Meeting the Challenge of the Undergraduate Space Lab Experience

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Abstract

Giving undergraduate students hands-on experience for space-related subjects is challenging. The instructor must create a lab experience that familiarizes students with the concepts used in testing space vehicles and hardware, allows for comparison of test results with analysis and illustrates important principles used in spacecraft design by using a ground-based experiment.

In industry, the tests done for thermal vacuum, vibration, mass properties, communications, sensor testing and propulsion (among others), generally require elaborate and expensive equipment. Such equipment is generally outside of the budgetary range of an undergraduate university. Using modest resources, the instructor must develop experiments that streamline these tests for illustration purposes, and simplify the tests to illustrate key principles.

This paper covers the experiments we have found helpful in meeting these goals and compares what we have done in our space lab to what has been done in other undergraduate aerospace programs.

I. Introduction

The US Naval Academy[1], Virginia Tech[2] and the US Air Force Academy[3] have all implemented some form of space laboratory experience for their undergraduate students. In addition, CU Boulder has also created several lab experiences related to spacecraft for their undergraduate students. The Naval Academy[1] has focused on Communications and Telemetry labs but has also done a few things with other aspects of spacecraft such as power, thermal control and a vibrations lab very similar to the one we present in this paper. Virginia Tech[2] has created several lab experiences involving satellite tracking and telemetry, in addition to a spacecraft attitude dynamics lab using an attitude dynamics and control simulator. Virginia Tech's undergraduate students have also designed and built a "nanosat" which gives the students direct involvement with the design of spacecraft. Several other universities have also been involved with the design and build process of a small satellite. Of particular note in this paper is the experience at the US Air Force

Academy^3 (USAFA) in using the design of a small satellite to teach students about spacecraft design. USAFA has launched several small satellite programs successfully and in doing so has provided the students real world experience with the end-to-end spacecraft design process. All of these efforts are commendable, but many require significant resources. Our efforts here are to provide a hands-on experience that illustrates principles used in space, but utilizes fairly low-cost systems to do it.

Our design sequence targets designing vehicles that will operate in space, and are assumed to get there by using a commercial launch vehicle. Because of this, our lab experience must address the concepts and testing used for space vehicles. Even so, most of the equipment used for spacecraft testing is fairly expensive and the analysis that accompanies the experiment is beyond our undergraduate, junior engineering students' level. Given this, our experiments are fairly simple, but illustrate some of the same concepts that are used in industry to design and test spacecraft.

Our class consists of a lab experiment for most of the subsystems on a spacecraft: structure, attitude dynamics and control, mass properties, power, thermal, communications, propulsion, manufacturing, and orbits. In addition to the labs, the students are required to do a final project in which they build equipment that either illustrates a concept used in spacecraft design, or that can be used by future generations for testing purposes.

This course is offered in conjunction with, but not necessarily simultaneous to a course in space systems. In the space systems course, the students are introduced to the theory of each subsystem and are introduced to the design drivers for each subsystem. The lab complements most of these subsystems by giving the student a hands-on experience for each of these subsystems.

II. The Labs

Structures:

Because our students get a fair amount of instruction in structures, our focus is not on determining buckling loads. Instead, we offer a lab on vibrations and a lab on composites and sandwich construction. It is critical that spacecraft survive the vibration environment they encounter during launch and many spacecraft use composite materials and sandwich construction in at least part of their design.

The vibrations lab consists of a one-dimensional part and a two-dimensional part. The one-dimensional part consists of finding the natural frequencies and mode shapes of a beam of various materials by clamping the beam to a vibration table. This experiment is very similar to the vibrations experiment described in (1).

The lower modes can be found visually and all modes can be found with an oscilloscope. The lower natural frequencies can be found by observation for the first few modes and the mode shapes can be visually observed. By using a strobe, the mode shapes can be "frozen". When the frequency gets too high, the magnitude of the deflections becomes too small to observe, and the students must find the modes with the oscilloscope and find the nodal locations by lightly moving their finger across the beam to where they feel no vibration. This is a fairly simple experiment, but the students leave with an understanding of resonance and natural frequencies.

Finally, we have the students compare their results to the theoretical modal frequencies and nodal locations[4]. This requires them to look up the material properties, calculate the natural frequencies and nodal locations, see how much error there can be and identify some of the possible sources for the differences in the measured locations and the theoretical locations.

Two-dimensional modes can be found as well. This experiment uses a flat plate, attached to the shaker table, and illustrates the two-dimensional mode shapes by putting sand on the plate. When the natural frequency is reached, the sand jumps everywhere except at the nodes and settles into the nodes, illustrating the nodal lines for the given mode. This was done very successfully in our spacecraft detail design class where the students built a spacecraft model structure and were testing for natural frequencies and mode shapes. In the laboratory course, this was used solely as a demonstration of what modeshapes look like in two-dimensions.

The students are introduced to the concept of a system's natural frequencies in both their dynamics class and their differential equations class, both at the sophomore level. However, the concept of multiple natural frequencies and modeshapes that occur for continuous flexible systems is not familiar to them. This experiment illustrates these properties of materials as well as shows how forcing a system at its natural frequency can lead to high amplitude oscillations – something spacecraft designers must be cognizant of. The experiment is laid out fairly clearly and there is little difficulty with the equipment used.

Because many spacecraft parts are made of composite materials, including materials with a honeycomb core, we have the students go through the exercise of building a composite, flat plate with a honeycomb core. We were fortunate enough to have some honeycomb material donated and we use this in the lab. The students learn about the process – how to mix the epoxy, roll out the layers, flatten the layers so that no bubbles occur and adhere the composite plate to the honeycomb. This is also what students in past detail design courses have for both making the backing for solar panels and for the flat, load-bearing parts of their structure. Finally, we have the students break a sample of their plate in the tensile tester with a three-point bend fixture to determine the bending strength.

This is a lab in which the students really get their hands dirty. The students seem to enjoy the opportunity to get their hands involved and this lab experience complements nicely their intellectual study in other classes.

Spacecraft Attitude Dynamics:

Spacecraft attitude dynamics and control is fairly difficult to illustrate. In addition, to illustrate autonomous control properly, students need more training in control systems than they have at the junior level. Attitude dynamics, however, can be illustrated at least in one dimension. Last year, our student project was to build a device that illustrated momentum exchange, which is used on spacecraft to change the orientation of the spacecraft without using propellant. The students built an external structure, meant to model the spacecraft, with a spinning wheel inside. The external structure is mounted on a bearing and thus is free to rotate. The wheel is controlled by an external speed control on the wheel motor and is attached to the external structure by a bearing. A laser pointer is placed on the external structure and the student changes the wheel speed to move the laser pointer onto a target and maintain it there. Changing the wheel speed causes the external structure to move due to conservation of momentum, so that the student can experiment with moving the external structure around, as well as cause it to stay on the target.

This illustrates the concept of momentum exchange, which is commonly used to control spacecraft. This year we used this as one of the experiments in the space lab for the second generation of students in this lab. In the lab, the students were required to measure the external structure's inertia by producing a constant rate on the external structure. The errors on this part of the experiment were very high and some work is still required to refine the experiment. The second part of the experiment was to compare the rate of wheel speed change to the torque applied to the spacecraft by changing the wheel speed while a torque is applied to the external structure, in an attempt to keep the external structure still. The students keep the laser pointer fixed on a target on the wall to visualize this. Their experimental results are compared to what they would expect due to momentum exchange with a constant torque applied. Unfortunately, the errors here are also fairly high, mostly due to the difficulty in applying a constant torque with a fish scale. Future iterations of this experiment will improve on this.

Independent of the large errors as compared to the theoretical results, the students get to be the control system and thus experience how momentum exchange can be used to change the attitude of a spacecraft and to counter external torque applied to a spacecraft. The difficulties in getting the parameters of the experiment accurate was a source of frustration to the students, however, the experience with momentum exchange was good. Figures 1 and 2 show the two different versions of the momentum exchange device.

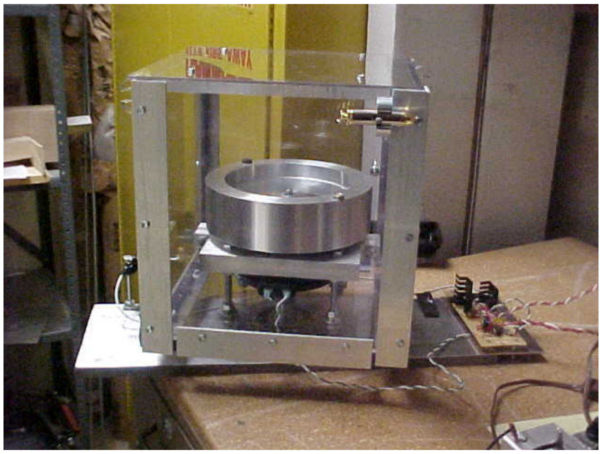

Figure 1: Momentum exchange experiment.

Figure 2: Momentum exchange experiment.

Virginia Tech has an attitude control experiment[2] that uses a spherical air bearing and can illustrate some of the same principles and in addition, allows the user to program a control algorithm. While this device gives the student a more comprehensive experience with the attitude control system, it should be noted that this device is fairly expensive and is used in conjunction with the research of the author of reference (2). While our experiment is not as elaborate or as comprehensive as this experiment, it does familiarize the student in a very involved way with the concept of momentum exchange.

Mass Properties Measurement:

To illustrate mass properties measurement, we measure both the center of gravity and the moment of inertia about one axis.

To measure the center of gravity, we use a set of three load cells that the students calibrate with weights and then measure the load produced by placing the load cells beneath three known locations on a single side of a spacecraft model. By knowing the total weight of the model, and the loads at known locations on the spacecraft, the center of gravity in two axes can be determined. This can be done on several faces of the model to determine all three components of the center of mass. Figures 3 and 4 show the students measuring the center of gravity of two of the design projects.

Figure 3: Students measuring the center of gravity.

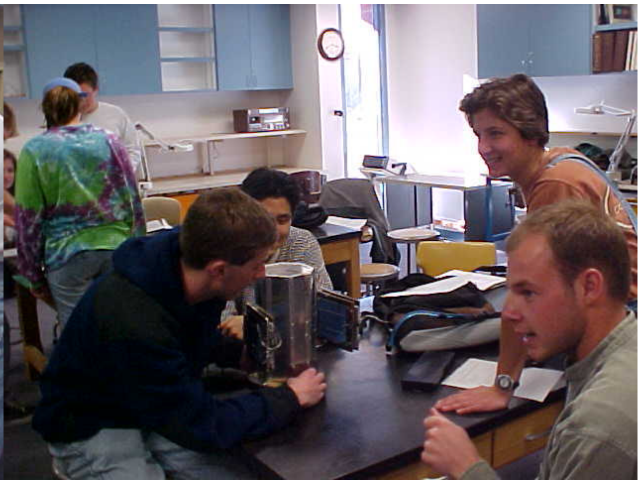

Figure 4: Students defining coordinate System on spacecraft model.

This experiment gives the students the opportunity to use what they have learned in statics as well as learning how to use a load cell and a data acquisition system. The students attach the load cells to LabView® and record the values off of the screen. The students are also required to select a coordinate system and learn that there are good and bad choices of coordinate system in terms of ease of measuring within the chosen system. The experiment is fairly simple to set up and the students are able to compare the results they get with where they would expect the center of gravity to be based on symmetries in their mode.

The inertia about one axis is determined by placing the model on a calibrated plate suspended by three wires. The device oscillates rotationally about the center of the system and the natural frequency can be both measured and predicted. By noting the change in natural frequency with and without the model, the inertia of the added body can be determined about the axis of rotation. The inertia measurement has not been implemented at the time of this writing, and is being designed as one of the student projects this semester.

Power:

We currently offer two power labs and have plans for at least one other. Since spacecraft must run various devices at different voltages, the bus voltage must be stepped down or up to the required voltage. One of the experiments has the students build the circuitry for a pulse width modulator, which varies the output voltage. The second lab requires that the student build a boost converter circuit. This lab uses a pulse width modulator to boost the voltage from some given lower voltage to a higher one.

We plan to implement a power lab similar to the power lab described in reference (1), in which a solar panel is attached to a controller to charge a battery and run a load. An additional lab in our plans for next year has students build an array based on some required voltage and current out of single (ruggedized) solar cells. This year we also had the students play with soldering solar cells together in series and they had the direct experience of seeing how fragile and difficult to solder the solar cells are.

Thermal:

In the vacuum of space, the only external factor acting to heat or cool the spacecraft is radiation. Simple radiation can be modeled fairly easily for selected shapes and with a few assumptions. A thermal vacuum chamber with an appropriate light source to model the sun is the ideal tool for this kind of testing. However, thermal vacuum chambers are fairly expensive, so to keep the costs down, our experiment uses a vacuum jar for the vacuum chamber and a halogen lamp for the light source – outside the vacuum jar. Inside the jar are three flat, rectangular plates of different materials that are instrumented with thermocouples so that the temperature can be read outside the chamber. The light is shone on the flat plates and the students record the temperature as a function of time. This gives them the time constant for stabilization of the temperature and the steady state temperature. The steady state temperature can be calculated and the students can compare their lab result with their predictions.

It should be noted that the Naval Academy in reference (1) has done a similar experiment, but without the vacuum jar. Instead, they have used a high-powered light source so that the effects of convection are minimal compared to the radiation effect. In their experiment, they used various coatings and multi-layer insulation to show how these surface properties affect the steady state temperature.

Communications:

Because of the remote nature of spacecraft, communications are a crucial part of almost any spacecraft. While the entire field of spacecraft communications cannot be illustrated in this class, a few key concepts can. The two that we have chosen to illustrate in this lab are the effect of noise on a signal and the relationship between antenna size, beam-width and transmit frequency.

The noise experiment is meant to show how the signal to noise ratio affects a signal. There must be some minimum ratio for the signal to be interpreted at the receive end. The experiment uses a known signal level in the form of a pure tone and combines it with a fixed noise source and puts the output through three ways. One output is a distortion analyzer from which you can determine the signal to noise ratio directly. Another output is an oscilloscope on which the students can see the signal with no noise, where the pure tone is seen as a pure sine wave. When the signal to noise ratio is degraded, the noise on top of the signal is apparent as it degrades the pure sine wave. The last, and probably most painful output for the students, is a speaker. The students can hear how the test tone degrades as the signal to noise ratio goes down. Increasing the signal to improve the signal to noise ratio means the students have to listen to a constant tone while they assess both the distortion analyzer and the oscilloscope. The students are able to vary the signal level to see the effect of the noise on the signal.

The antenna experiment is used to determine the beam-width of a given antenna, to find the nulls and observe the dependence on wavelength. We use a small, 24-inch diameter, parabolic dish antenna. Because the antenna experiment requires a large space to test the antenna, we use the auditorium at Embry-Riddle to do this experiment. A microphone is set up at one end of the room and the microphone output is attached to an amplifier. The signal goes from the amplifier to a display, which shows when the signal is at the 3 dB down point from the maximum signal. The parabolic antenna is set up at the other end of the room, opposite the microphone, and a small speaker is placed at the feed so that a signal (consisting of a single frequency) can be reflected off the dish. The antenna is on a gimbal so that a student can rotate the dish towards the microphone at the other end of the room and rotate the dish away from it. As the dish moves, the signal from the microphone is observed and the rotation is stopped when the 3 dB down level is reached. Once this occurs, the angular displacement from the maximum signal strength at the receiver is measured, which gives the beam-width and the effective dish diameter can be calculated. The physical size of the dish can be measured and compared to the effective dish diameter. This gives the students an understanding of how antenna size is related to wavelength and to the beam-width. Since the beam-width is related to pointing accuracy, the students are better prepared in their design class to assess the pointing requirements of their communications system as well as the size of the communications system.

It should be noted that the Naval Academy in reference (1) has done some very interesting experiments with spacecraft communication, using various types of antennas to measure the antenna pattern and the signal to noise ratio.

Propulsion:
Because propulsion is the main method used to change or correct the orbit of a spacecraft, some aspect of the propulsion subsystem needs to be illustrated. Liquid propellants are quite volatile and require far too much care to be useful in this context. However, cold gas thrusters or solid rockets are fairly simple to implement and are far safer. While we may implement a cold gas

thruster experiment at some point in the future, we are not prepared to do that quite yet. Solid rocket motors, however, can be purchased at a reasonable price and are available to hobbyists. This semester, we plan to do an experiment with one of these solid rocket motors. While we have not implemented this for the space lab et, several years ago, another professor had his students prepare a test stand for measuring the thrust profile of a small solid motor. We may do any of the following: predict the thrust profile and then measure it, or predict the height that the rocket will attain and then measure it.

The Air Force Academy[5] has done some very nice experiments with rockets in which the students build the rocket and fuel and test it. They have done both solid rockets and liquid rockets and have built several test stands and instrumented their rockets for testing.

Manufacture:

In the detail design class, which the students take in their senior year, the students are required to build a model that contains several spacecraft subsystems. Because of this, we have made a machine shop lab in their junior year, space lab, in which the students learn the capabilities of the machine shop equipment and gain some experience using it. We have the students build a simple metal box to illustrate the use of the equipment. It also illustrates how challenging it is to build a fairly simple object. The box looks great in the paper design, but the students find that the design has flaws that are related to the limitations of the manufacturing process they are using and that it is difficult to attain the required tolerances. In one case, we gave them a design that could not be cleanly implemented with the tools available in the shop. They were then required to discover a way around the design flaw with the tools available.

Orbits:

A lab experience with an actual orbit is difficult to achieve. However, a tool that illustrates orbits nicely is the Satellite Tool Kit (STK). The lab we are planning to do for orbits introduces the students to STK. This gives them the opportunity to have a visual image of the orbit, ground track and viewing geometries. They were also able to generate reports to compare with calculations they do in their orbital mechanics class work. We will do this for the first time this semester, so we don't know yet how it will work out. Students in the design class, however, have learned to use it quite effectively to illustrate the orbits part of their design. This will give the junior level students an opportunity to become familiar with this tool prior to the design class and hopefully, cause the orbital mechanics class to be more meaningful.

Both Virginia Tech[2] and the Naval Academy[1] have used the Satellite Tool Kit® in their labs to illustrate various elements related to orbits and ground tracking.

Final Project:

Finally, we have the students do a final project in the space lab. Last year was the momentum exchange experiment, which the students designed and built. This year, we are planning on having the students design and build an air table and/or a yo-yo de-spin device, similar to the one used at CU, Boulder, as mentioned below[6]. This final project helps the students to think about some of the concepts used in space and allows them to build something that can be used by future generations of students.

III. Space Lab Experience at Other Schools

Our ideas of what aspects of space we can illustrate in a laboratory environment is limited to our research and experience. In order to enhance our offerings and to build on what other successful programs have done, we have contacted several other schools to see what types of laboratory experiences they provide their students that are related to space. The two universities we contacted are Colorado State University at Boulder (CU, Boulder) and the US Air Force Academy in Colorado Springs.

CU, Boulder, has a de-spin experiment which also shows the use of momentum exchange to spin down a spacecraft. Also, they have a telemetry experiment, in which telemetry is obtained from a sounding balloon, collecting atmospheric data. The experiment shows how telemetry is collected as well as processes the telemetry and compares the collected atmospheric data to atmospheric models[6].

The USAFA began by using high altitude balloons (110,000 ft or 33.5 km) to collect data and transmit it back to ground. They now have a satellite program[3,5] in which students of all levels are involved in the entire process of building, testing, launching and monitoring their spacecraft. This gives the students the full scope of hands-on experience for an entire spacecraft project and is probably the most thorough way to teach key space concepts. However, it does require a fair amount of resources that we don't currently have.

IV. Future Plans

In the future, we would like to implement a lab that has students working with a power system that uses solar cells and a battery to power some small device, as mentioned above. This would enable them to go through the process of sizing their solar panel for the loads required for the device, sizing the battery for "eclipse" time (simulated) and building the circuitry to lower or raise the voltage from the solar panel to the voltage required by the device. By doing this, they would get experience working with a solar powered system, which is most commonly used in space, and be able to see the kinds of losses inherent in the voltage conversion process, among other things. Currently, several student teams are working on different projects related to this.

We would also like to implement some sort of telemetry lab, where students can see how data is gathered, broken down for transmission, re-created at the other end and processed to obtain meaningful information. We don't currently have a plan for how to do this, but it is something we are thinking about. Reference (1) from the Naval Academy has some good experiments that we can learn from.

Finally, as we see what other schools are doing in this area, we may also adopt other labs that are useful in illustrating spacecraft concepts and are do-able at our campus[1,2,3,5,6].

V. Conclusions

We have been able to find a host of lab experiences that illustrates concepts from most of the major subsystems of a spacecraft. This has given the students the opportunity to explore some of these concepts through experiments, in a way that they cannot get from a lecture class. Space experiments are challenging because of the vacuum and low gravity environments and simulating these environments can be very costly. We have created labs with minimal cost to illustrate some of these concepts in a way that balances cost with effectiveness of illustration. While there are some key subsystems to tackle in the future, we are on a path to improving the undergraduate experience of space.

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