The Virginia CubeSat Constellation Mission: MAE 4690 Spacecraft Design I
(Technical Report)

How will the Integration of CubeSats into Higher Education affect the quality of education for Undergraduate Engineering Students?
(STS Topic)

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Introduction

A CubeSat is a stackable small satellite classified as a nanosatellite. They are measured in Units or "U's" which are based on the volume of the spacecraft. One "U" consists of a 10x10x10cm cube that holds the instrumentation, electronics, and payload for the mission. Depending on the requirements of a mission and the volume needed for components, CubeSats can be combined to create 2U's, 3U's, etc. The Virginia CubeSat Constellation (VCC) mission is a collaborative project between four member universities in the Virginia Space Grant Consortium; The University of Virginia (UVA), Virginia Tech (VT), Old Dominion University (ODU), and Hampton University (HU). The aim is to provide undergraduate students with hands-on experience working on an engineering design project with real-world implications. Utilizing three 1U CubeSats built by UVA, VT, and ODU with data analysis support from HU, the scientific goal of the mission is to obtain measurements of the orbital decay of a constellation of satellites to develop a dataset on atmospheric drag and demonstrate the variability of atmospheric properties. Although the air density is significantly lower than the air near Earth's surface, the air resistance in the upper layers of the atmosphere where the three satellites are operating is still strong enough to produce a noticeable amount of drag. It is this noticeable effect from drag that motivated the conception of the mission. The data from the three CubeSats and the resulting density models from Low Earth Orbit (LEO) will aid in calculating deorbit times, help prevent collisions, and help predict the time and location of reentry for orbital debris.

The VCC mission at UVA takes the form of the capstone design course for Mechanical and Aerospace and is focused on having the students acquire a deeper understanding of engineering through active exploration of their specific sub-team topics and issues that the mission is facing as a whole. This style of student driven CubeSat projects is not unique to UVA or the VCC mission. Numerous other universities such as Stanford, MIT, Purdue, and Georgia Tech to name a few have similar programs that are significantly more established and have designed, built, and launched multiple CubeSats over the past two decades. The pedagogical approach shared between these programs is referred to as Project Based Learning (PBL). As described before, this structure differs from traditional classrooms in that it focuses on tackling a project where instructors facilitate, rather than offer direct instruction. The key to success for this approach and is creating an emphasis on active student exploration the topics that they are involved in. The motivation theory of education describes how students perform best when they are intrinsically motivated to do well, meaning they are curious and eager to learn the topic at hand. With a PBL structure and students actively researching topics they are interested in to work towards an engineering goal, I will analyze the structure of typical CubeSat capstone courses in different universities to identify the motivations of the participants within them.

Technical Topic

In 1979 NASA's first space station, Skylab, was reaching the end of its lifetime. The process of decommissioning the space station involved allowing it to deorbit and burn up in the atmosphere upon reentry. NASA scientists used atmospheric density models to calculate and determine that the location of re-entry would be the middle of the Indian Ocean. The initial drag predictions turned out to be more than what Skylab actually experienced while entering the Earth's atmosphere and as a result, pieces of the space station that would have fallen into the ocean fell across the Australian continent, hitting populated areas along the way. Although this turned out to be a blunder, it provided verification of an aerodynamic environment which was predicted and also provided data on the density model's reaction to rapidly changing solar flux over relatively short time periods (Dreher, Little, & Wittenstein, 1980). This accident may seem like it would have been a wake-up call for NASA to update its antiquated atmospheric density models, however publicly available atmospheric density models today still use approximations and data collected from over fifty years ago (Vallado & Finkleman, 2014).

The higher into the Earth's atmosphere one travels, the fewer air particles are present for objects to interact with. Although at any given point in time the drag effect on a spacecraft traveling in this location of the atmosphere is small, the effect of atmospheric drag is periodic in nature. This means that with each successive orbit, the drag force on the spacecraft increases. The periodic nature of these atmospheric drag forces results in the changing of the orbital characteristics of the satellite. Orbits are described as Keplerian Orbital Elements, which describe the size, shape, and direction of all orbits. When one of the orbital elements changes, it can have drastic effects on the resulting orbit. These forces, or perturbations, are not uncommon and include solar radiation forces from the sun, third body effects from the Moon's gravity, ocean tide forces, General Relativity forces, and geopotential perturbing forces resulting from the non-spherical shape of the Earth. Eshagh and Alamdari (2007) performed numerical integration calculations using mathematical models and orbital information from the CHAMP satellite to determine the magnitudes of these forces. What they found was that the geopotential perturbing force followed by atmospheric drag were they largest forces that the satellite experienced. What differs between these two forces is that geopotential perturbations are extremely well studied and taken into account, while atmospheric drag is highly variable and relatively imprecise even today. With atmospheric drag effects being the second largest forces on spacecraft, it is reasonable to ask why more is not being done to improve these predictions. The answer is that due to variability of the atmosphere with changes in solar activity in particular, it is incredibly hard to get long-term and reliable data. This is where CubeSats can help as a significantly cheaper method of acquiring atmospheric density data.

Currently “atmospheric density modeling represents one of the largest sources of error when determining and propagating the orbit of spacecraft and space debris in low Earth orbit” (Sagnieres & Sharf, 2017). Many models differ in what specific forces they emphasize and from these intrinsic differences, lots of uncertainties can arise. Using an Ornstein-Uhlenbeck process shown in Figure 1, Sagnieres and Sharf (2017) demonstrate the extremely variability of differing atmospheric models over time periods as short as 0.2 days. Each line in Figure 1 represents a different modeling method with the solid black line being the average of those methods. By using this stochastic framework, the authors are able to demonstrate that as a result of intrinsic differences between different atmospheric models, variability of results between them become drastic and it is useful to employ an Ornstein-Uhlenbeck process to obtain the least amount of uncertainty. On top of finding ways to limit the uncertainty, other scientists and mathematicians are attempting to utilize chaos theory and dynamical systems theory to provide lower uncertainties from this inaccurate data. Suryanarayanan (2017) utilizes these two theories to create a mathematical model that aims to predict events of space debris collisions and the probability evaluation of these collisions.

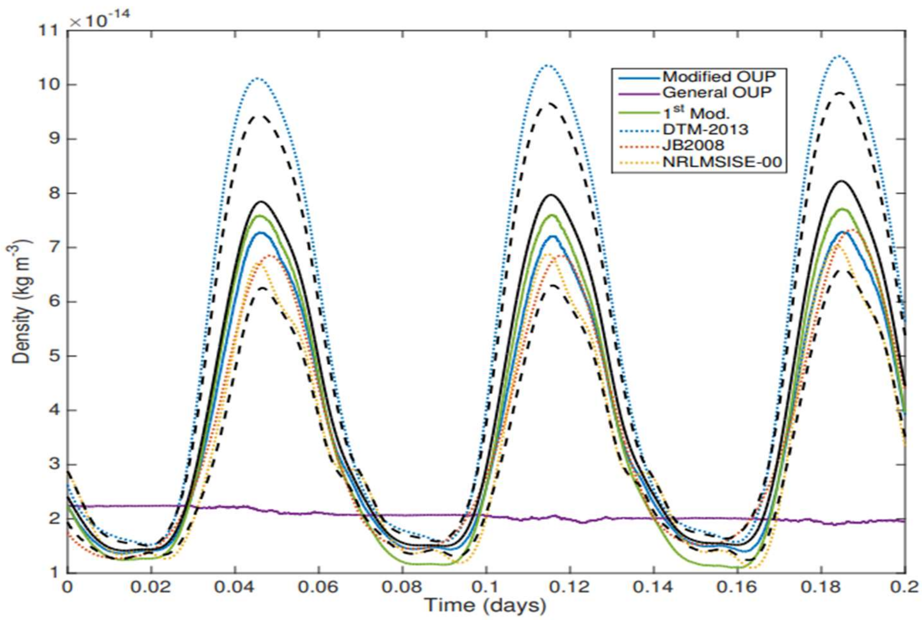

Figure 1: Ornstein-Uhlenbeck process applied to atmospheric density (Sagnieres & Sharf, 2017)

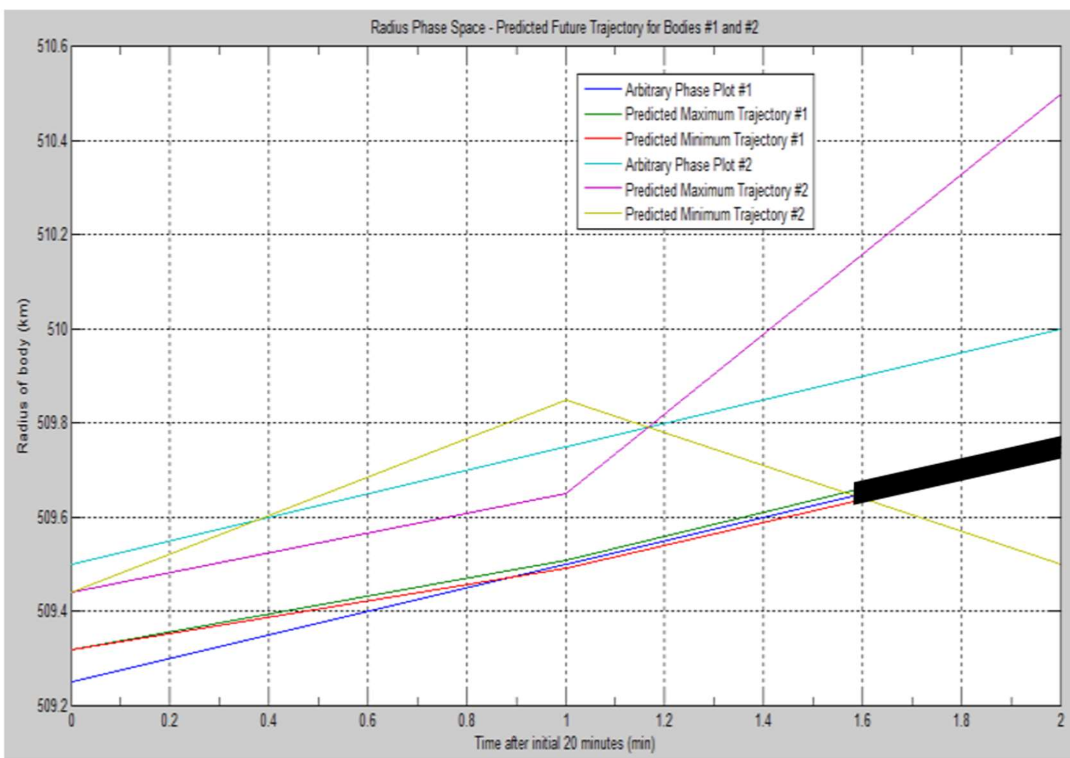

Figure 2: Identifying the collision probability (area shaded black is the convergence of trajectories in the radius-time space) (Suryanarayanan, 2017)

From the data that Suryanarayanan (2017) puts forward, some of which is displayed in Figure 2, the combinations of these theories could potentially offer insight into predicting orbital collisions within LEO. However, current progress that is being made in atmospheric density modeling comes through these novel approaches that attempt to treat the symptoms of inherently inaccurate data within atmospheric models rather than attempting to treat the root cause of the issue; Incorrect approximations of empirical data from 1967 (Vallado & Finkleman, 2014).

The VCC's proposed solution to this problem is to have each of the three satellites record position, velocity, and acceleration data in order to track the path that each CubeSat takes over the span of its lifetime. The ODU spacecraft will employ a drag brake in order to enlarge its effective geometric area and experience more atmospheric drag, causing the spacecraft to deorbit faster than the other two. This will serve as a comparable data set to UVA and VT's collected data to demonstrate how even small changes in area can greatly change the mission lifetime of an orbiting satellite. Current estimates show UVA and VT's CubeSats deorbiting between one and a half to two years and the ODU spacecraft deorbiting within one year. The data collected will then be sent to HU to create an atmospheric model at the altitudes which the spacecraft operated. It is the goal of the mission that this collected data will be able to potentially replace current data within atmospheric models. This will provide a more precise and accurate data set for public use when calculating deorbit times, predicting and avoiding potential orbital collisions, and determining reentry times and locations.

Student Self-Determination within CubeSat design courses

As a student studying to become an engineer, it is rare for projects to specifically model and emulate real-world engineering problems. The CubeSat was invented in 1999 by Bob

Twiggs and Jordi Puig-Suari to fill this role as an educational tool " to provide hands-on experience to students in space activities, allowing them to work on the entire cycle of a space project, from the initial concept until its operation in space" (Villela, Costa, Brandão, Bueno, & Leonardi, 2019). Since these were initially developed as educational tools, it was paramount that development, launch, and operational costs were as low as possible. Although initially viewed by the space industry as simply educational tools that hold little value besides teaching the engineering process, now the inherent value of CubeSats to satisfy niche data collection needs at low cost has been seen with the Air Force, the National Reconnaissance Office, DARPA, and even the National Science Foundation funding CubeSat development. Because of its development as an educational tool as well as its popularization in industry and government, CubeSats offer a unique path for students to involve themselves in serious projects with the potential to launch them into a very lucrative field.

One of the largest advocates for partnerships between industry and CubeSat development in education has been NASA. Through a number of programs such as the NASA Advanced Design Program (ADP), the NASA Student Explorer Demonstration Initiative (STEDI), the NASA Human Exploration and Development of Space – University Partners (HEDS-UP), the National Space Grant College and Fellowship Program, as well as these programs' successor the Revolutionary Aerospace Systems Concepts – Academic Linkage (RASC-AL), NASA demonstrated a significant interest in space education among students. Within the RASC-AL program, "each year over 250 students and faculty participate in the program, engaging over 2500 members of the public through academic and community outreach" (Cardenas, 2006). Implementation of the RASC-AL program has benefitted from using the lessons learned and the results and experiences of previous programs to build upon its ability to inspire young students.

From these programs, NASA concludes that through these real-life engineering and technology challenges, student motivation and interest in STEM is increased. This has led NASA to create programs such as the CubeSat Launch Initiative (CSLI) which directly pertains to CubeSat funding within institutions in order to stimulate CubeSat projects.

The key component that allows these programs to be so successful is the intrinsic motivation they inspire within students. Self Determination Theory (SDT) is a framework which describes the environmental factors and basic psychological needs which provide the optimal conditions for motivation. SDT argues that supporting individual's experience of autonomy, competence, and relatedness foster the highest quality forms of motivation and engagement for activities. Autonomy describes the capability of being the main driving force affecting one's behaviors, competence is an individual's ability and confidence to perform tasks, and relatedness is the desire to experience connection between individual learning goals. Deci & Ryan (1982) claim that intrinsic motivation is based on the innate need to be competent and self-determining.

This in turn leads people to pursue situations and activities that interest them, provide optimal challenges, and allow them to learn and achieve. Within PBL style classes, students are provided opportunities to explore topics they are interested in with the instructor used as a facilitator for exploration rather than as a traditional lecturer. This assertion shows that at its best, PBL classes set up students in an optimal setting to stimulate their own personal curiosity and intrinsic motivation to do well in the class. These claims are backed up by citing the author's previous paper (Deci & Ryan, 1980), which details numerous studies done to explore the conditions within which intrinsic motivation is likely to be diminished and enhanced. One other important aspect necessary for the success of a PBL class is having the instructor intrinsically motivated to want the project and the students to succeed. The authors state that an instructor must become an active teacher that is “a resource, a guide to students’ learning who would facilitate learning rather than control and evaluate it.” (Deci & Ryan, p. 33)

This assertion is supported by Lam, Chang & Ma (2009) who, through a study of 126 primary school teachers and their 631 students in Hong Kong, concluded after survey results that teacher intrinsic motivation predicted student intrinsic motivation directly as well as indirectly through the mediation of instructional support. When teachers reported higher intrinsic motivation in the program, their students tended to perceive getting more support from them and reported higher intrinsic motivation in their own learning experience.

As a result of these private and government efforts to increase CubeSat development, schools have built serious programs around their Aerospace Engineering departments. One notable example is at the University of Illinois Urbana-Champaign (UIUC), which is going on the 18th year of its CubeSat program. Through a 15-year case study of their PBL design course, UIUC has succeeded in improving its program to a point of great proficiency in educating their students through a design project that uniquely mirrors industry practices and adapts CubeSat timelines to a semester based University structure. Kroeker, Ghosh & Coverstone (2016) emphasize in their conclusions that education is the main focus of their design course, as should be the case for all PBL CubeSat courses. The focus is on “building engineers and not satellites.” Through the development of their program, the faculty at UIUC have instilled methods of maintaining intrinsic motivation within their students and instructors to provide the best educational experience possible.

Research Questions and Methods

The question that guides this research is: What are the motivations of students in capstone design courses within the Virginia CubeSat Constellation mission? There have been studies of intrinsic motivation in PBL style classes, but no specific studies on how the integration of CubeSats in higher education, using PBL style classes, affects the quality of education received by undergraduate engineering students. Although one could use these other studies as justification of CubeSats as an educational tool, performing more specific studies could potentially highlight unique challenges faced by PBL style engineering courses. I will analyze the topic at hand by conducting surveys of the current and previous graduating classes of the capstone design courses involved with the VCC project across the University of Virginia, Old Dominion University, and Virginia Tech. Using similar survey questions that Lam, Chang & Ma (2009) used to gauge the intrinsic motivation of students, my surveys will consist of questions gauging how these current and former students felt their intrinsic motivation and the perceived intrinsic motivation of their instructor changed or remained the same throughout the course of the class. I will also conduct interviews with the instructors of these CubeSat design courses and ask the same questions to see the opposite side of how the instructors felt their intrinsic motivation was and how they perceived their student’s intrinsic motivation to be during the class period. After collecting this data, I believe it is best analyzed through case studies of each of the different year’s students. Different classes have participated in considerably different steps of the design process during CubeSat design courses, therefore the intrinsic motivations over different years could drastically vary due to the unique situations each group of students experience. This current year’s course at UVA is split into three groups of separate CubeSat projects each at different stages of the design process, so it will be interesting to see if there are varying levels of intrinsic motivation over each project team.

Conclusion

The need for updated atmospheric drag data for models and orbital propagation software is a significant issue today. With an increasing amount of space junk and small satellites within LEO, calculating deorbit times, predicting collisions, and predicting the time and location of reentry for orbital debris is important now more than ever. The VCC mission aims to collect new atmospheric data in LEO to create a more accurate atmospheric density model and improve current models and simulations around the world. By researching how CubeSat design courses in higher education affect the quality of education for undergraduate engineering students, I will be able to highlight potential issues within these courses and demonstrate how motivation affects the students and teachers and shapes the outcomes. I will begin with a preliminary survey given to the instructor and the class at the beginning of next semester to gauge initial opinions and follow up with a second survey in March or April to see how student motivation might have changed. For former students I will send out a singular survey to see how their intrinsic motivations changed throughout their time in the course. I anticipate that initial intrinsic motivations will be lower due to difficulty adjusting to the teaching style, but later intrinsic motivations will be higher after already completing the class. This research will be done in hopes of improving future CubeSat courses to better prepare students for industry and to allow higher quality CubeSats to be built and answer the important research questions we have today.

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