

# Optimization of Inflatable Spacecraft Interior Volume Using Constraints Driven Design

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Over the past two decades, the emergence of mature associative geometry modeling tools and the related sophistication in associated manufacturing processes has enabled the design and realization of complex, nonlinear structures. To demonstrate the use of intelligent associative models, the design team developed an iterative method for refining the shell and interior design of surface endoskeletal inflatable modules (SEIM). The salient features of the design method are: the use of a custom shape-finding mathematical model written in the Processing integrated development environment (IDE) to determine the correct inflated shape of the shell; a 3D parametric model of the interior, built using the Grasshopper plugin for Rhinoceros 3D by Robert McNeel & Associates; and a semi-automated two-way transfer of data between the design and analysis tools. This paper presents preliminary results of the design method's application to the optimization of the habitat version of SEIM. Here the independent variable is the inflatable shell geometry, which is controlled by the length of the structural strands in the two principle directions. The dependant variable is the ratio of floor area with a minimum clear height of 2.15 meters to the total available floor area. Fixed parameters are the geometry of the rigid frame and the stowed volume inside the launch platform. The parametric model allows rapid evaluation of the quality of the habitable spaces for a number of shell geometries.

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## Nomenclature

<i>CAD</i>	= Computer Aided Design
<i>CAM</i>	= Computer Aided Manufacturing
<i>CDD</i>	= Constraint Driven Design
<i>CNC</i>	= Computer Numerically Controlled
<i>CQ</i>	= Crew Quarters
<i>DRM</i>	= NASA's Mars Design Reference Mission
<i>ECLSS</i>	= Environmental Control and Life Support System
<i>FE</i>	= Finite Element
<i>IDE</i>	= Integrated Development Environment
<i>ISS</i>	= International Space Station
<i>Hab</i>	= Habitat
<i>MIT</i>	= Massachusetts Institute of Technology
<i>MMDR</i>	= Micrometeoroid, Debris, and Radiation Shield
<i>NASA</i>	= National Aeronautics and Space Administration
<i>ProE</i>	= Pro/Engineer constraint-driven design CAD system
<i>Rhino</i>	= Rhinoceros NURBS Modeling for Windows by Robert McNeel and Associates
<i>SEIM</i>	= Surface Endoskeletal Inflatable Module
<i>TransHab</i>	= Transit Habitat

## I. Introduction

ARCHITECTS have had millennia to perfect the art of proportional design in terrestrial applications. The technical requirements and design constraints of human-rated spacecraft do not permit a direct translation of those practices into the field of space architecture. Although aerospace engineering continues to lead in the development of tools for vehicle optimization, spacecraft architecture has been forced to make do with “best available” habitable volume for the deployed phases of the vehicle’s life cycle. Until now, the best quantifiable approach available to space architecture has been to apply human factors assessments based on the Concept of Operations in a trade against existing structural engineering models, and thereby negotiate the best usable volume left available once those processes have run their course.

The successful application of parametric design methods to the pressure shell form, achieves not only a greater total usable volume for crew operations, but also offers savings to the total spacecraft mass budget. By fine-tuning the precise curvature of the deployed pressure shell, the spacecraft architect can optimize both the overall ratio of usable to pressurized volume and the vehicle’s ability to meet its operational requirements with the minimum possible mass penalty. In this paper we strive to demonstrate that Constraint Driven Design (CDD) fills a significant capability gap and may prove to be an important enabling technology for a future Exploration roadmap.

The first endoskeletal hybrid space module - TransHab – was developed by NASA in the late 1990s. In 2005 the Synthesis International team completed a preliminary study in adapting the paradigm to a module with similar operational requirements to TransHab, but operating in a planetary surface environment<sup>1</sup>. This Surface Endoskeletal Inflatable Module (SEIM) is a fundamental element of the critical path for human exploration: the surface habitat. This paper presents new work in applying CDD to the optimization of SEIM.

### A. Constraint Driven Design

Constraint driven design - also referred to as parametric design - has emerged as a mature design aid since the introduction of Pro/Engineer (ProE) by Parametric Technology and Catia by Dassault Systems in the early 1990’s<sup>2,3,4</sup>. CDD was first explored in the aeronautics and automotive industries, most famously in the development of the 777 wide body airliner by Boeing<sup>5</sup>. Architects and other designers began to explore the possibilities of parametric software initially, as a means to allow computer aided manufacturing (CAM) of geometrically complex forms, such as the columns and rose windows of the Sagrada Familia Church in Barcelona<sup>6</sup> and the walls of the Guggenheim Museum in Bilbao<sup>7</sup>. The integration of CDD into a seamless design process that includes performance modeling tools and rapid prototyping remains a challenge<sup>8</sup>.

One of the main challenges is the large time investment needed to generate a functioning associative/logical geometric model, and to extract useful geometry for use in analysis. Whereas changes can be made to a portion of a traditional geometric model relatively quickly, it is often necessary to rebuild an associative geometric model from

scratch. A new CDD CAD system by Robert McNeel & Associates called Grasshopper greatly enhances the efficiency with which architects and engineers collaborate in the design of complex systems. Grasshopper is a graphical algorithm editor that facilitates the creation of associative models via a visual interface while requiring little knowledge of programming or scripting. The program is tightly bound to Rhinoceros's 3-D modeling tools thus requiring minimal effort to export the resulting geometry to other software tools.

## **B. Shape Finding and Performance Evaluation**

In current design practice the geometric definition of complex products such as airplanes, cars, and space vehicles is done using a CAD system, and increasingly one that is capable of CDD. The geometry is then manually recreated in an analysis software package, most often one of many finite element programs for evaluation of the product's performance and manufacturing process. Translating between the geometry definition and analysis systems is typically not automated and consumes a large portion of the design team's time and effort<sup>3,8</sup>. There have been efforts to facilitate this transition - for example a method for combining the generative structural design system eifForm with GC is presented in Shea et. al. 2005<sup>4</sup>. In the current study, we present a holistic iterative method for the optimization of the design of a surface endoskeletal inflatable module (SEIM). It combines a shape finding mathematical model and constraint driven design using Grasshopper, with a high level of automation in the data transfer between the various tools in both directions.

# **II. Design Requirements**

## **A. Background**

Since the beginning of spaceflight, crewed vehicles have been comprised of rigid exoskeletal pressure vessels that, with the exception of the Space Shuttle and the short-lived Buran, have been directly derived from the rocket technology used to launch them. TransHab was the first detailed study that developed an alternative typology for space vehicles. The project demonstrated the viability of hybrid inflatable endoskeletal technology for use in space habitat applications<sup>9,10</sup>. Originally conceived to be a Mars transfer vehicle and later redesigned as crew quarters for the International Space Station (ISS), TransHab was optimized for the zero G environment of outer space and was unable to land or support any significant loads once deployed.

In response to the need for viable surface concepts to meet the NASA Exploration Vision, in early 2005 the design team at Synthesis International created a preliminary design of a Surface Endoskeletal Inflatable Module (SEIM) that adapted the lessons learned from TransHab to the fundamental element of the critical path for human exploration: the surface habitat (Figs. 01-02)<sup>1</sup>.

Similar to TransHab, the structure is comprised of a rigid core from which a structural membrane is inflated to provide an expanded habitable space. The rigid core, which is formed by eight longerons supporting two endcones, remains fixed in both the launch and the deployed configurations. Flat modular panels are packed around the longerons to provide shear and torsional stiffness during transfer and are subsequently deployed to form floors and partitions. The structural shell on the other hand is stowed around the core in the launch configuration and is activated only after deployment to contain the atmosphere.

The surface mission, however, necessitated fairly radical changes in form and appearance – led by the decision to reconfigure the orientation from vertical to horizontal<sup>1</sup>.

The surface endoskeletal inflatable typology can be adapted to meet numerous deep space mission scenarios. Versions of the basic concept can be developed for both the Lunar and Martian surface. A single SEIM can be utilized for several functions including laboratory, pressurized storage and habitation. The 2005 study concentrated on the habitation version of the module, which is the most architecturally challenging in terms of program complexity and functional and spatial requirements. It demonstrated how the SEIM can be adapted to meet the requirements of NASA's Mars Design Reference Mission (DRM)<sup>11,12</sup>. The original study defined a preliminary interior layout of the functional spaces, their relationships, and relative sizes.

The main functional areas of the habitation module can be divided into private and public areas. There is a private suite for each crewmember comprising:

- Sleeping/living area
- Desk/workstation
- Storage

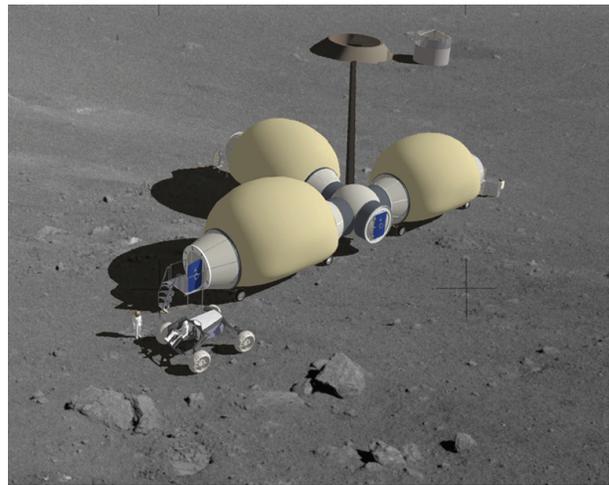
The public/social areas comprise:

- Galley
- Dining/meeting area, large enough to accommodate the whole crew at once
- Exercise/meditation area (yoga and other meditation techniques can relieve isolation stress)<sup>13</sup>
- Entertainment/multimedia area
- Bathing and toilet facilities
- Systems control and command, and communications area.
- Storage

The original un-optimized design of SEIM from the 2005 study, had a total shell area of 195 m<sup>2</sup> which enclosed a total pressurized volume of 280 m<sup>3</sup> excluding the endcones. The total horizontal floor area was 111 m<sup>2</sup>, 62 m<sup>2</sup> of which had at least 2.15 m of clear height<sup>9</sup>. These numbers were largely determined by the shape of the inflatable shell and served as a starting point for the optimization study.



**Figure 1. Axonometric of the interior layout of SEIM**



**Figure 2. Three modules assembled around a connector form the beginning of a Lunar base**

## **B. Design Process**

The shape finding model was developed using the Processing integrated development environment. It contains the geometric information of the design of the shell. The user can vary the end conditions and the length of the straps in both the longitudinal and radial direction. The resulting inflated surface is then manually exported and is used as the starting point of the associative model, which is constructed in Grasshopper. This model holds the parameters that control how the functional areas inside the shell are arranged, computes the relevant volume and area metrics, and exports them to a spreadsheet. The inputs to the shape finding model include:

- Initial typology of the geometry
- Launch vehicle dimensions
- Internal pressure

The associative model takes the following inputs:

- 3D shell geometry
- Interior floor and partitions geometry

An overview of the main steps in the design iteration process are shown in Figure 3 and are outlined below:

1. Define an initial shape-finding geometric model of the shell.
2. Calculate the actual geometry that the shell will take given the boundary conditions, internal pressure and shell area.

3. Bring the new geometry into Grasshopper and evaluate the resulting spaces.
  - a. The model automatically computes all relevant area and volume parameters.
  - b. Evaluate total pressurized volume
  - c. Evaluate total habitable volume (volume not taken up by mechanical systems and stowage).
  - d. Evaluate floor area with 2.15m or more clear height.
4. Adjust manually in Processing the lengths of the straps in order to alter the shell geometry where change is needed.
5. Re-compute shell geometry.
6. Iterate until satisfied.

The next step after we have demonstrated this capability will be to automate the link between the two models, so that the geometry in Grasshopper is constantly “live”. The shape finding and stress analysis will run in the background and any changes made in the Grasshopper model will be automatically updated without having to switch between tools.

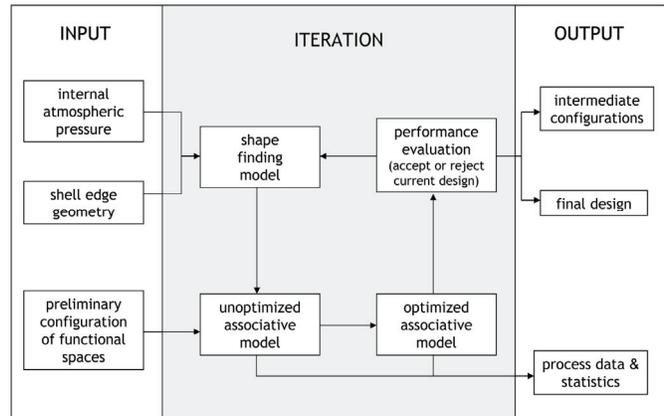


Figure 3 Design method overview

### C. Shape Finding Model

Particle-spring systems have been used extensively in numerous simulations of physical systems, especially in generating realistic animations of clothing and fabrics<sup>14</sup>. They have also been adapted to generate structural forms, as in the hanging chain work done at MIT by Axel Killian and John Ochsendorf<sup>15</sup>. Their paper has an excellent summary of how such systems work. Our shape finding model uses as its beginning a particle-spring physics engine developed from Processing by Jeffrey Traer Bernstein. The model defines a grid of points and connects them with springs in orthogonal directions to represent the straps of the shell. It then applies a force to the points that is always normal to the grid and recomputes the position of every point until an equilibrium is reached at the final inflated position. The model is controlled by fixing the edges of the grid to the desired location of the boundary condition for the shell and by varying the final length of the springs which corresponds to the length of the straps of the shell. In reality the shell is made up of thousands of Kevlar straps that are woven together. Here we used 13 radial and 20 longitudinal chains of springs to represent the whole surface.

```

physics = new ParticleSystem( 0.0, system_drag );
particles = new Particle[hGridSize][rGridSize];

float hInc = (float) (cHeight / hGridSize);
float radialInc = (float) ( TWO_PI / rGridSize);
float chLen = (float) (cDiameter * sin( radialInc * 0.5));
float arcBegin = (float) (PI * 1.5);
float gridStepH = (float) (cHeight / hGridSize);

for (int i = 0; i < hGridSize; i++) {
  for (int j = 0; j < rGridSize; j++) {
    float theta = (PI/(rGridSize-1))*j;
    float[] coords = coordsFromPolarCoords( cDiameter*0.5, theta, new float[] {width*0.5,height*0.25, cOrigin.x + (hInc * i) } );
    particles[i][j] = physics.makeParticle( 1.0, coords[0], coords[1], cOrigin.z + (hInc * i) );
  }
}

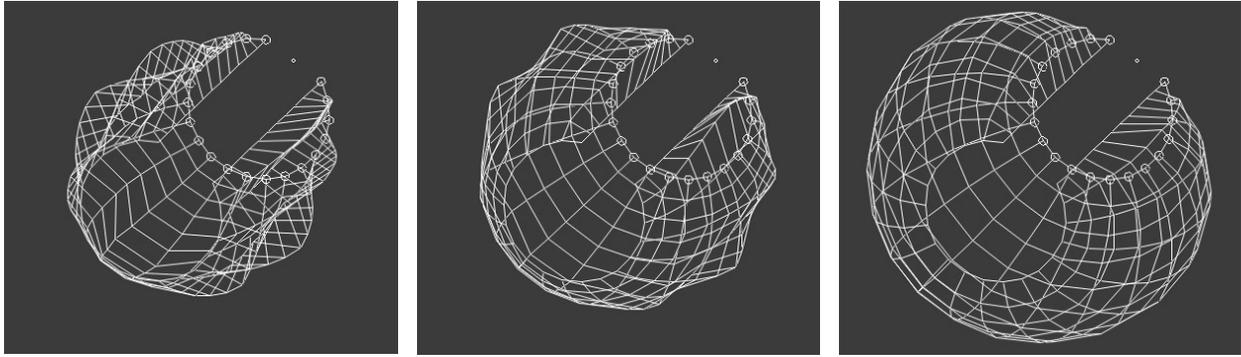
chain = new Chain(physics, particles, calcSprLengthLinear(), calcSprLengthLinear());

float[] tapLength = calcSprLengthLinear();
for (int i = 0; i < hGridSize; i++) {
  println("radial_len [" + i + "] = " + tapLength[i]);
}

tapLength = calcSprLengthLinear();
for (int i = 0; i < hGridSize; i++) {
  println("height_len [" + i + "] = " + tapLength[i]);
}

```

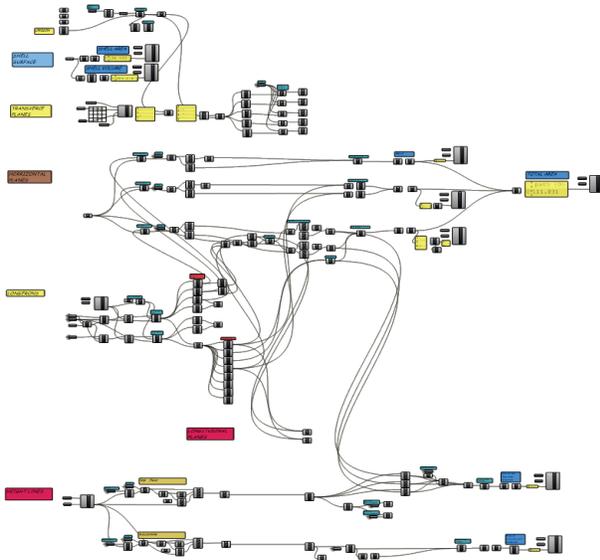
Figure 4. A Sample of the Processing code



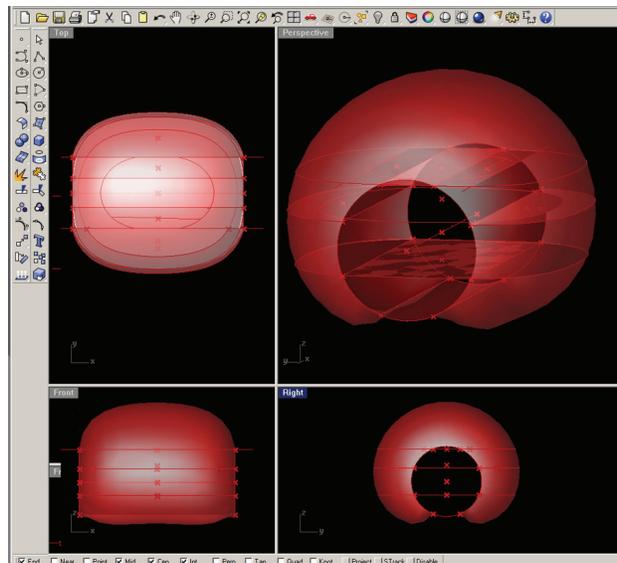
**Figure 5. Inflating of the particle system in Processing**

#### **D. Associative Model**

The associative model takes as its input the array of 3D points that represent the inflated shape. From them it builds the 3D surface of the shell. All of the internal geometry of the floors and partitions is defined based on its relationship to the shell. Once a new surface is defined, all of the internal geometry is automatically updated. The process is not entirely smooth and usually there is some redefinition of relationships which is necessary at every iteration. Once everything is debugged and the geometry updates properly, the model calculates all relevant area and volume parameters and outputs the results into a spreadsheet.



**Figure 6. Screen capture of the Grasshopper logic tree. Each box is a piece of geometry and the connecting lines are their associations.**



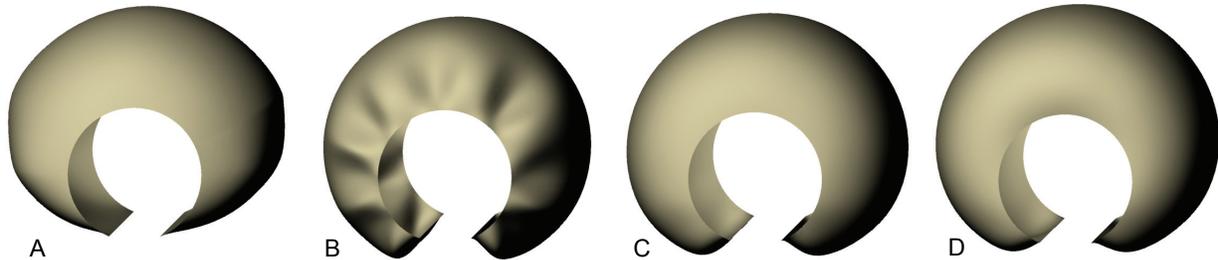
**Figure 7. Grasshopper geometry window**

### **III. Results**

The first step was to explore the surface from the 2005 study<sup>1</sup> (Surface A in Figure 08). At the time, we did not have access to a working shape-finding model, thus the geometry was an estimate of what the inflated shape would be. Using the same lengths for the longitudinal and radial straps resulted in inflated shape (Surface B in Figure 08) that exhibited wrinkles near the two endcone supports. This finding indicates that the surface is not a shape that a real membrane would inflate to. The shape-finding model showed that there would be a considerably bigger bulge

at the bottom than we had anticipated - a result with significant consequences for the design of the underside and the drive train of SEIM. In the second iteration (Surface C in Figure 08), the lengths of the longitudinal and radial straps were adjusted until the configuration of the inflatable achieved a smooth surface. This surface, however, did not improve the ratio of floor area with the height of 2.15m to total floor area. In subsequent iterations we noticed that increasing the length of the longitudinal straps near the top, while keeping the radial straps the same, causes the shell to bulge up at the upper portion and reduce the bulge at the bottom (Surface D in Figure 08). Moving from Surface C to Surface D the volume with head room was increased by 24% with only a 6% increase in the shell area.

The design process allowed us to quickly find a valid shell geometry that meets or exceeds the volume and floor area criteria set forth in the original study. The relevant parameters are summarized in Tables 01 and 02.



**Figure 08. Iterations of the shell geometry; A – the original 2005 study showing our best guess of the inflated shape, B – the same shell as the 2005 study, but showing the actual geometry that it would take as determined by the shape-finding model, C - the new 2010 study showing the adjusted shell leading to a realistic inflated shape, D – further optimization of the shell**

	TOTAL VOLUME	VOLUME WITH 2.15m HEADROOM	TOTAL SHELL AREA	TOTAL FLOOR AREA
	m <sup>3</sup>	m <sup>3</sup>	m <sup>2</sup>	m <sup>2</sup>
<b>2005 Study (Surface A)</b>	280.2	156.6	194.6	111.0
<b>2005 Study (Surface B)</b>	284.5	-	194.5	112.4
<b>2010 Study (Surface C)</b>	310.8	158.2	199.7	118.9
<b>2010 Study (Surface D)</b>	330.9	196.7	208.4	119.53

**Table 01. Summary of iteration totals**

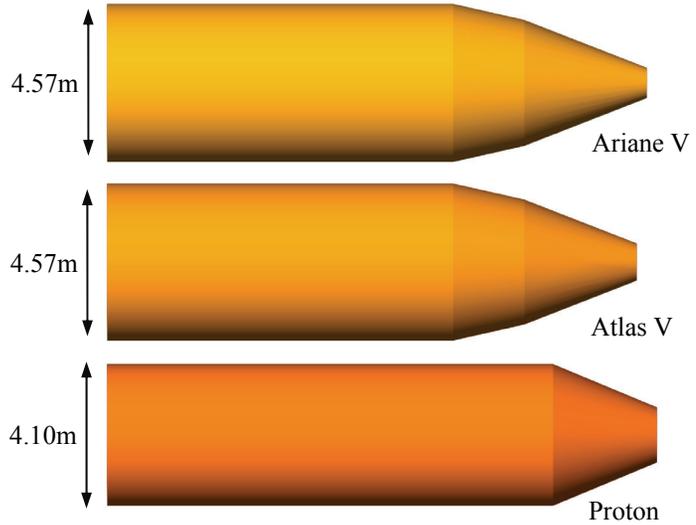
	Lower Level			Upper Level			TOTAL		
	with 2.15m headroom	total	ratio	with 2.15m headroom	total	ratio	with 2.15m headroom	total	ratio
	m <sup>2</sup>	m <sup>2</sup>		m <sup>2</sup>	m <sup>2</sup>		m <sup>2</sup>	m <sup>2</sup>	
<b>Surface A</b>	30.4	51.6	0.59	30.9	59.4	0.52	<b>61.3</b>	<b>111.0</b>	<b>0.55</b>
<b>Surface B</b>	30.6	54.6	0.56	22.0	57.7	0.38	<b>52.5</b>	<b>112.3</b>	<b>0.47</b>
<b>Surface C</b>	30.6	57.9	0.53	32.1	61.1	0.52	<b>62.6</b>	<b>118.9</b>	<b>0.53</b>
<b>Surface D</b>	30.6	56.7	0.54	43.7	62.9	0.69	<b>74.2</b>	<b>119.8</b>	<b>0.62</b>

**Table 02. Breakdown of iteration areas, comparing the total floor area to the floor area with at least 2.15m headroom.**



**Figure 09. Updated sections with the new geometry.**

Further we studied the configuration of the shell with respect to the available space in inside the largest obtainable payload fairing of several of the major operational heavy lift launch vehicles. Figure 10 shows several of the available volumes. The fairing for the Ariane V and Atlas V are virtually the same, while the one for Proton is narrower but longer. In the launch configuration the shell will be tightly stowed around the central rigid frame of SEIM. Assuming the frame and endcones are sized to maximize the use of the available volume, we adjusted the end conditions on the shape-finding model and optimized the resulting shells. The results are presented in Figure 11. Tables 03 and 04 compare the resulting area and volume parameters.



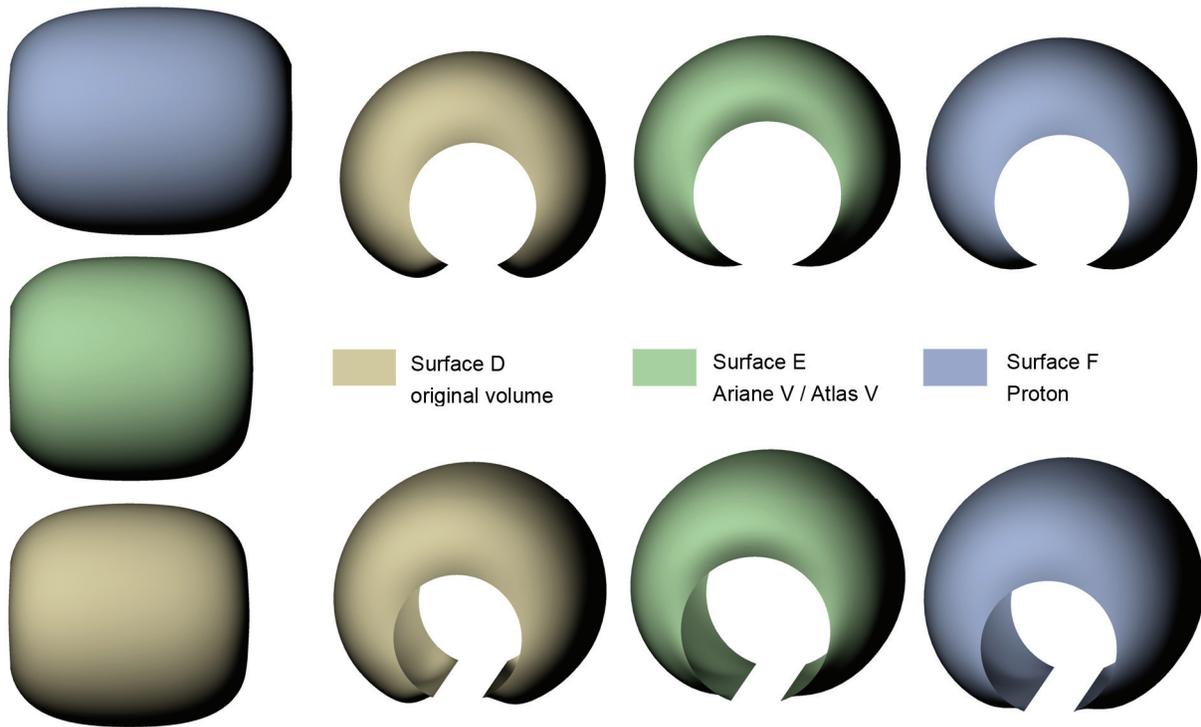
**Figure 10. Volumes inside the largest available payload fairings for major operational heavy lift launch vehicles.**

	TOTAL VOLUME	VOLUME WITH 2.15m HEADROOM	TOTAL SHELL AREA	TOTAL FLOOR AREA
	m <sup>3</sup>	m <sup>3</sup>	m <sup>2</sup>	m <sup>2</sup>
<b>Surface D</b>	330.9	196.7	208.4	119.53
<b>Surface E – Ariane V / Atlas V</b>	348.5	213.5	207.3	117.7
<b>Surface F – Proton</b>	414.3	266.5	243.5	142.5

**Table 03. Summary of iteration totals**

	Lower Level			Upper Level			TOTAL		
	with 2.15m headroom	total	ratio	with 2.15m headroom	total	ratio	with 2.15m headroom	total	ratio
	m <sup>2</sup>	m <sup>2</sup>		m <sup>2</sup>	m <sup>2</sup>		m <sup>2</sup>	m <sup>2</sup>	
<b>Surface D</b>	30.6	56.7	0.54	43.7	62.9	0.69	<b>74.2</b>	<b>119.8</b>	<b>0.62</b>
<b>Surface E</b>	34.9	53.8	0.65	41.2	63.9	0.64	<b>76.1</b>	<b>117.7</b>	<b>0.65</b>
<b>Surface F</b>	38.4	66.2	0.58	56.0	76.3	0.73	<b>94.4</b>	<b>142.5</b>	<b>0.66</b>

**Table 04. Breakdown of iteration areas.**



**Figure 11. Plans, elevations and axonometric views showing the configurations of the shell adapted for launch on several major heavy lift rockets. The available space inside the payload fairings governs the size of rigid frame from which the shell is inflated. This image shows the resulting inflated shape. Surface D – the original design volume made to fit inside both the space shuttle and Ariane V<sup>1</sup>. Surface E – Resulting geometry using Ariane V and Atlas V constraints. Surface F - Resulting geometry for Proton constraints.**

### **E. Structural Design**

The shape of the SEIM is critical to insuring a minimum-weight structure. An inflatable shell structure is optimally suited to enclose the maximum volume with the absolute least weight of the structure. So-called “minimal surfaces” are familiar in nature because such shapes require the least amount of total energy to maintain and thus enclose a given volume with the minimum surface area and thus the minimum mass. An optimum, minimum-weight shape could be formed if a soap bubble were stretched between the endcone assemblies and subjected to an internal positive pressure. The resulting surface would resist pressure through uniform axial membrane stresses.

Though such natural bubble shapes represent the absolute optimum shape for enclosing an arbitrary volume, they do not necessarily provide a least-weight solution for enclosing a habitable space. While perfectly optimized in a mathematical sense, spherical or cylindrical volumes are often difficult to fully utilize and can result in wasted or inefficient usage of space. As such, the efficiency of the inflatable shell shape should be judged both as a function of the total enclosed volume to the weight of the membrane, and as a function of the architecturally usable volume to the surface area or weight of the membrane. The concept of architecturally usable volume suggests that the weight penalty for using a SEIM shape that diverges from a true minimal surface - a shape with sharper corners, for instance - may be offset by the increased efficiency in the usability of the enclosed volume.

We studied the new geometry using Strand7 Finite Element (FE) Analysis System Release 2.4.1. We applied a uniform pressure of 62 KPa<sup>16</sup> normal to the surface. The resulting stress diagrams (Figures 12-14) show a uniform distribution of both longitudinal and radial stress meaning that our surface is close to a minimal surface and thus very efficient. The only deviations from uniform stress occur at the bottom and are primarily caused by the coarseness of the FE mesh.

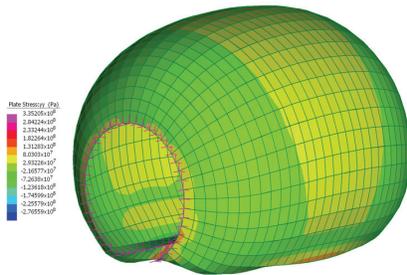


Figure 12. Radial Stress

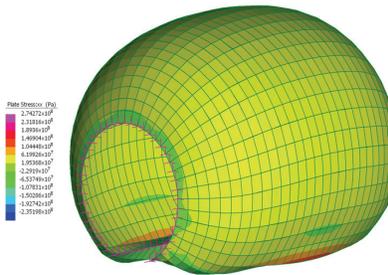


Figure 13. Longitudinal Stress

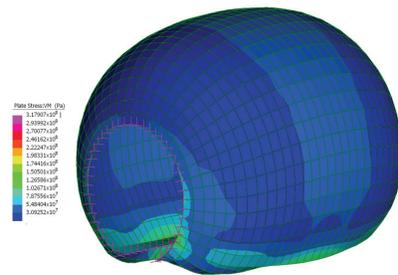


Figure 14. Combined Stress

#### IV. Forward Work

Although this study clearly demonstrates the utility of our modeling approach in optimizing a pressure shell for habitable volume, additional considerations particular to the nature of hybrid inflatables are required. The next step in this research will be to study other configurations of the internal secondary structures, different arrangements of the longerons, and alternative spatial planning of the volume inside the shell. Moreover, in order to make more informed design choices, additional interior parameters will be incorporated into the associative model. Important constraints will arise from the consideration of how equipment and utilities are packaged into the core structure, as well as from the assembly choreography necessary to transform the shear panels and other planar core structures used for resistance to launch and landing loads into habitable secondary structures. Other variables to be tracked might include travel distances, sightlines, and acoustical properties.

We also plan to investigate ways to reduce the number of separate pieces of software which we use for the optimization and mitigate the age old problem of sharing data between disparate applications<sup>17</sup>. One possibility is to explore the use of Kangaroo Physic<sup>18</sup>, a physics engine that runs directly in Grasshopper. This will allow us to drop Processing and combine the shape-finding and parametric models into one platform.

Further work will involve the study of other configurations of SEIM, such as a dedicated laboratory or storage module. Expansion of the capabilities of the shape-finding model to allow for the optimization of size, shape and location of openings and windows is also something that we would like to accomplish.

A final extension of the design methodology is to implement computer aided manufacturing (CAM). Explicitly adding constraints related to the manufacturing processes to the associative model leads to facilitating its connection to CAM. A great benefit of this augmentation is the ability to vary the geometry of every finished unit without significant time or cost penalties. One example is to use adjustable computer-numerically-controlled (CNC) moulds for the casting of the composite endcones in a variety of geometries. This would allow SEIM to be manufactured in a number of different configurations to fit inside a range of available heavy launch vehicles, thus greatly facilitating international cooperation and avoiding reliance on a single launch system that can delay the mission for long periods.

## V. Conclusions

In performing an iterative design study to optimize the SEIM shell geometry, we demonstrate the advantages of integrating form finding tools, parametric modeling techniques, and structural analysis in the design of complex structures such as vehicles for space exploration. This technique is a powerful design process that enables quick evaluation of multiple design alternatives and optimization of interior spatial layout, while improving cost, safety, and performance parameters in the mission risk profile. Potential advantages of this approach for cost savings during the development phase include: automating simple design checks through a number of iterations of the geometry variables; automating propagation of geometry changes; providing instant feedback to the designers about how well the current iteration meets the established performance criteria; and helping designers to define design rationale through clear geometric relationships.

In the operations phase, cost savings offered by this design system should serve also to improve the mission architecture and mass allowance. By optimizing the enclosure necessary to support the specific internal use requirements, our constraints-driven design process allows the completion of projects with reduced mass penalty. By reducing the environmentally conditioned volume served by spacecraft systems to that amount absolutely required for mission operations, the sizing of ECLSS, thermal control, and power systems can be more precise. Improvement in the precision of strength and geometric parameters for the structural components lowers both mission risk and cost in manufacturing while offering a measurably improved safety margin during mission operations. Of additional benefit is the flexibility this method offers by enabling designers to customize individual vehicles according to function, and to optimize integration with other mission systems such as launch vehicles.

As the technology behind constraints-driven design improves, the next level of sophistication in the design process would be the integration of the modeling and analysis tools. The shape finding and stress analysis will run in the background as the designer is changing the geometric variables. The model will thus instantaneously deform to take a realistic geometry. With the application of advanced CDD systems developed in industry to the latest spacecraft technology, we can significantly improve mission performance and safety while reducing development and operational cost.

## Acknowledgments

Jeffrey Traer Bernstein for use of the Traer.Physics 3.0 particle model.  
<http://www.cs.princeton.edu/~traer/physics/>

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