University of Colorado Boulder

Department of Aerospace Engineering Sciences

ASEN 4018

Project Definition Document

VANTAGE

Visual **A**pproximation of **N**anosat **T**rajectories to **A**ugment **G**round-based **E**stimation

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Approvals

Role	Name	Affiliation	Approved	Date
Customer	Dr. Penina Axelrad John A. Gaebler	CU/AES	P Axelrad	9/17/18 9/17/18
Course Coordinator	Jelliffe Jackson	CU/AES		

Project Customers

Name: Penina Axelrad Email: penina.axelrad@colorado.edu Phone: (303) 492-6872	Name: John Gaebler Email: John.A.Gaebler@colorado.edu Phone: (407) 760-4295

Team Members

Name: Aaron Aboaf Email: aaron.aboaf@colorado.edu Phone: (720) 212-1974	Name: Dylan Bossie Email: dybo6303@colorado.edu Phone: (719) 502-9826
Name: Sean Downs Email: sean.p.downs@colorado.edu Phone: (303) 502-0393	Name: Justin Fay Email: jufa5768@colorado.edu Phone: (970) 403-7165
Name: Marshall Herr Email: mahe1052@colorado.edu Phone: (817) 475-8298	Name: Joshua Kirby Email: joki2454@colorado.edu Phone: (303) 916-3127
Name: Lara Lufkin Email: lalu4246@colorado.edu Phone: (719) 486-9408	Name: Richard Moon Email: rimo1046@colorado.edu Phone: (720) 934-5508
Name: Nicholas Renninger Email: nire1188@colorado.edu Phone: (303) 999-5725	Name: Zach Talpas Email: zata1281@colorado.edu Phone: (303) 520-4939
Name: Jiarui Wang Email: jiwa7945@colorado.edu Phone: (253) 205-1115	

1. Problem Statement

The primary motivator for this project is to augment Space Situational Awareness (SSA) by improving on currently existing systems. The current method of tracking geostationary (GEO) satellites to obtain orbit parameters is done through the use of ground-based surveillance sites, typically using electro-optical telescope sensors. These sensors will take multiple images of satellites during their pass through the site's field-of-view (FOV), collecting them into a series of "tracks" which represent a small portion of that satellite's orbit. Smaller satellites like CubeSats are mainly deployed into low-earth-orbit (LEO), where orbit determination is primarily done using surveillance radar. Again, satellites are measured by a series of "tracks". By assimilating LEO, GEO and other orbital tracks from many sites located across the globe, the Joint Space Operations Center (JSpOC) is capable of acquiring and maintaining the orbital parameters of every satellite in orbit around the Earth[7]. Due to the limitations inherent to ground-based tracking systems, tracking data for CubeSats is often not available until several minutes to several hours after CubeSat deployment. This system therefore leaves room to be improved upon.

Collection sites that exist on the ground depend on many conditions for successful tracking. Although the telescopes at sites are typically able to be manipulated to aim anywhere on the site location's horizon, the telescopes themselves will have relatively small FOV's. As a result, the viewing window for a particular satellite will often be small. During this time period, it is essential that the weather be sufficiently clear in that section of the sky, as well as the satellite maintaining a sufficient visual magnitude to be visible at its current range. If these collections fail, data for that satellite will be unavailable until a successful collection can be made in the future. Additionally, these collections will only be attempted after being scheduled by the JSpOC administration. Once this is done, there will be a delay from the point of collection to when data is transferred before calculations can be done to accurately track the orbit parameters[8]. This project aims to eliminate much of this delay by providing initial measurements of CubeSats immediately after launch, which enables the shortening of delays inherent to ground-based orbital determination.

A successful project could lead to a prototype of a CubeSat tracking system with a path toward integration with the NanoRacks CubeSat Deployer System on the International Space Station (ISS). Our project's multi-generational objective is to create a system capable of providing initial relative position and velocity measurements for deployed CubeSats and corresponding quantitative uncertainties. The system will track these objects from immediately after release by the deployer up to a distance of TBD meters. Meanwhile, VANTAGE will be designed to use power, data, and structural interfaces which have a clear path towards NanoRacks deployer compatibility.

2. Previous Work

The concept of tracking objects from a space-based sensor is a well-explored topic. However, there are fewer projects focused on tracking CubeSats as they are deployed into orbit, at least with optical sensors. Further complicating matters is the industry trend of growing deployment sizes; ISRO (the Indian Space Research Organization) deployed a record-setting 104 CubeSats in 2017.[3] This makes the usage of previous space-based sensor projects difficult to build off of; even though the tracking data desired is fundamentally the same among many of these projects, most of these space projects aren't designed nor optimized for tracking a dense cluster of moving objects. which is the inherent nature of tracking CubeSats as they are deployed. PhD candidate John Gaebler, currently at CU, does have research towards multi-target tracking algorithms for CubeSats in their early orbit phase. This project was made with the intention of aiding his research, meaning that his research is relevant. Likewise, his research and experience in estimation algorithms is also relevant to the project, especially if a heuristic algorithm is used to reduce excessive computations. Although the project itself is aimed towards being a space-based sensor, most of the previously existing work that holds relevance to this project are those in general machine vision projects, such as those that focus on the topics of image recognition, multiple object tracking, and depth estimation algorithms.

Image recognition, with the focus on relative distance calculations, is relevant to the project, and happens to have many projects and studies on it. One of the projects was done by CU undergraduate Adam Boylston, who developed an algorithm that could derive the geometric center of CubeSats and find the relative position among them, for snapshot images; his work will most likely be relevant and is worth looking into.

Object tracking algorithms are a current topic of research, with a variety of approaches and run time complexities depending on the heuristics chosen.[1,4] For example, an algorithm for object tracking from sparse representations would not be ideal for tracking well distributed objects across the entire field of view, but would be more relevant for tracking objects that are densely clustered in a specific area, with most of the benefits coming from significantly reducing the number of irrelevant computations done.[5]

Depth estimation algorithms are useful in increasing accuracy of distance estimations from image processing. These algorithms tend to be used when the object of interest in image recognition is not uniformly lined up with the camera, as it allows the depth along the object to be measured.[2] Although these measurements by themselves may not be of great importance, they are useful when trying to calculate the actual scale of an object of known size but unknown distance. While the focus of these algorithms is usually on miscellaneous objects of varying shapes and sizes, the applications of using said techniques on CubeSats of known shape and size could potentially help in distance calculations for tracking CubeSats.

3. Specific Objectives

The following table sets forth the levels of success for the VANTAGE project. Higher levels of success imply fulfillment of the lower tier objectives in addition to the objectives stated at the higher level. The project deliverables that will show the lifetime evolution of the VANTAGE project are as follows: Project Definition Document (PDD), Conceptual Design Document (CDD), Preliminary Design Review (PDR), Critical Design Review (CDR), Fall Final Report (FFR), Manufacturing Status Review (MSR), Test Readiness Review (TRR), Spring Final Review (SFR), and the Project Final Report (PFR). All of these documents along with weekly status reports and the final VANTAGE system are also customer deliverables.

Additionally, the VANTAGE system will be tested at near the end of the Spring semester. The this project can be considered the first phase of VANTAGE which will be proof of concept testing. A test rig will be built to simulate the on-orbit application of VANTAGE on the ground. The test rig will interface with VANTAGE to mimic the planned on-orbit interface and the test rig will deploy Cubesat shaped objects at realistic velocities for VANTAGE to track. Procedures will be implemented such that the results that VANTAGE outputs can be cross referenced and confirmed with to critically evaluate the performance of the system.

	Structures
Level 1	**Context Summary:** A basic payload structure exists with models of potential flight components. • VANTAGE builds an engineering development unit (EDU) of the payload containing dimensionally accurate, non space-rated mock-ups of all system and anticipated system components. • VANTAGE mechanically interfaces with NanoRacks hardware model. • Total size of VANTAGE sensor system is less than **TBD**[*] m^3 (between 1U and 6U).
Level 2	**Context Summary:** System components demonstrated in a “flat sat”[†] state can be integrated mechanically into the payload structure. • All components fit when mounted within the volumetric constraints of the payload.
Level 3	**Context Summary:** A fully integrated sensor payload showing that all components fit and operate within the structural volume. • Flight-like wire harnessing and electrical connections between all system components are in an integrated state. • VANTAGE mechanically mates with exterior electrical connectors present in NanoRacks hardware model.
	Tracking (In ideal lighting conditions)
Level 1	• VANTAGE software algorithm identifies **TBD** (2-6) CubeSat shaped objects based on sensor input with **TBD** sensor FOV (0-30°). • VANTAGE obtains two still images of each ejected CubeSat within **TBD** seconds (1-10) of the ejection time. • VANTAGE tracking software takes and stores sensor readings/images of the FOV at **TBD** Hz (0.2-10). • VANTAGE calculates relative position within **TBD** m (0-10) tolerance and relative velocity measurements within **TBD** m/s tolerance (0-2). • VANTAGE determines successful or failed deployment by confirming payload ejection from the test system / mock deployer.

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[*] This and all following parenthetical ranges following **TBD**s in the table of success levels indicate that the **TBD** value is expected to lie in the range given

[†] A non-integrated state in which all payload components are laid out individually and connected such that they interact and operate as they would in the fully integrated system.

Level 2	• VANTAGE identifies **TBD** (2-6) CubeSat shaped objects until objects are beyond **TBD** km range (0-1). • VANTAGE reports measurements of position and velocity measurements of tracked satellites at **TBD** Hz frequency (0-30). • VANTAGE recognizes off-nominal ejection velocity and ejection time. • VANTAGE identifies CubeSats based on the planned ejection sequence. • VANTAGE erases any images which do not contain objects in order to save storage space.
Level 3	• VANTAGE also recognizes unexpected tumble rates and CubeSat mechanism deployments. • VANTAGE recognizes CubeSat deployable mechanism have deployed within **TBD** m (1-50) relative to sensor payload. • VANTAGE processes image video feed in real time and reports relative position and velocity measurements of all observed CubeSat objects at **TBD** Hz (1-10).
	Electronics: Power, Signaling, & Physical Memory
Level 1	• VANTAGE payload components electrically interface with one another and transfer power at **TBD** volts 3.3-12 and **TBD** amps (0.5-3). • A user-interfacing computer (mock deployer) sends commands to the VANTAGE payload using **TBD** communication protocol and **TBD** programming language. • VANTAGE has enough physical memory to store binary or grayscale images collected at a **TBD** Hz (0.2-10) for the duration of the observation period.
level 2	• Mock-deployer/NanoRacks-System-Simulator possesses an electrical interface simulator which has the same communication protocols and electrical characteristics as the NanoRacks system. • NanoRacks System Simulator transfers bit streams to the sensor payload and payload decrypts commands sent over the bit stream. • After activation command and deployment predictions are received VANTAGE payload is autonomous until output data is requested by NanoRacks System Simulator.
Level 3	• VANTAGE decrypts the deployment predictions containing ejection sequence, time, and velocity predictions in the same format as what will be provided by NanoRacks in the use-case. • VANTAGE stores images/video of mock deployment operations on-board and transfers these back to the NanoRacks System Simulator within **TBD** hours (0-2) of final payload ejection. • VANTAGE charges any on-board power sources through the NanoRacks electrical interface within **TBD** hours (1-24). • VANTAGE has enough physical memory to store **TBD** resolution color images collected at a **TBD** Hz (0.2-10) for the duration of the observation period.
	Command & Data Handling
Level 1	• C&DH system can control and manage data and information transfers between components of the sensor payload and between the payload and the user-interfacing computer. • Data communication between payload components possesses a bit error rate less than **TBD** errors/KB (1-20). • VANTAGE payload executes a **TBD** list of available user commands.
Level 2	• VANTAGE returns data through a serial interface which can be interpreted by the NanoRacks system.
Level 3	• VANTAGE's boot and transmission protocols comply with NanoRack's software and electrical communication standards.

4. Functional Requirements

Figures 1 – 3 below show the Concept of Operations (CONOPS) and Functional Block Diagram (FBD) for this mission. The Use-Case CONOPS diagram (Figure 1) shows the phases of operation and depictions of how the operations interact and fit within the VANTAGE and VANTAGE-utilitzing system as a whole. The Team CONOPS diagram (Figure 2) illustrates the project scope for this year, showing the phases of operation and depictions of how the operations interact and will be validated through ground testing. The FBD (Figure 3) is a high-level representation of envisioned system components and how those components will interact to enable VANTAGE to accomplish its functional requirements.

Prior to a deployment, an operator will transmit data to the system consisting of deployment predictions that define the context of the CubeSat deployment. At a minimum, this information must contain satellite identities, launch sequencing, and launch timing. Upon input of this information, VANTAGE will then autonomously process this data and prepare itself for data collection. At the time of deployment, the system will begin near-field sensing necessary to identify CubeSats within the sensor's FOV. This data will then be used to compute the position and velocity of the CubeSats relative to the deployer and one another while maintaining identity knowledge. This information will be output to an operator for future analysis.

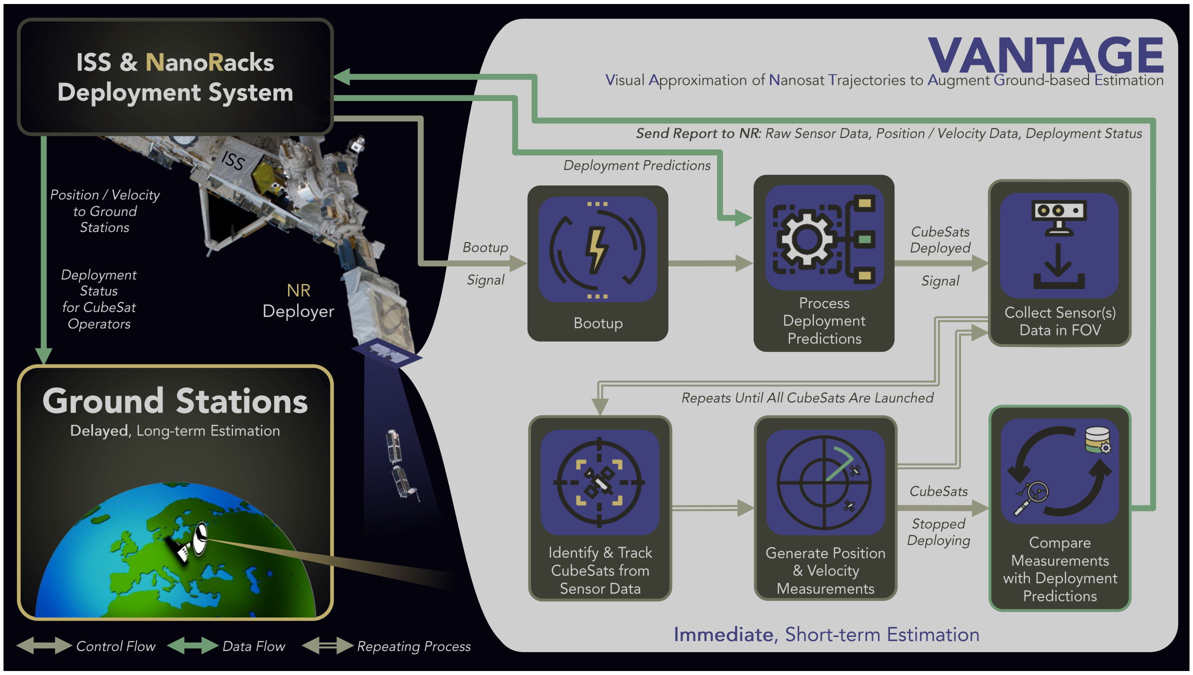

Figure 1. Eventual Use-Case CONOPS for the Multi-year Vision of the Project

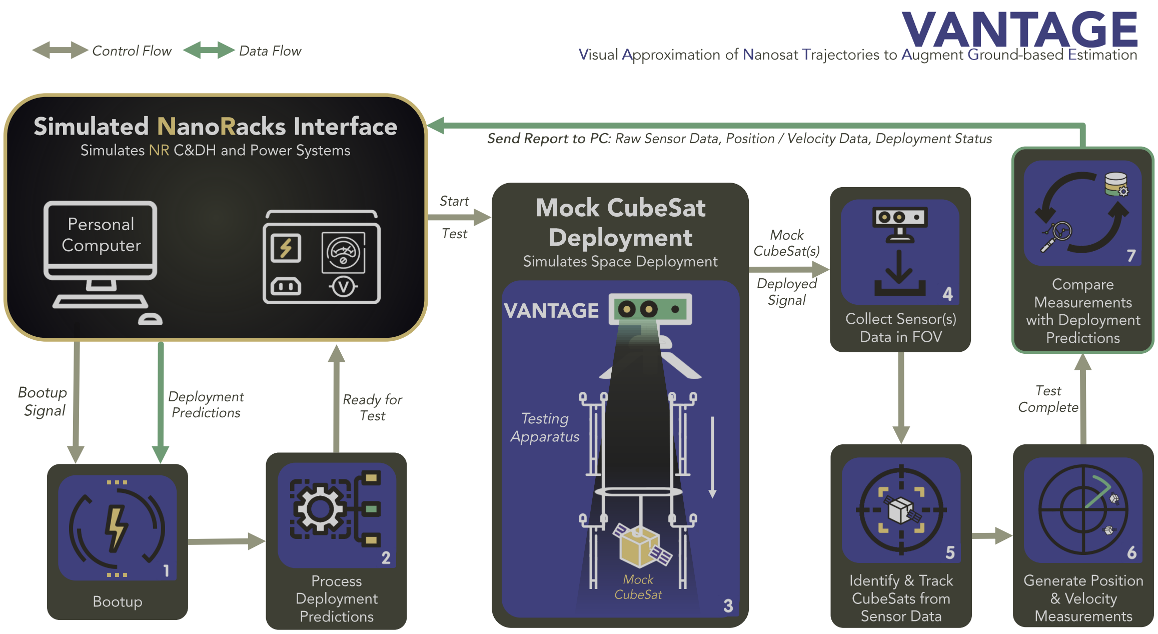

Figure 2. Team CONOPS for Our Proof-of-concept Project This Year

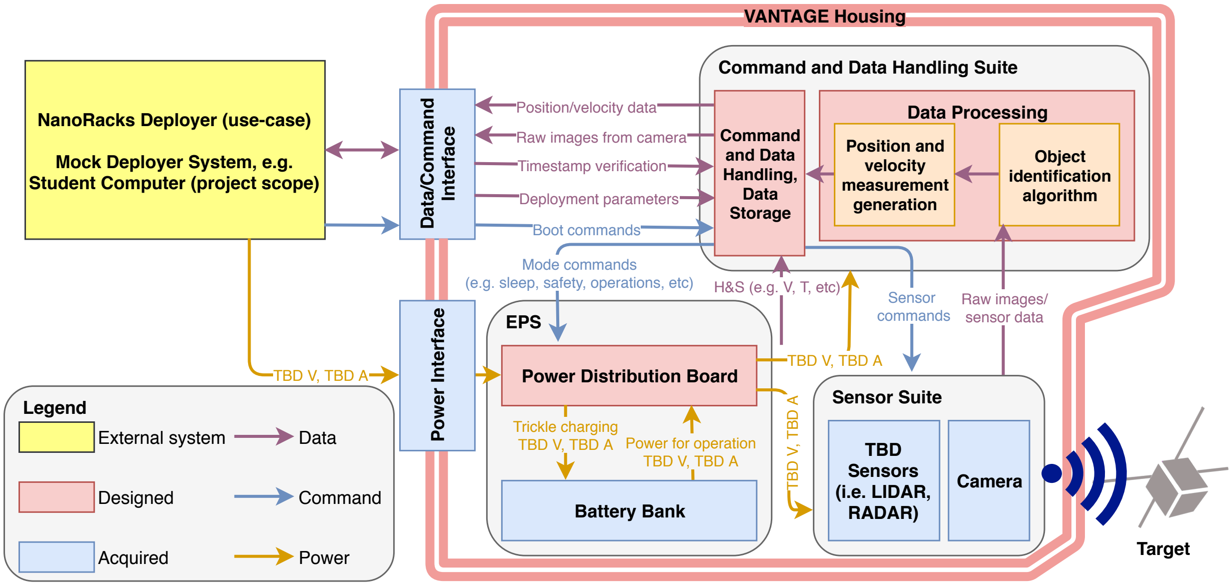

Figure 3. Functional Block Diagram (FBD) for VANTAGE

5. Critical Project Elements

5.1. Optical Functionality The optical system must be able to image CubeSats at a TBD range (0-1km) from the VANTAGE payload, which will define a TBD required imaging resolution. If the optical system is unable to take images of CubeSats as they exit the NanoRacks deployers, the entire system will be of no use to the customer. Cameras with substantive resolution are also very cost and power intensive and will therefore make up a significant portion of the respective budgets.

5.2. Object Recognition The image processing algorithms must have the capability to detect TBD (2-6) objects based on data input from the optical system FOV. If the system cannot detect multiple objects, it will fail in its objective of computing relative positions and velocities between them. Additionally, based on optical data, the system must have the capability to recognize the identity of each detected CubeSat with information provided by the input data set. If identification fails, the system will lose its usefulness in orbital determination for the launched satellites.

5.3. Estimation Algorithm The system must have computational algorithms which will process results from Object Recognition data for estimating relative position and velocity between each CubeSat within the sensor system FOV and the deployment station. This algorithm is the backbone of the system. If this algorithm fails, the system's mission cannot be satisfied.

5.4. Electrical Compliance The system must be designed to operate with a power supply of TBD volts and TBD amps which would be available from the NanoRacks system in the use-case. Additionally, an appropriate power and electrical interfacing solution must be designed to ensure that the system is capable of receiving power from the use-case system. If the system is incapable of interfacing properly while operating within the available power requirements, VANTAGE will be inoperable. This provides a unique challenge to VANTAGE design choices, since the TBD power limitations and interfacing methods available through the NanoRacks deployer may be severely constraining.

5.5. Embedded Implementation VANTAGE is expected to involve complex image processing and computational algorithms which must be implemented in an embedded system. The data handling system must have the capability of transferring images, as well as potentially other sensor data at a rate of TBD bits/s. The quality and output rate of images and position/velocity measurements will be constrained by the performance characteristics of the embedded system, which are typically diminished when limited power is available as in VANTAGE's case. If the embedded system fails at operating with the necessary bit rate, the system will be incapable of performing the necessary computations and image processing necessary for completing the required tasks.

6. Team Skills and Interests

Critical Project Elements	Team Members and Associated Skills and Interests
Optical Functionality	**Sean Downs** Experience with optical navigation camera equipment. **Marshall Herr** Taken Optics courses, experience working in an optics lab for 2 years. **Nicholas Renninger** Worked in FUV optical instrumentation lab for two years. **Jiarui Wang** Experience with optical lens with years photographic experience.
Object Recognition	**Dylan Bossie** Experience in image processing in high-level languages, and interested in working more in-depth with applied object recognition algorithms. Experienced in ground-based telescope object identification and tracking methods. **Joshua Kirby** Experience with image processing and star tracker algorithm development, implementation and validation in C. **Lara Lufkin** Experience with image processing and compression in high-level programming languages. **Richard Moon** Experience with Machine Learning and Computer Vision **Nicholas Renninger** Experience in Artificial Intelligence & numeric methods (SVM, PCA, etc.) for object recognition and tracking. **Zachary Talpas** Experience with image processing and data visualization.
Estimation Algorithm	**Dylan Bossie** Interested in working with estimation algorithms. **Justin Fay** Interest in simulation of dynamic systems and estimation algorithms. Familiarity with low-level programming languages. **Joshua Kirby** Experience with robust algorithm development from synthesized research papers, implementation of such algorithms in MATLAB/C, building up simulation environment within which to validate algorithms. Exposure to and interest in the field of estimation. **Richard Moon** Interested in working with estimation algorithms. **Nicholas Renninger** Interested in working with machine vision state estimation algorithms.
Electrical Compliance	**Lara Lufkin** Two years of experience designing and populating PCB boards including software development, soldering, and temperature profiling. **Nicholas Renninger** Extensive experience with space-grade electrical harnessing. Basic experience at LASP with EDA and fabrication. **Zachary Talpas** Interested in working with electrical systems. **Jiarui Wang** 5 years on a robotic team experience on electronic with robotic. Experience with draft circuit, prototype circuit, PCB design. **Aaron Aboaf** Interested in with electrical systems. Limited exposure to EPS, CH&H, and other electrical hardware on CUE3 and MAXWELL CubeSat projects.
Embedded Implementation	**Dylan Bossie** Experienced in various types of data science/analysis, and interested in the higher levels of the data handling within subsystems. **Joshua Kirby** Experience in satellite subsystem software architecture **Nicholas Renninger** Extensive experience in serial communications, professional software architecture, and design patterns. **Aaron Aboaf** Interest in working on embedded implementation with concurrent enrollment in 5519 Microavionics course.

7. Resources

Critical Project Elements	Resource/Source
Optical Functionality	**GoPro** - If desired, our team may have access to a GoPro camera provided by the customer.
Object Recognition	**John Gaebler** - a CU Boulder PHD candidate who is working with the customer and will be available for student questions. John Gaebler has experience with multi-target tracking and trajectory estimation. John Gaebler has published work relating to the development of our senior project.
Estimation Algorithm	**Adam Boylston** - an undergraduate researcher at CU Boulder who has previous experience in image processing, and has developed an algorithm for providing relative position data for snapshot images of deployed CubeSats. **Nisar Ahmed** - has research experience in the areas of dynamic state estimation and sensor fusion, and statistical system identification.[6] Professor Ahmed is faculty member at CU Boulder who may be willing to provide expertise relating to identification algorithms.
Electrical Compliance	**Trudy Schwartz and Bobby Hodgkinson** - run the Aerospace Electronics Shops at CU Boulder and are available for student assistance. **Aerospace Electronics Shops** - contain resources such as multimeters, oscilloscopes, function generators, re-flow ovens, and soldering equipment. Each of these resources may be useful for electronic, design, development, and testing. **Tim May** - ITLL electric lab, cover most special electronic instrument. **Advanced Circuits** - is a company that specializes in the production of PCB boards. Advanced Circuits provides a student discount when ordering simple PCBs CU Boulder supports the Altium software package that can produce the Gerber files necessary to work with this company. Altium can also be used for schematicc design and PCB development.
Embedded Implementation	**NanoRacks Team** - Specifically Mike Lewis who is the chief technology officer for the company. NanoRacks can provide assistance including specifications about existing data transfer capabilities between our system and the deployer. NanoRacks will also provide a sample set of deployer instructions/procedures that can be used for software development and testing.
Testing Resources	**NanoRacks** - this company will provide a model of their ISS hardware that can be used to confirm successful structural integration. **FLMG RECUV Lab** - To confirm software accuracy, a simulated launch will be completed and mock data will be taken. Our system requires at least 10m of space to test our system's ability to track at longer distances. The RECUV has a lab at FLMG that is large enough and can be reserved during the testing phase of our project.

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