SPACE SYSTEMS LABORATORY
UNIVERSITY OF MARYLAND

MORPHING UPPER TORSO (MUT)

PHASE I REPORT
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INTRODUCTION

The research presented here represents a novel concept in spacesuit design, the Morphing Upper Torso (MUT). As detailed in this progress report, the concept of the MUT has been developed and modeled mathematically and experimentally. This proof-of-concept research effort shows that MUTs may be a valuable step in the evolution of EVA suits.

One of the paradoxes of pressure garment design is that the same feature which makes a suit highly usable (close fit to body dimensions) makes it difficult to ingress and egress. Moreover, 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. Even this approach was imperfect, as body shape changes in microgravity were difficult to compensate for.

The basic concept proposed here is that of the morphing suit: developing a soft (fabric) pressure garment which can be dynamically reconfigured to tailor its shape properties to the wearer and the desired task set. As the test case for this concept, this project focuses on the suit upper torso assembly, bounded by the helmet, shoulder, and waist rings.

The MUT system is made up of one base plate (the back hatch) and four actuated plates (the helmet, shoulder bearings, 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 plates are interconnected Stewart platforms, which require six linkages per plate, connected in pairs at three distinct points on the plate. This design was chosen as it should, with further analysis and experimentation, represent a configuration that controls the position and orientation of each plate.

Experimental and analytical models of the MUT have been made and valuable tools have been developed to understand and explore the MUT concept. The data obtained experimentally has been compared and used together with the mathematical model to obtain some initial insight into the interconnectedness of the plates, the role of external forces generated by pressurized fabric, and the controllability of the system.

MODELING

The first step in this investigation was to calculate the inverse kinematics of the MUT system. The inverse kinematics specifies the individual link lengths required to position and orient each plate in a three-dimensional space. The forward kinematics, which specify the position and orientation of each plate given all link lengths, are exceedingly more difficult to calculate and will require significant research efforts beyond the scope of this report.

An initial link configuration was adopted as shown in Figure 1.

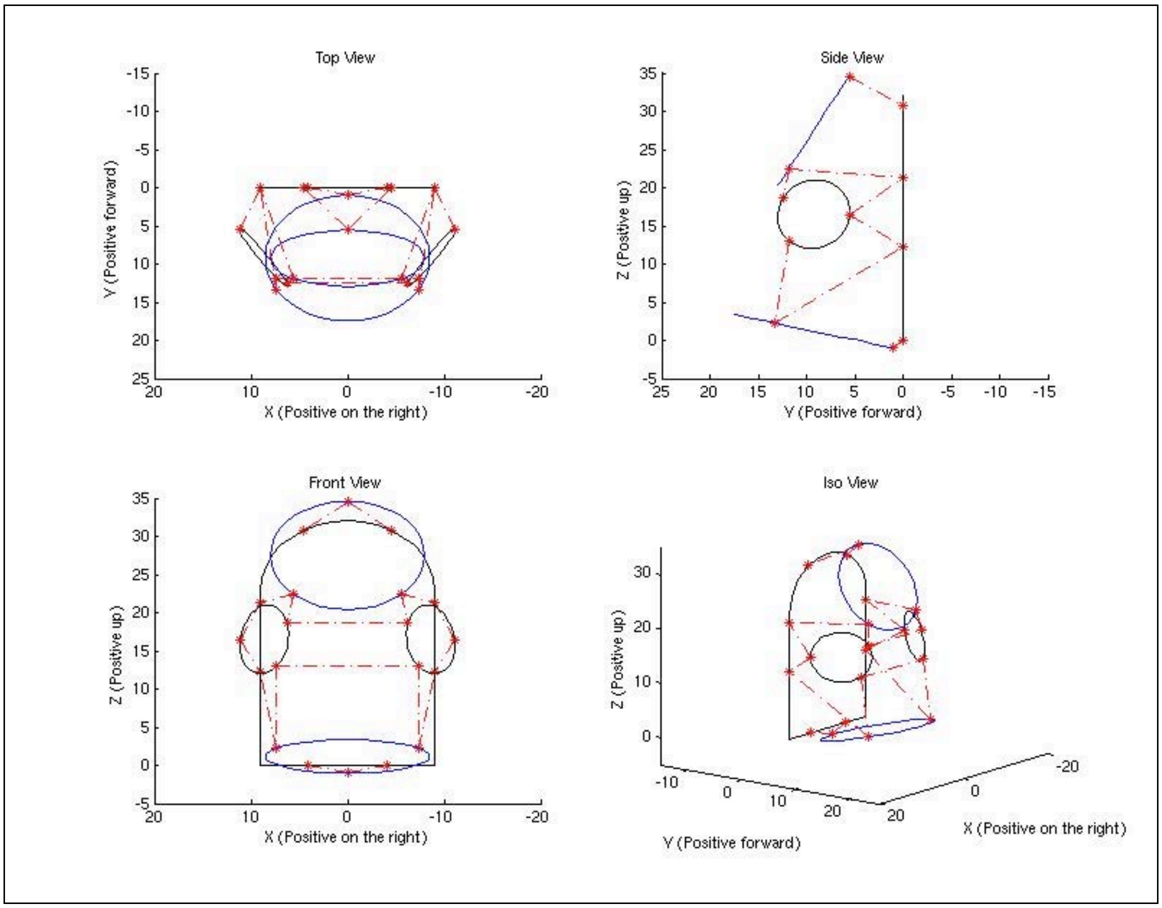

Figure 1: MATLAB generated model of the MUT configuration used to produce a scaled down version of the Space Systems Laboratory's MX-2 space suit analogue.

To model the link configuration in MATLAB, a reference frame is attached to each plate in the system. The origins of each plate are located at the center of that plate and begin coincident with the base frame coordinate system. This base frame is located at the center of the semicircle that shapes the top of the back hatch. Each plate is then translated and rotated to attain its desired location. Rotations are defined using Euler angle rotations most appropriate for the selected plate. A description of initial plate orientations and the order of Euler angle rotations are provided in Figure 2.

	Initial	Rotations		
	Plate Plane	**1st**	**2nd**	**3rd**
Helmet	XZ	Rx	Rz	Ry
Right Shoulder	XZ	Rz	Rx	Ry
Left Shoulder	XZ	Rz	Rx	Ry
Waist	XY	Rx	Ry	Rz
Backhatch	XZ	*<none>*		

Base Frame	Direction
+X axis	Suit's Right
+Y axis	Back to Front
+Z axis	Waist to Helmet

Figure 2: Coordinate frame descriptions for the MUT model.

Nodes are used to define the connection points for each link in the MUT system. These nodes (three per plate, eight on the back hatch) are positioned in the plate frame. Nodes are located on the perimeter of each plate with user-specified angular spacing. The transformation matrices used to position and orient the MUT plates are then used to locate the link nodes in the back hatch base frame. Using these coordinates, the node-to-node distance can be calculated and stored as the link length required to attain the desired MUT configuration.

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 SUT. As a first approximation this SUT-linkage interaction has been modeled as a constant offset. Rather than calculate specific link lengths, the difference between two inverse kinematics models can be used to estimate the changes in linkage lengths required to move the MUT model from one configuration to another. This approximation seems to be sufficient for reconfigurations within a reasonable range.

The ability to calculate link length changes for various reconfigurations provides insight into the sensitivity of the MUT system. The inverse kinematics model was run for a nominal case, followed by six perturbed cases with the following changes:

1. Helmet pitched up 5 degrees
2. Helmet pitched down 5 degrees
3. Arms pitched up 5 degrees
4. Arms pitched down 5 degrees
5. Arms rotated forward 5 degrees
6. Waist pitched up 5 degrees

The results of these configuration changes are summarized in Figure 3.

Nominal		Δ Link Length for 5degree Changes						
Lengths	**Link**	**Hup**	**Hdown**	**Aup**	**Adown**	**Afwd**	**Wup**	**Link**
8.10	*H-B*	**-0.57**	**0.58**	0.00	0.00	0.00	0.00	*H-B*
8.10	*H-B*	**-0.57**	**0.58**	0.00	0.00	0.00	0.00	*H-B*
3.83	*H-SL*	**0.21**	**-0.12**	**-0.01**	**0.03**	**-0.06**	0.00	*H-SL*
12.37	*H-B*	**0.43**	**-0.45**	0.00	0.00	0.00	0.00	*H-B*
3.83	*H-SR*	**0.21**	**-0.12**	**-0.01**	**0.03**	**-0.06**	0.00	*H-SR*
12.37	*H-B*	**0.43**	**-0.45**	0.00	0.00	0.00	0.00	*H-B*
12.53	*S-S*	0.00	0.00	**-0.32**	**0.33**	**-0.52**	0.00	*S-S*
14.64	*S-S*	0.00	0.00	**0.49**	**-0.50**	**-0.44**	0.00	*S-S*
11.98	*SR-W*	0.00	0.00	**0.02**	**0.01**	**0.02**	**-1.10**	*SR-W*
7.26	*SR-B*	0.00	0.00	0.00	0.00	**0.27**	0.00	*SR-B*
7.68	*SR-B*	0.00	0.00	0.00	0.00	**0.26**	0.00	*SR-B*
7.68	*SL-B*	0.00	0.00	0.00	0.00	**0.26**	0.00	*SL-B*
7.26	*SL-B*	0.00	0.00	0.00	0.00	**0.27**	0.00	*SL-B*
11.98	*SL-W*	0.00	0.00	**0.02**	**0.01**	**0.02**	**-1.10**	*SL-W*
17.57	*W-B*	0.00	0.00	0.00	0.00	0.00	**-0.85**	*W-B*
4.30	*W-B*	0.00	0.00	0.00	0.00	0.00	0.00	*W-B*
4.30	*W-B*	0.00	0.00	0.00	0.00	0.00	0.00	*W-B*
17.57	*W-B*	0.00	0.00	0.00	0.00	0.00	**-0.85**	*W-B*
H = Helmet SR = Right Shoulder (units = inches) SL = Left Shoulder W = Waist B = BackHatch								

Figure 3: Link length sensitivity to pre-defined plate rotations.

It should be noted that the nominal link lengths were calculated based on the geometric configuration of the Space Systems Laboratory's MX-2 space suit analogue. It is evident from Figure 3 that there are two classes of link adjustments: coarse adjustments of 1/8" or greater length, and fine adjustments on the order of a few thousandths of an inch. Lacking a formal model for forward kinematics, testing is required to evaluate the actual configuration changes when the fine link length changes are ignored. If these length changes are indeed significant to the final MUT configuration, the minimum step size requirement must be lowered from 0.125" to 0.010" or less.

The following sections will describe how the inverse kinematics model was used in a practical sense to aid in the experimental testing of the MUT. Future research in the area of mathematical modeling of the MUT system is also discussed in the closing sections of this report.

METHODS

The results from a kinematic model for a parallel manipulator such as the MUT system may, or may not, correspond to the behavior of the physical system. While geometrically, the link lengths from our model can orient the MUT plates as specified, it is possible the same lengths also represent the solution to an alternative orientation. In order to investigate the results of the analytical model, it was necessary to develop a proof of concept MUT, and a method for accurately measuring the MUT geometry. The following sections discuss these efforts.

<u>SUT Design</u>

The first step in developing a MUT test bed was to design an experimental SUT. The SUT was designed with 5 blanking plates (back hatch, helmet, waist, and two arms) integrated into a urethane-coated nylon pressure bladder. It was determined that a small-scale SUT would be more manageable and quicker to produce than a full size SUT, while still serving as a valuable experimental tool. Thus, the SUT plates are approximately 9/16 the size of those on the MX-2 Hard Upper Torso (HUT).

While traditional SUTs are shaped and sized by their fabric pattern, the MUT pressure bladder was designed with additional spacing to ensure that the linkages were fully responsible for positioning the SUT plates. Therefore, in the un-wired configuration of the SUT, the waist, helmet and arm rings are not at specific angles or locations. Instead there is enough space to allow the MUT to be manipulated into a scaled down MX-2 HUT model and beyond. Figure 4 illustrates this idea.

Figure 4: Examples of possible SUT reconfigurations.

<u>MUT – Connecting the Wires</u>

The next level of the design was to create a method of reconfiguring the SUT using adjustable links. It was necessary to allow for changes to both the length of the links and the locations of the attachment points on each plate. Thus a system of adjustable wires and multiple bolts as attachment points was incorporated into the SUT, completing the MUT system. Figure 5 shows the wires and attachment mechanisms.

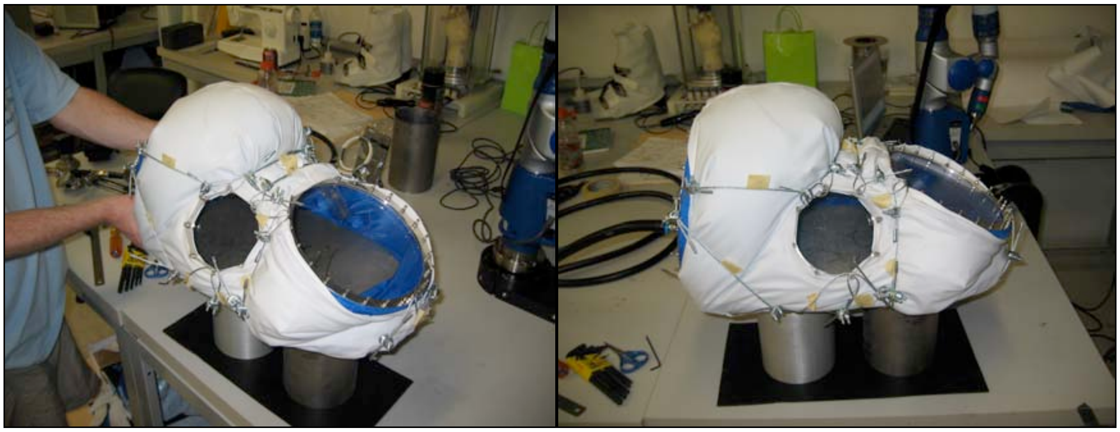

Figure 5: Illustration of wire linkages and their attachment to plate bolts.

Using the kinematic model as a guide, the lengths of the 18 wires can be set to shape the MUT in a user-specified configuration. Figure 6 illustrates a reconfigured SUT approximating the plate configurations on the MX-2 HUT.

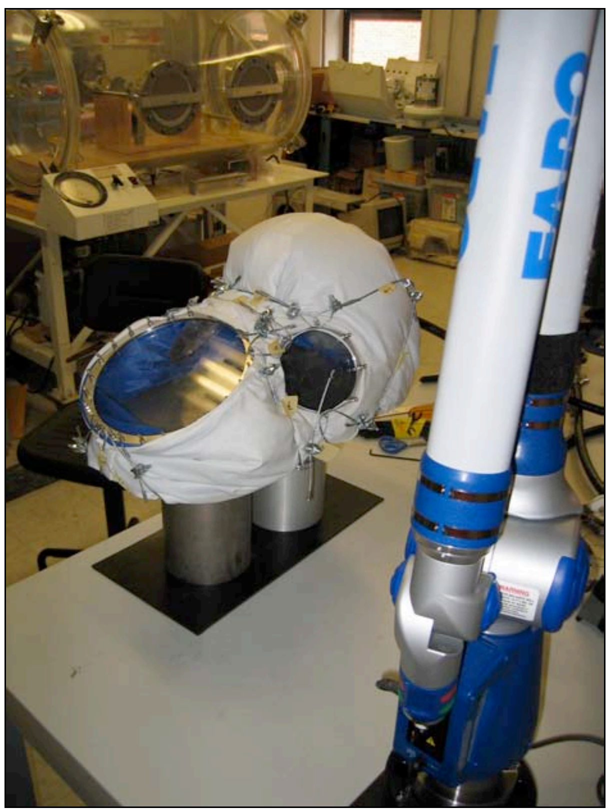

Figure 6: A preliminary MUT configuration to approximate the geometry of the MX-2 HUT.

<u>Data Collection</u>

To obtain the exact angles and locations of the plates as well as the exact locations of the attachment points, a 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 setup with the kinematic model. Figure 7 shows the FAROArm® in use.

Figure 7: The FAROArm® in use for data collection.

RESULTS

Phase 1 – *Calibrate the mathematical model to match attachment points of the experimental setup.*

The rings were designed to allow for several different sets of attachment nodes, but for the initial experimental phase, a set of 20 nodes were located on the rings of the SUT and held constant throughout. These nodes were selected to represent the link configuration shown in Figure 1 as close as possible. In order to ensure that the analytical model could be exactly compared to the experimental measurements, the actual locations of the attachment points on each ring were required to replace the estimated values in the mathematical model. The FAROArm® measurement output shown in Figure 8 provided highly accurate data to replace the estimated node spacing information in the analytical model.

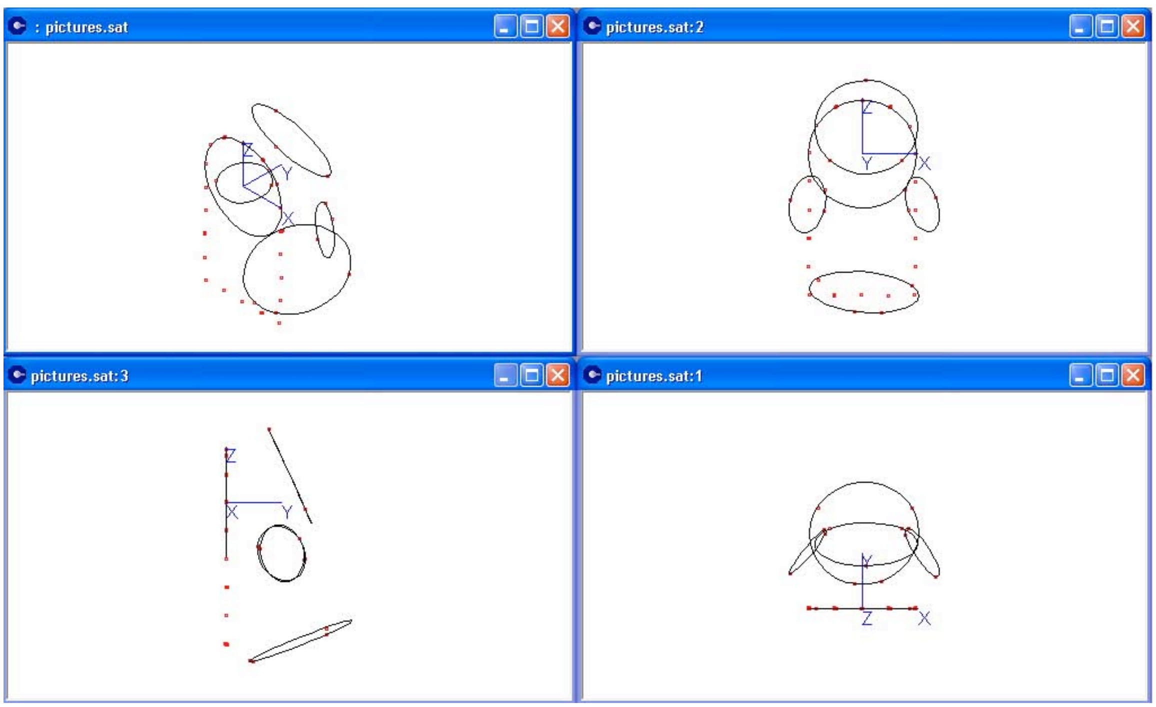

Figure 8: FAROArm® measurement of plate configuration and link node spacing. Note the close resemblance to the analytical model output.

Phase 2 – *Implement link lengths to replicate MX-2 HUT geometry on the scaled down MUT.*

With a calibrated mathematical model, and a user-defined plate configuration, the inverse kinematics produces a single solution of the point-to-point distances between the entire set of link nodes. These distances were used to estimate the wire lengths required to physically realize the desired plate configuration on the MUT. Since the actual wire lengths must account for link-fabric interaction and bending around plates, the actual link lengths need to be significantly longer than the calculated point-to-point distances. To account for this difference, a baseline MUT configuration is measured with the FAROArm®. The changes required to improve the baseline MUT to the desired configuration are then evaluated in the inverse kinematics model, which produces a list of length changes to each link. In this fashion the non-point-to-point link lengths are compensated for by working in relative link length changes as opposed to absolute link lengths.

With the improved wire lengths set, the MUT was again pressurized. The locations and angles of the plates were then obtained using precise measurements from the FAROArm®. It was found that the actual locations and orientations of the rings were within reasonable tolerances to the predicted positions and orientations (Figure 9). It should be noted that the dRy errors do not represent physical inconsistencies between the two models but rather a mathematical rotation of the plate within the plane of the plate itself. Thus the only significant errors in plate angles were in the rotation of the right shoulder about the z-axis (dRz) and the helmet rotation about the x-axis. These were caused by asymmetry in the links, and could easily be fixed with further experimentation.

This result was extremely encouraging as it showed that it was possible to experimentally correlate the physical MUT system to the mathematical model.

	Desired States - miniHUT			**MUTHUT**			**Errors**		
Helmet	x	y	z	x	y	z	dx	dy	dz
(inches)	0.00	5.20	3.83	0.05	5.59	1.69	0.05	0.39	-2.14
	Rx	Rz	Ry	Rx	Rz	Ry	dRx	dRz	dRy
(degrees)	27.50	0.00	0.00	24.56	-1.47	-2.17	-2.94	-1.47	-2.17
Right Shoulder	x	y	z	x	y	z	dx	dy	dz
(inches)	4.85	5.20	-2.36	5.01	4.90	-4.37	0.16	-0.30	-2.01
	Rz	Rx	Ry	Rz	Rx	Ry	dRx	dRz	dRy
(degrees)	-56.25	6.00	0.00	-56.44	25.15	-15.56	-0.19	19.15	-15.56
Left Shoulder	x	y	z	x	y	z	dx	dy	dz
(inches)	-4.85	5.20	-2.36	-4.57	5.00	-4.96	0.28	-0.20	-2.60
	Rz	Rx	Ry	Rz	Rx	Ry	dRx	dRz	dRy
(degrees)	56.25	6.00	0.00	55.06	9.85	-33.12	-1.19	3.85	-33.12
Waist	x	y	z	x	y	z	dx	dy	dz
(inches)	0.00	5.52	-11.84	0.53	4.83	-13.44	0.53	-0.70	-1.60
	Rx	Ry	Rz	Rx	Ry	Rz	dRx	dRz	dRy
(degrees)	10.00	0.00	0.00	8.93	-1.97	9.78	-1.07	-1.97	9.78

Figure 9: Results from an attempt to replicate the MX-2 HUT geometry in a scaled-down MUT.

Unfortunately, the positive 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. The inverse kinematics dictates that a certain MUT configuration requires certain link lengths. However, it is possible those link lengths may also correspond to one or more alternative MUT configurations.

Phase 3 – *Search for a secondary configuration with the same link lengths*.

To resolve this ambiguity, it was deemed necessary to search for another stable configuration with the same set of link lengths. The position of the waist ring was the most inaccurate in the first configuration, so it was believed that perhaps the configuration found was actually secondary, and by repositioning the waist ring in the correct position, the primary configuration would be found. The waist ring was repositioned in the correct position, the links reattached, and the MUT re-pressurized. Many of the link lengths were too long and thus were slack, and some could not physically be attached, as they were too short. Measurements showed that in fact many of the point-to-point distances were not as predicted. This encouraging result showed that perhaps the configuration found initially with the set of link lengths is indeed the only configuration possible. If this were the case, it would imply that the system is statically determinate and with further study and experimentation, the forward kinematics of the system may be defined. Further experimentation is clearly required, as is a focused effort to develop the formal forward kinematics of this highly complex and coupled parallel mechanism.

CONCLUSIONS

The testing conducted to date has provided a significant demonstration of MUT technology. In developing this proof of 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. However, more testing is required to confirm this deterministic nature of the system.

Testing has also illuminated several areas that still require exploration and testing. The most pressing issues involve the interaction between the pressurized SUT fabric and the linkages, and the role of fabric tension on the SUT plates. In the former case, 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. In the latter case, it seems that fabric tension at the SUT-plate interface plays a significant role in MUT configuration. Unlike a normal 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. The tools developed in this phase of the research will undoubtedly aid in future research for this project.

FUTURE RESEARCH:

As this research is just developing, there is still plenty of exciting work yet to come. Much like the focus of this report, the future research for MUT technology lays in two distinct areas: mathematical modeling and physical prototyping.

In the area of mathematical modeling, the next step will be 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. The most difficult work however, will be in the development of a forward kinematics model for this system. First, 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.

In terms of physical prototyping, the first prototype developed for this research has provided a wealth of knowledge on improvements for the second generation MUT. The next step will be to develop a full scale SUT for testing. This full-scale model will facilitate an investigation into linkage tensions and thus allow the specification of actuators required to power the MUT system. Potential actuation methods include passive winching, electric motors, air muscles, shape memory alloys, and other low profile devices. While the linkages used in the first prototype allowed for rapid development, the next MUT will incorporate improved linkages and more secure, adjustable connection nodes.

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