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Kinematic Analysis of a Robotically Augmented Pressure Suit for Planetary Exploration

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ABSTRACT

The next generation of pressure suits must enable large-scale planetary Extra-Vehicular Activities (EVA). Astronauts exploring the moon and Mars will be required to walk many kilometers, carry large loads, perform intricate experiments, and extract geological samples. Advanced pressure suit architectures must be developed to allow astronauts to perform these and other tasks simply and effectively. The research developed here demonstrates integration of robotics technology into pressure suit design. The concept of a robotically augmented pressure suit for planetary exploration has been developed through the use of analytical and experimental investigations. Two unique torso configurations are examined, including a Soft/Hard Upper Torso with individually adjustable bearings, as well as advances in Morphing Upper Torso research, in which an all-soft torso is analyzed as a system of interconnected parallel manipulators. The forward kinematics of the systems are developed, and tools have been generated to further quantify the dynamic requirements. In addition, the concept of using parallel manipulators to augment suit mobility has been extended to include the lower torso assembly. Coupling these analyses with previous work done on a wire-actuated glove and concurrent work on robotically augmented arm assemblies, it becomes feasible to envision a fully augmented pressure suit, one which significantly increases the astronaut's capabilities and the efficiency of future planetary EVA.

INTRODUCTION

Advanced pressure suit design is a tremendous challenge. The design engineer is faced with a multivariable trade space with complex tradeoffs between mobility, resizability, donn/doffability, manufacturability, modularity, and cost, among others. Historically, optimization of one of these variables results in compromising one or more of the others.

As the human race looks to return to the moon and eventually send humans to the surface of Mars, the need for a planetary exploration pressure suit arises. Pressure suit design for planetary exploration is further complicated by the fact that the suits must be light enough for an astronaut to traverse the surface for many hours while bearing the weight of the suit and Personal Life Support System (PLSS). This additional constraint favors Soft Upper Torso (SUT) architectures, whereas Hard Upper Torsos (HUT), such as those used in the current Extravehicular Mobility Unit (EMU), are optimal in microgravity. Torso design and overall suit architectures are currently being examined (Ferl et al. 2006, Dionne et al. 2006) for future planetary suits.

Several designs have been proposed, tested, and utilized in field trials to isolate these difficult problems and examine possible solutions. Each year NASA (Ross et al. 2006) performs a series of experiments using two such concepts, the Mark III and the I-Suit (Graziosi et al. 2006). Each of these suits has been shown to be extremely valuable and provide the wearer with a great deal of mobility and exploration capability. However, it is clear from these field trials that there remains the need for advanced space suit architectures to enable the type of exploration envisioned for the coming decades.

The proposed solution to this design challenge incorporates robotics concepts into the pressure suit, augmenting the suit as well as the wearer's capabilities. Using integrated systems of parallel manipulators, elements of the suit can be positioned and oriented to match specific wearers dimensions and needs. This presents a significantly enhanced level of resizability, mobility and donn/doffability in pressure suit design.

The concept of highly adjustable scye bearings was developed by Graziosi et al (2004). High strength linear actuators were attached across the front and back of a waist entry Soft Upper Torso, demonstrating that the bearings could be widely spaced during donning and doffing, and then controlled to a much narrower configuration during wear. This would allow the bearing to be accurately collocated with the center of rotation of the wearer's shoulder, maximizing shoulder mobility, without hindering donning and doffing.

This unique concept was furthered by extending the manipulability of the scye bearings to the entire torso assembly. The helmet, two scye bearings, and waist bearing were envisioned as a system of interconnected parallel manipulators. Parallel manipulators, as was seminally shown by Stewart (1965) can bear large loads and have high accuracy, but have relatively small workspaces compared to serial manipulators. This set of characteristics fit very well with the requirements of a resizable and highly mobile pressure suit, as each of the bearings, when connected by parallel linkages, will be subjected to large internal pressure loads, and will only require small adjustments to match the wearer.

Two different torso configurations are examined. The first torso is a Soft/Hard configuration, consisting of a modified rear-entry hard upper torso, with soft goods connecting the four bearings to the rigid shell. The torso section acts as a base to which actuators are attached, but does not define any of the dimensions of the suit, and should be easy to ingress and egress. Each bearing is connected to the torso as a wire-actuated Stewart Platform, such that it has six wires connected at three nodes around the perimeter of the ring. By adjusting the lengths of the wires, the position and orientation of each of the rings can be manipulated. In this way, the dimensions of the pressure suit can be dynamically adjusted to match the wearer and the wearer's needs. This Soft/Hard Upper Torso configuration is shown in Figure 1. The internal hard upper torso has been removed for visualization purposes.

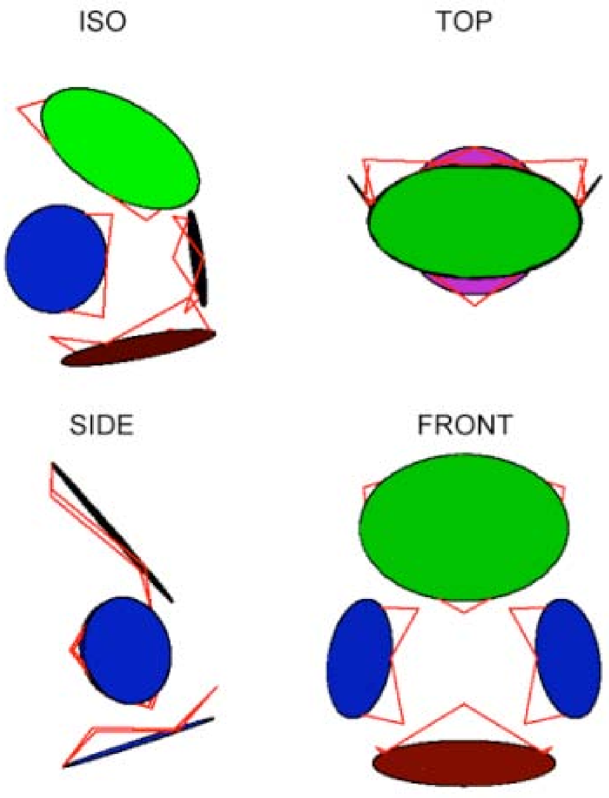

Figure 1: Four views of the Soft/Hard configuration. Each ring is modeled as a circle. The linkages are straight lines connecting two nodes.

The second configuration is an all-soft rear-entry upper torso, wherein linkages interconnect the waist, helmet and scye bearings, and the back hatch. This is referred to as the Morphing Upper Torso. The system of linkages and the bearings are shown in Figure 2.

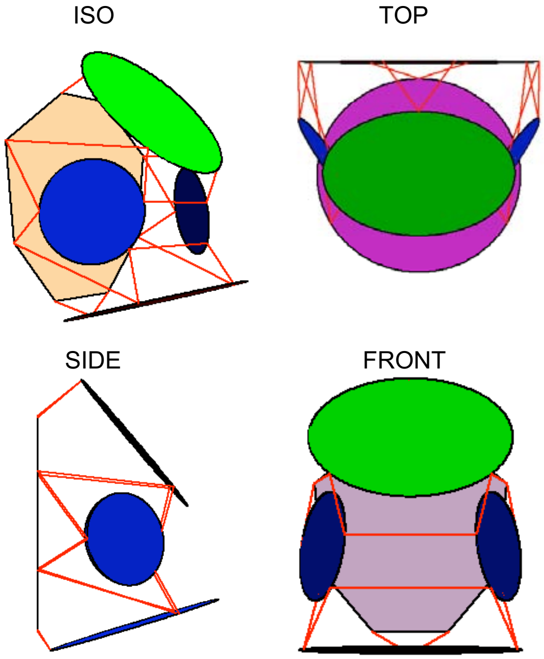

Figure 2: Four views of the all-soft Morphing Upper Torso. Note that some linkages now connect two mobile rings rather than the ring to the "base".

The robotically augmented torso concept, in either configuration, can be implemented in four modes, each of which provides enhanced capabilities over the previous mode.

1. **Passive Static:** Links are lengthened during donning and doffing, then manually reset to individual dimensions prior to pressurization. This enables one suit to fit perfectly to multiple users.
2. **Active Pressurized:** Links can be adjusted after pressurization, providing adjustment for body shape changes.
3. **Active Reconfigurable:** The suit can be set to specific configurations for each task. For example, the suit could be dynamically adjusted to dimensions optimal for walking, hammering, or sitting.
4. **Active Adaptive:** The suit continually adjusts to wearer's body kinematics in real time. For example, as the subjects brings their arms together, the scye bearings move inwards to compensate. As the subject bends over, the waist-bearing angle adjusts to aid the motion. This would provide maximum mobility and flexibility.

It is important to note that even the first mode taken alone provides significantly increased resizability while maintaining ease of donning and doffing. As well, suit mobility directly correlates to suit fit, thus this system should provide enhanced mobility over fixed SUT architectures.

The Inverse Kinematics of the MUT system have previously been analyzed (Jacobs et al. 2006), and will be briefly reviewed, and then the forward kinematics are examined in detail. The force and moment balance equations of the overall system are used to estimate the linkage tensions for each of the given configurations.

Two experimental investigations have been undertaken to supplement the analytical work. A full-scale model of the Morphing Upper Torso was used to verify the analytical model. For further investigation of the fundamental interactions between pressurized fabric and controlled linkages, an inflatable Stewart Platform was designed and manufactured. Precise three-dimensional measurements from this simplified experimental model, when compared with analytical models, provide insight into the effects of pressurized fabric on the entire robotically augmented pressure suit.

ANALYTICAL MODELING

The analytical investigation of a robotically augmented pressure suit involved the development of the kinematic equations and the use of several solving methods. The first model developed was an inverse kinematics model, which will be summarized here as it provided the backbone of this analysis. The formulation of the forward kinematics evolved from this model, and these equations were then solved using a variety of tools, which are described in detail. Additionally, the link tensions can be estimated by doing a static force analysis.

INVERSE KINEMATICS

The inverse kinematics of a parallel manipulator defines the transformation from the Cartesian position and orientation coordinates of the platform to the actuated link lengths. In other words, given a platform configuration, the inverse kinematics calculates the required length of each of the linkages. This is a determinate problem that can be solved using the geometry of the system. For the system of interconnected parallel manipulators in the robotically augmented pressure suit, the inverse kinematics equations were developed as follows:

- Coordinate frames were attached to the center of each ring, and a base frame attached to the center of the back hatch
- The attachment points for each linkage were defined as nodes. The position vector ${}^{Ring}P_i$ in the local ring-centered coordinate frame defines each node.
- The position of each ring is defined by the vector from the origin of the base frame to the origin of the ring-centered frame, ${}^{Base}P_0$
- The orientation of each ring is defined by 3 Euler angles, ie. Rotation of γ about the z-axis, rotation of β about the ring centered y-axis, and rotation of α about the ring-centered x-axis.
- A rotation matrix R is constructed from the 3 Euler angles, as shown in equation 1:

$$^{Base}R_{ring} = \begin{pmatrix} c\beta c\gamma & -c\beta s\gamma & s\beta \\ c\gamma s\alpha s\beta + c\alpha s\gamma & c\alpha c\gamma - s\alpha s\beta s\gamma & -c\beta s\alpha \\ -c\alpha c\gamma s\beta + s\alpha s\gamma & c\gamma s\alpha + c\alpha s\beta s\gamma & c\alpha c\beta \end{pmatrix} \tag{1}$$

- The link L_i is defined as the vector between two nodes. This vector is written in the base frame by transforming each node vector into the base frame, as shown in equations 2 and 3:

$$L_i = {}^{Base}P_i - {}^{Base}P_j \tag{2}$$

where:

$$^{Base}P_i = ^{Base}P_o + {}^{Base}R_{Ring}\ {}^{Ring}P_i \tag{3}$$

- The length l_i of link L_i is defined as the magnitude of the vector L_i, as shown in equation 4:

$$l_i = |L_i| = \sqrt{L_{ix}^2 + L_{iy}^2 + L_{iz}^2} \tag{4}$$

Figure 3 shows an example of the assignment of the base coordinate frame and a ring coordinate frame, and the corresponding vectors necessary to calculate L_i.

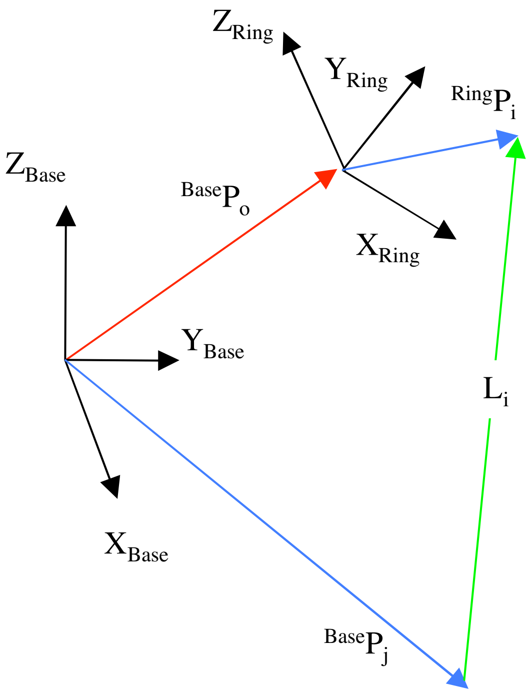

Figure 3: Assignment of coordinate frames

Ultimately equation 4 leads to 24 equations for l_i, i=1…24 in the Soft/Hard case, and 18 equations for l_i, i=1…18 in the MUT case. Each of these can be solved directly and independently. Results from the inverse kinematics model can be found in Jacobs (2006). Models of the all-soft Morphing Upper Torso in both expanded and contracted states are shown in Figure 4.

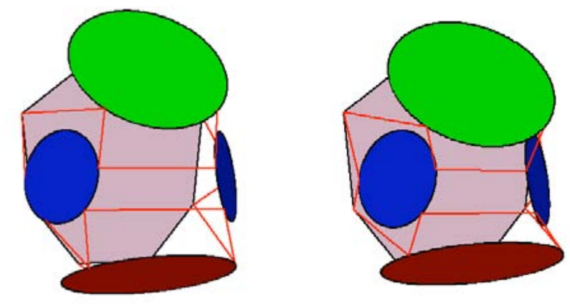

Figure 4: Analytical model of Morphing Upper Torso, in expanded state (left) and contracted state (right).

FORWARD KINEMATICS

The forward kinematics, as would be expected, is the opposite transformation of the inverse kinematics. For a parallel manipulator it can be defined as the transformation from the link lengths to the Cartesian position and orientation coordinates of the platform.

The forward kinematics model was developed to predict the position and orientation of each ring within the morphing upper torso assembly. The model uses the same node assignments and coordinate frames as the inverse kinematics model.

Soft/Hard Configuration

The kinematic equations for the Soft/Hard configuration - the hard torso shell with individually adjustable bearings - produce a system of 24 non-linear equations in 24 unknowns. The 24 equations are 4 sets of the standard equations for a Stewart Platform with non-planar base nodes. The unknowns are the three position coordinates and the three rotational coordinates for each of the four rings.

The system of 24 non-linear equations can be solved using the vector form of the iterative Newton-Raphson technique, yielding the most probable torso configurations given the link lengths. This well-known numerical solving technique (8,9) is incorporated as follows:

- Let X be a vector of the 24 unknowns, and L_i be the vector function of the 24 link length equations.

- A vector function f(X) is defined as:

$$f_i(X) = L_i L_i^T - l_i^2 \tag{5}$$

for i=1-24, where the l_i are the actual lengths of the linkages. Expanded this is written as:

$$f_i(X) = ({}^{Base}P_o + {}^{Base}R_{Ring}\;{}^{Ring}P_i - {}^{Base}P_j)\,({}^{Base}P_o + {}^{Base}R_{Ring}\;{}^{Ring}P_i - {}^{Base}P_j)^T - l_i^2 \tag{6}$$

- The solution will be the set of 24 positional and rotational coordinates of the rings such that:

$$f_i(X) = 0 \qquad \forall i = 1 \ldots 24 \tag{7}$$

- These equations can be solved using the iterative Newton-Raphson method. The nominal formula to iterate is:

$$x = x_0 - \frac{f(x_0)}{f'(x_0)}$$

(8)

- In vector form, equation 8 can be written as:

$$X = X_0 - [F'(X_0)]^{-1}F(X_0)$$

(9)

- In this model, the derivative of F(X) is the 24X24 matrix of partial derivatives:

$$F'(X) = \frac{\partial F}{\partial X} = \begin{pmatrix} \frac{\partial f_1}{\partial X_1} & \frac{\partial f_1}{\partial X_2} & \cdots & \cdots \\ \frac{\partial f_2}{\partial X_1} & \ddots & \ddots & \vdots \\ \vdots & \cdots & \cdots & \frac{\partial f_{24}}{\partial X_{24}} \end{pmatrix}$$

(10)

- Provided the configuration is not at a singularity, F'(X) is square and invertible. Given the nature of the astronaut motions within the suit, singular positions of the rings will not be located within the space spanned by the required positions and orientations of the rings. Thus singularities will always be avoided.

- A reasonable initial value is provided for X_0, and equation 9 is iterated upon until equation 7 is satisfied.

In practice, equation 9 is iterated until all of the f_i are reasonably close to zero, ie. within a certain tolerance. In addition, it is important to note that the necessary number of iterations to obtain a solution that meets this tolerance is variable and unknown.

This technique does not attempt to find all the possible poses of the rings given the link lengths, simply the most probable given the initial value of X_0. This numerical method is similar to the iterative-Jacobian method commonly used to solve the inverse kinematics of a serial manipulator.

An example of the helmet ring as part of the Soft/Hard configuration is shown in Figure 5. The link lengths are input, and the model outputs the position and orientation of the rings, here showing just the helmet. Typically the solution converges within 5 iterations. This scheme does show promise for real-time control implementation as it quickly converges, given a close approximation of X is known.

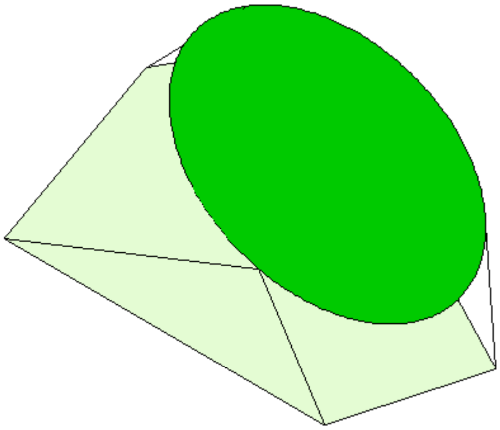

Figure 5: Helmet ring as part of the Soft/Hard configuration

Morphing Upper Torso Configuration

The MUT configuration is further complicated by the fact that while each ring has six linkages connected at three nodes, six of these linkages connect two mobile platforms, as opposed to connecting a platform to the base. Thus there are only 18 linkages while still 24 degrees of freedom of the rings. This is an under-controlled system and therefore the forward kinematics cannot be classically solved. The implications of this result are analyzed in the discussion section.

DETERMINATION OF LINK TENSIONS

The tensile force t_i in each of the links can be calculated by solving the force and moment balance equations for each ring. The internal pressure of the torso pushes out normally to all surfaces. Thus the constraint force F_N, on each ring can be modeled as normal to the plane of the ring and equal in magnitude to the product of pressure (P) and area (A). Each ring frame is aligned such that the ring is in the x-z plane, and thus the local y-axis is normal to the ring:

$$^{Ring}F_N = PA \cdot \hat{y}$$

(11)

Each constraint force is then rotated to the base frame, using the appropriate rotation matrix for each ring:

$$^{Base}F_N = {}^{Base}R_{Ring} \; {}^{Ring}F_N$$

(12)

The vector T_i represents the components of the link tension, as the force t_i acts along the vector L_i. Similarly to equation 4:

$$t_i = |T_i| = \sqrt{T_{ix}^2 + T_{iy}^2 + T_{iz}^2} \tag{13}$$

The system is static, thus the force balance equations for each ring are:

$$\sum_{i=1}^{6} T_i \cdot \hat{X} = {}^{Base}F_N \cdot \hat{X}$$
$$\sum_{i=1}^{6} T_i \cdot \hat{Y} = {}^{Base}F_N \cdot \hat{Y}$$
$$\sum_{i=1}^{6} T_i \cdot \hat{Z} = {}^{Base}F_N \cdot \hat{Z} \tag{14}$$

The node vectors r_i are rotated into the base frame, and as there are no external moments on the rings, the three moment equations are:

$$\sum_{i=1}^{6} (r_i \times T_i) \cdot \hat{X} = 0$$
$$\sum_{i=1}^{6} (r_i \times T_i) \cdot \hat{Y} = 0$$
$$\sum_{i=1}^{6} (r_i \times T_i) \cdot \hat{Z} = 0 \tag{15}$$

Equations 14 and 15 can be used to calculate the link tensions for either configuration, provided the positions and orientations of the rings are known or have been solved. These equations are linear and can be solved directly.

EXPERIMENTAL MODELING

FULL SCALE MUT

A full-scale experimental model of the all-soft Morphing Upper Torso was designed and manufactured to investigate the accuracy and feasibility of the analytical model. The fully constrained model is shown in Figure 6. Measurements of the model were taken using the FARO Arm, a coordinate measuring machine capable of very high accuracy (0.005”) three-dimensional measurement.

Figure 6: Experimental full-scale pressurized MUT model

The full-scale experimental model is a very valuable tool for use in conjunction with the analytical model. The present state of the model is that of a passive static mode, such that the torso is depressurized, the linkage lengths adjusted, and the torso re-pressurized. Resizing the suit in this matter can be physically demonstrated.

The torso has been manipulated into many different configurations using the system of 18 manually adjustable linkages. This is contradictory to the fact that the system is under-controlled and formulation of the forward kinematics is not possible. However, it is important to note that control of the roll degrees of freedom of each of the rings is not required. In the case of the scye rings, the controlled ring is the housing for a bearing, thus the roll will be completely controlled by the astronaut within the arm. The waist and helmet may also be bearings, and if they are not it is still unlikely roll control would be required.

Additionally, tensile forces in the fabric tend to stabilize the under-controlled system. Thus, while precise control of each of the 24 degrees of freedom is not possible, it is feasible that required positions and orientations spanned by the astronaut's workspace could be obtained, as the experimental model suggests.

There are several other important differences between the experimental and analytical models. The analytical models do not accurately predict the entire physical state of the system, such as the curvature of the linkages and the interaction between the pressurized fabric and the plate. The physical model allows investigation of these phenomena and provides a clear picture of the feasibility of the MUT system. The system is indeed feasible, as certain adjustments and offsets can be applied to the physical linkages to obtain the desired configuration. Ultimately these will be included in the analytical models to ideally obtain a precise understanding of the complex interconnected nature of the system.

INFLATABLE STEWART PLATFORM

A second experimental model was created to further investigate the fundamental principles of parallel manipulators constrained by internal pressure forces. The interconnected system that makes up the all-soft MUT is extremely complex and highly configuration dependent. Thus, to isolate these variables, an inflatable Stewart Platform was designed and constructed, as shown in Figure 7.

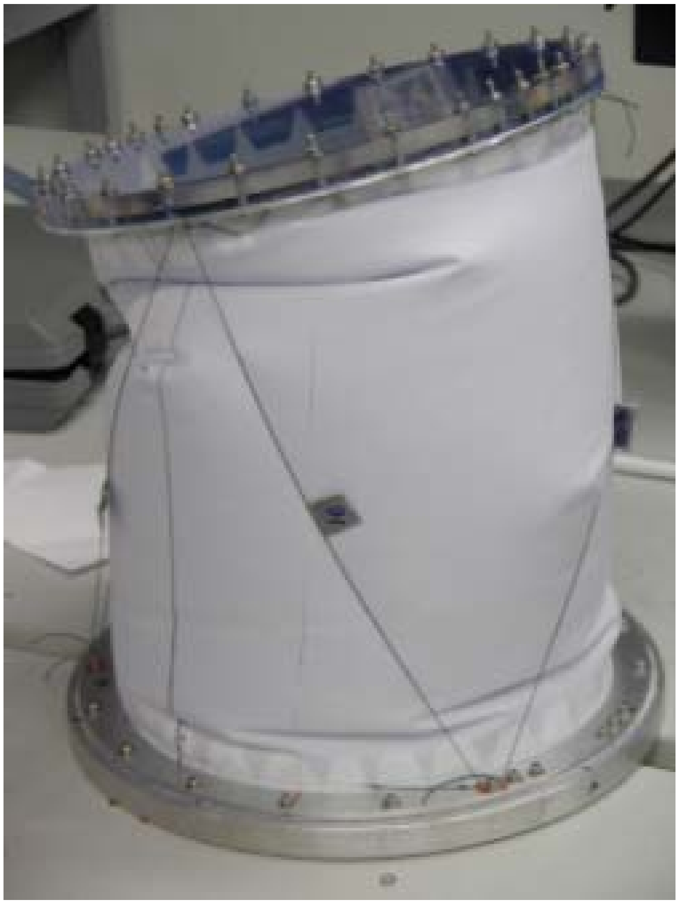

Figure 7: Inflatable Stewart Platform

One notable difference between the pressurized inflatable Stewart Platform and a nominal wire-actuated parallel manipulator is that the constraint force always acts normal to the platform. The internal pressure of the inflatable tube forces the platform outwards along the vector normal to the plane of the ring. This is fundamentally different from a typical Stewart Platform where gravity acts as the constraint, which will act in a fixed direction in space regardless of the orientation of the platform.

The inflatable Stewart Platform design clearly applies to the MUT system, as each ring has a constraint force normal to the plane of the ring. The model definitely demonstrates the feasibility of the Soft/Hard configuration, as each ring would essentially be a shorter version of this model.

DISCUSSION

CONTROL

Implementation of the MUT concept into a wearable pressure suit requires a real-time controller. The Inverse Kinematics provides the necessary mapping to perform open-loop control, as shown in Figure 8. The Cartesian positions and orientations of the rings can be input into the controller, and required link lengths generated to manipulate the suit into the demanded configuration. In passive static mode, the demanded Cartesian positions and orientations would be derived from well-known algorithms, which convert astronaut dimensions into critical suit dimensions, such as inter-scye distance. In the more advanced modes, such as the active adaptive mode, sensed motions of the astronaut would be converted into Cartesian inputs.

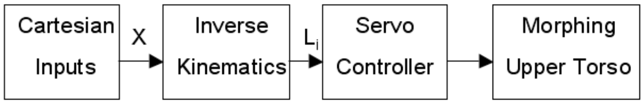

Figure 8: Open-loop Cartesian based control

The fundamental problem with the open loop control method is that there is no feedback of the state of the torso. This is the reason the forward kinematics are necessary, as the calculated position and orientation of the rings can be fed back into the controller, as shown in Figure 9.

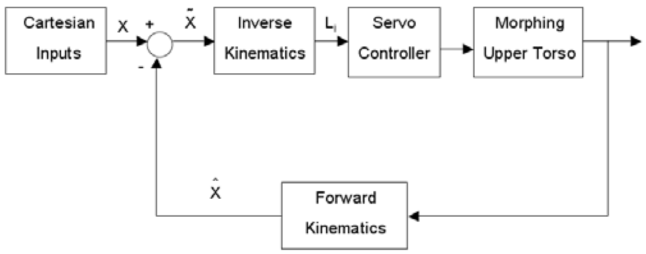

Figure 9: Closed-loop Cartesian based control

This controller could be implemented in the Soft/Hard configuration and provide real-time control of all degrees of freedom of the four rings. The all-soft MUT configuration though, will require further experimentation and analysis to develop a robust control scheme.

CONFIGURATION COMPARISON

The two configurations examined each have their advantages. The Soft/Hard configuration is a simpler design and the forward kinematics have been solved. Each ring is a traditional Stewart Platform, with the slight alteration that the constraint force always pushes normal to the ring. Thus this configuration is simple to implement in the near-term.

The Soft/Hard configuration also lends itself to implementation on a subset of the four bearings, such as the scye bearings only. The helmet and waist ring could be fixed rigidly in the hard shell, while the scye bearings could be individually adjustable, resizable and actuated. These varying levels of implementation provide the designer with greater options and more flexibility when considering the optimal incorporation of linkages and actuators into the suit. As well, implementation can occur in phases, allowing incorporation of the other rings further along the design path.

The forward kinematics of the all-soft MUT have not been solved, and closed-loop control is not presently possible, but the all-soft configuration has significant advantages that prevent the configuration from being immediately ruled out. Primarily it will be lighter-weight, due to the fact that there is no hard torso shell required, and also because it has fewer linkages. Fewer linkages translate to fewer actuators, batteries, and servos and thus significant weight and power savings.

Clearly the addition of any actuators in either configuration will add significant mass to the suit. The benefits obtained from increased mobility and resizability must be great enough to compromise these mass gains. This is certainly feasible considering that implementation of robotic augmentation into one suit could give it enough resizability to be worn by several astronauts. This has the potential to reduce the total number of suits needed for a lunar exploration architecture for example. Additionally, if the suit is in active adaptive mode, it will respond to the astronaut’s motions in real-time and aid the astronaut through their tasks, eliminating the concern of a heavier suit.

GLOVES, ARMS AND LOWER TORSO ASSEMBLY

Other elements of the pressure suit can also be augmented robotically. A robotically assisted space suit glove, termed the Power Glove, was shown to dramatically improve hand mobility (Sorenson et al. 1997). The Power Glove incorporated a non-linear adaptive controller, which enabled control of the Metacarpophalangeal (MCP) joint without the use of invasive sensors within the glove. The significant reduction of force at the MCP joint demonstrated the value of robotic augmentation of space suit elements.

Additionally, an arm resizing system (Benson et al. 2007) has been demonstrated that would allow dynamic adjustments to arm length. This system can also be extended to lower torso assemblies, as the pressurized cylinder of a spacesuit leg is very similar to that of a spacesuit arm. The kinematic equations and experimental models used in this study provide the fundamental background for future work in this area. The ability to accurately and dynamically resize the soft goods will dramatically improve comfort, fit and consequently mobility.

FUTURE WORK

The vision of a fully robotically augmented suit will take time to fulfill. Presently the main focus is to create a passive static system, which can both be achieved in the near-term and provide significant advances over traditional suit architectures.

Incremental steps include further analysis of the interaction between the pressurized fabric and the rings, as well as developing a robust understanding of the controllability of the all-soft MUT and its feasibility. Concurrently, the Soft/Hard configuration will be implemented into the MX-2, a space suit analogue designed for use in neutral buoyancy. The MX-2 is currently equipped with a large HUT, which will be modified into a Soft/Hard Upper Torso in a passive static mode. This will be accomplished by removing the bearings, cutting out portions of the HUT, and integrating soft goods and manually adjustable linkages that re-attach to the bearings.

Figure 10: The MX-2 neutral buoyancy space suit analogue. Note the large HUT, which will be modified into a Soft/Hard Upper Torso.

With advances in actuators, materials and battery technologies, ultimately robotic augmentation of the entire suit will be developed, including active adaptive morphing upper torso technology, cable driven arm and lower leg assemblies, and power gloves.

CONCLUSIONS

The analytical and experimental investigations described herein have further advanced the concept of a robotically augmented pressure suit. Two torso configurations have been considered; a Soft/Hard Upper Torso shell with individually adjustable rings, and an all-soft Morphing Upper Torso with interconnected adjustable rings. The kinematic equations have been developed and solved numerically for the Soft/Hard configuration, sufficient for future implementation of closed-loop control of the system. As well, models have been developed that predict the link tensions for any given configuration.

Two experimental models were developed as prototypes for the all-soft interconnected configuration. Experimentally it was shown that the torso could be reconfigured to several different sizes and orientations. The Morphing Upper Torso technology will now be mated to cable-driven arm resizing mechanisms and equivalent lower-torso assemblies to further the robotic augmentation concept.

The robotically augmented suit, when fully developed, will be capable of resizing to specific astronaut dimensions, increasing astronaut comfort and efficiency in specific configurations, as well as augmenting astronaut motions during specific tasks. This unique concept holds great promise for future planetary EVA.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

$^{Base}R_{ring}$: Rotation matrix required to rotate a vector from the ring coordinate frame to the base coordinate frame

L_i: vector between two nodes

l_i: magnitude of link vector = link length

T_i: vector of link tension components

t_i: link tension

F_N: normal force due to internal pressure

r_i: moment arm for each link

EVA: Extra Vehicular Activity

PLSS: Personal Life Support System

SUT: Soft Upper Torso

HUT: Hard Upper Torso

EMU: Extravehicular Mobility Unit

MUT: Morphing Upper Torso

MCP: Metacarpophalangeal