Design and Development of an Economic and Effective Hybrid Space Suit

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ABSTRACT: This research paper aims to create a hybrid spacesuit design by a unique amalgamation of the two most popular spacesuit design techniques - Gas pressure and mechanical counterpressure in such a configuration that the overall suit can essentially capitalize on both advantages. In contact with the skin, the mechanical pressure layer has been modified with bands of Magnetic Shape Memory Alloys (MSMA's) to reduce donning/doffing time and solve the key limitation of a static fiber by allowing it to fit securely over curves of the body. Numerous other enhancements and safety mechanisms have been made possible due to this unique configuration, all in a cost-effective package. Furthermore, experiments were conducted to construct a breathing bladder to map its pressure regions uniformity and map airflow vectors. Apart from this computational experiment, a physical glove was prepared to check the differential pressure and hand movements. Lastly, a trait study was conducted to observe the difference between our suit and the other commercial ready-to-use spacesuits.
KEYWORDS: Engineering Mechanics; Mechanical Engineering; Shape Memory Effect; Computational Pressure Mapping.

Introduction

With Project Artemis, Mars Missions, Space Tourism, etc. planned for the near future, new spacesuit designs must be brought into production to enhance efficiency and reduce the cost of these missions. Gas Pressure layers are very stiff and uncomfortable. The current models need to sacrifice sensitive fingertip control and fine motor skills. Poor-fitting results in a significant discrepancy between the wearer's and suit's movements. It is estimated that the wearer moves about 30% more than the suit, which is exhausting and inefficient.

Due to stiffness and rigidity, a solution has been adopted to adjust the internal pressure in a spacesuit at 0.3 atm. But this can cause decompression sickness, a medical condition caused by dissolved gases emerging from solution as bubbles inside the body tissues during decompression.[1] Current spacesuits are "anthropomorphic balloons," Despite over 50 years of development, the pre-breathe time and protocols make them high maintenance. The 100% pure oxygen pre-breathe protocol for Extra-Vehicular Activity (EVA) is a 12 hours-long process. Such emergencies will consume much valuable time for long missions on the Martian or Lunar surface.

Dust on other planets or moons is different from that experienced on Earth.[2] The soil is usually very coarse and jagged and tends to be very sticky. Thus, it is required that new spacesuit designs minimize gaps like zippers. Current suits are responsible for musculoskeletal injuries in the hands, shoulders, and other joints.

Our suit aims to tackle these challenges with a reimagined design, combining gas and mechanical pressure layers with the strategic use of new-age materials like Magnetic Shape Memory Alloys and thinner Breathing Bladders.

A new spacesuit design is not a luxury; it is essential to enhance the efficiency of future manned missions to the Moon, Mars, and beyond. With the increased focus on EVA, current systems, which use Gas Pressure, cannot sustain the demands of astronauts much longer.

Methodology

Firstly, a trait study was conducted (refer to Table 1) among the current commercial spacesuits and a thorough analysis of their shortcomings to decide on the garments to be used in the two pressure layers. The following six criteria were utilized. A scoring rubric was decided with a score range of 0-5, where 0 represented non-existence/critical failure, and 5 represented absolute success. This study paved the way to integrate the best features in our suit and introduce new features, as seen in the Results and Discussion sections.

Table 1: Trait study criteria for the physical and economic aspects.

Criteria	Meaning
Mobility	Describes how easy it is to perform movements
Feasibility	Addresses the difficulty of creating a full suit with cost considerations on its development
Decompression Sickness	Capability of the spacesuit architecture to prevent DCS and/or have quick contingency
Mass	Calculating the total spacesuit configuration weight
Complexity	Amount of parts needed to complete a certain configuration, which drives the capability to effectively operate over time
Robustness	Ability to withstand or overcome adverse/contingency conditions

Secondly, using NASA's Man Systems Integration Standards, Volume 1, Section 14 as a reference for the human body and device standards, a human body was modeled in Autodesk Maya and exported to Fusion 360 and ExactFlat for 2D cutouts (to get precise measurement) with our desired coverage area of breathing bladder on the torso (refer to Figure 1 for the pipeline). Torso covers two regions of significant importance. Firstly, the chest (C) and the abdomen (A). These are further divided into four regions for simulations, which are, Chest 1 (C1), Chest 2 (C2), Abdomen 1 (A1), and Abdomen (A2). C1, C2, A1, and A2 are the pillars of all calculations that are required to be carried out for the simulations.

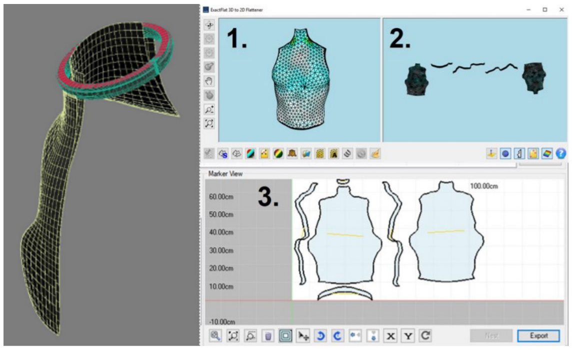


Figure 1: The pipeline of bladder creation. Autodesk Maya 3D model (left) and 2D cutouts in ExactFlat (right).

Accordingly, MIT's research document determined the volume changes for breathing bladder in two cases of EVA were decided, that are, 4 liters for adult males during maximal forced inspiratory and expiratory maneuver (MFIEM) and 0.5 liters for quiet breathing.[3] Using Fusion 360 static pressure simulation, the torso was divided symmetrically into four parts (refer to 2) to achieve uniform pressure on the whole bladder. Sample pressure applying needles were developed similar to those used by doctors to map put points on the Chest-Abdomen 1 (CA1) and Chest-Abdomen 2 (CA2) pressure applied to keep the breathing bladder in order with the body (as shown in Figure 2).

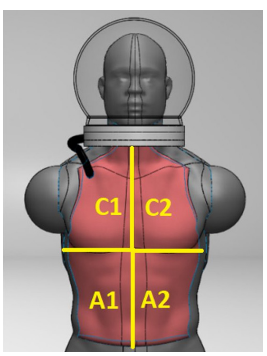


Figure 2: Symmetrical division of the breathing bladder on the torso.

Thirdly, a flow duct was designed between the gas pressure-filled helmet to identify the airflow vectors, which in turn helps us decode the breathing process for future astronauts and space tourists.[4] Here, low and high-pressure vectors were designed in the helmet. Through the CA1 and CA2 pressure data, the upper and lower limit of the airflow speed was set. Further, from NASA's xEMU (Extravehicular Mobility Unit) and mEMU spacesuit data, data was collected about the EVA missions to understand the physiological changes in astronauts.[5]

Fourthly, an Arduino-based glove prototype was made with five flex sensors, five servo motors, multiple resistors,[1] Arduino Mega Board, and batteries.[6] Each flex sensor was placed on one finger, and the same was followed with servo motors (refer to Figure 3). Additionally, glove materials were prepared using NASA's xEMU and mEMU paper, and we came up with our custom volume and thickness of the glove.[7] Figure 4 shows you the variables and a code snippet.

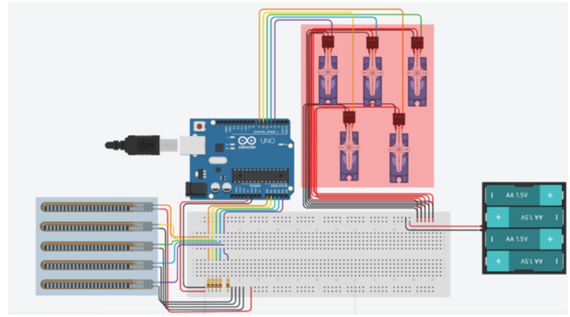


Figure 3: Circuit diagram showing the components.

```
#include <Servo.h>
//define servo motors
Servo pinkie, ring, middle, index, thumb;

//define flex sensors on glove (F1 = flex sensor 1)
const int pinkieFlex = A0; //bent - 710, flat - 900 (values vary depending on your own flex sensors))
const int ringFlex = A1; //bent - 920, flat - 965
const int middleFlex = A2; //bent - 966, flat - 993
const int indexFlex = A3; //bent - 808, flat - 870
const int thumbFlex = A4; //bent - 490, flat - 525


void setup(){
  //attach servo motors to digital pins
  pinkie.attach(13);
  ring.attach(12);
  middle.attach(11);
  index.attach(9);
  thumb.attach(10);
```

Figure 4: Code snippet highlighting the variables.

Results and Discussion

Spacesuit Configuration and Advantages:

In Table 2, a detailed comparison has been conducted between the commercial spacesuits and ours - CosmoVest and accordingly explained the scores below.

Table 2: Trait study scores for commercial spacesuits.

Factors/ Suit names	ILC Dover Extra Mobility Unit (EMU) (1983)	David Clark Company Incorporated Red Bull Stratos Pressure Suit (2012)	SpaceX Starman Suit (2018)	NASA xEMU (2020)	CosmoVest (To be done as per estimates by 2023)
Purpose	EVA	Test Suit+IVA	IVA	EVA	EVA+IVA
Mobility	3	2	3	3	5
Feasibility	2	2	1	4	4
DCS	2	1	2	3	5
Mass	1	3	4	3	3
Complexity	1	1	3	2	4
Robustness	2	1	1	3	5
Total	11	10	14	18	26

Mobility Factor: Elevated gas pressurization will increase system cost because it decreases mobility. Mechanical Counter Pressure (MCP) garments will do the same, but with less loss of mobility and increased pressurization. Our hybrid spacesuit will thus reign at first position here because other companies still use the 1960s and 70s-based gas pressure systems.

Feasibility Factor: Other configurations will have a smaller system cost than ours because they have been widely manufactured and successfully flown. Ours is equal to xEMU due to the objectives they both fulfill.

Decompression Sickness (DCS): Since our suit is driven by two pressure layers, it will reduce the chance of decompression sickness compared to the older suits, especially International Latex Corporation Dover's, which have only one pressure garment and no backup. Lower total pressure will increase system cost because it increases the risk for DCS, as seen in the David Clark Company Incorporated test suit.

Mass Factor: Our suit took inspiration from NASA's xEMU suit and used its garment for the gas pressure layer (external) but modified it according to the internal layer in our suit. This reduced the volume, thickness, and quantity of each material and its sublayers. This makes our suit light and production costs less. Compare this to xEMU with 20 times more mass than ours, International Latex Corporation Dover's commercial suits having 40 times the mass of ours.

Complexity: Designs incorporating both layers will increase internal components and make it easier and more accessible for astronauts during EVA. A significant factor is the storability of CosmoVest compared to International Latex Corporation Dover's clunky suits that took more space on the external layer for mechanical components than EVA tools.

Robustness: Designs incorporating only one layer will increase system costs because using both technologies decreases the risk if one technology fails.

Accordingly, the pressure layers were decided. Firstly, the mechanical counterpressure layer is a skin-tight thin layer working on the Magnetic Shape Memory Alloys (MSMAs).[8] SMAs mesh generates voltage-controlled mechanical counterpressure. Secondly, the traditional Gas Pressure Layer is the outermost layer that keeps the mechanical pressure layer tight by applying uniform pressure. This eliminates the need for a complex locking mechanism which has held back some other mechanical pressure designs.

The reason for combining these layers is to capitalize on both advantages. Since the gas pressure layer is not relied upon alone, only a 2-2.5 PSI layer will be required compared to a traditional 4-4.5 PSI, significantly reducing bulk and enhancing mobility.[9] Besides this, the skin-tight nature of the innermost mechanical layer allows for fine motor control. MSMAs are further used to ensure the mechanical pressure layer can be contracted upon curves and cavities, which has traditionally been a problem for mechanical pressure suits. The use of MSMAs also reduces the donning/doffing time as the MSMAs can be expanded/contracted to ease the process. Figure 5 shows the flexible working of the MSMAs.

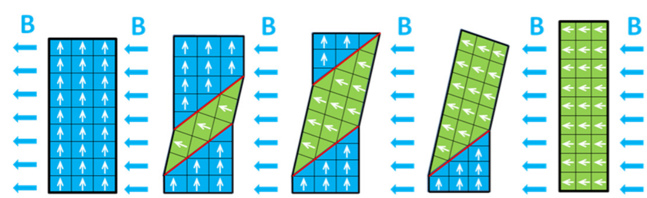


Figure 5: The shape memory effect of MSMAs.

Pressure Layers and Garments:

Table 1 shows that our space suit needs to be less bulky and less complex regarding its composition and mass load. Due to the two layers complementing each other and the internal layer (mechanical counterpressure layer) being so thin, it was easy to reduce the outer gas layer by 60%, decreasing each garment's volume and overall cost, as shown in Figure 6.

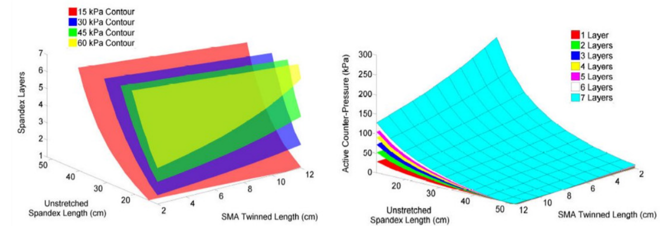


Figure 6: Each layer's pressure contour and thickness of the eight layers.

As explained in the previous section, it will work on the Magnetic Shape Memory Alloys (MSMAs). Pressure is distributed by a viscous thermal regulating gel layer (for regulating temperature shifts in alloys). MSMA has four primary layers (from outside to inside); the abrasion-resistant layer, SMAs mesh, distribution gels, evaporative cooling, perspiration, thermal control, and radiation protection layer (ECPTCRPL). The last layer further contains Shape memory alloys for fabric tensioning, nylon-spandex layers, boron nitride nanotubes (BNNT), aerogel radiation, and a thermal protective layer.10 Refer to Figure 7 for its layer.

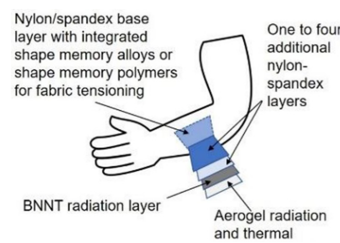
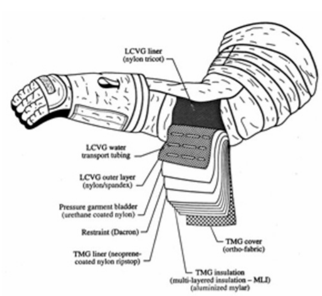


Figure 7: Mechanical counterpressure layer's garments.

The gas pressure layer (external layer) has an Ortho-Fabric inspired from xEMU suits that contain layers of multi-layer aluminized layer, neoprene coated ripstop for liner, and dacron resistant layer.[11] The LCVG is worn underneath the pressure enclosure and is designed to circulate cold water and oxygen to cool the user and ventilate the system. It uses a stretch, nylon knit fabric integrated with ethyl vinyl acetate cooling tubes and a nylon tricot comfort liner. This entire system together provides the functionality of the soft elements of the spacesuit and protects the user from the external environment (as shown in Figure 8).[13]



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Breathing Bladder Construction and Airflow Vector Simulation:

The breathing bladder of CosmoVest is made of semi-elastic and puncture-resistant thermoplastic polyurethane (TPU). The interior layer is composed of a latex rubber seal, and it is surrounded by an external layer to be attached on top of it, forming a complete seal. Gortex Fabric, a fabric semi-permeable to water vapor while remaining airtight, shall address the issue of sweat salt in the suit.[14] Two criteria were focused upon for the creation of the bladder, i.e., pressure and volume consistency throughout the suit, which is demonstrated in our computational experiment as well. The force to radius ratio was calculated through the relation,

$$F=Pbr$$

where F is force exerted, P is pressure applied, b is bandwidth, and r is the radius of curvature. Table 2 represents the Pressure to radius ratio calculated. Here each bandwidth was taken as 5cm as a standard reference in Table 3.

Table 3: The observation regarding the pressure to radius ratio.

Pressure (psi)	Radius (cm)	Ratio
5.6	1.92	3:1
4.2	1.72	2:1
3.5	1.43	2:1
2.9	1.15	3:1

Accordingly, the selected ratio was the smallest of 2:1, where the radius was the least. Hence 1.43 cm with a 3.5 psi was the ideal choice. The pressure and volume were balanced according to the standard guidelines. As our helmet would be filled with gas for pressure, the air must be regulated between the helmet and the breathing bladder. Two pressure conditions were identified to achieve a successful breathing and pressure flow. The first condition is low pressure, and the second is high pressure generated during EVA. Using MATLAB for the inputs and algorithm and SigmaPlot for the graphing with Adobe Photoshop, the airflow vectors were mapped with the pressure contours, as shown in Figure 9.

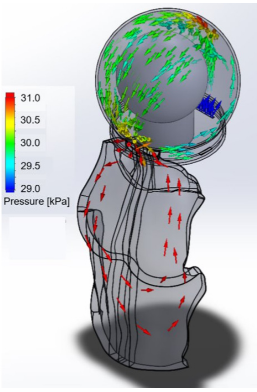

Figure 9: Internal airflow vectors at varying pressure contours.

Glove Prototype:

Firstly, the individual reading of the sensors was taken into account for a linear pressure increase in Figure 10. Secondly, the user's personal experience with stiffness was recorded too. Figure 11 shows the final prepared glove. A striking feature is that this design has reduced our glove's thickness to the maximum extent. Our glove is based on the principle of getting Earth-like uniform pressure for smoother movements. Hence the glove had external servo motors. Accordingly, it was found that Graph 2 is the best possible option based on the user's experience and experimental data.

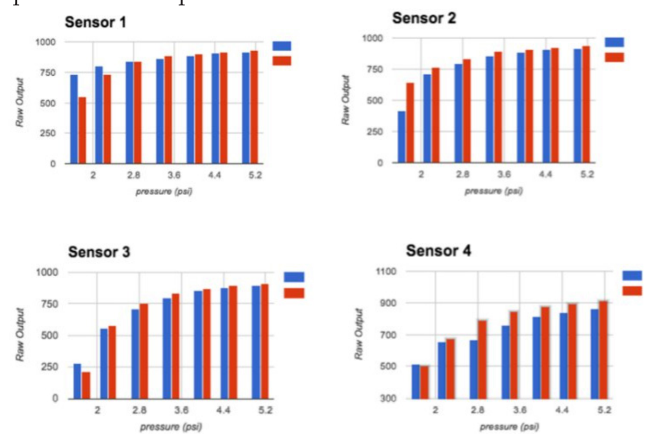

Figure 10: Graphs for each sensor placement.

Figure 11: Physical glove prototype.

Other External Components and Utilities

Utility Belt :

A simple yet functional utility belt (as shown in Figure 12) has been imagined that can be attached to the waist of the suit using hooks. This allows for convenient storage of tools/instruments required for ExtraVehicular Activity (EVA). This belt can also be used to store other modern accessories that are currently being researched by other members of the scientific community, including a surface impingement nozzle that stores the "magical" puncture healing resin - thiolene-trialkyl borane.[15]

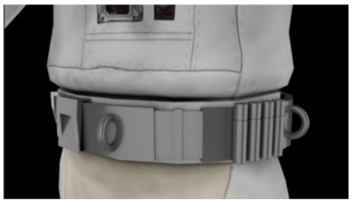

Figure 12: Utility Belt.

Portable Life Support System (PLSS):

A backpack-like module will host the life support systems in our design (as shown in Figures 13 and 14). This allows maximum freedom during EVA as the life support system exists separate from the suit's internal systems. The suit uses a Primary Life Support System (PLSS) configuration similar to those used in the Apollo Missions, with minor changes in the module's volume and total mass load.[16] No significant modification has been proposed to other generic components, such as the helmet, boots, etc.

Figure 13: The portable life support system.

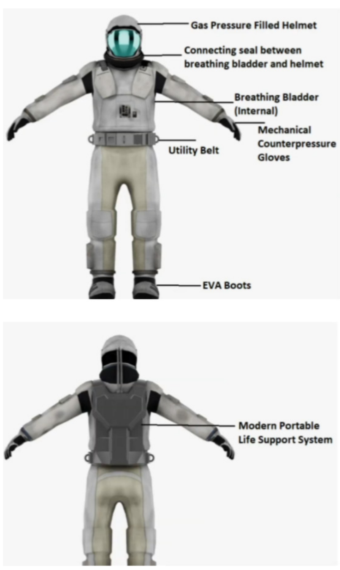

Figure 14: Front view of the suit with its major components (top) and back view of the suit with the portable life support system (down).

Conclusion

In this research, a realistic attempt has been made to categorically solve the issues in conceptualizing and manufacturing a hybrid spacesuit combining gas and mechanical counterpressure techniques. Our design combines contemporary gas and mechanical pressure layers, which provides enhanced motor control, reduced suit mass, lower cost, and other advantages which will be essential for future space missions. Using a Shape Memory Alloy further eliminates some of the significant drawbacks of a skin-tight space suit.

Compared to the expensive experiments for gloves, the team tried to simulate the same using Arduino. Computational results for the experiments show a positive sign that the suit's development is achievable and shall be a significant milestone in streamlining the future EVA missions for astronauts and space tourists.

Acknowledgments

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