The Space Elevator Concept and Dynamics

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Abstract. The Space Elevator or Space Lift is a radical technology for accessing space and the ultimate Earth-bound slender structure. The concept was first published in 1960 and was subsequently popularized in science fiction stories. After the discovery of carbon nanotubes in 1991 and subsequent calculations and measurements of their strength, the Space Elevator concept moved from the realm of science fiction to science possibility.

The Space Elevator is conceived to be a carbon nanotube ribbon stretching from an Earth station in the ocean on the equator to far beyond geosynchronous altitude. This elevator co-rotates with the Earth. Climbers ascend the ribbon using power beamed from Earth to launch spacecraft in orbit or to other worlds. The requirements of the ribbon material, challenges to the building of the space elevator, deployment, oscillations, design variations and the promise of the space elevator are briefly discussed in this paper.

1 INTRODUCTION

This paper begins with a description of the space elevator (SE) based upon the conceptual outline described in the book, *The Space Elevator*[1] by Edwards and Westling. This concept involves a meter-wide carbon nanotube (CNT) ribbon thinner than a sheet of paper that extends from a point on the Earth's equator to 100,000 km above that point to a counterweight. To use the ribbon to access space, mechanical climbers ascend the ribbon laden with payloads. Power for these climbers is expected to be beamed from the ground in the form of infrared, laser energy.

The center of mass of the system resides near geosynchronous altitude, thus the system co-rotates with the Earth. The counterweight, in uniform circular motion around Earth, provides a restoring force. At geosynchronous altitude the ribbon is widest because the forces are greatest. Below geosynchronous Earth orbit (GEO), the net force on a ribbon segment is toward the earth and the tensile strength of the segment must support all below it. For a ribbon segment above GEO, the net force is away from Earth and a segment must hold all segments beyond itself. As a climber ascends the ribbon, tension in the ribbon provides a restoring force that continually increases the angular momentum of the climber.

The SE system is analogous to a railroad and is subject to the economy of scale. Once the rails are laid, the cost to transport across the system is low. Chemical expendable rockets cost approximately $10,000 per kilogram to low Earth orbit (LEO). With the SE system, it is expected that the cost to LEO would fall by a factor of 3 with the first elevator, and later fall by factors of 10 and 100 as a space elevator infrastructure of larger capacity elevators are constructed. The cost to middle Earth orbit (MEO) and GEO would decrease by a greater factor. This dramatic drop in launch costs enabled by a space elevator infrastructure will enable the exploitation of space to solve Earth's problems.

The SE is a new paradigm for accessing space and as such is an enabling technology. Commerce in space including power generation, tourism, manufacturing, mining and commercial/government exploration will be developed because transportation will have dropped to a small part of the cost of the enterprise.

2 HISTORY AND MATERIALS

Many individuals may have conceived of an SE since the concept is a part of human consciousness. The Tower of Babel, Jack and the Beanstalk and references to "stairways to heaven" have existed for a long time. More recently, the academician, Konstantin Tsiolkovsky, a Pole living in Russia around 1895, wrote of towers extending from Earth up into the cosmos while visiting Paris and seeing the Eiffel Tower. In 1945, Sir Arthur C. Clarke patented the geosynchronous satellite and pointed out its usefulness for communications. There is a report that an American, John McCarthy, studied a "Skyhook" in the early 1950s.

The first published discussion of an SE-like structure was by the Russian engineer Yuri N. Artsutanov[2]. In 1960 he published a short article in *Pravda* for children. The concepts and numbers presented in this article make it clear that he understood the concept and had done calculations to back up his statements. The first journal article was published by four scientists from Woods Hole Institute[3] in 1966. Presumably the long cables that oceanographers used to explore ocean trenches inspired the authors to apply this technology to space. The last person to discover the space elevator was Jerome Pearson in 1975. Pearson published the most detailed physical study[4] at that time and has continued to investigate the concept up to the present.

These discoverers understood the promise of the SE. But they all recognized that no material existed that was strong and lightweight enough to manufacture the SE ribbon and make the SE a reality. Therefore, the SE existed in many forms in science fiction for many years[1].

In 1991 Iijima[5] discovered carbon nanotubes. CNTs have been reported theoretically to possess a tensile strength in the range of 300 GPa[6-7]. The Earth SE ribbon requires around 100 GPa of tensile strength minimum[1]. An actual ribbon would be built with strength contingency so consider 130 GPa or higher as the required strength. Thus, this new CNT material offers, for the first time, the possibility of building an SE ribbon.


В космос —
НА ЭЛЕКТРОВОЗЕ

Figure 1 The first Space Elevator article in Pravda

A macroscopic SE ribbon could be formed with CNTs by spinning individual fibers or by forming CNTs into a composite material. CNTs are essentially inert and do not want to form bonds between them. Only weak, ionic Van der Waals bonding operates between the individual CNTs. Its source is the electrical “landscape” on the surface of a CNT and are additive in the sense that the more and more regions along a CNT that are experiencing Van der Waals forces, the stronger the overall attraction. Spinning of nano-scale CNTs requires long tubes (possibly millimeters or centimeters) so that the weak Van der Waals forces are effective over a length sufficient to provide strong bonding between tubes. Handling nano-scale fibers is a challenge so spinning CNTs into micron size threads is another option. Using CNT composites to form the ribbon possess other challenges that include the chemical bonding of the CNTs to a matrix material, achieving uniform distribution of CNTs throughout the matrix and the alignment of the CNTs in the matrix.

Whatever technique is adopted for the SE ribbon, the process must be adaptable to manufacturing so that 100,000 km of ribbon can be fabricated in a timely fashion. Indeed, realizing the fantastic physical properties of a single CNT in a macroscopic assemblage of CNTs is currently impossible, but undergoing intense research. Currently, CNTs are an expensive material from which to make any macroscopic object because a typical cost for 5 micrometer long, single walled CNTs is around $12 per gram! The cost of CNTs must drop dramatically before an 800-ton SE cable can be manufactured cost effectively.

3 DEPLOYMENT SCENARIOS

In 1999 NASA held a conference on the SE. The scenario that emerged from the meeting was similar to Arthur C. Clarke's scenario in the Fountains of Paradise: an asteroid would be captured and placed into GEO around the earth. The carbon on the asteroid would be used to build a massive, CNT tower from the asteroid down to Earth's surface. Four magnetically levitated trains would run up the tower at very high speeds, delivering people and cargo to the GEO station. The asteroid would end up slightly above GEO to preserve the center of mass residing at GEO and would act as a counterweight. One estimate of the time to realize this vision was 300 years! As an astronomer, the author of this paper can assure you that it would take at least 300 years to convince astronomers to let a large asteroid that close to the Earth!

Now there is a "bootstrapping method" being developed for the deployment of the first space elevator – a major effort no matter the method used. The basic plan is to launch the components, deployment spacecraft and pilot ribbon, into LEO. This will take many launches as even a narrow (about 20 cm) ribbon and its deployment spacecraft are massive. Modern rocket launch vehicles do not have the capacity to carry such massive payloads to LEO in a single launch. In LEO the system is assembled possibly with the help of astronauts. Then the system must be lofted to GEO above the desired point on Earth, probably the ocean on the equator about 300 km west of the Galapagos Islands.

Two possible scenarios are being considered to thrust the system to GEO. The first scenario is to launch all the fuel to LEO and use an efficient high specific impulse engine to rocket the system to GEO. This increases the required number of launches. The second scenario is to launch propellant for an engine (say an ion engine) and then beam the power up to the system from 3 or more power beaming stations floating on the Earth's oceans. These stations will eventually converge on the ground point and be used to power climbers up the ribbon. The second scenario will require fewer launches and will prove the capabilities of the power beaming system.

Once the system is at GEO over the ground station, the ribbon can be let out. The end will need a small propulsion system to get the ribbon started toward Earth and to handle the angular momentum change as it descends. A "homing" device on the end will facilitate intercepting the ribbon and affixing it to the ground station. During the spooling out of the ribbon, the deployment spacecraft has risen above GEO so that the center of mass remains at or very near GEO. The spacecraft also must thrust to stay above the ground point because of the angular momentum change at different altitudes. Once the ribbon is completely deployed the spacecraft acts as the counterweight.

The pilot ribbon has a lifetime of only a few years because of impacts from small debris that cannot be actively avoided. Therefore, immediately, climbers must be sent up the ribbon to attach more ribbon to the SE. These climbers must be engineered for the small capacity of the pilot ribbon. As the ribbon capacity increases, the climbers will be larger and will carry more ribbon. After two years, a meter-wide ribbon rated at 20 tons (extra tension in the ribbon) would be completed. Subsequent, higher capacity SEs will be built with an existing SE in much less time, possibly 5 months. Indeed, each elevator's first task may be to build a successor ribbon thus building the SE infrastructure.

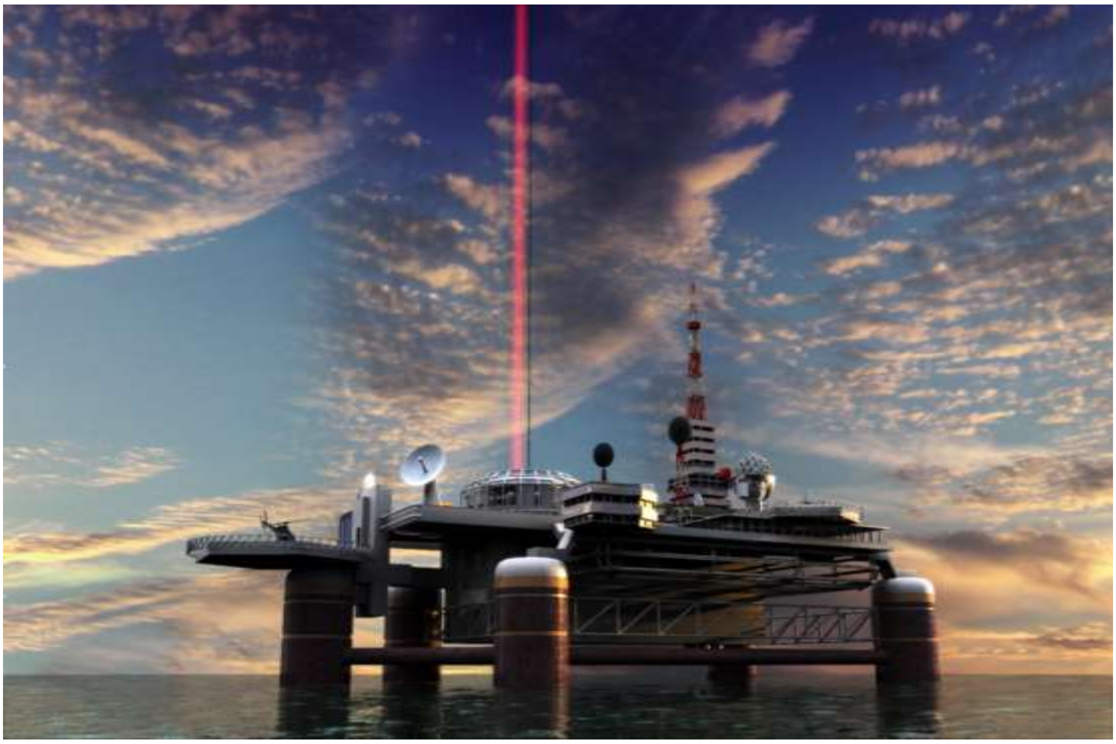

Figure 2 An artist's conception of the Space Elevator's Earthport

4 CHALLENGES

Even if the ribbon and deployment spacecraft were ready to go, there exist issues that must be dealt with before the SE can be deployed. These issues include the technologies required to ascend the ribbon, hazards to the ribbon and the problem of humans traveling on the SE above LEO.

Climbers that ascend the ribbon must operate over a wide range of environments, possess high reliability and climb the ribbon without damaging it. Climbers are assembled, loaded and launched on Earth at the bottom of the troposphere. Within the troposphere weather can be dangerous to climbers especially lightning. The regions encountered during ascent above the troposphere include the stratosphere, ionosphere, and magnetosphere. The atmospheric pressure decreases while the temperature and composition change dramatically as the altitude increases. The stratosphere extends from about 15 km up to about 55 km, the temperature increases from -51C to -15C. The ionosphere begins around 60 km and end around 1000 km. Solar radiation has ionized the atoms in this part of the atmosphere and so the climber must climb through a plasma, albeit a very tenuous plasma. The magnetosphere extends above the ionosphere far out into space. It is a very hard vacuum with very tenuous ions streaming through it. Earth's magnetic field and the solar wind effect its overall shape and boundaries by their effect on the ions. The climbers must operate in all these environments including the radiation environment of the magnetosphere. Climbers must be reliable enough to make at least one 100,000 km trip if not a round trip. A stranded climber could compromise the use of the SE.

Climbers also must have a wide range of uses and so will differ in design. Most climbers will carry and launch payloads. Others will carry out diagnostic measurements, repair tasks, ribbon laying, science experiments and rescue of stranded climbers.

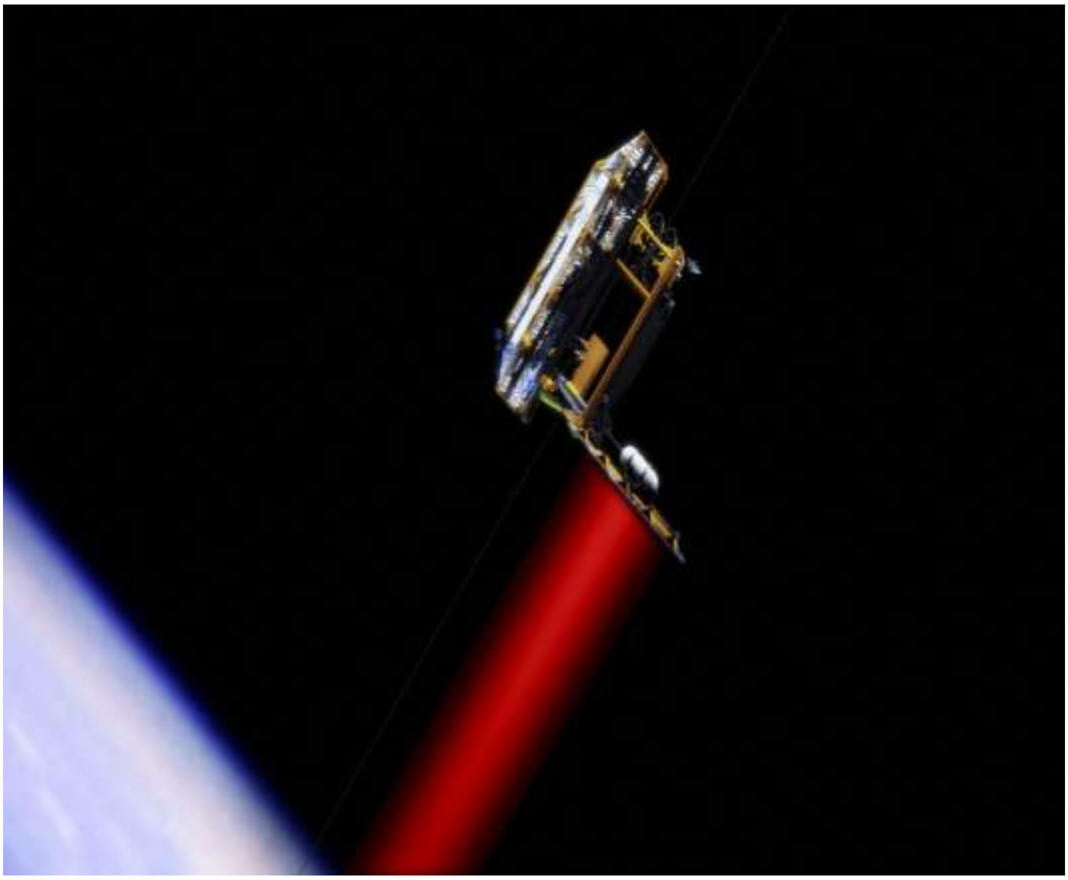

Figure 3 An artist's conception of the Space Elevator Climber ascending the ribbon near Earth and illustrating the power beaming to photovoltaic cells.

The power beaming system that will energize the climbers has three major system components: the infrared laser, the large (~12 meter) telescope and the adaptive optics system. Each of these components (or a close example) exists separately but has never been integrated and operated as a system. An adaptive optics system is required to focus the energy onto the climber photocells through the atmosphere. Current adaptive optics systems are not capable of phasing the entire aperture of large telescopes, but active, closed loop adaptive optics should achieve large aperture phasing.

Hazards to the SE include winds, lightning and aircraft in the troposphere, atomic oxygen in the upper atmosphere, and radiation, solar storms, orbital debris, orbiting satellites and meteorites in the magnetosphere. Placing the ground station on the equator in a region with few storms and defending a no-fly zone around the SE mitigate the troposphere hazards. Coating the SE ribbon with a metal such as nickel or aluminum would protect it from atomic oxygen in the upper atmosphere.

At LEO, space satellites and debris greater in size than 10cm can be avoided by moving the lower end of the elevator. Therefore, the ground station may be a ship or navigable floating platform. The width of the ribbon (1 meter) and its curved cross-section allow the SE to survive micro-meteor and small debris collisions. The statistical rarity of large meteors renders this hazard a low probability. The CNT ribbon is carbon and so is robust to most proton and electron radiation so the damage sustained should be manageable.

The climbers are envisioned to travel at about 200 km/hr. This means that the climbers spend a significant amount of time in the Van Allen radiation belts. The lower belt is mainly trapped energetic protons and the outer belt is primarily energetic electrons. Humans riding on the elevator spend so much time in the radiation belt that the radiation dose is beyond the safe level. Therefore, mitigation techniques must be developed or climbers must significantly increase in speed before humans ride the elevator beyond LEO.

5 SPACE ELEVATOR RIBBON DYNAMICS

Another hazard is the dynamics of the ribbon. This topic is of special interest to the Lift Symposium community so it was extracted from the Challenges section above and discussed here.

SE oscillations can be induced by winds, moving the ground station, the gravitational attraction of the sun and moon, solar storms, solar wind pressure, magnetospheric electromagnetic interactions, thermal heating/cooling and climbers operating on the ribbon.

The ribbon will need to be stabilized by active damping from the counterweight, base and possibly at GEO. Such active damping requires measurement of the oscillations and the appropriate application of impulses to cancel the oscillation. Accomplishing this implies a system that understands the perturbing forces and the evolution of the resulting oscillations as they propagate along the ribbon.

The portion of the Lift Symposium community that carries out dynamic analyses for elevator cables or other slender structures could fill a void in SE research by modeling the elevator cable dynamics realistically. This model would include the following, without knowing the specific properties of the ribbon material:

1. A ribbon with a changing cross section (and so changing mass/length).
2. A ribbon in which the gravitational force changes across its length.
3. A ribbon rotating with Earth by one end being attached to Earth's surface.
4. A ribbon with the other end experiencing a small restoring force in an otherwise free boundary condition.
5. A ribbon experiencing multiple perturbations along its length.
6. Sufficient resolution to model the local effects of a climber operating on the ribbon.
7. A large-scale perturbation such as a solar storm inducing a changing Lorentz force along the part of the ribbon in the magnetosphere.
8. An inelastic collision with an object.

This calculation has never been attempted, let alone approached in sophistication, by previous researchers. There is a great deal of insight to be gained by such calculations. The material properties of the ribbon could be "parameterized" so that as high strength material technology advances, the calculation could be re-run with superior material inputs until the actual ribbon material is fabricated and its properties measured.

6 SPACE ELEVATOR DESIGN VARIATIONS

Colleagues in the Space Elevator community have developed ideas about variations in Space Elevator design. Some of these involve historical variations like elevators with multiple ribbons connecting to Earth and joining into one cable at some altitude, and the free-flying skyhook orbiting Earth.

Other variations involve an adaption of the launch loop invented by Keith Lofstrom and called High Stage One. A very high-altitude platform (~80 km) serves as the starting point of the elevator ribbon thereby eliminating the hazards of the troposphere. A variation that uses similar technology to suspend the climber launch platform is the Multi-Stage Space Elevator.

Other researchers are defining the systems level view of the Space Elevator Transportation System by defining the operations and requirements of the parts of the overall system. Parts of the system include the Apex Anchor, GEO Node and Earthport.

The International Space Elevator Consortium (ISEC) holds a conference every year and has developed many study reports in which these designs are documented. One can join ISEC by going to www.isec.org. The website also has information on the ISEC Reports and other Space Elevator resources.

7 CONTROVERSIAL CARBON NANOTUBE COMMENTS

Years ago, the author of this paper left the Los Alamos National Laboratory to research CNT growth. The reason was that the progress in the field to grow long, strong CNTs appeared glacially slow.

The author attended a conference presentation by Dr. Benji Maruyama of the Air Force Research Laboratory. In his presentation, Dr. Maruyama described the limits of using the chemical vapor deposition (CVD) method to grow CNTs. His team found that the CNT growth was stopped and the CNTs were damaged for the following reasons:

1. The catalyst particles from which CNTs grow become coated with amorphous carbon thereby shutting off the path for free carbon atoms to become a part of a growing CNT,
2. The catalyst particles diffuse into the substrate thereby becoming too small to support CNT growth,
3. Ostwald ripening operates on the catalyst particles increasing the size of the larger ones and decreasing the size of the smaller ones thereby rendering both of the wrong size to grow CNTs,
4. CNTs are damaged by reactions with the hot carbon-bearing gases present in typical CVD growth.

The widespread use of the CVD method in the field is why progress to grow CNTs has been glacially slow. Consequently, traditional CVD is probably a dead end. Since the discovery of CNTs in 1991, the world has poured around $35 billion into CNT research and has only an approximately $700 million annual industry to show for it!

The author spent two years of part-time work developing seven novel synthesis (growth) processes. The first six were defeated by deeper study. Proof-of-principle experiments were carried out on the seventh process, and robust growth of CNTs was achieved. Currently, money is being raised to continue to develop the technology into a process capable of industrialization. If successful, then the promise of this technology will be realized.

The promise of this technology is continuous growth of CNTs that possess pristine molecular structure – exactly what is needed to create a materials revolution on Earth. Once the technology has been developed into myriad products that change our civilization, the Space Elevator will be built as the bouquet of the technology.

8 THE PROMISE OF THE SPACE ELEVATOR

The low cost of access to space promised by the Space Elevator (SE) will enable the exploitation of space. Currently, commercial space business is only profitable in the case of communications. With lower cost to space, many types of commerce will be profitable. Solar power satellites that beam power to Earth will provide clean, inexpensive electrical power. Earth observation and scientific space missions will be expanded in number and capability. Human and robotic exploration as well as colonization will be possible at much lower cost. SEs could be thrown to the moon and Mars and deployed to enable the suppling of settlements and two-way trade.

Space tourism, bolstered by the success of the Ansari X-Prize winning Space Ship One (the first private reusable manned spacecraft to reach space twice within two weeks) will be stimulated by the SE as well. Humans will ride to LEO at first, returning either back down the elevator or by dropping off the elevator and re-entering the atmosphere. Eventually humans will vacation at the GEO station or depart from the elevator to other parts of the solar system.

In conclusion, the Space Elevator will open up space and its resources to help mankind solve its problems here on Earth and to expand into the solar system. What could be better than to work on this project? After all, now that the history of the 20^{th} century is being written, it is clear that one of the greatest achievements was that humans landed men on the moon and returned them safely to Earth. When they write the history of the 21^{st} century, they will say that one of the greatest achievements was the building of the Space Elevator!

REFERENCES

[1] Edwards, B.C. and Westling, E.A., *The Space Elevator*, Houston, BC Edwards, 2002.

[2] Artsutanov, Y., V Kosmos na Elektrovoze, *Komsomolskaya Pravda*, 1960.

(contents described in Lvov, *Science*, 158:946)

[3] Isaacs, J.D., Vine, A.C., Bradner, H., Bachus, G.E., Elongation into a true 'Skyhook', *Science*, 151:682, 1966.

[4] Pearson, J, The Orbital tower: a spacecraft launcher using the Earth's rotational energy, *Acta Astronautica*, 2:785, 1975.

[5] Iijima, S., *Science*, 254:56, 1991

[6] Yu, M.F., Lourie, O., Dyer, M.J., Molini, K., Kelley, T.F., and Ruoff, R.S., *Science*, 287:637, 2000

[7] Yu, M.F., Files, B.S., Arepalli, S., and Ruoff, R.S., *Physical Review Letters, 84, no. 24:5552, 2000*

BIOGRAPHICAL DETAILS

Dr. Laubscher is a PhD in Physics with a concentration in Astrophysics. During his career at the Los Alamos National Laboratory that included R&D of astronomy projects, space mission design and system engineering, space particle instrumentation, remote sensing technologies, novel electrodynamic detection techniques and biometrics, Bryan became interested in the Space Elevator.

Pursuing the R&D of the Space Elevator has led him to start Odysseus Technologies, Inc, a small company based in Washington state with the goal of developing high strength carbon nanotube materials. Odysseus Technologies has invented a new way to synthesize carbon nanotubes and completed proof-of-principle experiments. Now the company is pursuing technology development and plans commercialization in the near future.

Bryan’s current non-profit Space Elevator activities include being on the Board of Directors of the International Space Elevator Consortium and presenting the Space Elevator presentations at various venues.

Bryan now lives in Olympia, WA with his wife Carla.