Tensegrity Ocean World Landers

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This paper explores the use of tensegrity structures as an end-to-end solution for descent, landing, and maneuvering through various depths of ocean worlds within the solar system. Ocean worlds are described as planetary bodies within the solar system that contain liquid bodies. They are key in the search for extra-terrestrial life and may provide insight into the development of the solar system. In this work, specific attention is paid to the exploration of the surface lakes of Titan. Analysis, test data, and literature review is used to validate aspects of this mission concept. Within the state of the art, tensegrity structure applications have been limited to landing and exploration of rocky worlds. There are many benefits to tensegrity structure probes. The structure serves as a directionally agnostic descent and landing vehicle with a nested payload, providing unobstructed fields of view of the environment during the mission. Furthermore, the robust, ultralight structure allows for higher than average mass-payload fractions to be achieved. By extending the application to ocean worlds, the structure's ability to swim via jet propulsion (i.e., as a biomimetic jellyfish) allows for extreme energy efficiency in exploration.

Nomenclature

a_g	=	*Acceleration due to gravity*
C	=	*Celsius*
C_d	=	*Coefficent of Drag*
C_L	=	*Coefficent of Lift*
COT	=	*Cost of Transport*
DOF	=	*Degrees of Freedom*
EDL	=	*Entry, Descent, and Landing*
g	=	*Acceleration of gravity on the surface of the earth at sea level*
h_0	=	*Height of zero velocity*
JPL	=	*NASA/Caltech Jet Propulsion Laboratory*
m	=	*Meters*
NIAC	=	*NASA Innovative Advanced Concepts*
S	=	*Planform surface aarea*
TOWL	=	*Tensegrity Ocean World Lander*
v_{impact}	=	*Velocity at surface impact*
v_∞	=	*Freestream velocity*
ρ	=	*Atmospheric density*

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I. Introduction

TENSEGRITY structures are a compelling platform to use as an end-to-end solution for an ultra-light weight probe (<100 kg) to explore ocean worlds throughout the solar system. Exploration of ocean worlds will allow greater understanding of the development of our solar system and the continuation of the search for life beyond Earth.[1] The tensegrity probe would serve as the descent stage, impactor, and mobility platform. The use of these structures to navigate liquid bodies after impact has not yet been studied in depth, but serves to broaden the potential uses of tensegrity structure within aerospace applications.

Tensegrity structures have been shown to have good impact resistance in entry, descent, and landing (EDL) applications on solid bodies. [2] They have also been studied extensively in the application of mobility platforms to traverse difficult, rocky terrain. [3] This includes the ability to traverse up slopes. However, few have studied the use of tensegrity structures to create an end-to-end mission concept that harnesses tensegrity for both EDL and roving. The NASA Innovative Advanced Concepts (NIAC) mission architecture study by Bayandor limited the use of tensegrity structures for exploration on solid land. [4]The NIAC study by Dr. Adrian Agogino from Ames Research Center studied tensegrity application on Titan, also focusing on exploration of the rocky terrain. [5] This paper will extend previous studies and explore a mission concept that uses tensegrity structures to explore and swim on Titan. By actuating a tensegrity structure to emulate a jellyfish, the tensegrity structure would be capable of energy efficient locomotion; jellyfish are one of the most efficient swimmers in the ocean.

On Titan, for example, a compelling unexplored use case is reaching terminal velocity (<20 m/s), impacting the lakes, and using the compression members as control surfaces to direct submerged movement. Unlike parachutes and airbags, tensegrity structures provide high drag, can be tailored to break liquid surface tension, and withstand impact from high-altitude insertions. A payload would be protected without the obstruction of a full enclosure, allowing for constant data collection. Orientation-agnostic impact allows structures to avoid many aerodynamic complications. Structures may be deployable, light-weight, robust, and actuated to explore extreme environments, enabling high mass payload fractions (≥8:1) and cost-effective data collection. Tensegrity structures for liquids builds on existing technology developed at the Jet Propulsion Laboratory to create an end-to-end solution for descent, landing, sensing, and maneuvering through various depths.

This mission architecture is studied by discussing every aspect of the proposed system. Initially presented is a discussion of ocean worlds, including scientific goals. Then, tensegrity structures are discussed through a historical context. A trade study of tensegrity geometries is carried for this mission architecture. Finally, the mission is discussed step by step going from orbital transfer through robotic exploration of Titan's surface lakes. Methods used for this study include analysis, testing, and literature review.

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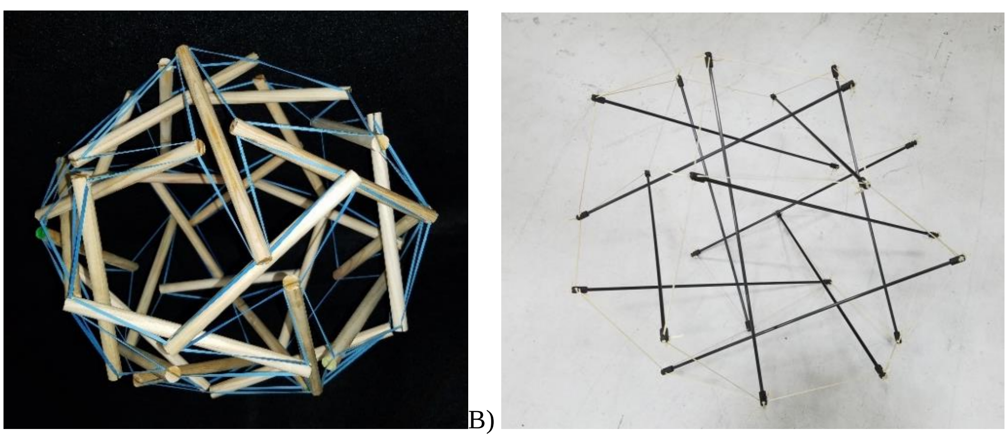


Fig. 1 A) 30-bar tensegrity structure built at JPL, and B) 12-bar tensegrity structure of carbon fiber and vectran with nylon joints built at JPL.

II. Ocean Worlds

A. Ocean Worlds and Their Scientific Merit

Ocean worlds are defined as planetary bodies with known current liquid oceans. Enceladus, Europa, Titan, Ganymede, and Callisto all have known subsurface oceans. Other potential ocean worlds are suspected to exist, but have not been confirmed. These include Triton, Pluto, Ceres, and Dione. [6]

Ocean Worlds have been, and continue to be studied for the following traits of scientific interest: Identify ocean worlds, characterize oceans, evaluate habitability, search for life, and study any life found. These traits have been outlined by the Ocean Worlds Program as part of the NASA Outer Planets Assessment Group (OPAG). This program has determined that in-situ investigation is required for the comprehensive exploration of these worlds. These exploration goals are also echoed in the 2013-2022 Planetary Science Decadal Survey. Figure 2 displays the state of exploration for each of the ocean worlds. Notably missing are future missions to explore Titan. [7]

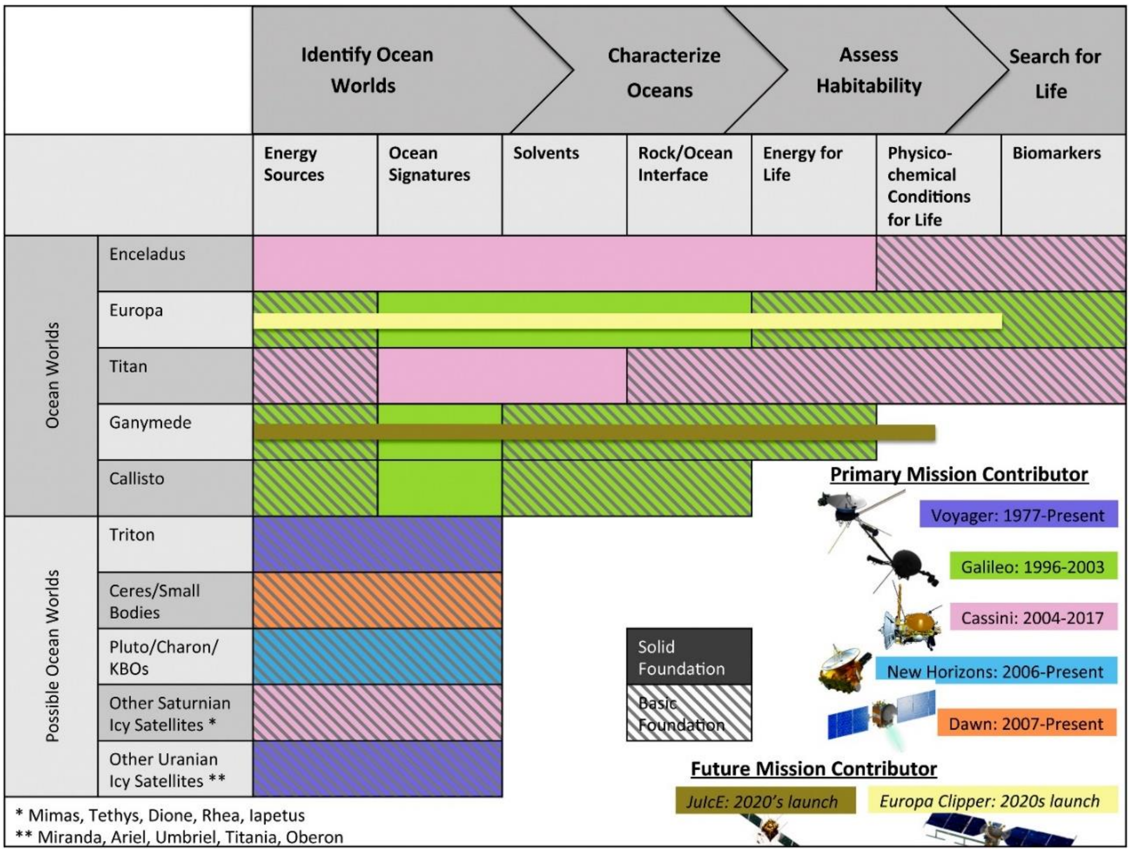


Figure 2: Ocean worlds and potential ocean worlds within our solar system. [7]

B. Titan

Much study has gone into the environment of Titan, especially the surface lakes in the north region of the planet as well as the subsurface ocean. The proposed mission concept targets the surface lakes serve as the primary target. The surface lakes of Titan, composed of liquid ethane and methane, were detected by the Cassini-Huygens space probe as well as the Hubble Space Telescope. Prior to the discovery, the Voyager 1 and 2 spacecraft had measured the Titan atmosphere determining that such bodies may be possible. [8] Cassini identified numerous forms of liquid-filled depressions. Vast seas, such as Ligeia Mare, can be hundreds of kilometers across. These seas are fed by channels comparable to rivers. Smaller, shallower lakes can also be found and are isolated from the river system. Ligeia Mare is the 2nd largest body of surface liquid on Titan and was studied using the Cassini RADAR instrument. Figure 3 displays the bathymetric profile measured by the instrument. The surface of Titan also holds topographic depressions that are dry. Figure 4 displays false color imagery of the lakes and depressions taken by the Cassini Probe. [9] Titan's methane lakes are part of the methane cycle on the moon, similar to Earth's own hydrologic cycle. The surface temperature of Titan -180 Celsius. The lakes themselves remain at a similar surface temperature estimated to be 3 degrees colder, -183 C. [10] Finally, there is some data that Titan may have “transient surface liquid water such as impact melt pools and fresh cryovolcanic flows in contact with both solid and liquid surface organics.” [7]

The NASA Outer Planets Assessment Group has recommended the use of numerous missions to explore Titan fully. The recommended missions include an orbiter, an atmospheric probe, an aerial mission, a submarine, a deep drill, and a lake lander. Specifically, the lake lander is focused on sampling the lakes to determine “bulk composition, trace dissolved species, and sediment depths.” The submarine may explore liquid composition, subsurface currents, map the bathymetry, and “determine seabed sediment composition.” [7]

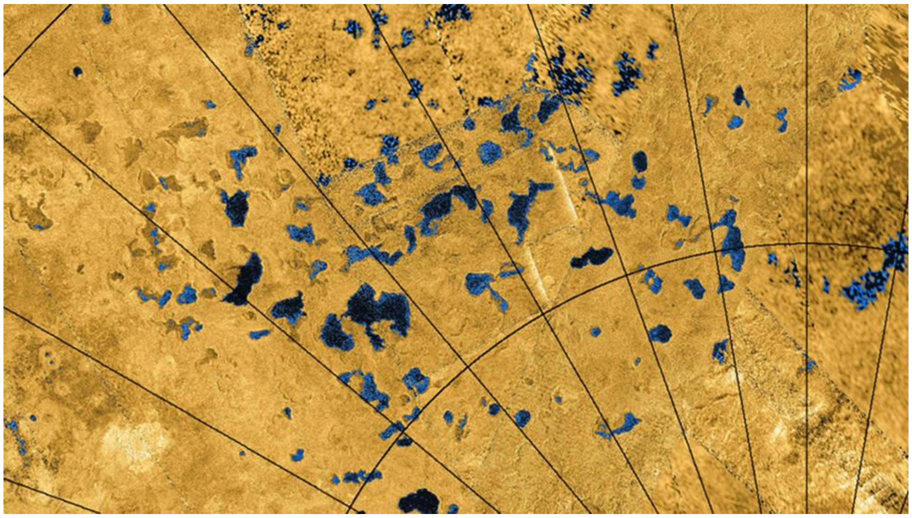


Figure 3: False color radar images from the northern area of Titan showing lakes and depressions in the area. [9]

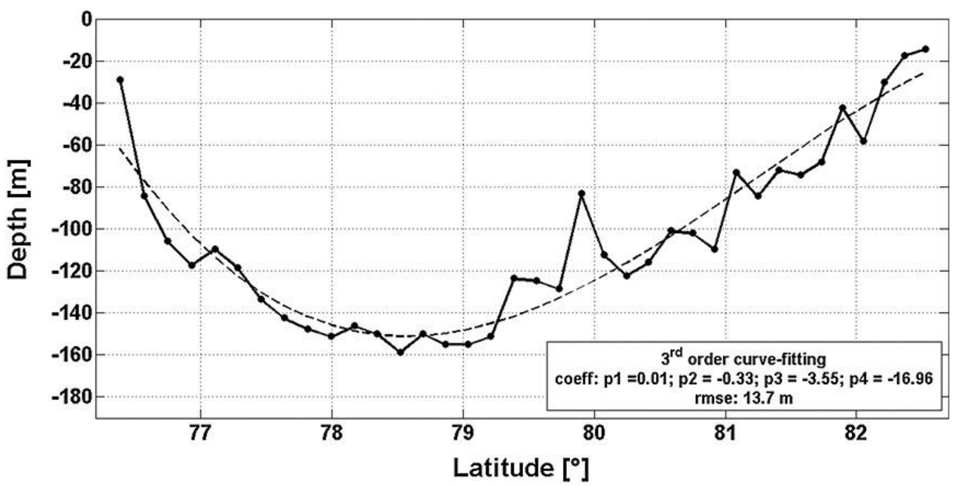


Figure 4: Depth profile of Ligeia Mare as measured by the Cassini Radar. [10]

III.Tensegrity Structures

A. History of Tensegrity

Tensegrity structures are a type of structure in which compression members are isolated within a network of tensions members such that compression members do not intersect. These structures emerged in the 1940s and were championed by Buckminster Fuller and Kenneth Snelson. Since then, tensegrity structures have been used in various applications including sculpture, architecture, engineering, and more. These structures can be lightweight, deployable, and tunable among many other advantageous characteristics. Often these structures are biomimetic, or comparable to biological structures.

Although the classical definition of tensegrity structures requires that no rigid members interact with each other, the definition of tensegrity can be expanded to include structures where rigid members are attached, but do not carry moment across the joint. For example, a class two tensegrity would have two rigid members joined, but not constrained, such that moment is not carried across the joint. A class three tensegrity would have three members joined at a single node with the same constraint. Only class one tensegrities were studied for this mission concept. Class two and class three tensegrity structures are a potential area of further study.

B. Tensegrity Geometry Study for Titan Probe

Tensegrity structures can take on an infinite number of geometries and at numerous scales. A study of various tensegrity geometries has been completed to evaluate potential structure geometries that would work for ocean world exploration. The structure geometries considered were:

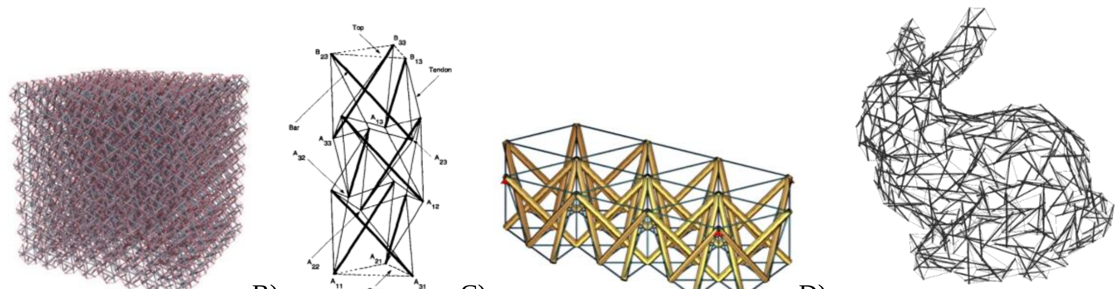
- Spherical structure
- Lattice of spherical structures (i.e. lattice with units made of spherical tensegrities)
- Tower structure (i.e segments built up linearly to form a tower)
- Oblate structure (i.e. plate-like)
- Freeform Geometry (i.e. tensegrity is designed to fit a specific desired shape)

These geometries are displayed in Figure 5. Spherical tensegrity structures are shown in Figure 1. Table 1 enumerates the characteristics of each structure with respect to ocean world exploration. Specifically, the structure is evaluated for key characteristics to ensure that it can perform each phase of the mission. This includes descent, landing, and swimming locomotion. The structure will need to safely carry avionics and scientific payloads at all phases of the mission. The payload mass is considered to be 15 kg in this mission architecture.

Ultimately, a spherical tensegrity geometry was selected. The primary benefits of a spherical tensegrity include near-directionally agnostic impact, a protected volume within the structure for the payload to be mounted, the impact dynamics have been well researched and understood, and a relatively low terminal velocity.

Table 1: Summary of tensegrity geometry trade study.

	Spherical	**Lattice Spherical**	**Tower**	**Oblate**	**Freeform**
Descent	• Somewhat directionally agnostic • Low terminal velocity	Extremely complex to model	• Higher terminal velocity • Known aerodynamic orientation	Known aerodynamic orientation	Dependent on geometry
Landing	• Somewhat directionally agnostic • Impact dynamics are well researched	Extremely complex to model	Unstable landing due to aerodynamic descent orientation	Unstable landing due to aerodynamic descent orientation	Dependent on geometry
Locomotion	Jellyfish biomimetic	Almost any method possible	Anguilliform locomotion	Anguilliform locomotion	Dependent on geometry
Actuated DOF needed for swimming	2 or more	3 or more	3 or more	3 or more	Dependent on geometry
Payload Capability	Central void provides good payload carrying capability	• Multiple volumes for payload • Very little payload space	Very little payload space	Very little payload space	Dependent on geometry
General Notes	Well researched in the literature	• Type 2 tensegrity allows for slightly more stability • Extremely low terminal velocity	Ballistic shape possible	Complex manufacturing	Geometry can be tuned for any use



A) B) C) D)

Fig. 5: Tensegrity geometries considered but not studied in depth for this study: A) Tessellated dimensional tensegrity lattice [11], B) Tensegrity tower [12], C) Oblate tensegrity plate [13], and D) Freeform tensegrity [14]

C. Tensegrity Construction

Over the past few years, the Jet Propulsion Laboratory has developed methods for prototyping and building tensegrity structures of various types. Figure 12 displays images of the structural joint design as it has evolved from a single 3D printed part, into a multi-piece assembly, and finally into a two piece spherical bearing joint. All joint iterations have been designed for the 12-bar tensegrity sphere. However, the design may be adjusted for any tensegrity geometry. During development, using polymer-based 3D printing, numerous designs failed due to delamination of the joint. Print orientation remains a key aspect of structural strength when using any type of additive manufacturing.

The two piece spherical bearing joint is printed simultaneously, with the spherical end captured within its mating piece. These joints have been additively manufactured such that moment is ideally not carried through the joint within the expected range of motion. However, the printing process may result in some surface friction. By additively manufacturing the joint from aluminum, higher loads may be reacted.

The payload placed within the structure is critical to ensuring that the structure can fully be tested. An Arduino based system was developed to track acceleration of the structures during testing. Further, a GoPro fusion camera was used to record 360 degree camera footage. These systems are shown in Figure 13.

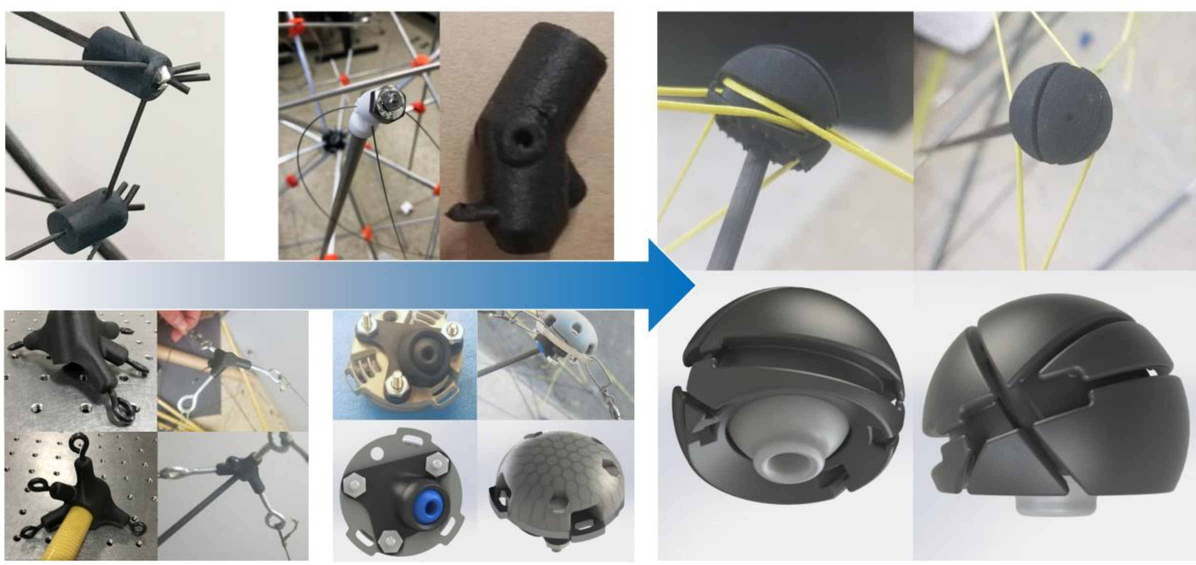


Figure 12: Tensegrity joint development for a 12-bar structure

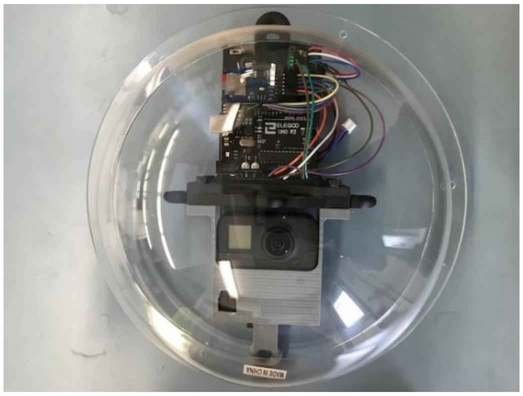
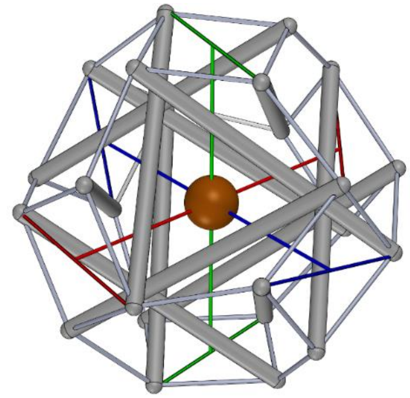
A)  B) 

Figure 13: A) Tensegrity payload within waterproof hemisphere case B) Conceptual image of tensgrity payload suspended within a twelve bar structure

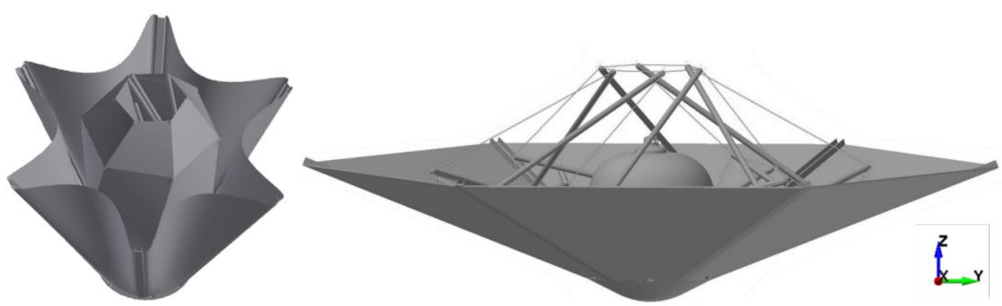
IV.Overall Mission Concept

The overall mission architecture can be separated into three primary segments: descent, landing, and submerged exploration. Each of these phases poses unique challenges and influences the design of the tensegrity structure.

A. Orbital Transfer, Approach, and Entry

The Huygens probe serves as precedent for the orbital transfer from Earth to Titan. This includes an 8 to 10 year transit entering the atmosphere at approximately 6.5 km/s. The Huygens probe carried a heat shield 2.7m in diameter with a probe size of 1.3m in diameter. This will serve as a bounding size for this mission architecture study. The NIAC study carried out by Ames Research Center took a similar approach, referencing Huygens. [5]

Furthermore, atmospheric entry for tensegrity structures has been considered at length by Bayandor in his NIAC report focused on Venus. For the purposes of this paper, Bayandor's study remains relevant. Figure 6 displays Bayndor's concept of a heat shield as attached to a tensegrity structure. Such a system is capable of being stowed for transfer, then deployed for atmospheric entry. This deployment can be actuated using a single degree of freedom. An identical actuation may be later used for swimming locomotion. Thus, Bayandor's concept for a deployable heat shield complements this mission architecture for a swimming tensegrity structure, but would need to be adapted for the Titan atmosphere. [4]



(a) (b)

Figure 6: Bayandor's concept for a heat shield as attached to a tensegrity. [4]

B. Descent

The descent phase of the mission would begin after atmospheric entry. For the Titan atmosphere, descent is considered from the altitude of 10 km. This is altitude is sufficient to reach terminal velocity during descent. The structural design for the descent phase of the mission is directly influenced by the design for submerged locomotion. For example, a jellyfish biomimetic locomotion method is proposed for tensegrity actuation while submerged. This locomotion method requires a jellyfish bell (mesoglea) to be actuated. This bell would greatly affect descent aerodynamics, potentially beneficially, and must be considered.

Descent normally is associated with parachute deployment. However, tensegrity structure landers may not need the use of a parachute. This is true for Titan and is discussed in the Descent Analysis section. Furthermore, the cross section of the tensegrity compression members has traditionally been a circle. A tensegrity structure design for descent should consider other possible cross sections as means of decreasing terminal velocity with consideration for impact and locomotion. This includes a square cross section which drastically increases the coefficient of drag for each member, up to double. Increased drag translates to decreased terminal velocity and impact speeds.

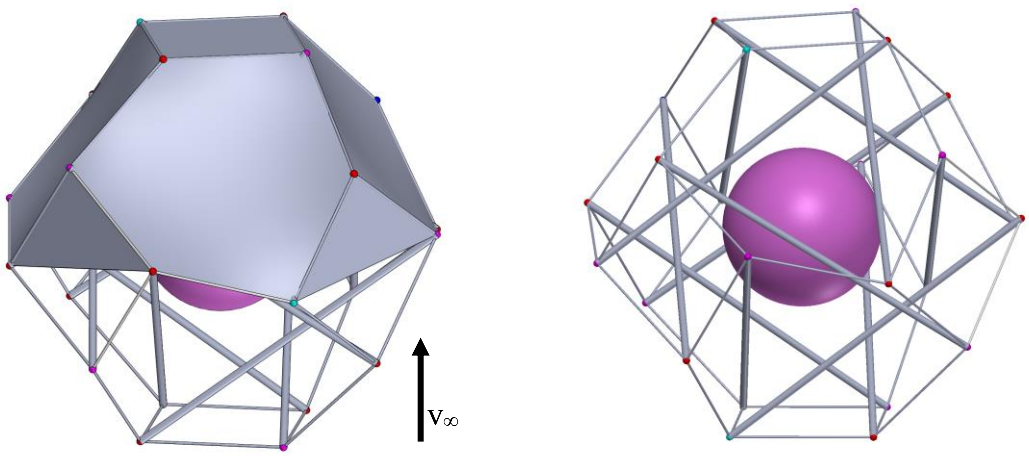
C. Descent Analysis

Two configurations were analyzed for the tensegrity ocean world lander (TOWL) based on a truncated regular octahedral tensegrity with twelve bars. Each configuration assumed a landed system mass of 20 kg. The configurations were:

1. A 1m diameter 12-bar spherical tensegrity with no membranes. Seen in Figure 7.B.
2. A 1m diameter 12-bar spherical tensegrity with a semi-hemispherical membrane. Seen in Figure 7.A.

Numerous atmospheres were studied such that performance on Titan may be compared to that on other planetary bodies. For each configuration, the free stream velocity was defined solely by freefall, at an average atmosphere. This model may be extended to include planetary weather and atmospheric altitude dependencies. For Titan, wind has been observed to be very light, less than 1 m/s, on the surface of the Methane lakes. [15]

Geometry for both analysis cases was analyzed directly from the 3D model. For simplicity, the structure was considered rigid, although some deformations will realistically occur during descent. Initially, a simplified version for beginning estimates was also created, based on geometry presented in the Rensselaer aerodynamics study on whiffle ball aerodynamics. [16] In all cases, the free stream is assumed to follow the direction shown in Figure 7.



A) B)

Figure 7: A) Tensegrity mesh with bell, and B) Tensegrity mesh without bell

Titan, Earth, Europa, Miranda, Mars, the Earth's Moon, and Ceres were all studied. Atmospheric values for each of the seven environments were estimated using current NASA definitions, then averaged over the meaningful drop altitude profile. For environments with negligible atmosphere, only gravitational effects were considered. Tables II and III show the atmospheric values used for each environment, along with the results for each geometry. A higher fidelity model may be created in the future, which would account for atmospheric changes with respect to altitude during the descent phase.

The aerodynamic performance of the vehicle was first estimated using simplified geometry to determine the inherent drag constant for each configuration. The final estimates were later compared to the Rensselaer study on whiffle ball aerodynamics, published numbers on baseball aerodynamics, and NASA data on falling sphere aerodynamics, as the tensegrity geometry should mimic these shapes, particularly with the added bell. [16] Tables II and III list these results.

These estimates are conservative, such that the actual drag of the vehicle will likely be greater, decreasing the impact velocity. Assuming an initial drop velocity of 0 with gravitational force driving purely ballistic vehicle motion, the terminal velocity of the vehicle follows the relationship shown in equation 1. Variables are defined in the nomenclature.

$$v_{impact} = \sqrt{2(a_g - \frac{1/_2 \rho v_\infty^2 S C_D}{m} - \frac{1/_2 \rho v_\infty^2 S C_L}{m}) h_0} \tag{1}$$

For environments with negligible atmosphere, lift and drag are considered to be marginal, and can be neglected. Free stream velocity is only applied until terminal velocity is reached, at which point the velocity term will be overridden by terminal velocity in lieu of v_∞. The terminal velocities of each vehicle configuration for each environment are given in Table II and III, along with impact velocities. Note the discrepancy between terminal and impact velocity for Mars. Due to the extremely low Reynolds number of Martian air, the vehicle will not reach terminal velocity before impact with the surface. This could change, depending on initial velocity, so the calculated terminal velocity is still considered a useful finding.

The Ames Research Center NIAC study empirically calculated the coefficient of drag of a tensegrity model to be 0.5, resulting in a terminal velocity of 11.4 m/s. Ames' study did not use the same tensegrity geometry. However, this terminal velocity estimate falls between the analyses carried out of this 12 bar tensegrity structure with and without the bell. With the hemispherical membrane bell, the calculated Titan terminal velocity is 3.65 m/s. Without the bell, the terminal velocity increases to 15.6 m/s. [5]

Table II. Vehicle Descent Parameters for Various Environments (No Bell)

Measure	Units	Earth	Titan	Europa	Miranda	Mars	Moon	Ceres
Reynolds Number	**N/A**	1,000,000	200,000	Negligible atmosphere	Negligible atmosphere	.000025	Negligible atmosphere	Negligible atmosphere
Drop Height	**m**	11,000	40,000	10,000	10,000	7,000	10,000	10,000
Terminal Velocity	**m/s**	620.	15.6	Negligible atmosphere	Negligible atmosphere	35,400	Negligible atmosphere	Negligible atmosphere
Impact Speed	**m/s**	620	15.6	162.	39.7	26,000	180.	73.5
Gravity	**m/s^2**	9.81	1.35	1.32	0.079	3.71	1.62	.270
Coefficient of drag	**N/A**	.40	.45	Negligible atmosphere	Negligible atmosphere	1.6	Negligible atmosphere	Negligible atmosphere
Coefficient of lift	**N/A**	0 (no spin) .15 (spin)	0 (no spin) .1 (spin)			0 (no spin) .01 (spin)		

Table III. Vehicle Descent Parameters for Various Environments (Including Bell)

Measure	Units	Earth	Titan	Europa	Miranda	Mars	Moon	Ceres
Reynolds Number	**N/A**	1,000,000	200,000	Negligible atmosphere	Negligible atmosphere	.000025	Negligible atmosphere	Negligible atmosphere
Drop Height	**m**	10,000	10,000	10,000	10,000	10,000	10,000	10,000
Terminal Velocity	**m/s**	130.	3.65	Negligible atmosphere	Negligible atmosphere	8,800	Negligible atmosphere	Negligible atmosphere
Impact Speed	**m/s**	130.	3.65	162.172	39.7492	8,800.	180	73.48
Gravity	**m/s^2**	9.81	1.35	1.32	0.079	3.71	1.62	0.27
Coefficient of drag	**N/A**	0.60	0.60	Negligible atmosphere	Negligible atmosphere	2.0	Negligible atmosphere	Negligible atmosphere
Coefficient of lift	**N/A**	0.20	0.15			0.015		

D. Landing

Landing may be considered the phase beginning when the structure first strikes a liquid body until submerged locomotion begins. The assumption is made that the probe will land directly into a liquid body. This is a realistic assumption considering the size of the lakes on Titan, some of which are hundreds of kilometers across. Furthermore, prime scientific interest is placed on exploring the largest lakes on Titan. This phase is when the structure will see the highest mechanical stresses. Due to the nature of tensegrity structures, impact loads are distributed throughout the structure and all compression and tension members help react impact forces. Studies have characterized tensegrity impact on land and, separately, others have studied entries of rigid bodies into liquids.

Initial testing at JPL has shown payloads suspended within a 12-bar spherical tensegrity structure may be subject to extremely high acceleration loads upon impact on land, around 70g's. Figure 8 displays some of the videogrammetry work that has been done when landing on rocky surfaces. This number is relatively high as the structure tested used compression members that did not elastically buckle and tension members with very little elastic elongation.

Similarly, using a six-bar tensegrity structure, Ames Research Center NIAC demonstrated the relationship between structure size and acceleration seen at the payload suspended within the structure. This relationship is seen in Figure 9. The tensions members used for the tensegrity structure had a spring constant of 44 kN/m. The tension members used to suspend the payload a spring constant of 10 kN/m. These findings were conducted at an impact speed of 15 m/s. This impact speed is similar to the 15.6 m/s terminal velocity impact speed discussed and calculated in the previous section. Because this probe will be landing directly into liquid, the impact accelerations it will need to survive are minimized. Therefore it is expected that the payload will experience less than 40g of acceleration as outlined in Figure 9. [5]

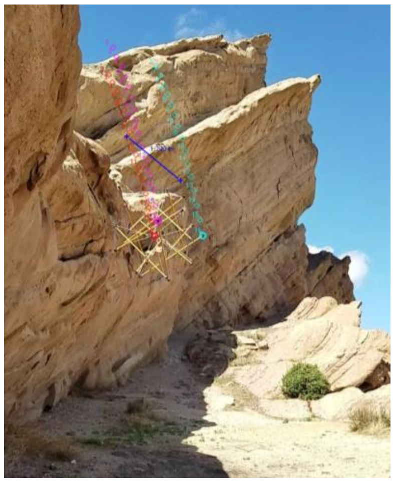
A)  B) 

Fig. 8 A) An example of videogrampetry as applied to a tensegrity landing test on solid land B) An examaple of data from videogrametry.

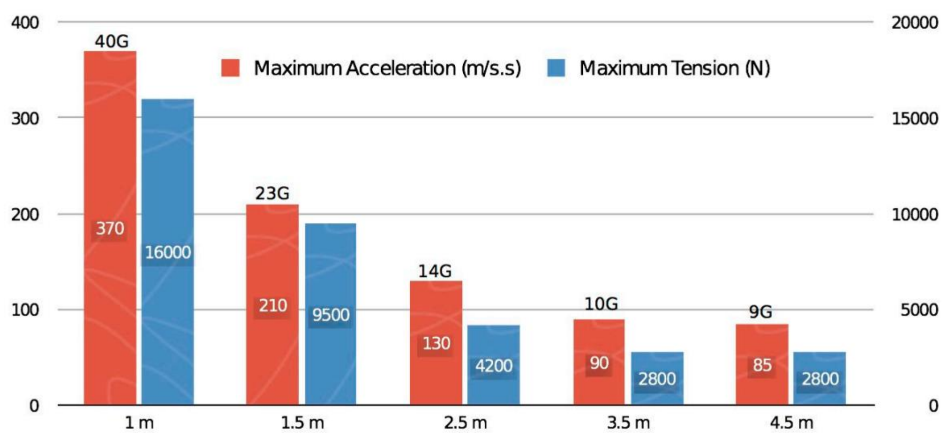


Figure 10: Relationship of compresssion member length versus payload acceleration loads for landing directly on Titan's rocky surface. [5]

Testing was carried out using a 1m diameter carbon fiber structure with vectran tension member. This structure utilized the 12-bar geometry. During this testing, a payload containing a 360 degreee camera and inertial measurement unit was suspended within the structure. The structure was then thrown from a height of 12 meters. Figure 10 displays a composite image from the payload's camera during the test. During this test, the structure reached speeds of 20 m/s. This confirms that an impact speed of 15m/s is feasible for landing in liquids. However, the viscosity difference between liquid water and liquid methane was not accounted for.

Testing with different cross sectional shapes of the compression mebers greatly decreased the terminal velocity of the structure. For exmaple, a compression member crosssectional area created by two tape springs facing opposite directions reached an impact speed of 14 m/s, versus 20 m/s achieved with round members. These speeds confirm that the rod geometry must not only be determined by impact loads, but also to minimize terminal velocity if needed. Moving from a round cross section to a square or spline-like cross section will decrease the loads these structures must endure, increasing the potential mass-payload fraction that is possible.

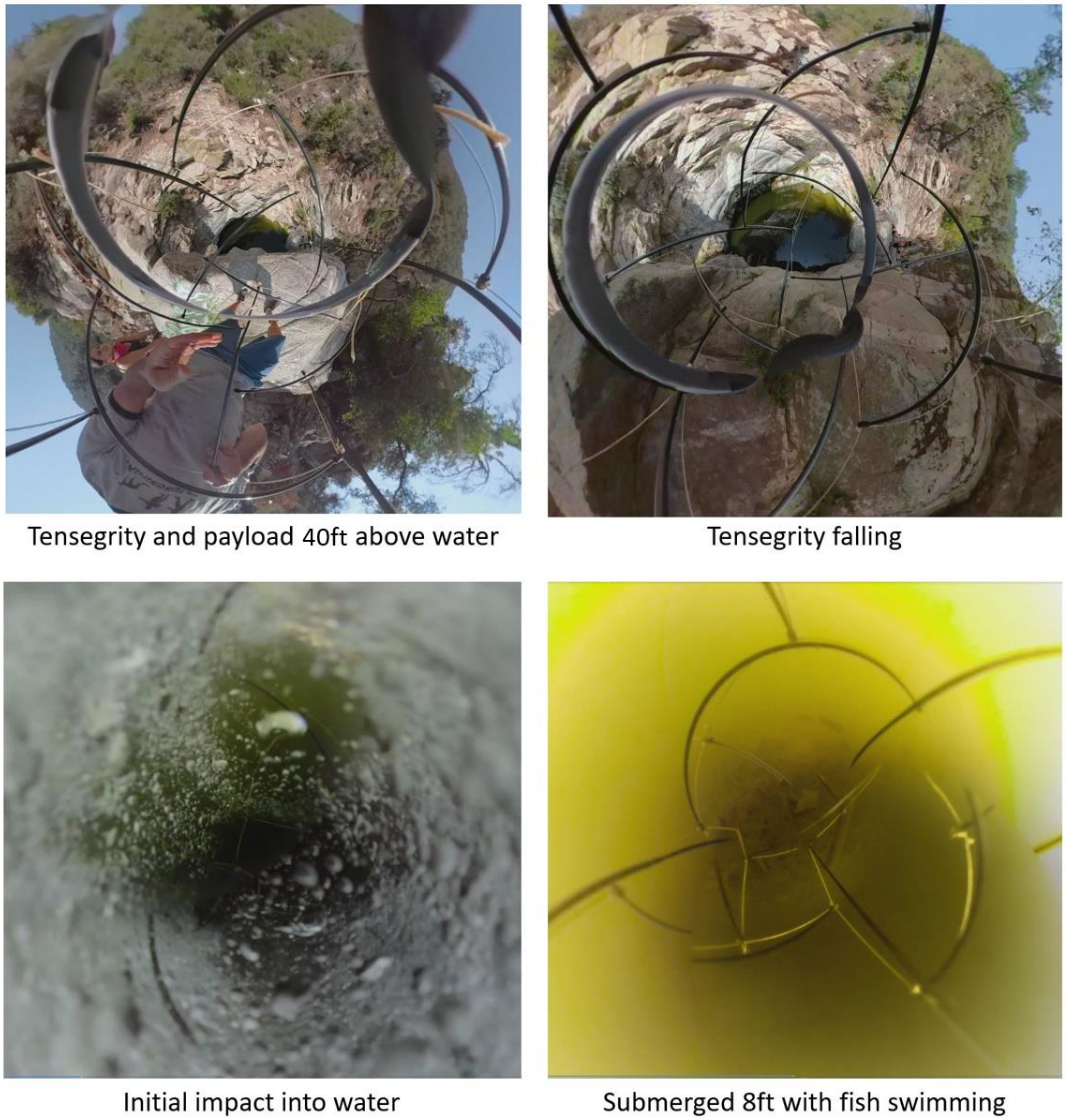


Figure 10: Composite image showing field of view from 360 degree camera inside of tensegrity structure as it lands in liquid boday.

E. Submerged Exploration

In creating an end-to-end solution for exploring ocean worlds, any locomotion design must allow for effective motion in liquid bodies without compromising the descent and landing portions of the mission. For a small probe, serving as a lake-lander and submarine, biomimetic jellyfish locomotion holds great promise for energy efficient exploration.

Figure 11 shows the Cost of Travel (COT) of swimming animals as presented by Gemmell. Aurelia Aurita, a type of jellyfish, has a propulsive advantage over other swimmers. Thus, biomimetic tensegrity structures will be able to efficiently explore ocean worlds. Gemmell demonstrates that this advantage decreases as the weight of the animal increases. This insight informs the sizing of the tensegrity explorer. Ultimately, the propulsive advantage of jellyfish locomotion is outweighed by fish-like locomotion at a wet mass greater than 100kg. For example, a moon jellyfish swims about 3.5 times more efficiently per unit energy than salmon. Jellyfish achieve this propulsive efficiency by creating a region of low pressure in the water ahead of them, functionally pulling themselves through the water. [17]

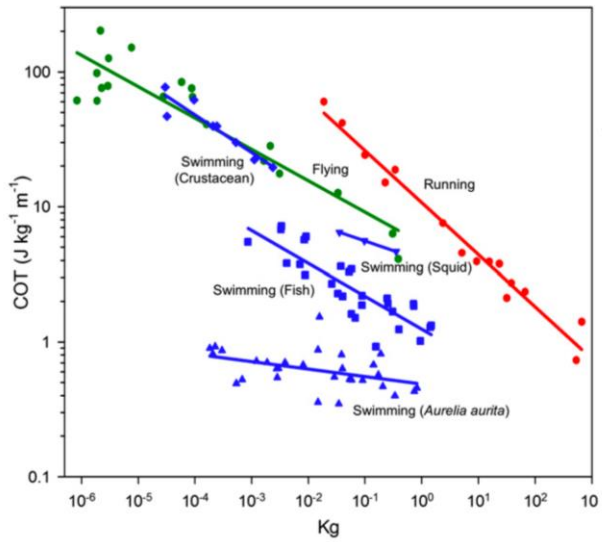


Fig. 11 Cost of transport based on wet mass classified by eneregetic swimming methods. [17]

Recreating this type of locomotion within the structure is feasible in numerous ways. Unlike actuating a tensegrity over a rocky surface, which is often achieved by the actuation of three or more tension members: Swimming motion may only require two actuated degrees of motion. Control of the center of mass (1 or 2 DOF needed) and control of the bell action. Key aspects to recreating the Jellyfish locomotion are:

1. Symmetry in the bell and complete bell contraction
2. Alternating action of relatively fast contraction and slow recoil
3. If lobes in the bell exist, the boundary layers should span the gap between any lobes [18]

Passive exploration is another means of data collection that should be discussed and explored further. Deploying a distributed network of unactuated probes across a large surface lake would provide spatial resolution to data collection, allowing for better understanding of any currents in the surface lakes.

F. Other Ocean Worlds

While the surface lakes of Titan are the primary focus of this mission, the ability to explore subsurface oceans is relevant to the exploration of Titan's subsurface ocean and other ocean worlds such as Europa. The tensegrity lander is not equipped with the ability to drill or melt through the ice to access the oceans. However, if a complementary system were able to drill through the surface, a tensegrity swimmer probe would be able to constrict itself to fit in a narrow passage and then deploy once it reached the ocean.

V.Conclusion

Tensegrity probes have a great potential for use exploring various ocean worlds. Ocean world exploration is currently a priority in the search for life beyond Earth. On Titan, their use should be expanded to exploration of the surface lakes. Descent, landing, and submerged exploration are all feasible and validated using testing, analysis, and literature review. The Huygens probe sets a historical precedent for the orbital transfer to the moon. Past studies have explored atmospheric entry using a deployable tensegrity structure. Descent analysis and testing have shown that a terminal velocity of 15 m/s or less is reached on Titan for a 1m diameter tensegrity structure depending on the structure geometry. Once the structure has landed in the surface lakes on Titan, locomotion will begin allowing for science data to be collected. Science goals have been outlined by the NASA Outer Planets Assessment Group.

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