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STUDENT DESIGN PROJECTS SET IN THE SPACE ENVIRONMENT

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ABSTRACT
In the coming decades, the rapidly growing interest in space exploration and exploitation will require designers who have some understanding of the challenges to be faced in the space environment. Student projects intended to give some of that understanding need to be based on information available from the 60 years since Sputnik 1 went into orbit. This paper extracts some of the underlying factors which influence designing for space from launch to low orbit, travel in deep space and coping with asteroid, moon and planetary environments. From autonomous probes to the complications of human crew and even extra-terrestrial colonization could all be part of the career path for designers now on higher education courses. This paper is intended to give an introduction to the challenges which could form part of design teaching or a foundation for literature research. Some differences from the normal Earth environment are quite subtle, but can have profound effects on design thinking. Students introduced to these factors usually rise enthusiastically to the challenge influencing their approach to other unrelated design activities.

Keywords: Projects, Space, Imagination, Sustainable Future.

1 INTRODUCTION

In the early part of my engineering design career, I worked in the UK on British and European space projects, then later in the USA on the design of Apollo Skylab, at the same time as the first trips to the Moon. This introduction to the imaginative challenge of designing for an environment I hadn't experienced affected my subsequent thinking so that I was more able to perceive things from an unusual perspective. Many years later, when I had to find projects to provoke an imaginative response from students, I drew on my space-work experience to awake a sense of both challenge and reward by asking them to tackle and solve design challenges in an unfamiliar environment. This paper sets out some of the differences between Earth-bound and space environments, which require designers to re-think their design mind-set, whatever their prime expertise. This can lead to a more imaginative approach to other design challenges.

2 DIFFERENT ENVIRONMENTS

2.1 Manufacture, Transport and Launch

For many more years, every piece of hardware used in space will be designed and made here on Earth. Many pieces of space hardware are light and delicate, intended to be used in a low gravity environment. However, they must first survive the manufacturing time spent in Earth gravity and the transport, testing and launch loadings imposed in order to get it to space. There are two basic approaches. You can design something in its final form, robust enough to withstand the rigours of high loading, but as light as possible. Alternatively, you can fold your delicate device into a compact, well-supported package, to survive heavier loads, which can then unfold in space to perform its intended function. This latter option may also be necessary just to fit the device within the space available in the launch vehicle.

The weight restrictions on items to be launched into space are severe. With chemically based rockets, escaping Earth's gravity and attaining orbital speed is only just possible. With current technologies, about 90% of the take-off weight of a launch vehicle is fuel and oxidant, even then as fuel tanks are emptied they must be discarded. Systems which can use oxygen from the air for part of the journey, such as the UK's Skylon vehicle, due for launch early in the next decade, should increase fuel efficiency. To achieve the low weight, safety margins on structural loadings on unmanned flights are as low as 10% and on manned flights 30% on the worst possible load cases.

All of this means that lightweight materials and construction techniques are the norm. A component might be made to serve more than one purpose (structure, thermal radiator, meteoroid protection and electrical conduit perhaps). Where launch may induce vibration from both the rocket motors and aerodynamic turbulence, structural stiffness may be more important than strength. All components are subject to testing before flight and duplicate models are often tested to destruction. Long duration vehicles spend extended periods in intense cold in vacuum chambers.

Once in orbit, or on their way to distant planets, small motors are used for course changes or corrections. Highly efficient low-thrust motors, using ionised gas, can be used to give long-duration gentle acceleration to high speeds. Under these low-gravity conditions, solar arrays and communication antennae can be deployed on lightweight supports. Care must be taken to ensure that any thrust acts through the centre of mass, CM, of the whole vehicle or it will veer off course or tumble.

2.2 Earth Orbit

A very low orbit implies a short life, since the slight atmospheric drag will eventually cause a satellite to fall back to Earth. All current lower orbit satellites are required to have some de-orbit system to reduce the build-up of debris. Power may be provided by batteries sufficient for the expected life. Most satellites are launched into orbital inclinations convenient to the launch site. Other inclinations require some vectoring thrust to adjust the path. Launch sites near the equator gain impetus from the rotation of the Earth. Polar orbits are usually achieved from higher latitude launch sites. GPS, for example, relies on clusters of thirty or more satellites in various orbits to ensure that there are always at least three in view from anywhere on Earth. Polar orbits can be arranged to be "Sun-synchronous" passing within view of all parts of the Earth's surface in daylight, to record weather or the progress of events such as forest fires, glacier reduction, or coastal erosion.

Further out, at 35 786 km above the Equator, a circular geostationary orbit allows a satellite to remain over the same point, orbiting in time with the Earth's rotation. This is used mainly for communication and weather observation satellites. Some parts of this orbit are becoming crowded with life-expired hardware, which must be moved to more convenient places. Perhaps, in the future, as access becomes easier, there will be large structures in this orbit to which components can be added or removed.

Where any two large bodies are in mutual orbit, as with the Earth and the Moon, there are five gravitationally null points, known as Lagrange Points. These are shown in Figure 1.

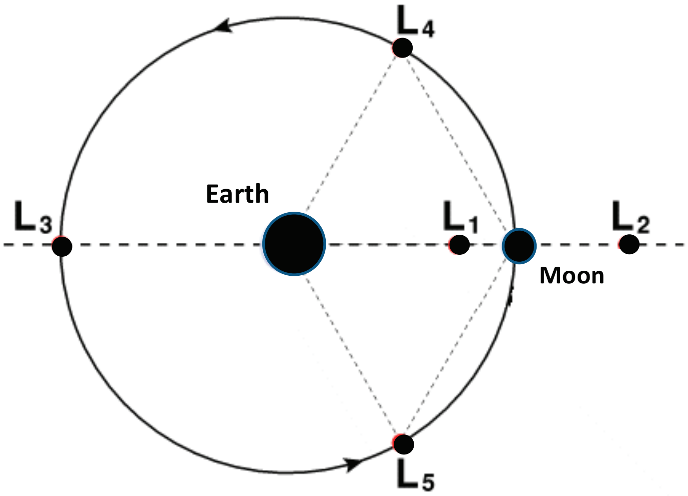

Figure 1. Lagrange Points in the Earth-Moon System

The three collinear Lagrange (or libration) points (L 1, L 2, L 3) were first discovered by Leonhard Euler a few years before Joseph-Louis Lagrange discovered the remaining two in 1772, in a mathematical analysis of orbital mechanics. These are neutral points within the gravity field. (L4 and L5 are also called "Trojan Points" because moons at those points in the Sun-Jupiter system are named after Trojan heroes.) Satellites placed in these positions revolve with both bodies, rather than orbiting either one. L2, behind the Moon could be used for radio-astronomy, since it is shielded from Earth's noisy radio transmitters, but arrangements would have to be made to communicate its observations. L4 and L5 are particularly stable, a satellite could orbit them. They have significant potential for future large space stations, as a space laboratory, or perhaps a "space-dock" for the construction of large spacecraft. They could also be used to relay communications from much of the far side of the Moon and L2. L1 in the Sun-Earth system is currently used by a solar observatory giving advanced warning of solar flare activity, which can affect communications and power distribution.

3 MAJOR ENVIRONMENTAL FACTORS

3.1 Gravity

The gravitational force pulling us down towards the centre of the Earth is resisted by the ground we stand on. The resulting internal stresses within our bodies give us a subjective feeling for weight. For a vehicle in orbit, the "centrifugal" forces of following a curved path balance the gravitational forces. Satellites follow an elliptical orbit with the Earth at one of the focal points. Parts significantly below the vehicle's CM, aren't moving quite fast enough for their orbital height and will try to fall inwards. Higher points experience the opposite effect leading to a tension across the vehicle, sometimes referred to as the "tide". A long thin structure will tend to remain radial to the Earth. Since the pull of gravity is higher at the lower end, this puts the centre of gravity slightly lower than the CM and produces a pendulum effect orientating the vehicle.

Equipment, or people, within the satellite, experience "free-fall". There is no up and down orientation or experience of weight. This allows experiments, such as in crystal growth or fluid mixing, without gravitational effects. Fluid components can be mixed, which would separate on Earth and other unexpected effects can happen. One experiment took a sample of maturing Scotch whisky to the ISS for some months, producing different subtle flavours from an identical sample left on Earth. Distillers are now trying to reproduce those flavours on the ground. Thermal convection doesn't happen, so fluids must be mechanically mixed when being heated and the atmosphere in a manned vehicle must be continuously stirred by fans to provide cooling and a breathable circulation for crews.

During launch, the thrust stops when stages burn out and fall away. The lack of weight means that the liquids in the tanks of upper stages float away from the outlet pipes and can't be pumped to start the engines. Usually, small solid fuel rockets fire to give some thrust, settling the liquids, allowing the pumps to work and start the engines on the next stage. The similar problem occurs in any vessel not completely filled with liquid in free-fall, the liquid floats or sticks to the sides. Thus, equipment on a space station from drinks dispensers to water purification systems would have to be designed to overcome the problem. One solution is to have flexible walled "concertina" vessels able to adjust their volume so as to always remain full.

3.2 Vacuum

In the absence of an atmosphere, any oxidation layer on metal will tend to evaporate leaving a bare surface. Two such surfaces moving into contact will tend to weld together making further movement impossible. If the operation of the satellite requires such sliding motion, vacuum resistant coatings must be applied. The design of the satellite must allow all parts exposed to vacuum to "outgas" as the launch progresses and external pressure drops, otherwise the internal pressure could burst the structure. This includes cellular structures such as foam or honeycomb sandwich panels, which must be perforated. In a vacuum, an electrical charge can spark across longer distances than in air. Wires and other conductors, such as in circuit boards or connectors, which on Earth could be left bare, must be insulated or sufficiently separated, depending on the voltage.

3.3 Radiation

The Earth's atmosphere, and its magnetic field, protects us from the radiation in space, most of which comes from the Sun. Radiation consists of both electromagnetic radiation and atomic particles. It can degrade some materials and erode exposed surfaces such as solar array panels and instrument lenses and mirrors. Some will penetrate structural materials and presents a clear danger for long-term exposure. In times of intense Solar activity, the crew on the ISS take shelter in a well-protected section of the station. Recent research has shown that the human brain is particularly vulnerable and can suffer significant permanent damage [1]. Perhaps we could generate a magnetic field around a spacecraft, or even a Lunar or planetary habitat, to increase the protection level.

Radiation also exerts a slight pressure, which can produce a significant force when acting on a large area. This can be used to advantage with solar sails deployed when moving away from the Sun and turned edge on to minimise the pressure when moving towards it. In this way a vehicle accelerates on each orbit, gradually raising its height and speed. The effect is small but over a number of orbits can have a useful result. It has been proposed that a solar sail race could be held from low Earth orbit to the orbit of the moon, taking some 18 months or more. The large solar sails would be visible from the ground for most of the world's population. The gambling industry would make a fortune.

3.4 Micro-meteorites

There are three major sources of high-speed particles in space. The Sun is a strong source, which varies with solar activity. The Earth passes through twelve known streams of particles following the paths of old comets orbiting the Sun. These appear as "shooting stars" in the atmosphere at particular times of year. There is also a general background of particles orbiting the Sun, which can come from any direction. In low orbit, there is also a danger of impact from space debris, remnants of previous satellites and their launchers, or impacts between satellites. A particle with a mass of a few grams, but moving at some 50 000 Km/hr can penetrate structures and cause significant damage, particularly on pressurized areas.

To shield a sensitive area, such as a manned module, a single sheet of material needs to be relatively thick and heavy to stop a high-speed particle. A lighter solution is to use two thin sheets spaced apart. A particle will penetrate one sheet, but break up into smaller pieces each with insufficient energy to penetrate the second sheet. Exposed equipment should be shielded as much as possible. High pressure steel gas tanks, to replenish the atmosphere on Apollo Skylab, had to have protective shielding even though they were 25mm thick, after ground tests showed them to be vulnerable.

4 FUTURE PROJECTS

4.1 Nanosatellites

The miniaturization of electronics has generated a growing market for small satellites in the 20 Kg, 50 Kg and 100 Kg ranges. In the past, these have often been added on to launches of larger satellites. Now dedicated launches are putting up clusters of "NanoSats" perhaps for communication and navigation, or shorter lived scientific or observation purposes in lower orbits. (India recently launched 104 satellites on a single rocket.) The best known are standard "CubeSat's", made in modules of a mere 10 x 10 x 11 cm. Larger satellites are made by joining several modules end to end. These are a way of getting cheap access to space for short periods, within the budgets of research groups and even undergraduate projects. The UK has been a leading producer of these small satellites for some years, despite not having had a very active government sponsored space programme until recently.

4.2 Asteroids

The asteroids, which mainly orbit between Mars and Jupiter have the potential of being a significant source of materials. Twelve Near-Earth asteroids, which are accessible with current rocket technology, have been identified as early targets for exploitation. They have a low speed relative to Earth and could be moved to a more convenient orbit or even a Lagrange point for refinement. The rocket power needed to move materials to Earth orbit would be similar to lifting-off from the Moon, but the transit time would be longer. Some asteroids are known to have large quantities of useful materials currently becoming scarce on Earth. Extracting or mining materials from a low-gravity asteroid, and carrying out preliminary processing, will require the design of some interesting equipment.

4.3 Exploration

Most of the planets, and a few of the moons, in the Solar System have now been visited, at least by a fly-by craft, less often by an orbiting satellite and a few by landers able to examine the surface environment. The Moon is the only extra-terrestrial body to have been visited by people, and the last of the 12 people to walk on the Moon, Gene Cernan, left 44 years ago. Robot explorers have already travelled across the surface of Mars. Advanced plans for people to re-visit the Moon and travel to Mars are already in place in the USA, India, China and several other countries. Probes have sent back data from Saturn's moon, Titan, and on a comet. Other vehicles orbit Saturn, Mars and soon Jupiter, and have flown past most of the other planets. The Voyager probes, after some 40 years of travel, are far beyond the orbit of Pluto, and still providing useful information.

4.4 People in Space

Manned spacecraft introduce further complications. With people in control, decisions can be made with more flexibility and problems can be overcome more easily. However, the immediate requirements for a breathable atmosphere, food, water and the disposal of human waste, even on short-term voyages, take up considerable effort in design and execution. For longer term trips, such as long stays on the ISS, a stay on the Moon or a voyage to Mars in a decade of two, exercise to reduce loss of bone and muscle, the ability to grow food, and re-cycling systems will all add a considerable burden on the spacecraft designers. At all times, safety is paramount, but the risk is high.

4.5 Colonizing Moons and Planets

Within this century, we are likely to begin long-term stays and then colonization of the Moon and Mars. Designs for Lunar habitats, transport, temporary shelters and more will have to survive a 28-day long cycle of solar heat days and Earth-lit dark nights. The sooner we begin to explore the design options, the more time we have to evolve solutions which will work. Mars introduces additional problems of dust storms and very long voyages. Initially, all supplies will have to come from Earth, but gradually locally produced articles will reduce their dependence. Full self-sufficiency is unlikely for a long time.

4.6 Colonizing Space Itself

Space stations have been envisaged for more than a century. Early ones orbiting the Earth will probably be laboratories, like the current ISS, then docking platforms to construct deep space vehicles and then habitats for permanent occupation. A similar sequence will probably be followed as humanity spreads further out into the solar system. It has been proposed for many years that a rotating station could use centrifugal accelerations to produce the effects of gravity. This ignores the human balance system, which is very sensitive to rotation making moving around difficult, probably inducing motion sickness. This needs to be carefully explored before embarking on a potentially very expensive mistake.

Asteroid mining and other activities will require people to live long-term in space, with frequent space-walk activities. The effects on the human body are being explored on the ISS, and it may be necessary to bring crews back to Earth after a period in space. If longer durations are possible, then proper living quarters would need to be designed, along with medical and other facilities.

5 SCOPE FOR ACADEMIC PROJECTS

5.1 General Approach

One of the major obstacles to designing for space is having an Earth based imagination. In the various environments I have described, everything we are used to is affected. In order to design we must be able to imagine ourselves in a different world (literally) from the one our instincts tell us about. We can take nothing for granted. There are a number of technical sources giving in-depth details of the analytical aspects of spacecraft design [2] and a wide range of sources of details of past projects [3]. In addition, there are many articles in technical magazines [4] and web sources [5] [6] [7].

5.2 Examples

In an OU Summer School, I gave an introduction to the challenges presented in a Lunar environment, when considering the design of a town size colony under a dome maintaining an Earth normal pressure. I allowed the students to decide for themselves which aspects to consider in small groups. I gave examples such as the design of structures, exercise in low gravity, clothing and hairstyles (hair and clothes don't "drape" in the same way), keeping cool when air circulates more slowly. In low gravity, transport will have difficulty accelerating, braking and cornering, when there is lower weight on the ground to generate friction. The same applies to running or most of our sporting activities. (Archery is one which could be practiced with normal equipment.) We reassembled a few days later to discuss the outcomes. Various examples of light structures, water distribution, and sports equipment were described. However, a few of the groups had worked together on personal transport. Clothing would include a light cloak. To travel across the habitat, you would enter a parabolic running track and begin to run. The rotation would increase your apparent weight allowing you to accelerate to a faster speed. Leaping from the top of the parabola, you could spread your cloak and hang-glide to your destination using air circulation fans to gain lift.

In free-fall, similar project investigations could include: surgery, hair cutting, clothing repair, food growing and cooking in orbit (How do you make soup, when there is no convection and you have to keep the lid on? Design a mixer or blender?). Almost any product we use here on Earth will have to be re-designed for free-fall or low gravity use. A careful consideration of the differences in the environment, and a little thought in setting a design project, is often enough to get student imaginations to rise to the challenge. Often unusual solutions will be found by the students and be a learning experience for the academics as well.

6 CONCLUSIONS

This paper is inevitably only a brief overview of some of the factors to be considered when designing for the space environment. Our experiences in space show that people can adapt to a free-fall environment for long periods. The challenge is to provide them with the surroundings they need to enjoy the experience and thrive. Students are asked to solve problems for which there are no existing solutions and any result will be interesting. This is not just thinking outside the box, but thinking outside the planet.

The experience allows students to reconsider the implicit assumptions they make in all their design work, even if they never work on space projects again. This gives them an overview of the design activity which will be a significant benefit. It may even help them take a career path they had not previously considered.

REFERENCES

There are many sources of information on space activities and this is only an indication of those available.

[1] “Space Radiation Risks to the Central Nervous System,” F. A. Cucinotta et. al. *Life Sciences in Space Research*, Vol 2 pp 54-69, July 2014.

[2] “Elements of Spacecraft Design”, Charles D Brown, AIAA (and many other texts).

[3] “Haynes Manuals” series, for example, includes a number giving technical details of many historic and current launch vehicles and spacecraft (some fictional). Go to www.haynes.com

[4] “Designing for Spaceflight”, Colin Ledsome, “Engineering Designer” (IED Journal), July, September and November (3 parts) 2016.

[5] NASA website: www.nasa.gov is an extensive source of historic and current information and future proposals.

[6] National Government Departments such as the UK’s Space Agency: www.gov.uk/government/organisations/uk-space-agency

[7] Learned societies such as the UK’s British Interplanetary Society: www.bis-space.com for information on involvement in current activities.