamics (CFD) and experimental dynamics (EFD) has been an important component of aeronautics for more than 40 years and had a significant impact on the development of new vehicles. A point relevant to this study is that CFD has reduced the number or experimental configurations tested in the wind tunnels but that the experimental data from wind tunnels had, in turn, provided measurements essential to the calibration and validation of the CFD models. This is similar to the "Virtual Twin" analyses pursued in our Phase I study and reported under Task 3. .

The term "digital thread" originated in the Aerospace Industry to describe an integrated system engineering process for "digitally managing the entire process from the 3-D CAD design of system components through the manufacturing, assembly and delivery of the system". The DT included model-based engineering (MBE), digitized drawings, list of materials, the manufacturing processes, logistics, configuration management through delivery of the system. The USAF invested in a technology thrust whereby physics-based modeling would be combined with data from the DT to improve manufacturing, operations, and sustainment of the (in this case) aircraft. This process was called the "Airframe Digital Twin" with the future goal of incorporating real world data and probabilistic analysis to forecast the life cycle by part number and by aircraft – the overall intent to **reduce the cost of Manufacturing, Operations, and Sustainment.**

An important output of this process is the creation of an "authoritative digital surrogate representation" which is formed by combining reduced order models and empirical data as the system moves into physical prototyping and testing. The DT then becomes a single authoritative digital surrogate representative of the system at any instance in time, accessible by both the government and industry. At each step in the process, the DT can be optimized with additional test data. Other customers of the DT include flight simulators, system integration laboratories, etc. A translation of this to an EVA suit would also include a number of contractors who are currently each trying to design Lunar Lander airlocks and habitats with EVA interfaces without clear understandings of the current EMU design and the requirements for such items as umbilical length, etc.

At the time of the 2016 Kraft paper, the definitions used by the USAF OSD, in collaboration with industry were as follows:

Digital System Model - A digital representation of a *weapon* system, generated by all stakeholders, that integrates the authoritative data, information, algorithms, and systems engineering processes which define all aspects of the system for the specific activities throughout the system lifecycle.

Digital Thread - An extensible, configurable and Agency enterprise-level analytical framework that seamlessly expedites the controlled interplay of authoritative data, information, and knowledge in the enterprise data-information-knowledge systems, based on the Digital System Model template, to inform decision makers throughout a system's life cycle by providing the capability to access, integrate and transform disparate data into actionable information.

Digital Twin - An integrated multi-physics, multi-scale, probabilistic simulation of an as-built system, enabled by Digital Thread, that uses the best available models, sensor information, and input data to mirror and predict activities/performance over the life of its corresponding physical twin.

7.2 The Market Place of Tools:

There are essentially three categories of tools: (1) Those that need to be developed in order to support specific applications (such as our proposal for the EVA suit Virtual Twin) as well as the Digital Twin at product delivery; (2) State of the Art Tools for development, such as CAD, ABAQUS, ANSYS, Inventory Management, 3D printers for AM, etc.: and (3) the digital communications infrastructure which "threads" all of the models and data bases together. This is somewhat analogous to the development of *concurrent engineering* in the 1990's without the completeness of the rest of the "Thread".

One particular area of interest is model based engineering, MBE, which may require computational capabilities beyond the reach of small companies, but is being pursued by government agencies and large corporations. The field of "Digital Engineering, as a whole is rapidly developing but does not yet have a standard set of definitions or requirements. The Aerospace Corporation is one entity attempting to facilitate development and rigor in the discipline for its primary customers, the Air Force and NRO. Of note is that University Engineering Departments are generally still discussing how to introduce DT into undergraduate and graduate education in order to prepare them for the 4.0 Manufacturing "revolution", but there is an acute need for text books and deliverable content.

7.2.1 DOD Example: In 2008, the DOD High Performance Computing Modernization Program established the CREATE™ Program to enable major improvements in defense acquisition workflows. One of four primary elements, CREATE™-AV is designed to develop, deploy and support a set of multi-disciplinary physics-based simulation software products (currently supporting air vehicle programs). One of the products, Da Vinci, is an early phase acquisition tool designed around a unified life-cycle engineering model encompassing multi-fidelity analysis for a wide range of applications. It provides next generation modeling for functional analysis, alternative design evaluation, trade space exploration and acquisition planning.

Although there are DT products developed or in the process of being developed for the AF, it is still an on-going development program both in government and industry, especially for combining new products with historical legacy data bases and processes. The USAF applied elements of DT to the F-22 program for optimal Design of Experiments (DOE), with the intent of determining when another CFD solution was at a point of diminishing returns. DT was validated in this pilot study. Figures 34 and 35 are replicated from Kraft's paper:

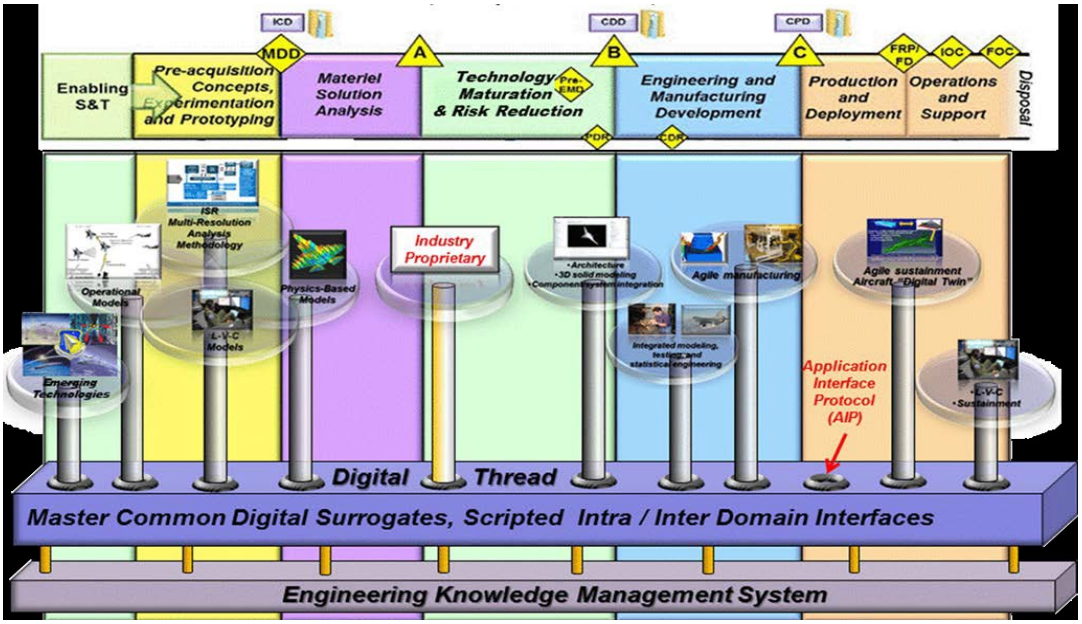


Fig. 34: Air Force Digital Thread Architecture (Kraft, 2016, AIAA SciTech -- Permission to Reprint Pending)

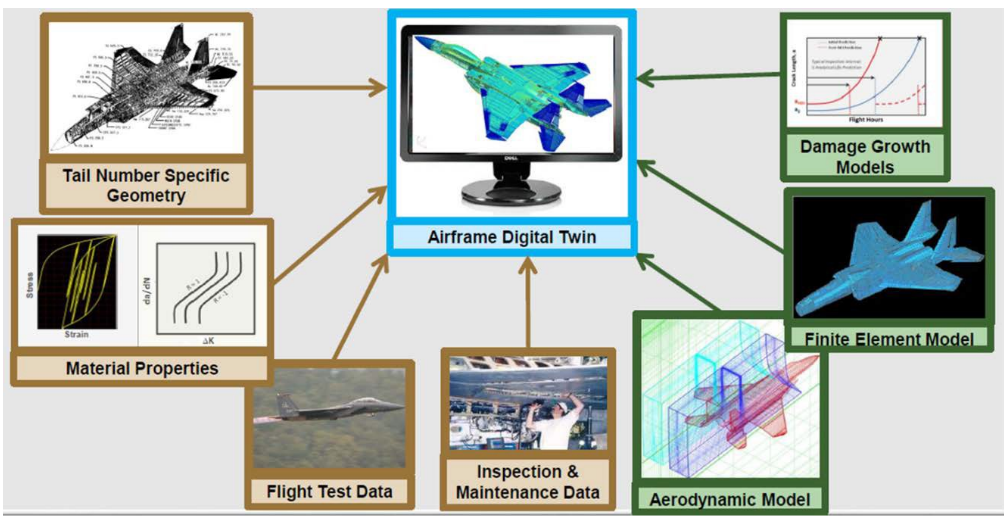


Fig 35: Air Force Airframe Digital Twin Approach, (Kraft 2016 AIAA SciTech – Permission to Reprint

7.2.2 Commercial Tools: With the emergence of sophisticated Digital Engineering, Digital Twins, Model Based Engineering, and other elements of the Digital Thread, there are a number of companies now offering this service, tools, or consulting to companies. Some tools will be generic to all industries, but some will require customization or new development. A typical DT architecture developed by General Electric is shown in Fig. 36:

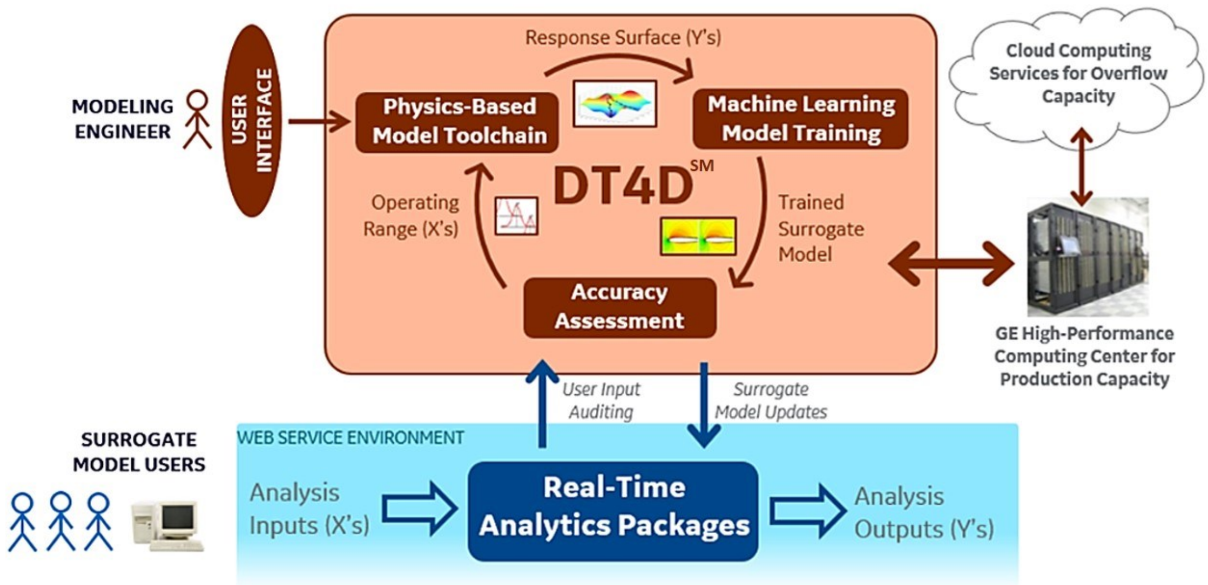


Fig. 36: The GE Digital Thread Architecture: https://www.ge.com/research/technology-domains/digital-technologies/digital-thread-design

7.2.3 DT Consultants and Delivery Companies*:* Many new companies are emerging to help industry with the development and delivery of the DT. Their tools address a number of systems engineering capabilities or processes, such as CAD, Scanning Technologies, Tracking Customer Requirements, Suppliers; Procurement; Specifications; Process Design; Test Results; Assembly/Robotics/Hard Components; Change Management; Flight Experience; Inspection; Qualification and Acceptance Testing Results; As Built Configuration Control; Logistics, Sparing; Model Based Engineering; Inspection Data, etc. Most of the products and services provided by the companies to develop or implement DT for the client are proprietary. A current challenge in any company is the software linkage of disparate heritage software systems and languages with emerging DT applications. Table VIII lists a few relevant companies and their web sites:

Table VIII: Sample List of DT Delivery Companies

Company	**Header**	**Web Address**
Challenge Advisory	What does a digital thread mean and how it differs from digital twin	https://www.challenge.org/ https://www.challenge.org/insights/digital-twin-and-digital-thread/
iBASt	What is the Digital Thread	https://www.ibaset.com/what-is-the-digital-thread/
Siemens,	The Growing Importance of the digital thread across the A&D Product Lifecycle and associated systems	https://resources.sw.siemens.com/en-US/white-paper-digital-thread
Aras	Why the Digital Thread Should Be the Top Initiative for Manufacturers	https://www.aras.com/en/resources/all/executive-summary-digital-thread
Kalypso	We Deliver Digital Transformation Across the Value Chain	https://kalypso.com
Rockwell Automation	Digital Thread: Unlocking your Digital Potential	https://www.rockwellautomation.com/en-us/capabilities/digital-thread.html

7.3 Developing Industry Standards – NIST: As the DT industry processes for both DT and 4.0 manufacturing mature, it has become apparent that standards are also required. Subsequently, the National Institute of Standards and Technology, NIST, https://www.nist.gov/ established **"The Digital Thread for Manufacturing project"** which "will deliver methods, protocols, and tools for developing, conformance testing, increasing user-awareness, and industrial adoption of product definition standards necessary for the digital transformation of manufacturing enterprises." https://www.nist.gov/programs-projects/digital-thread-manufacturing. NIST also initiated a Pilot Project for 3D machining: *Rockwell Collins products made by Gator Smart Machines* (specifically a heat shield for aircraft circuit board). A video of this initiative can be accessed at https://youtu.be/iGtM8VGLn5M.

7.4 State of the Art for 3D Human Scanning:

In our notional DT process illustrated in Figure 8, the process begins with a digital scan of a crewmember integrated with a CAD of a space suit. CADs are the point of entry for most DT processes and is one of the set of tools used for our feasibility study. However, scanning humans to develop digital models integrated with inanimate CADs is new. This is the first step in the *Virtual Twin* and it depends upon the maturity of the scanning technology. Laser or photogrammetric human scanning has progressed significantly in the last ten years, particularly in the medical industry to support surgery as well as prosthetics. Digital Scanning is used by athletic equipment designers, and by the military. For example, scanners are used at NASA JSC, Army (Natick Laboratories) and Air Force facilities, but not used for direct manufacture of custom protective equipment. In the case of NASA, they are used to determine whether or not an astronaut *candidate* fits into the existing (*and limited sizes*) EMU suits – a screening condition for astronaut selection.

In our Aerospace Human Systems Laboratory, AHSL, (Figures 37 and 38) we are well equipped to take the more mature digital scanning technology into the TRL 2 development of a *Virtual Twin*. The 3dMD motion capture system utilizes active stereo-photogrammetry to create 3D models of the scanned subject. Stereo-photogrammetry measures the 3D coordinates of an object by capturing an image from multiple camera positions. Some scanning systems determine geometry information solely based on existing surface detail, which is considered passive stereo-photogrammetry. In the case of the 3dMD motion capture system, existing surface detail is supplemented with a projected speckle pattern on the subject. Utilizing the distortion of this supplemental pattern in the resulting camera images (active stereo-photogrammetry) generates more discernable geometry data of the object. 3dMDperform software creates a 3D mesh from the correlation of 2D images of a surface from different camera views. The result is a 3D object model for every instance (defined herein as a "frame") of a motion sequence, which can be displayed as a wireframe mesh, a monochromatic surface, or a surface with full-color texture. After performing a scan and creating the

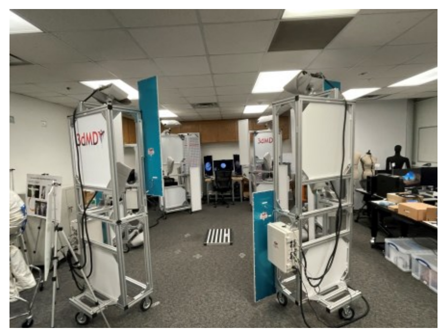


Fig. 37: 3dMD Scanning System at the AHSL

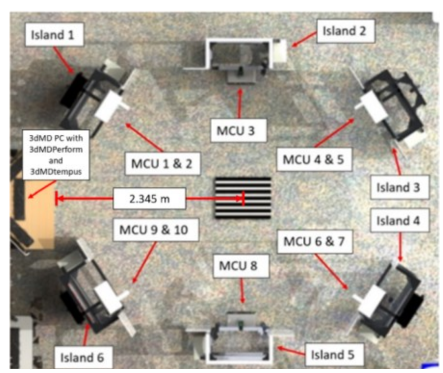


Fig. 38 3dMD 10 Camera, 6 Tower Configuration

200-frame sequence of 3D surface meshes, the sequence can be rendered as a motion animation on 3dMDtempus software. 3dMDtempus allows the operator to view each 3D surface mesh frame by frame. 3dMDtempus also allows the operator to view the solid surface with or without overlaid texture as well as the respective surface mesh. specific motions and postures. This captured surface shape retains motion data of the whole body and can correlate data points to the body, instead of just reflective target locations in a point cloud. For any standard scan, more than 200,000 mesh vertices are created.

A supporting3dMD software program, 3dMDvultus, allows users to perform any anthropometric measurement, landmarking, and analyses on generated models. This software is used to manually track landmarks across a scan sequence to generate ROM data. All required anthropometric measurements are available to 1 mm accuracy, including total volume, volume segments, and surface area. This anthropometric product has an inherent advantage over reflective target strategies as it enables the capture of the complete 3D shape of the human subject as it moves through

Our current scanning systems are accurate enough to be used as a direct digital input to digital twins and *yet-to-be developed* kinematic models. While we developed a first “VT” for an EVA arm in this Phase I study, the DHM kinematic models do not yet exist. There is some development from the garment industry with respect to fashion design in moving subjects, but it is still at a very low TRL. For example, the Vitronic Vitus Laser Scanning in our Aerospace Human Systems Laboratory (AHSL) produces full body scans with 1 mm accuracy (Figure 39). The accompanying CAD-VIDYA software can simulate up to 20 different multi-layer materials on scanned subjects and calculate stresses, strains and “fit”, but the software does not allow the

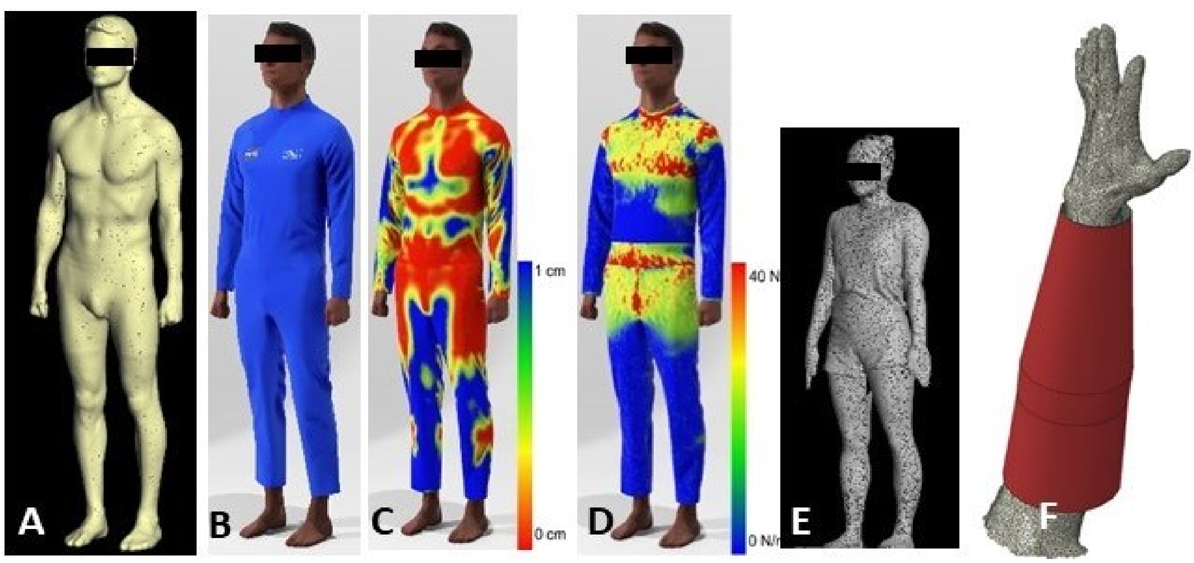


Fig. 39: 3dMD and Vitus Laser Scanning with Software Tools: A) Raw Scan with Vitus Laser Scanner; B) Application of CADVIDYA Software to design Flight Suit; C) Introduction of material properties generates heat map of distance from body and D) fabric stress; E) 3dMD motion tracker creates 200 views in 20 seconds so that the best view F) can be extracted and segmented for further analyses ;

garments to be pressurized and has only a few “canned” body motions. There is no Virtual Twin capability.

7.5 Human Systems Integration (HSI) and Digital Human Models (DHM):

HSI, has been recently included in the NASA and Air Force Systems Engineering handbooks, so is receiving more attention in aerospace designs. DHM, which is used to model human kinematics, was introduced into the automobile industry about ten years ago, is quickly accelerating digital modeling of human kinematics and soft tissue responses during accidents but has not been applied to pressurized spacesuits – a much more constraining environment, but one that should be evaluated in the present day due to current crew injury reports in the EMU. The potential for DHM was evaluated in this study, with results reported in Section 8.4.

7.6 DT Professional Development Opportunities:

The internet is now providing numerous opportunities to train in elements of the Digital Thread and Digital Engineering. One notable opportunity is focused on the Aerospace Industry: "Foundations of Digital Engineering" provided by TSTI (Teaching Science and Technology, Inc.) https://www.tsti.net/course-selection-guide. This company provides a course with the following objectives focused on the Aerospace Industry with the following syllabus:

1. Compare and contrast analog engineering, traditional Digital Engineering and the value proposition for more fully integrated Digital Engineering ecosystems.
2. Explain the elements of the Digital "Trinity" and how they relate to each other.
3. Describe the Lifecycle Modeling Framework as a thinking tool to conceptualize integrated Digital engineering ecosystems.
4. Understand the DoD DE Strategy goals and their associated metrics in the INCOSE maturity guide.
5. Characterize types of engineering and project models and their application across the product lifecycle.
6. Generalize the challenges and techniques for developing, integrating and curating models.
7. Analyze approaches for using models to evaluate "digital threads" in a system.
8. Explain the advantages of having an ASOT.
9. Discuss the challenges of managing multiple sources of truth in a project.
10. Describe the elements and requirements for an idealized Digital Engineering Ecosystem. Data sharing models?
11. Evaluate current commercial DE ecosystem products.
12. Discuss the potential applications for AI/ML to enhance the value of DE.
13. Appreciate the IT requirements and challenges of establishing an integrated DE ecosystem across an enterprise.
14. Recognize the value of agile techniques to accelerate the digital transformation in an organization (DevSecOps).
15. Apply the INCOSE maturity metrics to evaluate the transformation state of your organization.
16. Discuss plans of action to lead and support digital transformation including workforce development requirements.

6.7 Summary of Findings:

Finding 1: The aerospace and military aircraft industry has been leaders in the digital twin concept with their desire to improve future program performance. Now, however, these concepts are becoming significant in other fields such as digital manufacturing and cyber-physical systems.

Finding 2: Adopting a digital thread concept with a single framework strategy for manufacturing systems, such as EVA suits, will enable controlled analysis of data throughout its lifecycle. The measure's being made in real-time will be effective in delivering digital data in both simulation and assembly.

Finding 3: Applying DT to Manufacturing: Digital threads can improve manufacturing in that product quality will be improved by preventing mistakes in engineering specification being manually translated across the product value chain. The digital thread allows planners, designers, and machinists to share results. This can be expanded to crewmembers and trainers.

Finding 4: DT Tools are proliferating in 4.0 Manufacturing, and can substitute for standard “paper” tracking methods. They should be available to both current xEVAS contractors as they develop the next generation spacesuits, and could be included in future contract requirements.

Finding 5: Digitally manufacturing multilayer fabrics is still a low TRL with significant technology gaps.

Finding 6: There is no known *Virtual Twin* technology which will allow for digital analyses of a scanned crewmember in an EVA suit CAD to determine mobility and fit in a pressurized environment prior to the manufacture of the suit.

8.0 RESULTS OF TASK 3: Task 3: ASSESS THE FEASIBILITY OF MAPPING EVA SUIT DESIGN, COMPONENTS, MANUFACTURING, AND OPERATIONAL REQUIRMENTS TO EXISTING DT ARCHITECTURS.

8.1: Assessing DT for EVA Suit Development:

The DT is composed of digital models, data bases, and communications systems. For many of the components shown in Figure 8, standalone data bases exist and the challenge is digital and "automatic" communication between the components. Thread components, which should exchange data, include supplier information, procurement and supply chain information, engineering design and design changes (such as concurrent engineering), etc. More recent advances in 3D and Additive Manufacturing have made their way from hobby to aerospace metal engine components. According to the literature, one of the biggest challenges is the rapid and accurate exchange of this data in existing companies with legacy software. For many companies implementing the DT strategy, they are hiring consultants and new software companies to deploy an integrated set of tools.

As one might expect, there are **no publicly available Digital Thread** information available for either the Apollo A7LB or the current EMU. In the case of the A7LB, those systems largely did not exist for the first 40 years of the space program. . For the current EMU, they do not exist at NASA since the EMU was ILC proprietary equipment delivered to the government. It is also surmised that there may be few if any DT linked systems at ILC. For example, we were not able to locate any digital failure data bases at NASA over the 40-year history of the EMU. Therefore, any new development (such as xEVAS) is beginning with a new software architecture and set of tools.

Another element of DT, that of linking all the components of DT with common software is a systemic problem in all systems and industries, and so is not in the scope of our studies. Some components such as documentation, and requirements traceability are straight forward. *When considering the DT path in Figure 8, we decided that the primary DT technologies or low TRL challenges for entry into the EVA DT path are as follows and our feasibility assessments focused on these three components of a DT. They are further illustrated in Figure 40.*

1) **Assess the feasibility to predict performance and mobility (e.g. torque and force) for deformation of pressurized fabric joints, such as the elbow and knee prior with scanned human digital files prior to manufacturing (Virtual Twin)**

2) **Explore the application of 3D printing/knitting to soft fabrics and pressure bladders**

3) **Benchmark Digital Human Modeling (DHM) in pressurized enclosures with tissue responses and expected kinematics using anthropometric scans rather than standard Avatars.**

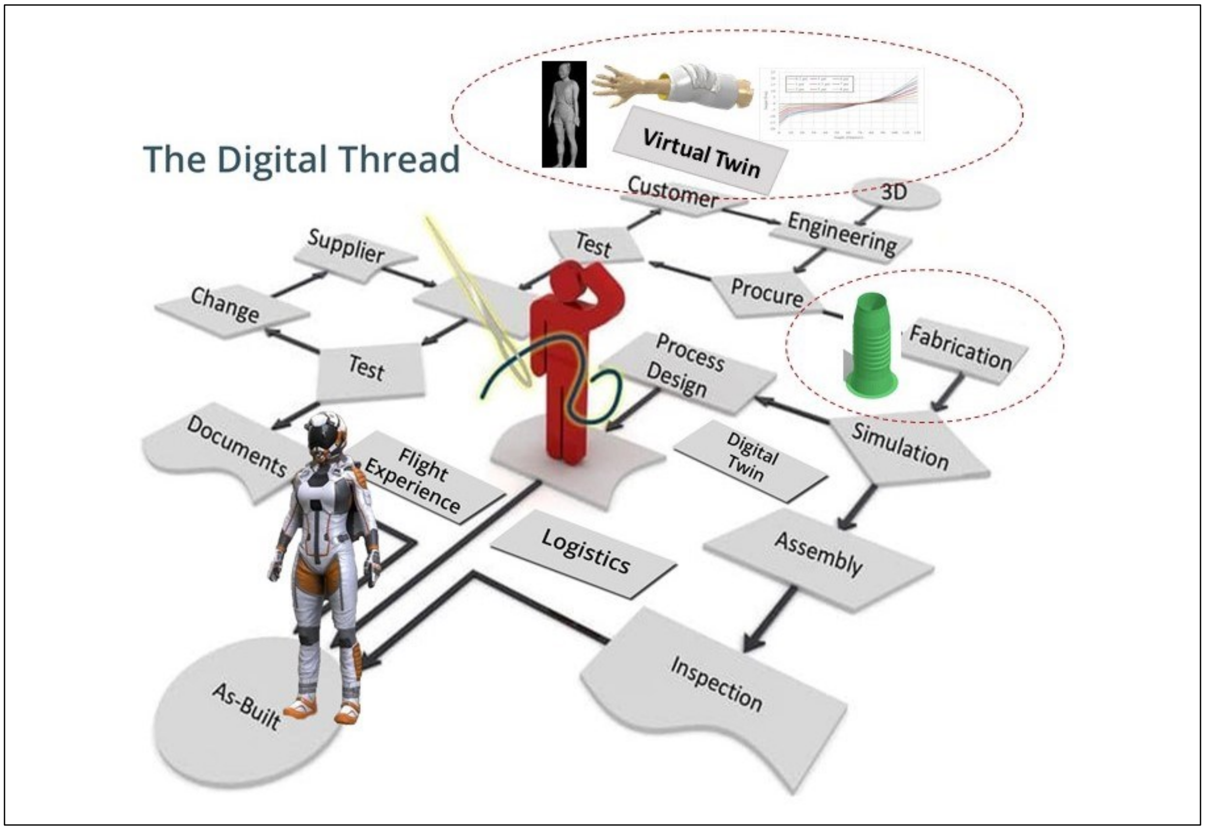


Fig. 40 The new Mapped DT composed of a new tool for Virtual EVA Twin Models and 3D/AM for EVA pressure bladder

8.2 Feasibility for Developing the Virtual Twin for pressurized soft fabric components – Texas A&M University

8.2.1 State of the Art: Using computer-aided design (CAD) to predict space suit sizing and fit for individuals, is a relatively new technology, motivated by the need in the early 2000s to digitally visualize joint designs for the EMU and how they interact with the astronaut. However, all of the recent advances in this area have been made using "hard" components in contact with scanned but non-deformable digital humans.

A review of computational methods for modeling human-suit interaction was published by Sterling et al which showed an extensive review of the current research performed in this field. Extensive work from has been produced from the NASA Anthropometry and Biomechanics Facility (ABF) and the NASA Crew and Thermal Systems division at Johnson Space Center. Margerum et al. performed the first detailed DHM case studies with current NASA suit components. This involved the overlay of the EMU HUT (a hard component) onto scanned individuals to evaluate fit, clearance and contact points. While no metrics exist that compared fit between suit sizes, the main conclusions of this study emphasized the use of scanning technology as a viable means of virtual suit fit testing.

NASA ABF has continued developing more rigorous analyses for characterizing human-suit interaction and metrics that would constitute good or bad fit. Recent work on human-space suit interaction models involved integration of a parameterized human model with existing suit CAD models. (Figures 41 and 42) NASA ABF researchers and suit designers utilized virtual fit check and 3D printing validation methodologies since previous methods using boundary manikins only considered a small number of 3D body shapes. The new methodology follows a Monte-Carlo

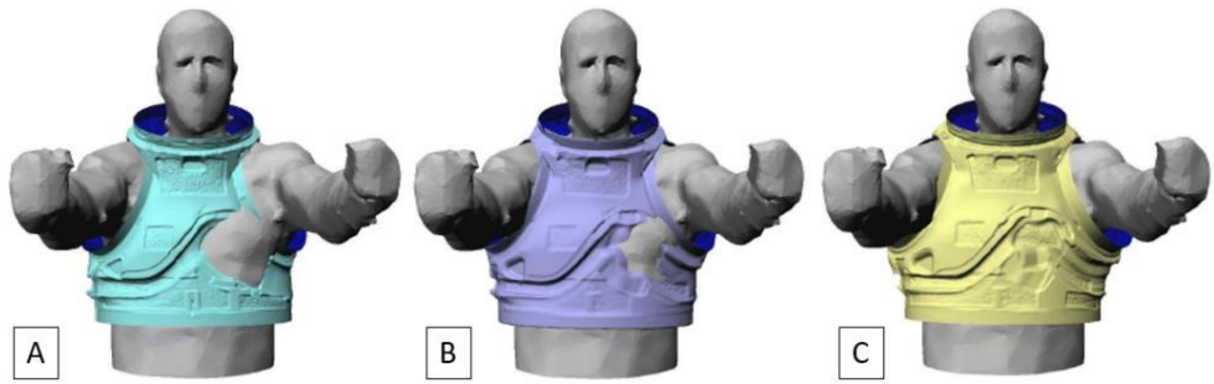


Figure 41: Model estimated body geometry incorporated with CAD drawings of an EMU space suit, NASA ABF

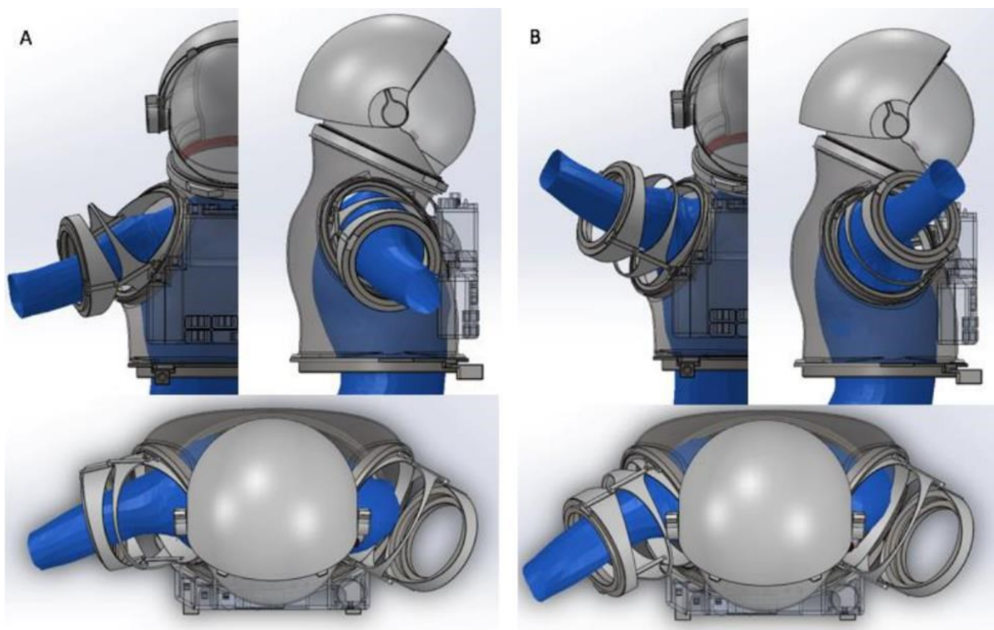


Fig. 42: Attempt to determine hard contact points between digital body scan and CAD of HUT hard components. Soft components are not considered. (NASA ABF)

type of fit assessment that utilizes many 3D scanned body shapes instead of a few "worst-case" models. Fit was determined by the amount of suit-to-body contact and penetration depth observed on overlapping CAD models of varying body shapes and xEMU HUTs. Most recently, NASA ABF utilized this technique based on a hybrid of virtual and physical fit checks to perform preliminary fleet sizing for the xEMU Waist-Brief-Hip assembly (WBH) Results predicted that the baseline design brief is expected to accommodate 90.6% of the female and 78.4% of the male crew population. A modified design brief was also tested and was predicted to accommodate 95.8% of the females and 90.0% of the male population. Additionally, the Advanced EVA Pressure Garment Development team at NASA JSC performed preliminary finite element analysis to determine if the external link rolling convolute shoulder design of the xEMU was vulnerable to kick load requirements, which could immobilize the shoulder joint. High stress areas were identified, and the design is being changed to reduce the stresses, thus improving the performance of the shoulder under a kick load. However, again, all of this work compares non-mobile human scans interacting with hard components.

The past decade provides most of the current literature on virtual space suit fit and performance technologies. Work by Kim et al. focused on analyzing the contact volume and clearance between the suit and body surfaces at different shoulder joint orientations. Using a series of fitting and parametric geometry estimation models, a template human upper body model was fitted to a dataset of raw body scans collected from a 3dMD body scanning system. The model-estimated body geometries were integrated with CAD models of an EMU HUT to consider interactions between the human models and the HUT surfaces. Observations from this work showed a reduction in clearance in the upper-rear portion of the arm as the shoulder was elevated, especially in extreme positions. These observations demonstrated that CAD tools are capable of modeling hard interface interactions between the human and pressure suit and that modeled results can provide valuable suit design information for suit engineers, but these studies did not have the capability for predicting mobility or energy expenditures due to force and torque in a **flexible fabric deformable pressure garment.**

8.2.2 FEA "Virtual Twin" (VT) Modeling – results of Phase I

Based on EVA suit evaluations and what part of the suit would benefit the most from Virtual Twin, VT, modelling, it was decided to focus the VT effort and potential new fabrication technologies on the EVA suit lower arm. The lower arm at the elbow is a "workhorse" for EVA at LEO, required for tasks/mobility and is currently the most problematic for the EMU because of fit issues. EMU Material Layers are shown in Table IX with the bladder and restraint layer highlighted

Table IX: EMU Material Layers used for the Arms, Legs, and TMG.

1	**LCVG Liner (Tricot)**	5	Pressure Garment Restraint (Dacron)
2	**LCVG Water Tubing**	6	**Thermal Micrometeoroid (TMG) liner (Neoprene coated nylon ripstop)**
3	**LCVG Outer Layer (nylon/Spandex)**	7 -13	**TMG Insulation (Aluminized Mylar laminated with Dacron)**
4	Pressure Garment Bladder (Urethane coated nylon)	14	**TMG Cover (Ortho-Fabric – Blend of Gore-Tex, Kevlar, and Nomex)**

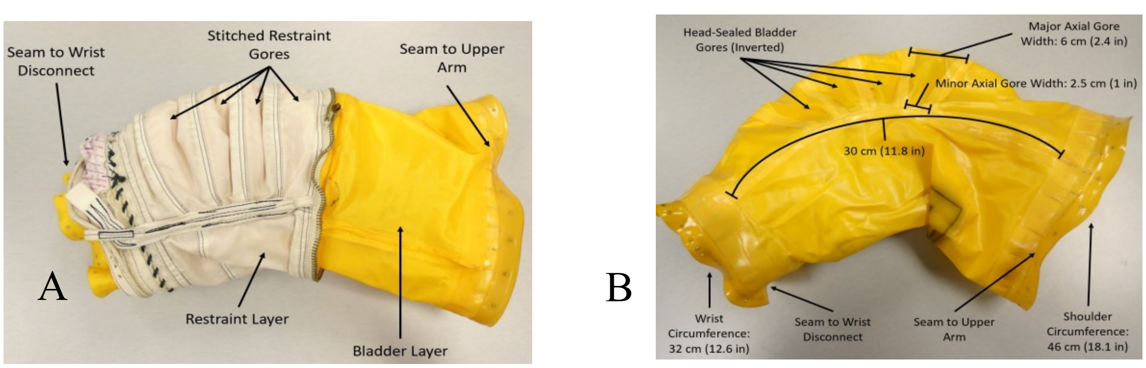


Fig. 43 Size 04 EMU Pressure Garment Elbow Joint (left) from the outside (A) and Inside (B)

in red, since they will be the focus of this study. The combination of the pressurized bladder and the restraint layer provide the most resistance to deformation when pressurized. Fig. 7 shows a size 4 lower arm sleeve with Urethane coated nylon pressure bladder and Dacron Restraint Layer. Figure 8 shows a full arm with bladder, restraint layer, convolutes, shoulder bearing, and to wrist (minus wrist disconnect ring)

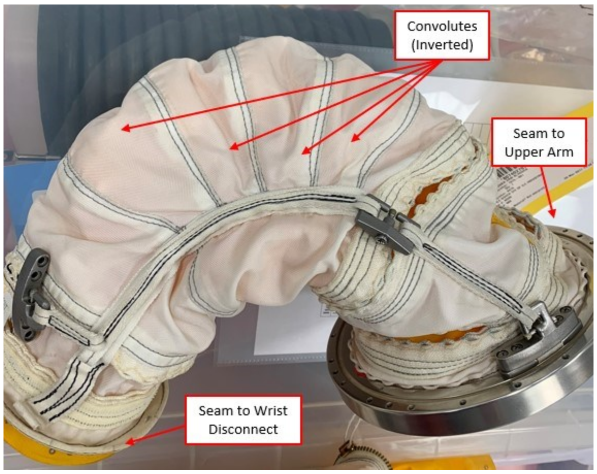


Fig. 44. Full EVA arm with bladder, restraint layer and semi-circular gores.

As discussed previously, it is difficult to predict the pressurization impacts to fit and mobility until after the EMU suit has been manufactured and is being evaluated in the Neutral Buoyancy Laboratory (NBL) or Pressure Chamber. A new method is required to digitally model and predict human performance in a pressurized space suit prior to its manufacture, testing, and service. Finite Element Analysis (FEA) modeling tools, such as ABAQUS, and customize software were developed to provide a pathway for iteratively predicting EVA suit fit and performance in a pressurized suit.

To achieve this *Virtual Twin* goal, we integrated modelling for inflatables, and for the first time considered the properties of two distinct material layers. This Phase I work created the **first generation of a FEA Virtual Twin model** of a Size 4 EMU Sleeve with both a pressure layer and a restraint layer, and estimated material properties based on available data and direct measurements of an analog material. **New innovations** to this modeling was the introduction of two layers at pressure - typical FEA modelling of pressurized multi-layer systems assign one value for all the material properties grouped together, derived from empirical testing.

Fig. 45 First Step -. 3dMD Digital Scan

We also a scanned digital human arm using our 3dMD photogrammetric scanning system. This is the first step in **virtual twin** modeling of a custom EVA suit. Figure 45 shows the subject (a graduate student in the AHSL) scanned with the 3dMD, with an accuracy of 1 mm and a final mesh of more than 200,000 vertices. From this, the subject's arm was extracted for use with a FEA model EVA sleeve. Figure 46 and 47 show the arm inserted into an FEA modelled EMU sleeve (unpressurized and pressurized) which was scaled to the measurements taken from our NASA Excess inventory sleeve. In this case the sleeve was a good fit to the subject's

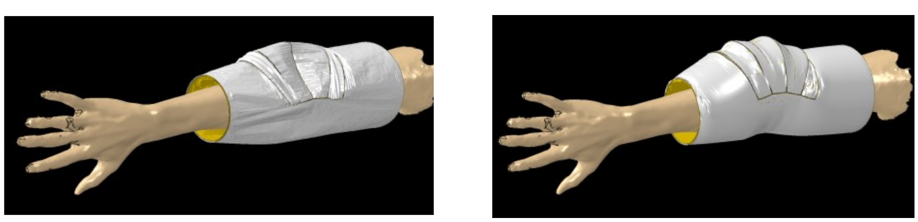


Fig. 46: (L) Scanned arm inserted into two-layer unpressurized sleeve. (R) Scanned arm inserted into two-layer pressurized sleeve.

arm. We elected to first evaluate a sleeve which matched a scanned subject, however, we also have smaller female scans which will be next evaluated.

Fig, 47 shows elements of the progression of the model from scanning a subject's arm to creating a two-layer sleeve, the introduction of EMU gores at the elbow, dynamic bending and visualizing the stress map. The results of this modelling were within the published range for torque and force at 4.2-4.4 PSID (the current operational range). The published range was from 3.2 – 13.7N-m, while our FEA Fig. 48 shows the data when compared to the literature at various delta pressure values. It should be emphasized that this modeling was for a standard EMU arm with a 3-sigma male arm -- after comparing the subject with available anthropometrical data. Note that the null position is at about 70 degrees bend of the elbow. This was an intentional design of the EMU so that the "neutral position" is with the arms slight bent in front of the chest. The EMU was designed for microgravity work in front of the chest with tools, not for planetary exploration. Therefore, it requires force to also 'straighten" the pressurized arm.

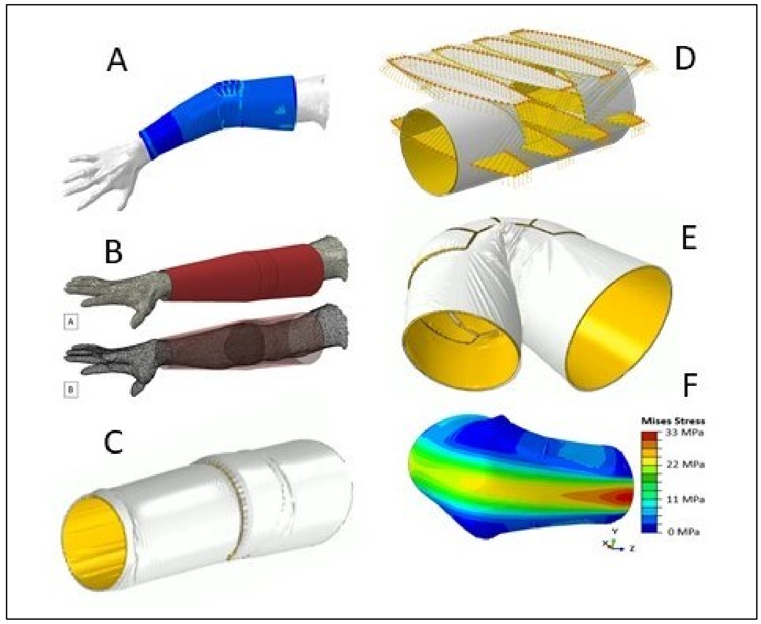


Fig. 47. Phase I TAMU/AHSL VT Development: (A) Scan Arm/section (B) Model Pressure Bladder and Restraint Layer (C) Model Sleeve (D) Insert Gores (E) deform with external force (F) Measure External Stresses and Force/Torque to deform

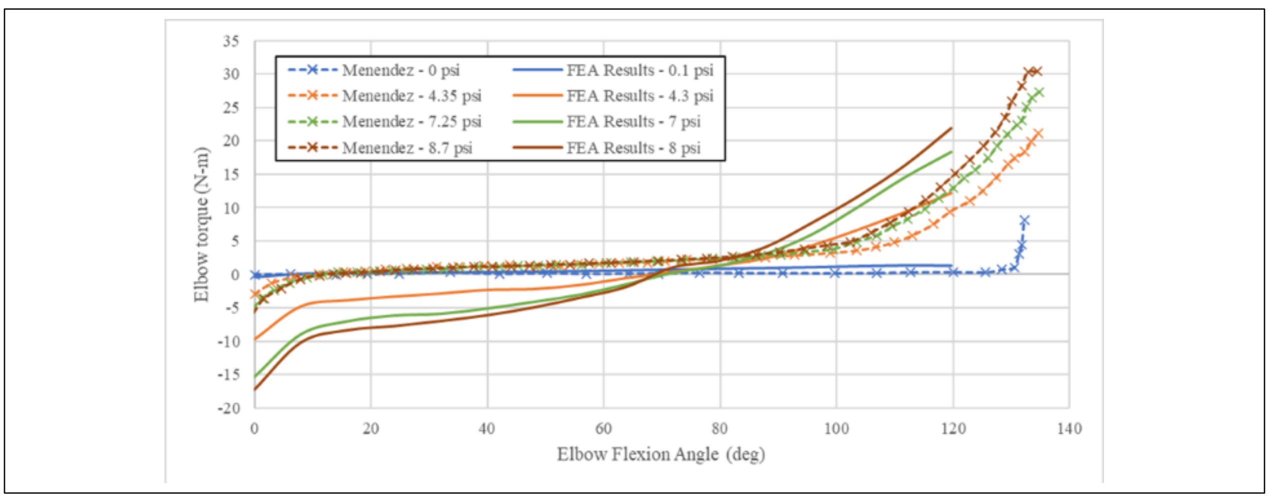


Fig 48: Empirical Validation with Published Literature - Comparison of empirical and FEA results for EMU joint torque data as a function of operating pressures. Note the neutral position and force required to extend the arm.

We also explored the effects of varying the delta pressure at finer increments. Fig. 49 shows the elbow torque as a function of Delta P, with the current suit operating at a Delta P of 4.2-4.4

PSID. The general joint torque profile was consistent across pressurized cases and demonstrates increased torque with increasing pressure, as would be expected for this design.

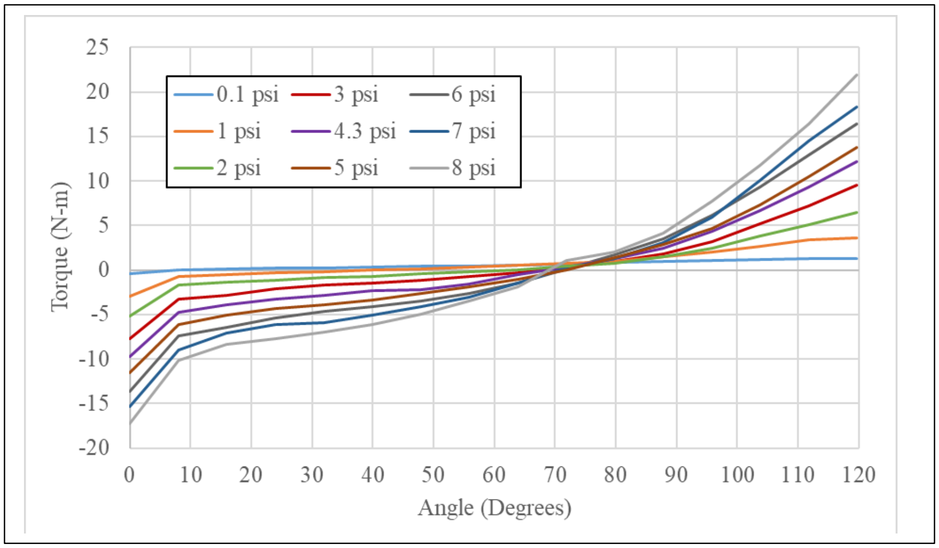


Fig. 49 FEA Virtual Twin Model– Arm angle as function of Torque EMU and Delta P: arms have a neutral elbow position of about 70 degrees. Pressure = 0.1, 1, 2, 3, 4.3, 5, 6, 7, and 8 PSID.

That there was little to no required torque at PSID = 0 shows unpressurized joint torque tests should produce negligible torque. Note that the EMU arms do not "hang straight". Because of the semicircular design, there is a neutral (no torque) angle, depending upon the number of gores. For this VT, the angle was approximately 70 degrees. This agrees with crew observations and photo imagery.

It was also noted, that some of the sleeves had different numbers of gores. The effect of the number of gores on torque is shown in Fig. 50. Increasing the number of gores decreases torque – an effect which agrees with observations made with the small EMU development in that decreasing the number of gores to align with a shorter arm actually increased the torque required.

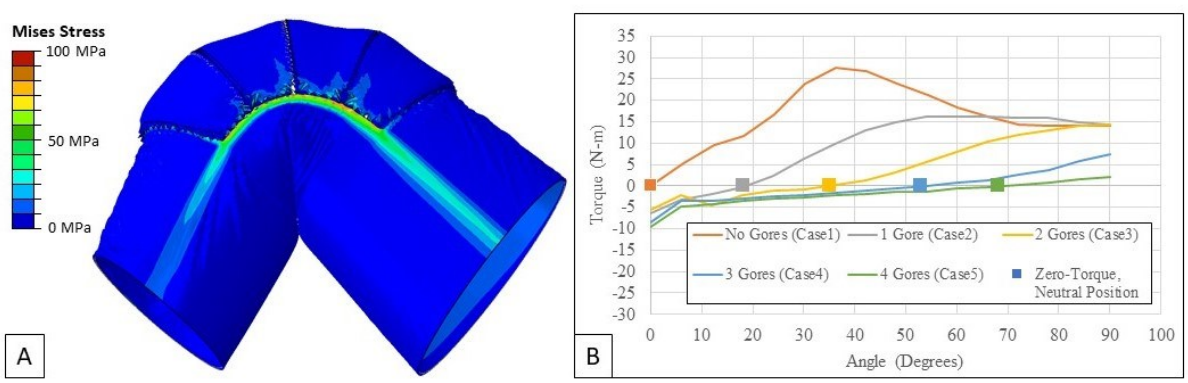


Fig. 50: A) The FEA Stress Map which demonstrated that the stress was maximized along the lateral seam, which provides rationale for the placement of some restraints B) Torque as a function of the number of gores demonstrating the influence of the number of gores related to arm length.

We also attempted to demonstrate the condition where the elbow of the crewmember is not aligned with the expected elbow of the sleeve. This happens more frequently than officially reported (based on personal communications). Since the misalignment increases torque and the sleeve is semi rigid at a delta P of 4.3 psid, crewmembers will frequently “reach around” the “rigid” elbow to manipulate the lower arm. This is especially true of females who normally have a smaller arm diameter than the one size arm sleeve which fits 3 sigma males. In the model in Figure 51, the rotational point was offset by 3 inches (worst case). As shown in Figure 52, this significantly increased the bending torque from approximately 2 Nm at 90 degrees to 15 Nm.

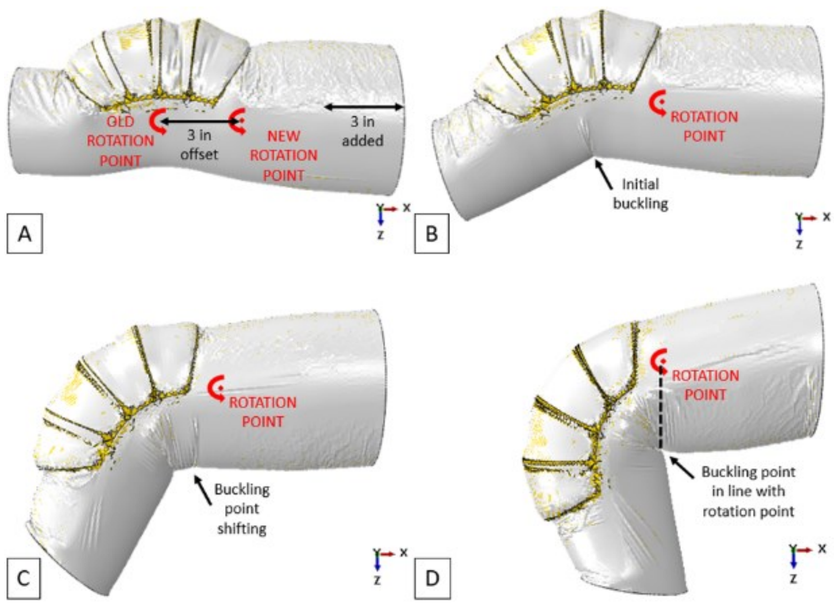


Fig. 51: A – D: progressive torque required to bend the sleeve assuming a 3-inch offset between the subject’s elbow and the designed sleeve elbow in the middle of the gores

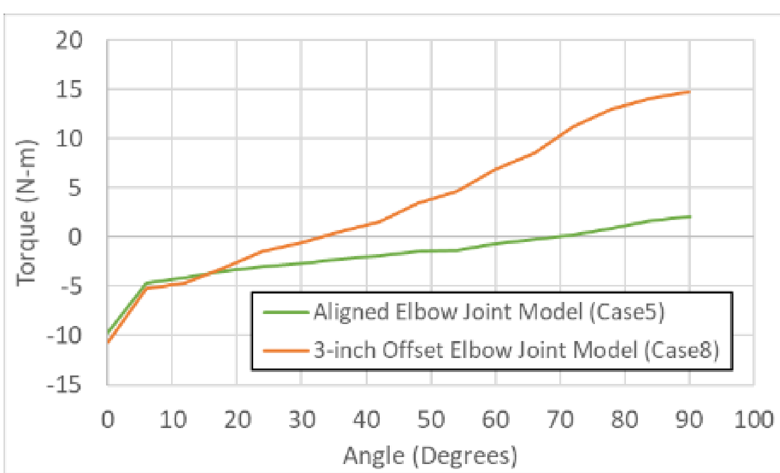


Fig. 52. Elbow Torque as a function of 3-inch offset between crewmember elbow and intended elbow of the EVA EMU Size 04 suit sleeve.

CONCLUSION: Intermediate parametric FEA study results demonstrate that it is **feasible** to explore EVA pressurized suit soft good performance with the Virtual Twin ABAQUS FEA model developed in the AHSL Laboratory at TAMU and that these can be customized to digital human scans. The maturation of this technology beyond TRL 3-4 will require increased supporting computational capabilities and future integration with new Digital Human Models (DHM) which model soft tissue behaviors.

8.2.3 Empirical Validation of FEA Model:

In order to test the FEA model, our lab is designing an experimental test tool as part of a student's Master of Science Thesis: RAESTAC: *Robotic Arm Experiment for Evaluating Spacesuit Torque and Contact* .(Figure 53) The fabric materials properties used in the FEA model are the same fabrics as used in the test sleeve. The pattern measurements were taken from an EMU excess sleeve acquired by our laboratory from NASA Excess property. The PLA arm is a print from one of our graduate students scanned with the 3dMD Photogrammetric scanner. The torque is supplied by a motor and measured by load cells instrumented into the arm. All controls and data collection are via a connected lap top computer. Although the sleeve is an idealized model of the current bladder and restraint layer assembly, we believe that iteration of model and testing, along with the incorporation of test sleeves supplied by industry will allow us to take this to TRL 3 in the future. RAESTAC has completed CDR and is proposed for a Phase II follow on study.

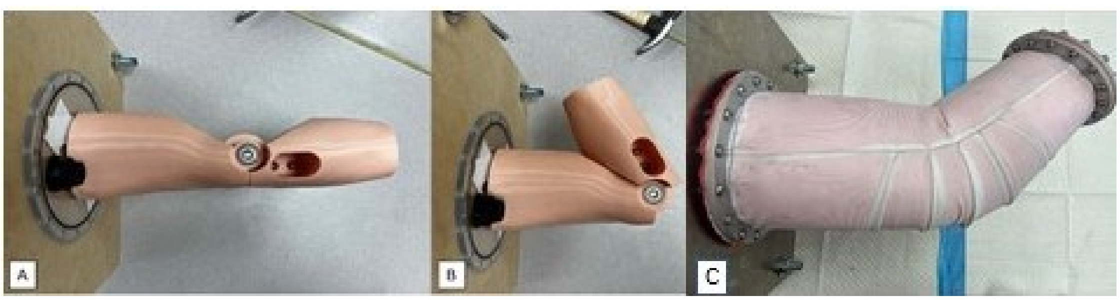


Fig. 53: RAESTAC Empirical Torque Tester: (A) PLA 3D printed arm scanned from 3dMD Scan with internal instruments, pulleys and load cells, (B) Elbow deflected by pulleys and (3) Pressure bladder/restraint layer mounted to the inner mounting plate and wrist end cap and pressurized to 4.3 PSID

8.3 Feasibility for the application of 3D printing/knitting to soft fabrics and pressure bladders – Moonprint Solutions LLC

In addition to adding the Virtual Twin to the DT, we were particularly interested in the following continued and combined technology developments: (1) Exploration of 3D technology for printing polymer pressure bladders from Moonprint Solutions and (2) a feasibility assessment with FabDesign of producing complex multi-materials with 3D knitting applicable to restraint layers. An assessment of these processes also considered the environment of Mars, and what materials would be most amenable to repair or replacement in situ.

8.3.1 The 3D/AM Printed Polymer Pressure Bladder: Overview and Notional Suit Materials

To achieve the full benefits of employing the Digital Thread and supporting digital technologies in space suit design and manufacture, we began by assessing the processes and equipment used to manufacture EVA space suits. If prior prototypes are considered in addition to the A7LB and the EMU, there are two basic families of EVA space suits; Those primarily composed of multi-layered soft goods materials (fabrics, coated fabrics, and films with some rigid elements such as bearings), and rigid components (composite or machined metal). The Shuttle/Station EMU is an example of a hybrid consisting of a rigid upper torso, numerous metal bearings, with most of the rest of the suit being soft goods. This suit has been manufactured by ILC Dover under contract to Collins Aerospace (formerly UTC Hamilton Sundstrand) since the onset of the space shuttle program in the early 1980s. Many of the technologies, components, and manufacturing processes used today **are similar if not identical to when the suit was first qualified for service more than 40 years ago.**

Historically, ILC Dover has developed several variant suits over the years in support of different exploration programs (SEI, Constellation, Artemis, etc.), including the I-Suit, MK-III, CSSS, and Astro). These suits are all fabricated from standard sized components of various sizes which were intended to be configured to fit the crew. This approach was selected because it was envisioned to be a low-cost way of fitting a wide range of anthropomorphic sizes and numbers of crew anticipated during the Shuttle and ISS programs. Unfortunately, as discussed previously in this report, several negative impacts of this architectural approach have been observed over the life of the program including difficulty in achieving optimal fit of some crewmembers, shoulder injuries, and performance degradation due to fit issues.

The majority of the soft suit components have been standardized in design and manufacturing practices. For example, the lower arm (elbow) is very similar in configuration to the knee, and the bearings are all somewhat similar in configuration. Aside from fit and mobility, the components of the ISS EMU and related suits are well designed to meet an extensive list of environmental and operational requirements. Over the last 40 years, these suits have been manufactured with a wide range of processes and complex equipment, by highly trained operators.

A breakdown of some of the materials and processes by Space Suit Assembly, SSA, subcomponent are shown in Table X. Additional information regarding use on Mars is offered to contextualize the data with respect to the application of DT technologies. Red and green shading are used to highlight elements that are particularly challenging or unfavorable.

Table X: EMU Materials as a function of manufacturing processes and suitability for Mars

Sub-component	Material	Processes	Equipment	Op. Skill	Tolerance	Probability of Degradation on Mars*	Life Limit	Level of Reusability
International Space Station SSA (part of the EMU) - Lower Arm / Upper Arm / Leg								
Bladder	Urethane coated Nylon	Weaving, Coating, Cutting, Thermoforming, Thermal welding, RF welding	Fabric loom, coating machine, thermoform machine, heat seal, RF heatseal	Very High	Low	Very High - Degrades with cycles, O2 & rad	8 yr shelf	Poor - Limited Life - Could the TP be melted and used as AM stock? Fiber reinf issue?
Restraint	Polyester Fabric & Thread	Weaving, cutting, sewing, hot-knife	hot knife, fabric loom, sewing machine	Very High	Low	Moderate - Degrades with O2 & rad	8 yr shelf (can extend)	Moderate - Can reuse until polyester cross-links
Restraint Lines	Polyester Webbings	Weaving, cutting, sewing, hot-knife	hot knife, fabric loom, sewing machine	High	Moderate	Moderate - Degrades with O2 & rad	8 yr shelf (can extend)	Moderate - Can reuse until polyester cross-links
Clamping Rings	Anodized AL	Machining, Anodizing	CNC mill, acid electrolyte bath	Very High	Moderate	Low	Indefinite (30 yr)	Very High
O-rings	Silicone	Injection mold	injection molding machine, molds	Very High	Very High	Moderate (creep)	8 yr shelf	Poor - Limited Life
Lubricant	Grease	Hand application	dispenser	Low	Low	High	2 yr?	Poor - Limited Life
Sizing Brackets	SS	Machining	CNC mill	Very High	Very High	Low	Indefinite (30 yr)	Very High
TMG	Multiple woven fabrics, aluminized mylar, and coated fabrics	Weaving, cutting, sewing, hot-knife, casting	hot knife, fabric loom, sewing machine, hot knife, thermal press	Very High	High	Moderate - Degrades with wear and exposure	8 yr shelf (can extend)	Moderate - Can reuse some layers until worn through.
Arm Bearing, Leg Bearing, Waist bearing, shoulder Bearing								
Races	AL	Machining, precision finishing		Very High	Very High	Moderate	Indefinite (30 yr)	Very High
Lip Seals	TPU	Casting	molds	High	Very High	High	8 ys shelf	Poor - Limited Life
Ball Bearings	SS	cutting, press, precision finishing hardening	press, specialized grinder, furnace	Very High	Very High	Moderate	Indefinite (30 yr)	Very High
Screws	SS	cutting, Machining, hardening	mill, grinder, furnace	Very High	High	Low	Indefinite (30 yr)	Very High
Lubricant	Oil	Injection	dispenser	Low	Low	High	2 yr?	Poor - Limited Life

Analysis of the processes currently used to produce EVA space suits indicates that fabrication of spares or repair of damaged components away from earth will be challenging if not impossible with the processes used to manufacture the current suit. Limiting spares when going to the surface of Mars (or other exploration/habitation locations) is critical because of logistical and cost impacts associated with launch, storage, and the number of different sized spares required. Therefore, these issues, in conjunction with the limitations experienced with the ISS EMU and related suit types, lead to a paradigm shift in future space suit configuration approach and design that emphasize digital technologies. In other words, we will need to redesign the space suit to facilitate processes of the future if we are to minimize cost and optimize performance of future exploration and habitation activities. Making a paradigm shift around the benefits of existing digital technologies in the DT, as well as those that will evolve by the time we establish habitation on Mars, will lead to significant mission cost and crew performance advancements.

In order to address first order low TRL investments considered in this study, a **notional** space suit concept was developed to assess the feasibility and potential benefits of redesigning the suit to leverage DT technologies and information thread components (Figure 54). This approach establishes a new paradigm in spacesuit design and manufacture that facilitates the rapid fabrication of inexpensive mass customized or customizable Extra-Vehicular Activity (EVA) space suits to perfectly fit any wearer for optimal performance. This approach also provides a foundation for objective and requirements driven trade studies between the A7LB and EMU, for example one-piece vs multiple components; zipper closures vs quick disconnect joints, the need for self-donning, vs IVA assistance, etc.

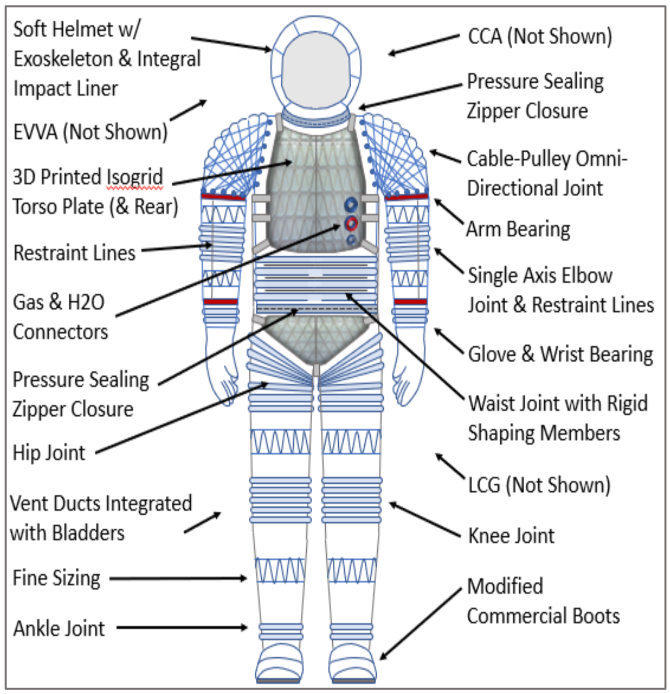


Figure 54 – Notional Low-cost mass customizable EVA suit architecture baseline

Newly developed manufacturing techniques for seamless components and the use Additive Manufacturing (AM) could be employed to reduce production time on earth, and facilitate manufacture off earth. Improved constant volume space suit mobility joints could build-off of Apollo A7LB geometry for excellent mobility and low torque. Structural elements could be designed that force the pressurized volume to match the human form while reducing suit weight and increase mobility. This is important because inflated components always take the shape of a cylinder or sphere. Collectively this digitally driven approach will dramatically reduce cost, shorten schedules, increase performance and comfort on EVA by enhancing fit, and reducing stress in the torso pressure envelope (gas containing bladder & structural restraint) for improved safety. The DT driven process could leverage proven technologies and manufacturing methods from the Phase VI EVA custom glove fabrication process currently used in support of ISS, and techniques used by the high-tech apparel industry to synthesize a rapid and inexpensive customization process.

As noted in the development of the *Virtual Twin*, the process should include 3D scanning the human form, extracting critical anthropometric data, using algorithms to automatically create custom Computer Aided Design (CAD) components / forms / patterns, and fabricating those items using Additive Manufacturing (AM) and other rapid processes. Coupled with the development of Virtual Twins, the manufacturing process would proceed from 3D human digital scans as shown in Figure 55

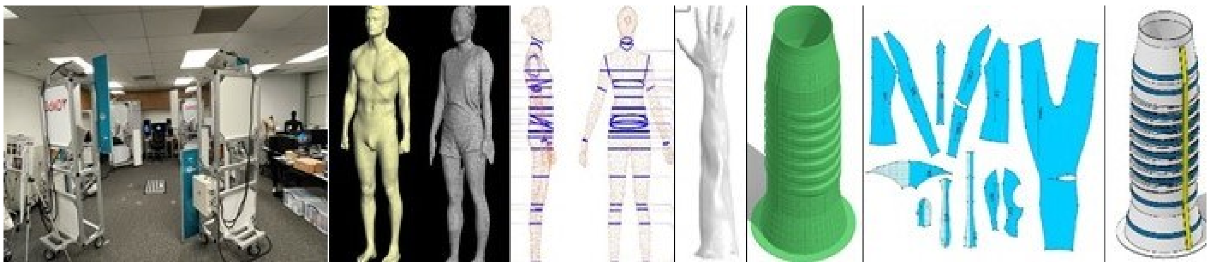


Fig. 55 - The customization process could move quickly from body scans (the 3dMD shown), to critical dimension identification, extraction of scanned body parts (such as the arm), automated pattern & part model generation, AM fabrication (bladders/molds), to integration with restraint system.

Such a process has been implemented by Moonprint Solutions LLC for a 3D printed Helmet/Chest Plate. (Figure 56).

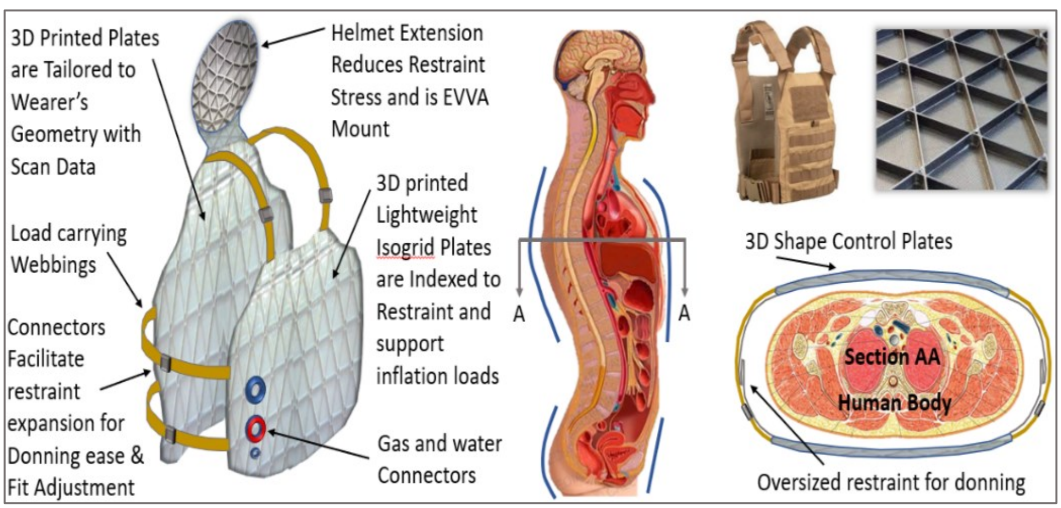


Figure 56– 3D printed isogrid plates form the inflatable to the body's shape; credit Moonprint Solutions, LLC

New manufacturing processes could be developed that reduce touch labor and will not require the level of manufacturing skill needed for current suit manufacture, therefore reducing labor costs and facilitating production off-planet. Because different missions will have unique EVA requirements / plans, an open architecture should be developed that can be adapted to mission preferences as they are established (IVA/EVA or EVA only suit, high-performance or tourist suit, customized or standard components, etc.).

The ability to use AM and new joint manufacturing techniques opens new avenues in design because it removes the limitations of current manufacturing practices. We could manufacture convolutes in any shape desirable and not be limited by heat-seal head sizes or dipping constraints. Functions can be built into AM parts to reduce part count such as bladders with integrated comfort pads, vent tubes & impact attenuation). To reduce fabrication and system level risks, the suit must be designed to match the manufacturing technologies capabilities to extract their benefits. The main features being pursued in the new SSA are outlined in Table XI, along with the ROI and associated technical approaches.

TABLE:XI Features and Benefits of a Digitally Driven SSA Design

New SSA Feature	Benefit (ROI) in Relation to EVA Suit	Technical Approach
Mass Customizable, rapidly manufactured EVA suit components	● Anthropometric inclusion – everyone can fly ● Reduced mission & schedule cost ● Fit = comfort = lower torque/fatigue = lower mass = performance ● Easily adaptable to multiple EVA Platforms	● AM technologies ● 3D Scanning and algorithmic modeling ● Simplify fabrication & assembly techniques
Removable / reusable high-cost components	● Reduced cost of each suit ● Built-in spares for other suits	● Component integration design ● Modular & scalable approach
Automated Suit patterning and AM file generation	● Opens design space (unconstrained by mfg. processes) ● Seamless components reduce touch labor & the need for highly skilled assemblers ● Off-world reproducibility with minimal equipment	● 3D Scanning of suit subjects ● Extract critical anthropometric data with standardized algorithms ● Develop method to automatically generate AM files and patterns
Constant Volume convolute-based soft mobility joints (single axis & omni-directional) with webbing Exoskeleton that offloads restraint fabric hoop stresses	● Low joint torque with excellent ROM and outstanding comfort ● Eliminate injuries (shoulder) ● Integrated AM ripstops and abrasion layers for durability ● Improved safety via reduced stresses & seams in restraint & bladder (eliminates tear propagation potential & leak paths) ● Redundant load paths for safety	● Advance technology from Apollo to USAF AHAFS to a new state-of-the-art soft joint ● AM build approach to demonstrate simplified assembly
Custom AM rigid plates for torso & brief shape control, generated from 3D scan data	● Dramatically improved fit / comfort & increased impact protection ● Improved aesthetics (commercial benefit) ● Easy & lightweight for donning & doffing	● Rigid AM Technology ● Design and Modelling for Stress ● AM Prototypes built ● Physical & fit evaluation
Eliminate Hardware used on EMU SSA (HUT, scye bearing, waist bearing, etc.)	● Simplify manufacture & ability to replace ● Elimination of mass (30-40%) for up/down mass cost reduction ● Elimination of failure points	● Replace function with new soft constant volume joints & Rigid torso & brief plates

8.3.2 Feasibility of 3D/AM Pressure Bladder – Results of Phase I: In order to demonstrate the feasibility of applying AM to an arm pressure bladder, a single-axis Constant Volume (CV) lower arm design and CAD model was developed by Moonprint Solutions (Figure 57). A lower arm was designed that had an AM bladder assembly (unsupported film) and a 3D woven restraint that function in tandem. Normally bladders are reinforced with textiles to increase tear strength, but this is not currently possible with AM. However, advances are being made on machines that can print multiple combined materials at fine resolution, so structural reinforcement will be possible in the future. In order to enhance safety with the unreinforced bladder a ripstop was added, and the bladder with designed to be oversized compared to the restraint (and therefore unstressed when pressurized). The lower arm model was generated and component fabricated using Selective Laser Sintering (SLS) to prove feasibility of the approach. **The component was successfully manufactured demonstrating a path to AM component fabrication.**

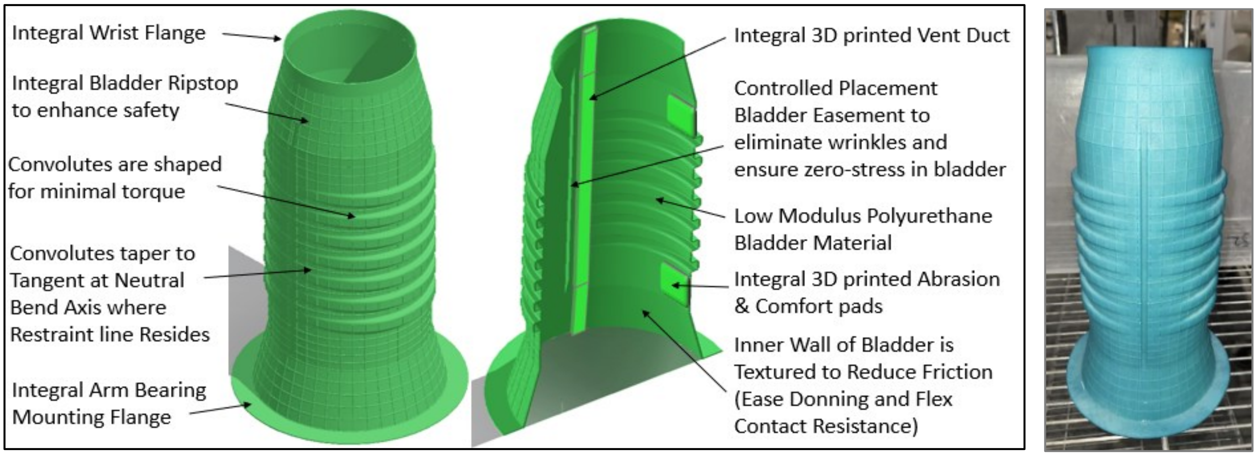


Figure 57 – Customizable AM Lower Arm Bladder CAD Drawing and Fabricated Component (credit Moonprint Solutions)

One finding of note was that the Thermoplastic Polyurethane (TPU) materials currently available for thin-walled component fabrication will not be sufficient to meet EVA suit requirements and match performance of existing urethane coated nylon fabric approaches. Advancements in materials and thin-walled processing techniques to match architecture needs can be made with minor investments. Many flexible elastic AM fabricated components are being manufactured today (Figure 58). These components are manufactured from TPU and demonstrate that highly flexible customized components can be manufactured.

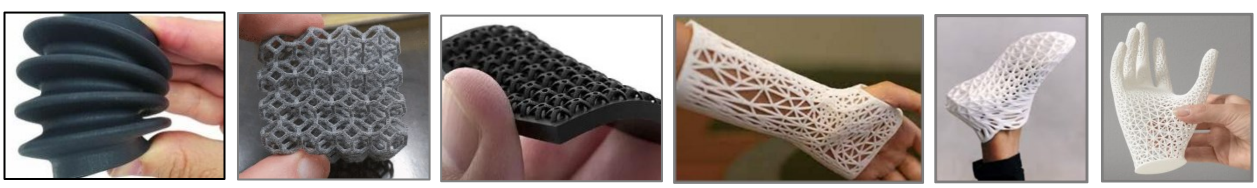


Figure 58– New Seamless bladder design, Polyurethane AM Bladder, and examples of elastomeric AM components

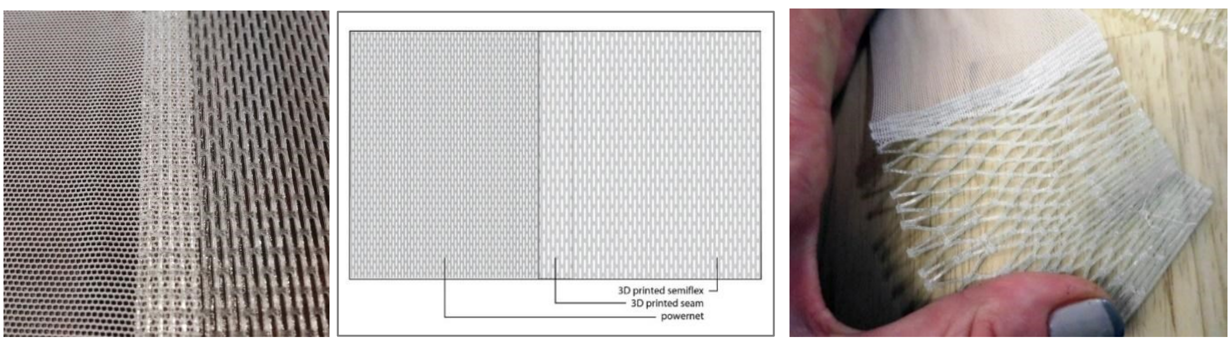
AM can be used to add internal features such as texturing for donning ease and comfort enhancement via sliding friction reduction, localized abrasion protection and localized impact protection. Other features can be studied to take advantage of AM's capabilities including designing LCVG components into integral vent tubes that are positioned strategically for optimal comfort and cost reduction, and impact protection pads (comfort and attenuation as required in the helmet or shoulder areas).

Space suit restraints are typically manufactured by sewing flat patterned parts into 3D shapes. This will be possible in space or on planetary surfaces, but will be time consuming for the crew and will require training and skill. A near-term step towards AM restraint fabrication is 3D weaving, which could be investigated in Phase II. This process can be used to fabricate some highly complex parts of variable geometries, multiple materials, and variable thicknesses.

Unfortunately, the equipment required for manufacturing 3D woven parts is large, complex, and requires significant skill to operate and maintain. Therefore, a more probable distant future path will be to manufacture restraints using AM. The state of the art is currently being expanded through the manufacture of printed 2D textiles in a wide variety of weave styles using both inelastic fibers and elastic fibers (Figure 59).

https://3dprintingindustry.com/news/the-mit-scientists-making-3d-printed-fabrics-as-soft-as-skin-157609/

https://www.fabbaloo.com/2020/07/major-development-in-3d-printed-fabric



https://www.instructables.com/3D-Printed-Stretch-Fabric-Seams/

Figure 59– Various Weave Styles Using Inelastic Fibers (Top) and Elastic Fibers with Seams (Bottom)

Many developers are printing 2D textiles which can be used in the construction of clothing in the fashion industry. 3D woven components are not yet being manufactured, but the rate of development suggests that they will be soon. When this is achieved, AM can not only be used to produce bladders but also restraints with integral restraint lines, structural enhancements, and no seams to reduce failure points.

Considering AM capabilities of the future opens new capabilities that are an important part of the Digital Thread. AM capabilities will advance over time to improve manufacturing tolerances, resolution, facilitate integration of multiple materials in single part, etc. Methods to use AM fabrics in space suits of the future include:

- Altering strength as required to minimize mass and increase safety – ripstops, restraint lines, abrasion patches, etc.
- Adding local features for sizing, closures, indexing, integration – zippers, attachment loops, snaps, indexing tabs, etc.

- Producing any weave style required to facilitate stretch or maintain geometry while under load – square, unbalanced, stretch, etc.

This information leads us to consider a 3D printable custom space suit that can be produced inexpensively here on earth, or with minimal equipment when on Mars or other location off earth. AM technology development is progressing at a rapid pace with a wide range of inexpensive but highly-capable machines now commercially available. A small sampling of the AM machines available can be seen in Figure 60.

Figure 60 – Commercially Available AM machines

All of these machines used standard spools of feed stock, and most are capable of printing multiple types of material. Some very general information on these machines shown can be found below:

5AXISMAKER 5XM600XL
- Versatile 3D printer, can be used as a milling machine as well
- Tabletop machine with moderate build space

Intamsys Funmat Pro 610 HT
- Dual Extruders
- High temperature nozzle, can print metals, ceramics, woods, and high-performance thermoplastics (ex. PEEK, PEKK, ULTEM, etc.)
- Large build space (610 x 508 x 508mm)

Creality Ender 3 S1 Pro
- Moderate build space
- Can print a good number of thermoplastics, including TPU and even wood due to the high nozzle temperature (max 300 degrees Celsius)

Dynamism Ultimaker S5
- 20-micron layer resolution
- Dual extrusion
- Capable of printing many different materials

Stratasys F370CR

8.3.2 Feasibility Study for 3D Knitting Applications:

A possible future step towards AM restraint, TMG, or even the LCVG fabrication, is 3D weaving during initial manufacturing. This process could be used to fabricate some highly complex parts of variable geometries, multiple materials, and variable thicknesses. We toured and met with the company and the they are part of our Phase II proposal. Fab Designs is a leading technology company for 3D knitting, a process that could revolutionize manufacture of the spacesuit soft components such as restraint layers and even the LCVG. Similar to many automated 3D manufacturing processes, it also allows sensors to be imbedded and dissimilar materials to be integrated. Fig. 61 illustrates examples of 3D knitting to shape and performance. Fab Designs has over 35 years of experience in advanced textile engineering, design, development, and

Fig. 61: Designs from FabDesign using 3D knitting to design compression garments with up to X different fibers from polymers to ceramics to metals. Company fabricates to custom patterns and scans

manufacturing of 2D, 3D, 4D and 5D textiles, specialized apparel, medical devices, aerospace projects, automotive, advanced footwear, and other products. The company pioneered "3D integrated Knit Technology", which is a modern innovative textile manufacturing format that uses knitting as additive manufacturing and advanced materials engineering. (https://fabdesigns.com)

8.4 Feasibility for Digital Human Modeling in EVA Suit Design – Purdue University

8.4.1 Summary Conclusions for integrating DHM into the Digital Thread: Commercially available digital human models (DHM) are used to provide support for ergonomic analysis in digital mockups. These can also provide support for sizing in relation to product design and occupant packaging and these can reduce the need for prototyping. The commercially available digital human models are available from various providers.

However, there are limitations to current models when applied to EVA suits. For example, clothing modules and ergonomic analysis tools tend to remain independent. Where clothing can be added to manikins, it is not typically possible to perform ergonomic analysis of forces created by task elements and the clothing is not pressurized. For example, where a manikin may be positioned according to task requirements, external loading can be analyzed. However, the internal stresses, for example, of elbow or shoulder against the suit or clothing cannot be calculated through the commercially available software. Where adding a suit to manikin may be possible, the method is not typically known to most users. Though a manikin typically appears to have clothing as covering, adding any protective equipment such as space suit or other, remains a function (adding a layer over the manikin) that would usually be done by the developer of the DHM software rather than an engineering analyst.

Following a remote Zoom panel discussion with the DT Team (Dr. Bonnie Dunbar, Dr. Nancy Currie-Gregg, Mr. Dave Cadogan and Dr. Dillon Hall), students completed an analysis of ergonomic aspects of a picking task from a space rover in Mars environment. The panel held during IE578 Applied Ergonomics discussed current issues related to space suit design. Ability to be able to adapt to a variety of anthropometrics was emphasized. Students followed a six-step approach to learning the DHM software and assessing capabilities and limitations. In terms of workforce development, the students in the class learned more about the space-related design issues than they previously knew. They remain hugely enthusiastic about the subject following completion of the course.

8.4.2 DHM - Integration of Spacesuits and EVA – Results of Phase I. Space exploration and the design of spacesuits has captured the imagination of the public, including students, for decades. The Spacesuit Digital Thread team integrated this project into respective undergraduate and graduate classes taught at Texas A&M University and Purdue University. The Purdue course focused on DHM under Dr. Vincent Duffy. Four of the student project reports are included in Attachment 1.

1) Bag, Akanksha, Ahmed, Naufel Mehmood Basheer and Dahal, Utsav, 2022. Simulation in Space Ergonomics: A Systematic Review, project report in Prof. Duffy's IE578 Applied Ergonomics course, completed Nov. 2022 following panel discussion about NIAC phase I project, pp.1-14.

2) Chaudhry, Hassan and Zhang, Andy, Simulation Software in Space Applications, 2022. project report in Prof. Duffy's IE578 Applied Ergonomics course, completed Nov. 2022 following panel discussion about NIAC phase I project, pp.1-20.

3) Islam, Md Tariqul, Sepanloo, Kamelia and Valluvakkandy, Ronak, 2022. Modeling digital human measurements for space environment, project report in Prof. Duffy's IE578 Applied Ergonomics course, completed Nov. 2022 following panel discussion about NIAC phase I project, pp.1-17.

4) Jin, Kevin, Richards, Mackenzie, Lee, Kevin, 2022. Application of Ramsis Digital Human Modeling to Space Human Factors, project report in Prof. Duffy's IE578 Applied Ergonomics course, completed Nov. 2022 following panel discussion about NIAC phase I project, pp.1-15

In the first course, there were 60 students that participated in the course. In Spring 2023, the two courses (IE556 Job Design and IE558 Safety Engineering) were filled to capacity. Including two online sections, the total number of students participating in these courses in Spring 2023 is 182. 86% of the 60 students were graduate students in Fall 2022 and 95% of the 182 students are graduate students in the Spring 2023 semester. Majors in Fall 2022 included Industrial Engineering, Mechanical Engineering, Engineering Management and Aviation Technology. Approximately one-third of the class was female.

8.5 Summary of Findings and Recommendations:

Finding 1: Many elements of DT architectures can be transitioned to EVA suit design, test, and production at a high TRL, with the exception of the following low TRL technologies, which appear feasible based on research conducted in this Phase I study, but must be further explored:

(1) *Virtual Twin* (VT) modelling of scanned subject in custom pressure garment assembly
(2) Use of 3D/AM printing for pressure bladders,
(3) Use of 3D knitting to produce Pressure Bladder Restraints, Garments, and
(4) Digital Human Modeling with custom human avatars in custom pressurized suits and soft tissue modeling.

Finding 2: Manufacturing of hard components such as umbilical connectors, wrist and neck rings, and helmets lend themselves to proceeding from CAD file to 3D/AM printing by robotic assembly, but the assembly of multi-layered soft fabric goods are still largely assembled by hand, although robotic textile assembly is rapidly progressing.

Finding 3: The TAMU AHSL was the first to explore a "Virtual Twin" model with FEA for an EVA suit arm using two pressurized layers: Pressure Bladder and Restraint Layer. The resulting parametric data is closely aligned with the literature, but must still be tested empirically. This promises to be an innovative DT tool – for assessing crew performance and fit prior to manufacturing an EVA suit

Finding 4: As demonstrated by Moonprint Solutions LLC, the use of 3D/AM for manufacturing pressure bladders appears to be promising and should be pursued to a prototype which can be analyzed using the VT in Finding 3.

Finding 5: While DHM tools are not capable of modeling humans in pressurized garments at the present time and are proprietary commercial "avatar" focused tools, NASA should engage vendor companies in new developments. This was evaluated with graduate student teams at Purdue University.

Finding 6: Implementation of a DT is a unique opportunity to engage with the two new companies developing EVA suits under the xEVAS contract, Collins Aerospace and Axiom Space, in order to benchmark or implement DT processes in preparation for a Mars EVA suit production in the 2030s.

Finding 7; EVA suits and operations are attractive topics for today's students and there is workforce demand for this expertise from legacy and emerging Aerospace companies. Drs. Dunbar, Duffy, and Currie-Gregg all teach courses which address EVA design, environments, and operations. This could be the topic of a NASA sponsored text book.

9. 0 RESULTS OF TASK 4: INTEGRATE THE MARS CONOPS AND DESIGN REFERENCE MISSIONS TO ASSESS EVA SUIT REPAIR, LOGISTICAL RESUPPLY AND MATERIAL REPURPOSING INTO THE DT ARCHITECTECTURE.

The Exploration architectures for Mars – long distance, infrequent resupply, long delivery times, and communication latency - require that we integrate the EVA supply and logistics architectures, which will differ significantly from our LEO and future Lunar experience base with the EVA suit design. It also requires us to rethink the design and manufacture of the EVA suit prior to the Mars Mission with these variables considered.

With EVA intensive missions, even with the shorter SAC 21 30-day scenario, suits are exposed to dust, mechanism failures, electrical failures, and possible suit material failures. During the Apollo program, the A7LB was a robust well-fitting customized suit. During its entire operational lifetime, it experienced no failures during missions. But the EVA time in each suit was limited compared to proposed EVA architectures, and the Earth was only about 3 days away in an emergency.

In the prior results section we found that it was feasible to use the DT to customize EVA suits and to optimize the design through Virtual Twin modeling prior to manufacture. It is also determined to be feasible to manufacture component parts on the Earth with digital technologies such as 3D printing/AM which can be purposely designed to provide Mars In Situ repair and replacement. It is with this in mind that we provide the following conclusions and findings:

9.1 Summary of Findings:

Finding 1: Simplification of EVA suit design and use of purposely selected materials, along with the provision of 3D/AM printing equipment on the pre-deployed supply missions, minimize resupply and optimize in situ repair capabilities.

Finding 2: Mars EVA suits are likely to have pressurized fabric and bladder components which are subject to damage and wear. A Mars habitat or laboratory should consider the following in its IFM (In flight Maintenance) inventory:

1) 3D Printing/AM equipment for replacing bladders and hard components
2) Dependent upon the ability to minimize mass, a 3D knitting machine
3) A Sewing Machine
4) Methods for heat sealing polymer fabrics
5) A Digital Thread Data file (on a flash drive) for each crewmember’s suit with drawings and procedures for repair and manufacturing

Finding 3: When considering soft fabric packing materials for items at launch and resupply, consider using materials which can be repurposed for EVA suits or other garments, similar to the soft fabrics used for current payload packaging (light, fire retardant, etc.,) With a multi-layer approach using Mylar, and new 3D knitting processes, the packing could be optimized and repurposed once on the surface of Mars.

10.0 Results of TASK 5: ASSESS A PRELIMINARY DT ARCHITECTURE WHICH COULD SUPPORT THE DIGITAL THREAD MANUFACTURE OF FUTURE EVA SPACESUITS

10.1 Key Recommendations and Investments for the Architecture:

This proposal sought to investigate the feasibility of manufacturing "custom" cost-effective high-performance exploration spacesuits for Mars and beyond utilizing the Digital Thread (DT), which integrates digital analytic components for manufacturing in development of the final Spacesuit. The vision is a "digital human scan to digital design/analyses to robotic manufacture" while integrating the entire life cycle of the EVA suit, including all documentation, testing and planetary performance into a digital thread. A full **Digital Thread** has never been applied to EVA suit manufacturing, but this study is the first step in realizing that vision, part of the newly evolving Digital Engineering (DE) landscape in Aerospace

The study has identified key components of a spacesuit and current manufacturing technologies; mapped those to DT elements; identified technology gaps; benchmarked required technologies and has developed a conceptional DT model for future Spacesuit Development and operational support. The technologies to manufacture a suit on the Earth and to possibly repair in situ on Mars have been identified. Some manufacturing elements shown in the DT of Figure 8 are currently high TRL, but those we explored in detail are low TRL technologies which are critical to successful DT implementation. These provide the opportunity for additional investment in order to enable the vision of rapidly manufacturing customized exploration EVA suits.

The specific goal of this study was to insert the digital crew member into a digital suit to reliably predict (and minimize) forces and torques to operate the suit and with minimal manufacturing time and cost. We focused on the EVA suit sleeve with the elbow as being the most important EMU component for optimizing mobility and with a known design. Preliminary research data is provided in this report specifically for EVA suit virtual twins and additive manufacturing for a pressure garment. The use of Digital Human Modelling and 3D Knitting are also explored.

This approach addressed several problems facing deep space travel, in particular:

1) The ability to rapidly design and manufacture Extravehicular Activity (EVA) space suits which are best suited to the anthropometrics of the individual crewmember (male and female) in any gravitational environment;

2) The need to build digital twins which are continually modified based on lessons learned and design optimization

3) The ability for crew in deep space to manufacture or repair some EVA suit components in-situ based on digital files and available repurposed materials (such as that used for stowage packing)

4) The ability to digitally incorporate the EVA suit into the entire Mars Mission DT Architecture and Concept of Operations, including spacecraft and habitat design, and logistical resupply.

Specific Near-Term Recommendations required for this new DT pathway follow:

1) For the new xEVAS contractors, recommend the implementation of a DT system (tools and software communication) for benchmarking and for developing a "Lessons Learned" data base which can be implemented for the Mars EVA suit.

2) Include in the new DT architecture an institutional memory base – from Apollo through ISS. This would include materials, manufacturing processes, failures, crew comments, fit problems, injuries, etc., This may require a workshop similar to what was conducted for the Apollo crewmembers, but including engineers and managers with institutional memory.

3) Consider custom suits at the outset, but with a trade space for optimization of certain components. For example, during Apollo it was considered more important to customize the A7LB torso to each crew member in order to optimize operations and mobility, but the EMU was designed with a limited modular chest and waist ring sizes. The disadvantages of this approach have been discussed in this report – including impacts on mobility, metabolic endurance, comfort and injuries. The EVA suit is critical to mission success and safety. On the other hand, oxygen umbilicals and their connectors are likely to be standard for each suit so trades studies should address what may be common and what may require customization using the new DT digital tools now available.

4) VIRTUAL TWINs: after a digital scan is acquired, and an initial soft fabric multi-layered system is designed, evaluate mobility and fit of the design with the crewmember through digital iterations prior to manufacturing the suit. If there are later iterations, keep records so that the model can be refined. Apply this strategy to any study which suggests increasing the EVA suit pressure beyond 4.2 PSID. A notional process for developing the VT is shown in Figure 62 and has been proposed for Phase II.

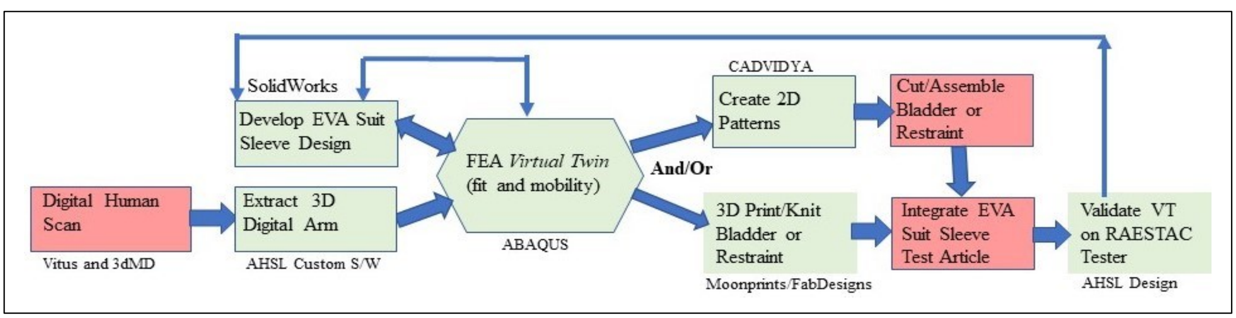


Fig. 62 A conceptual Virtual Twin Development for Pressurized multi-layer EVA lower arm suit sleeve.

5) Digital Twins: Following the design, development and manufacture of each suit, develop a Digital Twin for that suit. This Twin would include records of failures and later fit problems. It can also be used to optimize the Virtual Twin through an integrated DT feedback process. A copy of the Digital Twin for each assigned crewmember should be placed on board a Mars Exploration Vehicle. Just as the medical records for each crewmember may included into the Smart Virtual medical systems on-board, so should all available information for their suits be available in the event there is no consultation available with earth-based control centers.

6) Work with the commercial developers of Digital Human Models (DHM) to optimize their tools for EVA interfaces and pressurized garments in those interfaces (e.g. seats, rovers, habitats, etc.) Develop the capability to migrate digital human scans into the avatar models.

7) Develop 3D Printing/Additive Manufacturing and 3D knitting for EVA components.

8) Collaborate with the Textile and Clothing Industries for robotic assembly of garments

10.2 Proposal Task Summary for a Phase II effort.

The findings and recommendations identified in Phase I, were used to develop and organize our thoughts for a Phase II study. The tasks summarized in Table XII are proposed for a Phase II effort and would continue the work of Phase I in order to achieve at least a TRL 3 for the VT and 3D printed pressure bladder. There is also the potential for an on-ramp to an xEVAS contractor, Collins Aerospace, which has expressed an interest in collaborating with us in our DT research. Collins Aerospace approached us during Phase I to explore the possibility of collaborating on Digital Thread deployment while they manufacture the EMU optimization for ISS. They are also investing in future technologies to posture themselves for planetary exploration. The collaboration with Collins Aerospace will be to exchange information on DT: gaps, challenges, and opportunities. The opportunity to collaborate with Collins Aerospace, one of the xEVAS contract recipients, who are investing in DT and future EVA suit technologies is an excellent off ramp opportunity. Current discussions include developing a Master Research Agreement (MRA) between TAMU and Collins to benchmark the implementation of DT and for low TRL high risk technology development complementary to that proposed in Phase II.

Table XII: Proposed Future Research Objectives Evolved from Phase I Findings and Research

	Task/Research Objective	Expected Outcome
1	Continue trade studies on EVA suit DT: component materials, mass, volume, manufacturing, cost, schedules, in situ repair	More refined analyses of these mission architecture variables as a function of the Mars DRM: All
2	Advance VT FEA Model to TRL 3 for multilayer fabric Pressurized EVA suit lower Arm/Elbow EVA	Validated TRL VT Model/Proof of Concept for EVA design, development and fit/mobility using a newly designed robotic RAESTAC tester: TAMU
3	Complete Robotic Arm Tester (RAESTAC)	Required to Validate FEA models: TAMU
4	Develop a 3D Printed polymer Bladder for FEA VT model analyses and testing	Demonstration of AM polymer print pressure bladder by Moonprint Solutions
5	Continue evaluation/feasibility for DHM Solutions using scanned subjects in custom Pressurized Garments rather than avatars	Coupled with FEA, could provide a more complete design tool with final objective for predicting tissue responses and injuries – Purdue University
6	Conduct Feasibility Study for application of 3D Knitting to Restraint Layers	Feasibility may result in prototype restraint layer by FabDesigns
7	Collaboration with Collins Aerospace on DT deployment and integration of FEA modelling and technology demonstrations	Collins Aerospace will exchange data on the deployment of a variety of DT tools; will fund low TRL technology development and infuse back into Collins xEVAS contract.

11.0 Additional Recommendations for EVA Suit Related Studies

The following section evolved from discussions regarding how to optimize the EVA suit design and operations while on the surface, based on debriefings from the Apollo crews. Use of the DT strategy should include the topics of how to minimize failures due to Lunar/Martian "dust" in the design and consequently how to minimize adverse health outcomes due to Lunar/Martian regolith introduction into spacecraft and habitats. We also propose a new look at the PLSS – a one size Life Support containment for all sizes of space suits, affecting the CG of each crewmember differently, and which appears to be increasing in mass and volume, rather than decreasing, as recommended by the Apollo crewmembers. In future DT studies, the PLSS should be part of the trade studies and integrated DT manufacturing strategy and implementation. The following sections provide more context to both concepts.

11.1 Consideration of an Overgarment for Planetary Surface Dust Protection

Lunar dust is known to be considered a significant risk to EVA suits and has been a primary debrief topic of all Apollo Astronauts who walked on the surface. While the impact of Martian "surface dust" is not yet known, crewmembers should be prepared to address the potential hazards, based on the Apollo experience. Hazards include intrusion into bearings and quick disconnects, as well as to the health of the crewmember, Lunar regolith embedded itself into the EVA suit TMG and could not be removed by brushes supplied for that purpose. (personal discussion with Buzz Aldrin and provided at debriefs) The protective garment would keep potentially hazardous particulates from reaching the wearer or EVA suit bearings, zippers, or other connectors, and could be removed after each use. It could be manufactured from a smooth robust polymer which can be "cleaned" or simply discarded/repurposed for protecting external hardware from the Martian dust storms. Several "active" solutions are being explored by NASA, including the introduction of electrical fields to repel the particulates. One potential "passive" solution (developed by Moonprint Solutions - Figure 63), which would be integral to future EVA suit design, involves reusable covers for the spacesuit. It is important to consider these potential mitigation strategies early in design, rather than trying to retrofit after design is complete.

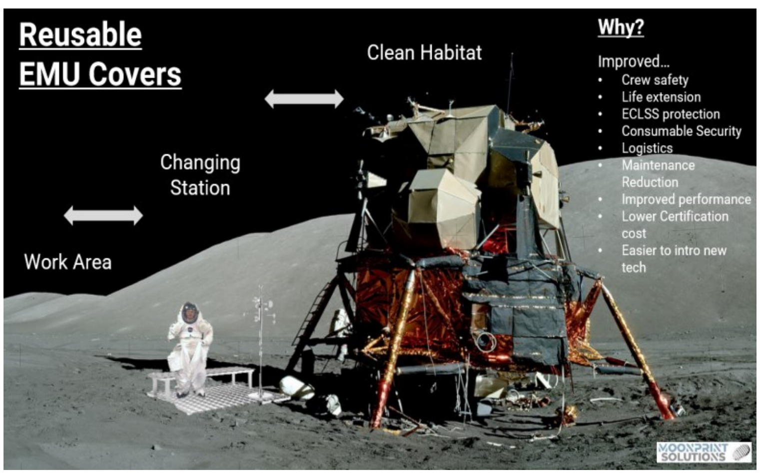


Figure 63 – Conceptual operational steps of EVA dust covers on the Lunar surface – possibly extensible to Martian surfaces. (Moonprint Solutions, LLC)

Conceptually, a passive cover could be employed during EVA, or while the suit is IVA, depending on the configuration. These covers could offer critical protection and could be generated with DT technologies so that they could also be manufactured to be easily donned with a given suit design, or assembled in-situ, if required.

This will likely require new ways of approaching materials selection and layering of the environmental protection garments for creating a barrier that completely prevents Lunar/Martian dust from compromising the EMU, and eliminates the pathway for dust to enter habitable spaces. Mock-up testing was conducted at ILC Dover in 2007 and is shown in Figure 64.

Figure 64 - Mock-up testing at ILC Dover 2007 that validated donning/doffing

During Apollo crew interviews conducted in 2010 by the NASA JSC/EC5 US Spacesuit Knowledge Capture (KC) Series, they noted the following with respect to Lunar dust. Without specific experience with Martian dust, we should consider the same concerns:

(1) Lunar dust is a "pain"
(2) Keep equipment that is exposed to dust separated from the living quarters
(3) Suits will need to be cleaned after every EVA, inside and out, particularly TMGs, bearings and suit seals

11.2 Consideration of the Design Impacts of the PLSS:

This feasibility study only considered the EVA suit, not the PLSS. However, the PLSS is both a design driver and an operational consideration when connected to the suit, and should be considered in future DT development. First of all, the PLSS is one size fits all which drives the interfaces to the small suits. For a rear-entry suit, such as the xEMU, it could impact how the upper body is designed since the entry port is "one size fits all". This would be a similar impact experienced during the small EMU development which could not impact a "one size fits all" Display and Control (DCM) on the chest. For the A7LB and the EMU, it was also one size fits all. EMU crewmembers could accommodate the mass and volume through suit interfaces, and operating in a microgravity environment, but for the smaller crewmembers, it required developing a different sense of body envelope when training in the NBL (e.g. one had to guess how much head space was required to transit through the hatch due to lack of visibility of that interface). However, it was more problematic on the surface of the Moon, since the back placed PLSS moved the Center of Gravity of the suited crewmember/PLSS combination up and aft of the body. This affected both gait as well as balance. During Apollo crew interviews conducted in 2010 by the NASA JSC/EC5 US Spacesuit Knowledge Capture (KC) Series, they noted the following with respect to both the PLSS and EVA suits:

1) Mission Design philosophy must include the total systems, EVA included, with complete seamless integration of the crew into the facilities and equipment. The equipment should be designed to fit the task, not the reverse.
2) Design strategy should be characterized by simplicity and reliability, while anticipating routine tasks
3) Suit mobility should be the driving consideration on the suit pressure.

4) **Testing since 2005 have suggested that "on the back" weight for PLSS systems is less an issue on the Moon that it will be for Mars**
5) Simplicity in suit maintenance must be a key design provision for long duration planetary missions.
6) All things considered, soft suits were favored over hard suits.
7) The Apollo PLSS was given high marks for its reliability, functionality and capabilities
8) The key to future PLSS design will be lowest possible mass and the highest possible reliability
9) Integrating the suit and the PLSS, similar to the STS EMU was considered good
10) Automate the PLSS and suit where appropriate, but do not forget the KISS principle

NASA should consider future studies on the PLSS sizing and component distribution. While the Apollo crews did not support umbilicals to rovers and habitats (although they were used on Skylab), it is apparent that an effort to simplify systems for in situ repair and reconsider the effects of mass in 3/8g and the effects of the CG distribution on individual crewmembers should start as soon as practical. These would be excellent funding opportunities to universities, both for graduate and undergraduate research opportunities.

12.0 Press and Media Outreach

Interviews:

1) Press Interview by Los Angeles Voyage Magazine, VoyageLA Magazine
2) NIAC Children's Book: Katherine M. Reilly
3) Interview with Sally McDonald, the Sun Post in Scotland
4) Interview with Rose Annis, Warner Media (Women in Space and Spacesuits) warnermedia@m.webex.com

Print:

1) Houston Chronicle, March 21, 2022

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Finding right fit for suits in space

Scan at A&M lab can fine-tune NASA gear

By Andrea Leinfelder
STAFF WRITER

Bonnie J. Dunbar had bruises on the back of her arms after wiggling into the hard upper torso of the NASA suit used for spacewalks.

And once inside, the suit never fit right. The sleeves were too big, and the suit's elbows didn't bend where her elbows bent.

Custom-made suits, like those worn by Apollo astronauts who walked on the moon, were too expensive for the space shuttle's larger astronaut corps. But Dunbar couldn't help recalling a science fiction movie in which an astronaut stepped into a full-body scanner and then walked out wearing a personalized suit.

Today, Dunbar's lab at Texas A&M University can scan a person's entire body within 1 millimeter of accuracy. And with a $175,000 NASA grant, Dunbar will study if this technology – plus other advances – could be used to scan an astronaut's body and then create an affordable, custom suit just days or weeks later.

"There's no such thing as a standard human," said Dunbar, a professor in aerospace engineering and retired NASA astronaut. "I started thinking about this 20 years ago. How do we get back to the Apollo model of custom suits that, generally, the crew was very happy with, but do it in a cost-effective matter?"

Dunbar is receiving grant money through the NASA Innovative Advanced Concepts program, which places seed investments in technologies that might benefit missions 20 or 30 years from now.

Her vision, which includes the ability to repair suits, could be particularly useful when dozens or hundreds of people are living on Mars, said Mike LaPointe, acting program executive for the NASA Innovative Advanced Concepts program office.

Mars will be a harsh environment for suits and a far-flung lo-

Suits continues on A12

SUITS

From page A1

cale for shipping replacement parts. Fit and mobility will be vitally important for the scientists who've traveled so far to study this new terrain.

"We want them out there exploring," LaPointe said. "We don't want them rehabbing in physical therapy."

Relying on layers

Suits worn for spacewalks – or working on another planet – are designed to be human-shaped spacecrafts. NASA spends roughly $125 million a year to maintain and use current spacesuits on the International Space Station.

Spacesuits must protect astronauts from wide temperature swings, harmful radiation and impacts from dust or small debris. They must also regulate body temperature and provide drinking water, oxygen and communication systems.

To do this, spacesuits rely on layers. One of the first things astronauts put on is a cooling garment made of stretchy spandex material and water tubes. Chilled water is run through the tubes near the astronaut's skin to remove extra heat.

The outermost spacesuit layer reflects heat from the sun and is made of fabric that blends threads that are water resistant and fire resistant and also are used for making bulletproof vests.

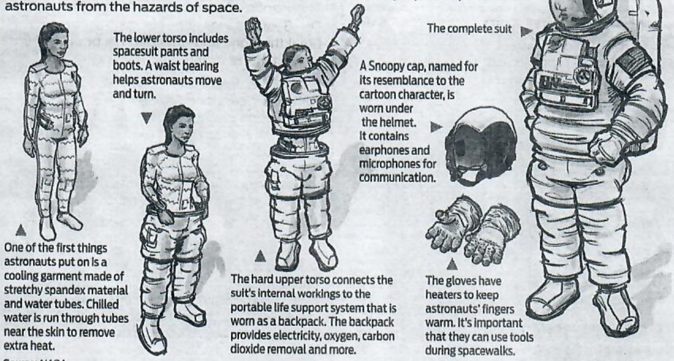
In between these layers is a bladder made of polyurethane-coated nylon. When it's pressurized, the bladder is filled with pure oxygen used for breathing and protecting the astronaut from the vacuum of space. Without some pressure being exerted on the body, gases inside the astronaut could start to bubble. These bubbles could block arteries and veins, preventing blood from moving through the body and reaching the brain.

This pressurized bladder, however, makes it difficult to move. So spacesuits must have joints that help astronauts bend their arms and legs. This is where the one-size-fits-many approach can have its issues. Astronauts' elbows and shoulders don't fall in the same places.

An ill-fitting suit can cause wasted energy, and an immobile suit can impede science. The Apollo astronauts, for instance, had to fall over to pick up a rock, said Chris Hansen, NASA's deputy program manager overseeing spacesuits and rovers.

A little spacecraft you wear

Current NASA spacesuits worn for EVAs (extravehicular activities) are like human-shaped spacecrafts. They're complex and require many layers to protect astronauts from the hazards of space.



Source: NASA

Ken Ellis / Staff graphic

Dunbar didn't go on a spacewalk during her 50 days in space. But she realized the importance of fit and mobility while training for spacewalks in a large swimming pool that simulates microgravity.

Some of her colleagues reported shoulder injuries from the ill-fitting suits. And many other women (plus some men) became ineligible for spacewalks after NASA changed the available sizes. There were initially five sizes for the suit's hard upper torso – extra small, small, medium, large and extra large – but budget cuts reduced those to just medium, large and extra large, Dunbar said.

These three sizes are still used today for spacewalks on the International Space Station. And in 2019, NASA had to reschedule its first all-female spacewalk after discovering only one medium hard upper torso, which both women required, was on the International Space Station.

Artemis suits

NASA is working to fix these issues before sending astronauts to the moon through its Artemis Program.

NASA has spent the past 15 years researching new spacesuit technology. Its latest design will fit petite women and large men, thanks to adjustable shoulder bearings and a wide variety of swappable components that accommodate different arm, leg, torso and hand sizes, Hansen said.

The suit, which is being tested at the Johnson Space Center, was intended to be a reference design that the private sector could build. That plan has pivoted a few times.

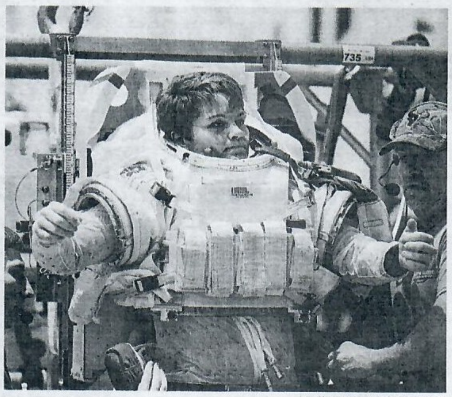
After former President Donald Trump challenged NASA to return to the moon by 2024, NASA decided to send its reference suit to the moon to meet the condensed timeline, Hansen said. But then it made significant progress on the suit and pushed its moon landing to no sooner than 2025, so NASA decided companies could build the suits. They can choose to use NASA's reference suit to guide their designs.

In a departure from its previous spacesuits, which were built by contractors but owned by NASA, these suits will be owned by the companies that build them. It's part of a broader NASA effort to partner with commercial companies, which reduces the agency's costs and helps stimulate a space economy.

NASA said it invested $420 million to accelerate development of the new spacesuit technologies, but costs for future use are unknown as the agency "finishes a competitive selection process."

That procurement process is underway. But NASA Inspector General Paul Martin recently said the time needed to develop and test both these suits and the landing system that will lower astronauts to the moon could contribute to astronauts not returning to the moon before 2026.

Hansen, however, said the suits will not prevent NASA from reaching the moon in 2025.



Yi-Chin Lee / Staff file photo

Suit engineer Wesley Wilson, left, and suit technician Don Smith help astronaut Anne McClain with training in early 2020.

Designs for the future

Looking to Mars, Dunbar, who has a Ph.D. in engineering, will spend nine months scrutinizing the feasibility of her digital-to-physical suits.

Dunbar's lab, the Aerospace Human Systems Laboratory, will work alongside retired astronaut Nancy Currie-Gregg, Purdue University professor Vincent Duffy and Moonprint Solutions CEO Dave Cadogan. They will focus on the suit itself – not the portable life support system that houses the communication system, provides oxygen and removes carbon dioxide.

Here's their plan: Each suit would start with a digital file, also known as a digital thread, that's collected when an astronaut steps into a full-body scanner. This scanner creates more than 200,000 digital points that can be used to measure every inch of the astronaut.

They'd use this to create a digital spacesuit to fine-tune fit and mobility. Then the suit would be robotically manufactured at a facility on Earth. It'd be made from a mixture of hard components, such as stainless steel or composites, and flexible fabrics, such as urethane-coated nylon, Mylar, Gore-Tex and Kevlar.

The custom suit could be available just a few days or weeks after the body scan.

Then the spacesuit, digital file, extra fabric and 3D printers with raw material would be packed for a trip to Mars. The digital file, fabric and 3D printers could enable astronauts to repair certain parts of their suits while on the Red Planet.

Dunbar knows this future is many years away. But through her feasibility study, she will examine if the vision is possible with today's technology. She would also identify any new devices, materials or processing methods that would need to be invented.

"It's really a long way off, and we realize that, but that's what we do," said LaPointe, with NASA Innovative Advanced Concepts. "What is science fiction now that might be science fact later on?"

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Simulation Software in Space Applications

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Abstract

This report aims to utilize digital human modeling software analysis along with supplementary literature to develop and determine the importance of an ergonomically efficient vehicle for human usage in outer space applications. Human exploration has evolved beyond just planet Earth and has expanded into space and the other planets in the solar system. Space exploration allows scientists to prove or disprove scientific theories on Earth. While most of this work is theoretical, it becomes practical when humans or human-made systems come into direct contact with such extraterrestrial bodies. As such, it is important to design commodities, such as a Mars rover (automotive vehicle), that can be effectively utilized for information gathering. Ergonomics plays a key role in determining how effectively such tasks are accomplished. Digital human modeling (DHM) enables the creation of a virtual human being with the ability to modify many physical parameters. The utilization of such a property in a simulation environment where responses can be observed against changes in a system provides designers and engineers with a powerful framework to create working environments where people can thrive in performing their responsibilities to yield the best return on material investments. The software package RAMSIS was employed to conduct this analysis. Through a six-step series in learning the software, we constrained different-sized manikins to the space rover and analyzed their discomfort, visual field, and center of gravity.

Keywords

Human Modeling, Ergonomics, Space, Vehicle

1 - Introduction and Background

Human modeling is an aspect that has always been at the forefront of ergonomics engineering. The design of systems, products, and processes that improve people's efficiencies in various working environments are responsible for serving as a platform for further innovation. When humans are satisfied with their working surroundings and derive satisfaction from their work, they are more likely to engage in practices that encourage innovation and perform at their best (Ahmad et al., 2010). Digital human modeling (DHM) has provided engineers and designers with a method of assessing human responses to changes in a system without modifying any real-world parameters. With the ability to change desired numbers of variables that might not be economically, socially, or bureaucratically viable in the real-world, computer-aided technology has revolutionized human execution in environments that involve any form of work by making them more accessible and less strenuous (Chang et al., 2007). This is especially true in the harsh environments of outer space. Reproducing the atmospheric and physical conditions of Mars on Earth would be a highly resource-intensive and difficult task. DHM and relevant simulations provide a platform where any number of variables can be modified in a virtual environment without putting stress on real-world systems. DHM allows the "mirroring" of a human, which enables designers to consider and then implement safety considerations. Safety is at the forefront of all engineering design. This becomes even more important in space applications as even slight errors are greatly amplified (Ahmed et al., 2018). The combination of DHM with vehicular simulation is a viable combination to design environments and systems that not only protect users but also encourage optimal performance.

Humans are intrinsically unique from each other. The design of products and services that encompasses as large of an audience as possible is an inherent need for service providers to expand upon their sphere of influence (Zhang et al., 2005). Solutions that discriminate against people of different proportions are not likely to be successful in a very competitive market (Chang et al., 2007). Digital human modeling offers one resolution to such an issue. DHM is a computer-aided design tool utilized in fabricating 2D and 3D models of humans from anthropometric data of a target sample and/or population for analysis and applicability of fits from virtual to real-world data. The use of simulation software can enhance this effort by re-creating physical work environments into a virtual atmosphere, inserting the human model in such environments, and observing responses to various triggers and changing conditions. Benefits of such an approach include low initial costs for entry, reduction in design time, and optimization of developmental resources, in contrast to the restrictive and expensive aspects of physical human modeling (Zhang et al., 2005).

Advancements in computer technology and processing power have pervasively enabled people to simulate complex and detailed models, leading to the rise of digital human modeling as an emerging field of ergonomics. This department is primarily focused on how ergonomic analyses are performed, why humans respond to stimuli the way they do, and what can be done to improve the user's experience in environments where there may be conflicts or drawbacks. With today's computing power, models are much more sophisticated and realistic; despite this extra realism, they are not carbon copies of the living human, so there are still some limitations in applying results from simulations to the real world (Naumann et al., 2007). However, numerous studies have explored this appropriateness and have reached similar conclusions: overall, the correlation between DHM simulations and real-life applicability is fairly high (Ahmed et al., 2018). DHM can be utilized in a variety of applications: occupational health and safety, medical fields such as surgeries, user experiences while controlling media such as TVs, and driving vehicles are all examples of where refinements in human interactions with appliances can improve desired outcomes. The latter will be the primary focus of this article.

2 - Overview of Report Requirements

2.1 - Problem Statement

Consideration of standard settings where ergonomic simulation can be applied for analysis yields aspects like warehouses or manufacturing plants. The only alternative here to conduct such analysis is to build physical prototypes for testing and collecting data. This procedure is far more expensive and time-consuming in comparison to simulations, so it is not favored. For the design of equipment and workspaces in space, building physical prototypes is almost not an option. Such equipment like a space rover is far more expensive than a forklift for example. Furthermore, human bodies behave entirely differently in zero-gravity environments. Over long periods, these environments can physically change someone's body. This can be hard to account for especially when considering different-sized astronauts with different needs (Ahmed et al., 2018). The RAMSIS software is utilized and relevant literature is referenced to design a vehicle environment suitable for applications in outer space to preserve human health and maximize the required procurement of results through DHM simulations (Chang et al., 2007).

2.2 - *Methods*

The software utilized for vehicle and driver ergonomics analysis in this report is RAMSIS, created by the company Human Solutions. RAMSIS is a digital human modeling program used for ergonomic vehicle design. This software is unique in that its creation was guided by leading German car manufacturers whose inputs were consistently considered in the implementation of the software's primary functions (Luebke, 2022). RAMSIS enables users to create 3D "dummies" for placement inside a vehicle, with the ability to not only adjust the manikin(s) inside compartments but also to optimize the placements of interior systems such as seats, steering wheels, and other amenities. As cars evolve throughout the years, so do people. People are consistently growing in height, weight, and other body proportions. To keep analyses as up-to-date as possible, RAMSIS conducts anthropometric surveys and updates its size databases in incremental periods (Luebke, 2022). The software package contains a diverse amount of tools for data-gathering and variable control, enabling a designer to cover all aspects of a real driving system without having to modify or deal with a physical structure and all its corresponding restrictions. RAMSIS can find the optimal balance between service design and practicality, connecting the driver and passengers with their vehicle in a manner that provides the most ergonomic and functional experience for their needs. Lab-specific analysis within RAMSIS is expanded upon in the following sections.

2.3 - *Procedures*

2.3.1 - Bibliometric Analysis

A bibliometric analysis was conducted to procure relevant articles for use in this report. Concrete metrics like the number of citations, timelines, keywords, and authorship were used to measure source reliability. Vosviewer was utilized to observe links and relationships between articles and authors, further narrowing down the selection criteria. The main search engine utilized was SCOPUS due to its focus on STEM-based research. The following table summarizes search results for each combination of keyword(s);

Table (1) 2.3.1 A: Quantity of Keyword Search Results

Keyword	Number of Document Results
Human Modeling, Ergonomics, Space, Vehicle	630
Human Modeling, Ergonomics, Space	2,255

Human Modeling, Ergonomics	10,402
Human Modeling	381,625

Two leading tables in SCOPUS were used to further narrow the final list of citations to be referenced, as the 630 quantity exceeded the download limit.

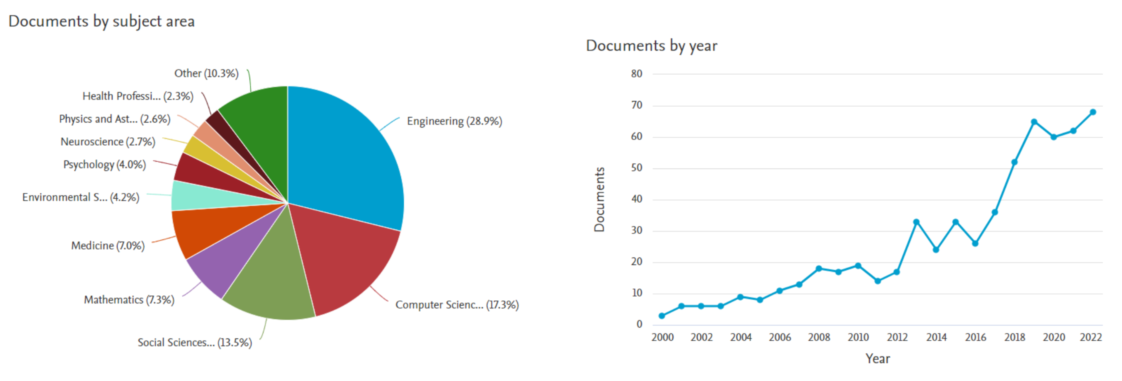

Figure (1) 2.3.1 A (left) and Figure (2) 2.3.1 B (right): Document Distribution by Subject Area and Documents Released by Year for Designated Time Period for Keywords

Figure 2.3.1 A above was utilized to select articles in the realm of engineering, as the latter is the primary focus of the human modeling aspect of this report. Through **Figure 2.3.1 B**, the inflection point for article releases in this subject appears to be the year 2000, so the 279 articles published during that year and after were finalized for analysis. These entries were exported into an Excel .csv file for co-occurrence and co-authorship analysis in Vosviewer:

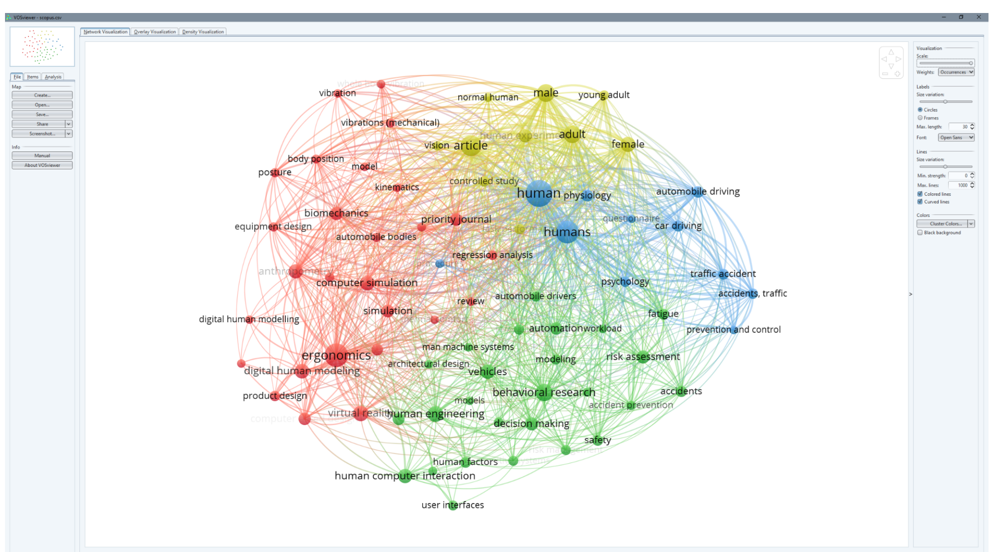

Figure (3) 2.3.1 C: Co-occurrence Analysis with Vosviewer

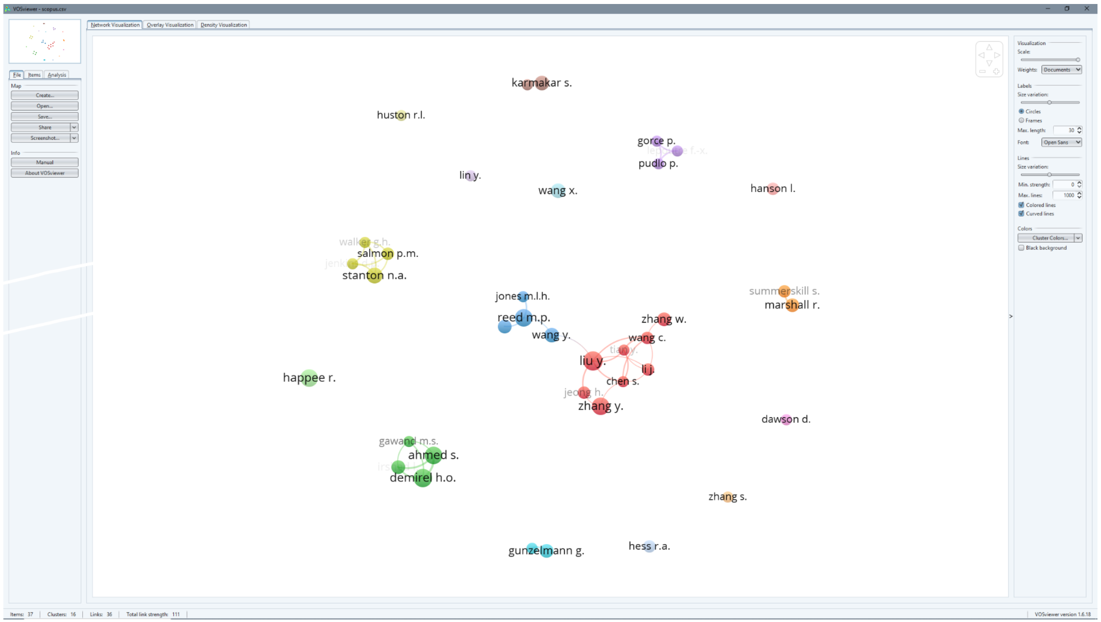

Figure (4) 2.3.1 D: Co-authorship Analysis with Vosviewer

The co-occurrence analysis was used to derive the main ideas for this set of articles. The criteria were specified to only note a term if it was used more than 15 times. By searching specifically for the keywords obtained from the co-occurrence analysis in articles with no maximum, but at least three authors, the final set of research articles was selected as listed in the *5 - References* section of this report.

2.3.2 - *Create Boundary Manikins*

The first step to creating boundary manikins is to copy-paste a few so the entire anthropometry can be covered. Two manikins are enough to cover both size extremes such that the 5 and 95 percentile of body types are covered. When a manikin is pasted, they will overlay on top of each other. They can be moved out of the way by selecting each manikin in the project tree and then applying the *translate objects* tool at the top of the screen. In **Figure 2.3.2 A**, three manikins are ready to be altered:

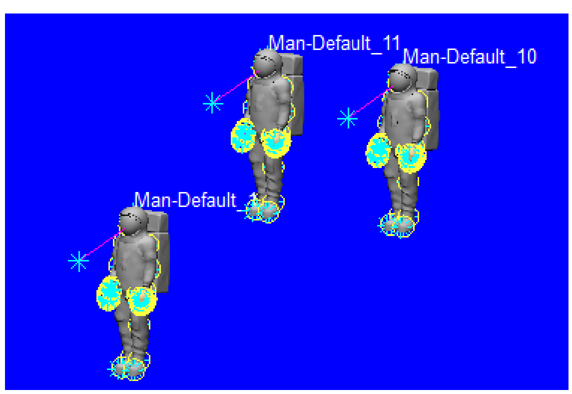

Figure (5) 2.3.2 A: Three Manikins

The second step is to edit the manikin's body measurements. There are two ways to get to this setting: A simple double-click on the manikin or right-click on the figure and selecting *object properties*. Either step will take the user to the following menu in **Figure 2.3.2 B**. Here, topology can be selected and the manikin's nation, height, reference year, corpulence, age group, and proportion can be changed. There are a few things to note about these options since full access to the entire database is not provided on the student version of the program. The nation option is limited to simply *Germany* or *Germany 2004*. *Germany* was utilized for analysis along with the reference year of 2008 and an age range of 18 - 70. Height, corpulence, and proportion do not come with percentiles. These parameters are defined by small, medium, and large labels which are not as descriptive as percentiles but will work for our analysis.

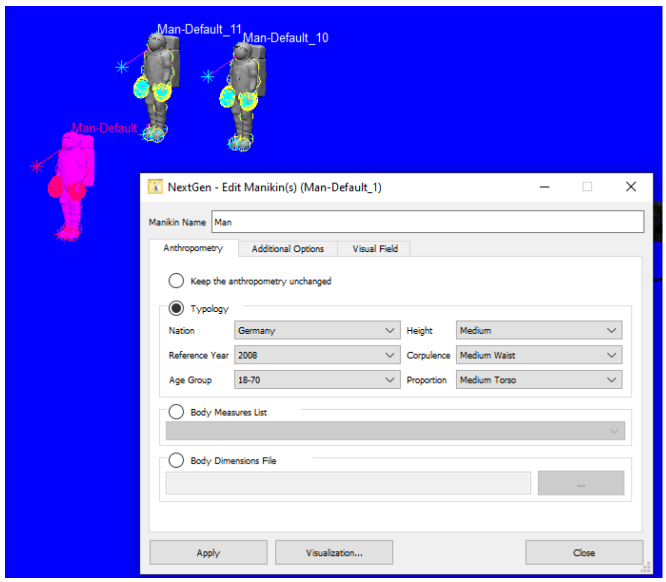

Figure (6) 2.3.2 B: Object Properties

Figure 2.3.2 C shows the resulting manikins after edits are made to their body measurements. As can be seen by the size, left to right goes from small to medium to large. This corresponds to the 5th, 50th, and 95th percentiles.

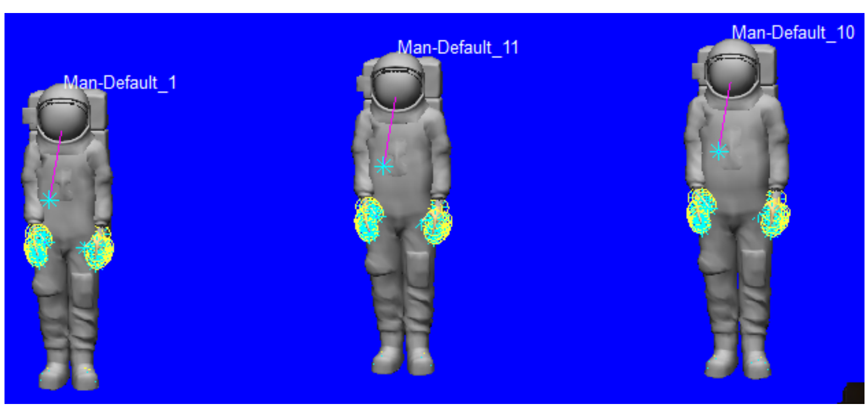

Figure (7) 2.3.2 C: Manikins of Different Sizes

2.3.3 - *Reposition Boundary Manikins and Locate Manikins in Vehicle Seat*

Before repositioning boundary manikins, it is helpful to hide most of the rover so the seats can be better seen like in **Figure 2.3.3 A.** Reposition the boundary manikins into the vehicle seat by first defining a point on the seat for the manikins to be anchored to. Go to the geometry drop-down menu at the top and click the *point* tool as shown in **Figure 2.3.3 B**. This prompts the user to select an object where the point will be defined. Simply double-click the seat where the point needs to be placed.

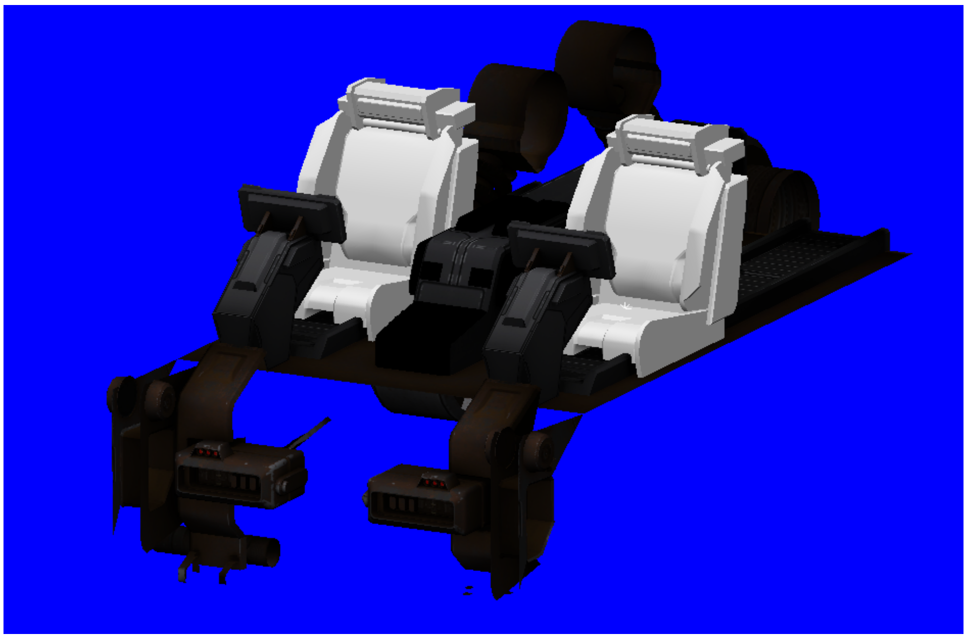

Figure (8) 2.3.3 A: Car Seats

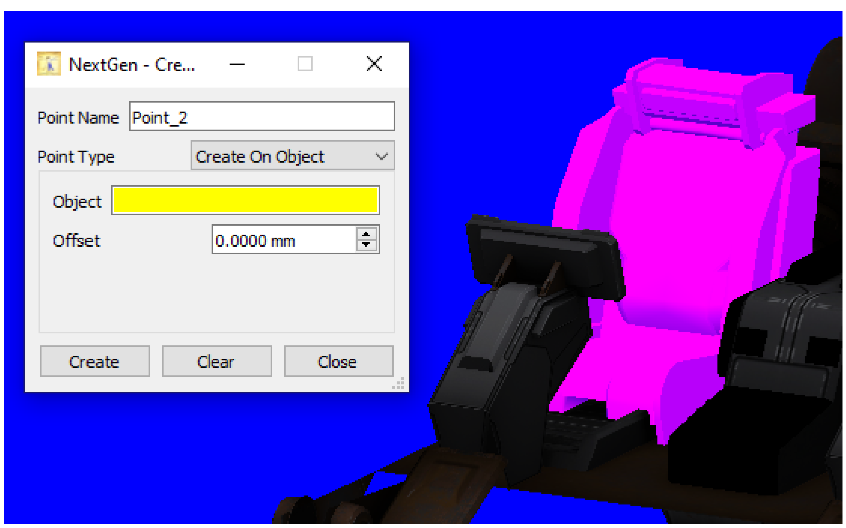

Figure (9) 2.3.3 B: Creating a Point

With the point created on the seat, a restriction is defined to move the manikin to that point. **Figure 2.3.3 C** demonstrates the *define restriction* tool which allows to define the Manikin Composition by typing in “PHPT” and the environment object for restriction which is the point from earlier.

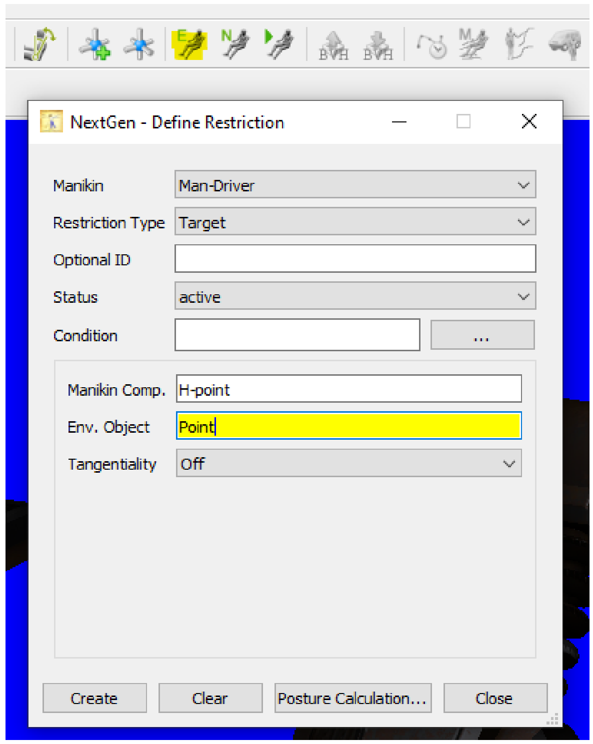

Figure (10) 2.3.3 C: Define Restriction between Manikin and Seat Point

Hit create to define the restriction, but it won’t load until the *posture calculation* tool is run. Open up *posture calculation* and hit start. After it runs, the menu can be closed and the resulting manikin should look like **Figure 2.3.3 D**.

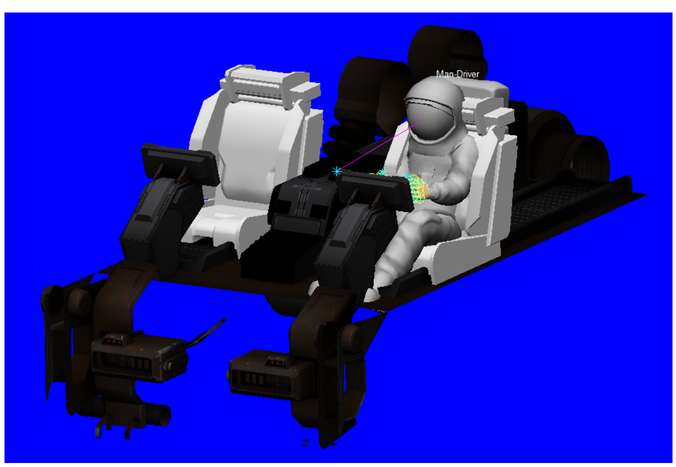

Figure (11) 2.3.3 D: Seated Manikin

At this point, it's nice to do some fine-tuning to the manikin's positioning. The translation tool can put the manikin in a more realistic position as in **Figure 2.3.3 E**.

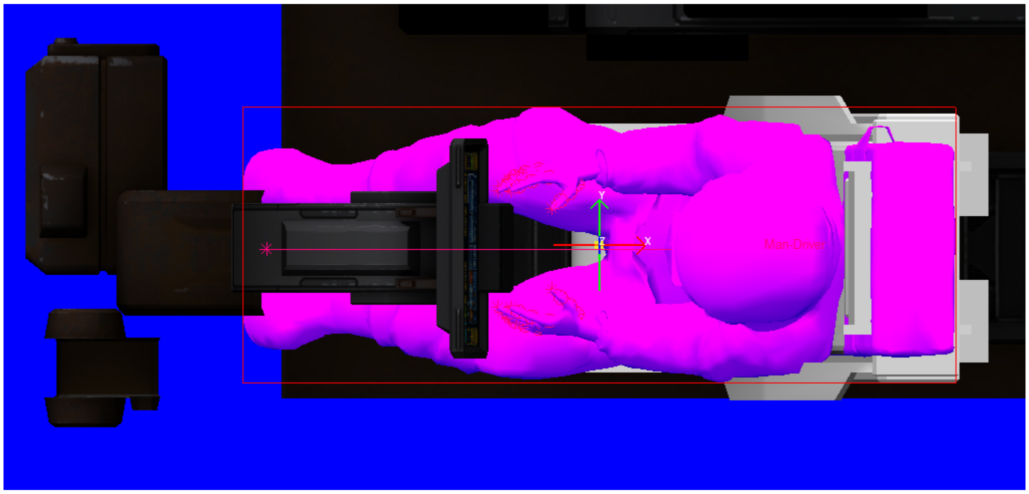

Figure (12) 2.3.3 E: Repositioned Seated Manikin

Once the manikin's position is finalized, the *copy body points* tool creates a new anchor point based on the manikin's current position. Please see **Figure 2.3.3 D** for what this tool looks like. Type "PHPT" as the body point, hit add, and then hit copy. After this step, delete the old point that was used to make the initial movements.

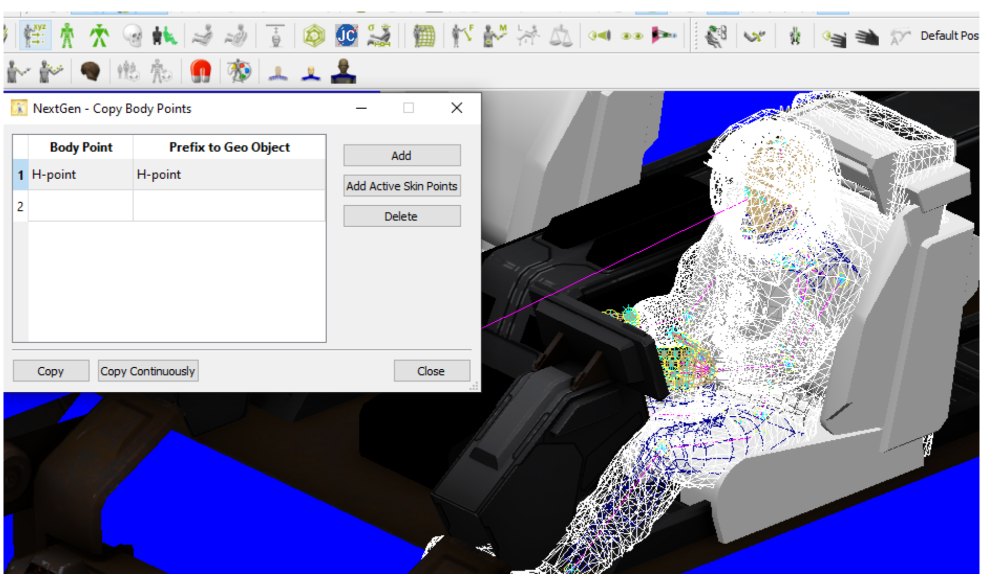

Figure (13) 2.3.3 D: Copy Body Points Tool

2.3.4 - *Evaluate and Optimize the Seat Adjustment Range for All Manikins*

To evaluate and optimize the seat-adjustment range for all manikins, the first part of this section is focused on bringing a single manikin into the seat. This process for a single manikin will be thoroughly covered because the steps for the other manikins are very much the same.

Hide the manikin and find the anchor point that was defined with the *copy body parts* tool from the previous step. This anchor point represents one position for a manikin, but a range of sitting positions is more useful. Luckily, RAMSIS lets the user define a line on the manikins to place their anchor points. The first step is to copy the anchor point and drag it out along the seat with the translation tool. Next, go under *geometry* on the top of the page and hit the *line* to define this line for the manikins. Define the starting and end points by clicking the boxes and then clicking the points. The following **Figure 2.3.4 A** demonstrates this.

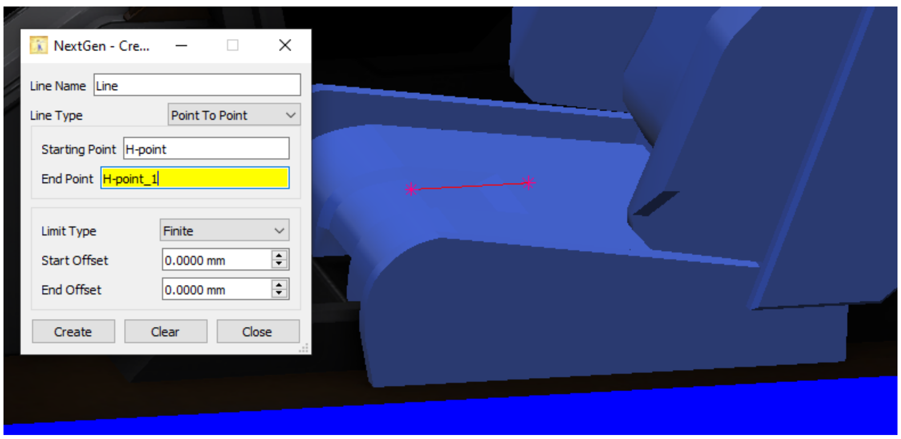

Figure (14) 2.3.4 A: Creating a Line

In previous steps, the *define restriction* tool constrained the manikin to a point on the seat. Now that a line is defined, redefine the restriction to the line as in the following **Figure 2.3.4 B.**

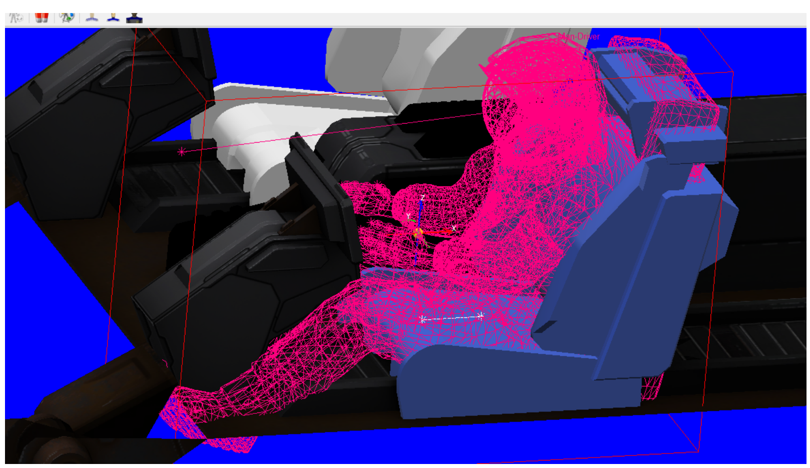

Figure (15) 2.3.4 B: Manikin Constrained to the Line

In the previous **Figure 2.3.4 B**, it is clear that the manikin's feet are through the floor of the car. This is not realistic and needs to be adjusted before moving forward. Overall, the strategy here is to define a plane with the geometry tool at the floor of the vehicle and then restrict the skin contact points of the foot to be above the plane. Skin contact points are seen in yellow in **Figure 2.3.4 C** and are points along the body that's position can be fine-tuned by defining restrictions. Skin contact points for the hands came equipped with the space manikin, but the feet did not. Adding hiking boots to the manikins give them similar contact points. Look closely at **Figure 2.3.4 D**, there is a point on the floor of the car near the foot. This is what will be used to define the floor plane for the foot to rest on.

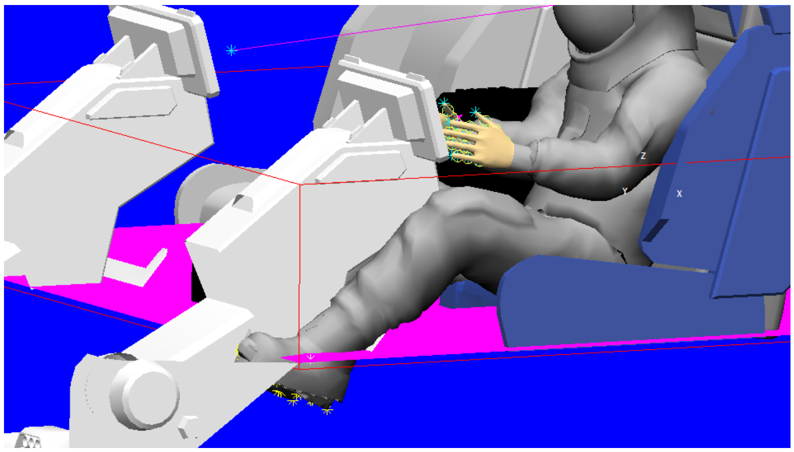

Figure (16) 2.3.4 C: **Skin Contact Points**

Defining the plane is done with the following **Figure 2.3.4 D**. Under *geometry*, select the plane and change the plane type to *point and vectors*. This defines a flat plane that is level with the floor of the car. Use the point defined earlier for the point definition and select the x and y axis by right-clicking each vector box and finding the appropriate label.

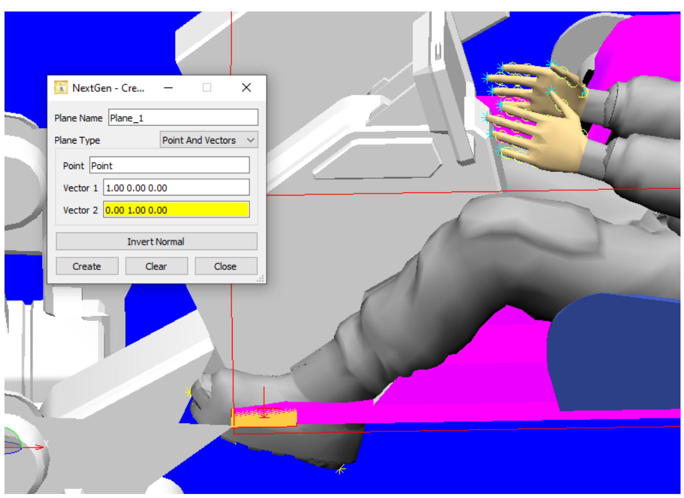

Figure (17) 2.3.4 D: Defining a Plane

To actually constrain the heel above the plane, go to the *define restriction* tool as in **Figure 2.3.4 E**. The two parameters of interest here are manikin composition and environment object. Set *LeftHeel* by clicking the left heel skin point and *plane* by clicking the plane. Click create which should add one more item to the manikin's task tree that is under the project tree.

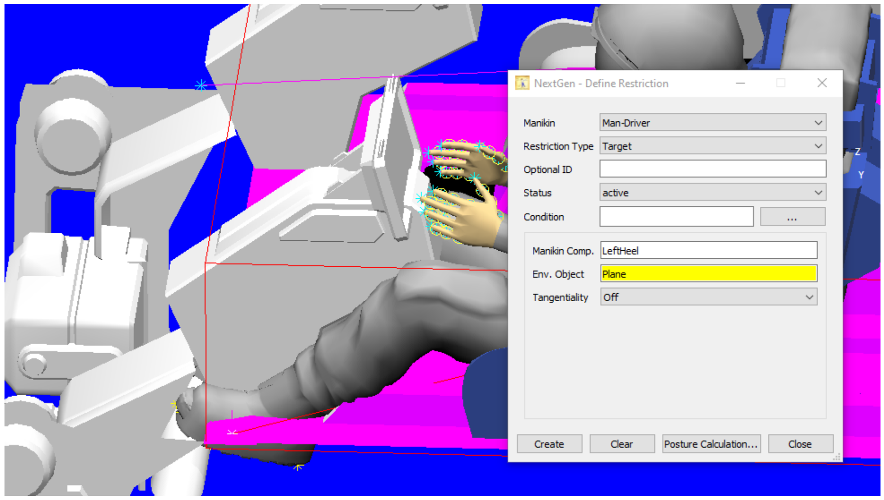

Figure (18) 2.3.4 E: Define Restriction for Foot and Floor Plane

Finally, use *posture calculation* to recalculate the positions of the manikins. This will force the foot above the plane as in the following **Figure 2.3.4 F**. However, this isn't quite finished yet because the inside of the manikin's leg is within the central counsel. Similar to the floor plane and the left heel, define another plane on the central counsel and use the skin contact point of the inside heel. All of these steps need to be repeated for the other foot as well and will result in **Figure 2.3.4 G**. This is what the manikin looks like fully constrained in its seat. The last and final step is to repeat this process for other manikins with different measurements to fully evaluate the seat adjustment range for all manikins.

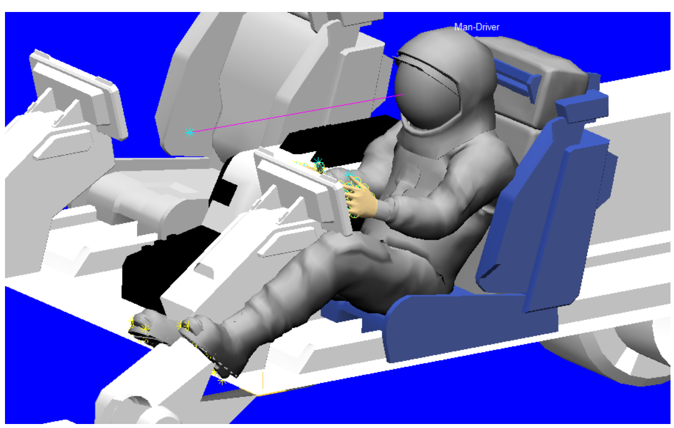

Figure (19) 2.3.4 F: Left Foot in Proper Location

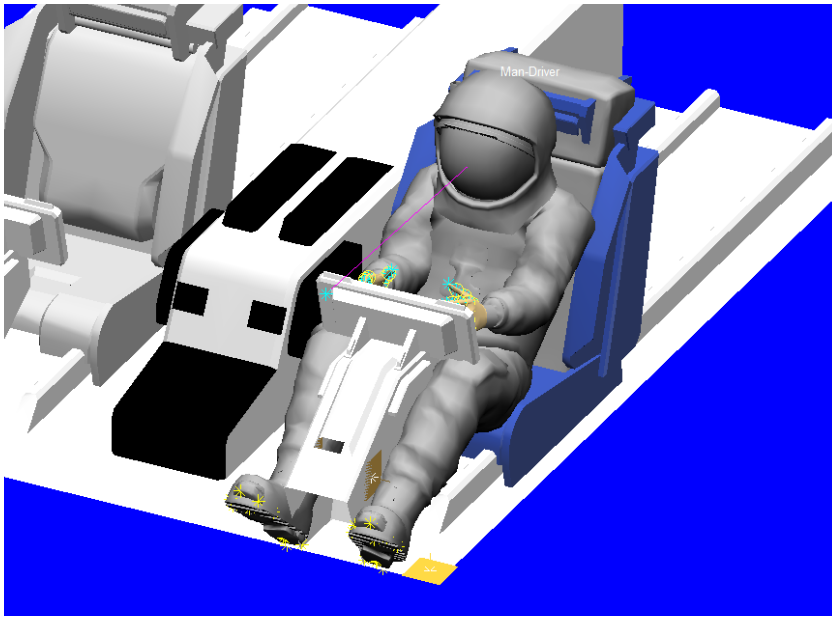

Figure (20) 2.3.4 G: Final Configuration of Manikin

The single manikin in the seat is medium-sized. To get the small and large manikins into the seat, select the medium-sized one and then use the *special copy* tool. Select the other two manikins next and hit *special paste* but only specify the restrictions. The following **Figure 2.3.4 H** shows all three manikins in their seat.

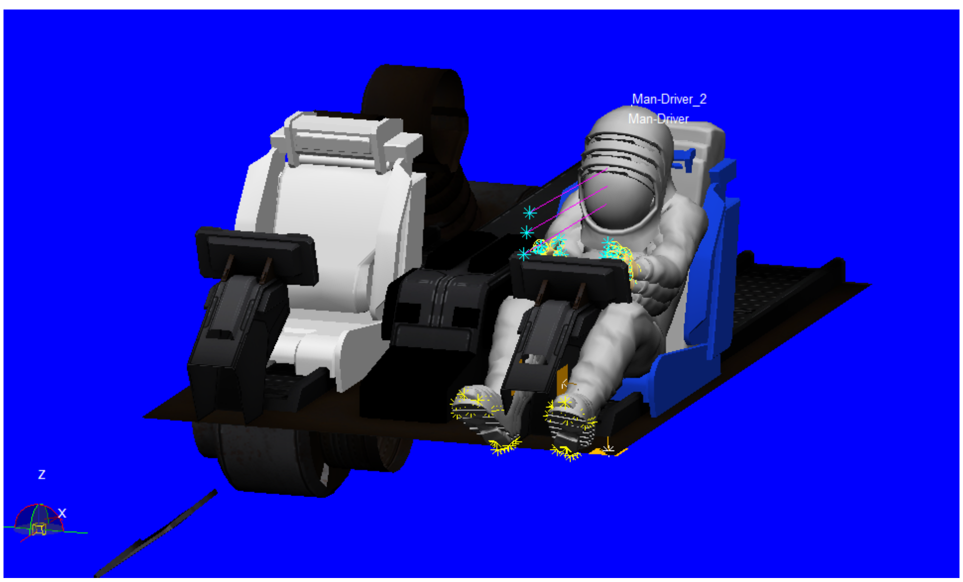

Figure (21) 2.3.4 H: All Three Manikins in the Driver's Seat

With all the manikins in the seat, discomfort analysis can be conducted with the *discomfort assessment* tool. This generates a plot as seen in **Figure 2.3.4 I** which can be viewed for all the manikins. The discomfort scores for health were high which means that the seating positions are not good for their health.

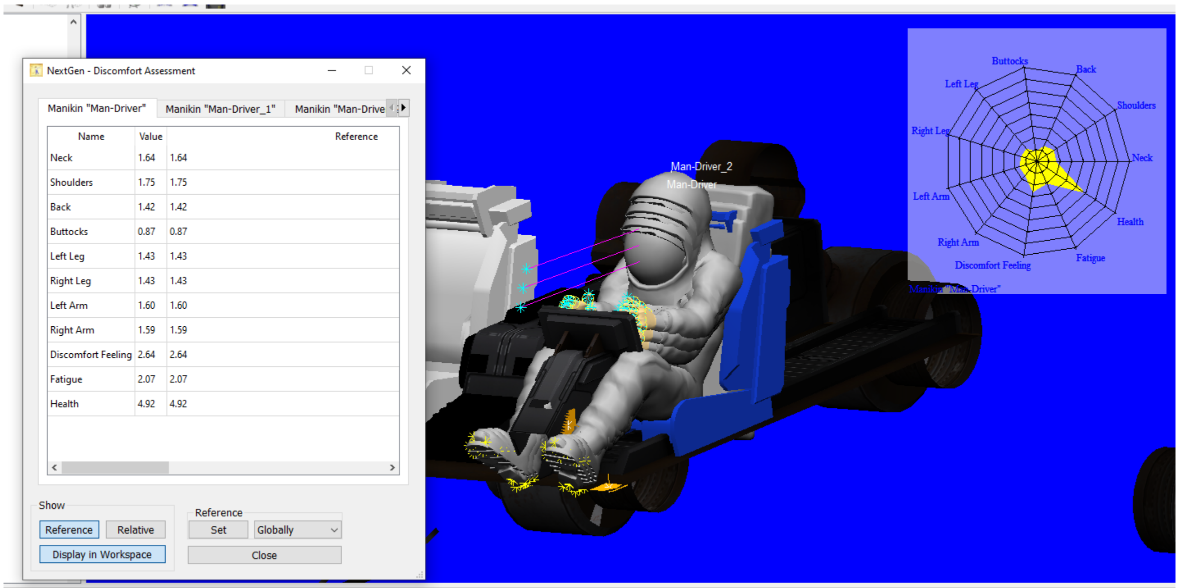

Figure (22) 2.3.4 I: Discomfort Analysis

2.3.5 - *Evaluate the Location, Reach, and Comfort of Touch Screen for Passenger*

Use the *reach definitions* tool to create reach and comfort zones for the manikin. In the videos, Andre uses a reach option under analysis to define the comfort zones. This team could not find these options so the *reach definitions* tool to create both zones. The first one is the reach zone as in **Figure 2.3.5 A** which is created from the middle fingertip relative to the shoulder joint. This represents the max reach of the manikin, but it doesn't represent the practical range of the manikin. Comfort, on the other hand, is created from the knuckle joint relative to the shoulder joint. This is a more realistic working range and is seen in **Figure 2.3.5 B**. An overall picture of what both zones look like can be seen in **Figure 2.3.5 C**.

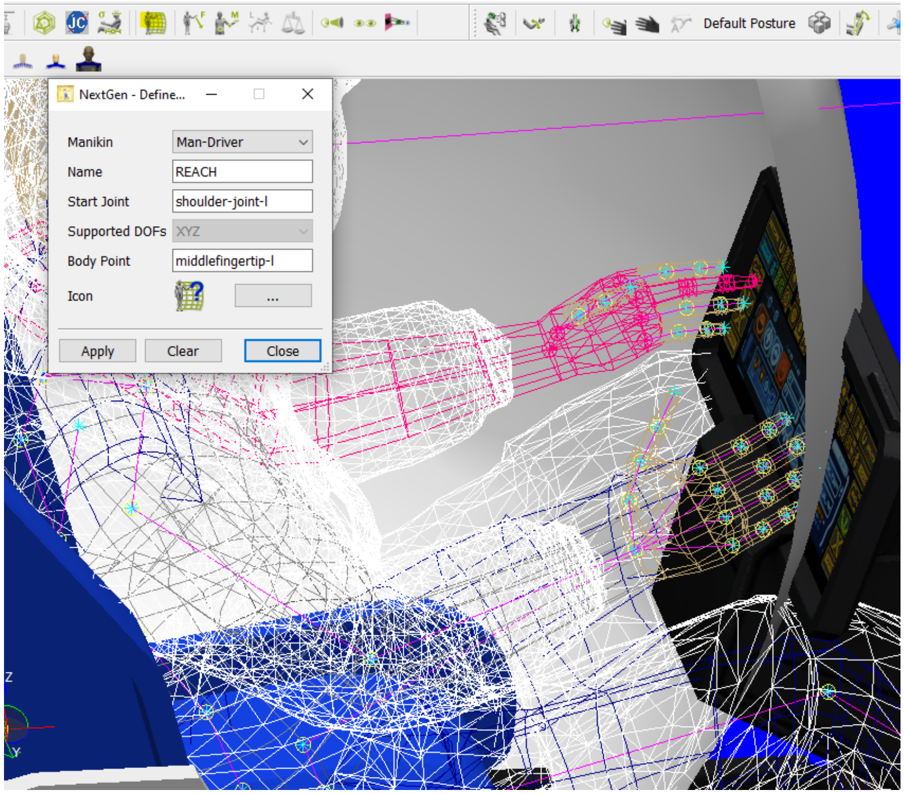

Figure (23) 2.3.5 A: Reach Zone

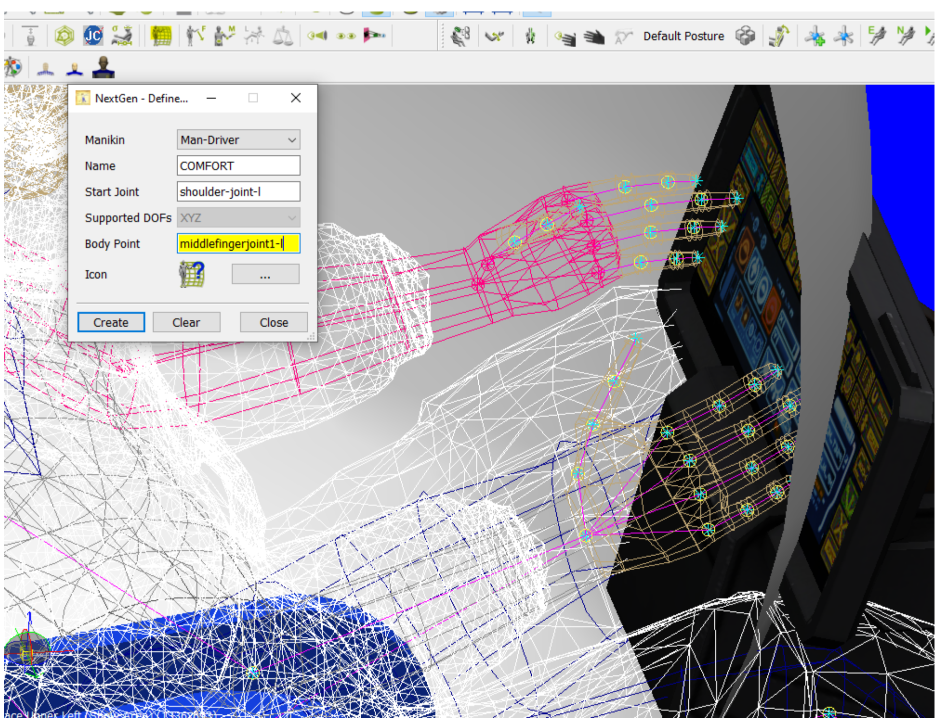

Figure (24) 2.3.5 B: Comfort Zone

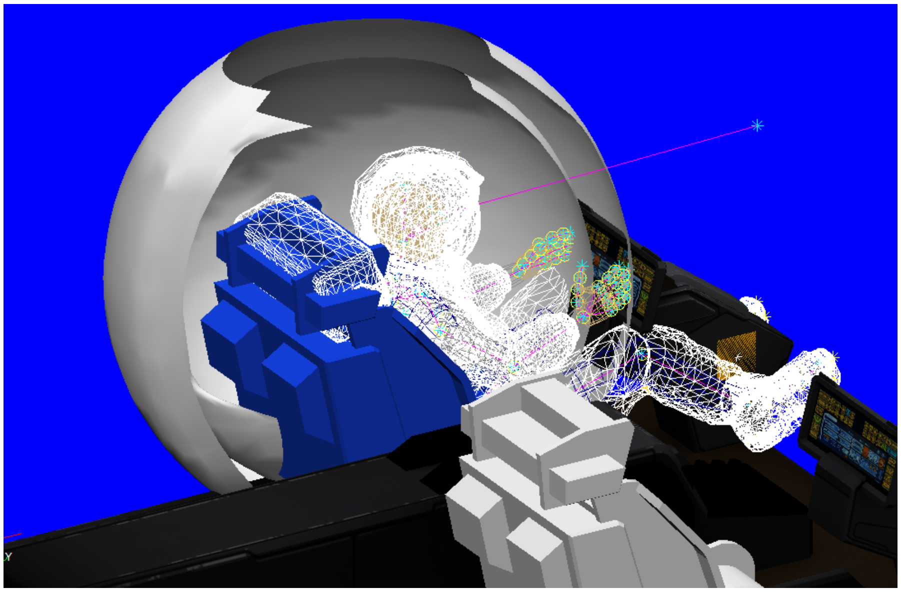

Figure (25) 2.3.5 C: Both Visual Zones

2.3.6 - *Evaluate Visibility for Driver or Passenger while Actuating Controls*

This team had to use the *limits of visual field* tool to analyze visibility which is different from Andre's use of the *direct vision* tool under analysis. That setting could not be found. However, the *limits of visual field* tool accomplishes similar goals. The most useful feature is the teal cone which represents the manikin's working visual field. With the shape of the windshield, the manikin cannot see out of every window from their current position. This, however, shouldn't be a big issue since the manikin should be focusing on the road in front of them along with the control panel they use to steer. Since both these items are well within the teal cone, this team concluded that the visibility is acceptable.

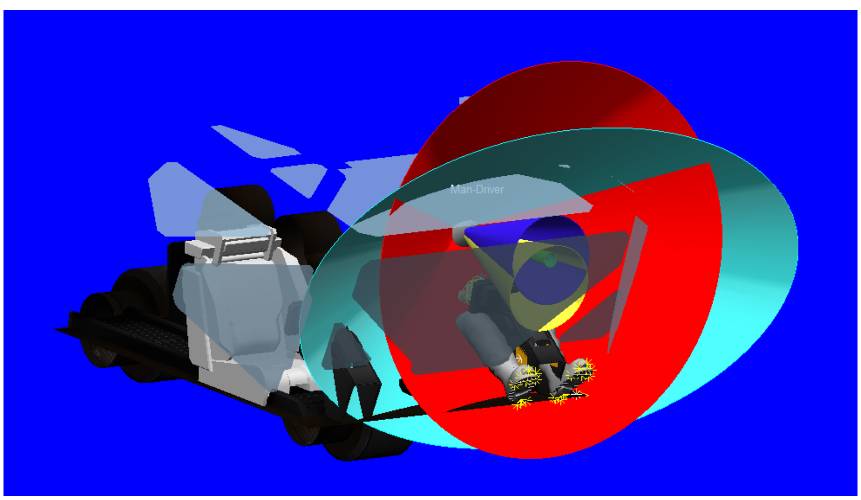

Figure (26) 2.3.6 A: Visual Cones

3 - *Results and Discussion*

3.1 - *Results*

Overall, the analysis looks at three different manikins of the 5th, 50th, and 95th percentile body types seated within a space rover. All three manikins had no problems with being placed inside the rover after appropriate restrictions were made to keep their feet and legs outside the equipment. However, all three manikins indicated discomfort issues related to their health through our discomfort analysis. Aside from that, there were not any other issues with their placement since our visual analysis indicated that manikins were able to see everything important to operating machinery well enough.

3.2 - *Discussion*

3.2.1 - *Center of Gravity of Manikins With and Without Spacesuits*

Andre covers how to visualize the center of gravity in his tutorial series, but this is not the most helpful tool in analyzing the manikin's center of gravity because it does not provide any coordinates. Regardless, if the manikin is selected, right-click to object properties, hit *visualization* at the bottom, check the *center of gravity* and apply the changes, the user should be able to see orange crosses along the curvature of the spine like in the following **Figure 3.2.1 A**. These are faint but represent the locations of each body part's center of gravity.

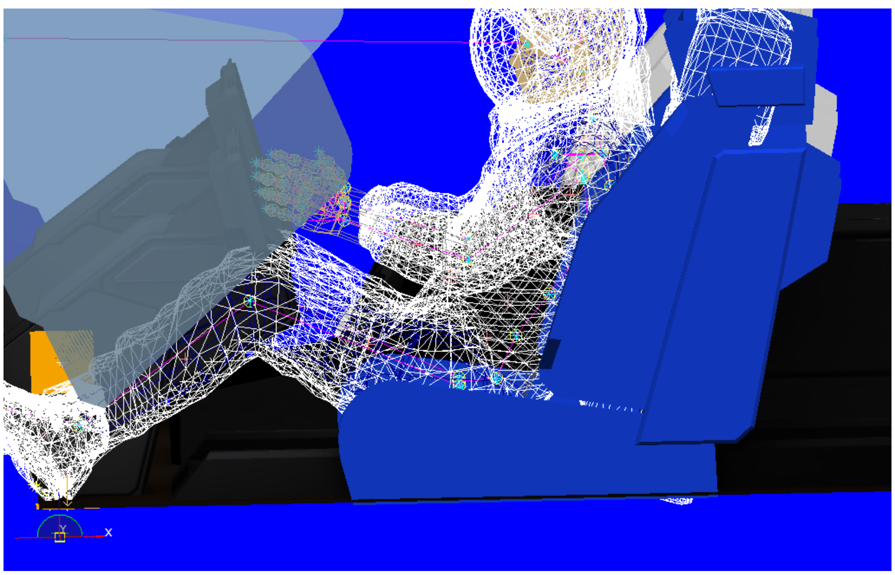

Figure (27) 3.2.1 A: Centers of Gravity

By selecting the manikin and hitting the *body mass* tool, a table is generated as seen in the following **Figure 3.2.1 B**. Not only does this include the coordinates of the overall center of gravity but also includes the coordinates for each part of the body. This makes it a very helpful tool in evaluating stresses in the hip for example.

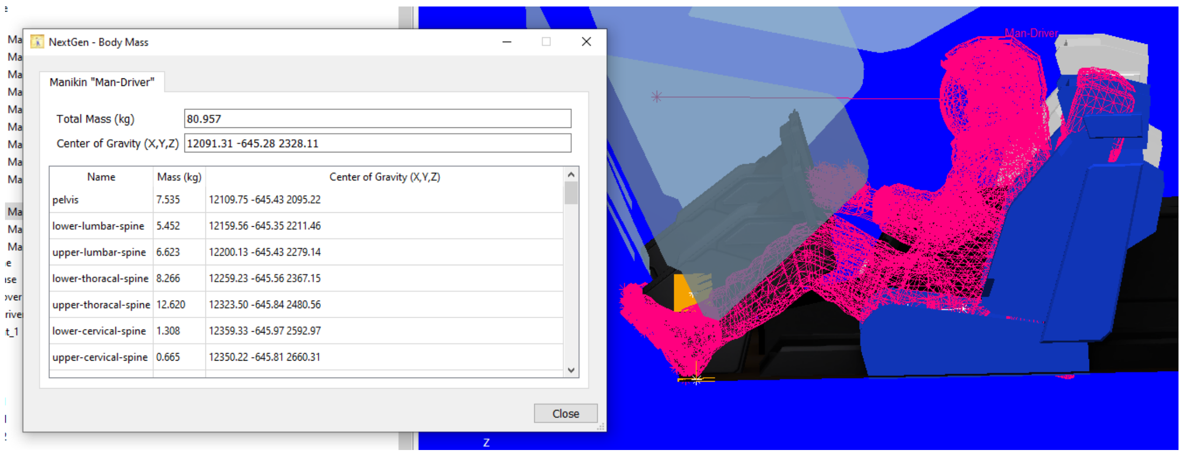

Figure (28) 3.2.1 B: Body Mass Tool

This section also required analysis of the manikins with and without the spacesuits. However, generating a manikin without the spacesuit model was not an option. Workarounds like hiding a component of the manikin were explored but not successful.

3.2.2 - *Can Restricted Motion Conditions be Analyzed Ergonomically for Potential Risk*

Given the diversity of tools offered by RAMSIS and other ergonomic simulation software, there is no reason that restricted motion conditions could not be analyzed ergonomically for potential risks. One of the great things about RAMSIS is the ability to define joint angles and constraints that replicate real-world scenarios. This lab is a great example of applying these tools to look at multiple different positions of astronauts within a space rover. Restriction tools, which were used frequently, allow us to control how the manikin sits by defining where they sit, where their feet are, and even the position of their hands with respect to the steering wheel. These are restricted motion cases since the large suits make movements bulky and uncomfortable. Thus, a lot of the analysis is centered around the impact that these spacesuits have on the manikin's ability to drive the space rover safely by looking at their reach and visibility. With restricted motion conditions, it's also important to conduct discomfort analysis to understand these restrictions affect people's health and safety long-term.

4 - *Conclusions and Future Work*

4.1 - Conclusions

Digital human modeling is a powerful and comprehensive tool used to simulate changing conditions for the human physique in virtual environments. The ability to modify a wide variety of variables is an opportunity that is seldom present in the real world due to financial or bureaucratic constraints (Naumann et al., 2007). Observing responses to those changing variables provides engineers with the data to design systems that are ergonomically efficient for their target audiences. This enables users to derive high levels of satisfaction from their work environments, not only fulfilling their own requirements but also promoting the work and image of the company or designers that created the physical product (Ahmad et al., 2018).

Despite the small scope of our RAMSIS analysis, our results on the discomfort, reach, and visibility of the driver manikins were rich and helpful in our understanding of the overall ergonomics. RAMSIS has proven itself to be an excellent tool because of the seemingly limitless possibilities that can be simulated within it. The ability to restrict and constrain even the smallest of joints in our manikin models gives us a lot of control over what to analyze. With respect to the created manikins, results indicate that the seated positions for the driver role are suitable despite slight discomfort.

4.2 - Future Work

The ceiling for the potential of DHM is very high. While current methods utilize realistic models, significant advances are being made to incorporate other, more specialized aspects of the human body. Through innovations in anthropometric data collection and artificial physique recreation, DHM is soon able to simulate how people's abilities change with age and be able to recreate the behaviors of those with disabilities, two aspects that are currently not widely implemented (Maurya et al., 2019). This is made possible with methods that are able to collect biomechanical data, those that can more accurately model non-traditional movements of the limbs. This will be a huge breakthrough; the elderly and specially-abled often have to suffer through uncomfortable and unhealthy work environments as these usually do not have the capabilities to consider specialized samples of the population. With this advancement, DHM can assist underrepresented people by providing them with job surroundings that can ease unique workplace-related problems. The next step in this process would be to create comprehensive anthropometric and biomechanical databases as a standard for use in different software packages, in addition to finding ways to record tangibles such as strength, endurance, miscellaneous motions, and variable cognitive demands (Maurya et al., 2019).

Additional advancements are made in the artificial environments where DHM is employed. Virtual ergonomics is an emerging field where virtual manufacturing (VM) and virtual reality (VR) are applied for furthering 3D ergonomic tasks (Rajesh et al., 2016). VR and VM enable designers to fabricate and manipulate humans in personable, "life size" models. This provides engineers an additional view of their systems, and one that can be used to simulate the real-world experience of using a product or service designed in virtual environments. An example in vehicular systems would be a designer creating a driver's seat based on average data, inserting themself into that seat, and noting whether different aspects like the steering wheel, navigation control and windscreen visibility meet design requirements.

With respect to RAMSIS lab work, future improvements would center around less generalized cases in addition to analyzing manikins in different roles. The current model is a static one, but the ergonomics can change in such a dynamic and unpredictable environment like outer space. For example, a different analysis may show that a manikin is comfortable in its flat, seated position. However, this can be very different if the rover is driving through a crater or some other rough terrain. RAMSIS does not appear to have any dynamic simulation capacities. Something similar could likely be achieved by running analysis on different orientations of the rover. Future work also includes analysis on different manikin roles. This report is solely focused on manikins of different body types as a driver for the rover. Some other roles to consider would be the co-driver, a researcher at the base, and so on. All in all, these future developments would give a more holistic and complete picture of the ergonomics of this moon base.

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Application of Ramsis Digital Human Modeling to Space Human Factors

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Abstract. This paper will cover using Ramsis for simulating and modeling a new Mars site. Ramsis is a 3D computer-aided design (CAD) modeling software used to design vehicle interiors and manikin positioning. Other related applications are reachability, seat belt routing, and field of view limitations. Our paper covers the procedures used to create manikins, optimize seat range, evaluate location/visibility, and other relevant ergonomic-related analysis. The paper will also cover simulation research, bibliometric analyses, discussion, and future work. References will be listed at the end. Applying ergonomic analysis and the Ramsis software is the main purpose of this lab report, building upon our foundation research in lab 1.

Keywords: Ramsis, Digital Human Modeling, Ergonomics Analysis, Simulation

Introduction

1.1 Ramsis Introduction

With the rise of fully automated cars, safety has become an increasingly concerning factor in vehicle design and management. Ramsis, a CAD software, enables engineers to model the safety and use features of vehicles. Prototypes are simulated in a virtual environment to determine vehicle functionality and evaluate overall vehicle design. Ramsis and other digital modeling software have numerous benefits, including timeliness of simulation, cost reductions, and accuracy analysis (Meulen, 2007). These benefits justify the investment in vehicle software modeling, addressing many challenges for ergonomic engineers and human factor researchers.

2 Overview of Report Contents

2.1 Problem Statement

Digital human modeling has long been used to design and evaluate the ergonomics of cars. Using simulation software like Ramsis allows designers to create better-designed systems that work with a wide range of body types. These analyses are easier to conduct with simulation and can occur earlier in the design process before prototypes are made, saving time and money. As newer and more advanced products and technologies are introduced, human design and ergonomics are further linked together. While those two factors work to meet safety and comfort requirements, they will result in low production costs and an increase in sales. It will also result in better product ratings with fewer discrepancies as well as setting a foot towards new advancement in the era within the field (Chaffin, 2001). Ergonomics and human design will evaluate the productivity and reliability of any finished design without bias. Human modeling-type simulation is important for applied ergonomics for a variety of reasons. Product and system design require significant research to understand intricacies and proper use. According to "Digital Human Modeling for Vehicle and Workplace Design," engineers need to know early in the design process how effectively and efficiently humans will be able to interact with them." Simulation modeling assists in understanding how systems work in their designated environment, allowing for life-size scaling after ergonomic analysis is considered. In the context of space human factors, an emerging area of ergonomics, existing simulation software must be applied to the new challenges outer space brings.

2.2 Procedure

The first step in using Ramsis to analyze ergonomic situations in a space human factors context was learning the basics of the software. Through incremental class assignments, the authors were able to familiarize themselves with the process of digital human modeling and ergonomics analysis, culminating in a larger assignment that used the knowledge and skills from the previous assignments. To perform an ergonomics analysis on astronauts interacting with a Mars rover, a boundary manikin was created using the "test sample" function under ergonomics analysis. Default options were selected and the manikin's posture and joints were able to be manipulated. Boundary manikins were created using standard settings, which will be adjusted for percentile compositions later in this analysis. Next, the manikin was placed into the rover as a driver and a passenger was added. Figure 1 shows these manikins situated inside the vehicle in seated positions.

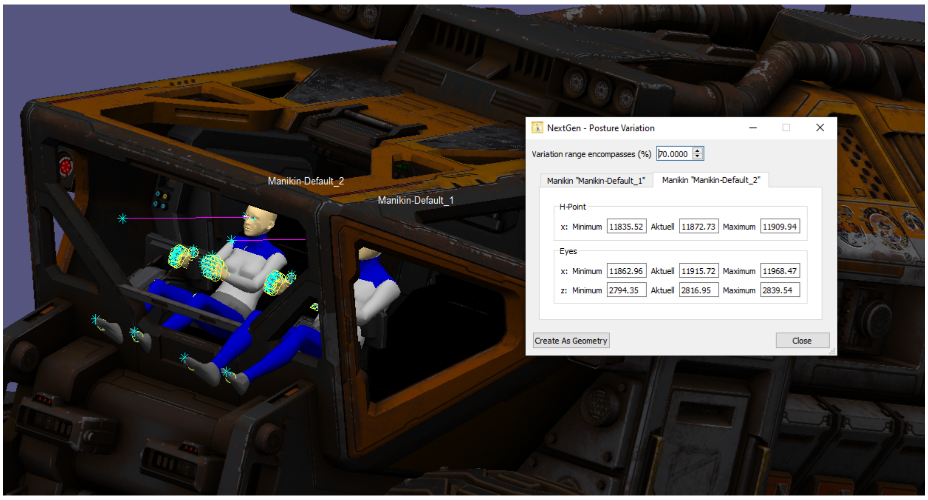

Fig. 1. Default German Ramsis manikins in Mars rover as driver and passenger.

Once the manikins were in place using a built-in option, the ergonomics analysis could begin. To do this, the first metric evaluated was the seat adjustment range. The goal was to create a range in which all percentile manikins had a comfortable reach to the rover's main controls. The smallest female and largest male manikins available in the Ramsis German population database were used to cover the entire spectrum of percentiles in the population. This method captures 90% of the population, allowing the ergonomic design to be marketed nearly to everyone. Figure 2 shows the comfort analysis of these manikins. Upon additional evaluation, each limb remains in the "comfort range." If accommodations for larger individuals were considered, there may be significantly more discomfort, as the manikins are already adjusted to optimal positions.

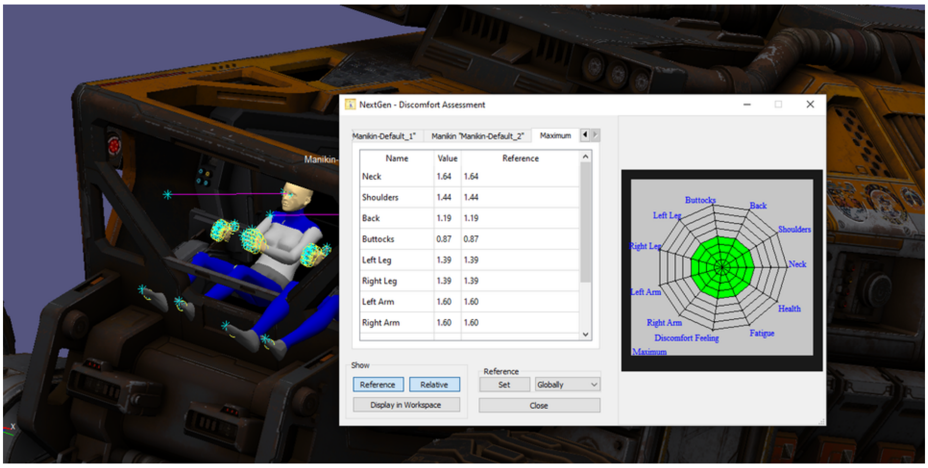

Fig. 2. Comfort analysis for smallest and largest manikins in the Mars rover.

The next method of ergonomics analysis was to evaluate the location, reach, and comfort of the touchscreen controls for the passenger. Two built-in functions were used to determine joint angle limitations and joint capacity. These measurements determine the maximum distance a manikin can move within the rover and the reachability of manikins to the appropriate locations within the structure. Upon further analysis, some of the smaller manikins are unable to reach across the rover to the screen, whereas larger manikins have definitive dimension constraints. Testing was conducted for 90-95% of the population, using the built-in German modeling data. Figures 3 and 4 show the results of these calculations.

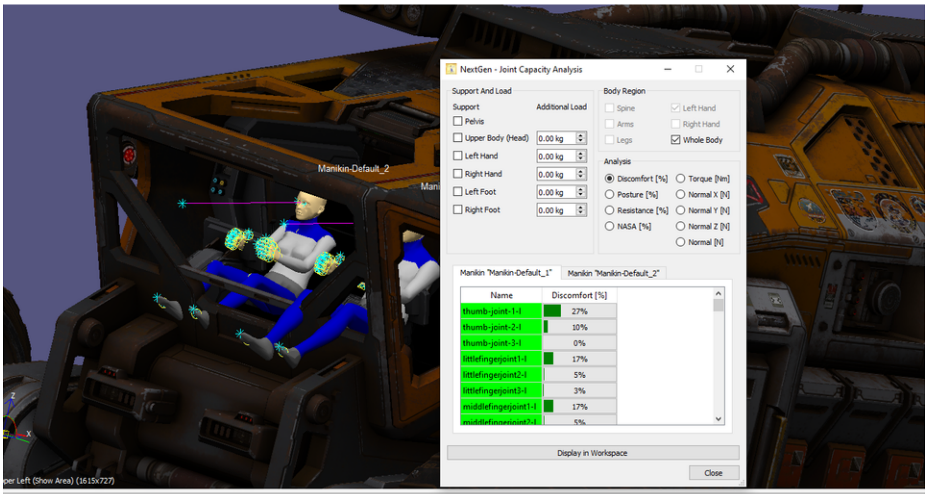

Fig. 3. Joint capacity analysis for the passenger to the touch screen.

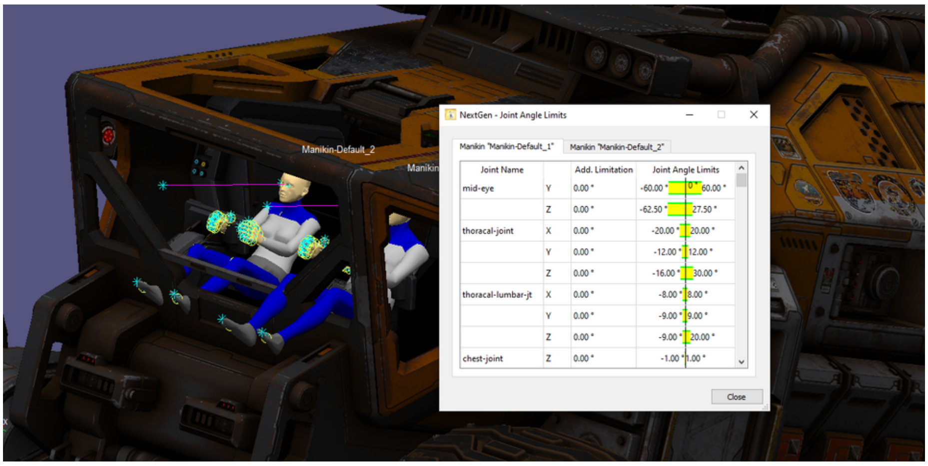

Fig. 4. Joint angle limit analysis for the passenger to the touch screen.

Finally, the visibility for both the driver and passenger when inside the rover was evaluated. The limits of visual fields function in Ramsis were used to display the vision radius of each manikin for both eyes. Visibility does not seem to be limited while operating the rover, since both manikins can see the Mars base adequately. This was determined using the sight limit function to display that drivers can detect the object of interest, the Mars base in this case, in their visual field shown by the visual cone. Figure 5 shows this visual cone for both the driver and the passenger. Overall, there do not seem to be sight limitations, however other factors such as glare, window tint, and atmospheric conditions may play a role. Similar to the in-person lab Sameeran hosted, there are numerous safety risks associated with impaired visibility. On Mars, there are numerous factors to consider. Risks include, environment, heat, ventilation, safety equipment, wind, workspace quality, window quality, and suit composition. These factors may all play a role in determining overall visibility for drivers, as the simulation is unable to capture all these factors. Simulating more environmental distractions may aid in future research using Ramsis.

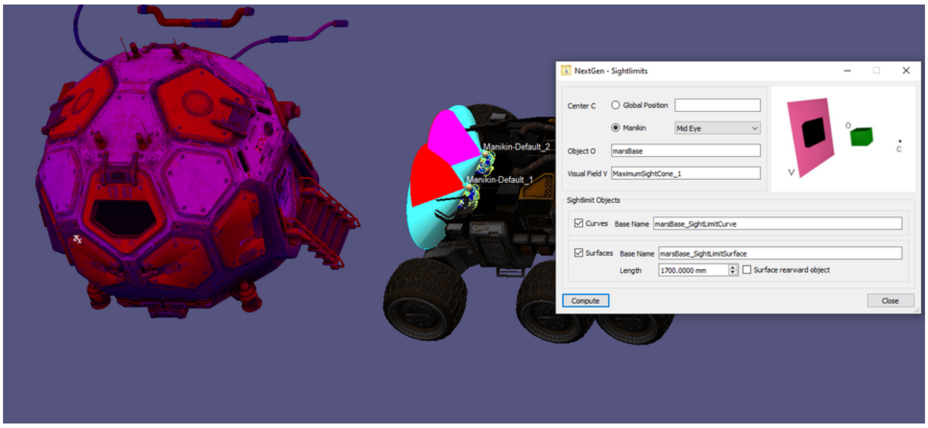

Fig. 5. Visual analysis and cones for Mars rover driver and passenger.

2.3 Results

Based on the ergonomics analysis conducted, the seats and controls of the rover must be highly adjustable. This will allow for comfortable accommodation of passengers from both ends of the size spectrum, 5^{th} percentile females and 90^{th} percentile males. A high level of adjustability also improves safety, as personal protective equipment like space suits and the vehicles used to traverse new planets must fit an individual extremely well and exactly as intended. As indicated in Figures 3 and 4, the reachability is undesirable for both the smallest and largest members of the population. This is the result of a fixed display that does not allow for ergonomically important adjustments to be made. The seating position of the passengers is not an issue, as the comfortability analysis results are within the acceptable range for all manikins tested. Visibility is also not an issue for the vehicle itself, but consideration must be made for the helmet passengers will be wearing when on the surface of Mars. No matter how good visibility of the vehicle is, a helmet that blocks vision is what the passengers will be seeing out of, so its design must be carefully considered. Safety and comfort must both be considered for final designs. According to an article in Sage Journals, there are "several items involving tradeoffs between safety and comfort." Engineers must properly consider environmental conditions to optimize suit parameters within a budget. This is relevant in future sections of this report, during analysis of center of gravity and force (Requirements 2.6 & 2.7).

2.4 Bibliometric Analysis

A bibliometric analysis of existing literature on simulation to applied ergonomics, and especially the use of simulation to evaluate ergonomics principles in a vehicle design setting was conducted to gain insight into the current climate of these applications of simulation. First, several databases were selected to search for relevant articles, including Scopus and Dimensions. These databases were searched with two sets of keywords: "ergonomics analysis" AND "simulation" and "ergonomics" AND "vehicle design" AND "simulation modeling." For the first set of keywords, Scopus yielded 78 results. The leading table analysis of these publications is shown in Figure 6. Using these same search parameters in Dimensions AI database, a much larger number of publications was presented, with 84,297 results to analyze. The leading table analysis of these results is shown in Figures 7 and 8. These results show that there is increasing interest in the topic of simulation to ergonomics analysis with a spike in 2019. The University of Michigan is a significant contributor to the conversation, and while it is more commonly talked about in engineering, other disciplines are also interested in the application.

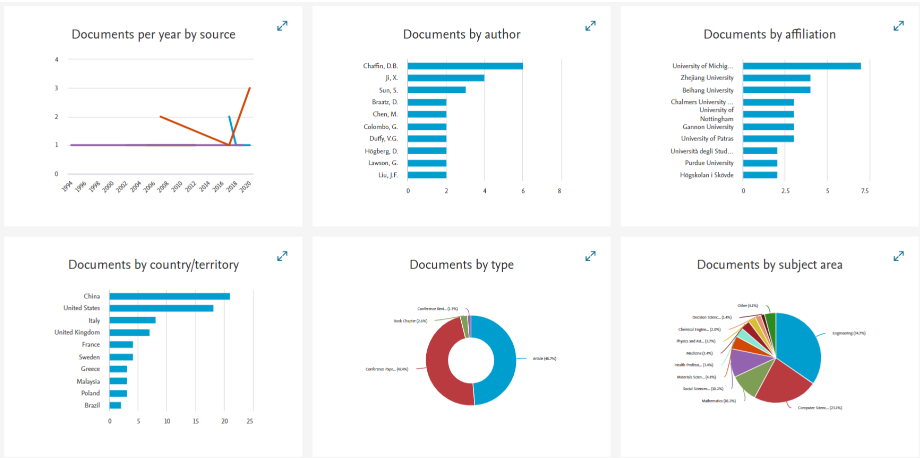

Fig. 6. Meta data analysis from "ergonomics analysis" AND "simulation" papers in Scopus.

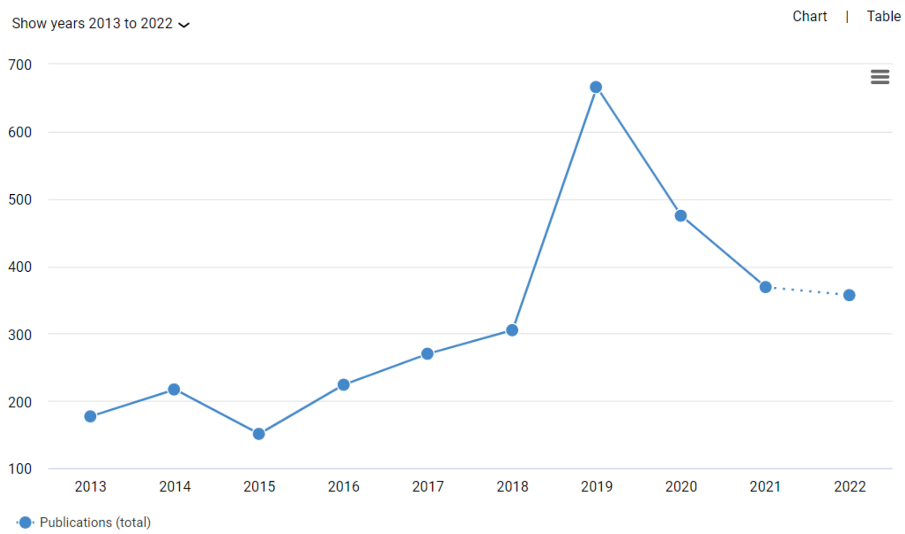

Fig. 7. Number of "ergonomics analysis" AND "simulation" publications by year as presented by the Dimensions database.

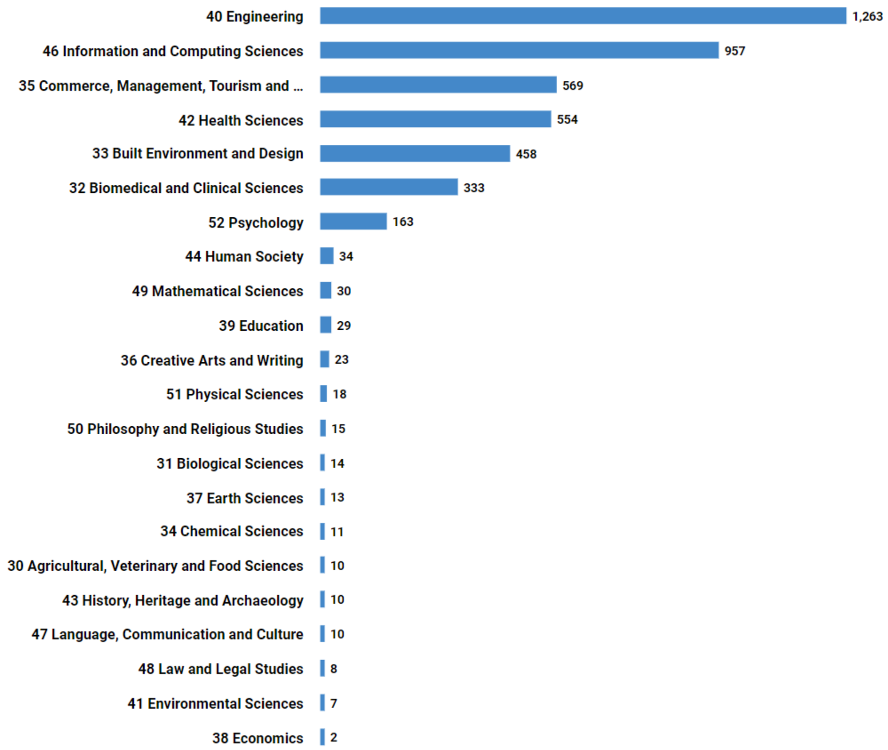

Fig. 8. Categories and number of papers within each category for "“ergonomics analysis” AND simulation” publications in Dimensions AI.

Using the second set of keywords as the search parameters in Scopus, only one publication was found as shown in Figure 9. The paper, “Guide and documentation system to support digital human modeling applications,” was written in 2006 and discusses a method with which to reduce discrepancies and errors in digital human modeling. This was also the only result when searching Web of Science, but Dimensions yielded 574 results. There is also increasing interest with this set of keywords in a recent spike as shown in Figure 10.

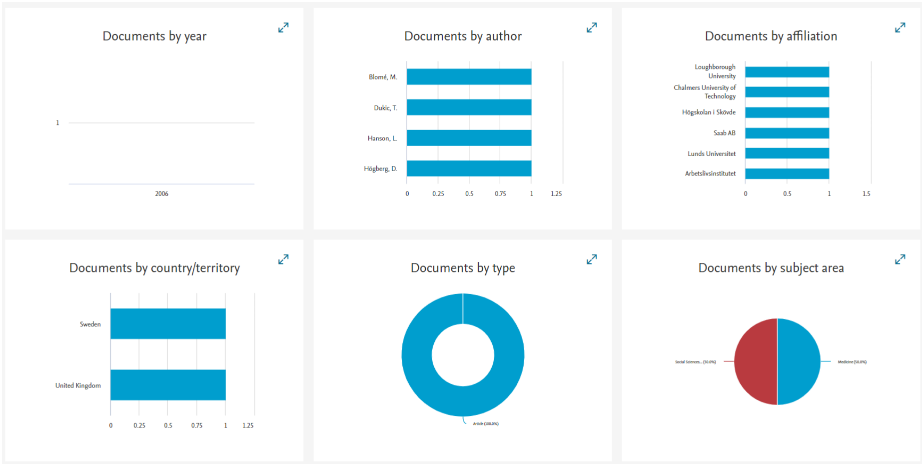

Fig. 9. Leading table Scopus result for “ergonomics” AND “vehicle design” AND “simulation modeling.”

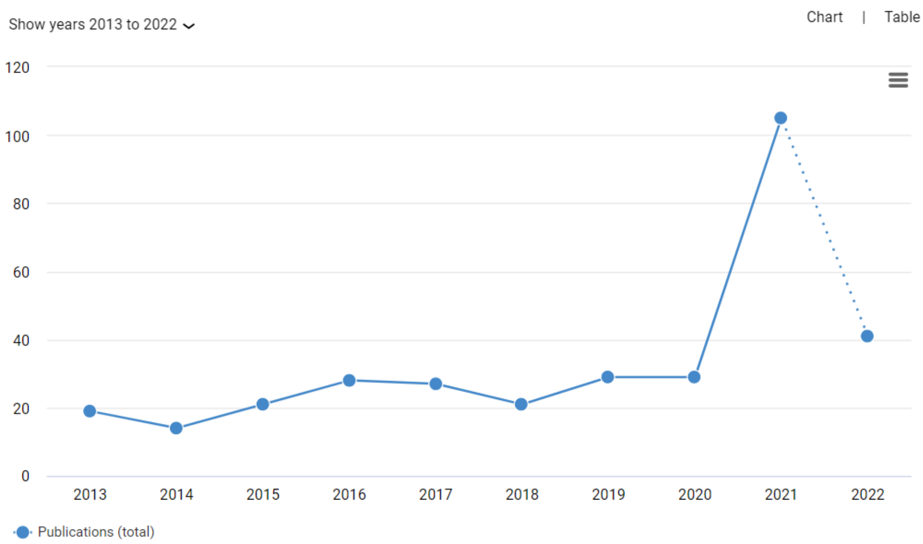

Fig. 10. Number of “ergonomics AND “vehicle design” AND “simulation modeling”” publications by year as presented by the Dimensions database

2.5 Discussion

The authors were introduced to digital human modeling in an applied ergonomics course in the context of space human factors. The challenges of Mars rover designs, space suit fittings and repairs, and astronaut comfort are all important to consider when planning a manned trip to Mars. Ramsis was used to fit a manikin to a space suit and in the driver's seat of a vehicle. Figure 11 shows the initial environment used to introduce the authors to the Ramsis software.

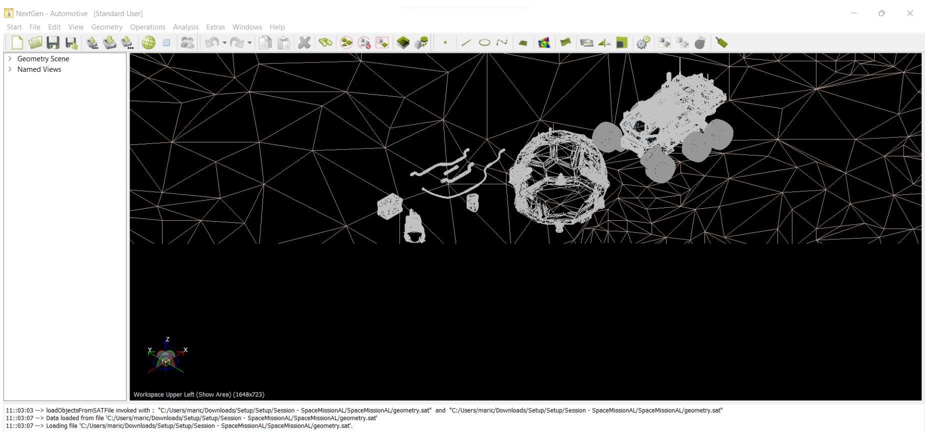

Fig. 11. Ramsis environment screenshot from initial Ramsis class assignment.

One challenge faced when completing the analysis for this assignment was effective use of the Ramsis software in general. As students with no prior digital human modeling experience, the mechanics of creating a manikin and manipulating its skeletal points was a new concept to grasp. This took considerable troubleshooting and rewatching of the tutorial videos and sessions provided. For future students, it would be useful to know that the analysis portion of the assignment is a familiar process and relatively self explanatory. Once the initial hurdle of understanding how Ramsis human modeling works, the ergonomics analysis is intuitive.

Based on the ergonomics analysis results of this assignment, the Mars rover should have an adjustable control display screen as well as an adjustable seat. This would allow for comfortable operation of the vehicle for a wider range of the population. With an increase in customizability for passengers, the rover also becomes safer. Space is hard on the bodies of astronauts. It is known that bone loss occurs in space, but effective methods of reducing its effects have yet to be determined (Greenleaf). With how little is known on effective methods of reducing bone loss, it is important to take every available opportunity to reduce the effects of joint strain and damage that are known. By creating a more inclusively fitting vehicle, the strain on astronauts bodies is reduced and safety is increased.

Requirement 2.6

The center of gravity for a passenger wearing a suit would be different from the center of gravity of a passenger not wearing a spacesuit. Since a suit has weight and mass added onto the passenger, it will have greater force acting on it and center of gravity will be different from that of the passenger without a suit. A space suit is also a different shape than a human not wearing bulky gear. This changes the weight distribution and therefore the center of gravity. To calculate the difference in center of gravity using Ramsis the evaluation would need to be done twice, once with a standard passenger and once with the passenger wearing a spacesuit. For the purposes of this report, the calculations were made using a standard manikin with no external suit. In order to more accurately perform an ergonomics analysis, the proposed suit design would need to be modeled in Ramsis and fit to specific manikins. These modifications would alter the comfort level, reach, and percentage of users operable for the rover. With this suit in the software, an ergonomics analysis of the Mars rover could be tailored specifically to a vehicle, person, and mission.

Requirement 2.7

For motion conditions on the Mars rover, a couple of risks must be analyzed to determine safety compatibility with suits and machinery. To begin, inner pressure within the suit may affect the user's upper extremities. A study between July 2002 and July 2003 conducted a study of training sessions with extravehicular mobility units. Over 50% of participants had injuries or suit fit problems involved in their upper extremities, including "hand in 122 cases, the elbow in 14 cases, and the shoulder in 66 cases" (Viegas, 2004). From this study, additional research needs to be conducted on the long-lasting impact of extensive extraterrestrial vehicle travel. Participants in the study have also been identified with nerve damage, including "cell necrosis, apoptosis, axonal microtubular transport degeneration, or segmental demyelination." These neuropathic degenerations require extensive and continuous examination of Mars Rover passengers. Conditions may change between Earth and Mars, especially considering the gravitational and atmospheric differences. Longevity of studies and intensity of vehicle use are also additional factors that must be ergonomically analyzed.

Outer forces of the steering wheel may also yield risk under improper training or harsh conditions. In a Swedish study, ergonomic engineers found that 55% of males and 64% of females hold their hand position above 10 and 2 o'clock. These extended hand positions "might affect spinal posture and thereby increase backset distance, which influences neck injury risk in impacts" (Jonsson, 2011). Though the study focused on automotive transportation on Earth, results may apply to the Mars rover, as the vehicle structure is similar. From the study analyzed, there seems to be agency in drivers to reduce outer force trauma and minimize injuries. An article examining blunt cardiac injury in traffic incidents came to a similar conclusion. Various simulations were carried out for thorax-to-steering impact at different heights. Results indicated that "contact force was decreased when the inclination angle was decreased." These results can be further extrapolated to conclude outer force risk, specifically for steering wheel against driver, may pose an issue for passengers. However, results indicate that these risks can be reduced from ergonomic research.

For both outer and inner pressure forces on passengers, risks can be mitigated with proper training. For degenerative conditions that may occur in outer space, additional exercise training may reduce deterioration of muscular strength, increase cognitive performance, and prolong bone loss risk (Greenleaf, 1989). Vehicle collision risk can also be reduced with proper driving techniques and additional safety protocols established for Mars rovers. Both external and internal forces can be analyzed ergonomically for potential risk and can be reduced accordingly.

2.6 Future Work

As human design is a key factor in designing any prototypes regarding space missions, multiple types of research are done and recorded on NSF as well as awards pertaining to such research. Before designing a spaceship or space transmission machines, it is necessary to understand humans' musculoskeletal systems. Researchers from Rutgers University has been awarded by NSF for their research on such topic on the musculoskeletal system and their goals were as follows: Allow real-time calibration through overlay between fluoroscopic images and optical images; Automatically reconstruct 3D bone models from CT and MRI scans in real-time; Automatically estimate 3D in vivo bone movement through 2D/3D registration; Automatically establish 3D bone coordinated systems and convert the 3D in vivo movement into 3D joint kinematics; Fuse the accurate joint kinematics, whole body kinematics, muscle activation, and body reaction forces and visualize all the information on digital human models. (Referred from the Award page listed in references. Rita Rodriguez, the primary researcher and program manager from NSF, has made her point clear that algorithms of human bodily functions are far more important than doing any other operations on machinery. There must be steps to be taken prior to any research or procedures in order for an operation to be successful. She and her team plan on taking CT and MRI as well as X-Ray of the musculoskeletal system in a real-time space setting to prevent any injuries or limitations an astronaut could have in space.

Future publications based on this research are infinite. It will not only involve industrial engineers and aerospace engineers, but it will also bring forth biologists as well as psychologists to the field. It could lead to such simple publications as the human musculoskeletal system in space to complicated publications such as the biological and psychological limitations of humans in space. Since space is full of uncertainty, researchers can only perform experiments in space-like settings that most closely imitate space. Each experiment could lead to different results and various findings. The most anticipated publication from this award seems to be how to prevent injuries considering space human factors.

2.7 Experience

The preparation in lecture was crucial for conducting sound bibliometric analysis using a variety of tools. Further analysis using said tools can be seen in Professor Duffy's chapter on "Human Digital Modeling in Design," where analysis in CiteSpace, VOSviewer, NGram, and other bibliometric software are used. From prior experience in IE 330 and IE 578, we applied the same concepts to conduct analysis on a variety of topics ranging from ergonomics to statistics. There is a clear link between the applications used in class and the reports synthesized in industrial fields.

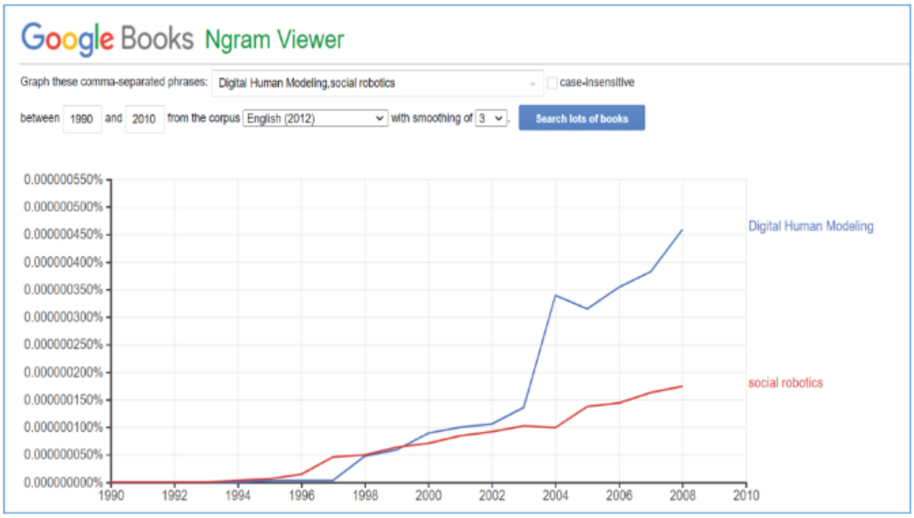

Fig. 12. NGram Viewer in Salvendy Handbook, portraying search results of Digital Human Modeling and Social Robotics over time.

Other similar figures are seen throughout Chapter 29, indicating the relationship between key subjects and citation analysis. From prior experience, the team has used similar software to model data via an educational medium. For future research, proper citation and data visualization tools are useful for communicating information effectively. Within the professional space, the team has used Powerpoint and other presentation software to monitor changes and provide updates. Applying the lessons learned throughout the chapter and during lecture remains evidently crucial for career success.

Kevin Jin's personal experience lies within the consulting field. He has had the opportunity to work within numerous consulting projects, all requiring some form of data analysis and reporting. From these projects, a team had to extrapolate different sources of data within Excel and other forms of research. Reporting this content created the challenge of conveying information effectively and appropriate to each audience member. For example, C-suite executives typically like big ideas and profit analysis, while project managers are informed on project status, challenges, and risks. Applying the skills learned in class, he was able to optimize his presentation style and delivery according to a specific audience by using different graphics and structuring the presentation in a thoughtful manner. Citing sources also played a pivotal role in maintaining credibility and aligning company objectives. Proper citations organized his portfolio, thus allowing for easy access across hundreds of files. Overall, the concepts explained in Chapter 29 enabled success within his professional career.

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Modeling digital human measurement for space environment

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This report focuses on creating digital human models (DHM) that incorporate reliable posture and motion prediction models for a range of populations. To provide validity for simulations of complicated dynamic tasks, the posture and motion prediction models currently used in DHMs must be modified and made based on actual motion data (Ahmed et al., 2018). Furthermore, if reliable human posture and motion prediction models are created and put to use, they can be combined with psychophysical and biomechanical models to provide a deeper understanding of dynamic human performance and population-specific limitations, and these new DHM models will eventually function as an effective ergonomics design tool. In this regard, we are using RAMSIS software to provide methods for predicting driver postures and comfort. RAMSIS's main component is a highly accurate three-dimensional human model based on anthropometry databases from around the world that can be used to simulate occupants with a wide range of body measurements. We use a variety of additional analysis tools, such as those for comfort studies, eyesight, reach, and force inside this software to have an assessment of comfort in the design process.

Keywords: Ergonomic Analysis, Digital Human Modeling, RAMSIS, Simulation

1 Introduction and Background

Early in the media and entertainment business, digital human modeling (DHM), a technology for replicating human interaction with a product or workplace in a virtual environment, was introduced. The manufacturing, agriculture, healthcare, transportation, and aviation industries are rapidly adopting this technology to proactively assess human performance and its constraints. However, DHM's applicability in designing ergonomic products and work environments for the space environment is restricted.

Since new-generation simulators are used in training for spacecraft launch, flight, and landing, distributed simulation is essential for modeling complex systems. Astronauts now spend hours practicing in simulators for every minute they spend in space so they are comfortable with the scheduled tasks and can respond quickly to unforeseen circumstances. They rehearse their own decisions and learn to predict the reactions of their teammates, which is crucial for successfully overcoming an unanticipated issue in space. In addition, simulations are essential for flying tests since this is where everything comes together.

After multiple iterations of development and testing, the results are analyzed to optimize designs for specific situations. To achieve required scalability, the design strategy leverages the benefits of having several layered architectures and more flexible middleware solutions. This virtual review approach is effective for producing user-centered products by adding human factor concepts at an early stage of design, which decreases design time and enhances product quality. Several distributed simulation research projects have focused on web-based worldwide cooperation and its structures for improved model implementation.

The term "model" can apply to any component of the human; however, it most commonly refers to a mathematical instrument for the simulation (typically in software, which makes the simulation digital) and prediction of some aspect of human performance and future results. This area is limited to the use of human models in physical design, for instance in human factors engineering. Typically, this design endeavor involves human interface design, and the computer models employed are anthropometric (Digital Human Modeling, n.d.).

To represent the real world in simulations, a simplified model that captures the actions conducted during a process or the phenomena that emerge throughout a process might be utilized (Litwin & Stadnicka, 2019). The chance for students to observe a process in action is usually limited. As a result, simulations can be used to study the behavior of processes. In today's engineering workspaces, modeling, simulation, and computational tools are commonly used to aid in the research and design of systems. Because of this, modeling and simulation capabilities have been included into several scientific and engineering fields as analytical tools to improve the understanding of complex phenomena and as predictive tools to evaluate the viability of new designs (Magana, 2017).

Professionals can effectively augment theoretical and experimental methodologies to the discovery and innovation processes in engineering workplaces by using modeling and simulation. Engineering education policymakers and practitioners, among other stakeholders, have stressed the need for educational researchers and educators to consider strategies to integrate students in the activities of professional science and engineering through modeling and simulation.

Recent advancements in computer technology over the past 20 years have made it easier to build computer simulations for ergonomics. Digital human modeling (DHM) simulations are used to rate the productivity of human operators. DHM can also be used in conjunction with computer-aided design to evaluate the ergonomics of product design (CAD).

Simulation can aid in the evaluation of an ergonomic design by offering a preliminary evaluation of ergonomic characteristics in a simulated or virtual environment. A crucial aspect of enabling simulation in ergonomic-related investigations is the capacity to assess alternative state-of-the-art solutions or the impact of advancements from an ergonomics standpoint [2]. One of the most important components of ergonomic design to consider is human-centered design (HCD). To better address user needs, HCD emphasizes iterative system development while also guaranteeing that end users and stakeholders are actively involved in the design process (Margetis et al., 2021).

One of the key elements essential to human well-being is good health. As healthier populations live longer and are more productive, it also contributes to the economy's advance (Vardell, 2020). Employees frequently engage in some sort of physical activity at their place of employment. Some job functions necessitate continuous manual effort. An ergonomically sound workplace can minimize musculoskeletal pain, increase efficiency and productivity, cut expenses associated with production, and promote overall well-being (Chim, 2019).

More advanced tools are now required to move heavier goods, equipment, and material throughout the workplace as needs for job sites have increased. The introduction of the mars rover addressed this need in the space environment. These vehicles are frequently used for exploration and carrying out routine research tasks in the space environment. However, the rover must be properly designed to meet all the needs of an astronaut, where the needs cover a broad range of physical, cognitive, and research needs. A poorly designed rover may be uncomfortable for the operator and will not accomplish the intended research objectives. For a mars rover, like any other, seat design is one of the most crucial steps among all other design considerations. Long durations of time spent riding on uneven terrain with poorly designed seat characteristics can result in repetitive use injuries to the musculoskeletal system, much as those experienced by forklift users, according to research (Collins et al., 1999). Musculoskeletal injuries, such as sprains, tears, strains, discomfort, and pain, account for roughly 52% of reported injuries for 10,000 workers (Larsson & Rechnitzer, 1994), posing a serious risk to human health(*U.S. Bureau of Labor Statistics*, n.d.).

It is crucial to establish an ergonomically sound workplace for safe working conditions. A comfortable workplace can enhance productivity by fostering a positive work environment. The key goal is to thoroughly comprehend how astronauts will interact with the environment of the mars rover and apply that knowledge into the design. In order to do this ergonomic evaluation of Digital Human Modelling utilizing a 3D CAD manikin tool that replicates a real-world setting, RAMSIS is one of the leading simulation tools on the market. The decision-maker in an organization can better grasp prospective consequences based on design modifications with the use of visualization using digital human models.

To improve the physical ergonomics of workstations, the discipline of ergonomics is becoming more and more dependent on digital human modeling of workers (Bäckstrand et al., 2007). This modality is relatively inexpensive and more effective than traditional physical ergonomic modeling techniques. Engineers can modify the surroundings of workstations and evaluate how ergonomic changes to them will affect human operators using computer-aided design software applications like RAMSIS (RAMSIS NextGen Ergonomics, Human Solutions, Kaiserslautern, Germany).

2 Problem Statement

In this report, we use RAMSIS software to simulate astronauts' posture while driving the mars rovers and assess their comfort accordingly. To assure optimal accommodation of these occupants from the outset of the design process, RAMSIS' main purpose is to give designers a realistic depiction of occupants in their CAD model, both in terms of anthropometry and posture. Therefore, we first model a set of boundary manikins inside the vehicle with the optimal posture. To reduce discomfort to an appropriate level for all manikins, this project focused on evaluating the level of comfort experienced by various operators (i.e., 5th, 10th, 20th, 30th, 40th, 50th, 60th, 70th, 80th, 90th, and 95th percentage body measurements) and the adjustment ranges required for several aspects of the driver's seat, driver's touchscreen, comfort, visibility, blind spot, and readability in the space environment

3 Procedure

For this project, the following statement of work was performed, which guided the analyses used in this project:

1. Creating boundary manikins for the tasks
2. Moving the boundary manikins and placing them in the car seat
3. Analyzing and enhancing the seat adjustment range to ensure that all percentile manikins can comfortably access the primary controls.
4. Assessment of the passenger's comfort level and the position, reach, and reach of the touch screen
5. A review of the driver's visibility when operating controls
6. A discussion of the center of gravity for both the body and the suit of the passenger
7. A discussion of restricted motion situations, exterior forces (such as the driver's anatomy and the steering wheel), and internal pressure from the body against suit.

Before getting into the analysis using RAMSIS, we first conducted several bibliometric analyses on different platforms using the keywords " Ergonomic Analysis, Digital Human Modeling, Simulation " From Scopus, 88 research articles were screened by the website (shown in Figure 1).

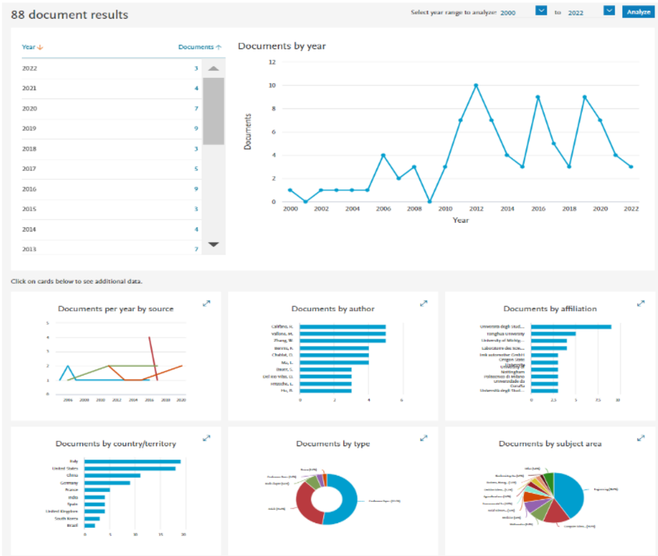


Figure 1: Bibliometric analysis of Scopus articles

Using VOS Viewer, the associated research networks were also recognized (shown in figure 2). This software is used to construct and visualize bibliometric networks. These networks can be constructed through citation, bibliographic coupling, co-citation, and co-authorship links, and they can include journals, researchers, and individual publications.

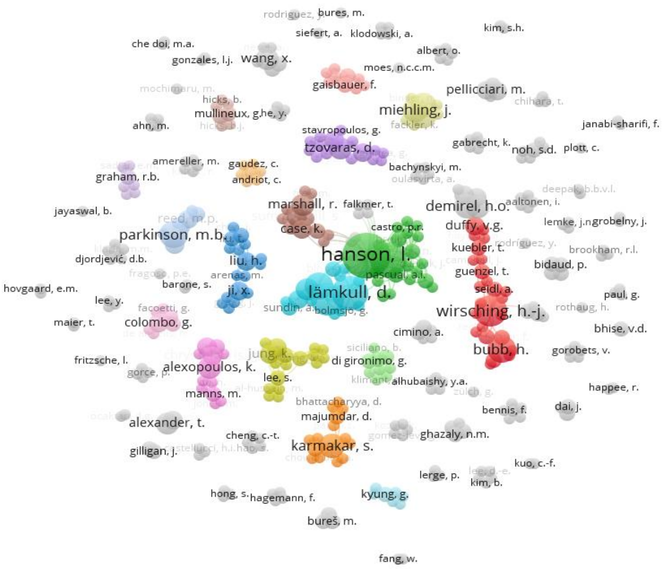


Figure 2:Bibliometric analysis of research networks using VOS Viewer

3.1 Boundary Manikin Creation

As mentioned, RAMSIS software allows us to simulate vehicle occupants realistically and analyze the ergonomics of interiors. In other words, it enables us to generate any target group, to define size, gender, population and age-specific characteristics and model them in 3D. Figure 3 shows the platform of RAMSIS software.

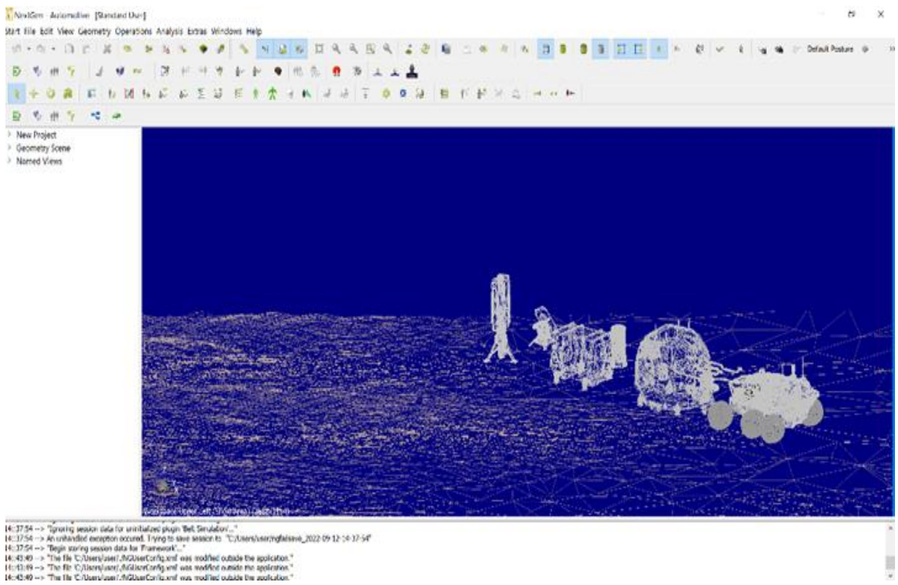


Figure 3: Ramsis software environment

To integrate the mars environment into the digital modeling platform, NextGen Automotive was opened from the RAMSIS folder. Following that, the "Anthropometry" menu's "Define Typology" button was clicked. Both male and female manikins were generated using the "Germany 2004" anthropometry database. Subsequently, to specify the special typology for each manikin, the "Control Measurements" option under the anthropometry tab was chosen. The male manikin's age range was set to 18 to 70, and the established percentile values (i.e., 5th, 10th, 20th, 30th, 40th, 50th, 60th, 70th, 80th, 90th, 95th percentage body measurements) were used to determine the manikin's body height, waist circumference, and sitting height. Following the development of these physical typologies, by selecting the feature "Role Definition," different roles of manikins (i.e., driver, passenger, and mars) were generated.

In other words, different roles can be assigned to the RAMSIS inhabitants, each of which is familiar with its typical posture and movement patterns. Based on the inside of the car, RAMSIS automatically determines these task- and role-specific postures. Figure 4 shows 4 manikins with roles of driver, passenger, standing, and standing symmetrical.

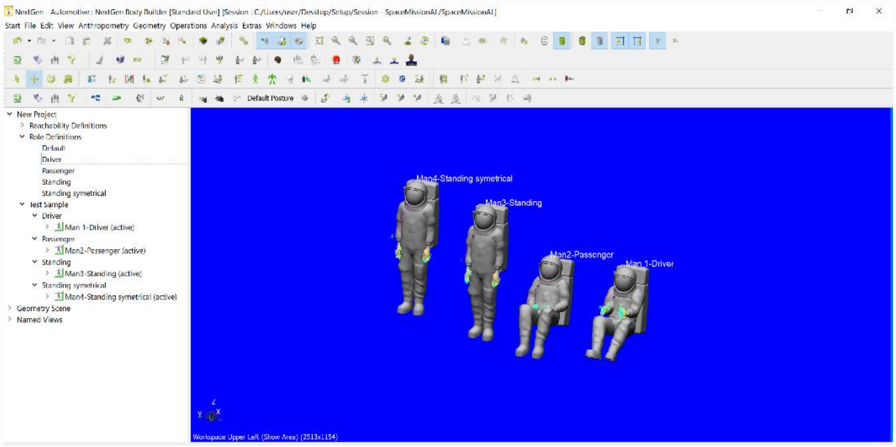


Figure 4: Manikins in 4 different roles

We selected a 5th percentile male body, named it "5th percentile male," and assigned it a "driver" role. Similarly, we assigned the driver role to all the manikins of different percentiles that we created in the last step. We kept the other options as they defaulted in the additional options section. We also created two other roles of type "co-driver" and "mars" manikin.

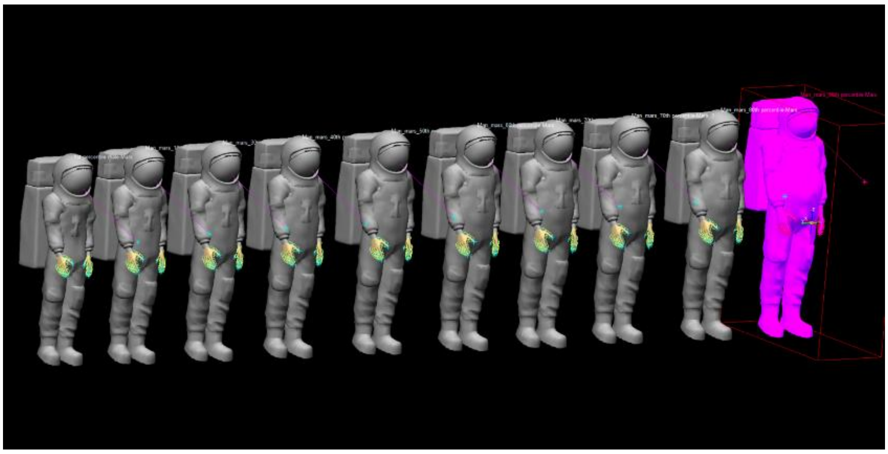


Figure 5: Boundary manikin generation

3.2 Placement of the manikin in the seat

The rover seat design should be flexible enough to accommodate all ranges of manikins or people in real life. That is why we put different use case-based constraints to the seat at this stage. Here, flexible seat design means that the manikin must be able to reach the paddle, the screen, and other navigating equipment, which was designed to ensure a safe and comfortable ride.

Initially, the geometry downloaded and provided didn't have the seat adjustment function. To achieve that, we first clicked on the seat, highlighted the geometry, clicked on the geometry tab, clicked on point, and then from the drop-down selected the option "create on object" and then clicked on the "object" box, which was then turned yellow. After that, when we clicked on the seat geometry, the geometry identifier was immediately entered into the object field. At that point, we discovered one red point that had formed on the seat. Because of the difficulty of color contrast, we, therefore, modified the color of the seat to make the red point apparent (we did that by clicking on the seat and then changing seat properties).

The "define constraints" icon was clicked (before that, we have to ensure we have the driver manikin selected). We selected "target" as the restriction type, followed by "manikin comp" and "PHPT," which eventually changed to "H point" automatically. After that, we clicked on Env.Obj and clicked the point we had just constructed. The manikin was then placed on the seat automatically when we pressed apply. The manikin was sitting, but its position concerning the seat was not well defined. The manikin should occupy the center of the seat, but in this instance, it was positioned improperly.

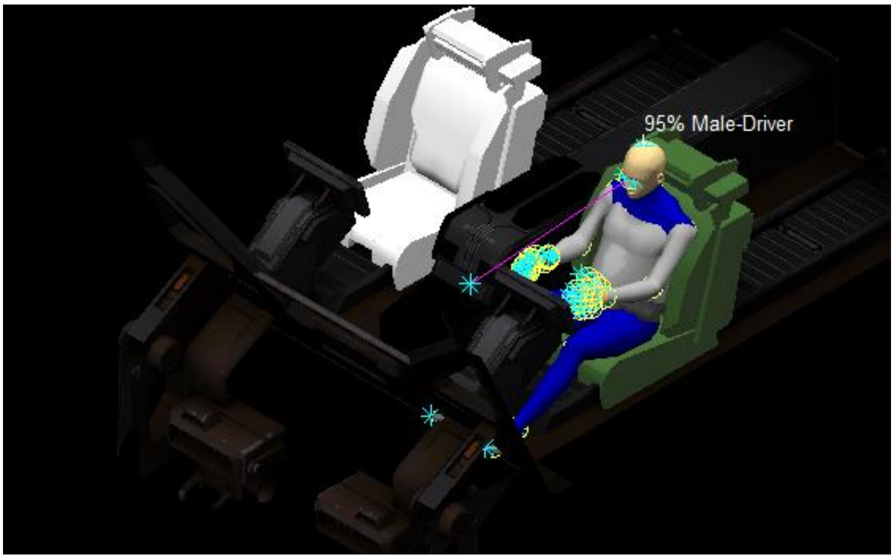


Figure 6: Placement of the manikin in the rover seat

We used the keyboard keys "T" for top, "F" for front, and "L" for left view in the model window. So, to fix the seating alignment, we clicked on the manikin, chose the "translate" icon, and then in the translation mode, chosen "relatively/vector." We might then enter particular X, Y, and Z values to move the manikin in relation to its present location. By hitting the "T," "L," and "R" keys appropriately for our needs, we kept the manikin in the view we chose during the process.

To simulate this seat adjustment, we have drawn one line in the forward direction, allowing the seat to move back and forward in accordance with the needs of the person occupying it.

To achieve this, we employed a tool feature. When we chose the "analysis" tab, "calculate body point," "add," and "PHPT" in the body point fields sequentially, a new point was generated at the boundary of the person's heap. After clicking the newly formed point, we duplicated another point by clicking "edit" > "copy" > "edit" > "paste." Next, we moved the x-axis position by 200 mm using the translate icon. Next, we clicked "create geometry" on the geometry tab once more, choosing the "point to point" line type while selecting the initial and last points we had already generated. We were able to establish a line for horizontal seat adjustment in this way.

Then, using the "define restrictions" option, we added another constraint to the newly created H point, just as we had done with the first point. The line that was just built served as the Env. Object in this new constraint, allowing us to guarantee that the manikin can move anywhere along the line. After choosing the line, we selected the "create" and "posture calculation" tabs. By doing so, the manikin could now sit with its back against the seat line. We must choose the line length when building this restriction so that the manikin can support the touchscreen and the necessary control hardware.

We didn't have any shoes on our manikin at this point. To place some shoes on the manikin, we opened object properties with the right mouse button, navigated to additional options > shoe model, selected "workboot" as the type, and then clicked apply to activate the shoe.

At that point, we added another constraint to restrict the left heel of the manikin's movement in the XY plane. To view the points, we were creating beforehand, we had to turn off the texture. Then we selected geometry > point > construct on object and clicked to designate a point on the car's base.

Then, by selecting Geometry > Create Geometry > Plane > Point and Vectors, we generated a plane. The first vector should be the x axis and the second vector will be the y axis, and the point should be the point we generated previously. Now that we've done that, we've added a new restriction to ensure that the shoe's heel stays above the surface we made. To accomplish this, we choose constraints > define restrictions > manikin comp. Here, we had to choose the lowest position on the left heel, which was labeled "LeftHeel" in the Manikin comp. The plane that we previously generated was selected in the environment object before we clicked the "posture calculation" icon and "start" button. So, the plane was marked on the heel of the manikin. We repeated the process with regard to the identical restriction for the right heel.

To prevent the feet from touching the steering sidebar in the XZ plane, we added more constraints in the following stage, similar to how we did for the heel. To do that, we first built the surface via the aforementioned method (first creating one point using geometry and then creating one plane using point and vectors where the vectors will be X and Z axis this time). At this point, we selected the "define restrictions" button, the "limit surface" restriction type, and the "left Inner Ball" small yellow point on the left heel of the manikin. We entered "Negative Y direction" in the orientation field and added a 50 mm offset. At this point, the manikin will tilt if we calculate posture, and the right foot will encroach on the steering sidebar. In order to prevent it, we added additional restrictions by clicking on define restrictions, restriction type (pelvis rotation), selecting "tilt sideways," clicking "update to current angle," and then clicking on posture calculation. We were still getting the right feet inside the steering bar at this point. To prevent it, we implement the identical offset constraint that we did for the left feet, except this time the constrained surface is the right side of the steering wheel bar instead of the left.

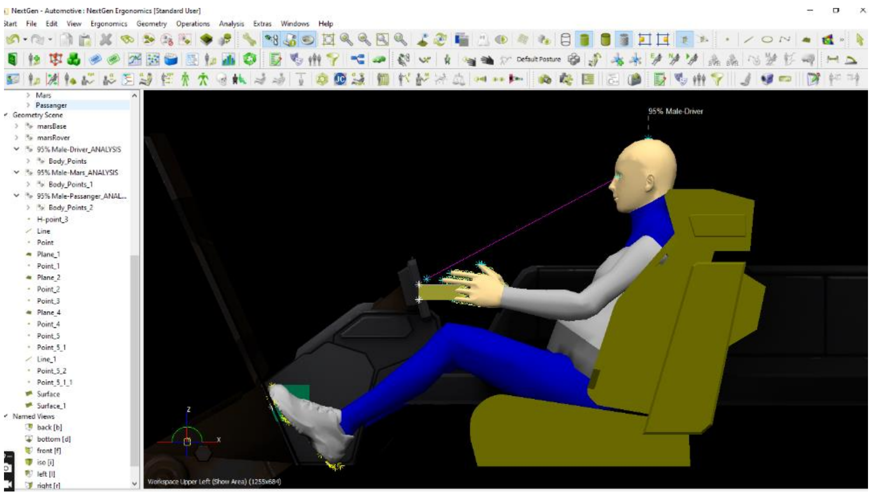


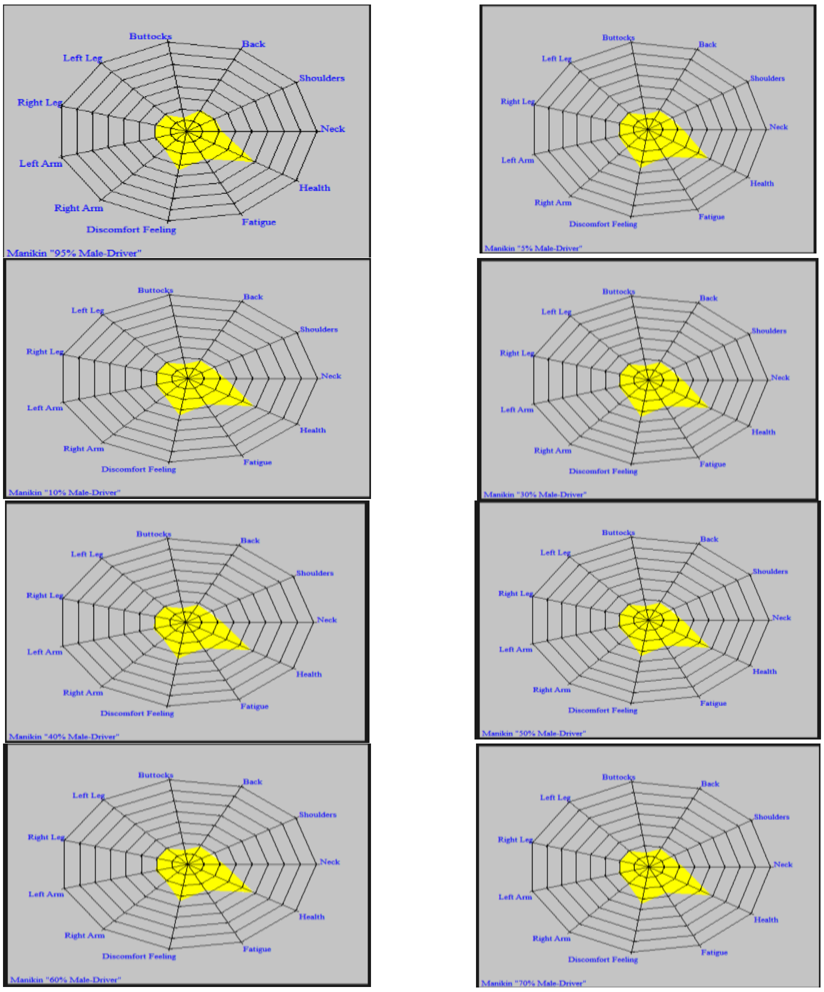
Figure 7: Touch screen adjustment restriction and manikin shoe assignment

3.3 Comfortability assessment

We defined a plane (200 mm * 50 mm) in the XZ plane for the display touch screen adjustment for both hands for the manikins in the following phase. Then, to ensure that the driver can access the touchscreen while seated, constraints were put in place. At this point, we copied all the constraints we created for this particular manikin and used a special paste to apply them to all the manikins of various sizes. Then, with the posture calculation active, all of the manikins of different sizes were seated on the rover seat with the previously mentioned predefined restrictions.

Figure 8 displays the results of the discomfort assessment tests performed on the mars rover driver manikin for each of the anthropometric measurements outlined above.

According to the results of a discomfort evaluation on different body parts, a value from 1 to 8 are given, where 1 denotes the most comfort and 8 is the lowest comfort. For instance, the pressure load on the spinal column correlates with the assessment's health score. So a lower health value is preferred. According to the evaluation, the current seat design provides all of the manikins with a good comfortability matrix. When we compared the achieved comfortability values to reference values, we observed that our proposed system ensures a value that is lower than or equal to the reference values for all the manikins.



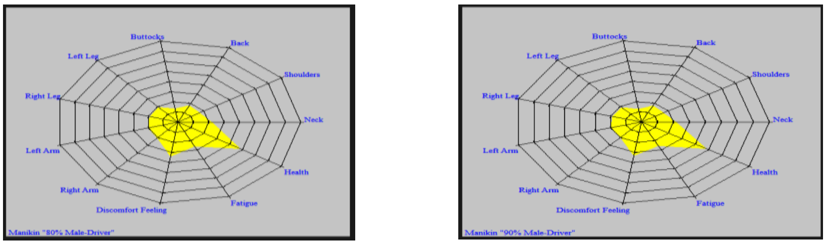


Figure 8: Comfort assessment for the manikin's of varying anthropometric measurements

We also adjusted the manikin's neck posture to ensure that it was looking at the touch screen. Figure 9 shows the posture of the neck and body when staring at the screen. We also evaluated the smallest font size necessary for the manikin to comfortably read the content on the touch display. As seen in figure 9 (right), this analysis indicates that the display's minimum font size should be 1.98 mm in width and 3.02 mm in height.

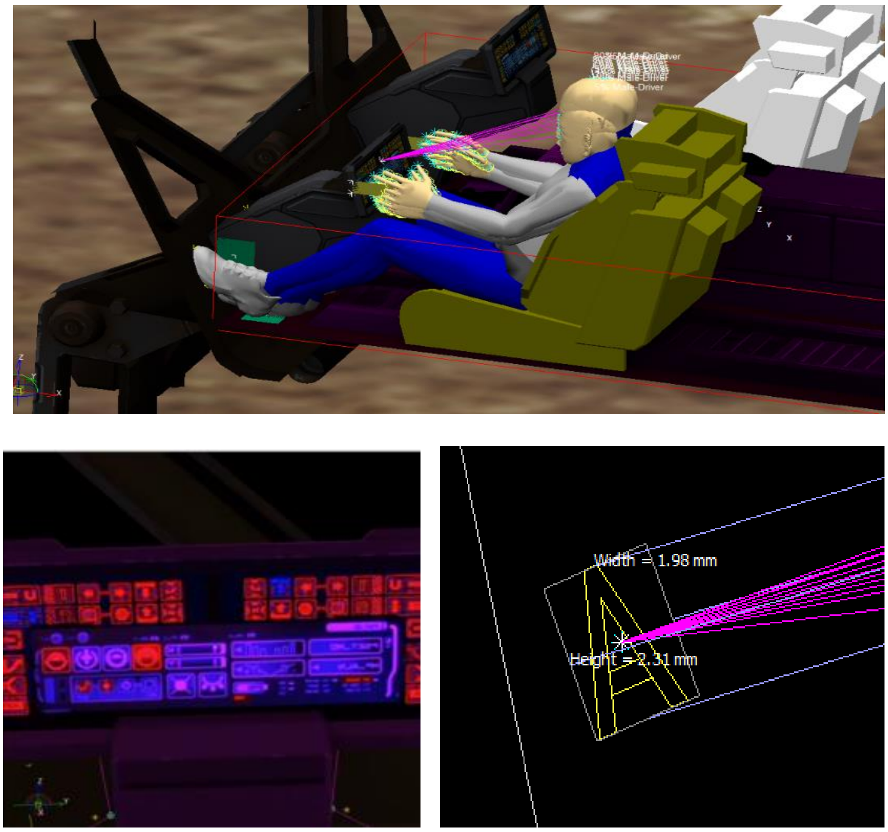


Figure 9: Neck posture (top) display gazing point (bottom left), and, minimum font size (bottom right) of the manikin

A picture of the 95th percentile driver's field of vision is shown in Figure 10. Parts of the windshield glass structure block the driver's forward vision when he is looking down, creating an awkwardly angled blind spot. Due to this blind zone, the driver may find it difficult to control the vehicle safely. As a result, the driver may compromise the safety of the rover and the object in that blind region. This suggests that the windshield design has to be modified to improve visibility to the front left corner.

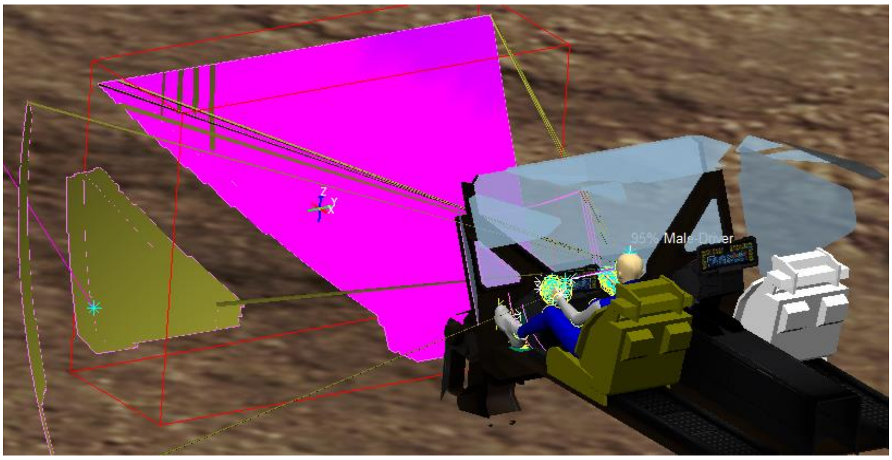


Figure 10: Visibility study and blind spot detection

The 95th and 5th percentile manikins' left, and right arms were likewise assessed for reachability. Figures 11 show that, for both percentiles, the touchscreen is within the manikin's reach, ensuring that the existing design will meet the needs of all other manikins since it is already accommodating two extreme examples of manikin sizes. Here, the 95th percentile male's reachability is represented by the larger half sphere, while the 5th percentile male's reachability is represented by the smaller half sphere.

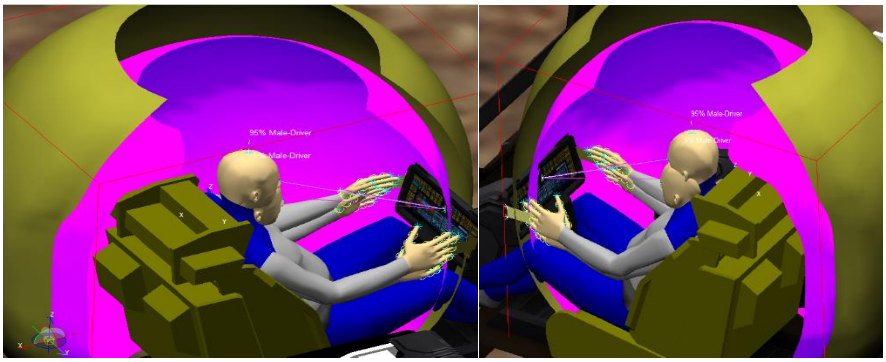


Figure 11: Left and right arm reachability for 95th and 5th percentile manikin

3.4 Proposed design changes

Based on the data and corresponding analysis, we recommend an adjustable touchscreen monitor which can move in the XZ axis where relative X and Y movement values should be at least 200 mm in X direction and 50 mm in Y direction. In addition, the front windshield should be redesigned as due to the support structure of the left side glass, there is a big blind spot which may compromise the safe operation of the vehicle in mars environment.

4 Discussion

The current study was done with the assumption that the driver was not wearing a space suit inside the rover. Nevertheless, based on our investigation, we created the seat adjustment so that the driver could sit on the rover while wearing the suit. However, the substantial weight of the suit will cause the astronaut's center of gravity to shift from where it is currently, therefore this must be taken into account when analyzing movement while wearing the suit. Currently, since the manikin was not thought to be wearing a suit, the center of gravity would be in the front as opposed to when the manikin was wearing a suit, where the extra weight of the suit would cause the center of gravity to shift backward. RAMSIS allows us to conduct this further analysis. This might be one effective way to continue this work in the future. This knowledge would be beneficial to have in addition to a question-and-answer session with a RAMSIS representative once an initial demonstration is finished so that users can troubleshoot any outstanding problems with their help. Additionally, more discussion is required regarding the numerous studies conducted and the correct interpretation of the results. Our interpretation of this data may deviate from its intended use because, specifically, the visual field analysis at the back of the rover was not covered during the demos for the current study.

5 Future work

The surrogate modeling strategy utilized in the DHM research provides a time- and resource-efficient alternative to conventional reactive ergonomics approaches. The computational method proposed in this study does not require the presence of an HFE expert in order to conduct experiments and evaluate early design concepts. In contrast, executing task simulations with idea product models in DHM can provide the benefit of iterating digitally on design concepts (Ahmed et al., 2018).

Anthropometry is a key part of DHM-based product design and workplace evaluation. Various anthropometric databases are incorporated in RAMSIS software to obtain the manikin for the targeted population in the simulation process; however, in the current version of RAMSIS, we are limited to the Germany and Germany 2004 databases, so expanding the database would allow us to model a manikin that is more representative of the population as a whole.

After attending HCI2023, the International Conference on Design, User Experience, and Usability, it became clear how important it is to validate the suggested method by researching to determine the applicability of the DHM and surrogate modelling concerning human-product interaction. Frequently, designers place a greater emphasis on other technical aspects of product development than on some of the most essential HFE evaluations.

We have not shown the feasibility and effectiveness of the design method in this article. This is essential for industries to embrace our model to conduct a validation study comparing the results received from our model, which includes a functional Mars-rover prototype, with the results obtained from people using a simulator setup. Despite the financial burden and delays in the total time-to-market, many software can embrace these costly prototypes and time-consuming human subject data collecting according to the outcomes of this study.

Implementing artificial intelligence (AI) to produce or synthesize models, which is gaining acceptability, is a second possibility for future work. Their duties are currently limited to specific performance types, but this is increasingly changing. The relationship between actual humans and digital humans will strengthen over time. It will go beyond observing a computer-based manikin. However, such an integration of technology for the space environment is currently restricted and would require substantial collaboration between ergonomists and designers to develop. DHM users must comprehend human variability and its impact on design, the implications of variable and unpredictable human behavior, the extent to which the models are indicative of a particular capacity, and the ramifications of contemplating a plan univariately (Rabelo et al., 2013).

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Grammarly Score (Initial):

Performance

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74

Word count

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Words	4,829	Speaking time	37 min 8 sec
Sentences	291		

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84

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Simulation in Space Ergonomics: A Systematic Review

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Abstract: There are numerous potential applications for human modeling in the fields of ergonomics and human factors. This paper presents a RAMSIS simulation experiment, useful for computing ergonomic performance metrics in space systems. The amount of versatility in human modeling, which can include several anthropometric variations in demographics, body structure etc., is critical to consider while before starting the production run of the product design. It is interesting to note that the demonstrated application of human modeling in the paper is relevant in different industries from automotive designs to ergonomic analysis of products used at home. The conducted ergonomic simulation is discussed for applications in design and optimization of industries including healthcare and human computer interaction systems. The paper talks about the importance of Digital Human Modelling in various situations during the product development phase. The simulation studies done using RAMSIS uses a human modeling interface and help compute ergonomic performance parameters in space systems as a sample study. Factors such as visibility, reach, comfort etc., are parameters evaluated to arrive at optimal design considerations for a space seating system in Mars environment. To understand the ergonomic effects of a system that can be varied with different states without actual use of costs to run production trials and testing is a widespread application of the study.

Keywords: Simulation, Ergonomics, Human Modeling, RAMSIS.

1 Introduction and Background

1.1 Problem Statement and Objective

An ergonomic analysis is a critical part of product design in many current-day industries. Cell phones, automobiles, etc., are examples of commercial ventures which need design parameters related to ergonomics pre-ingrained in the product design procedures.

While there have been abundant research in recent years in relation to human modeling and related ergonomic simulation, the field has only come out to major interest in the last decade. Since a small percentage of engineers have been trained in human factors and ergonomics, and only a small percentage of human factors and ergonomics specialists have the opportunity to learn about DHM as a part of course curriculum, the developers of the analysis tools are currently tasked with that effort of facilitating adoption within their client organizations [1]. Software developers such as Siemens-Jack, CATIADelmia, Ramsis-Human Solutions and others have been great facilitators so far for this emerging area that has such great potential for impacting product design and consumer applications in a positive way [1].

This paper addresses a critical issue on how to simulate ergonomic parameters in a product design phase before spending capital on actual production. These simulation studies are thus intended to avail multiple cost savings while iterating the ergonomic parameters to the best possible optimization, and also demonstrate methods of applications for a wider use.

Sample analysis is done using RAMSIS software to understand how anthropometric variations can considered while aiming for ergonomic designs of human machine interaction systems. Here, space applications are used to evaluate parameters like comfort, reach, vision etc., for a Mars environment.

2 Literature Review

The objective of this literature study is to understand how the field of ergonomics has played an important role in similar aerospace disciplines. With an increasing number of research pointing out the decreased comfort of astronauts during manned spaceflights, it is important to understand ways to improve ergonomic boundaries using simulation of the actual space conditions. To understand the details of research in the areas of space ergonomics, our team conducted a bibliometric analysis and reviewed published literature, papers, and journals during the last 50+ years. We used the keywords 'simulation', 'ergonomics', and 'space' as three keywords.

Using those keywords, the first analysis was to understand the frequency of these keyword usages with the help of Google Ngram. This resulted in the following graph showing the usage of three keywords from the period 1800 – 2019. The figure also shows how the usage of keywords progressed over the years. The word 'Space' tops the Ngram chart with the graph showing an upward trend after the 2000s. The words 'Simulation' and 'Ergonomics' have also been prevalent during this period but were relatively less cited as shown below.

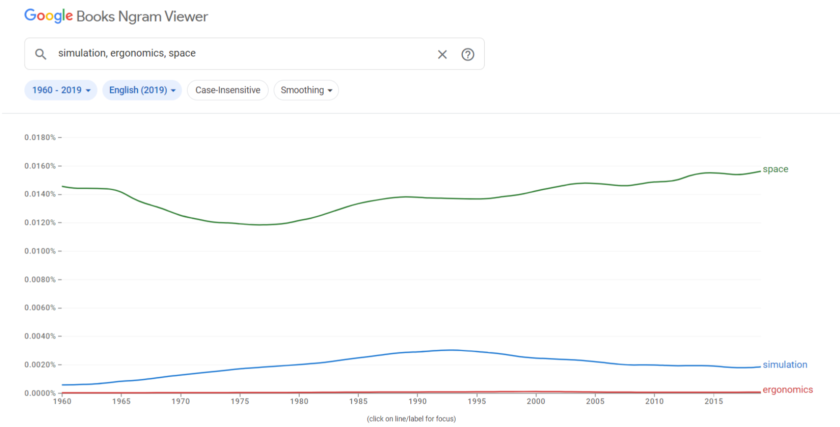

Fig 1. Google Ngram of 3 Keywords

The next step of the bibliometric analysis was to understand the usage of the keywords in different sources – conference papers, articles, conference reviews, books, journals, and editorials. This is done with the help of Scopus. The three keywords yielded 328 results in the 1963-to-2022-time frame.

Fig 2. List of results in Scopus

On further analysis, our team gained deeper insights into the usage of the above keywords in different categories. The figure below shows the research work conducted in areas – 'of space', 'ergonomics, and 'simulation' and the way it is documented. As can be seen, most of the research work in these areas is published in conference papers (50.6%), followed by Articles (44.5%).

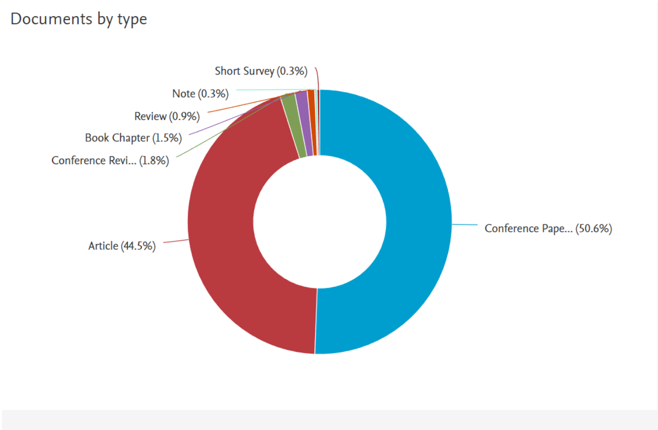

Fig 2. Analysis showing the type of document published

Next, figure 4 mentioned below gives us an idea of how the research on the keywords evolved over a period. As we can see, the research in these areas started spiking up after the 1990s with a huge upward trend seen after 2008. In the period between 2018 – 2022, 100 papers were published in the areas of space ergonomics and simulation. This shows that research in this field is on a surge and is a precursor to strong future research in this field

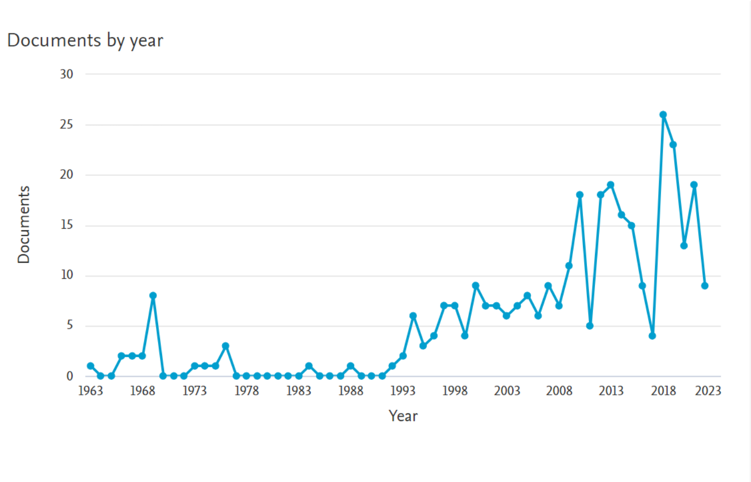

Fig 3. Analysis by year of publishing

The published research for keywords is in different subject areas ranging from Engineering to Psychology with most of them published in areas of Engineering (24.1%), followed by Social Sciences (18.8%) and Computer Science (13.7%) as shown below.

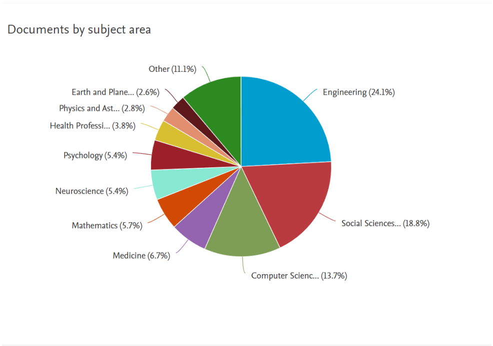

Fig 4. Analysis of documents by subject area

The graph below shows the documents associated with keywords and their affiliations. As we can see, several documents are affiliated with universities and space research organizations. This confirms that these documents are published by centers of expertise in space research.

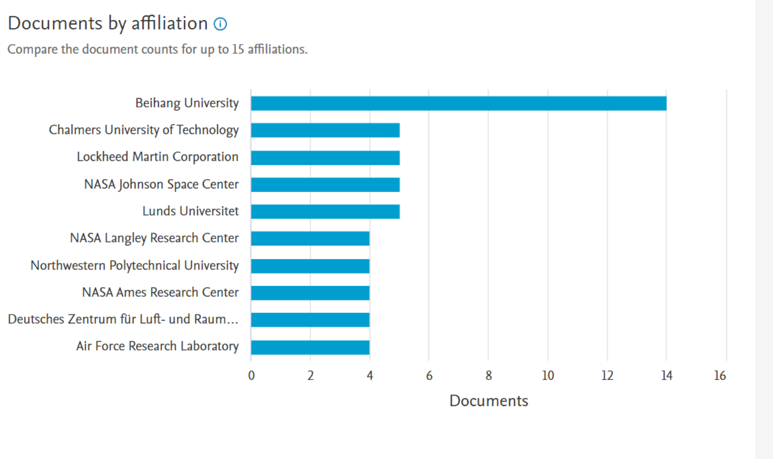

Fig 6. Analysis of document by affiliation

A deep dive into the above affiliation showed articles closely related to ergonomic improvements in areas of space vehicle design and human comfort in space. These articles gave us an insight into why ergonomic simulations are the need of the hour to tackle the problem of human comfort in space travel.

3 Procedures

An ergonomic analysis is an extremely crucial part of the design of any vehicle. A comfortable seating posture for the driver and passengers needs to be achieved for a variety of different anthropologies across different countries, genders, and distinctive physical attributes of the human body to be able to develop a good and profitable vehicle that can be used by a vast population. Other critical aspects of ergonomic analysis that need to be considered during the design phase of any vehicle are vision analysis for optimum vision range and blind spot recognition and reach analysis to determine what areas and features of the vehicle can be easily reached and accessed. RAMSIS software is an excellent tool to conduct these types of studies and determine the adjustability in the design of the vehicle so that the maximum percentage of the adult population and be comfortably accommodated in the vehicle.

In this report, we will look at the detailed steps of such analysis which were conducted with the Mars Rover. The first step was to create boundary mannikins which will encompass a large portion of the population. For that, we have considered 3 mannikins with the anthropologies of 5th percentile male, 50th percentile male, and 95th percentile male from the Germany 2004 database. Also, three different roles were defined as the Driver, Co-Driver/ Passenger, and Mars/Standing to put the mannikins into different positions.

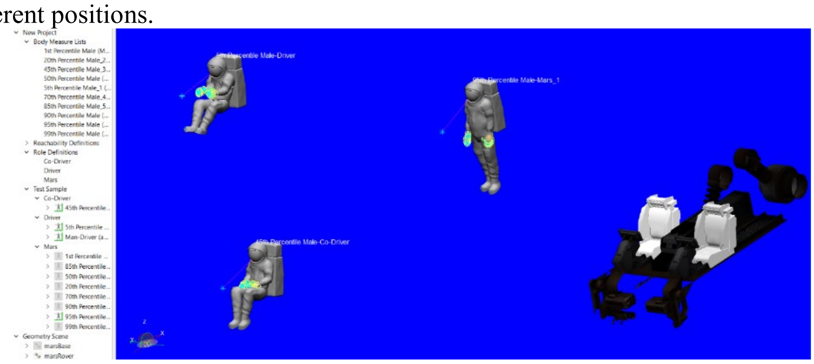

Fig 7. Boundary Mannikins and role definition

In the next step, we repositioned the test mannikin into the seat of the Mars Rover. This was done by defining the restriction target to position the mannikin's H-point on a line across the surface of the seat. Once the Mannikin was seated at the seat, other restrictions were defined to make sure that the heel of the foot is touching the floor of the Rover, the balls of the feet are touching the front portion of the vehicle and both the feet are positioned 50 mm away from the display assembly on each side. To achieve this, different geometries like a point, line, and plane were created on the surface of the Mars Rover, and various skin points of the mannikin were assigned to these geometries to achieve the desired restriction in posture. The different types of restrictions defined were:

- Target restriction H-point, Left and Right Heel, and Left and Right Ball
- Limit surface restriction for the Left and Right inner ball at a 50 mm distance from the Display assembly.
- Pelvis rotation restriction to avoid angles in pelvis rotation while achieving the above restrictions.

The final seating position of the mannikin abiding by all the restrictions defined above can be seen in Fig. 8.

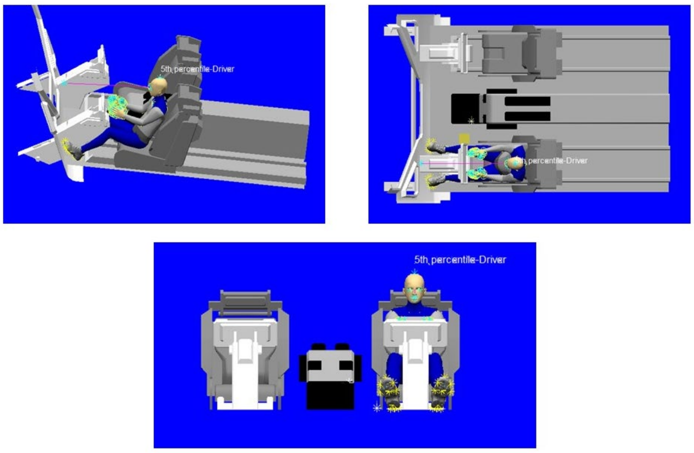

Fig 8. Mannikin seated in Rover seat using defined restrictions

Now, these defined restrictions were copied onto the other 2 mannikins using the Special Copy and Special Paste functions of RAMSIS. Running the posture calculations on all three mannikins, made all the mannikins seat in the Mars River and abide by all the same restrictions as the first test sample. Based on their different anthropologies, the difference in their seating position on the seat can be observed in Fig 9.

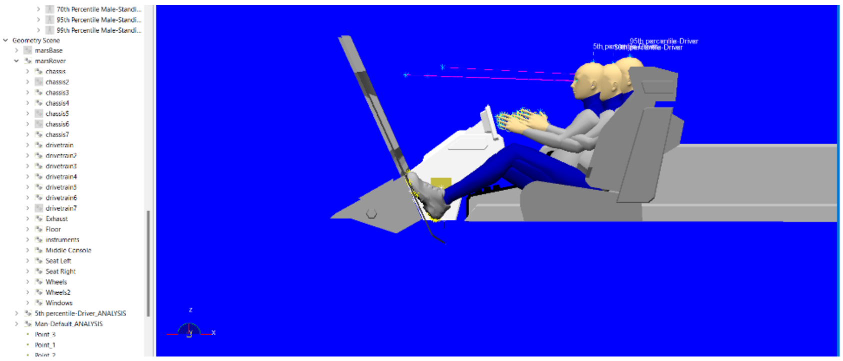

Fig 9. Different seating positions of distinct anthropologies

As can be seen in Fig 9., the seating position, angle of the legs, and the position of the hands at a comfortable driving position are different for all the 3 mannikins. In the next step, we did the Comfort feeling analysis to see what the discomfort level is of the 95^{th} percentile mannikin (furthest away from the display) to be able to touch the Display/Steering wheel.

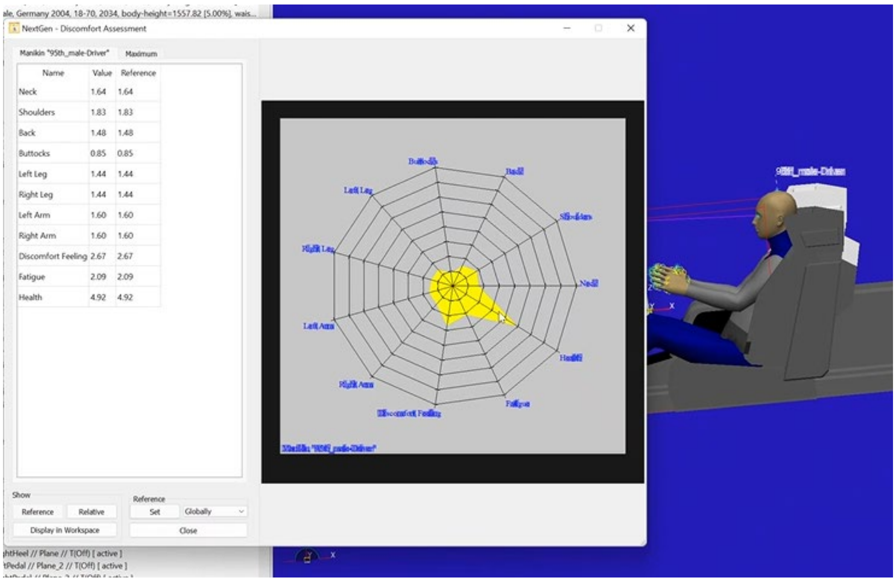

Fig 10. Comfort Feeling analysis for normal driving posture.

Fig 10., shows the original driving posture of the mannikin and the Comfort Feeling analysis for it. This is a comfortable position for driving; however, the driver is not able to reach the Display/Steering.

We then defined restrictions for the hands to grab the display and did the same Comfort Feeling analysis for the resulting posture.

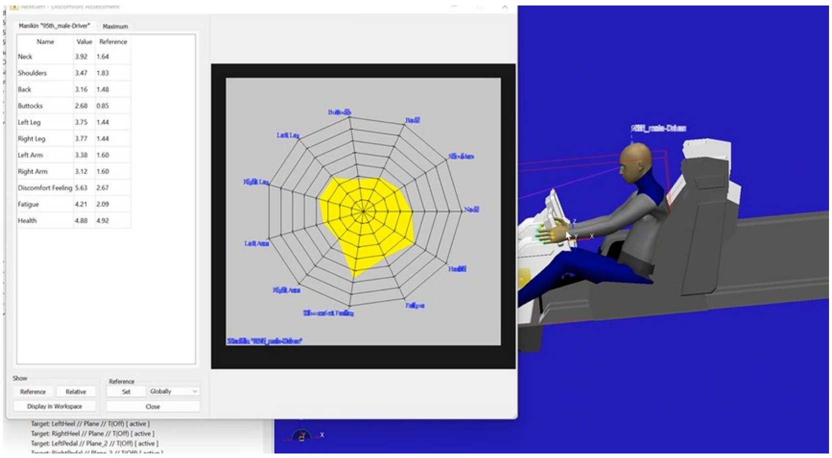

Fig 11. Comfort Feeling analysis for Mannikin trying to reach the Display.

As seen in Fig 11., the driver must lean forward to be able to reach the display which is causing significant discomfort to the driver.

Thus, the objective now is to calculate the adjustability range for the display assembly such that all three different anthropologies can easily reach, touch, and see the display. This will be achieved by designing the vehicle such that the display can be moved forward and backward along with height adjustment. For the anthropologies, we were analyzing, we defined an adjustability range of 20 mm (forward and backward) and 5 mm (height adjustment). By doing this, all the anthropologies can comfortably reach the Display/Steering which can be seen in Fig 12.

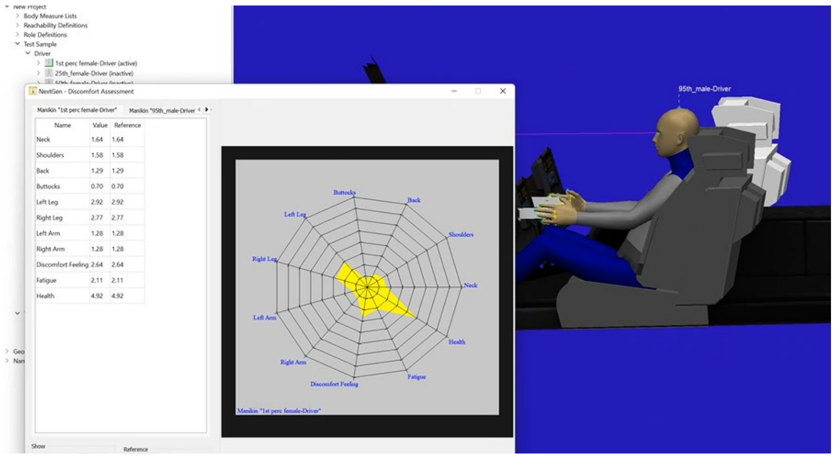

Fig 12. Comfort Feeling analysis for mannikin with a defined adjustability range

To visualize the area that the driver can reach vs the area driver can comfortably reach, we did the reachability analysis. This can be seen in Fig 13. The outer white sphere shows the maximum areas that can be reached by the tip of the middle finger, but the pink sphere shows the areas that can be comfortably reached by Mannikin.

Fig 13. Reachability Analysis

Another important factor of ergonomic analysis is also the vision analysis for the mannikins to determine what portions of the screen and the outside scenery can be seen while sitting inside the Mars Rover. Fig 14., shows how well the display is visible to the driver. The analysis also tells us the minimum character height required for 20-20 vision and the optimum distance from the screen.

Fig 14. Display Visibility Analysis

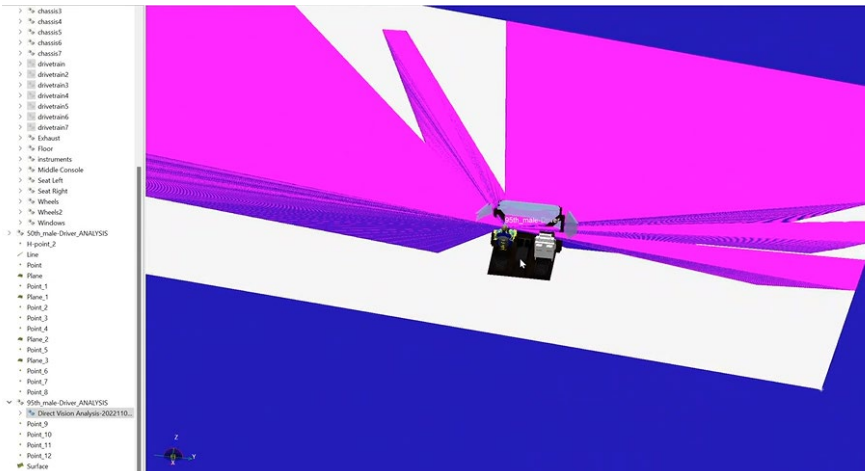

Fig 15. Direct Vision Analysis

The areas that are visible from inside the Mars Rover to the Driver are highlighted in Fig 15. The white spaces depict the blind spots of the driver. These blind spots are caused due to the structure of the vehicle and its windows.

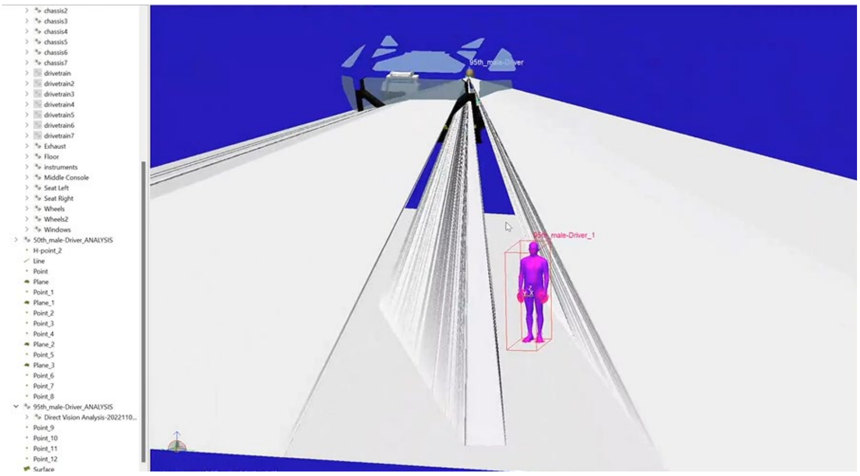

Fig 16. Blind Spot Analysis

It is extremely critical to analyze the blind spots of the driver during the design phase of any vehicle as it could be a major safety concern. This can be seen in Fig 16., where a person standing on the Mars surface is completely in the blind spot of the driver of the Mars Rover which can be a very critical safety concern.

A similar ergonomic analysis was also conducted for the Passenger/Co-Driver of the Mars Rover.

4 Discussions

The analysis has been important in understanding and elaborating, how the use of RAMSIS can be used as an ergonomic simulation design tool for common-day commercial industries of automobiles and other hardware devices. Most of us have a background in the automobile industry where interior design forms a major part of the product introduction procedure. Pre-assessing the ergonomic parameters of a design and optimizing them before rolling out production is critical to saving cost and time. Thus, these applications in RAMSIS are critical to the modern-day industry.

One issue which can slow down the application of RAMSIS simulation across application groups is the complexity of the user interface of the software. In such scenarios, it is recommended to subscribe to a support service from the service developer like the one which we had available at an academic institution. While these issues do pose an initial hurdle, constant communication and discussion with the support service do help in a better understanding of the software and its widespread application.

4.1 Analyzing center of gravity and load/force ergonomics in restricted motion

Lehto et al. 2012, describes sample analysis and NIOSH guidelines on human loading. While the application discussed is around lifting actions and are not the circumstances in discussion for the space modeling case, i.e., internal load of space suit on human body and restricted motion force like that of steering on the body, corollaries can be extended which include moment analysis considering difference in center of gravity between suit, the body and the resulting momentum on spine and other joints. Additional insight on motion resistance of the steering wheel, foot pedals, and joysticks to the force exerted by the operator are missing data points on the current RAMSIS practice [4]. The closest approach for simulating this is by adding these additional data points on weights on the manikin's joints under joint capacity analysis [4]. This shall give the percentage loading on each joints basis the forces used as input and help in refining the design further.

While designing a vehicle, the center of gravity analysis of the driver and the passenger in different possible positions is very important. RAMSIS has the function of Body Mass which calculates and gives the center of gravity for each body part like the arms, torso, and hands. Fingers etc. RAMSIS also displays these Cgs on the skeletal form of the mannikin which makes it very easy to visualize the individual part Cgs and the Cg of the entire mannikin in a specific position (Fig. 17). The center of gravity of the mannikin would change while wearing a suit and a backpack due to the added weight of the suit and the backpack on the body mass of the mannikin. To calculate the combined Cg of the mannikin with the suit, we need to analyze the effects of external and internal forces acting on the body of the mannikin and the suit, and based on those calculations, we will be able to pinpoint where the combined Cg lies with respect to the Cg of the mannikin and the suit. These calculations cannot be done very easily in RAMSIS.

Fig 17. Sample CG analysis in RAMSIS

However, the Iowa Technology Institute has developed Santos, a highly advanced Digital human model that can be used to test human capabilities in various imported CAD realities [3]. This physics-based simulation modeling platform has an extensive set of analysis tools that can be used to perform detailed ergonomic and human factor analysis

[3]. Santos and its female counterpart Sophia distinguish themselves from other human models by providing a basis for the most comprehensive multi-scale digital person, as well as a suite of integrated, real-time, verified, physics-based, predictive capabilities [3]. For example, asking Santos to carry a given load for a lengthy period of time will result in fatigue calculations, energy expenditures, and an estimate of hydration levels while adding extra gear and equipment will lead to restricted mobility [3]. Thus this platform can be very useful for the calculations of the load of the suit and the backpack on the mannikin and also help in the analysis of restricted mobility caused due to the suit, helmet, backpack, and other equipment [3].

5 Future Work

The future applications of similar studies can be in the fields of industry 4.0 HCI as well as the healthcare industry. NSF studies have been conducted in fields of health science that involve ergonomic assessment for a disabled group of users. Seated posture studies during pregnancy, human and machine coordination in movable robots, etc., are a few studies that have been able to seek award grants already from NSF and can further develop in the future.

James Schmiedeler, for example, is a researcher who has been working in human modeling in human-robot interactions for the healthcare industry. He is currently associated with the University of Notre Dame in the department of aerospace and mechanical engineering. Some of the research works he has done include simulation of lower limb prosthetic control, human motor coordination for robot-assisted rehabilitation, etc.,

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