IAC-04-IAA-3.8.3.05

SPACE ELEVATOR SYSTEMS LEVEL ANALYSIS

Bryan Laubscher
Los Alamos National Laboratory
blaubscher@lanl.gov
LAUR-04-5909

ABSTRACT

In this paper an outline of systems engineering activity is presented. Then systems engineering principles are applied to the highest levels of the space elevator system. The first level of the space elevator system is broken down into nanotube ribbon, deployment, climber technology and ground station and discussed briefly. Each one of these systems is sub-divided into its subsystems and those subsystems are discussed briefly. These subdivisions illustrate how the complex and massive tasks of perfecting the technologies for the space elevator, designing the first operational space elevator and deploying the first space elevator can be "attacked" in small pieces that teams of researchers can tackle. When systems engineering principles are enforced, the efforts of these multiple teams can be brought together efficiently for the successful conclusion of a complex project such as the space elevator.

INTRODUCTION

The Space Elevator (SE) represents a major paradigm shift in space access. It involves new, untried technologies in most of its subsystems. Thus the successful construction of the SE requires a significant amount of development. This in turn implies a high level of risk for the SE. This paper will present a systems level analysis of the SE by subdividing its components into their subsystems and discussing briefly their technologies. In this way, a complex and massive project such as the building of the first SE can be seen and dealt with as many smaller, interrelated tasks.

A rational way to manage such a high-risk endeavor is to follow a disciplined approach to the challenges. A systems level analysis informs this process and is the guide to where resources should be applied in the development processes. It is an efficient path that, if followed, minimizes the overall risk of the system's development.

One key aspect of a systems level analysis is that the overall system is divided naturally into its subsystems, and those subsystems are further subdivided as appropriate for the analysis. By dealing with the complex system in layers, the parameter space of decisions is kept manageable. Moreover, resources are not expended capriciously; rather, resources are put toward the biggest challenges and most promising solutions. This overall graded approach is a proven road to success.

The analysis includes topics such as nanotube technology, deployment scenario, power beaming technology, ground-based hardware and operations, ribbon maintenance and repair and climber technology.

SYSTEMS ENGINEERING PRIMER

Systems engineering (SYEG) is guided at the highest level by the overall budget, schedule and mission requirements. The mission goals are used in a disciplined way to derive a set of engineering requirements for the physical system. These engineering requirements are then flowed down into the specifications for each of the subsystems.

The systems engineer approaches a complex system like the SE from the top down. The system is broken down level by level into its constituent parts. These parts represent components that must be conceived, designed or built. Some of these parts can be off the shelf parts whereas others must be adapted from existing hardware or invented anew.

Each subsystem can influence other subsystems. The effect could be compatibility or conflict and require redesigns. These relationships are "managed" by SYEG. The influence of a certain choice in one subsystem can have consequences across the entire system and SYEG endeavors to distill the best set of choices for the overall project from myriad choices.

SYEG "owns" the error budgets and the trade space in which decisions are made. Thus SYEG apportions the error budget across the various projects as trade studies are carried out and decisions are made. This process continues through the design, fabrication and deployment stages.

If you ask 20 people about SYEG, you will get 20 different opinions. This paper uses the above definition of SYEG for the following discussion.

SE MAJOR COMPONENTS

An outline of the top sublevel of the SE system is shown in Figure 1. This represents only one top level of the parameter space of possible designs, decisions and technologies that are available to build the SE.

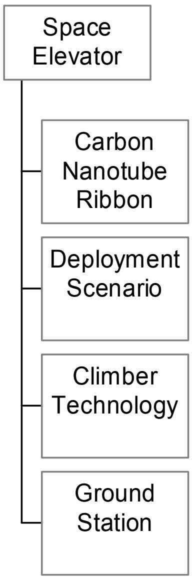

Fig. 1 The First Sublevel of the Space Elevator
Note that this division of the first level is that of the author for the purpose of this paper. A formal, disciplined study of the SE system might yield different subsystems.

The carbon nanotube ribbon subsystem is the heart of the SE and its enabling technology. A ribbon with the required strength to weight properties does not yet exist. The deployment of the SE requires large masses lifted to orbit and places the initial SE pilot ribbon in a hostile environment. Deployment carries great risks. Climber technology is undeveloped and the economic success of the SE transportation system relies on climber reliability. The ground segment includes the floating platform, anchor mechanism and the power beaming system. These vital system have existing hardware used in other applications that may be adapted for SE system use.

The SE is currently at the conceptual level. Furthermore, it involves many technologies that are novel such, as the carbon nanotube ribbon, climber technology, power beaming stations, anchoring technique and deployment method[1]. Thus a common complaint is that the SE requires the development of so many new technologies that its inherent risk is very high. Obtaining funding with these perceived problems is very difficult. A disciplined SYEG study can identify and quantify risks and then act as a roadmap to the optimal conceptual design. It should be noted that when significant funding is obtained, the studies carried out (and orchestrated by SYEG) will lower the risk by determining through analysis or experimentation what technologies are best. During fabrication, systems engineering is present throughout to manage the inevitable difference between the plan and reality.

NANOTUBE RIBBON

The trade space that concerns the carbon nanotube (CNT) ribbon is especially important. CNT ribbon is critical technology that has not been demonstrated. Indeed, the SE emerged from science fiction when the CNT was discovered because this material possesses the strength-to-mass properties required for the SE. The promise of the material has not yet been realized in a configuration that is useable as a ribbon. The first "ribbon trade study" is between woven CNTs and a composite ribbon in which CNTs are distributed in a composite matrix. Figures 2 and 3 illustrate the sublevels of each of these ribbon technologies.

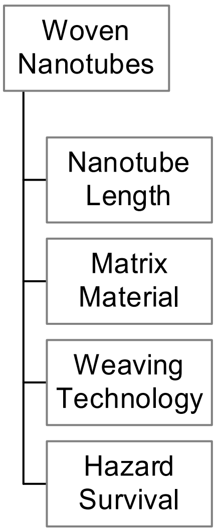

Fig. 2 Woven Nanotube and its First Sublevels.

Woven CNTs is a bit of a misnomer. In reality, the technology involves creating micrometer size fibers composed of a CNT composite with high CNT density (CNTs are nanometers in diameter). These micron fibers would then be spun into threads by machines. Longer CNTs enable a more efficient fabrication process and a stronger thread. A ribbon composed of these woven threads would presumably be less massive for the same strength. The chemistry of bonding CNTs with a matrix material into a fiber is in its infancy. Also, weaving these CNT fibers is unproven technology. The length to which CNTs can now be made is a restriction on the spinning process. Manipulating CNTs that are less than 2 nanometers wide, bonding them into fibers with a matrix, and spinning them into thread will require technological development in separating and handling CNT and the composite fibers. Finally, a CNT ribbon may require coatings to protect the CNT material from the hazards (such as free atomic oxygen) that the SE will encounter once deployed and the efficacy of coating these woven ribbons are unknown.

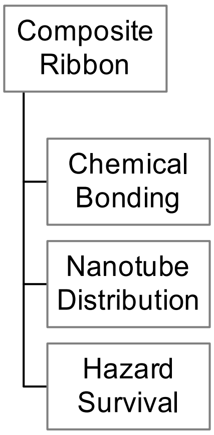

Fig. 3 Composite Ribbon and its First Sublevels.

A high-tensile strength ribbon made out of a CNT composite matrix requires that the CNTs be distributed throughout the bulk matrix and that good interfacial absorption be achieved between the CNTs and the composite. The techniques for distributing and aligning CNTs in the composite are being studied in the laboratory at this time. Moreover, the chemistry of bonding between the CNTs and the composite are also being researched. Finally, a composite matrix ribbon may require different protective measures and may erode more during climber operation than a woven CNT.

Although the decision between these two ribbons cannot be made yet, a trade study will probably be required to choose. Such a study would include the effect of the ribbon choice on the other systems of the SE. For instance, the greater mass of the composite cable would have ramifications for size of a pilot ribbon, a small ribbon initially deployed from orbit. A smaller pilot ribbon implies greater risks from micro-meteors and space debris[1]. More time is required to finish the ribbon to its final width with a composite because the initial ribbon cannot carry as much weight and the final ribbon is more massive. Also impacted is the size of the initial climbers that are adding ribbon to the pilot ribbon, thus requiring further engineering. In turn, longer construction times and higher risk tends to scare off investors. Therefore, the ramifications of design decisions propagate through the systems and can impact seemingly unrelated aspects of the system.

Alternatively, the composite technology can provide the aerospace, automotive, railroad and construction industries with valuable products and so may be developed sooner and more thoroughly. Thus enabling the SE to be built sooner and with a greatly reduced ribbon cost.

SPACE SEGMENT

The first sublevel under Deployment is the Space Segment. This includes the deployment spacecraft, its power source and the technique of deployment. Comparing Space Segment to the other deployment sublevel, Ground Segment (Fig. 5) shows the interrelations of many of the systems. Note that each deals with power systems. In some deployment scenarios, the power beaming stations supply power to the spacecraft before their use for climber power.

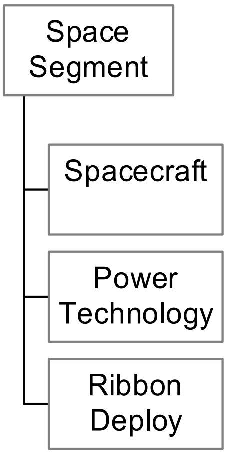

Fig. 4 The Space Segment and its First Sublevels.

Figure 4 outlines the sublevels of the space segment. Once the ribbon type is determined, the space segment design trades can begin in earnest. One must consider various issues: the mass launched to low Earth orbit (LEO), the size of the pilot ribbon deployed, the time to complete the first SE and the risk of a small cable size.

The trade space concerning the launch to LEO is three-fold. First is the familiar mass versus cost relationship. At $10,000 to $23,000 per kilogram to LEO, this is the major cost driver of the first SE[1]. Therefore, minimizing the mass launched into space is important. Second is the reality that rockets have a maximum payload capacity to LEO, which is small given the size of the SE deployment requirements. Finally the power considerations are substantial.

It has been suggested that the SE is so vital and profitable that the entire cable should be launched, in segments, and deployed at its final width[2]. This simplifies the ground segment, reduces dramatically the time to complete the ribbon and eliminates the risk of a pilot ribbon being severed. The downside is that the launch costs alone would be far beyond the total $6 billion price tag of the more conservative approach.

The second concern of the trade space comes into play since rockets come in specific sizes with certain payload capacities. The entire ribbon could not be lifted at once, and neither could the deployment mechanism. The large number of launches and the subsequent on-orbit integration of the individual payloads delivered to orbit would be problematic. In LEO, astronauts could construct the entire deployment system. However, as the system transitioned to geosynchronous orbit (GEO), any other repairs to the complex system would require robotics because the radiation environment is incompatible with humans, at least using our current space technology. Getting the astronauts to GEO is also beyond our current capabilities.

No matter what scheme is chosen for the ribbon deployment, another major design trade is the power system of the space segment. This includes the power used to change the orbit from GEO to LEO, deploying the ribbon and station keeping during deployment. Any power source that requires all its fuel to be launched to orbit will drive the cost. The elegant solution of using the power beaming stations does possess risks. Power beamed from the ground at infrared wavelengths must contend with cloud cover and storms. Another interruption could be caused by failures in the power beaming systems. These interruptions in power supplied to the spacecraft would impact both the LEO to GEO transfer portion of the deployment as well as the ribbon unreeling portion, which begins at GEO above the point on Earth where the floating platform will be stationed. Interruptions during the ribbon unreeling may be the most important to avoid since the pilot ribbon is vulnerable to destruction by micro-meteors and space debris.

On the other hand, power beaming is the only energy source expected to operate the climbers[1]. Therefore, using power beaming as early as possible will provide the opportunity to work out all the problems.

GROUND SEGMENT

Figure 5 outlines the sublevels of the ground segment. Because of the transponder that is anticipated to be at the end of the ribbon that is deployed downward to Earth, it will be assumed that the ribbon capture is straightforward[1]. The expected difficulties in the ground segment are expected to be power beaming technology and adding the ribbon to build up the final ribbon width and capacity.

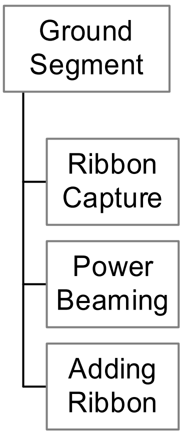

Fig. 5 The Ground Segment and its First Sublevels.

Power beaming has been extensively studied elsewhere[3]. Free electron lasers, 10-meter telescopes and adaptive optics are known technologies. A system that combines all these parts and keeps its power on a small platform ascending the SE has not been demonstrated.

Moreover, the demonstrated systems are research related and so are not operated continuously, in the harsh ocean environment and with long periods between maintenance. Engineering these systems to be robust and deployable to a remote location would take development.

Adding new ribbon to the pilot ribbon to construct the final ribbon (from a 15 cm wide pilot ribbon to 1 meter wide final ribbon[1]) is new and untried. In principle, the technology can be developed during the cable technology studies. One of the requirements is that the attachment technique cannot add much mass to the cable. Ideally, the attachment would be a weaving similar or identical to the webbing design of the cable itself. Moreover, a “cable attaching” climber that fails would need to be rescued and have its work completed by another climber in a seamless fashion.

At this time no specific trades can be discussed because these technologies are still in their infancy.

CLIMBER TECHNOLOGY

Figure 6 outlines the sublevels of the climber technology. The climbers represent untried technology as well. No current technologies specifically address clamping onto a CNT ribbon and dragging 20 metric tons over 100,000 kilometers with the forces on the climber varying in magnitude and direction. All this must be accomplished without significant ribbon damage.

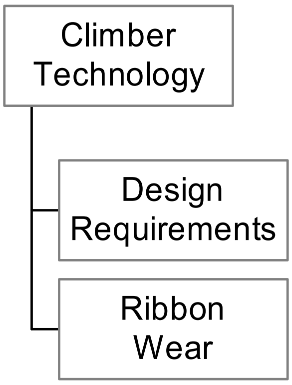

Fig. 6 Climber Technology and its First Sublevels

Climbers must be robust enough to operate for over 100,000 kilometers with very high reliability. Climbers must be loaded and begin their operation in the troposphere. Once in ascent they will spend approximately 30 minutes in this region of the atmosphere where the temperature falls to minus 40 degrees Celsius and the atmosphere thins dramatically. Weather and its associated dangers, high winds and lightning are experienced in the troposphere. The next level is the stratosphere, where the climber will spend about 100 minutes. The atmosphere continually thins, and the temperature climbs to 100 degrees Celsius. The thermosphere and ionosphere are traversed in approximately 2.4 hours and temperature climbs to 1200 degrees Celsius. Spacecraft charging becomes an issue at this altitude. Much of this area is unexplored, since it is above the altitude of balloon flights and below orbital altitudes. The magnetosphere is where the climber will spend most of its time (about 495 hours if it travels to the end of the SE). Although an excellent vacuum, the charged particle environment of parts of the magnetosphere is severe. Since the climber traverses the magnetosphere so slowly, the total dose will require appropriate shielding for electronics and sensitive payloads. Because all satellites orbit in this region, electronic component shielding is well understood. A climber must withstand all of the dangers that are encountered in each part of the space it traverses.

Climbers must be capable of communicating to and being commanded from the ground. These vehicles must perform many missions, such as cable laying, payload delivery to orbit, diagnosis and repair of the ribbon, construction of support facilities (nominally at GEO), rescue a stranded climber, erect a new ribbon by unreeling a new ribbon as the climber ascends the SE, conduct science experiments, traverse a round-trip (up one elevator and down another) and eventually carry humans to orbit. All these missions will require differing designs although the goal is to design a system that is mass producible with as many interchangeable parts as feasible. These new devices represent a great engineering challenge that will need to be surmounted for the SE to succeed.

GROUND STATION

The ground station represents a very large trade space. In reality, there are political, economic and defense considerations about where to place the SE. The ribbon handling such as tension control, health status, danger avoidance and maintenance are all ground station responsibilities. Finally, the operations of attaching climbers, loading payloads, launching and traffic control are all ground station tasks.

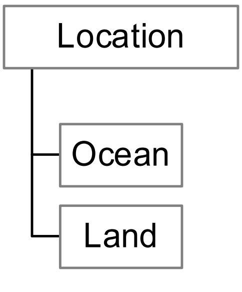

Fig. 7 Location and its First Sublevels

The location of the SE is best, in a dynamical sense, at the equator. Only here does the ribbon rise straight out to 100,000 kilometers. Earth’s equator has much ocean and few stable countries. Therefore, the political considerations are great.

Hurricanes also do not occur on the equator and so the ocean is a reasonable place to site the SE. Indeed, the baseline scenario is that of a floating oil platform, sited about 200 kilometers west of the Galapagos, a region of few storms.

The SE will be required to avoid existing satellites and large pieces of space debris to survive and to conform with international law. The mechanism for this will be to move the lower end of the ribbon around roughly 10 kilometers. In this way the vast majority of colliding objects that are in LEO will be avoided. This maneuver also gives ocean basing an advantage.

Handling and transferring payloads and supplies in the open ocean is troublesome but done now routinely for oil platforms.

Defense considerations also favor ocean basing. Most terrorist attacks are perpetrated on land and a remote ocean site, defended by a naval force, discourages terrorists.

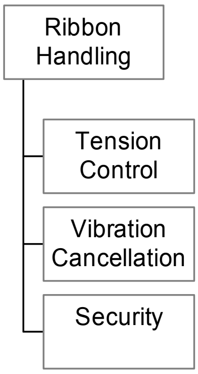

Fig. 8 Ribbon Handling and its First Sublevels

The ribbon handling mechanism will receive the captured ribbon, maintain tension and damp out vibrations induced in the ribbon. The security in the vicinity of the ribbon will be very stringent. Figure 8 illustrates the sublevels of Ribbon Handling.

It is conceivable that the tension in the ribbon will need to be constantly monitored and adjusted. Heating through the day, dynamics of climber operations and the interaction of the SE with its many environments could require continuous tension optimization.

The forces in the SE from the wind, magnetospheric interactions, payload releases, gravitational interactions, etc. will induce vibrations in ribbon. The ground station will be required to sense the state of the ribbon and induce cancellation vibrations.

Finally, the security in and around the ribbon must protect the cable from attack by persons on the platform itself. The ribbon has tremendous longitudinal strength, however, it is susceptible to being severed in shear. Ironically enough it is predicted that an appropriately designed saw could sever a paper-thin, 1 meter wide ribbon in a few seconds. This represents a grave danger to the SE.

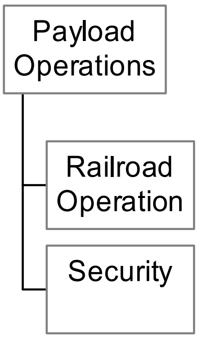

Fig. 9 Payload Operations and its First Sublevels

Many aspects of the payload operations (Fig. 9) are unknown and will remain so until the system is operational. However, one would expect the climbers to be designed with the integration of payloads, interface procedure with the ribbon and the desire for streamlined operation in mind. Railroads were very efficient and so became the first mass transit system. SE operations will strive for the same efficiencies.

Payload screening will be necessary to ensure SE security. Thus the system will be designed to accommodate thorough inspection of each payload. This could be accomplished at the port of origin before being loaded on the transport ship or during the voyage to the SE site.

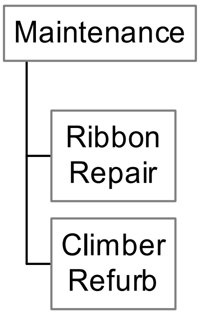

Fig. 10 Maintenance and its First Sublevels

Maintenance involves both ribbon repair and climber refurbishment (Fig. 10). As the SE ages or catastrophic events occur, the ribbon damage will need to be addressed. Currently, it is expected that the same technique used to build up the pilot ribbon to the final meter-wide ribbon will be adapted for use on repair climbers to repair damaged spots on the ribbon. Either every climber or special diagnostic/repair climbers will monitor the ribbon health. A database of damage will be maintained and then repair climbers dispatched to mend the tears in the ribbon fibers. Certain weaves are known to stop tears so this my be a SYEG consideration in the ribbon design. Certainly with any ribbon, its ability to transfer increased stress from a damaged section is important for the SE survivability. These capabilities will be weighed when ribbon trade studies are carried out.

Furthermore, an SE infrastructure will consist of multiple SE ribbons and will allow the recovery of all climbers. (Note that some economic analyses show that with one or two low capacity SE ribbons, throwing away the climbers is more cost effective than stopping the up traffic.) At this time the climbers will be recovered, refurbished and reused. Economically speaking, it will be important to engineer the climbers so that refurbishment can be carried out efficiently.

CONCLUSION

Systems engineering and its technique of systems level analysis have an important place in the SE project even at this early juncture. As research defines technologies and techniques, systems analyses enables an optimal design to be “distilled” from the large parameter space of possible designs. This paper has discussed a few representative trade studies and identified technologies so immature that no trade studies can be discussed at present.

REFERENCES

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

2. Price, Andrew, 2nd Annual International Space Elevator Conference, Sept. 2003, Santa Fe, NM, private communication.

3.http://www.isr.us/pdfs/SE/SE_Ideal_App_for_FEL.pdf