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New Methods of Manufacturing Space Suits for Deep Space Exploration

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Abstract

The Extravehicular Activity (EVA) spacesuit is a complex machine that provides astronauts with a flexible enclosure and life support system allowing them to perform EVAs in space or on planetary surfaces. As humans continue to explore the Solar System, the ability for space fairing organizations to become Earth-autonomous is a necessity, and the need for an Earth-independent spacesuit is unavoidable. With the evolution of additive manufacturing technologies, it may be possible to produce 3D-printed soft goods that can replace the labor-intensive bladders and restraint layers currently in pressure suits.

The Human Spaceflight Laboratory (HSFL) at the University of North Dakota has demonstrated the ability to use additive manufacturing to develop various soft spacesuit components. By utilizing flexible filaments in combination with interwoven mesh fabrics for improved durability, the HSFL has been able to produce various soft goods components, a functional elbow mobility joint and a boot/ankle assembly. The components have been successfully tested at nominal spacesuit pressures along with burst tests at higher pressures.

Through development and testing of these early prototypes, the HSFL has proved that additive manufacturing can be utilized to fabricate spacesuit elements. The HSFL plans to build upon the advancements discussed in this paper and continue to employ additive manufacturing techniques with the end goal of developing a fully functional 3D-printed pressure garment based on our existing NDX-1 planetary suit architecture.

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I. Introduction

Additive Manufacturing (AM) offers unmatched flexibility in terms of part geometry, material composition and lead-time. Fused Deposition Modeling (FDM) AM is the process of making three-dimensional objects from a digital model and is achieved using an additive process where successive layers of material are laid down to form individual components. This is different from conventional machining methods, which rely on the removal of materials by methods such as cutting or drilling, which are a subtractive process. Until recently, AM has been viewed as a tool for rapid prototyping but recently it has taken substantial steps forward making it possible to manufacture high-quality intricate parts[1]. The use of AM has great potential for producing, high-value, complex, and individually customized components, and has the potential to revolutionize manufacturing of aerospace and space components by enabling novel 'design to constrain' components that could not be fabricated using the traditional methods[2]. It also aids in eliminating the reliance on original equipment manufacturers (OEM) for critical spares, and by extending the life on in-service parts through innovating repair methodologies.

NASA is actively researching AM methods to fabricate complex components that are either cost prohibitive or, in some cases, impossible to produce using more traditional methods of manufacturing. NASA's Advanced Manufacturing Strategic Development Projects and the Space Technology Mission Directorate (STMD) both express interest in furthering the use of AM for space rated components. NASA's strategy for AM is to eventually migrate Earth-based AM process to planetary surfaces to aid in human exploration in space[3]. The STMD has invested in numerous commercial companies that are investigating and experimenting with AM to create space rated hardware.

SpaceX has recently developed an AM fabricated combustion chamber for their Draco rocket engine[2]. California start up, and NASA supported, Relativity Space is investing methods to completely produce a rocket and its components utilizing AM, with the long-term goal of 3D printing and launching the first rocket on Mars[4]. NASA, in collaboration with the company Made In Space, has also experimented with AM on the ISS since 2015, and was able to develop a 3D printer capable of printing tools in microgravity for use aboard the International Space Station (ISS) [5]. The success of human exploration beyond Low-Earth Orbit will rely on AM capabilities. However, an area where AM is lacking is in the production of flexible components and wearable technologies. SpaceX, Relativity Space, Made In Space and many other NASA backed companies are all investigating AM methodologies for rigid components, very few groups are researching and developing 3D printers that are capable of producing flexible and pressurizable garments.

The ability to successfully produce pressurizable wearable flexible components with AM may potentially revolutionize the manufacturing process of spacesuits. The Extravehicular Activity (EVA) spacesuit is a complex and intricately designed machine that provides a flexible pressurized enclosure for astronauts. However, fabrication of spacesuit soft components has relied extensively on traditional methods of garment fabrication. The labor associated with manufacturing a spacesuit requires thousands of hours of artisan-like abilities that include patterning, cutting, sewing, gluing, applying rubber components, pressure testing, etc. By implementing AM to produce flexible components for spacesuit fabrication may enable NASA and its contractors to manufacture and repair spacesuits in-situ, which allows for a sustainable presence on the moon and Mars. We propose under this project a change in paradigm for a next generation of spacesuit manufacturing using AM.

II. Background

Extravehicular Activities (EVAs) are vital for future human spaceflight operations, in particular for long duration missions. NASA listed in its Space Technology Roadmap that there is a need for robust spacesuits and in-situ methodologies for manufacturing and maintence of EVA equipment[6]. If humans are to fulfill the ambitious plan of creating settlements on Mars, a paradigm shift in spacesuit development and manufacturing is required. The research proposed by the University of North Dakota, Human Spaceflight Laboratory is studying and experimenting with additive manufacturing techniques with the objective of producing a fully operational, pressurizable 3D-printed spacesuit. The methods, technology and design that is emerging throughout the duration of this research project will potentially aid in NASA's ability to create an EVA system that can be used, maintained and fabricated on off-Earth locations.

Historical and current pressure suit design methodologies are inadequate for long duration spaceflight for the following key reasons; Apollo suits for example, were expensive, tailor made for each individual crewmember, could not endure sustained surface operations and had limited reliability. Past Shuttle and current ISS suits suffer from the same drawbacks as the A-7L/A-7LB suits and additionally, were not designed for surface locomotion. The A-7L/A-7LB suits used in the Apollo missions were the last operational spacesuits designed with walking mobility as a requirement[7]. The biggest detriment that historical and modern spacesuits suffer from, lies within their in-ability to be maintained, repaired and assembled in-situ. Apollo suits that were used on the lunar surface experienced severe issues when exposed the lunar dust. The dust had the ability to clog bearings and zipper systems and penetrate the pressure bladder of the suit[8,9]. If the Apollo missions were not short in duration and the continued use of the A-7L/A-7LB's were required, the missions were more susceptible to failure because there was no method to repair suits on the moon. This is a problem faced on the ISS today, as the Environmental Mobility Units (EMU) spacesuits were originally designed under the Space Shuttle program, and as such, they were developed to be sent down to Earth for maintence and repairs during their life span. Due to the retirement of the Space Shuttles, there were a number of modifications, in order to be maintained aboard the ISS. Still, this was a compromise solution due to the reduced logistics the US had to operate after 2011.

The logistical hinderance of current spacesuit maintence and fabrication will limit NASA's endeavors of long-duration spaceflight and sustained presence on Mars and beyond. With the implementation of AM for spacesuit fabrication, in-situ production, can be attainable and aid in eliminating the need for an Earth-dependent spacesuit system.

Our team has previous experience building advanced planetary spacesuits and are implementing the lessons learned from the development of the NDX-1 and NDX-2 spacesuits, and the next step was to reduce the dependence of the traditional garments fabrication using AM. Utilizing the NDX-1 spacesuit architecture, the team has been creating computer-aided design (CAD) models, and modifying the suit to begin creating a 3D-printed functional prototype based on the NDX-1. The prototype will be used to validate this innovative manufacturing method.

The NDX-1 was identified as the suit to be used as a template due to its success as an experimental planetary suit. The NDX-1 has been tested at various NASA centers with experiments that range from studying kinematics to understanding how Martian dust abrasion affects suit performance[10].

Figure 1a. NDX-1 Prototype Suit. **Figure 1b. NDX-1 at Lunar Regolith Lab (Kennedy Space Center).**

III. Scope of Research

The objective of this research was to create a novel AM method to produce highly complex and flexible spacesuit components that do not rely on traditional fabrication methods.

Recent testing aboard the ISS demonstrated the feasibility and practicality of manufacturing 3D printed components in microgravity. Under reduced gravity conditions, such as those found on the moon or Mars, it may be even easier to employ additive manufacturing. The techniques used for the development of the new suit included scanning of joints to minimize manufacturing time, improve repeatability of components, and eventually allow the process of fabricating, testing, and servicing a spacesuit to be Earth-independent.

While under the initial scope of our project, we developed and tested successfully individual joints, the next step will be the development of a fully functional bladder and restrait layer of a pressurizable spacesuit.

The deliverables of this three-year project will be:

1. Produce a full-pressurizable (4.3-PSI) prototype of planetary spacesuit based on the design of the NDX-1, manufactured primarily by additive manufacturing processes. This new suit prototype will be named NDX-3 (North Dakota eXperimental-3).
2. The design and development of a high temperature thermoplastic 3D-printing machine required to produce the components.
3. Test the mobility of the suit with standard pressure testing procedures.
4. Produce a final report defining the manufacturing process and the results of testing.

IV. Mobility Joints

A design feature of every spacesuit is the mobility elements designed to allow the wearer to move and operate in the suit. This mobility is accomplished by creating joints that are approximately constant in volume through out the range of motion, minimizing the work expended compressing the air inside the suit. The current NDX-3 architecture utilizes a bellows type mobility joint. Historically bellows joints have been of either single wall laminate or dipped rubber construction. By 3-D printing the joint, the variability in the production is minimized and a thin single layer pressure element can be created eliminating inter-layer friction of multilayer mobility joints.

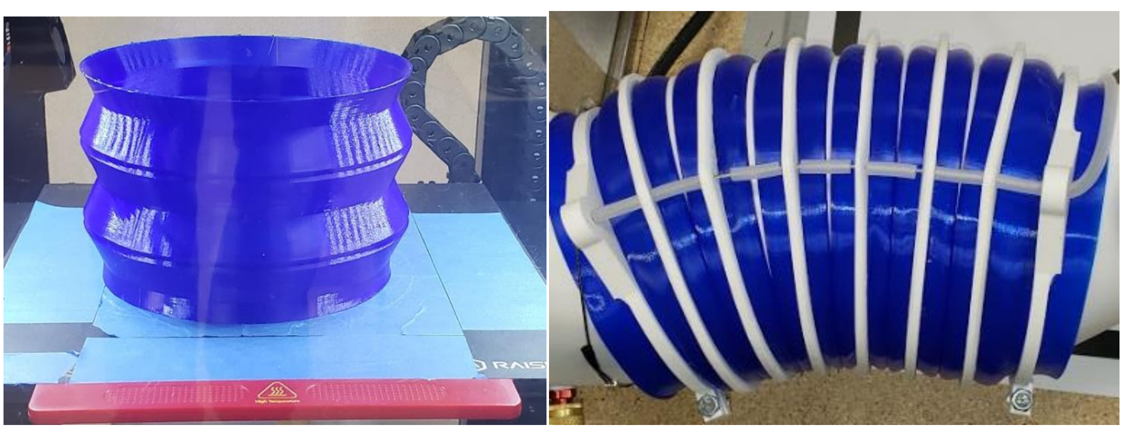

Figure 2a. Flexible Filament pressure layer. **Figure 2b. Assembled and pressurized mobility element.**

A. Soft Joints and Collapsible

A design feature that has been implemented in all operational spacesuits, and will be implemented in the design of this prototype, is that all suits up to date, historical and modern, are comprised of mostly soft goods (the Shuttle/ISS EMU is a hybrid spacesuit, meaning it has soft mobility joints but a Hard-Upper Torso (HUT)). A suit that is primarily made up of soft goods components has an advantage over hard suits, in that it can be collapsed when not in use and stored easily aboard spacecraft with limited volume. The suit that will be developed as part of this research will be a suit prototype with reduced metal components, except where strictly necessary and be comprised of all soft-goods mobility joints.

B. Reduced Mass

The mass of a Mars spacesuit is critical, the suit will need to be as light as possible to lessen the fatigue of wearing the spacesuit on the crewmember. By utilizing AM to fabricate the spacesuit the mass of the suit will potentially be reduced. This is because AM allows for the control of material thickness and the ability for spacesuit elements to have fewer parts. This is something that cannot be as readily achieved using traditional methods. Additionally, planetary suits need to be robust while providing sufficient mobility. This mobility is particularly important in the Lower Torso Assembly (LTA) of a suit. A properly designed LTA allows astronauts to traverse the planetary surface more efficiently, based on the success of the NDX-1 a similar LTA will be utilized in our next generation spacesuit.

Connection points, such as the gloves, boots and helmet will be 3D printed as well using carbon-fiber reinforced filaments to produce lightweight and robust interconnecting components. Having these components 3D-printed will allow us to not compromise the mechanical design of the elements due to CNC limitations and will allow manufacturing outside the Earth.

V. Current Status

A. Preliminary Results

Investigation of the new fabrication techniques to produce a suit prototype using flexible filaments have begun at the Human Spaceflight Laboratory at the University of North Dakota in 2019. The team has developed a series of modifications on several 3D-printers that were able to successfully print a number spacesuit arm assemblies, disconnects, a HUT portion, low Technology Readiness Level (TRL) boot and ankle assembly, and a flexible glove.

B. Spacesuit Arm Assemblies

Multiple 3D printed spacesuit arm assemblies of various sizes have been manufactured. These use a hybrid soft/hard design, combining a flexible filament pressure layer with rigid and semi-rigid restraint elements and disconnect hardware.

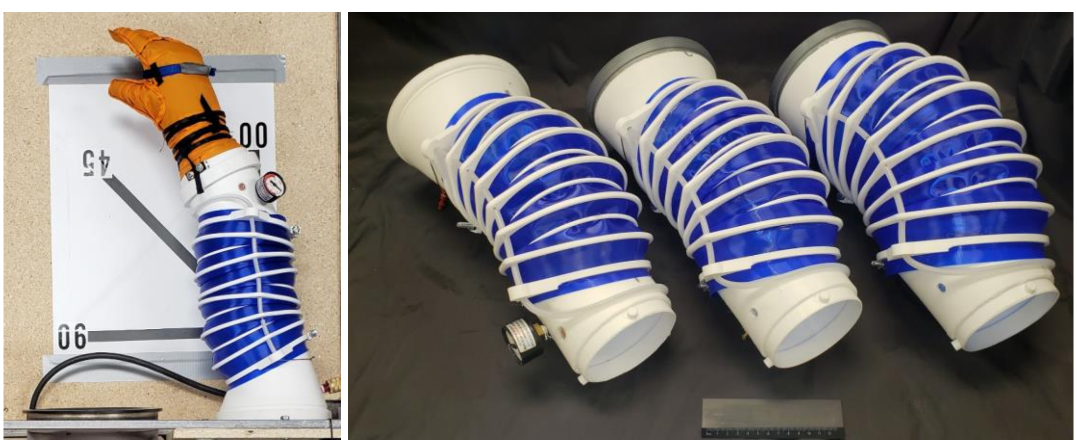

Figure 3a. Spacesuit arm assembly integrated into a robotic joint testing device. Figure 3b. Three different sizes of spacesuit arm assembly (restraint and bladder).

C. **Disconnects**

Two types of disconnects have been designed to allow the quick and easy replacement of suit elements. The first type is a quick disconnect, allowing for the rapid removal of gloves and boots to ease the donning and doffing of the spacesuit while providing a gas-tight seal when the parts are combined.

Figures 4a and 4b. AM Carbon-Fiber Filament Glove Disconnect.

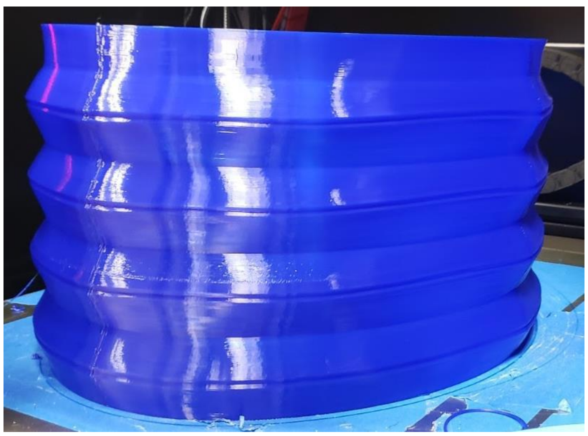

Figure 5a. Waist Assembly.

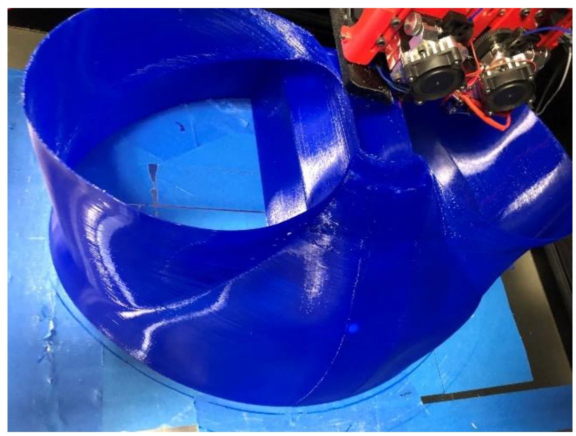

Figure 5b. Brief Section during printing (upside down).

D. **Hard Upper Torso Component**

Using a large volume 3D printer, a replica of a lower portion of a NDX-1 Hard Upper Torso (HUT) was manufactured.

Figure 4. 3-D printed HUT (in white) portion next to NDX-1 HUT.

E. Manufacturing Techniques

Our team has assembled a dual extrusion AM printer that is capable of printing high temperature flexible and rigid materials simultaneously. The ability to print two materials at once also enables us to employ a water-soluble support material to reinforce flexible complex prints while on the build plate.

F. Materials

The materials that are required for fabrication od this prototype are a range of high temperature flexible filaments, varieties of glass and carbon fiber reinforced Nylon filaments, and water-soluble filaments for support structures. Utilizing additive manufacturing techniques such as multiple filaments extruders it can be possible to use the flexible and rigid materials in synergy to fabricate a new spacesuits and its intricate components using a completely different fabrication than the traditional systems used until now.

G. Pressure Testing

Pressure testing has been conducted at 4.5 PSID and 6 PSID respectively. Additional testing is necessary to determine mobility, as compared with conventional spacesuit joints but the preliminary observations are auspicious that they will rate similar or equal.

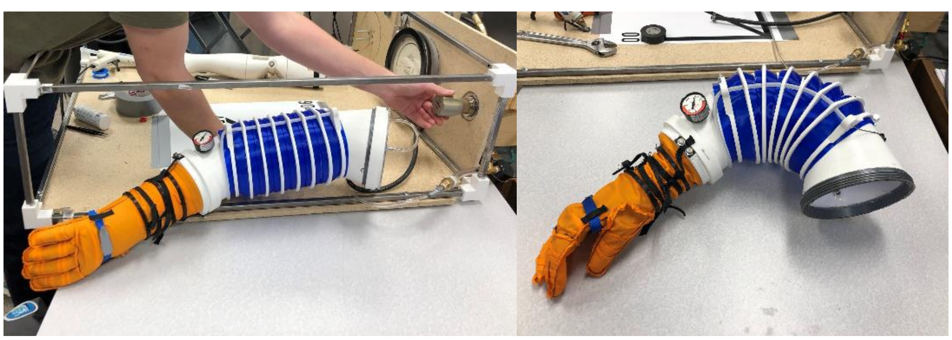

Figure 5a. Arm joint during pressure test. **Figure 5b. Arm joint and disconnect.**

Figure 6. Preliminary unpressurized fit test of Arm Joint.

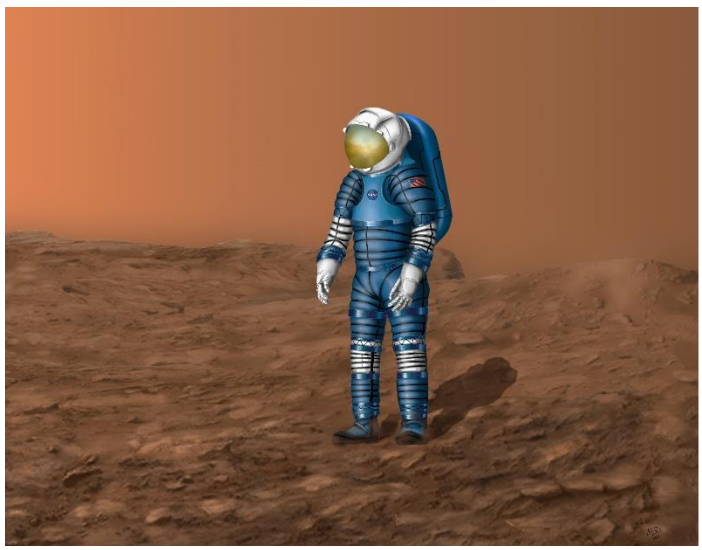

Figure 7. Concept Drawing of NDX-3. Drawing by Martin Demonte.

VI Summary

As humans continue to explore beyond LEO the ability for space organizations to become less reliant on Earth based support is a necessity, and at a certain point, the need for an Earth-independent spacesuit system will be an essential requirement. With the advancements made in AM and its capability to produce flexible components it can be possible to produce a new manufacturing process that can produce spacesuits in-situ. This research is directed to aid in the development of: 1, an advanced additive manufacturing system to produce spacesuits with reduced dependence on Earth, and 2, to produce a next generation spacesuit using the new manufacturing techniques that are being developed throughout this research, while capitalizing on the lessons learned during our previous spacesuit development projects at UND.

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The invention presented in this paper is protected by U.S. and International Laws. De León, P. PRINTER AND PRINTING METHOD FOR SPACE AND PRESSURE SUITS USING ADDITIVE MANUFACTURING. 11/18/2019. Patent Application # 17098008. U.S. Patent and Trademark Office.

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