NASA USIP SFRO

Free-Space Optical Data Transmission

Undergraduate Student Instrument Project
Student Flight Research Opportunity

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Introduction:

Along with Manhattan College, our Capstone project will be designed around the NASA USIP (Undergraduate Student Instrument Project) SFRO (Student Flight Research Opportunity). We propose to develop, launch, and operate a 3U (30cm x 10cm x 10cm) CubeSat satellite - a small object used to conduct small experiments in space. They are deployed by NASA, and are scattered into orbit along with a number of other CubeSat projects. A ground station will be designed to accompany the satellite, and it will be concerned with testing the feasibility of free-space optical communication technology.

The successful execution of this project will enable high bandwidth, high throughput communication for future CubeSat projects, while testing the feasibility of a larger adaptation, for possible uses in large-scale applications. The ground station will utilize a near-infrared laser, and the CubeSat receives this signal with a precise camera. Any future CubeSat project that is data intensive can now rely on free-space optical transmission, instead of radio-frequency transmission.

The project will be undertaken over the next two years, covering the Spring of 2016 to the Summer of 2017. Most of the organizational work will be handled by senior students in the Capstone class, with minor tasks being assigned to the other underclassmen from either other classes or clubs. The project will feature a Summer Internship opportunity, in which students will continue work on the project over the summer months in exchange for credit. The work-plan has been divided into modules that may fit into students' schedules, with certain phases of development being handled per semester.

The current team of Capstone Seniors will be covering budget finalizations, the system architecture, and prototype development. Currently, there is still a decision to be made regarding the size: 2U (20cm x 10cm x 10xm) or 3U (30cm x 10cm x 10xm). Once we finalize required components, factor in weight and power requirements, we can decide on a final size. A prototype of the ground station laser will be designed to scale, and an accompanying camera array will be constructed in order to test feasibility of short-range free-space optical data transfer. In order to process this data, we must also develop the system architecture. This will be crucial in the encoding/decoding process for data transfer.

Purpose:

The underlying experiment of the CubeSat project is to successfully detumble, and record data obtain from receiving free-space optical data transmission from the ground station laser. After being launched via NASA rocket and enter low-earth orbit. The first challenge presented to the CubeSat will be to stabilize after being jettisoned from the launch vehicle. In order to do this, the CubeSat will utilize an internal battery in combination with a magnetorquer in order to stabilize itself. To clarify, a magnetorquer is a device that utilizes the Earth's magnetic field in order to create mechanical energy. This energy will be used to change the momentum of the CubeSat until it is perpendicular to the Earth while maintaining a geosynchronous orbit. The CubeSat will then obtain energy from the attached solar panels in order to begin radio transmission and detecting laser light. The CubeSat will, hopefully, receive the laser transmission and then transmit a signal over radio frequency to confirm the transmission.

The explicit task of this Capstone class of 2016 is to test the feasibility of a ground to space laser keeping in mind power budget, size budget, safety concerns, as well as cost. The goal of this experiment will be to first determine feasibility in terms of the aforementioned factors, then testing this laser over smaller distances. This data will be used to create the timing required within the control systems.

Requirements:

There are various requirements that must be met in order to successfully design a feasible CubeSat system. The first of these requirements is the rate of data transfer. We must ensure that the transfer speeds of the various parts is fast enough and can move large enough data packets at once in order to allow for appropriate timing with the control systems. This includes the data obtained from both the RF antennae and the camera. The power, which will be determined later depending on the size, must have a maximum value that is met by the solar panels on the surface of the CubeSat. Size is also a large consideration, which will be one of the deciding factors of the choice between a 2U and 3U system. Another factor to consider is if the laser light that will be used is even allowed according to FAA regulations. Finally, these factors are all weighed in terms of importance relative to cost. This is to say, that power and the communications systems will be prioritized in terms of determining the size of the system.

Specifications:

The specifications required for the CubeSat rely primarily on the power budget of the parts used in order to determine the use for either a 2U or 3U CubeSat. The actual dimensions of the cube are 2U (20 X 10 X 10 mm) and 3U (30 X 10 X 10 mm). This decision is also affected by the size of the parts inside the CubeSat. A majority of this component will be taken up by the processor and control system. The size will affect the magnetorquer as it needs to produce enough torque to sufficiently detumble the CubeSat.

Our idea in the positioning of the equipment we'll start with having the GPS, Radio, ADCS Control, and EPS on the top of the cube all equaling 1U, whilst the middle area will house the heavier equipment such as the battery and magnetorquer, and the motherboard, ppm, and camera will be housed in a 1U on the bottom. Figure 1 above illustrates this arrangement.

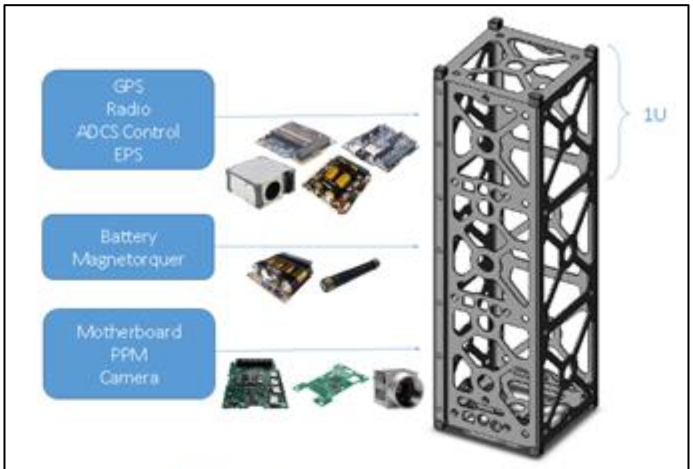

Figure 1: CubeSat Arrangment

Design:

To achieve pointing accuracy for downlink communication, a laser designator tracking bi-static consists of a laser source which transmits a beam from a ground station that is detected by an on orbit camera. The ground laser would operate in at 800nm and would generate a beam which is launched through a telescope. The main design parameters of the ground system are the laser transmit power and beam divergence which the transmit power is set at 10W. The ground station will begin tracking the satellite after launch. When the downlink beacon is detected, the ground station will respond with a confirmation packet on the radio uplink. Once received, the satellite will respond with its telemetry information which will lead to the ground station to uplink updated ground station information. This can be seen in Figure 2 above. The ground station will then use this

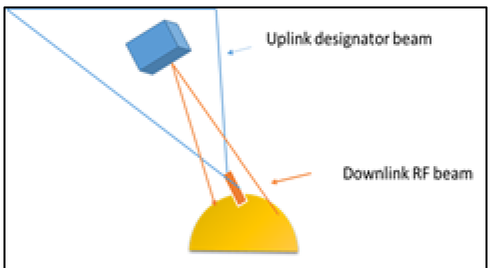

Figure 2: Uplink/Downlink Interaction

location information and satellite information to predict time and angles to target the satellite when it rises above the horizon. This will fire the laser while tracking the estimated location of the satellite. The satellite scan for the laser using its wavelength sensitive camera which is encoded with good correlation properties to minimize false positives and false negatives. When the laser is detected, the processor on board will send a packet on the radio downlink including the time and location information. When the ground station receives packets, it will continue to fit the model of the orbit which will be continuously refined as it receives hits. A successful mission is measured by the ability to close and maintain the uplink for a significant portion of the overhead orbit. The uplink is anticipated to be established and collect sufficient data within two months of operation.

In order to keep within design constraints and save as much space as we could our team selected a small USB 3.0 camera that will allow us to take high resolution NIR pictures. With a 5MP resolution we can capture 60 frames per second at a 2590 x 2048 resolution per photo. This is state-of-the-art performance for its size. The camera has many global shutter capabilities one being CDS or correlated double sampling and. CDS, as its name states , samples the image twice and on the second sampling it will remove the reference voltage from the input signal of the pixel it captures(after it resets and begins a new sample) at the end of the sampling. This effectively reduces noise and increase the dynamic range of the picture. In addition these global shutter capabilities allow for higher sensitivity and high quantum efficiency in the NIR spectrum.

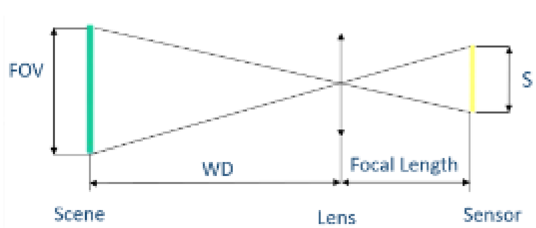

Figure 3: Ground Station Lens Construction

Along with the camera, we have 2 optical filters which allow us to hone in on our designated wavelength and another filter to protect the lens from UV light. The NIR bandpass filter is what will allow us to hone in the 852 nm wavelength by improving the responsivity of the photodiodes. The other filter is a cold mirror filter or long-pass filter. It works by covering the lens and filtering out the UV light to reduce the transmission below 700nm which is part of the UV and visible spectrum. You can see the arrangement of the lens system in Figure 3 shown on the previous page.

Problems:

We will spread the laser beam using ground based optics. By spreading the laser beam using ground based optics, this makes it easier to overlap a portion of the beam with the satellite. Tradeoffs would include the incident energy density on the satellite sensor decreases with increasing beam angle. If it is spread too much then there would not be sufficient signal to noise ratio at the receiver. If detection is not made with the signal, the beam spread angle and dithering range will be adjusted until we find appropriate tradeoff. If unable to find appropriate tradeoff to achieve lock, the mission can be changed and still gain useful information. One of the advantages of using a sensor with high resolution is being able to perform remote sensing of the earth's surface. Due to the camera's lens arrangement, the camera will image a fairly large field. The position ambiguity and the limited angular stabilization of the magnetorquers will set the overall accuracy and resolution.

Another significant risk is the failure of the infrared camera. The shock and vibration of launch and the thermal shock associated with stage operations could damage the device and make it inoperable. Only connected via a USB, it could be loosened during launch. Environmental qualifications and screenings can produce confidence in the camera's suitability for space. Radiation could affect individual pixels which will be excluded from the dataset. If camera still fails after these measures are taken, the mission will be adapted to study GPS reception and radio propagation effects at different satellite attitudes. We will characterize the ease of gaining and maintaining GPS lock even when the antenna is not ideally aimed. The radio downlink can be directly measured by measuring the received signal strength. This would salvage the mission and provide us (students) with a continuing learning experience.

Timing synchronization coupled with accurate GPS based location determination is critical to aiming the laser. An accurate time-of-fix information is required due to the high velocity of the satellite. This accuracy must be maintained and correlated with the ground station which is responsible for the steering of the lase r. Although in general, the satellite will not be directly overhead, the track offset from pass to pass can be accurately calculated. This should lead to an algorithm to synchronize the two timers. This algorithm is described in the IEEE-1588 timing synchronization standard which will be adapted for our purpose. The algorithm assumes fixed delay times between stations which is not our case as we plan to use Doppler information to find the zenith. Rather to say we will not be able to synchronize, we may not be able to synchronize to the level of accuracy desired. Preliminary analysis shows that millisecond repeatability is sufficient for precise targeting. This would be simulated in MATLAB and Simulink to estimate practical margins that should be dealt with. The main consequence of poor synchronization is a residual position ambiguity which reduces the effectiveness of using the dithering approach to find the satellite that will force us to use a wider beam. This wider beam decision could compromise the optical link budget. If unable to overcome timing synchronization challenge during flight, we will pursue an alternative mission of infrared imaging of the earth.

Backup Plan:

The backup plan for the Capstone project in case the NASA proposal is not accepted for Manhattan College will consist of attaching solar panels on top of the Manhattan College parking lot in order to generate green power. Using standard solar panels, an array can be constructed on top of the parking lot utilizing sunlight for PV energy connected to the power grid. This will allow for free energy to be provided in order to power the lights, and possibly provide power to an external battery for future use. Another possible route is to use transparent solar panels placing it above the existing rooftop garden. This will allow for a continuous study of the effects of UV light deprivation on plant life.

The project will utilize fundamental aspects of electrical engineering. One such way is in understanding how to manage the power provided by the solar panels in order to connect them to the grid. This will then need to be utilized by the power grid and prioritized in such a way that solar energy is used first. Naturally, this may involve a control system or reconfiguring an existing one. All of this must be done in such a way that it meets industry standards in a safe way.

Development:

In the spring 2016 semester, we will be focused with accomplishing three things: finalizing the budgets, constructing a prototype, and developing the system architecture - however, development of the system architecture will continue into the summer 2016 internship program. Accomplishing these three tasks are important because they lay the foundation for the rest of the design. The budgets will act as canon to the future developers, the system architecture is required to continue any software development, and the prototype determines feasibility. The feasibility of this project is the main focus during the Spring 2016 semester, and will consume most of the development. Because of this, budget finalizations will have to be accomplished first, and then the design can begin - and with it, the system architecture development. The chart below details important milestones along with their expected due dates to be completed throughout the course of the project.

Milestone	**Description**	**Expected Date**
M.1	Optical Systems Feasibility Determination	5/18/16
M.2	Final Power Requirements and Evaluation	5/18/16
M.3	Final Size and Weight Budget	5/18/16
M.4	System Architecture	8/28/16
M.5	Optical Path Prototype Test and Evaluation	8/28/16
M.6	Radio Link Development and Testing	12/16/16
M.7	Power Profile and Predictive Analysis	12/16/16
M.8	Firmware Development and Testing	12/16/16
M.9	Ground Station Laser Targeting Platform Development, Assembly, and Testing	5/19/17
M.10	Ground Station Laser Targeting Platform Software Development and Testing	5/19/17
M.11	CubeSat Assembly	5/19/17
M.12	Acceptance Testing	8/27/17
M.13	Environment Testing	8/27/17
M.14	Deliver to NASA	TBD
M.15	Launch	TBD
M.16	On-Orbit Checkout	TBD
M.17	Operation Experiments	TBD
M.18	Final Reports	TBD

The issue of 2U vs. 3U will decide all four of our major budgets: the size budget, the weight budget, the cost budget, and the power budget. The size and weight budgets will be used in the detumbling calculations and for further attitude adjustment purposes by the magnetorquer. The size budget also affects optimal solar panel coverage - both of these effects impact the power budget, and may cause fluctuations in our EPS system calculations. All of these changes in budgets will have a large impact on the cost budget, although hopefully it should not push past our current budget of $100,000. The cost of the parts leaves plenty of room for adjustment at the cost of student's stipends, so we will try to avoid changing this as much as possible.

A prototype will be developed that tests the feasibility of short-range free-space optical data transmission. A scaled version of the ground laser will be constructed, and a camera array will be designed to receive a signal. Eventually, we can design filters that would mimic the effects of atmospheric attenuation and degradation to simulate long-range free-space optical data transmission. This prototype will be used in our first feasibility report, in which we analyze how successful the project might be. In order to interact with our prototype and sensor array, we will also need to begin the development of the system architecture.

The system architecture will initially be designed to process the incoming signals, and then analyze them to retrieve that data. This can be accomplished by using filters to remove any source of light other than the laser's frequency. A DSP will have to be chosen in order to process these signals, and then we must develop how we interpret this information - this includes the encoding/decoding process to ensure proper transmission. Because the system architecture development stretches into the summer internship session, development of the encoding/decoding process will most likely not be handled in the spring 2016 semester.

Once the current Capstone Seniors graduate, the upcoming seniors will take over project management. At this point, if awarded, the NASA USIP SFRO project should have become integrated in current courses' curriculums. This would give underclassmen experience with working on a large project, and can develop interest in future projects. There are plans for starting a Space Club as well, and they would be tasked with participating in the further development of this project.

We have decided to divide the milestones into sections that fit into Manhattan College's semester schedule. For the summer session of 2016, we have the system architecture and optical path prototype test and evaluation scheduled for completion. We have scheduled these two together because they both focus on the optimization of the system architecture, which needs to be extensively tested in order to guarantee operation. For the Fall 2016 semester, we have scheduled Radio Link, Power Profile, and Firmware development, because each of these fits into a category for the EECE department: Radio Link development focuses on Physics, Power Profile depends on Electrical and Computer Engineering, and the Firmware depends on Computer Engineers – the interaction of these departments is crucial in maintaining schedule and completing the project on time.

During the spring 2017 semester, we have assigned the construction of the CubeSat, Ground Station laser and optical scope, and the development of the Ground Station software. Again, we have scheduled these tasks together to maintain inter-department cooperation: construction of the CubeSat relies on the combined efforts of the Electrical Engineering, Computer Engineering, and Physics department – along with outside consultation from the Mechanical Engineering department – the Ground Station laser and optical scope construction is handled by the Physics and Electrical Engineering departments, and the Ground Station software is developed by the Computer Engineering department. As stated before, the inter-operability between departments is crucial for this project.

The final tests are run during the summer session of 2017, which focus on acceptance and environmental testing. These ensure that our design will survive the harsh environment of space, and will be able to withstand launch and orbital forces. Once the final testing is complete and the satellite is deemed flight-ready, it is then delivered to NASA at an unknown date, with the proceeding events of launch, on-orbit checkout, and performance of experiences to take place at a later date.

Conclusion

The project we have at hand is rather daunting, but our team is up to the task. Our team is well rounded, with two Electrical Engineers and two Computer Engineers, and have shared many classes together. Each student has participated in selective internships in the Tri-State area, and their experiences there will aid them in managing such a large project. The spring semester should bring exciting developments in the world of free-space optical data transmission.

The research we are conducting will have a small impact at first, but create large implications for the future. If free-space optical data transmission does prove to be fruitful, it will impact the way future data-heavy CubeSat projects can communicate with each other and their accompanying ground station. The project could be further developed so as to include a laser transmitter on the satellite as well as the ground station, in order to test the feasibility of free-space optical data transmission uplinks and downlinks. If this research also proves fruitful, it could radically change the way larger satellites communicate with each other.

Since radio frequency transmission has a significantly lower rate of transmission than fiber optic transmission, free-space optical transmission, which works in the same way, will also carry similar benefits. Satellites could then rely on this technology in order to broadcast and transmit data at a significantly higher rate. While the impact does have the possibility to be quite large, chances are it will only have an impact on smaller satellite applications until further development can occur.

Overall, this design will further ourselves in terms of education, personal experience, and management skills. By managing a project from an upper-level, we are obtaining important skills that will be useful in the professional engineering world. Interacting with a professional team of engineers is an important skill in facilitating inter-operability and optimal work patterns. By participating in this project, we are not only furthering the reputation of Manhattan College, but also furthering our own careers and expanding our knowledge, while implementing all we have learned as students.

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