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TENSEGRITY HEAT SHIELD FOR ATMOSPHERIC ENTRY THROUGH CELESTIAL BODIES

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ABSTRACT

Heat shields play a vital role in protecting space vehicles during the atmosphere reentry. Therefore, they are essential for space vehicles, and better designed heat shields will vastly improve the ability both of robots and humans to explore extraterrestrial destinations. The main goal of the current paper is to investigate the feasibility of designing, building and deploying a tensegrity-based heat shield, which would withstand the atmospheric reentry of a low gravity and dense atmosphere celestial body (such as Titan), where the reentry accelerations and therefore, drag forces, will be lower than in the case of a high gravity planet (e.g., Earth or Mars). The paper is a preliminary study, which investigates the parameters that would be helpful in designing tensegrity-based heat shields. We explore the dynamics of entry and how the atmospheric forces interact with the heat shield. Tensegrity structures consist of tension elements used in conjunction with rigid rods which are actuated by changing the lengths of the tension elements. The advantage of the proposed approach versus the traditional one (rigid heat shields) is that tensegrity structures are flexible structures able to adapt the shape to obtain an optimal reentry configuration. The proposed heat shield will be able to fold in a small space during transport (e.g., to the target celestial body), unfold when the target is reached and provide additional mobility for an optimal reentry pattern. However, to achieve a deployable configuration, the tensegrity structure must withstand significant dynamics and thermal loads. We will use NASA Tensegrity Robotics Toolkit (NTRT) to simulate the structural designs of the heat shield as well as for designing the controllers.

Introduction

Tensegrity systems are hybrid soft-rigid systems that are very flexible and can perform unique maneuvers because of the tension element based structure. These robots are more dynamic than conventional rigid robots but more agile and sturdy than soft robots [1]. Other characteristics of tensegrity robots are that they are highly compliant structures that have the ability to fold. Due to the compliance, these robots can withstand high impact forces. This design allows tensegrity robots to be more maneuverable and for them to exhibit a complex range of movement as determined by the design of the robot. Tensegrity robots are built using tensile and compression elements [2]. Commonly, these would be high tension cables and rigid rods that form the structure of the robot. The design and arrangement of the rods are based on desired properties and structural capabilities of the robot. Different actuator types can be used to actuate these robots however there is one commonality to all actuation solutions, i.e. the actuator elements change the length of tensile elements in order to make the robot change its structure which consequentially controls the dynamic tensegrity structure.

As spacecrafts enter atmosphere of celestial bodies at very high speeds, it causes the spacecrafts to heat up to very high temperatures. Heat shields are essential to protect spacecrafts from exposure to such high temperatures. The temperatures are enough to vaporize the spacecraft and if the vehicle does not have an effective heatshield, it can catch fire, scientific payload can potentially get damaged or other systems in the vehicle can malfunction causing it to lose stability. Tensegrity based heat shields offer a revolutionary way of designing heat shields. It is possible to mount protection material on a tensegrity robot for the purposes of thermal protection when entering the atmosphere of a celestial body.

A few determining factors for atmospheric entry are deceleration rates, entry angles, types of entry methods, thermal protection systems and structural compliance.

State of the Art

Aerodynamic decelerators are designed to handle extremely high temperatures encountered at very high altitudes during entry of a spacecraft through the atmosphere. Thermal protection system (TPS) materials are used in order to protect the spacecraft. At such high temperatures, TPS materials pyrolyze and ablate in order to deal with aerothermal heat load [3]. The Adaptive Deployable Entry and Placement Technology (ADEPT) heat shield and Hypersonic Inflatable Aerodynamic Declerator (HIAD) are the two main aerodynamic decelerators that are being developed at this point of time.

The ADEPT heat shield is a mechanically deployable decelerator that is used for thermal protection of a spacecraft as it enters and descends through the atmosphere. As discussed by Smith et al, heat shields can protect a spacecraft from heat at hypersonic speeds.Low supersonic speeds can result in an angle of oscillation that would lead to oscillation amplitude growth and consequentially be dynamically unstable at low supersonic speeds. ADEPT attempts to tackle this problem by deploying a supersonic parachute to stabilize the entry vehicle [4].

Hypersonic Inflatable Aerodynamic Decelerator (HIAD) is an inflatable structure designed to protect space crafts during entry. Once the structure is deployed, the inflation system built into the inflatable reentry vehicle maintains the pressure in the aeroshell throughout the descent of the vehicle [5].

Heat shield design process is an involved and a rigorous process, however one central theme to the design process is analyzing the trajectory of the probe when entering a particular atmosphere and the forces that the probe would experience. This process is discussed by Edquist et al, as they elaborate on the design process of the Mars Science Laboratory(MSL) heatshield [6]. Following this process, the thermal protection systems (TPS) are developed for heat shields. Ablative solutions are very common for TPS material in modern heatshield designs [3]. Factors such as the forces a heatshield is able to withstand, the thermal protection system it requires and the dimensions depend heavily on the atmospheric environment. Such factors determine the design of heatshields [7].

Advantages of a tensegrity heat shield over current heat shield designs

Tensegrity heat shields are dynamic, lightweight and very compliant structures. These characteristics would allow us to increase the scientific payload for exploration purposes. Tensegrity heat shields would not destabilize the flight in low altitudes. Due to the dynamic shape of the heat shield, it would be able to adapt to flight and atmospheric conditions in low altitude.

Titan Atmospheric Entry

The entry modeled is very similar to the Huygens' probe entry through Titan's atmosphere. The probe entered Titan's atmosphere on 14 January 2005 [8]. The entry and descent phase data was reconstructed and the tensegrity heat shield entry is based on this data. The reconstructed altitude, inertial and descent velocity of Huygens' probe used for model fits and analyses in Figures 1-9 were taken from Kazminejad et al [8] . The altitude and the inertial velocity data (data from [8]) was used to generate a spline model and an exponential model as shown in figure 1.

Figure 2 and figure 3, show the exponential model that was found. The exponential model fit on the inertial velocity data is shown below along with the residual plot. The following relation was also found:

$$v_{inertial} = 7027exp(-0.000141a) - 17490exp(-0.007379a) \tag{1}$$

where a is the altitude in kilometers (km) and $v_{inertial}$ is the inertial velocity in meters/second (m/s). This model was used along with data reconstructed from Huygens' probe during its entry through Titan's atmosphere.

Residual plot helps us know how accurate the model fit is and helps compare different models for accuracy and agreement with empirical observations as seen in figure 3, figure 6 and figure 4.

Another method that was used to approximate inertial velocity during the entry phase was modeling the data using a spline

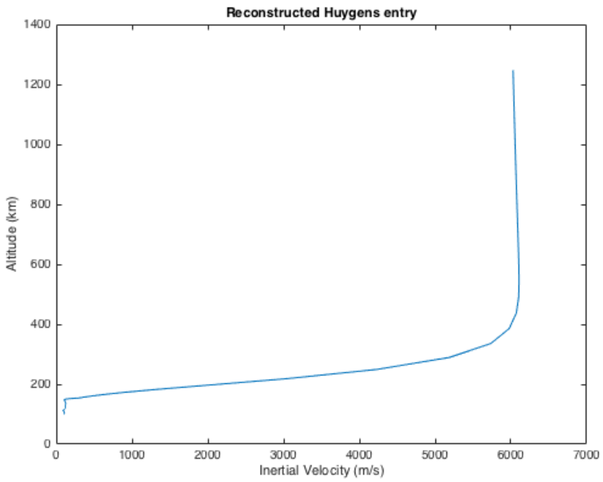

FIGURE 1. Huygen probe's entry phase velocity in Titan's atmosphere (Data from [8])

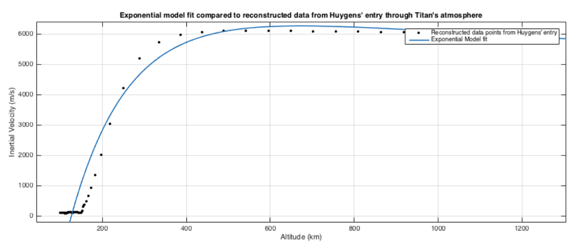

FIGURE 2. Exponential model to determine entry phase velocity

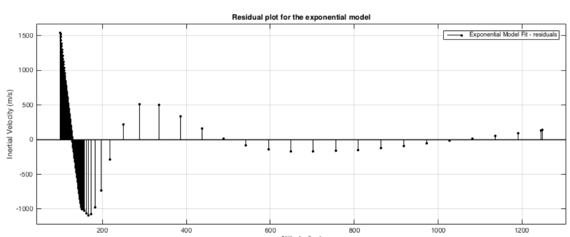

FIGURE 3. Residual of the entry phase exponential model

interpolation of 4th order. Other than approximating data with remarkable accuracy(residuals of the order of 10^{-12}), this method helps find the 1st derivative and 2nd derivative more accurately than other methods (such as exponential fit modeling). Using the spline fit model, the acceleration during the entry phase was also modeled as demonstrated in 4. This is useful in order to understand the effects of atmospheric forces on the heat shield globally as opposed to determining forces acting on the body locally.

We used the reconstructed data from the Huygens' probe

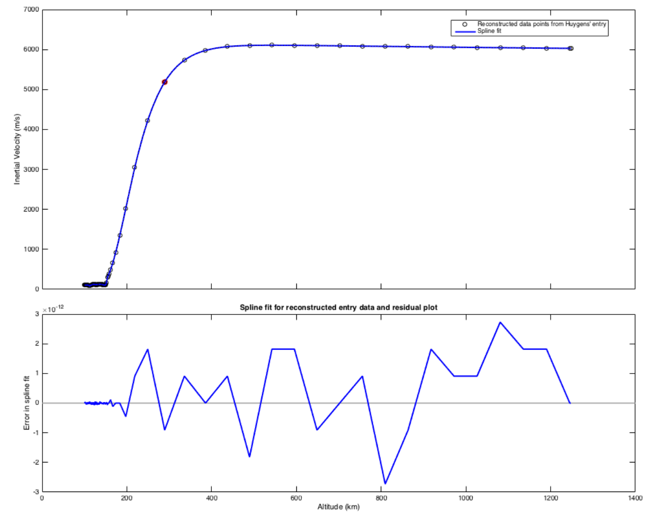

FIGURE 4. Spline fit model for reconstructed entry data from Huygens' entry to Titan's atmosphere and residual of the spline fit.

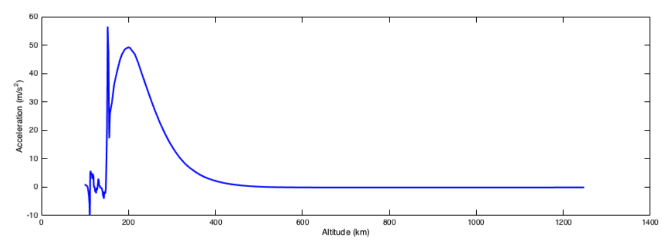

FIGURE 5. Acceleration of the probe found using the spline model

from the descent phase and found a spline interpolation of 4th order to approximate the empirical data(figure 5). The empirical data was reconstructed by Kazeminejad et al using raw data from Huygens' probe [8].

From figure 7, it can also be observed that the residual is of the order of 10^{-14} which indicates that the approximations from the spline interpolation model is indeed accurate. Using the same spline model, the acceleration of Huygens' probe during the descent phase was found.

There is an important point of contrast to note in the approximation techniques. Even though interpolation models used in this paper can approximate very accurately, the first order derivative of velocity is oscillatory and not smooth.

It was found that using a least square approximation will generate a much smoother curve (as observed in figure 9) for descent acceleration, albeit there is a slight trade-off with the residuals of the models. The residual of a least-squares based approximation is higher (residual of least-squares based approximation is about ± 15) than interpolation models.

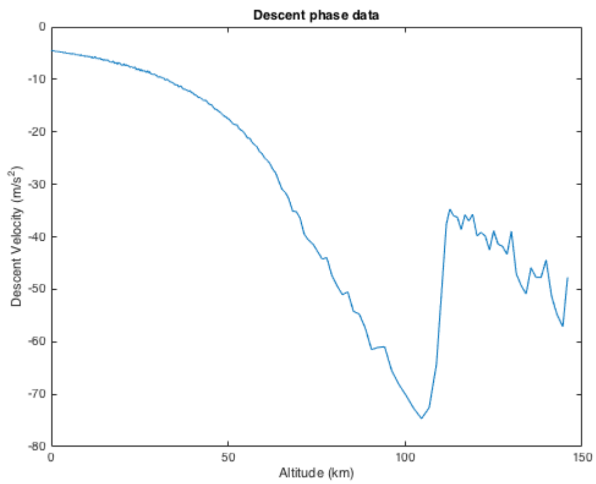

FIGURE 6. Model of atmospheric descent phase using a 4th order spline interpolation and residual plot of the fit

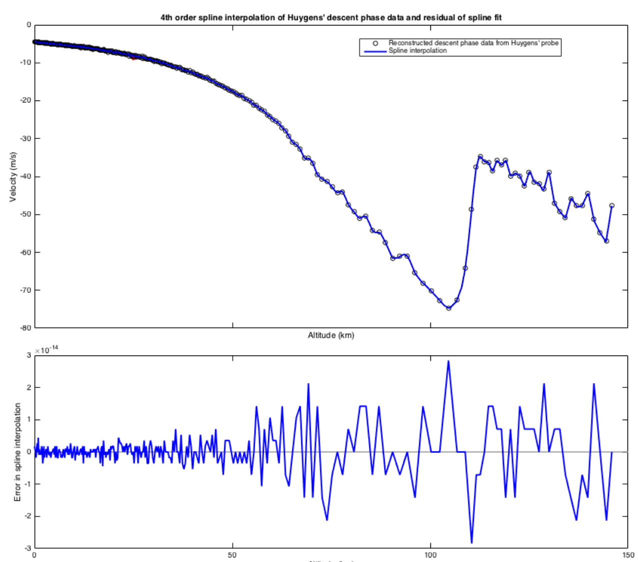

FIGURE 7. Model of atmospheric descent phase using a 4th order spline interpolation and residual plot of the fit

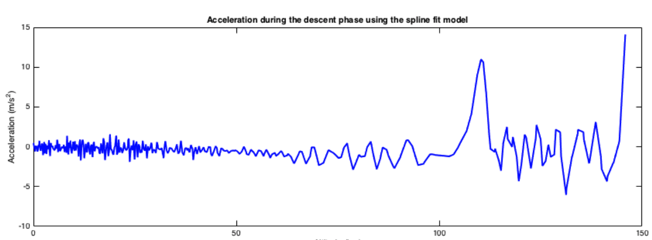

FIGURE 8. Acceleration of the probe during descent phase using the spline model

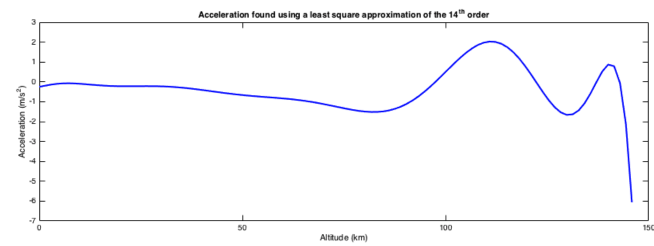

FIGURE 9. Acceleration of the probe during descent phase using the least squares approximation method of 13th order

Modeling approach and preliminary results

In the current paper, the reentry shield was modeled using NASA Tensegrity Robotics Toolkit (NTRT) [9–11]. This package uses Euler-Lagrange formulation to solve the tensegrity problem taking into consideration that the structure consists of rigid compression elements and flexible cable under tension[1]. The package accounts for the interaction between the tensegrity structure and the environment.

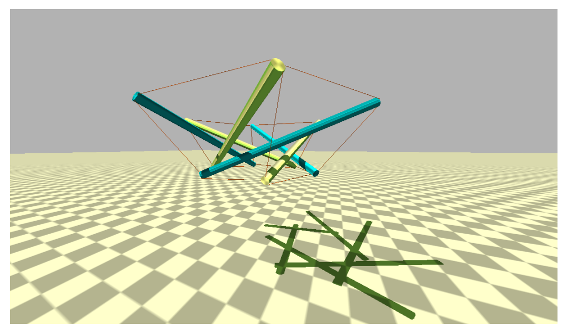

FIGURE 10. A tensegrity heat shield modeled using NASA Tensegrity Robotics Toolkit (NTRT)

Figure 10 shows a heat shield modeled using NASA's NTRT. This simulated structure consists of rigid rods and high tension cable designed in an arrangement such that thermal protection systems can be mounted on this structure. The NASA Tensegrity Robotics Toolkit is based on the bullet physics engine and is specifically built to create, design and simulate tensegrity robots [2]. NTRT makes it possible to simulate the structural integrity. It helps find an optimal configuration of tension elements and how they are connected to the rigid rods.

The toolkit also helps design controllers for tensegrity structures, provides data at each actuator node and state of tension cables at each time step of the simulation. One of the ways NTRT

[1]NTRT's rigid body dynamics and collision handling is based on Bullet Physics Engine which is a well known open source physics simulator. More information about Bullet Physics: http://bulletphysics.org/wordpress/

helps in designing tensegrity robots is that it helps inspect the tension from each node, if the robot lacks tension at any region, the integrity or form of the structure may not be achieved. NTRT helps find flaws in tension element configurations. If a tensegrity system is not structurally stable and is unable to withstand forces applied by the simulator, that particular tension element's force log is a value close to 0. Forces exerted by Titan's atmosphere on each cable in the structure is shown in figure 17. These are some ways NTRT helped in designing the tensegrity model of the heat shield.

In figures 11, 12 and 16 it can be seen how different heat shield designs were made and how NTRT helps in iteratively designing dynamic tensegrity structures.

Using controllers designed in NTRT it is possible to make a design that can fold or unfold and change it's structure during various phases of flight.

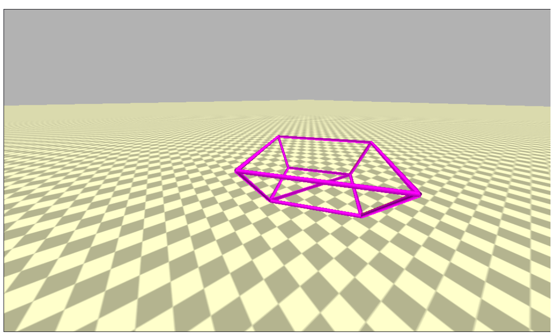

FIGURE 11. High rigidity tensegrity model

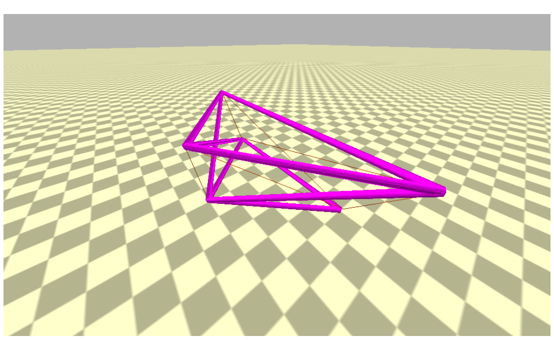

FIGURE 12. Tensegrity model with more tensile components

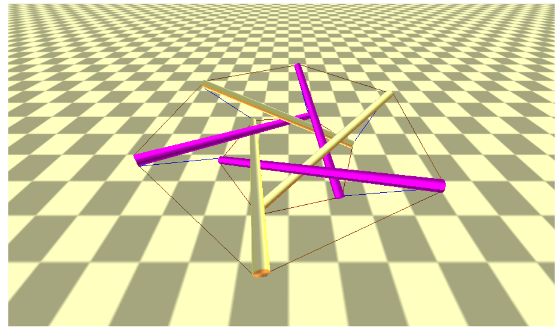

FIGURE 13. A tensegrity heat shield based on tensile and rigid components (NTRT)

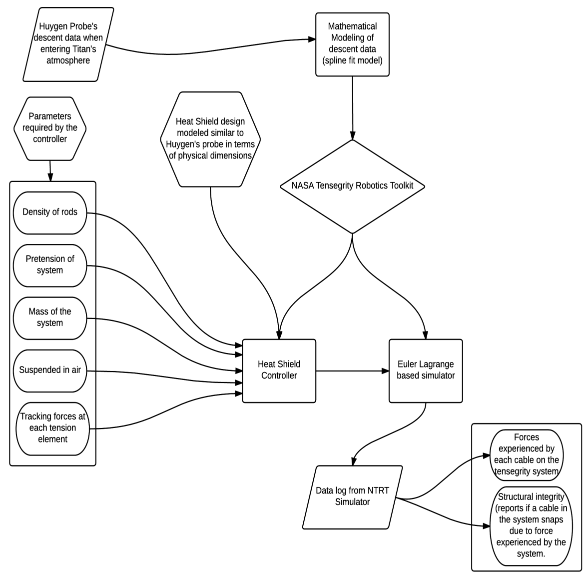

FIGURE 14. Flowchart highlighting the process of using the spline fit mathematical model to simulate tensegrity heat shield in NTRT

Preliminary Results

Figure 10 shows a folded tensegrity structure, which represents the "skeletal" frame of a reentry shield. Due to the interaction with the environment during reentry, this structure will change - This could be a significant advantage in a future design, because the structure's geometrical shape could be adapted for an optimal reentry solution.

For a preliminary study, we consider the tensegrity structure shown in Figure 10 will be subjected to the reentry phase data of the probe obtained from Kazminejad et al [8] (figure 5 above).

The model we developed is based on a spline fit curve. Following that, we found the first derivative of the spline fit which provided the acceleration that the probe experienced during the entry phase. We used these acceleration data values to emulate the force on the heat shield using NTRT. The simulation engine was used to monitor changes in each cable length at each time step. Based on the changes in length of the the cables and variable stiffness value for the cables, a force (in Newtons) on each cable is calculated and is displayed by the system.

Figure 17 shows the forces applied on all the cables during reentry. It should be noted that the the tensegrity structure has two sets of cables - the upper and the lower ones. Where the maximum stresses (green rods in figure 10) are applied on the lower cables. It should also be noted that the cables are initially pre-tensed, so the additional forces will lower the stress of certain cables (figure 17).

This approach was considered to increase the stability of the tensegrity structure. As this is a feasibility study, we use certain fixed parameters for the simulations. The parameters are as follows: the mass of the system is assumed to be $320kg$, a pretension of $500N$ is applied on the system and the density of the rigid rods is $8050kg/m^3$. The heatshield's diameter in the simulation is $1.35m$. NTRT's simulation engine applies acceleration provided by the mathematical models developed from descent data in Kazeminejad et al.'s study [8].

For the simulation data presented in this paper (figure 17), the spline model data was used (figure 5). It is important to note that even though the figures of the heatshield simulation show the ground, the forces logged from the simulator (figure 17) are performed when the heatshield is suspended mid air (as shown in figure 10). The simulator engine applies the forces from the mathematical modeled we developed. The impact phase of the heatshield is not analyzed in this study. The entire process of mathematical modeling and simulation of the tensegrity heat shield is discussed in figure 14.

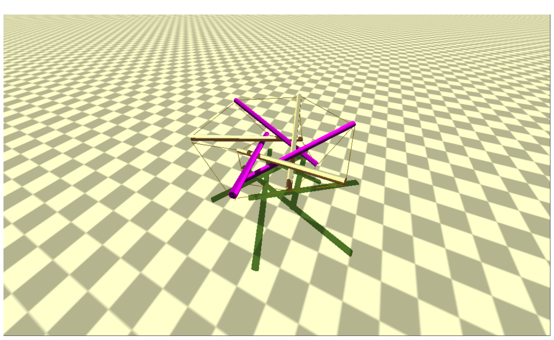

FIGURE 15. Unfolding tensegrity structure

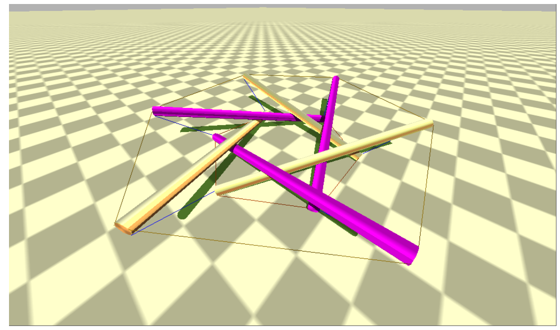

FIGURE 16. Fully unfolded tensegrity structure

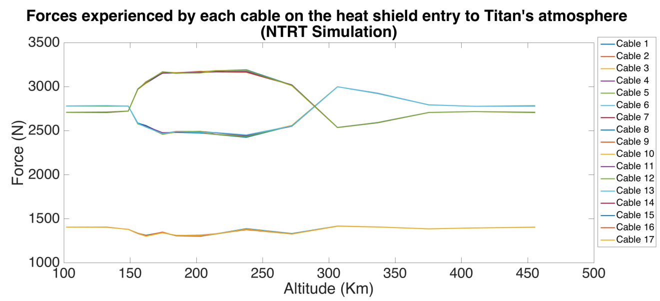

FIGURE 17. Forces on each cable in the heatshield during titan entry phase simulation in NTRT

Conclusion

Various mathematical modeling techniques are compared in this paper. These methods are used to determine atmospheric forces with proven accuracy. This gives us key insights as to which method is the best to use for input to the simulation engine. Based on the mathematical and design representations in this paper, it concludes that tensegrity models for heat shields can be tested thoroughly by scrutinizing existing descent data by mathematically modeling them. Following that, a toolkit such as NASA's Tensegrity Robotics Toolkit (NTRT) is used to advance the design process of tensegrity heat shields.

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