Lunar Base Design:
A Paradigm for the Capstone Design Course

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ABSTRACT

Most engineering programs have a capstone design course, as per the Accreditation Board for Engineering and Technology (ABET) requirements, the recognized US accreditor of college and university programs in applied science, computing, engineering, and technology. This paper proposes that such a course be placed in a larger and coupled design framework, that is, that all student design groups choose or be assigned a project that considers some aspects of the design of a lunar surface structure intended for human habitation. The senior Mechanical and Aerospace Engineering Capstone Design course is a two-semester six credit course sequence that is intended to expose each graduating engineering student to the full spectrum of engineering experience. A review is given of the essentials of lunar surface structures design. Example project areas are given.

INTRODUCTION

Mankind set foot on the Moon over three decades ago. Ever since, NASA and other space agencies have planned to build an outpost on the Moon for changing reasons. At first it was to show the technical advances of the US during the Cold War. Today's reasons for a base on the Moon are more practical, with astronomy, mining, or tourism as possible arguments for a human presence on Earth's only natural satellite. This paper has an educational program as its focus. There are numerous papers that discuss lunar structures; some are listed in the references at the end of this paper.

PRIMER ON LUNAR STRUCTURE DESIGN

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Lunar constructions will be designed for and built with the following prime considerations in mind:

- *Gravity:* On the Moon the gravity is only 1/6 g. That means a structure will have, in gross terms, six times the weight-bearing capacity on the Moon as on Earth. A mass-based rather than weight-based criterion is recommended to be developed in order to maximize the utility of concepts developed for lunar structural design.

- *Internal air pressurization:* The lunar structure is in fact a life-supporting closed environment. It will be a pressurized enclosed volume with an internal pressure of nearly 15 psi (103.4 kPa). The enclosure structure must contain this pressure, and must be designed to be fail-safe against catastrophic and other decompression.

- *Shielding:* A prime consideration in the design is that the structure be able to shield against the types of hazards found on the lunar surface: continuous solar/cosmic radiation; meteorite impacts; extreme variations in temperature and radiation.

- *Vacuum:* A hard vacuum surrounds the Moon. This will preclude the use of certain materials that may not be stable under such conditions.

- *Dust:* The lunar surface has a layer of fine particles that are easily disturbed and placed into suspension. These particles cling to all surfaces and pose serious challenges in the utility of construction equipment.

- *Ease of construction:* The remoteness of the lunar site, in conjunction with the high costs associated with launches from Earth, suggests that lunar structures be designed for ease of construction so that the extra-vehicular activity (EVA) of the

Astronaut construction team is minimized. Construction components must be practical and, in a sense modular, in order to minimize local fabrication for initial structural outposts.

- *Use of local materials:* Launches from Earth are very expensive. Today's costs are at approximately US $20,000 per kg load brought into orbit. A minimum of dead load of the structure itself would drastically reduce the costs for a lunar outpost. A sophisticated scheduling of the erection, sealing, and pressurization is required for the lunar construction site. A significant design constraint is to utilize as much in-situ material as possible. This is considered extremely important in the long-term view of extraterrestrial habitation; but feasibility will have to wait until a minimal presence has been established on the Moon.

The design engineer must consider the following loads:

- *Dead Loads:* Lunar structural dead loads will primarily be caused by gravity of 1/6 g, internal pressurization, and shielding.

- *Live Loads:* These include loads caused by elevators, traveling cranes, machinery, power-driven units, human locomotion, and secondary vibrations resulting from landings.

- *Impact Loads:* Accidents such as vehicular impacts or meteoroidal impacts.

- *Temperature:* Temperatures on the lunar surface change approximately 250°C in the transition between day and night, which occurs in roughly two-week cycles. These extreme changes may lead to fatigue problems.

Many structural concepts have been developed until today. Those concepts use a variety of materials and engineering approaches ranging from "tuna can" steel structures to inflatable membranes and even structures made of lunar concrete. In 1996-1997, NASA undertqok an initiative to create "development technology roadmaps" for a variety of technical and scientific areas critical to exploration of the Moon, Mars, and beyond inner planets. The NASA Habitat and Surface Construction Working Group introduced the following set of definitions that shall herein be used to classify existing designs:

- *Class 1: Pre-Integrated.* Hard Shell Module delivered complete to the surface. These structures will most likely be similar to today's ISS-modules. Complete cylindrical modules can be landed on the lunar surface. These Composite structures are near current technology with a high reliability and can be easily repaired.

- *Class 2: Pre-Fabricated.* Inflatable deployed or assembled structures. Pillow-shaped structures have been proposed as possible concepts for a permanent lunar base. The proposed base consists of quilted inflatable pressurized tensile structures using fiber composites. An overburden of regolith provides shielding, with accommodation for sunlight ingress. A pressurized membrane structure as a permanent lunar base. It is constructed of a double-skin membrane filled with structural foam. A pressurized torus-shaped substructure provides edge support. Shielding is provided by an overburden of regolith. Briefly, the construction procedure requires shaping the ground and spreading the uninflated structure upon it, after which the torus-shaped substructure is pressurized. Structural foam is then injected into the inflatable component, and the internal compartment is pressurized. The bottoms of both inflated structures are filled with compacted soil to provide stability and a flat interior floor surface.

- *Class 3: In-Situ Resource Construction.* Lunar concrete, masonry, lava tubes. Design of a tied-arch structure of indigenous materials has also been proposed.

There are a number of challenges with which the designer needs to be concerned:

- *Safety and reliability: What is an acceptable level of safety and reliability for a lunar site, one that must be considered highly hazardous?* Such questions go beyond engineering considerations and must include policy considerations: *Can we afford to fail? Or better yet, what kind of failure can we afford or allow?*

- *Materials:* Chemically and molecularly stable materials for hard-vacuum environments have to be found (keyword out-gassing for exposed steels). The relationships between severe lunar temperature cycles and material fatigue are an issue for research. Very low-temperature effects and the possibility of brittle fractures have to be studied.

- *Non-technical Issues:* Financing the return to the Moon, and understanding human physiology in space are important topics as well.

MAE CAPSTONE DESIGN

The senior Mechanical and Aerospace Engineering Capstone Design course is a two-semester six-credit course sequence that is intended to expose each graduating engineering student to the full spectrum of engineering experience. The first semester focuses on the definition of the design space, options, economics, and the beginnings of fabrication and construction. There are approximately 20 groups of four to five students each. The instructor leads the students through a general set of preparations. Each group also has a specialist faculty/industry advisor.

Currently, each group selects its project independently of the others. Efforts are made to obtain industry sponsorship and mentorship. The students are responsible for all aspects of the project that culminates in a designed and manufactured product.

It may be interesting and useful to link all the projects under an umbrella project. *What is better suited to this than the design and erection of a lunar structure for human habitation?* The extreme environment on the lunar surface challenges any engineer to be efficient and very effective with the design. Key environmental concerns are: radiation and micrometeorite shielding, the need for internal pressurization, the existence of temperature gradients, the regolith dust problem, and the potential for accidents and rapid depressurization. There are numerous secondary issues.

One can envision a spectrum of projects leading to components required for the lunar structure. Faculty/industry experts in structures, robotics, thermal and fluid sciences, materials, and design would advise these groups. While all aspects of the design and fabrication of such a structure cannot be tackled by these twenty groups, a significant proportion can be studied, with the added benefits of being related to each other, thus requiring a higher level of design optimization along with the excitement of the application of the end product.

This effort requires more than the usual background preparations by the specialist advisors since none are expert on the application. They will need to read a bit on lunar structures and issues related to the lunar site. They need to be willing to exchange ideas with each other and to get up to speed on the relevant science and technology.

In the end, a very exciting and potentially useful set of products will be analyzed and fabricated. An effort will be made to publish and present the results of the overall effort.

POTENTIAL DESIGN PROJECTS

- Structure,
- Airlocks,
- Materials Handling,
- Fluids/Piping Design,
- Recycling Technologies,
- Shielding Design and Handling,
- Energy Sources: Solar/Nuclear,
- Electromechanical Systems,
- Rover/Surface Transport.

These are general examples only. Since in our Capstone course, students are required to design *AND* manufacture their components, the design projects need to be considerably focused to ensure the possibility that student/advisor groups can not only analyze and design but also build their products.

EDUCATIONAL ORGANIZATION

For such a Capstone model to be effective, especially the first time it is attempted, interested faculty and industrial sponsors must make significant preparations. The Department must obtain reference materials for both faculty and students. An example is the book by Eckart [9]. This excellent reference is not only valuable as a resource, but also to help define and refine possible, doable, projects. Since such a Capstone set of projects is deemed worthy of several years of efforts, there are other references from space conferences that need to be acquired for a reference library for the course.

This list of possible projects needs to be thought out in great depth during the summer before the beginning of the semester. Ideas and paths need to be mapped out, as there will not be enough time to do so during the semester. A series of in-house seminars need to be given to faculty and teaching assistants associated with the Capstone course so everyone will be up to speed regarding the technology and design constraints.

As the semesters begin and work is limited, students would be encouraged to present their aspects of the lunar base design to their colleagues. This serves two functions, to learn about the larger framework, and to build camaraderie. They are all part of a larger adventure. Groups will also, in a sense, be competing with each other. They will not want to be seen as coming up short in their designs or manufactured products.

At the end of the second semester, where each design group will be presenting their analysis and designs, the scale of the year's work will finally become apparent. It can truly be a singular event, worthy of widespread publicity, much to the pride of the Department.

CONCLUSION

This paper outlines ideas that are in the works and are under discussion in the Mechanical and Aerospace Engineering Department at Rutgers University. As mentioned earlier, quite a bit of preparatory reading and work is needed to make the capstone course experience for the seniors a fruitful one and the process is just starting.

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