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Morphing Upper Torso: A Novel Concept in EVA Suit Design

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ABSTRACT

The University of Maryland Space Systems Laboratory and ILC Dover LP have developed a novel concept: a soft pressure garment that can be dynamically reconfigured to tailor its shape properties to the wearer and the desired task set. This underlying concept has been applied to the upper torso of a rear entry suit, in which the helmet ring, waist ring and two shoulder rings make up a system of four interconnected parallel manipulators with tensile links. This configuration allows the dynamic control of both the position and orientation of each of the four rings, enabling modification of critical sizing dimensions such as the inter-scye distance, as well as task-specific orientations such as helmet, scye and waist bearing angles.

Half-scale and full-scale experimental models as well as an analytical inverse kinematics model were used to examine the interconnectedness of the plates, the role of external forces generated by pressurized fabric, and the controllability of the system. The kinematics of the system were investigated, and tensile forces in the links were quantified to determine actuator requirements. A third experimental model was developed to eliminate material effects and thereby quantify the loads born by the pressure garment, thus allowing further understanding of the behavior of this highly complex system. This lightweight, resizable, dynamically reconfigurable suit certainly makes the MUT concept appealing as a candidate for a next generation planetary exploration suit.

INTRODUCTION

As NASA shifts its focus to the exploration of the moon and Mars, the need for a planetary exploration pressure suit becomes increasingly immediate. New suit architectures must be developed to enable astronauts to explore these environments for long periods of time. Mobility, don/doffability and low mass are among the priorities for a feasible, next generation suit [1-3].

One of the greatest challenges of pressure garment design is that a key feature that makes the suit highly usable (a close fit to body dimensions) makes it difficult to ingress and egress. An examination of various suit-entry types for traditional Hard Upper Torso (HUT) architectures has shown that each presents its own compromises between dimensions and don/doffability [4]. A well-known illustration of this compromise is the inter-scye dimension in waist-entry suits, which must be large enough to allow ingress, causing misalignment of the scye bearing and the shoulder, and therefore reducing shoulder mobility.

Maximizing mobility in a pressure suit is paramount to enable astronauts to perform a wide array of tasks without fatiguing. Working within the pressurized volume of the suit requires strength and endurance, as the pressurized fabric increases the required joint torques [1,5], making even simple tasks difficult and tiring. Soft goods engineers have developed methods of reducing these additional joint torques through the use of gores and convolutes, which maintain the volume of the joint throughout the motion [2,3]. A constant volume joint has also been achieved through the use of all hard suits, such as the AX-5 [2,3]. While these methods have successfully reduced the induced joint torques, they have not eliminated them completely. The goal in suit design remains to completely eliminate the induced joint torques and achieve nude body performance.

An additional complication is that the closer the fit of the suit, the more unique each suit becomes, complicating issues of fabrication and support logistics. The ultimate example of this approach was the Apollo suit system, where each astronaut had custom-made suits. This eliminates all possibilities of flexibility in fitting suits to new astronauts, and clearly increases manufacturing, maintenance and repair costs. This architecture aimed to maximize mobility through a close fit, but even this approach was imperfect, as it became apparent that it was difficult to compensate for body shape changes in microgravity.

The modular system employed in the EMU uses various sizes of each component, which can be assembled into many different combinations, guaranteeing a fairly close match to each astronaut. This reduces production costs and increases flexibility and interchangeability, but at the cost of reduced mobility due to inexact fit.

Another concern for a planetary pressure suit is that it must be lightweight. The HUTs used in the EMU and the Russian Orlan suits, designed for use in zero gravity, are too heavy for planetary exploration, even in the relatively low 1/6th g lunar environment. The feasibility of all-hard suits for planetary exploration is also clearly limited by this lightweight requirement. Completely soft suits, such as those used to explore the moon during the Apollo missions, the Apollo A7L and A7L-B, are much lighter and could provide the baseline for the next generation planetary suit. However, the limited mobility of these suits severely restricted the Apollo astronauts, and must be improved upon for the next planetary exploration missions.

To date there is no solution to the challenge of making a suit resizable, form fitting, highly mobile, lightweight, and easy to ingress/egress. Each suit architecture compromises one or more of these features to maximize others.

In light of these challenges, new and completely different suit architectures must be developed to enable astronauts to explore the moon and Mars. The concept proposed here is the Morphing Upper Torso; a soft pressure garment that does not compromise mobility nor don/doffability. It has the potential to be lightweight, resizable, form fitting to any astronaut and easy to ingress/egress. The concept could also prove to enable incredible mobility, perhaps even surpassing nude body performance.

The concept of the MUT has been developed and modeled mathematically and experimentally. Following an overview of this novel concept, the inverse kinematics model is presented. This mathematical model enables analysis of the feasibility of the system, and was used in conjunction with experimental models. Results from these models led to the creation of a full scale MUT, a modification made by the University of Maryland of a Soft Upper Torso (SUT) designed and manufactured by ILC Dover. Precise measurements of link tensions and reconfiguration kinematics are presented, and the correlation with the mathematical model is discussed. Finally, future studies, which will enable implementation of the MUT technology into a usable experimental pressure suit, are discussed.

MUT CONCEPT

The University of Maryland Space Systems Laboratory (SSL) has been performing research in the areas of space suit design and robotics for over 20 years. The MUT concept is a merging of these two fields, integrating robotics technology into a soft upper torso. This produces a pressure garment that can be dynamically reconfigured to tailor its shape properties to the wearer and the desired task set, through the use of interconnected parallel manipulators.

The most common example of a parallel manipulator is the Stewart Platform [6], which consists of a platform connected to a base by 6 prismatic linkages. Spherical joints at the base and universal joints at the platform connect the linkages, such that control of the linkage lengths allows control of the position and orientation of the platform. This system yields a 6 degree of freedom, high precision, high strength manipulator which has been used in a variety of applications, most notably flight simulators [7,8].

Most parallel manipulators employ linear actuators in-line with linkages in compression. Recently, efforts have been put forth in the field of wire-actuated manipulators, using linkages in tension [9,10]. Control of an n degree of freedom wire-actuated manipulator requires n+1 wires, unless there is a mechanical constraint such as gravity, in which case n wires are needed.

The MUT is a system of four interconnected, wire-actuated, parallel manipulators. It is made up of one base plate (the back hatch) and four actuated rings (the helmet, shoulder rings, and waist ring). The base plate serves as a reference plane, or ground, for the entire system and is the only plate with more than three connection points. The four actuated rings each have six linkages attached in pairs at three distinct nodes. The pressure pushing the plate outwards along a vector normal to the plane of the ring is a mechanical constraint, which maintains the tension in the linkages. This configuration of 6 wires and a constraint allows control of the position and orientation of each ring, through length changes of the linkages.

Nodes are used to define the connection points for each link in the MUT system. These nodes (three per ring, eight on the back hatch) are located on the perimeter of each ring with user-specified angular spacing. Labels for the nodes and links were developed for communication and clarification purposes, and will be used throughout the paper. Nodes 1-3 are located around the perimeter of the helmet (H), 4-6 on the right shoulder (RS), 7-9 on the left shoulder (LS), 10-12 on the waist (W), and 14-20 around the perimeter of the backpack (BP). Table 1 relates the link assignments to the nodes. Figures 1-3 show graphically the linkage-ring configuration; the four maneuverable rings are the solid-lined circles, the linkages are the red dashed lines, and the back hatch is the solid-lined door-shape. Note that the configuration of rings, links and nodes is symmetric about the Y-Z plane.

Link	Node 1	Node 2	Physical Location
1	1	13	H-BP
2	1	20	H-BP
3	2	9	H-LS
4	2	14	H-BP
5	3	4	H-RS
6	3	19	H-BP
7	4	9	RS-LS
8	5	8	RS-LS
9	5	12	RS-W
10	6	18	RS-BP
11	6	19	RS-BP
12	7	14	LS-BP
13	7	15	LS-BP
14	8	10	LS-W
15	10	15	W-BP
16	11	16	W-BP
17	11	17	W-BP
18	12	18	W-BP

Table 1: Description of links

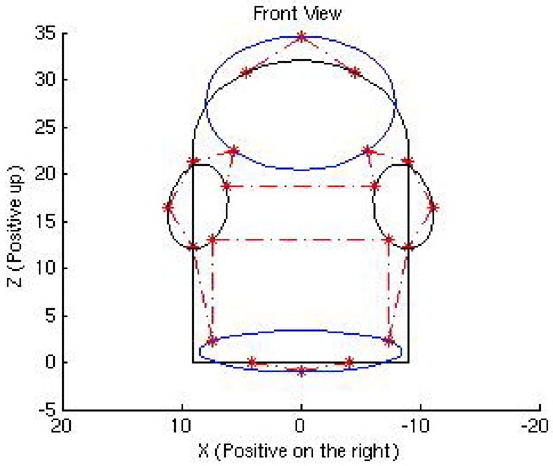

Figure 1: Linkage-node configuration, Front View

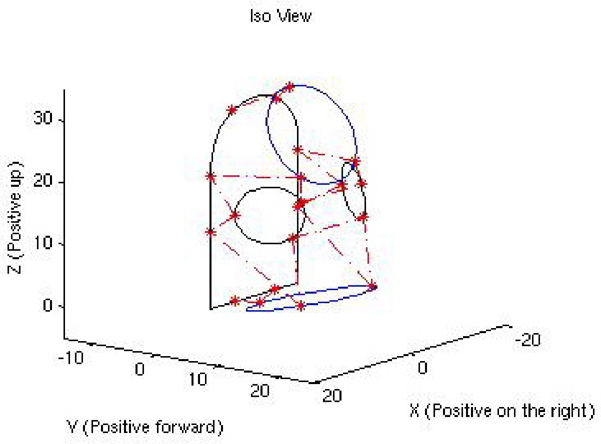

Figure 2: Linkage-node configuration, Isometric View

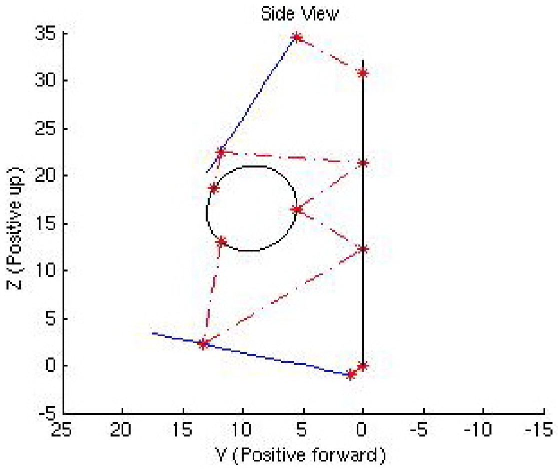

Figure 3: Linkage-node configuration, Side View

The advantages of this concept are numerous. Primarily, it creates a suit that is easy to don and doff and could exactly fit the anthropomorphic dimensions of all subjects. This is possible because adjustable linkages, rather than fixed soft goods (pressure bladder and restraint layer), define the suit dimensions. The initial dimensions of the linkages and soft goods are designed to be larger than the largest subject, ensuring simple ingress/egress for all subjects. Once the suit is donned, the linkage lengths are adjusted, positioning the plates such that the dimensions of the suit exactly match the subject. Dimensions such as the inter-scye distance, critical to shoulder mobility, can be perfectly tuned to each astronaut. The same suit could be used by a large man or a petite woman, achieving a level of resizability and mobility (due to close fit) unparalleled in present suit architectures.

In addition, orientation-control of each ring allows real-time task-specific adjustments. Examples include tilting the helmet towards the astronaut's line of sight, tuning the scye angles for required arm motions, or manipulating the waist angle while bending over or crouching. Not only would the suit exactly match the astronaut's body dimensions, but it would also match the optimal orientations of each ring.

Finally, the MUT technology would incorporate motion-following control algorithms; the actuated linkages would dynamically adjust the positions and orientations of the rings as the astronaut moved. Acting as a powered exoskeleton, the morphing suit would enable extraordinary mobility, not only eliminating induced joint torques due to pressurized fabric, but actually increasing the astronaut's capabilities.

METHODS

ANALYTICAL MODEL

To expand the MUT from concept to reality, an analytical model was developed, which produces 3-D models of the torso and calculates the inverse kinematics of the system. Inverse kinematics is defined as the calculation of the individual link lengths required to position and orient each plate in a three-dimensional space. For parallel manipulators, such as the MUT, it is the transformation from the Cartesian-Space of the plates, to the Joint-Space of the links. The forward kinematics, which calculates the position and orientation of each plate given all the link lengths, have not yet been solved; significant research efforts will be put forth in this area in the future.

The following approach was used to calculate the link lengths based on input ring positions and orientations. A reference frame is attached to each ring in the system, and the origins of each ring are located at the center of that ring. The base frame is located at the center of the back hatch. The desired position and orientation of each ring are input into the model; the position is input as the location of the origin of each ring frame in base frame coordinates, and rotations are defined using Euler angles.

The coordinates of each of the nodes are known in the frame of the corresponding ring. To calculate the distance between two nodes, they must be represented in the same coordinate system. Transformation matrices, which relate the position and orientation of the MUT rings to the base frame, are calculated and used to determine the coordinates of the nodes in the back hatch base frame. Using these coordinates, the node-to-node distances can be calculated for any torso configuration.

Primarily, these calculated distances provide an estimate for the link lengths, which are used in experimental models to obtain the desired configuration. The linkage lengths required to position the MUT into the exact configuration of any size EMU HUT, for example, can be calculated. The experimental MUT model is derived from the ILC I-Suit SUT, thus this was chosen as the nominal configuration for the results presented, however truly any configuration could be input into the model.

In addition, the analytical model provides insight into actuator and linkage requirements. Calculating the link lengths for the extreme configurations of the rings approximates the range required for the linkages. The sensitivity of the system is also investigated by examining changes in link lengths due to small changes in position and orientation of the rings.

EXPERIMENTAL MODELS

A small-scale MUT was designed and constructed by the SSL for initial experiments. The MUT was designed with 5 blanking plates (back hatch, helmet, waist, and two shoulders) integrated into a urethane-coated nylon pressure bladder and nylon restraint layer. The MUT plates are approximately 9/16 the size of those on the SSL MX-2 HUT.

While traditional SUTs are shaped and sized by their fabric pattern, the MUT soft goods were designed with additional material to ensure that the linkages were fully responsible for positioning the MUT plates. Therefore, in the un-wired configuration of the MUT, the waist, helmet and shoulder rings are not at specific angles or locations, rather there is enough space to allow the MUT to be manipulated into a scaled down EMU HUT model and beyond.

For initial static analysis, a system of manually adjustable links was created and integrated into the small scale MUT. Figure 4 shows the configuration of the links.

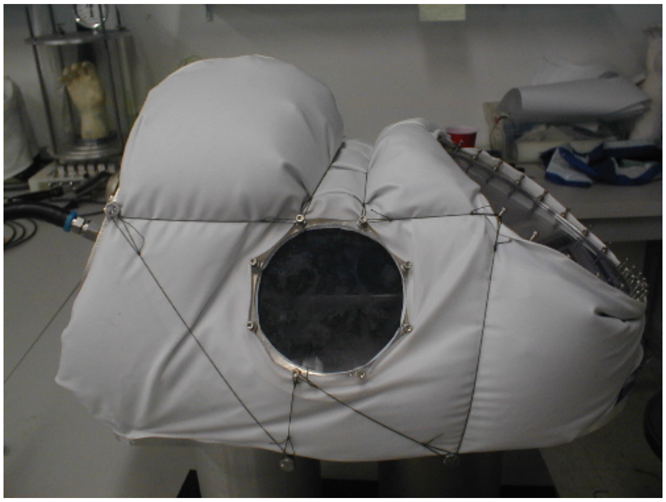

Figure 4: Initial configuration of links on small-scale MUT

A second experimental model was created to examine the role of the pressurized fabric on the MUT system. The soft goods were removed from the MUT, and a test stand was developed to support hanging weights attached to each plate. The weights are attached such that the force pulls exactly normal to each plate, along the same vector as the force due to internal pressure in the pressurized model. This model is identical to the MUT in every way, other than the removed soft goods, successfully isolating the influence of the pressurized fabric on the system.

Figure 5: Experimental model of MUT system without pressurized fabric

The third experimental model is a full scale MUT, an SSL modification of an expanded SUT designed and manufactured by ILC Dover. The expanded SUT design is based on the torso of the I-suit, an experimental all-soft multi-bearing space suit developed by ILC Dover [11]. The helmet, waist, back hatch and shoulder rings implemented in the MUT are identical to those of the I-Suit. The difference lies in the soft goods, which were expanded from the baseline I-Suit dimensions. Each of the four actuated rings was displaced outwards along the normal vector, and the shoulder rings were canted outwards from the body centerline. This provides excess soft goods and therefore the ability to reposition and reorient the rings with the use of tensile linkages. Models of the expanded SUT and the baseline I-Suit SUT are shown in figure 6.

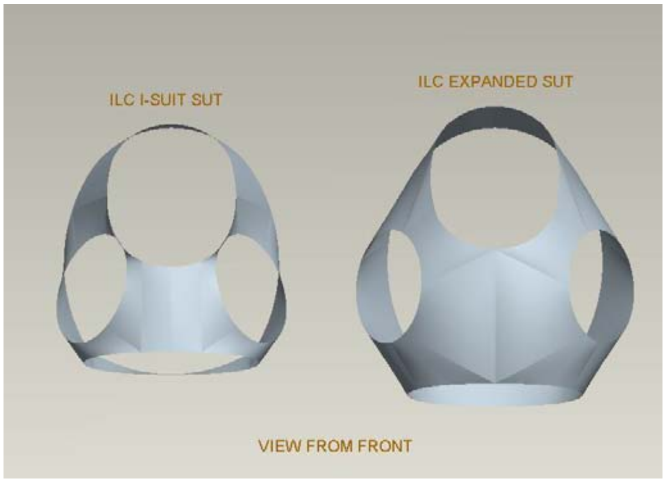

Figure 6: Models of the baseline I-Suit SUT and the expanded SUT

The corresponding pressure bladder and restraint layer were designed, and fabricated of the same materials used in the I-Suit. The complete expanded SUT, shown in figure 7, was then modified to produce an experimental MUT, using similar methods to those used for the construction of the small scale MUT. The full scale reconfigured MUT is shown in figure 8.

Figure 7: Expanded SUT

Figure 8: Reconfigured MUT

To obtain the exact angles and locations of the plates as well as the exact locations of the attachment points, the FAROArm® was used. The FAROArm® is a portable Coordinate Measuring Machine (CMM) capable of high accuracy (0.0005") 3-D measurement. This provided an excellent means of quantitatively comparing the experimental models, and correlating the data with the mathematical model. The FAROArm® was used to take measurements on all three experimental models. Additionally, link tensions were measured using an in-line force transducer.

RESULTS

The inverse kinematics model was first used to calculate the link lengths for various torso configurations. As the model calculates the node-to-node distances, it is evident that the calculated link lengths have some inherent error, as they are linear distances and do not compensate for the added lengths required to bend around the pressurized torso. This error is approximately constant for a single linkage, thus the difference between two inverse kinematics models can be used to estimate the changes in linkage lengths required to alter the MUT from one configuration to another. This approximation is sufficient for reconfigurations within a reasonable range.

The expanded SUT is extremely large and as such is easy to ingress and egress. The initial lengths of the linkages need to be at least as long as the material dictates, to ensure this relative ease is maintained. These initial lengths were calculated by inputting the positions and orientations of the rings of the expanded SUT into the analytical model. The link lengths were also calculated for a MUT configuration that exactly matches that of the I-Suit SUT. This nominal I-Suit configuration represents a torso that is a relatively close fit to an average male. To truly take advantage of MUT technology, dimensions specific to each subject would be input into the model. For the purposes of demonstrating the feasibility of the MUT, however, the ability to reconfigure to the I-Suit dimensions was chosen as the nominal reconfiguration. Table 2 shows the changes in link lengths necessary to contract the expanded SUT down to a nominal I-Suit SUT. Figures 9 and 10 graphically show the results from the analytical model. The helmet and waist ring are represented as triangles for simplicity, due to the irregular shapes of the I-Suit rings.

Link	Length (inches) Expanded SUT	Length (inches) Nominal SUT	Length Change (inches)
1	5.44	3.61	-1.83
2	5.44	3.61	-1.83
3	6.76	4.17	-2.60
4	14.32	12.34	-1.98
5	6.76	4.17	-2.60
6	14.32	12.34	-1.98
7	14.66	9.77	-4.88
8	16.79	11.79	-5.00
9	7.60	5.54	-2.06
10	9.32	7.62	-1.70
11	8.74	7.81	-0.93
12	8.74	7.81	-0.93
13	9.32	7.62	-1.70
14	7.60	5.54	-2.06
15	16.31	15.36	-0.95
16	5.67	4.20	-1.47
17	5.67	4.20	-1.47
18	16.31	15.36	-0.95

Table 2: Link Lengths for Expanded and I-Suit configurations

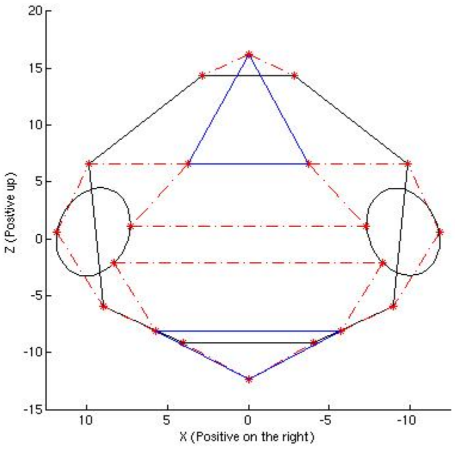

Figure 9: Inverse Kinematics model of expanded MUT

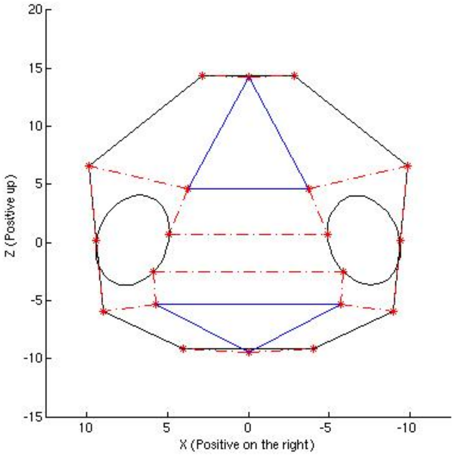

Figure 10: Inverse Kinematics model of contracted MUT

Unfortunately, the results found using the inverse kinematics model do not imply anything about the forward kinematics of the MUT system. In particular, the results do not prove that a given set of link lengths will guarantee a specific MUT configuration.

Therefore, lacking a formal model for forward kinematics, experimental testing was required to evaluate the actual configuration changes when the links are adjusted. The length changes shown in table 2 were applied to the full-scale MUT model, and the positions and orientations of the rings were measured. The resulting configuration of the experimental model was very close to that of the analytical model, as can be seen by the correlation between figures 8 and 10. The relative location of the nodes and the rings correlate very well: the inter-scye distance has been shrunk to that of the I-Suit, the waist ring has been lifted and tilted upwards, and the helmet ring brought downwards and towards the back hatch. Similar results were obtained with the inverse kinematics model and the small scale MUT, as it was successfully reconfigured into a 9/16-scale model of the SSL MX-2 HUT. Thus far, in all cases, measurements have shown that the configuration changes predicted by the inverse kinematics model produce similar outcomes when applied to the experimental models.

In addition, the link length changes shown in table 2 provide information critical to the design of the actuators, yielding a baseline for the amount of travel necessary for each link. Clearly the actuator range requirements vary greatly, as some of the links require up to five inches of travel, while others require less than an inch.

The ability to calculate link length changes for various reconfigurations also provides insight into the sensitivity of the MUT system. Four perturbed cases were investigated:

1. Helmet pitched down 5 degrees (H_{down})
2. Shoulders pitched down 5 degrees (S_{down})
3. Shoulders rotated forward 5 degrees (S_{fwd})
4. Waist pitched up 5 degrees (W_{up})

Presented in table 3 are the nominal lengths of each link, followed by the change in link length for each case. Positive changes indicate an increase in link length and negative changes require the link to be shortened.

Link	**Nominal Length (inches)**	**Length Change (inches) H_{down}**	**Length Change (inches) S_{down}**	**Length Change (inches) S_{fwd}**	**Length Change (inches) W_{up}**
1	3.61	0.31	0.00	0.00	0.00
2	3.61	0.31	0.00	0.00	0.00
3	4.17	-0.25	0.00	-0.07	0.00
4	12.35	-0.28	0.00	0.00	0.00
5	4.17	-0.25	0.00	-0.07	0.00
6	12.35	-0.28	0.00	0.00	0.00
7	9.77	0.00	0.07	-0.53	0.00
8	11.79	0.00	-0.39	-0.42	0.00
9	5.54	0.00	0.11	0.10	-0.39
10	7.62	0.00	0.00	0.14	0.00
11	7.81	0.00	0.00	0.11	0.00
12	7.81	0.00	0.00	0.11	0.00
13	7.62	0.00	0.00	0.14	0.00
14	5.54	0.00	0.11	0.10	-0.39
15	15.36	0.00	0.00	0.00	-0.14
16	4.20	0.00	0.00	0.00	0.19
17	4.20	0.00	0.00	0.00	0.19
18	15.36	0.00	0.00	0.00	-0.14

Table 3: Link length sensitivity to plate rotations

It is evident from table 3 that rotations of any plate can by done by making specific length changes. This could enable precise tuning of the rings to each astronaut's body shape and to specific tasks. Tilting the helmet ring down, for example would be ideal for an astronaut walking on the surface and looking downwards to maintain footing. Interestingly, for even small rotations, link length adjustments of up to half an inch can be necessary. This will influence the design of motion following control algorithms, as well as the sensitivity of the actuators.

A force transducer was installed in-line with the linkages to record the link tensions in the full size MUT. Tensile forces in the links are a function of suit pressure, but since the operating pressure of a future planetary suit is unknown, the results presented here are for a suit pressure of 3 psi. Table 4 shows the measured forces in the links, which are all in the range of 100-150 lbs. Due to the symmetry of the nominal configuration about the Y-Z plane, corresponding links on either side of the suit have the same tension. Links 7 and 8 connect the two scye rings across the chest, and thus do not have corresponding links. Several of the links were too short to accommodate the force transducer and are not included below.

Link(s)	Tension (lbs)
4 and 6	117
7	134
8	107
11 and 12	125
15 and 18	147

Table 4: Link tensions

Finally, the experimental models were used to investigate the role of the pressurized fabric in the MUT system. The link lengths were maintained constant for both the pressurized and the hanging weight model, and positions and orientations of the plates were measured and compared. Differences along the x and y axes were small (on the order of 0.1”) and could have been due to experimental error, however a large and significant difference between the two models could be seen along the z-axis (pointing straight up the torso's head, see figures 1-3), as shown in table 5.

Ring	Displacement of ring center along the z-axis (inches)
Helmet	2.4
Shoulders	3.0
Waist	1.0

Table 5: Differences between pressurized and un-pressurized MUT models along the z-axis

This data provides some insight into the effects of the soft goods. The large changes along the z-axis show that for a given set of link lengths, the positions of the plates are not congruent between the two models. Thus the pressurized fabric plays a major role in the system, which must be accounted for in the formulation of the forward kinematics.

CONCLUSIONS

The testing conducted to date has provided a significant demonstration of the MUT concept. It has been shown that given a desired suit configuration, a calibrated inverse kinematics model can provide adequate information on link lengths to accurately control the MUT reconfiguration. Furthermore, preliminary testing seems to indicate that specified link lengths provide a unique configuration of MUT plates. More testing is required to confirm this deterministic nature of the system.

Results obtained from both experimental and mathematical models have produced preliminary actuator requirements for a powered MUT. Actuators must be low profile, yet in some cases able to change the link length by up to several inches. Ideally actuators will be placed in-line with the linkage, however mounting the actuators on the backpack and utilizing a cable driven system to adjust the links is also a possibility.

Testing has also illuminated several areas that still require exploration and testing. One of the most pressing issues involves the interaction between the pressurized SUT fabric and the linkages. It is important to understand how the deformation of linkages due to the pressurization of the SUT affects link length. Also, it will be extremely important to evaluate the nature of linkage intrusion into the main torso volume of the suit.

Additionally, results from the experimental models have shown that fabric tension at the SUT-plate interface plays a significant role in MUT configuration. Unlike an ideal Stewart Platform, forces acting on the SUT plates – in this case due to fabric tension – may have to be incorporated into the mathematical model of the MUT to predict forward kinematics.

Finally, and perhaps most importantly, this research has led to the development of a system capable of exploring MUT technology in great detail. The combination of mathematical modeling with prototype testing and precise measurement techniques facilitates an efficient and effective means of exploring the behavior of MUTs.

FUTURE RESEARCH

A great deal of research should be done, using both mathematical and experimental models, to advance the Morphing Upper Torso concept. In the area of mathematical modeling, efforts must be made to improve the link length determination of the inverse kinematics model. With further analysis of the prototype geometry and SUT linkage interaction, it should be possible to improve length estimates beyond the point-to-point estimations of the current model. Algorithms will be developed that convert exact anthropomorphic measurements of astronauts into ideal positions and orientations of the rings. Once input into the inverse kinematics model and length estimates obtained, further algorithms will calculate exact lengths of the physical links.

The most difficult work however, will be in the development of a forward kinematics model for this system. The deterministic nature of the MUT system must be investigated to determine if a closed form solution to the forward kinematics equations is attainable. Should this prove impossible, it will be necessary to develop numerical methods to evaluate the forward kinematics for actively controlling a powered MUT.

The experimental models also require advanced development. Further measurements of force and range requirements will yield precise actuator specifications required to power the MUT system. Potential actuation methods include electric motors, air muscles, shape memory alloys, and other low profile devices. These actuators must be integrated into the system in such a way that they do not encroach on the subject or hinder the suit's performance.

The combination of these research efforts will ultimately lead to the end goal of a reliable MUT for manned evaluation.

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The URL for the Space Systems Laboratory is http://www.ssl.umd.edu

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