AIAA SciTech 2019

Tensegrity Ocean World Landers

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California Institute of Technology

Pre-Decisional Information – For Planning and Discussion Purposes Only

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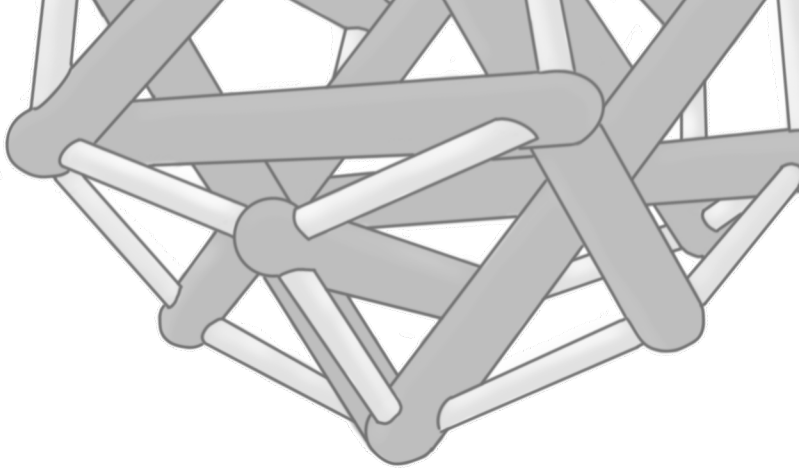
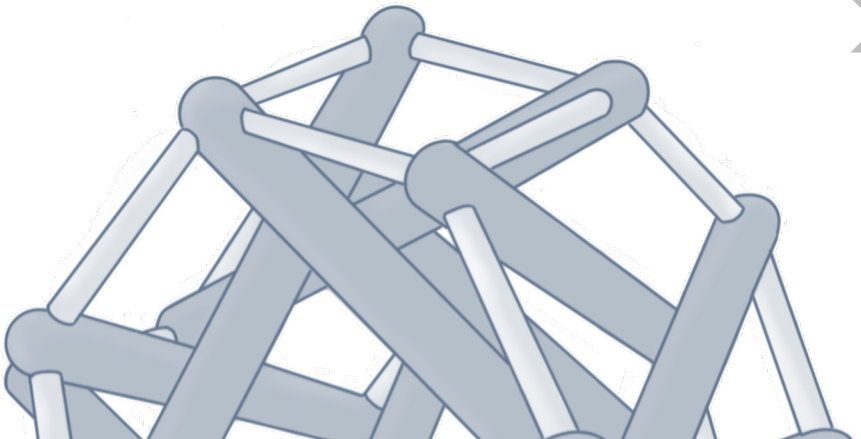


Tensegrity Structures

Ocean Worlds and Titan

Mission Concept

Analysis and Test

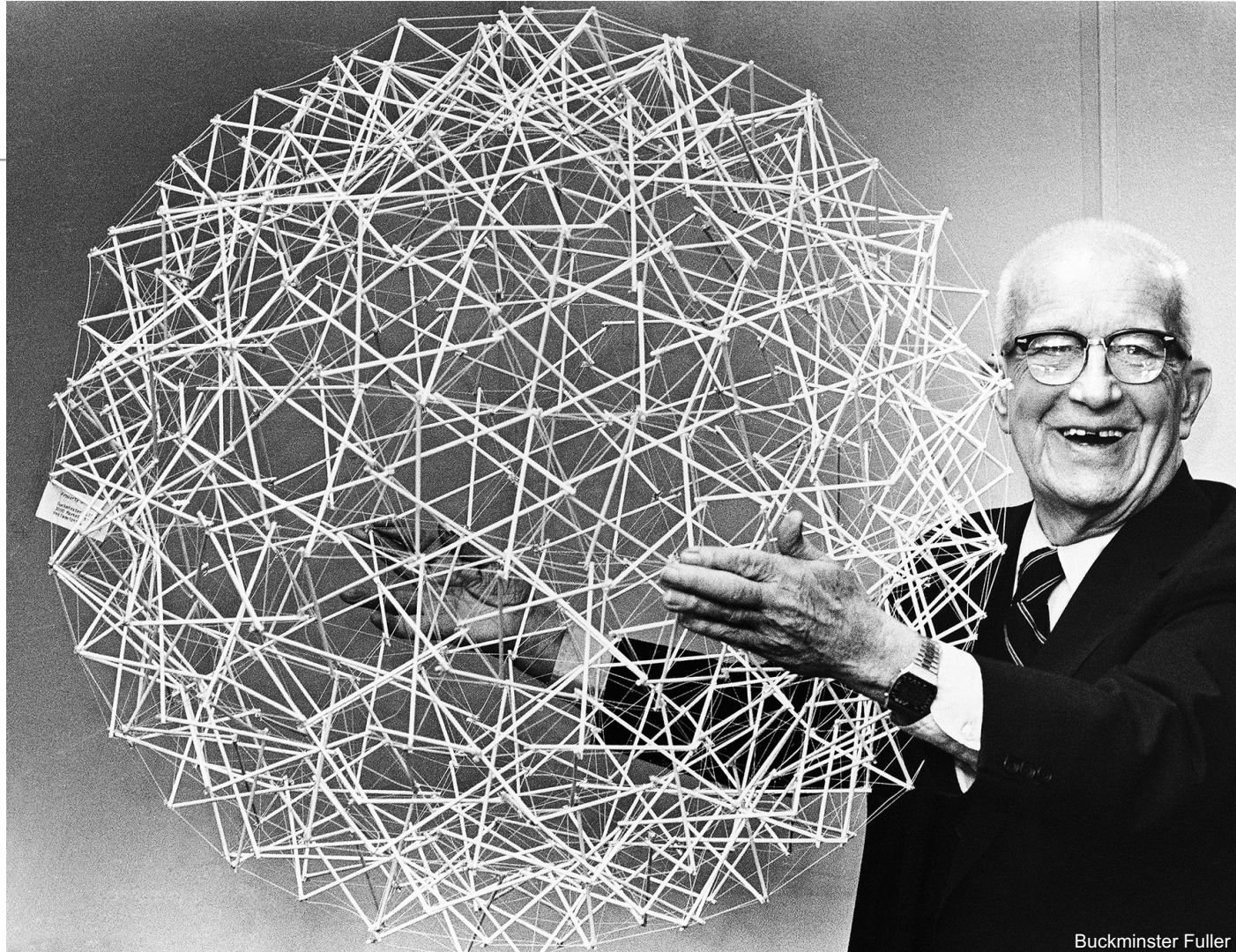


Tensegrity

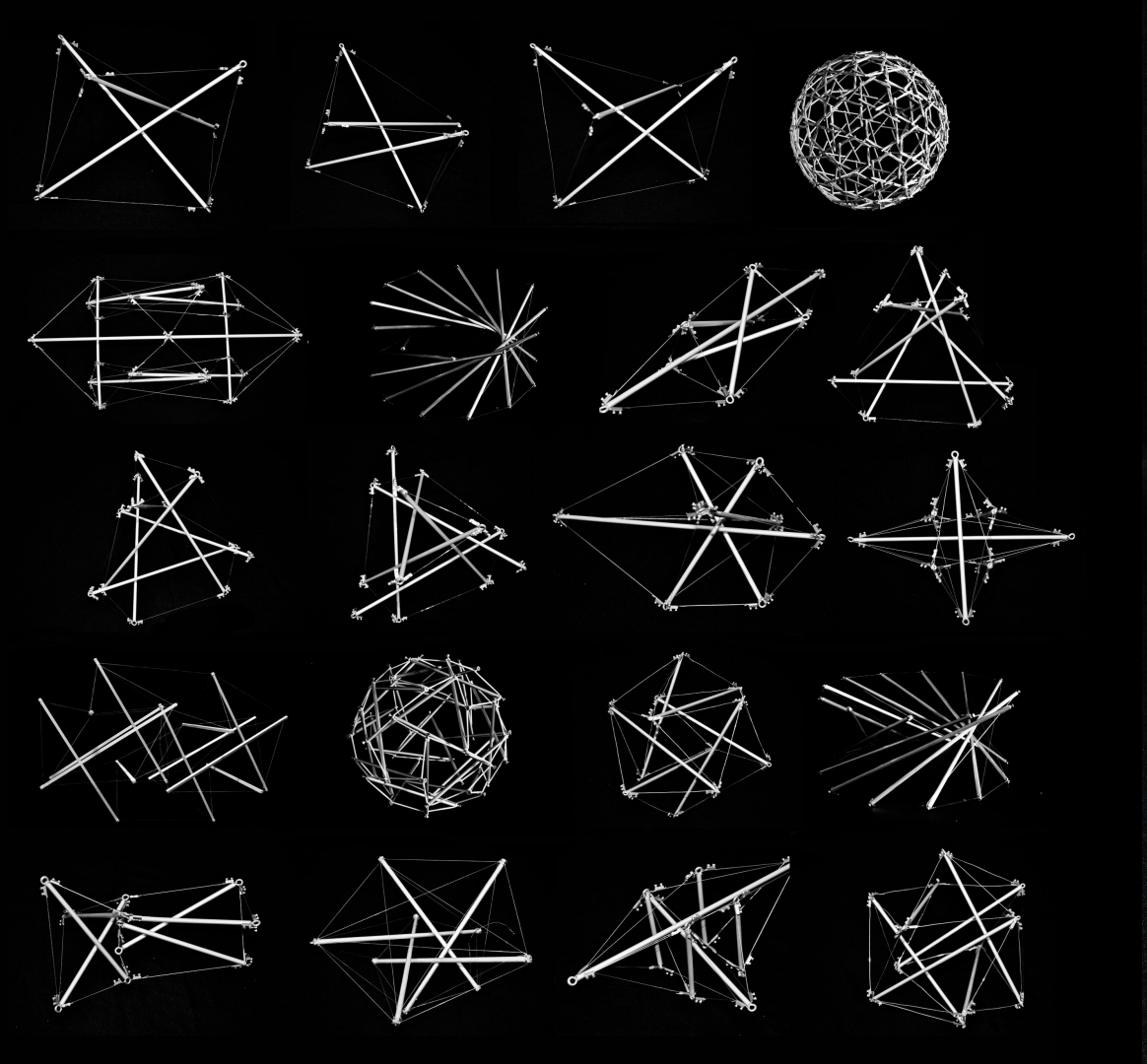
Compression members suspended within a network of tension members.

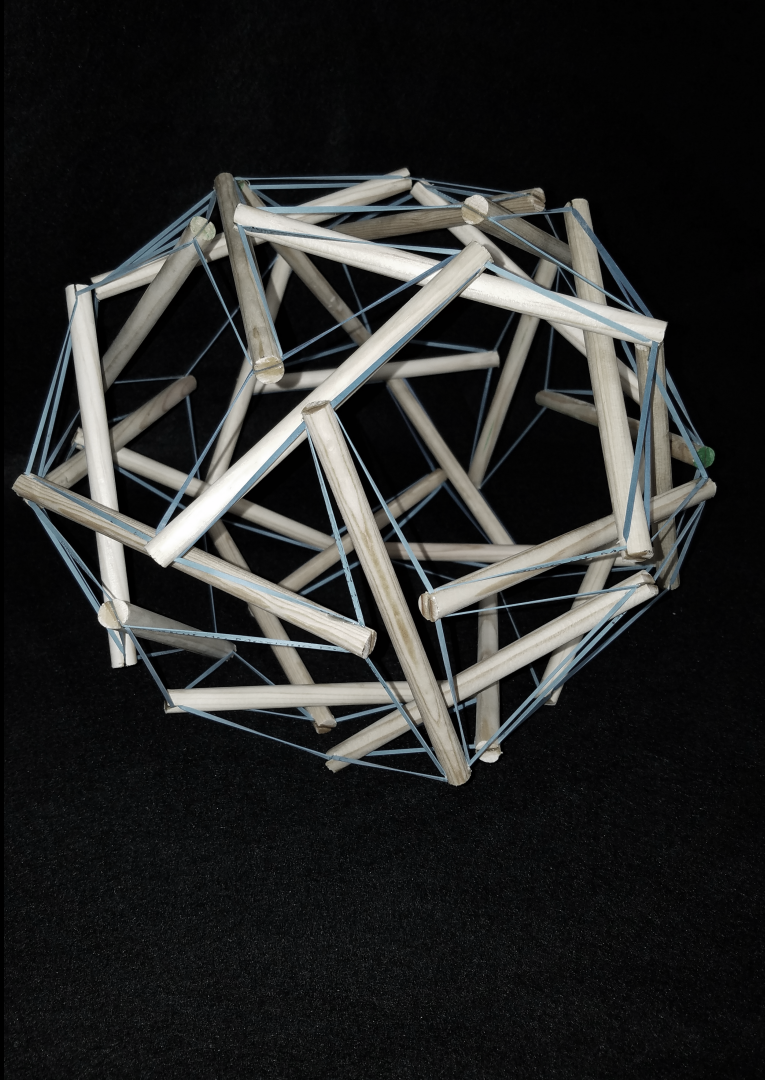
Biomimetic structural inspiration.

Applications scale from sculpture, architecture, and engineering.

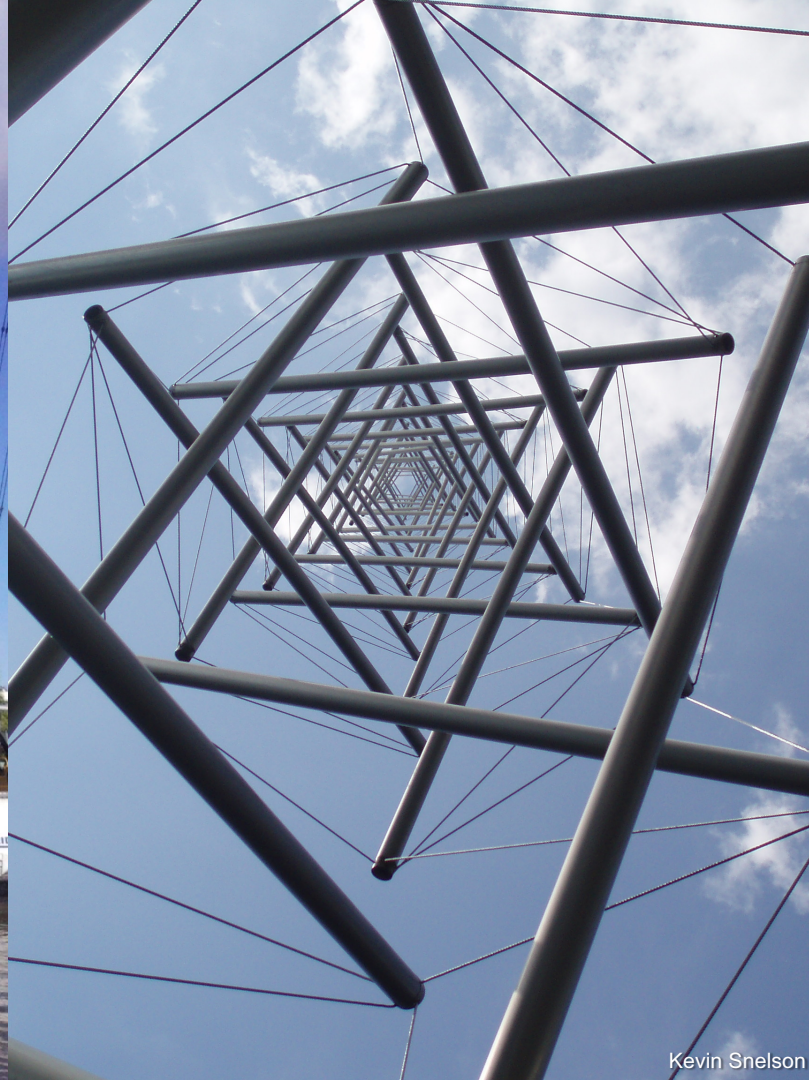


Buckminster Fuller



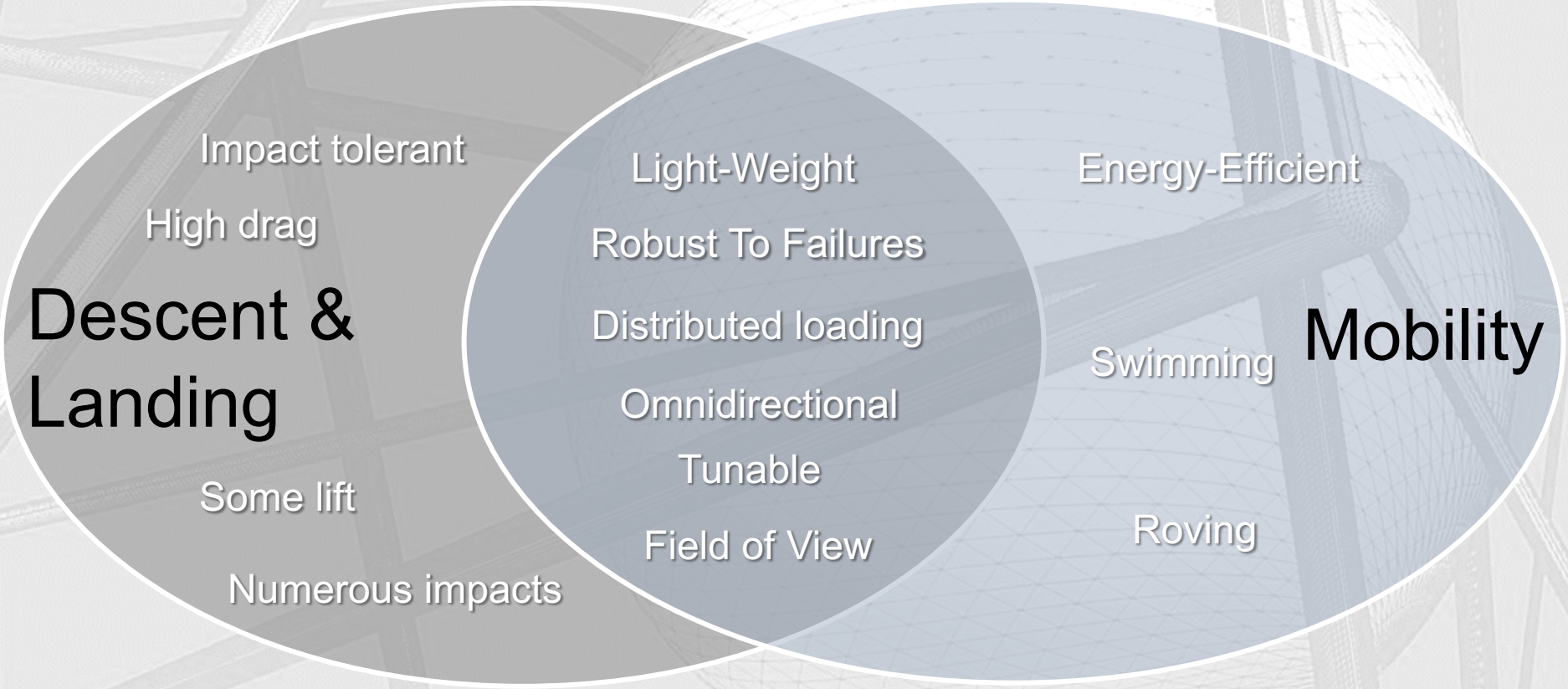


Kurilpa Bridge, Brisbane, Australia



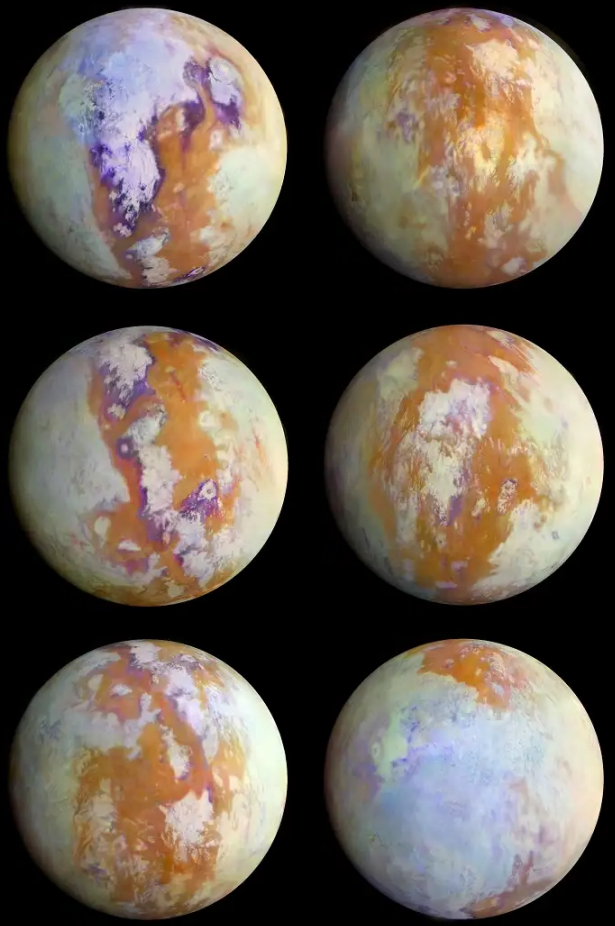
Kevin Snelson

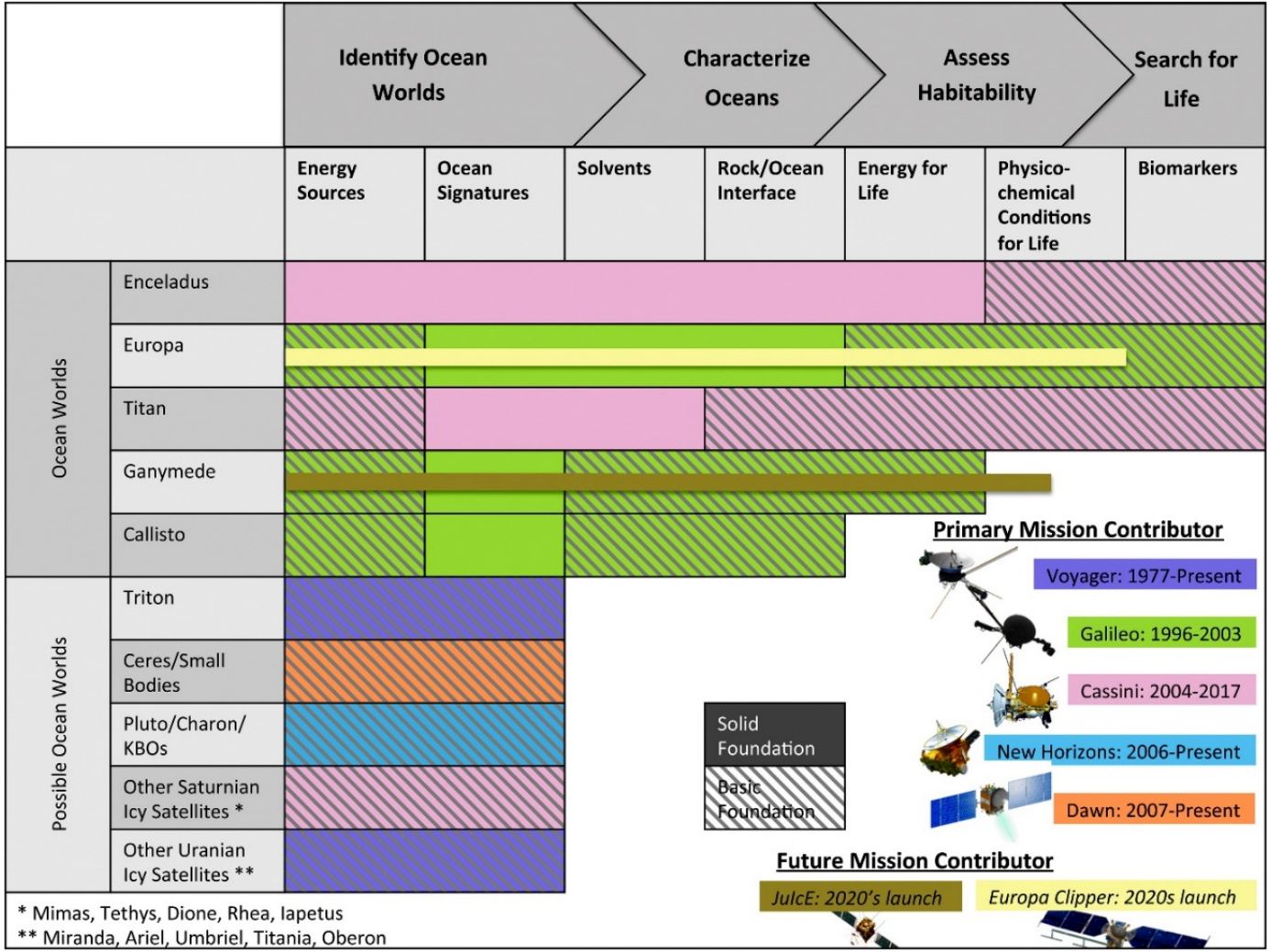
Tensegrity Characteristics



Ocean Worlds

- Ocean worlds are planetary bodies with known current liquid oceans.
  - Enceladus, Europa, Titan, Ganymede, and Callisto
  - Other worlds are suspected, not confirmed: Triton, Pluto, Ceres, and Dione
- 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 and study any life found.
- NASA Outer Planets Assessment Group (OPAG) have determined that in-situ investigation is required for the comprehensive exploration ocean worlds.
  - Exploration goals are echoed in the 2013-2022 Planetary Science Decadal Survey.





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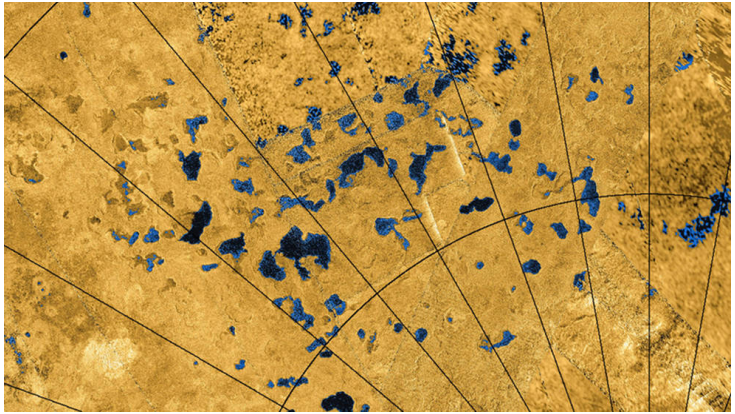
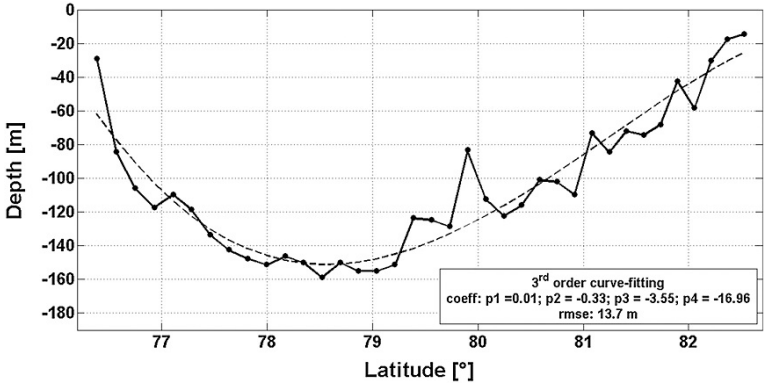
Titan

- Surface lakes in the north region of the planet as well as the subsurface ocean.
- Surface lakes of Titan, composed of liquid ethane and methane
  - Detected by the Cassini-Huygens space probe and Hubble Space Telescope.
- Titan's methane lakes are part of the methane cycle. similar to Earth's water cycle.
- Surface temperature of Titan -180 Celsius. The lakes estimated to be -183 C.
- The NASA Outer Planets Assessment Group has recommended an orbiter, an atmospheric probe, an aerial mission, a submarine, a deep drill, and a lake lander.





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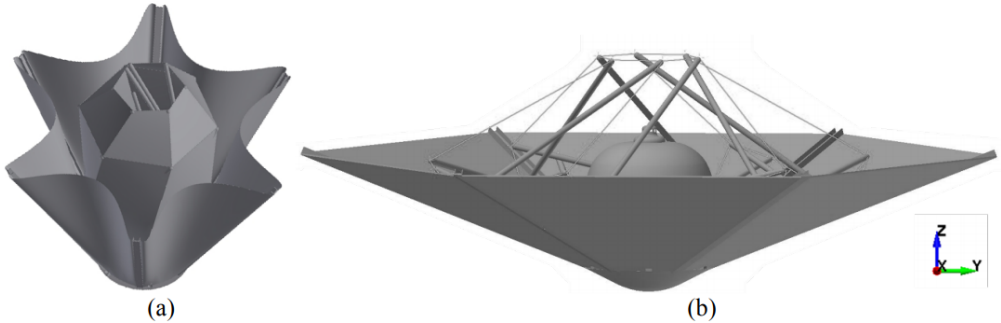
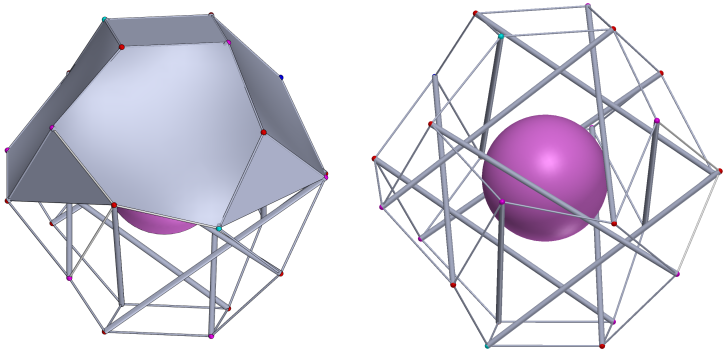
Mission Concept

- Orbital transfer precedent from Huygens probe
  - 8-10 year transit
  - Atmospheric
  - 2.7m diameter heat shield
- Descent analysis shows terminal velocity of 3.65 m/s with bell and 15.6 m/s without bell.
- Landing directly into Titan surface lakes
- Swimming locomotion allows for efficient exploration





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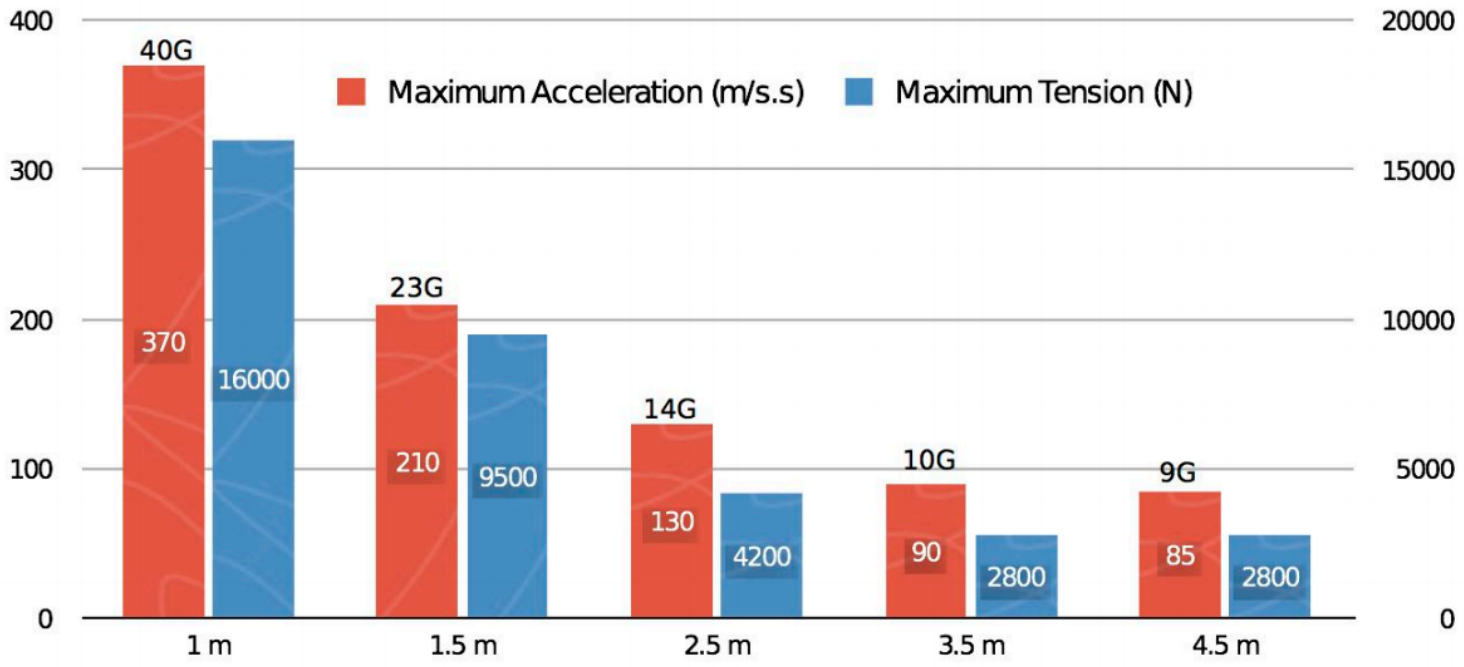
Relationship between acceleration and structure tuning



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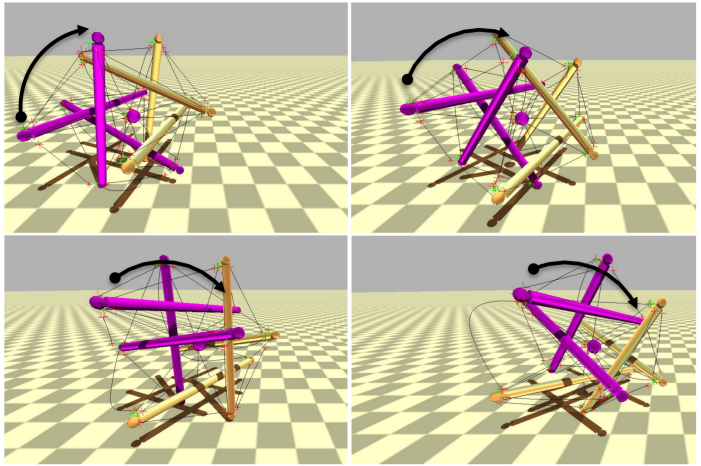
Rolling Locomotion

- Redundant to cable loss
- Capable of rolling uphill
- Studied in NIAC at Ames
- Numerous methods (CG, lengths, ect.)



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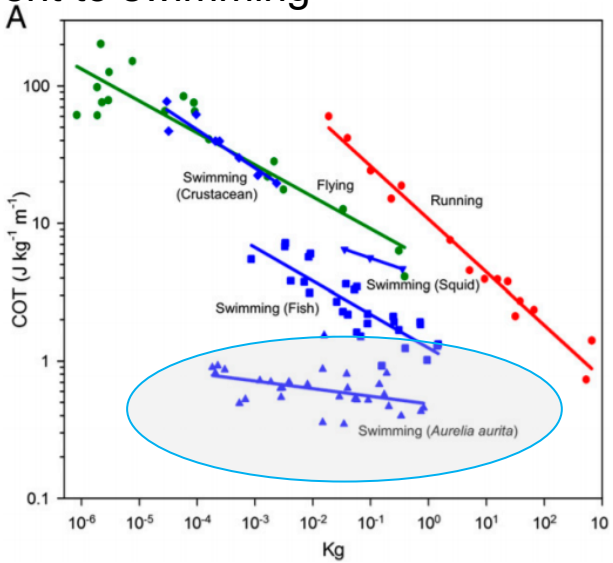
Swimming Locomotion

- Jelly fish locomotion is most efficient form of locomotion up to a weight limit
- Reynolds number difference from descent to swimming



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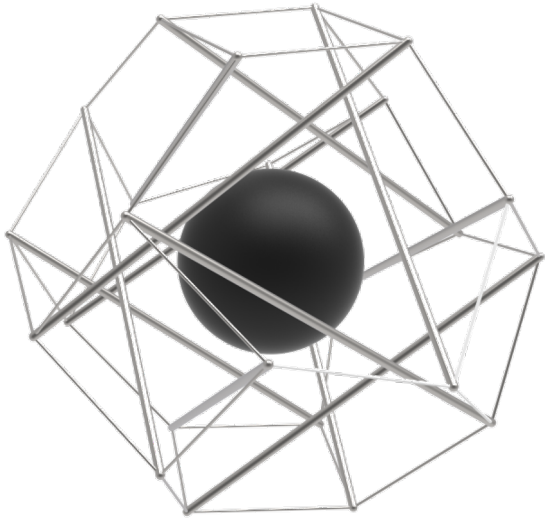
Descent and Landing in our Solar System

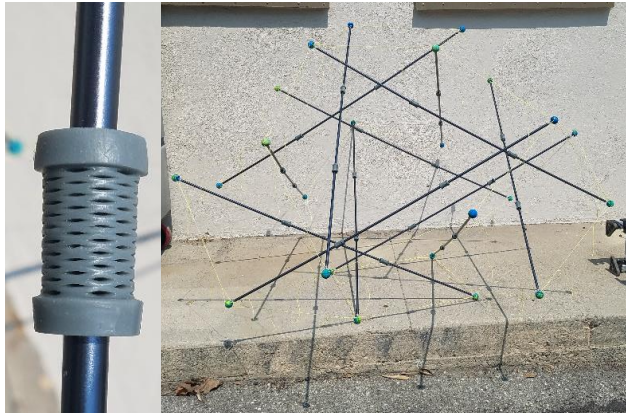
Measure	Units	Earth	Titan	Europa	Miranda	Mars	Moon	Ceres
Reynolds Number	**N/A**	1,000,000	200,000	Negligible atmosphere	Negligible atmosphere	.000025	Negligible atmosphere	Negligible atmosphere
Drop Height	**m**	11,000	40,000	10,000	10,000	7,000	10,000	10,000
Terminal Velocity	**m/s**	620.	15.6	Negligible 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)		

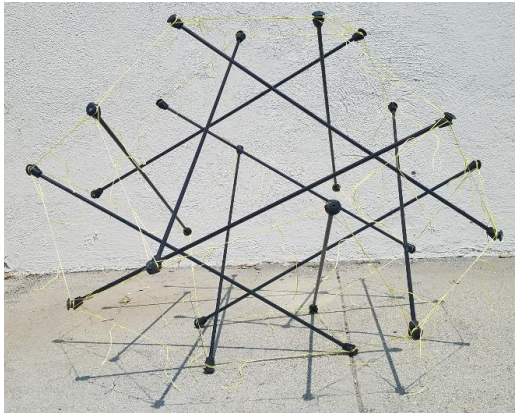
1m class 20kg probe.

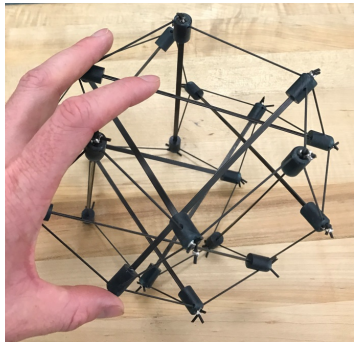


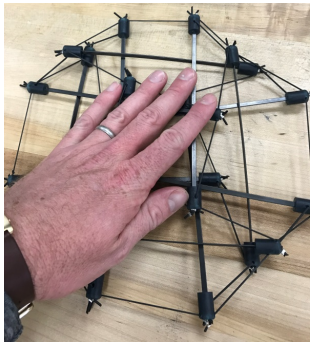
With help from Anna Woodmansee, JPL

Prototyping

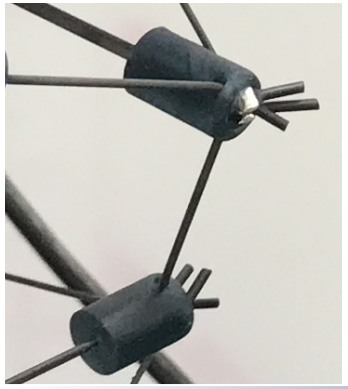


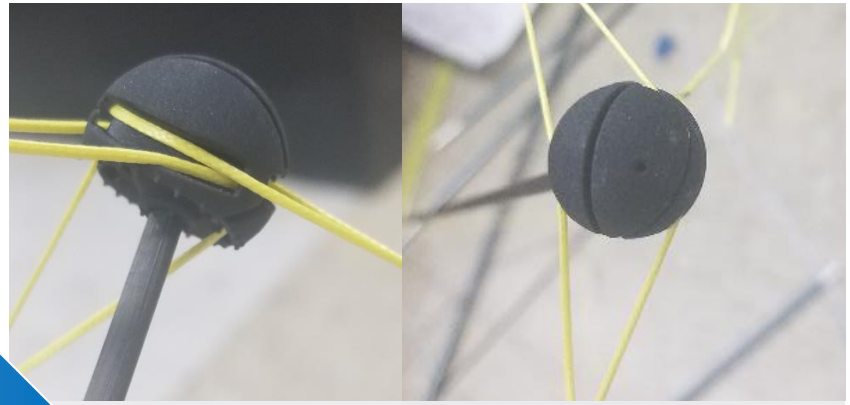






Joint Design

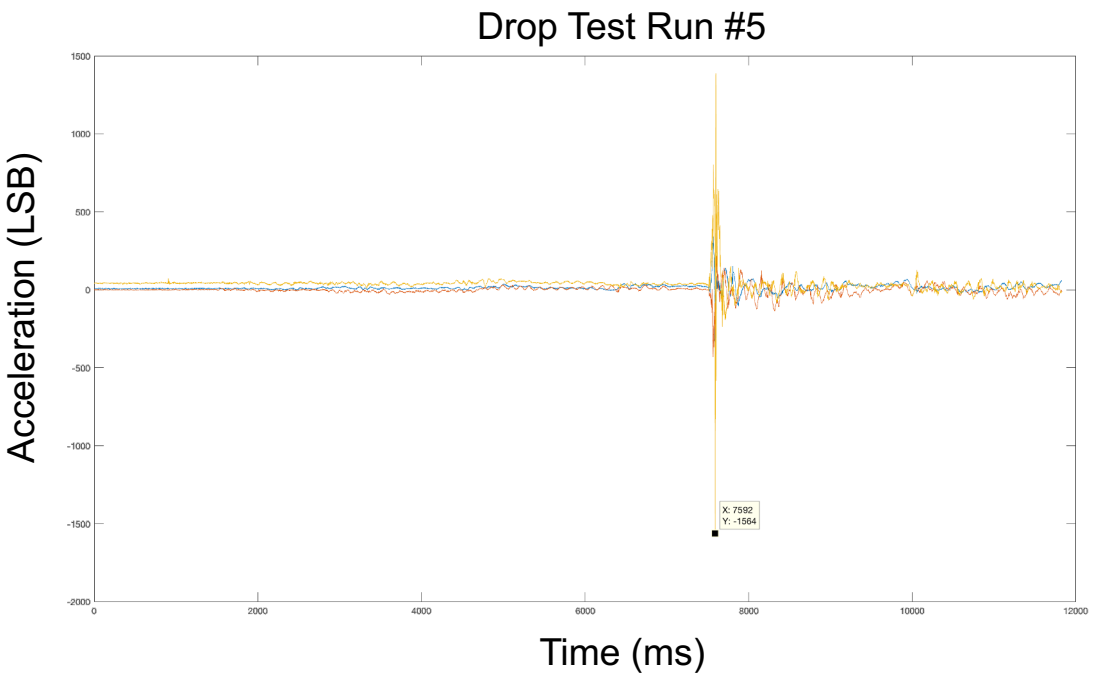




Some images and design by Julie Kraus, Georgia Tech/JPL

Test data

- Initial testing with a brittle Kevlar tensegrity
- Peak of 75 g's on impact
- Confirmation that elasticity and buckling of compression members is very important to lowering impact loads
- Payload environments need to be fully defined



0.014 m
MFG
y=0.000
axes selected (set angle to ch

The Tensegrity Team

- Kalind Carpenter (JPL)
- Julie Kraus (JPL/Georgia Tech)
- Dr. Samuel Case Bradford (JPL)
- Dr. Julian Rimoli (Georgia Tech)
- Dr. Doug Hoffman (JPL)
- Anna Woodmansee (JPL)
- Collaborators at Ames Research Center

Jet Propulsion Laboratory
California Institute of Technology

Academic References

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Image Sources

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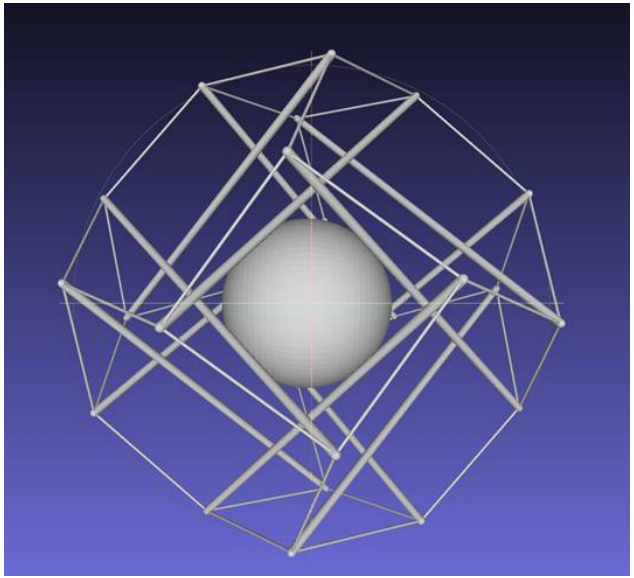
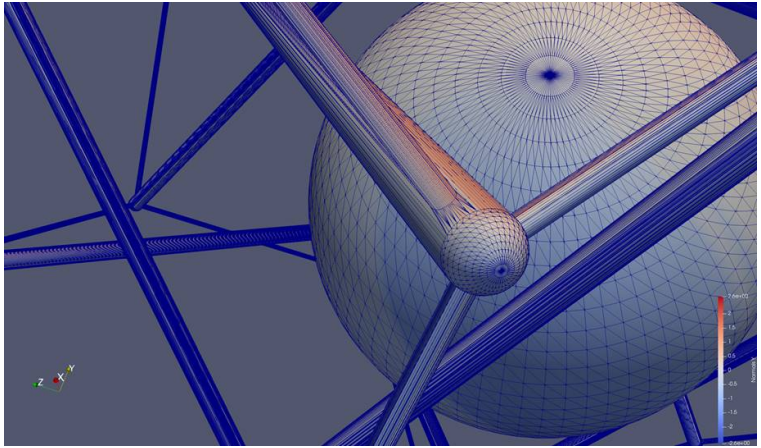
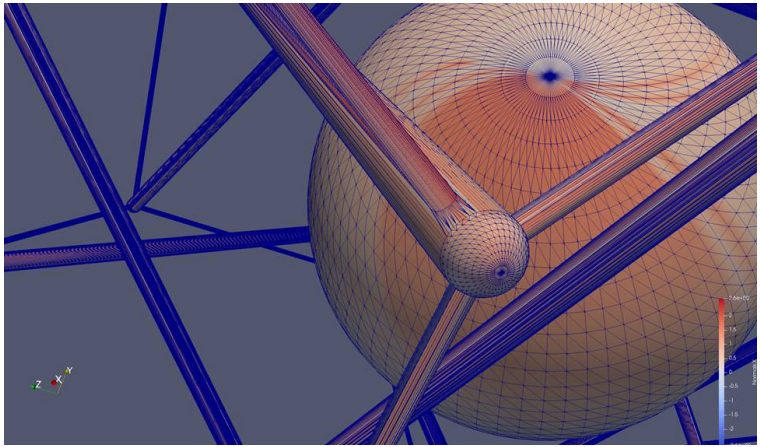
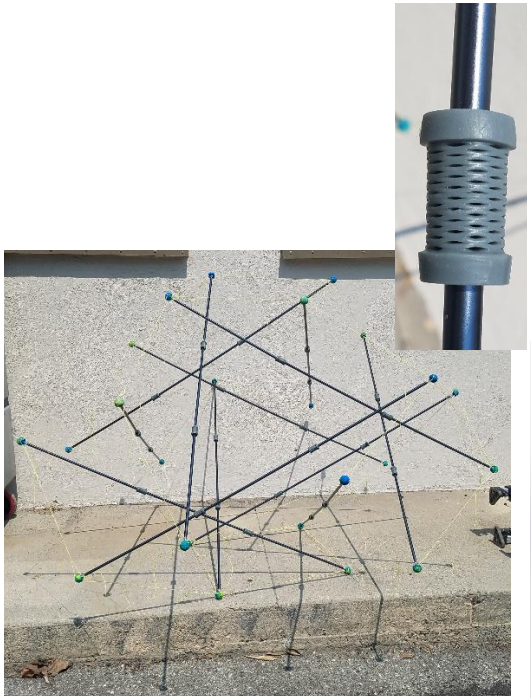
CFD Pictures

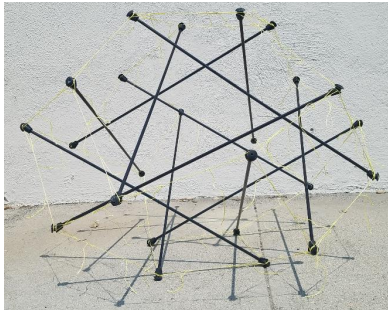


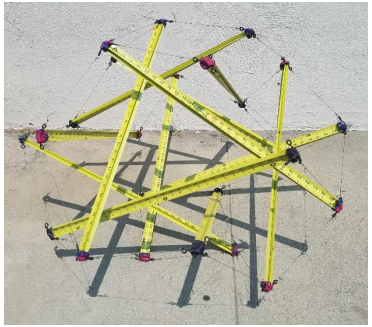


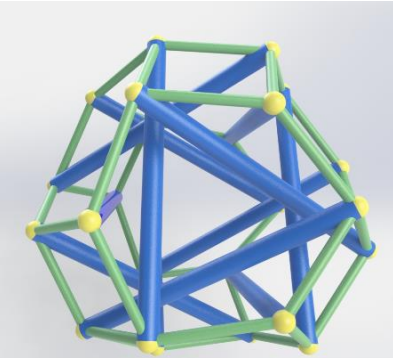


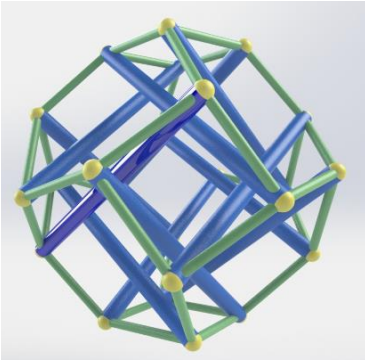
Structure Pictures

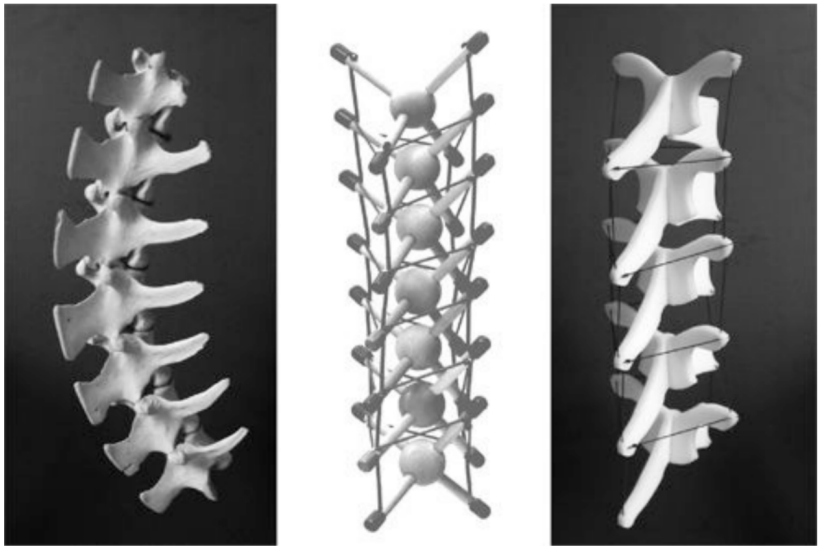


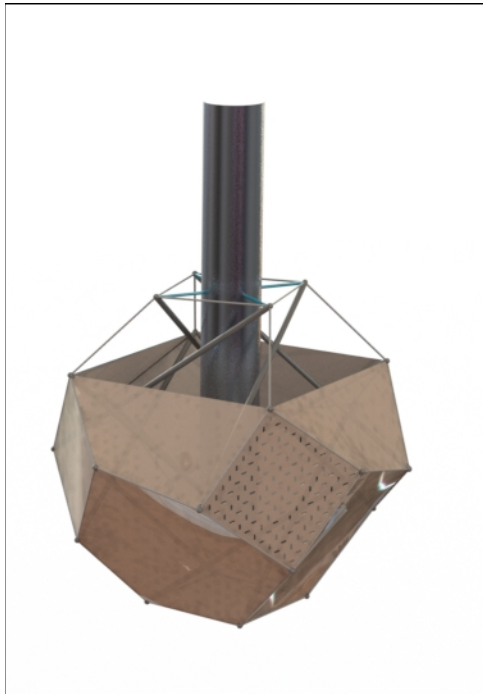












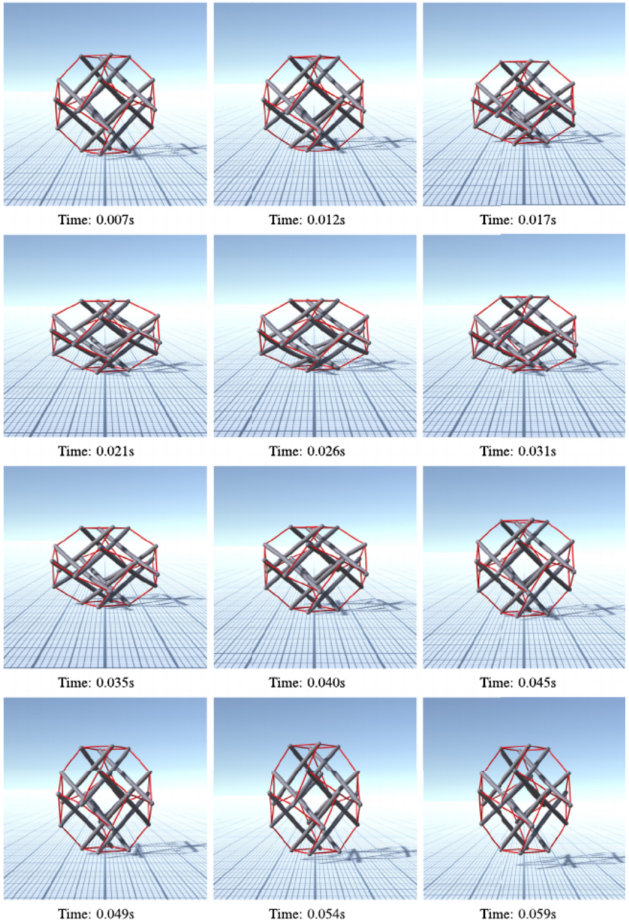
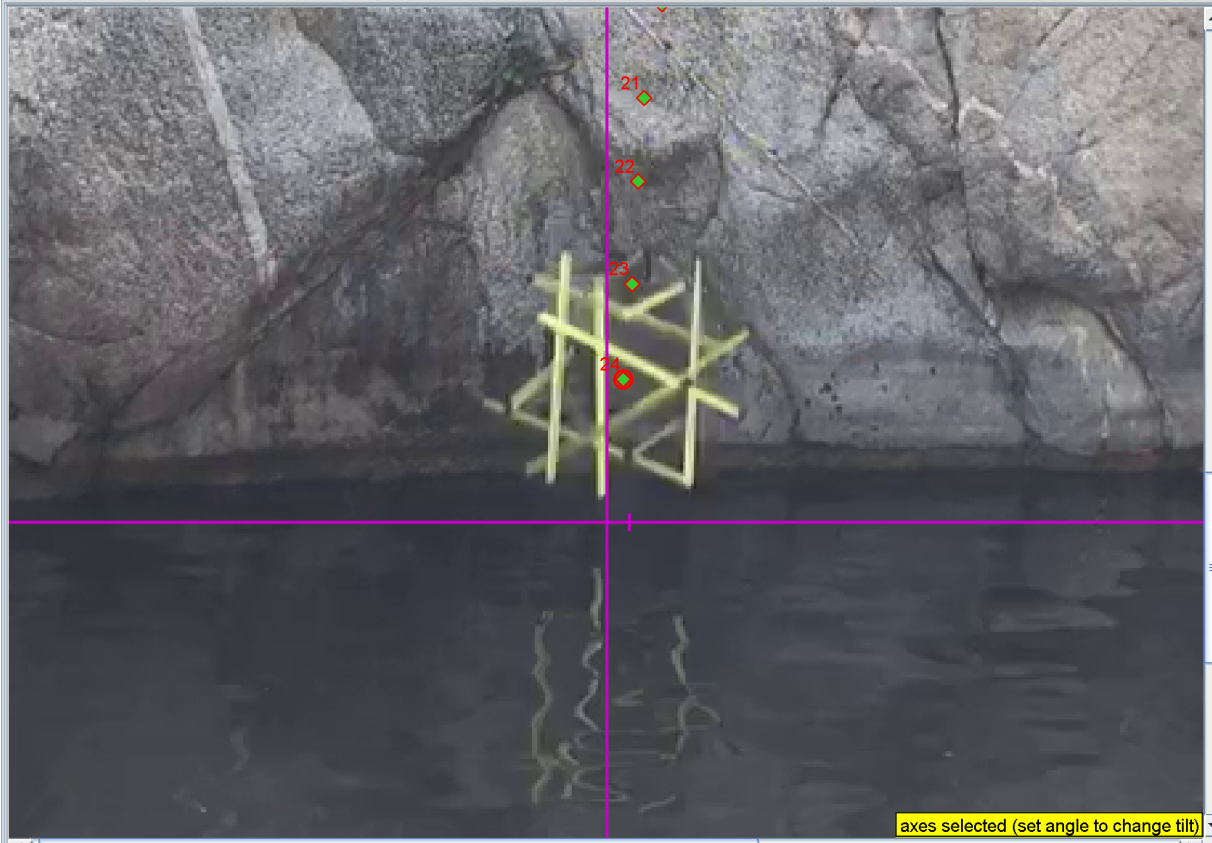


Fig. 10. Temporal evolution of a virtual drop test for a tensegrity lander with impact velocity $v = 12$ m/s and pre-stretch $\lambda = 0.996$.

- The initial contact load is lower than the peak load, implying that loads on bars reach their maximum value at the instant in which the lander is most deformed.
- Once the impact event ends, the lander exhibits a motion which results from the combination of low frequency worm-like oscillations and higher-frequency beam bending vibrations.
- The frequency of the worm-like oscillations increases as the impact speed augments.
- The peak load tends to saturate around the value of the bar buckling load as the impact velocity is increased.

axes Grid origin pixel positi... 230.3 914.6 angle from horizontal 0.0°

Now available: version 5.0.6 memory in use: 74MB of 247MB



433 70% 1

Plot mass A

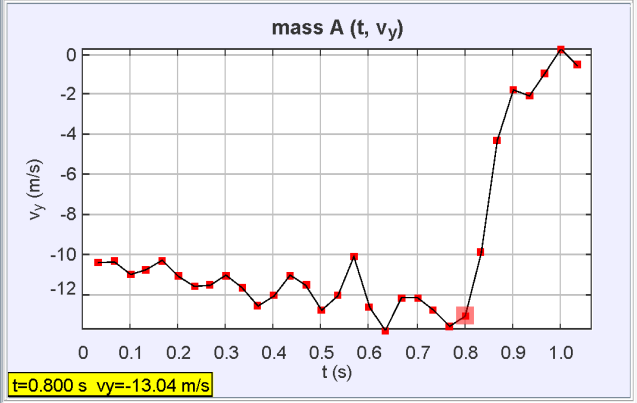


Table mass A

t (s)	x (m)	y (m)
0.333	0.686	6.372
0.367	0.611	5.957
0.400	0.577	5.536
0.433	0.537	5.156
0.467	0.509	4.803
0.500	0.448	4.388
0.533	0.387	3.954
0.567	0.380	3.587
0.600	0.353	3.281
0.633	0.299	2.744
0.667	0.251	2.364
0.700	0.170	1.936
0.733	0.143	1.556
0.767	0.115	1.087
0.800	7.472E-2	0.652

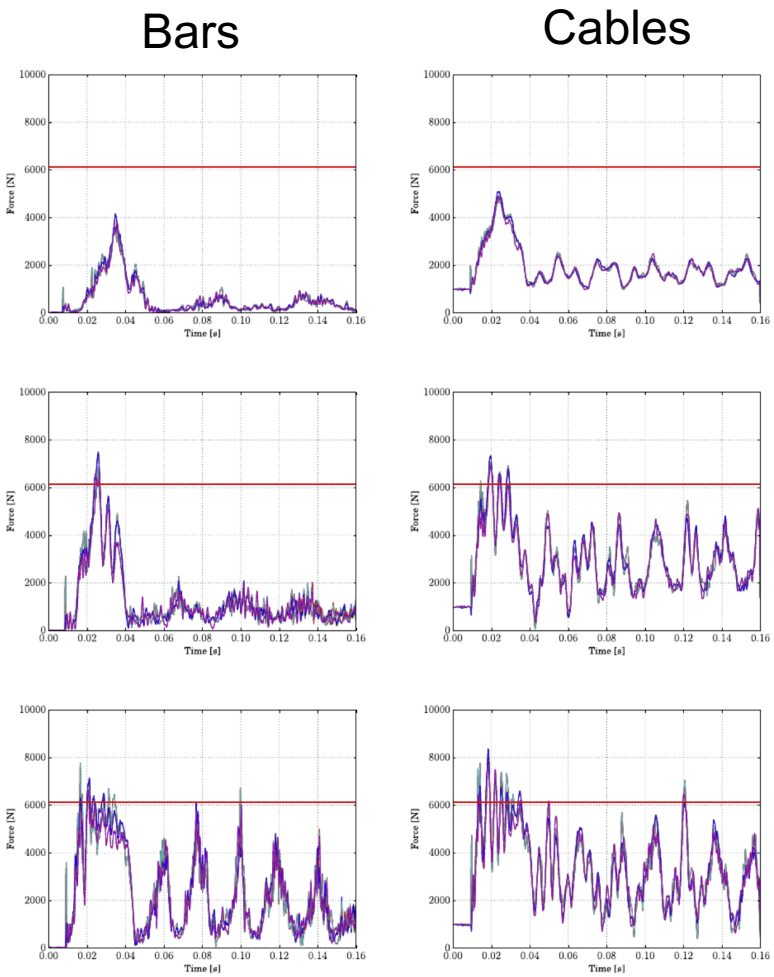
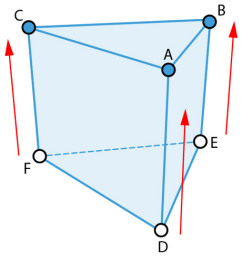


Fig. 11. Force history on bars for different impact velocities and cable pre-stretch levels. (For interpretation of the references to color in the text, the reader is referred to the web version of this article.)

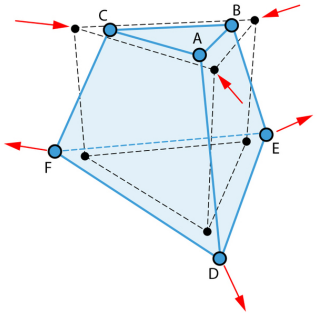
Module variations

Extrude 90 - 110%



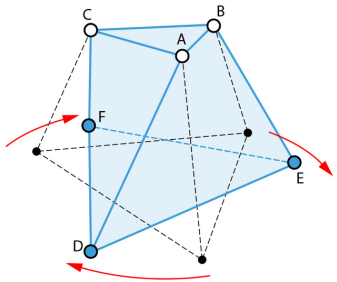
The hight of the module informs the depth of the envelope.

Scale 10 - 20%



The scale of the top and base informs the degree of curvature.

Rotate 30° - 40°

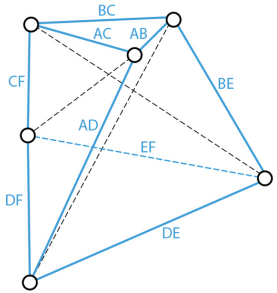


The rotation of the module is a result of tension in the tensegrity system.

http://ad009cdnb.archdaily.net/wp-content/uploads/2014/10/542db8f4c07a80c9ea00042e_students-of-ball-state-construct-parametric-tensegrity-structure-for-local-art-fair_005_module_variation.jpg

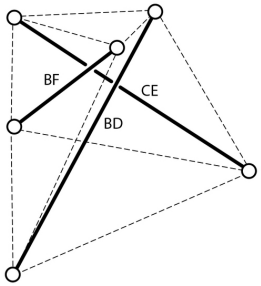
Module components

Cables



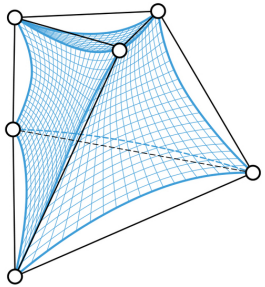
The two triangles with their connections form a closed network of continuous tension.

Struts

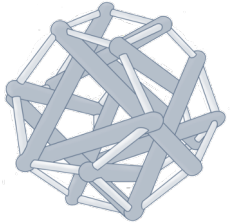
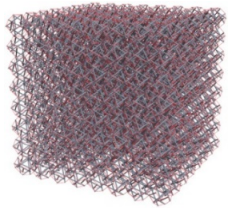
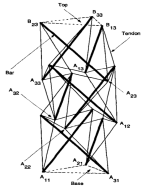
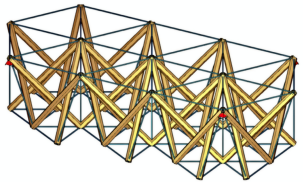
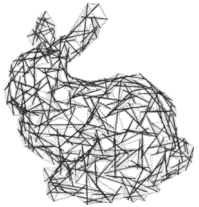


The aluminum struts inside this network of cables are in pure compression

Fabric



The fabric is added after the modules are assembled.

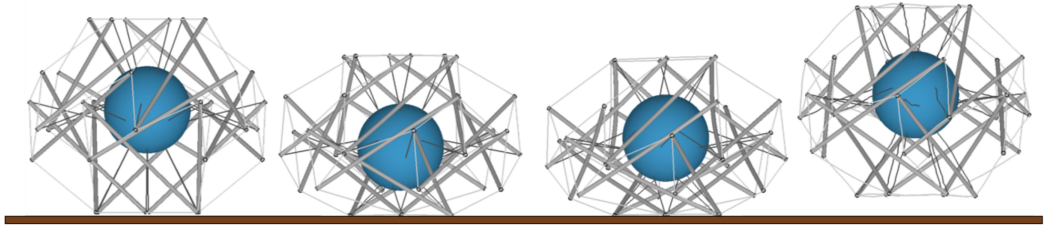






	Spherical	Lattice Spherical	Tower	Oblate	Freeform
Descent	• Somewhat directionally agnostic • Low terminal velocity	Extremely complex to model	• Higher terminal velocity • Known aerodynamic orientation	Known aerodynamic orientation	Dependent on geometry
Landing	• Somewhat directionally agnostic • Impact 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

Basis

Where does tensegrity fit in?

- Opportunity rover airbags
- Opportunistic exploration
- Swarms
- Small to mid-sized landing scenarios
- Multiple Impacts



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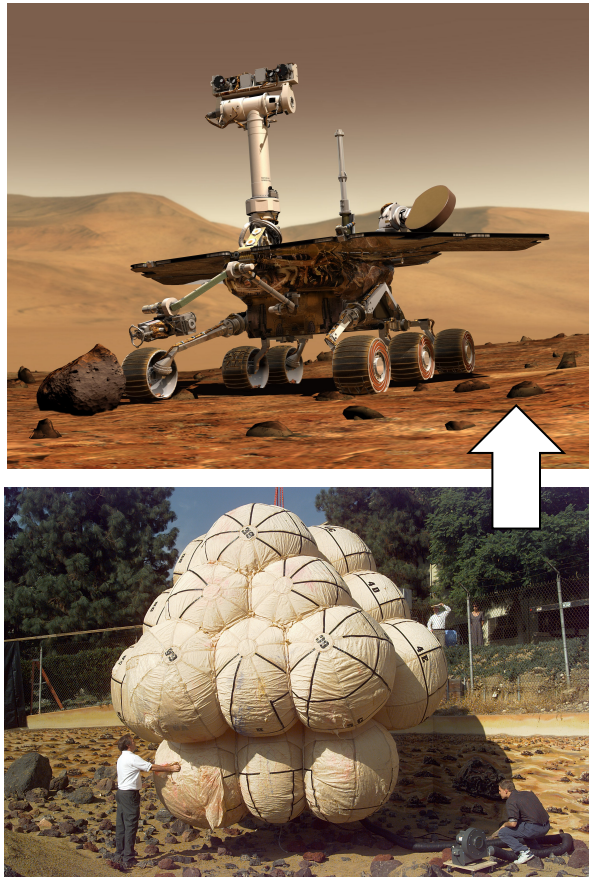
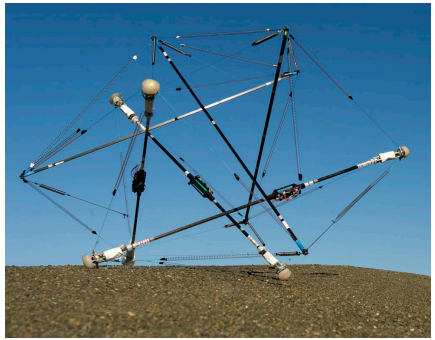
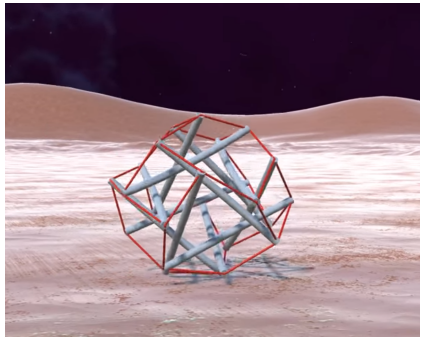
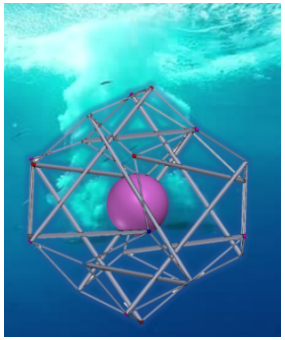
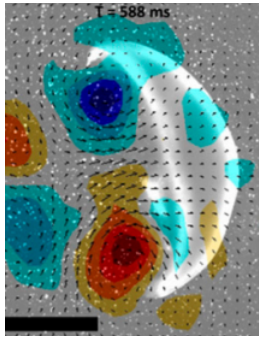


Icy/Rocky Worlds

- End-to-End exploration solution
- Impact resistant
- Robust locomotion architectures
- Low terminal velocity
- High payload mass fraction
- Can sustain numerous impacts





Ocean Worlds

- End-to-End exploration solution
- Payload is protected without the obstruction of a full enclosure, allowing for constant data collection
- Efficient locomotion underwater
- Low terminal velocity