Flexible Inflatable Spacesuit Technology (FIST)

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I. Introduction

NASA's ongoing Artemis mission aims to establish a long-term presence on the moon, including a station on the lunar surface [1]. Astronauts will perform long, complex extra-vehicular activities (EVA). EVA operations are currently limited due to the bulky nature of spacesuits, with the gloves posing a particular issue. An astronaut's hands are most vulnerable to injury and mobility issues during an EVA, a problem caused by the necessity of protecting from extreme conditions. Astronauts on the moon can experience a 250-degree temperature fluctuation while being bombarded by solar radiation. The current EVA gloves maximize protection for the astronauts but sacrifice functionality to do so, which calls for an innovation of the design. The purpose of this document is to present a solution to the spacesuit glove that increases dexterity, endurance, safety, and comfort.

The concept of operations for the use of FIST will allow further study of the lunar surface and expansion of the lunar base. The deployment of FIST will be conducted within four phases. In Phase 1, FIST will launch via payload storage the SLS 1 Rocket from Kennedy Space Center, FL. Phase 2 is the journey to the moon, in which the core stage will dock at the Gateway station and prepare for deployment on the moon. Phase 3 will be the transportation of FIST onto the lunar surface. Phase 4 will be the utilization of FIST by the astronauts to assist in expanding the lunar colony.

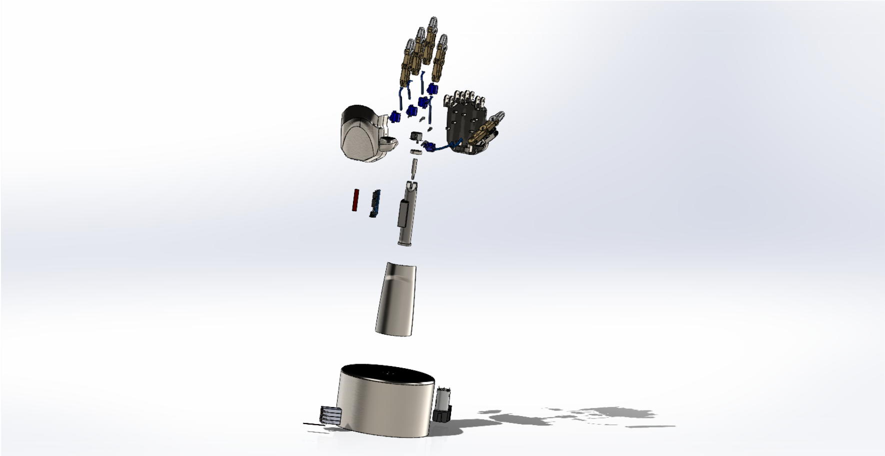

Fig. 1 FIST Assembly Exploded View

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A. Literature Review

Optimized Guidance, Navigation, and Control Systems are imperative to successful space missions. Space missions require precise and accurate data making GNC necessary to achieve objectives. GNC systems provide autonomy as they can make real-time decisions based on local sensor data. Inertial measurement units are used in many different applications such as robotics, aerospace and aviation, automotive, and anywhere navigation and position data is needed. An IMU with three sensor types, an accelerometer, a gyroscope, and a magnetometer, has 9 degrees of freedom. The accelerometer measures linear acceleration and rotation angle (pitch and roll). The gyroscope measures angular velocity and rotational angle (pitch, roll, and yaw). The magnetometer also measures angular velocity and rotational angle (pitch, roll, and yaw) and can be calibrated to the gyroscope data to reduce the effects of drift issues [3]. Robotic hands designed to perform grasping tasks have been controlled by PID position control previously. PID control is capable of reducing noise, disturbances, and friction that occur in a process [4]. The controller is used to minimize the error between a processed state and a reference state.

In the exploration of space, batteries have always played a crucial role in powering everything. In particular, lithium polymer batteries have proved to be an ideal choice due to their compactness and low weight without compromising on capacity. LiPo batteries offered an opportunity for CubeSat developers to reduce weight and costs [12]. Other small satellite designers have been seeking to reduce the volume with an even greater performance. Their studies recommended LiPo batteries as state-of-the-art due to their geometric flexibility [7]. The global automotive industry is undergoing a massive change in the battery department. Well-known companies such as Tesla use LiPo batteries. Following that, LiPo batteries have now flown on crewed SpaceX spacecraft and installed on the International Space Station. For the same reason that space engineers ventured into the lithium polymer world, engineers at the University of California San Diego have built soft robotic actuators that are compact, portable, and powered by LiPo batteries. A study on different battery technology applications in untethered soft robots yielded encouraging results for LiPo batteries. LiPo batteries are commonly used due to their ability to support high-current pulses. In addition to the benefits of light packaging and flexibility, LiPo batteries fit most of the requirements for current variation, specific power, and safety making them an ideal selection for wearable robots such as an exoskeleton. LiPo batteries are readily available and environmentally friendly in addition to having a long shelf life. LiPo batteries have been used for electrical system design for a soft robot toolkit.

Pneumatics is a general term for the branch of engineering that creates or makes use of pressurized gas or air. As such, pneumatic systems have seen extensive use in space from the very beginning. Heat pumps, compressing fuel entering an engine, and of course the air that astronauts breathe, all require compressors. Because pneumatics is such a broad field, the testing required to verify a pneumatic system depends on what exactly the system is but generally involves ensuring there are no leaks and that the system operates within the desired pressure range. Pneumatic systems are commonly used to provide movement to soft robotics. Particularly in small or portable soft robotic systems, microcompressors are employed for their low weight and small size. [17] [1].

Structures of a soft robot consist of an elastic air chamber and solid support systems. A soft robot uses flexible air chambers to actuate movement instead of hydraulics or mechanical actuation. The air chambers of soft robots are most commonly made with silicone epoxy resin which is a rubbery material, that when inflated can expand to over 3 times its original size [16]. The silicone air chamber is specifically patterned so that when it inflates, it can actuate to various positions and motions [16]. Soft Robotics in space is a relatively new idea, but the technology has been developing over the past years. Soft Robotics were originally invented in the 1950s by Joseph Mckibbin to help polio patients suffering from paralysis, with an actuated muscle. Recently soft robotics have been used in projects to study the bio-metrics of animals [15]. Many of these biometric robots have been used in the ocean as "spyfish" to study the schooling, feeding, and mating behaviors of select species of fish. A material such as silicon allows for these robots to be flexible and elastic, while also having a waterproof seal to protect the wiring and pneumatics on the inside.

Survivability is a well-developed aspect of spacecraft mission design at this point. Thermal, radiation, and physical protection have been implemented on a variety of space systems, including, most immediately relevant, the Apollo spacesuits, which performed admirably, especially regarding abrasion resistance to lunar debris. With temperatures on the moon ranging from 40-396 Kelvin, the temperature of spacecraft devices does need to be regulated. Thermal systems today include a variety of methods for heat management, with passive methods such as thermal property-altering coatings and active methods like heaters or louvers. One such example of this is the TURKSAT-3USAT, launched in

2013, which featured active heaters and passive control methods [14]. Radiation protection has developed somewhat in recent years; layered shielding composed of different metals, called z-shielding, appears to be the current cutting-edge. However, most CubeSats generally appear to use simple aluminum shielding as a cheaper alternative [13].

The microcontroller is considered the brain of a robotics project. It is responsible for taking in the data, executing any of the necessary calculations, and transmitting the desired data to each subsystem. The Arduino board is a popular choice when it comes to microcontrollers in robotics. It is affordable, easy to implement, comes in many different sizes, and accepts a variety of programming languages. Arduino boards have been used in soft robotics projects before, specifically to allow the robot to interact with other objects, such as moving and picking them up, through the implementation of a virtual reality environment. The Arduino board is particularly preferred for these types of interactive projects due to its ability to receive and process several inputs of data at the same time, all through virtual environment integration. The Arduino implementation also allows for performance improvements, such as response delays, by simply modifying the structure of the program [11]. The most common utilization of this project is the rehabilitation of patients who suffer from strokes and/or accidents and who need to improve their mobility [11].

The information from the literature review was applied into the functional requirements of FIST.

B. Functional Requirements

FR.1 FIST shall remain fully operational during an EVA mission

FR.2 FIST air chambers shall withstand punctures, abrasion, and other common mechanical wear.

FR.3 FIST shall not exceed 6 kg.

FR.4 FIST shall communicate with the microcontroller to state that the input data from each displacement is detected.

FR.5 The microcontroller shall use the input data to calculate the amount of air pressure needed to mimic the displacement read in by the sensors.

FR.6 FIST shall withstand a temperature range of 40-396 Kelvin.

FR.7 FIST shall withstand punctures, abrasion, and other common mechanical wear.

FR.8 The Guidance, Navigation, and Control system shall maintain control of FIST at all times.

FR.9 FIST shall produce a pressure of 3 psi

FR.10 FIST shall not impact the internal pressure of the EVA suit

These functional requirements were fulfilled by the six subsystems of FIST.

C. Subsystems

1. Guidance, Navigation, and Control

The Guidance, Navigation, and Control (GNC) System relays bidirectional communication between the astronaut and FIST. This system will maintain control of FIST at all times. It receives input from the astronauts' hands and mimics the motion with FIST. The trajectory of FIST will be tracked by the Navigation System. Functional requirement **FR.8** further explains what is expected of the GNC system for this mission. The design solution for the GNC System consists of IMUs and Arduino microcontrollers to perform different functions. Specifically, multiple Adafruit 9-DOF Absolute Orientation IMU Fusion Breakout - BNO055s, are attached to the inflatable actuators of FIST and embedded in the Sleeve. The Sleeve is a glove-like device the astronauts' hands will be inside of. The volumetric dimensions of these sensors are 20mm x 27mm x 4mm / 0.8" x 1.1" x 0.2". These sensors measure absolute orientation, angular velocity, acceleration, magnetic field strength, linear acceleration, gravity, and temperature. This tracking data informs the controller of possible errors between the state of the astronauts' hands and the state of FIST so a control input is generated accordingly.

2. Power

To keep FIST running for the duration of its mission, it needs electrical power supplied to all other subsystems. The power subsystem, which solely consists of batteries, is responsible for the storage and distribution of power for the entirety of FIST. Functional Requirements **FR.1** and **FR.3** further detail what is expected of the subsystem for a successful mission. To satisfy these requirements, a proposed design solution of eight 3.7 V 10000 mAh batteries, with a group of four batteries being connected in series which are connected to another group of four batteries in parallel to increase capacity. Thus producing a nominal voltage of 14.8 V and a battery capacity of 20000 mAh.

3. Pneumatics

The pneumatics subsystem provides the pressure necessary to actuate FIST's soft robotics and allow for movement. If the pneumatics subsystem fails to work as needed, the function would slow considerably or even halt entirely. Pneumatics must ensure pressure is high enough to allow for movement, but never so high as to risk damage. It must also integrate smoothly with the rest of the suit without causing issues. These requirements are described in greater detail in functional requirements **FR.9** and **FR.10**. Pneumatics is powered by a N
C B08RCRJH9M Micro Diaphragm Pump directing air through miniature 2-way solenoid valves.

4. Structures

The structural integrity of the air chambers in FIST is what allows movement for each joint. If an air chamber were to fail, that would halt movement in that joint. Punctures and leaks would cause the air chamber to fail and the joint to become unresponsive. The main casing of FIST provides stability and protection for the subsystems inside the casing. This also means that FIST itself must be durable, but also light enough for astronauts to carry for long periods. Functional Requirements **FR.2** and **FR.3** outline in greater detail the requirements of the structures and materials of FIST. For the design solution, the TPU film will be heated between a layer of fabric, creating an air and water-tight seal. The TPU fabric will then be cut into specified shapes, and the edges will be fused according to the pattern. This will create the air chamber that when inflated curves 90 degrees, and when deflated returns to a neutral horizontal plane. The air chambers will have one side connected to a tubing that carries allocated air from the pneumatics subsystem. The casing and supports will be 3D printed as per the 3D model in Figure 4.

5. Survivability

FIST requires protection from dust and debris as well as thermal regulation. General survivability from daily use is also a concern. Functional Requirements **FR.6** and **FR.7** represent these needs. The design solution for survivability consists of an MLI blanket-like fabric covering that protects from wear-and-tear as well as improving the thermal characteristics of FIST. A kevlar outer layer protects from abrasion and punctures, while 3 layers of aluminized mylar (separated from each other by scrim layers) provide improved performance in radiative heat transfer.

6. Communication and Data Handling

For FIST to be able to properly function, it must be able to read and transmit the data from one subsystem to another. This includes reading the data from the sensors of the GNC system and transmitting it to the compressors in the Pneumatics system to correctly mimic the movement of the hand. Functional Requirements **FR.4** and **FR.5** detail these needs. For the design solution, the communication and data handling systems will use two microcontrollers. The Arduino Uno WiFi will be located in FIST, and the other on the Sleeve will be on the astronaut's arm. The microcontroller in the Sleeve will be the Arduino Due, it contains 54 I/O ports, and it is compact and lightweight. The second microcontroller used will be the Arduino Uno WiFi, which will be located in the forearm of FIST, and contains 14 I/O ports. Both microcontrollers will be used to connect to the BNO055 sensors from the GNC System, and the Arduino Uno WiFi located inside of FIST will also be used to communicate with the diaphragm in the Pneumatics system.

Each of these subsystems was evaluated for potential risks. These risks were explored and solutions were found to mitigate them.

D. Risk Management

Several potential risks were identified that could threaten the performance of FIST or its ability to carry out its mission. There are two main categories of risk identified: technical and administrative. Technical risks are potential mechanical or system failures that would impede the operation of FIST, pose a risk of injury to the operator, or otherwise reduce the functionality of FIST. Administrative risks are situations that could impede the successful completion of the project. Each risk was rated for both likelihood and consequences on a scale of 1-5, with 1 being low likelihood or consequences, and 5 being high likelihood or catastrophic consequences. The primary identified risks are listed in the table below.

Risk	Type	Designation	Likelihood	Consequences
Mechanical failure of component	Technical	T-1	2	3
GNC system gives misinput	Technical	T-2	3	4
Software bug causes failure	Technical	T-3	1	4
Premature battery drain	Technical	T-4	1	5
Temperature exceeds operational limits	Technical	T-5	2	4
Pneumatics are over/under pressure	Technical	T-6	2	4
FIST does not meet mass constraint	Technical	T-7	3	2
Budget overrun	Administrative	A-1	1	3
Schedule slip	Administrative	A-2	2	3

Table 1 Identified risks

A Goddard risk matrix, as seen below, illustrates the relative risk of these.

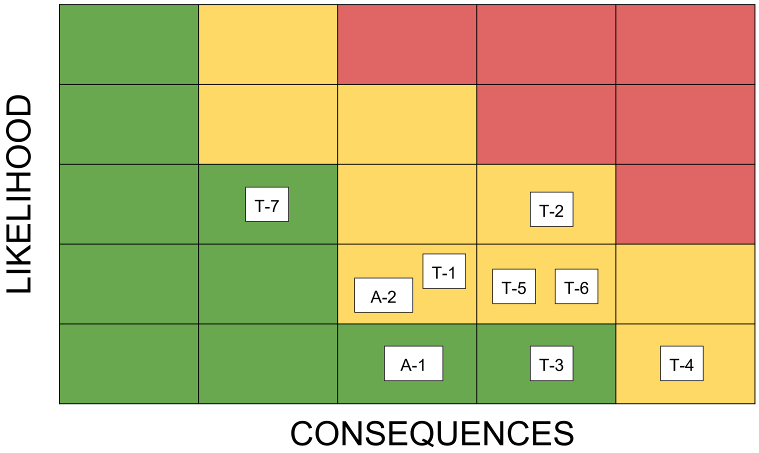

Fig. 2 Goddard Risk Matrix

A risk mitigation plan was conceived for each identified risk, in order to mitigate the likelihood and/or consequences of each risk. The mitigation plans are summarized in the table below.

Following the risk mitigation plan, the estimated risks were re-evaluated and are displayed in the revised Goddard Risk Matrix below.

Risk	Designation	Mitigation Plan	New Likelihood	New Consequences
Mechanical failure of component	T-1	Determine structural limits of FIST	2	3
GNC system gives misinput	T-2	Ensure sensor connections are correctly wired and consider handling for unexpected inputs	2	4
Software bug causes failure	T-3	Conduct rigorous testing of software before implementation	1	3
Premature battery drain	T-4	Full cycle tests will be conducted and a power budget will be made to ensure the battery keeps FIST running.	1	4
Temperature exceeds operational limits	T-5	Conduct thermal testing and implement redundancy	2	3
Pneumatics are over/under pressure	T-6	Implementation of a plenum and relief valves	2	3
FIST does not meet mass constraint	T-7	Implement mass budget for subsystems and monitor adherence	2	2
Budget overrun	A-1	Identify costs before purchase of components and eliminate unnecessary purchases for the prototype	1	3
Schedule slip	A-2	Maintain weekly meetings and check progress against planned schedule regularly	2	3

Table 2 Mitigated risks

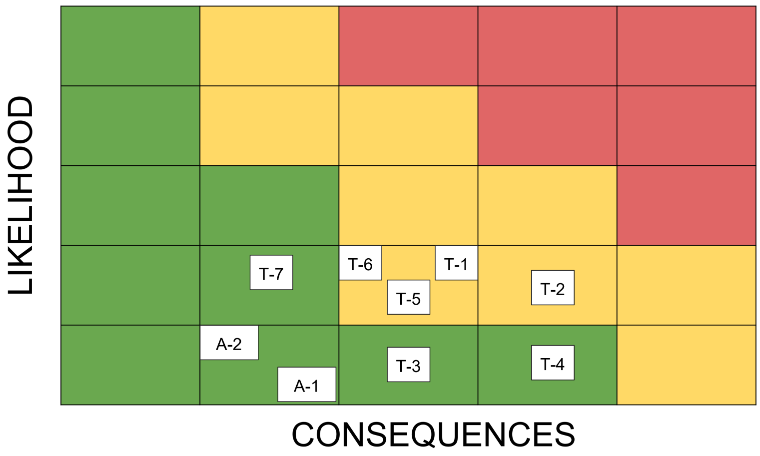

Fig. 3 Revised Goddard Risk Matrix

Taking into consideration the risks identified and the mitigation plan conceived, the design of FIST was concluded, and manufacturing commenced.

II. Methodology

The following figure depicts an exploded view showing the many subsystems and components within FIST.

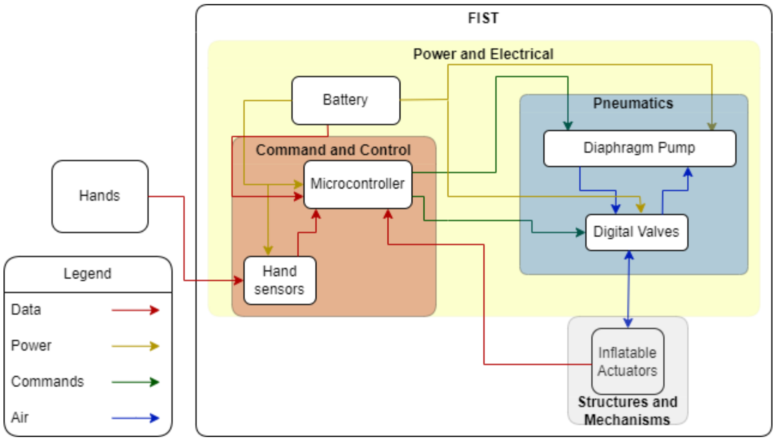

Fig. 4 Functional Block Diagram

The functional block diagram seen in Figure 5 illustrates the connections between the subsystems seen in FIST, starting from the Sleeve and leading towards the glove component. A battery powers both the microcontroller and the compressor. The GNC System will conduct bidirectional communication between the Sleeve and FIST. The Guidance System utilizes its components to access the desired positions and attitudes of the astronauts' hands. The Navigation System will establish and maintain an accurate knowledge of how the inflatable actuators move through space. The microcontroller will perform real-time error calculations between the Guidance System's reference signal and the Navigation System's output signal and adjust its commands accordingly. The microcontroller also then computes that displacement, calculates the air needed to mimic that displacement in the exoskeleton, and sends that pressure value out to the compressor. The compressor reads that value and displaces the air in the location(s) of the hand that match the displacements in the Sleeve. This is achieved through the inflatable actuators, powered by a micro diaphragm pump, and allows for the successful movement of FIST. The sensors on the fingertips of the exoskeleton also relay data back to the microcontroller.

A. Manufacturing

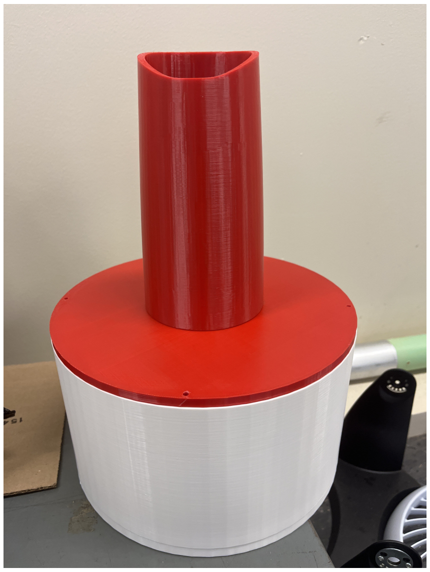

Fig. 5 3D Printed Base of FIST

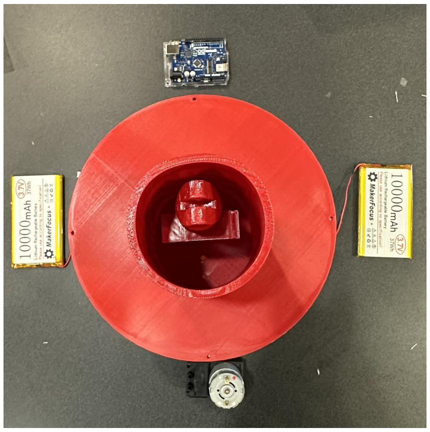

Fig. 6 View Inside Forearm of FIST

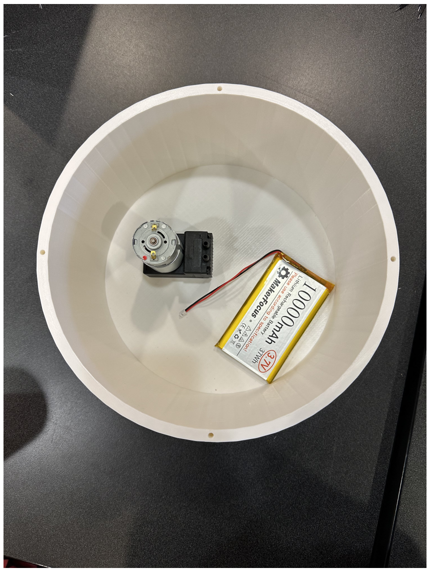

Fig. 7 View Inside Base of FIST

1. GNC and Communication and Data Handling Manufacturing

The GNC subsystem required minimal manufacturing. The components involved in this subsystem included the IMUs. The IMUs arrived in two separate pieces: the main board and the pins. There were a total of fourteen IMUs each accompanied by fourteen pins. The manufacturing process for the IMUs included severing the pins into three smaller groupings: six pins, four pins, and fours pins, setting aside one grouping of four pins as these were extra, plugging the long sides of the groupings of six and four pins into a breadboard, placing the inertial measurement unit on top of the pins so that they fit into the holes on the sensor, soldering the pins to the inertial measurement unit, removing the entire inertial measurement unit from the breadboard and store in a separate organized pile, and repeating these steps for all 14 IMUs. In addition to assembling the sensors themselves, the Sleeve also had to be constructed. The Sleeve is a wearable glove that includes 4 IMUs, an Arduino Due, a small breadboard, and several male-to-male jumper wires. The IMUs are located at the thumb, index finger, middle finger, and pinkie finger. On the back of the hand exists a pouch for the Arduino Due and breadboard. The Vin, GND, SDA, SCL, and ADR pins were soldered to wires that connected to the breadboard. The breadboard was wired to the Arduino Due.

2. Power

The manufacturing of the power subsystem involves wiring the batteries together and installing them into FIST. The items and tools needed are jumper wires, PH2.0 female connectors, wire nuts, and batteries. The female PH2.0 connectors were connected to the battery's built-in male PH2.0 connector. The positive leads were connected to the negative leads with a wire nut to make a series connection between the batteries. Then the two battery groups were connected by twisting the positive and positive leads to an external jumper wire and then repeating the same for for the negative leads. The exposed jumper wires were then extended to supply power to other subsystems by soldering, twisting wire nuts, or using a breadboard as necessary.

3. Pneumatics

The pneumatics subsystem required minimal manufacturing, with the components being ready for use as-is and requiring only connecting. To allow for smaller tubing routing through FIST's body, the compressor's tubing size was reduced to a smaller diameter, and then split 5 ways using two cross unions. Each output was fitted to a solenoid valve and then routed to FIST's air chambers. A second set of solenoids and connectors, in the same configuration, was also fitted to the air chambers to allow for air to move into one finger and out another simultaneously. Heat shrink was applied around the solenoid connections and shrunk with a heat gun to help attain a tight connection and reduce the risk of leaks.

4. Survivability

Manufacturing of the survivability subsystem consisted of creating a glove-like covering from the multilayered fabric that was created. The fabric was sewn into the proper shape and is meant to slip on and off the larger device, for ease of access to interior components of the prototype.

As FIST is being manufactured, the functionality and safety of its subsystems were evaluated in a series of verification and validation tests.

III. Results and Discussion

The verification for the GNC System evaluates the performance of the IMUs with tracking position and attitude of the astronauts' hands. A successful test called for all four IMUs that were embedded in the Sleeve to read their changes in position. A second test verified the responsiveness and accuracy of FIST's new position. The second grouping of five IMUs on the inflatable actuators was tested to ensure they could provide feedback on how FIST moved. Success would have demonstrated that the Navigation components work and that the closed-loop control system can be programmed on the Arduino. The procedure of the IMU tests included coding in Arduino IDE for communication to an Arduino Uno, connecting the Arduino Uno to a power source with a USB-A, inserting an IMU on the breadboard, wiring the IMUs to the Arduino Uno, compiling and uploading code from laptop a to Arduino, simulating all ranges of motion, and repeating steps 1-6 for all 14 IMUs. The results were that all 14 IMUs were able to track and transmit roll, pitch, and yaw data. It was concluded that since the sensors could track necessary position and attitude metrics, they could be utilized as part of the Guidance, Navigation, and Control subsystem.

The first Power subsystem test was conducted on MATLAB by simulating the power consumption of all subsystems to verify the battery's capability to power FIST for the intended duration. This was done by calculating the battery's discharge time and analyzing a voltage discharge curve. The results show that the battery can operate for approximately 11 hours, however, in the final 3 hours the battery's voltage drops exponentially, thus being operational for 8 hours and meeting **FR.1**. The second test was conducted experimentally by connecting the battery to a load while monitoring the voltage and current with a multimeter and comparing the measured voltage to the battery's listed voltage. The voltage drop when connecting a load and the load current will be used to calculate the internal resistance of the batteries. The voltage readings are compared to the batteries' listed voltage and the internal resistance is evaluated for safety. The success criteria for this test are that the batteries will have an approximate voltage reading of 3.7 V when loaded and unloaded individually, and an approximate voltage of 14.8 V when connected which is the designed voltage based on the battery's listed voltage. Additionally, an internal resistance of less than 0.1 Ω. The results showed that the voltage of the batteries met and surpassed the success criteria. The internal resistance of the batteries was in the range of 0.04-0.05 Ω which is sufficiently low.

The verification tests for pneumatics showed that the purchased components met design requirements by connecting the compressor to a pressure chamber and recording both the magnitude of pressure produced and the rate of increase. These values were used both to show that the desired pressure values can be obtained and to calculate the amount of time it would take to move the full volume of FIST's air chambers between the minimum and maximum working pressure values. Both were successful, with the compressor being capable of producing 10x the needed pressure and actuating all of FIST's fingers at once in under half a second.

The verification structures tests verified the structural integrity of FIST. The first test was conducted in the NCSU Textiles Design Lab by creating samples of the TPU (Thermal Polyurethane) fabric used for the air chambers and running an abrasion test using a Martindale Abrasion Machine for at least 5000 cycles. If the samples finished the test with minimal to no pilling, tears, or holes the fabric would have succeeded. The second test was conducted in the Senior Design Lab, using the strain gauge to test samples of fabric. If the stress on the fabric does not exceed one-third of the critical strength of TPU fabric, the fabric would have succeeded. Both tests were successful, with no abrasion being present after 10,000 cycles and the samples had a yield force of over 4 times the average force the air chambers would experience in use.

The verification for the Survivability subsystem has accomplished three main goals. First, the thermal characteristics of FIST (most importantly, radiative heat flux) have been determined to be within the necessary boundaries for optimal battery life and operation. Second, the impermeability of the fabric covering to lunar regolith has been verified experimentally. Lastly, the impact structural integrity of FIST has been determined to be more than adequate for unforeseen impacts, as demonstrated in an ANSYS drop test simulation.

The verification for the Communication and Data Handling subsystem ensures that the microcontroller can read data from the IMUs in FIST. This test was conducted by connecting the Arduino Due to a power source using a micro-USB cable, connecting the BNO055 sensor to a breadboard, and wiring it to the Arduino board. The Arduino IDE environment is then used to compile and upload a code to the microcontroller, to read and store the data collected from the different motions of the IMU. The result was that the Arduino Due board was successfully able to read the different motions of the sensor. Test 2 verified that the Arduino Due microcontroller was able to transmit data in a closed-loop system, through coding. To conduct this verification, an LED light, a 270 Ω resistor, a breadboard, and the Arduino Due board were used. A simple circuit was built, and the Arduino Due was connected to a power source using a micro-USB cable. A successful test would result in the LED light turning on and off in intervals of two seconds, once the data was compiled and uploaded to the microcontroller. Both tests were successful, showing that the Arduino Due board meets all the necessary criteria for the Communication and Data Handling System.

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