University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018
Cubesat Active Systematic CApture DEvice (CASCADE)

Conceptual Design Document (CDD)

Monday 26th September, 2016

1 Information

1.1 Project Customers

Name: Lad Curtis Email: Lad.Curtis@sncorp.com Phone: 720-877-1317

1.2 Team Members

Name: Chad Eberl Email: chad.eberl@colorado.edu Phone: 970-619-0803	Name: Andrew McBride Email: andrew.mcbride@colorado.edu Phone: 307-251-7659
Name: Matthew Fromm Email: matthew.fromm@colorado.edu Phone: 970-396-7343	Name: Noel Puldon Email: noel.puldon@colorado.edu Phone: 786-201-2264
Name: Timothy Kiley Email: timothy.kiley@colorado.edu Phone: 720-840-05732	Name: Keegan Sotebeer Email: keegan.sotebeer@colorado.edu Phone: 720-891-7533
Name: Haoyu Li Email: haoyu.li@colorado.edu Phone: 720-483-7432	Name: Morgan Tilong Email: tilong@colorado.edu Phone: 720-296-1491
Name: Tony Ly Email: tony.ly@colorado.edu Phone: 970-313-3427	

Contents

1.3 Acronym Definition

CRS	CubeSat Recovery System
CRST	CubeSat Recovery System Testbed
DOF	Degree Of Freedom
DR	Design Requirement
FR	Functional Requirement
GRASP	Grapple Retrieve and Secure Payload
ICD	Interface Control Document (SC to Payload)
SC	Spacecraft
SNC	Sierra Nevada Corporation
RPM	Rotations Per Minute

2 Project Description

2.1 Recent Project Descope

On Thursday 9/22/16, during discussions involving the course director, the client, and Team CASCADE, a project descope occurred. Table 1 presents a before and after image for the descope. Subsequent findings in this document represent post-descope research and design work.

Table 1. Descoped Elements

Before Descope	After Descope
-Design and fabrication of a capture device prototype capable of interfacing with Sierra Nevada Corporation's SN-50 MicroSat (from both the hardware and flight software side) -Design of a software algorithm capable of autonomously executing the capture of 3-DOF rotating CubeSat (at the highest success level) utilizing space dynamics. -Demonstration of the capture of a rotating CubeSat with a procured or fabricated capture device	-Fabrication of a testbed to demonstrate the ability to autonomously(closed-loop utilizing active testbed feedback sensors) calculate the trajectory needed for successful capture of a rotating physical CubeSat model with a procured or fabricated capture device, 1-DOF rotation (max), 1-DOF translational (max).

2.2 Project Overview

With the recently emerging market for CubeSat missions in addition to the buildup of space debris and dead satellites comes an increasing need for spacecraft capture technology. Between the years of 2000 and 2012 there were a total of 133 CubeSats and NanoSats launched. Due to decreased launch prices and the rise of the commercial space industry, the years between 2013 and 2015 saw the launches of an additional 356 CubeSats and NanoSats[1]. CubeSats have proven to be useful projects in start-up and university settings, as they can often serve as a low-cost, low-risk platform for useful scientific missions and experimentation. A limitation to CubeSats, however, is that they are generally not equipped with any sort of propulsion system. The CubeSat recovery project, proposed by Sierra Nevada Corporation, is aimed at developing technology that allows a more capable satellite to approach a CubeSat, capture it, and release it into another orbit. Having this ability would give CubeSats increased functionality for experimental and scientific missions while keeping them low-cost and easily accessible. On another note, space debris is becoming a major problem with the increased number of satellites being launched. Eventually, this capture and release technology could be further developed and applied to the removal of dead satellites and space debris as an added benefit.

The goal of Team CASCADE is to successfully demonstrate the autonomous capture of a 3U CubeSat model through a ground-based testbed. The testbed will be aimed at demonstrating autonomous capture capability, rather than replicating the dynamics of the space environment. The capture demonstration will begin from an initial distance of 1 meter and will include the CubeSat model spinning about a single axis. The testbed shall demonstrate the capture of a CubeSat model under 1 degree of relative translational motion and 1 degree of rotational motion. Although this is a simplification, it is not entirely unreasonable, as functional CubeSats in orbit will generally be rotating closely about their major axis. In addition, once orbital rendezvous has been achieved, the maneuvers required to actually come into contact with another object are essentially linear, and so in that respect, it is fair for the testbed to include only one degree of translation. For the initial conditions, the capture device will be aligned with the axis of rotation of the CubeSat model since that is the easiest way to approach a spinning object without increasing the risks of undesired impact since the capture device can more easily match the angular velocity and orientation of the CubeSat for capture. This initial condition makes sense as rendezvous with the CubeSat is not in project scope and the highest level of success is 1-DOF translation (see Section 2.3). The rotation axis of the CubeSat is about the center of mass of the CubeSat parallel to the X axis shown in Figure 2. The center of mass is not the symmetrical center of the CubeSat due to the presence of solar panel(s).

Based on the SN-50 MicroSatellite, developed by Sierra Nevada Corporation, the available envelope for the capture device payload is shown in Figure 1. The geometric definition of the CubeSat to be captured in the ground demonstration, as required by SNC, is shown in Figure 2. The 3U CubeSat is the most commonly used size for CubeSat missions.

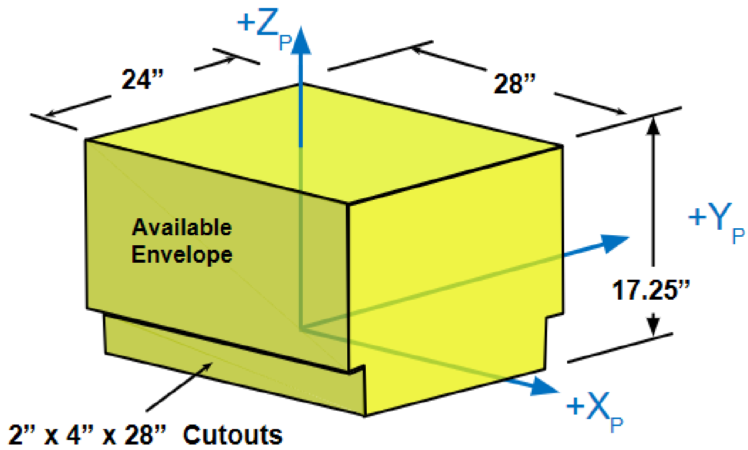

Figure 1. Defined Volume the Capture Device must fit into

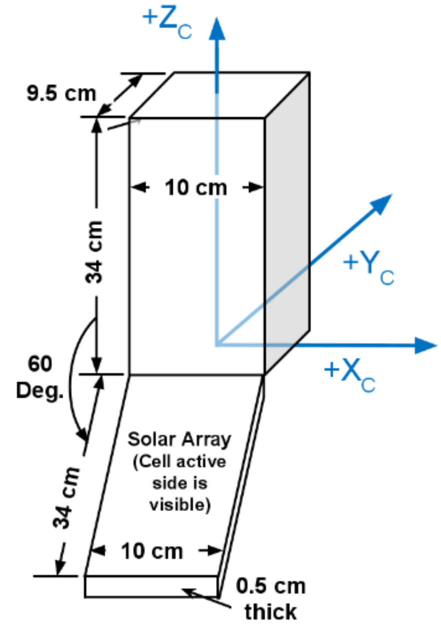

Figure 2. Defined Cubesat

2.3 Specific Objectives

The primary objective of CASCADE is to design, build and demonstrate a system that is used to capture a CubeSat. The levels of success pertaining to the project are shown in Table 2. The team shall design for the highest level of success for each category and modify the design of the project as needed to ensure the highest level of success is achievable. Level 1 is minimum level of success for SNC with all higher levels corresponding to additional SNC goals that would be desirable but not required.

Table 2. Levels of Success. Each higher level assumes success of lower level has taken place unless specifically noted.

Success Levels	**Testbed Demonstration**	**Capture Device Control**
Level 1	-Capture of CubeSat from an initial distance of 1m -No visual damage -ONLY 1 DOF Translation	Commanded trajectory (open loop)
Level 2	ONLY 1 DOF rotation	Obtain closed-loop data and compare to open loop commands to validate algorithm
Level 3	1 DOF rotation AND 1 DOF translation	Implement closed-loop algorithm (autonomous)

The critical project elements are shown in Table 3.

Table 3. Critical Project Elements

Hardware		
H1	Capture device end effectors	An effector at the end of the deployment mechanism is necessary to perform the capture of the CubeSat and to manipulate the CubeSat once captured. The team has little experience with robotics.
H2	Capture device deployment mechanism	A deployment mechanism is needed to bring the capture device effector into position to grab the Satellite. One of the challenges of the deployment mechanism include being able to cover the necessary degrees of freedom for capture.
H3	Testbed hardware interfacing	In order to determine the necessary variables for the capture algorithm there must be an electronic interface that collects data from the sensors and signal the actions for the actuators to take.
Software		
S1	Approach and capture algorithm	The approach and capture algorithm is needed to characterize the capture mechanism dynamics and develop an optimal path for the capture. The way that the algorithm integrates with the input data from testbed sensors provides a technical challenge.
Manufacturing		
M1	Linear translation system	The CubeSat may be translating so it is necessary to have a system that will allow for that linear translation. Due to the specialized requirements of the mission it is possible that one of the challenges will be to fabricate the system.
M2	Rotational system	The CubeSat may be rotating so it is necessary to have a system that will allow for rotation. Due to the specialized requirements of the mission it is possible that one of the challenges will be to fabricate the system.
M3	Capture Device	If it is deemed infeasible to purchase the components of the capture device such as the endeffector or the deployment mechanism or both they will need to be fabricated. This poses a significant technical challenge for the team since there is very little experience in robotics.
Testing		
T1	Autonomous Guidance System	In order to provide input to the approach and capture software there must be a system that can collect data on the position, velocity, and orientation of the smallsat and capture device.
T2	CubeSat Capture	One of the project functional requirements is the completed capture of a CubeSat by the capture device. The challenge of capturing the CubeSat lies in developing the capture algorithm and controlling the movent of the capture device.
T3	CubeSat Release	The capture device should be capable of releasing the CubeSat without incurring any damage to demonstrate the utility of the smallsat capture system as a device for CubeSat reclamation
Financial		
F1	Testbed Mechanical Systems and Sensor procurement	The majority of the financial burden lies in the cost of procuring all the necessary hardware such as the capture device components and the fabrication of the motion system. With the number of components required to accomplish the mission it may be challenging to stay in budget

2.4 Concept of Operations

The overall concept of operations is show in Figure 3. Sierra Nevada Corporation's primary plan is to rendezvous with the CubeSat using a capture device. After capturing the CubeSat, the two body system is stabilized and then moved to a different orbit using the propulsion system on the capture satellite where the CubeSat is released.

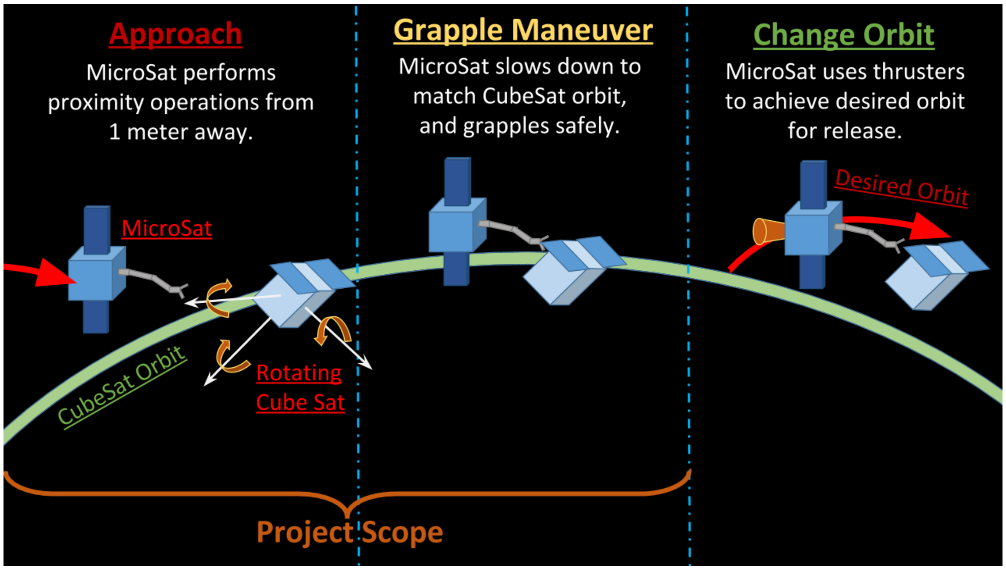

Figure 3. Concept of Operations Overview

A physical demonstration shall be created to verify functionality of an approach and capture algorithm, and capture device from the initial conditions stated in Section 2.2. Figure 4 shows the concept of operations of such a demonstration. This demonstration shall be autonomous at the highest level of success. Once the demonstration starts, the approach and capture algorithm will determine the commands to be sent to capture the rotating CubeSat model. The commands will go to the capture device and CubeSat motion apparatus connected to a rail at the bottom of the testbed. The CubeSat motion apparatus shows the translation and rotation of the CubeSat with respect to the capture device. The controllers in both the capture device and CubeSat motion apparatus will take the commands and output the signals to the servos and motors of the CubeSat motion apparatus and capture device. There will be feedback sensors to determine the position and rates of the CubeSat motion apparatus and capture device to provide feedback to the approach and capture algorithm to correct and determine the next set of commands. This process is completed at each time step until capture is confirmed.

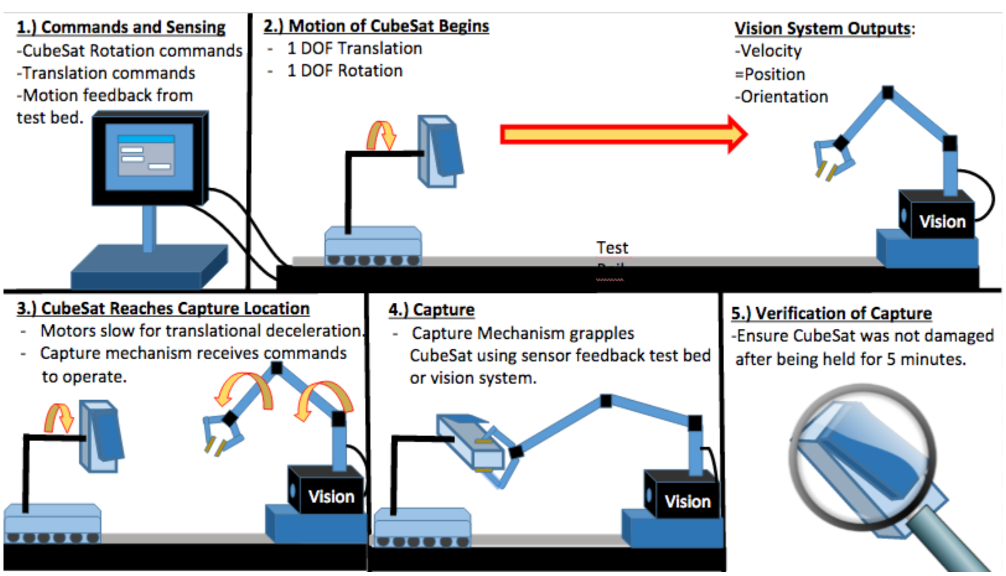

Figure 4. Project CONOPS

2.5 Functional Block Diagram

Shown in Figure 5 is the functional block diagram of the CASCADE project. The demonstration begins with the user sending the signal to start. The CubeSat will start spinning at the desired rate of 0.5 RPMs. After the demonstration has commenced, an algorithm is started which determines the relative motion of the CubeSat compared to the capture device and determines what commands are needed for approach and capture of the CubeSat. The algorithm FBD is shown in Figure 6. Commands are sent to controllers which control the linear motion of the capture device origin as well as the position of each joint on the capture device. A check is made after each cycle of commands(each time step) to determine if the CubeSat has been captured. If the CubeSat has not been captured, the algorithm determines the next commands to be sent. If the CubeSat is captured, the demonstration is concluded.

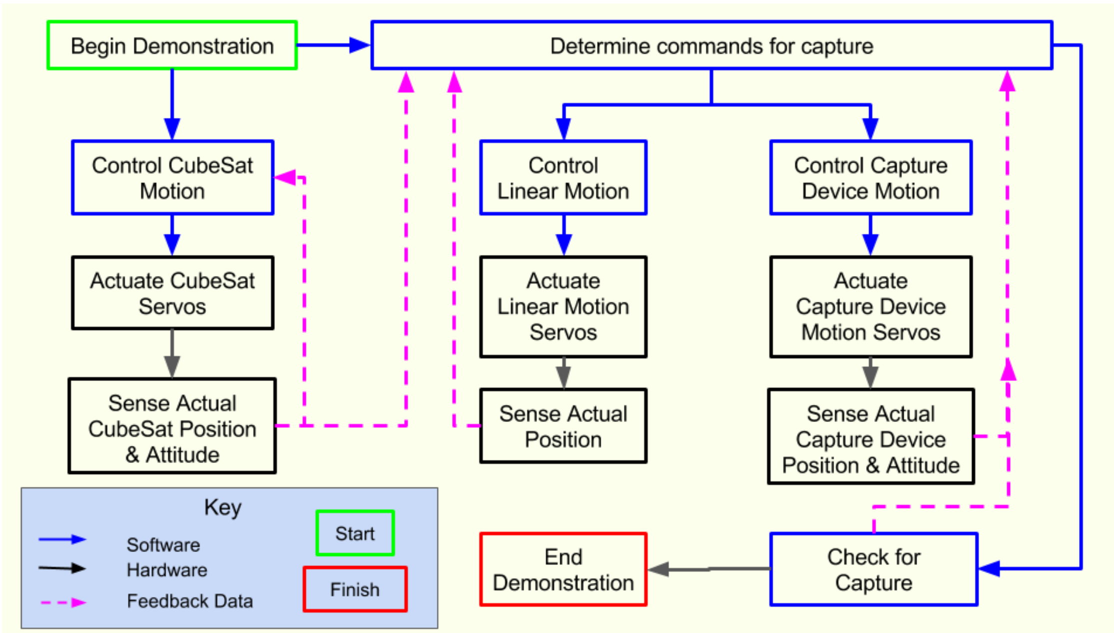

Figure 5. Functional Block Diagram

After the start of the demonstration, an algorithm will determine the best relative position and orientation of the capture device to capture the CubeSat which are calculated based on initial conditions. Based on the nominal grab location, the algorithm will minimize risk of damaging both systems and determine the optimum solution for moving the capture device into the ideal position. The algorithm will generate a list of optimum positions between the start and end of capture.

Figure 6 shows the logic after the known optimum approach and capture solution. The purpose of *Determine commands for Capture* is to compare the current state of the system to the nominal model for approach and capture.

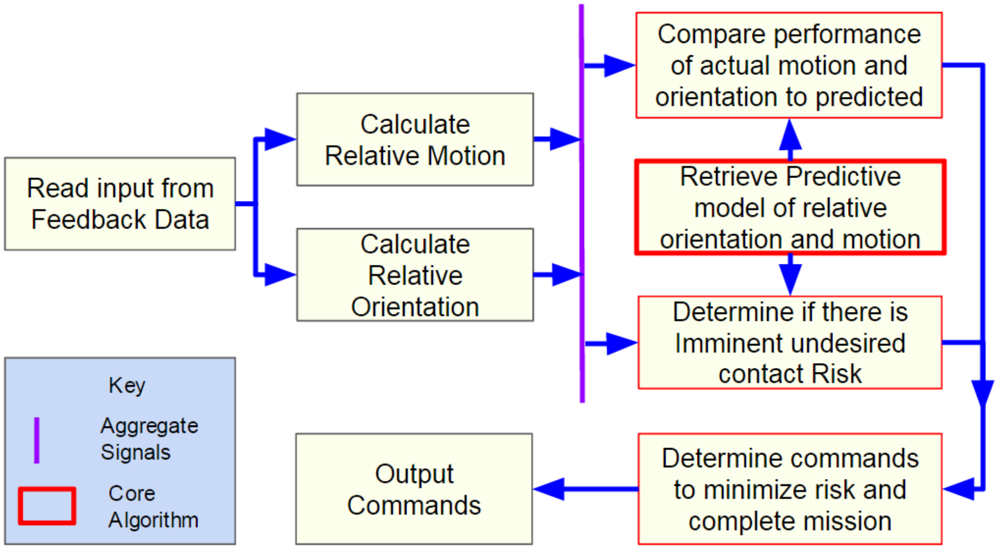

Figure 6. Functional Block Diagram of Algorithm

The red box in Figure 6 determines the optimum configuration of the capture device relative to the CubeSat at every step required to approach and capture the CubeSat. *Configuration* is defined as the state of each degree of freedom of the capture device. The capture device is constrained by undesired contact with the CubeSat. The capture device's joints are also constrained such that the moments commanded must be possible to perform.

With these constraints, the solution space can be defined. The configuration space, C is defined as the space which captures all possible configurations a capture device can engage. The dimension of this space corresponds to the capture device's number of degrees of freedom and linear translation. Since the problem is defined as relative motion with respect to the CubeSat, there is also the obstacle space $\mathcal{B}$ needed to avoid crashing into the CubeSat[2]. Mapping $\mathcal{B}$ on to C yields a space $C_{obstacle}$. The goal of Cascade is to determine the optimum approach path contained within C_{free}, which is the space where there is a minimal chance of collision, in order to avoid undesired contact. The solution must be constrained by the limitations to the degrees of freedom of the capture device and the approach path.

The most common planning method is the graph based model, Figure 7. Each node represents a step in order to solve the problem. Node 1 is the start location and node 20 is the desired end location (captured CubeSat). At each step, there is a configuration that fits into the constraints of the problem. The goal of the algorithm is to determine the optimal path for traversing the graph from start configuration to end configuration.

There are numerous algorithms that can be used to solve the autonomous problem[3], CASCADE plans to do more research due to the complexity of even the simplest algorithms after the capture device and testbed configuration have been chosen.

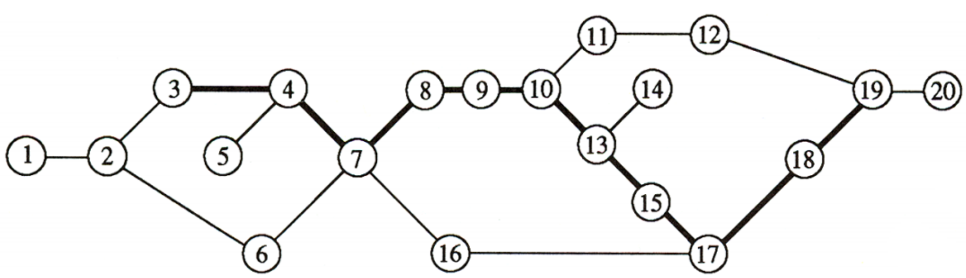

Figure 7. Graph of possible Configurations[2]

2.6 Functional Requirements

FR 1. The CubeSat Recovery System Testbed (CRST) shall demonstrate the successful capture of a physical CubeSat model.

- **FR** 1.1. The CRST shall demonstrate the motion of a CubeSat analogue during the demonstration.
- **FR** 1.2. The CRST shall determine the relative position and attitude of the CubeSat and capture device during the demonstration.
- **FR** 1.3. The CRST shall determine the relative position and attitude rates of the CubeSat and capture device during the demonstration.
- **FR** 1.4. The CRST shall calculate a capture trajectory capable of capturing the CubeSat during the demonstration.
- **FR** 1.5. The CRST shall command the relative linear motion between the CubeSat and the capture device based on the calculated capture trajectory during the demonstration.
- **FR** 1.6. The CRST shall command the motion of the capture device based on the calculated capture trajectory during the demonstration.
- **FR** 1.7. The CRST shall execute capture of the physical CubeSat model by a capture device during the demonstration.

3 Design Requirements

This section presents the design requirements flow down used to the limit the design space. The design requirements are flowed down from the functional requirements presented in Section 2.6. Each design requirement also includes the Source and Motivation (S&M) as well as Verification and Validation (V&V) descriptions.

FR 1. The CubeSat Recovery System Testbed (CRST) shall demonstrate the successful capture of a CubeSat.

FR 1.1. The CRST shall demonstrate the motion of a CubeSat analogue.

★ **DR** 1. The CubeSat analogue shall include a physical model of a 3U CubeSat with dimensions specified in Figure 2.

S&M: In order to demonstrate of the motion of a CubeSat Analogue, a physical 3U CubeSat model will need to be fabricated since it is easier to manufacture than to purchase.

V&V: Inspection: Measurements will be taken of the 3U CubeSat model by the team to verify it meets the correct volume specifications. No mass requirement is given since the CubeSat will be supported by the structure of the testbed.

★ **DR** 1.1. The physical model of a 3U CubeSat shall include at minimum one significant protrusion to represent solar panel(s).

S&M: SNC Requirement. In order to make the problem definition more applicable to space, protrusions to represent solar panels were added as a constraint.

V&V: Inspection: Measurements will be taken solar panel(s) mock-up by the team to verify they meets the correct volume specifications. No mass requirement is given since the CubeSat will be supported by the structure of the testbed.

★ **DR** 2. The CubeSat analogue shall allow for translation motion about one axis.

S&M: In order to model the relative position between the capture device and the CubeSat, translation of the CubeSat has been chosen as the design constraint since it is easier to move than the capture device due to its weight and complexity.

V&V: Test: The team will verify that the CubeSat can translate toward the capture device as per the initial conditions specified in the Section 2.2.

★ **DR** 3. The CubeSat analogue shall allow for rotational motion about one axis.

S&M: In order to model the relative angular velocity between the capture device and the CubeSat the CubeSat will need to rotate about one spin axis as specified in the Section 2.2.

V&V: Test: The team will verify that the CubeSat can rotate about the spin axis specified in the Section 2.2.

★ **DR** 3.1. The CubeSat analogue shall allow for a angular velocity along the rotational axis at minimum 0.5 RPM.

S&M: SNC Requirement. Due to the slow spin rate of objects in space that are in control, 0.5 RPM was chosen as the design constraint for angular velocity of the CubeSat. This speed allows for added complexity while still being feasible to design for and is also inline angular velocities of common artificial space bodies.

V&V: Test: The team will verify that the CubeSat can rotate about the spin axes specified at a rate of 0.5 RPM using sensors attached to the testbed.

FR 1.2. The CRST shall determine the relative position and attitude of the CubeSat and capture device during the demonstration.

★ **DR** 1. The CRST shall employ sensors to gather data during the demonstration.

S&M: In order to determine the relative position and attitude of the CubeSat relative to the capture device various sensors will be needed to gather the actual data from both bodies.

V&V: Test: The team will use LabView to analyze data outputted by the sensors.

FR 1.3. The CRST shall determine the relative position and attitude rates of the CubeSat and capture device during the demonstration.

★ **DR** 1. The CRST shall employ sensors to gather data during the demonstration.

S&M: In order to determine the relative position and attitude rates of the CubeSat relative to the capture device various sensors will be needed to gather the actual data from both bodies.

V&V: Test: The team will use LabView to analyze data outputted by the sensors.

FR 1.4. The CRST shall calculate a capture trajectory capable of capturing the CubeSat during the demonstration.

★ **DR** 1. The CRST shall employ software to calculate a capture trajectory capable of capturing the CubeSat during the demonstration.

S&M: The calculation of the capture trajectory is best handled by software due to its complexity.

V&V: Demonstration: The software algorithm will be validated with successive successful captures.

FR 1.5. The CRST shall command the relative linear motion between the CubeSat and the capture device based on the calculated capture trajectory during the demonstration.

FR 1.6. The CRST shall command the motion of the capture device based on the calculated capture trajectory during the demonstration.

FR 1.7. The CRST shall execute capture of the physical CubeSat model by a capture device during the demonstration.

★ **DR** 1. The CRST shall include a physical capture device used to capture the physical CubeSat model.

S&M: SNC Requirement. SNC requires Team CASCADE to fabricate a capture capable of capture a 3U CubeSat. This capture device prototype/concept could later with modified to interface with one of SNC's satellite buses, namely the SN-50 MicroSat.

V&V: Demonstration: The CRST shall demonstrate capture of the CubeSat using the capture device.

★ **DR** 1.1. The capture device shall occupy no more volume than the pay-load bay shown in Figure 1.

S&M: Team CASCADE self imposed design constraint. After the descope, volume, mass, and power constraints were kept to limit the design space and better reflect constraints associated with that of an actual payload.

V&V: Inspection: The team will conduct measurements to verify volume constraint it met.

★ **DR** 1.2. The capture device shall have a mass budget of 15kg.

S&M: Team CASCADE self imposed design constraint. After the descope, volume, mass, and power constraints were kept to limit the design space and better reflect constraints associated with that of an actual payload.

V&V: Inspection: The team will weigh the capture device.

★ **DR** 1.3. The capture device shall have an average power of no more than 100W.

S&M: Team CASCADE self imposed design constraint. After the descope, volume, mass, and power constraints were kept to limit the design space and better reflect constraints associated with that of an actual payload.

V&V: Test: Voltage and current will measured to derive power consumption.

★ **DR** 1.4. The capture device shall have an peak power of no more than 168W.

S&M: Team CASCADE self imposed design constraint. After the descope, volume, mass, and power constraints were kept to limit the design space and better reflect constraints associated with that of an actual payload.

V&V: Test: Voltage and current will measured to derive power consumption.

★ **DR** 1.5. The capture device shall have an peak current draw of no more than 10A.

S&M: Team CASCADE self imposed design constraint. After the descope, volume, mass, and power constraints were kept to limit the design space and better reflect constraints associated with that of an actual payload.

V&V: Test: Current will measured with an ammeter.

★ **DR** 1.6. The capture device shall have an peak voltage draw of no more than 28V ± 6V unregulated.

S&M: Team CASCADE self imposed design constraint. After the descope, volume, mass, and power constraints were kept to limit the design space and better reflect constraints associated with that of an actual payload.

V&V: Test: Voltage will measured with a voltmeter.

★ **DR** 2. The demonstration shall begin at a minimum distance of 1m between the physical CubeSat model and the capture device.

S&M: SNC Requirement. Used to limit the testbed size needed for the demonstration. Due to the small size of the CubeSat, a longer initial distance would not add much value. A longer initial distance would also be more difficult to store in the test facility.

V&V: Inspection: The team will measure the initial distance prior to the start of the demonstration.

★ **DR** 3. Control of the demonstration after initiation shall be autonomous (closed-loop) in nature.

S&M: SNC Requirement. SNC's main focus is understanding how the capture algorithm works in a autonomous environment with the capture device capturing a CubeSat.

V&V: Demonstration: No human intervention will occur after initiation of the demonstration. Commands given by the algorithm will be based on an active closed-loop feedback with testbed sensors.

★ **DR** 4. The CRST shall capture the CubeSat with the capture device in less than 30 minutes.

S&M: Team CASCADE self imposed design requirement to limit the demonstration time. Prior to descope, this time interval was an SNC requirement and the team felt that it should be kept (similar to the mass,volume, and power constraints.)

V&V: Demonstration: Software will time the demonstration.

★ **DR** 5. The CRST shall capture the CubeSat with the capture device without visible damage to the CubeSat nor the capture device.

S&M: SNC Requirement. SNC desires that both satellites are undamaged from the capture so they can be reused and repurposed. Also, this requirement minimizes the creation of space debris which is an important benefit.

V&V: Inspection

★ **DR** 6. The CRST shall allow for five repeated demonstrations without human intervention.

S&M: SNC Requirement. SNC desires that both satellites be reused and repurposed. From SNC perspective and to limit the demonstration period, a limit to five repeated demonstrations is sufficient to show this.

V&V: Demonstration: The CRST will run repeatedly for five time without human invention between capture attempts.

★ **DR** 7. The capture device shall be able to release the CubeSat after capture without human intervention.

S&M: SNC Requirement. The system is required to be reusable, and as such the capture device must be releasable so that the CubeSat and capture device may separate to repeat the demonstration without human intervention.

V&V: Test: The team will verify that commands can be sent to the capture device to release the physical CubeSat model.

4 Key Design Options Considered

4.1 Capture Device Deployment

A key aspect to how the capture mechanism will function is the *deployment*. Without a method of deployment, the end effector, or the device that grips onto the surface of the CubeSat, will have no method of reaching the surface due to volume restrictions. The ideal deployment method will be very precise and capable of accurately delivering the end effector to a specific location on the CubeSat. The cost of developing a deployment mechanism, including algorithm complexity, is explored within the options below.

4.1.1 Robotic Arm

Seemingly the best design option to optimize the functionality of the capture device, a *Robotic Arm* would provide the most degrees of freedom out of any of the deployment options. Implementing such a device would allow for a precise and flexible approach for locking on to the ideal location to capture. This deployment option would enable any of the end effectors to capture without a need to fine tune the attitude of the SmallSat at the time of closest approach with the CubeSat, as the robotic arm would have the ability to make any necessary corrections. This device has a high potential for release following capture and reusability, which are two substantial motivators when weighing the device against the other options.

The biggest concern with the robotic arm is the high cost for procurement or purchase of the device. A high end, industry grade robotic arm with the necessary capabilities could run between $5000 - $20,000, which in itself would exceed the budget of the project. Affordable options, including the 7Bot arm show in Figure 8 below, are being explored to determine if the utility provided will be sufficient.

Other concerns with the robotic arm are the development of algorithms and the power required for operation of the device. Programming this device would require extensive knowledge of robotics, a concept of which the team has limited experience. It would be beneficial to select a device for purchase with interfacing capabilities that play to the strengths of the team. Additionally, extensive research on robotic arms indicate power requirements ranging between 60%-300% of the payload's power budget of 100W OAP (Orbital Average Power). This is a significant concern even on the lower end when considering design margin. A summary of the pros and cons can be found in table 4 below.

Table 4. Pros and Cons of a robotic arm

Pros	Cons
High DOF and flexibility	Complex algorithm development
High potential for reusability	High procurement costs
	Substantial power required

Figure 8. 7Bot: Candidate for Robotic Arm[4]

4.1.2 Boom

A popular concept for deployment within the satellite industry is the *boom*, which has numerous design options and functions. Two of these concepts are of particular interest to the team as viable options for capture of the CubeSat, which are a telescoping structure and hinged extendable arms. Each of these options has the advantage of relatively simple implementation at the cost of flexibility. The linearity of these devices provides a single DOF which is concerning for capture accuracy and the need for precise spacecraft attitude. Payload volume could potentially be an issue depending on the ability to collapse and compactness of these devices.

A significant advantage to the boom is a simpler algorithm to complete capture. Because these devices are so common, many concepts have been developed in the industry that could be mimicked. This device would be concerned with less degrees of freedom. Concepts of each device can be seen in figures 9 and 10 below, and a summary of the pros/cons in table 5.

Table 5. Pros and Cons of a boom

Pros	Cons
Low material cost design options	Single DOF & possible attitude adjustments needed
Relatively simple implementation	Manufacturing complexity
Popular in industry	Mechanical parts vulnerable to wear & tear (reusability)

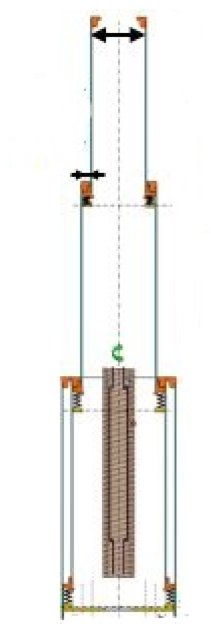

Figure 9. Telescoping Structure[5]

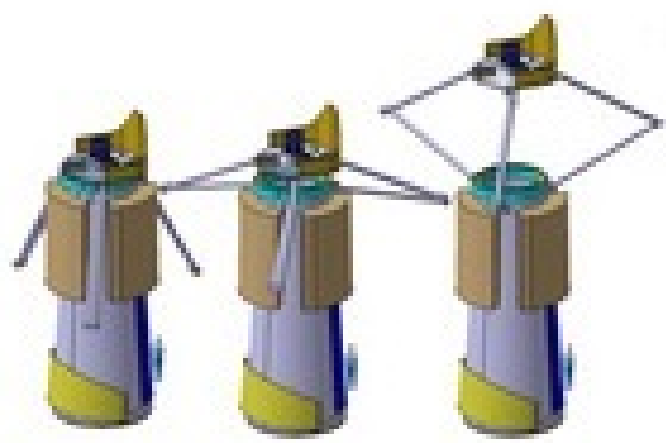

Figure 10. Hinged Arms[6]

4.1.3 Tether

A *momentum exchange tether* uses a long thin wire to transfer momentum from one object to another. The objects move close together and the capture satellite deploys the cable onto the desired object. The two then separate into different orbits. Differences in the gravity of the two orbits will cause the objects to be pulled apart. This is due to the gravity gradient force, or the tidal force. The wire can be designed to be an electrical conductor, which will cause current to flow through the cable while passing through the Earths magnetic field, allowing the generation of electrical power to the satellite deploying the tether[7]. This method of changing the orbit of a small object can be used with a variety of end effectors.

An advantage of using a tether system is that it requires a small amount of time to transfer objects to another orbit, this is due to the impulsive manner at which the momentum transfer occurs. A tether system may also be favorable due to the reduction in proximity distance for a successful capture, which would minimize the risk of the capture satellite coming in contact with the CubeSat. The power generation in the cable is an added benefit that could be utilized to reduce the power budget, and could even be used to power the end effector of the capture device.

Using a tether for capture presents added complications such as having to position the spacecraft holding the tether very accurately above the object in order for the end effector to come in contact. In other words, the ability to precisely grapple a specific spot on the CubeSat is very difficult. The main pros and cons discussed above are shown in table 6.

Table 6. Pros and Cons of a tether deployment.

Pros	Cons
Current induced in the tether can be used to generate power.	Not able to control the tether itself.
Simplistic design and easy to deploy.	Very precise approach required.
Low mass and volume since it can be wound up.	Testing complicated and costly.

4.2 Capture Device Effector

The *effector* of the capture device is a very important component, as it will be what actually grips to the surface of the CubeSat in some way. There are many effectors for use in various manufacturing industries, but only some of these are suitable for the capture of a CubeSat. The ideal end effector would be low cost and easy to implement. A less complex approach to the CubeSat is desirable, but precision is important when considering other criteria. Of course, the manufacturing cost and difficulty will be considered, as well as the cost of developing the effector technology. Various design options for end effectors are described below.

4.2.1 Claw

The *claw* is a high risk, high reward end effector option. Such a device would have the advantage of being able to release the CubeSat with ease, granting it a high chance of reusability for multiple cycles. With an effective approach algorithm, the claw would be capable of precise capture. Ideally, a well-designed claw would not add significant mass to the payload.

To model the problem of this project realistically, the CubeSat will not possess any special features for grabbing. Most CubeSats have solar panels to provide enough energy to run the on-board instruments. In theory, a solar array might be used in certain applications as a rigid feature for capture. However, the force required to grip with the claw could pose significant risk to the solar array and will not be considered an option within the project. Furthermore, this requires that the claw grips the primary CubeSat structure. For this to occur, the claw will need to be a relatively large mechanism such that it fits around the entire CubeSat, adding substantial volume and complexity. For a capture to be successful, the claw would need to clasp at all contact points within a small window to prevent an unequilibrated force from spinning or pushing the CubeSat. Too much force or force applied in undesired locations also poses damage risk, and the mission must not create debris to be considered successful. A summary of the pros/cons can be found below in table 7.

Table 7. Pros and Cons of a claw

Pros	Cons
Reusable	Possible volume concern
Precise capture assuming proper implementation	Risk of forces/torques that alter CubeSat dynamics
	Risk of debris

4.2.2 Engulfer

In 2004 a *deployable engulfer* technology was demonstrated in micro gravity to capture an uncontrollable spacecraft. The technology proved the ability to capture and manipulate small objects in space with a high moment of inertia, such as small asteroids, uncontrolled spacecraft, or space debris. The GRASP system developed by Tethers

Unlimited Inc. uses inflatable tubes to deploy a engulfer formation to capture objects. It then deflates using a drawstring mechanism that allows for secure hold on the object[8]. Since the GRASP mechanism was designed to fit within a 1U volume, a similar engulfer would be a very suitable option for the payload volume for CASCADE. The power required to deploy the engulfer was less than 10 W, well within the power requirement.

This method of capture has the advantage of being simple to execute, all that is needed for a successful capture is positioning in a location in orbit that the object will pass through. There is also no need for an added deployment other than the inflation of the tubes, and the drawstring mechanism. Inflatable tubes and the engulfer material are less rigid than other capture device options, which means less risk of damaging the CubeSat upon capture.

However, a deployable engulfer system may have a shorter lifetime than other forms of capture due to the integrity of the inflatable tubes and engulfer material. The system would also be more difficult to implement the release of an object. This system adds the risk of the object becoming stuck permanently in the engulfer, which would mean end of lifetime for both satellites. This could be mitigated by adding some sort of film in between the engulfer material, but this would increase the complexity of the engulfer, and at least double the volume before deployment according to *Tethers Unlimited* estimates. The pros and cons of an engulger effector discussed above are shown in table 8.

Although the GRASP mechanism was not designed for release ability, but rather only for capture of space debris it may not be suitable for the repurpose of a CubeSat. However, the *Tethers Unlimited* company was contacted for information about the release ability. According to the designer of the GRASP system slight modifications could be made to allow for a system that could release objects as well. The cost of a prototype for this material would be much less than the minimum of $100,000 quoted by *Tethers Unlimited* for a space ready GRASP system. The manufacturing of an engulfer would likely still be higher cost and difficult to implement, but less expensive than developing a technology such as electrostatics.

Table 8. Pros and Cons of an engulfer effector.

Pros	Cons
Ultra lightweight and compact.	Extremely difficult to release captured objects.
Approach for capture is simplistic.	Costly and difficult to manufacture.
Low power requirements.	High risk

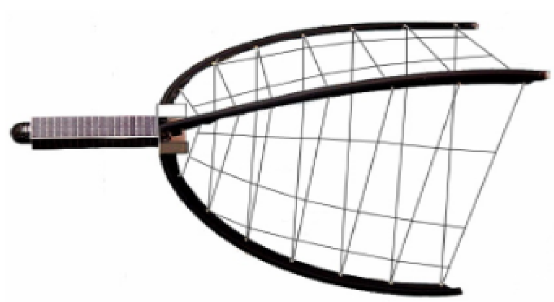

Figure 11. Concept for a deployable Engulfer capture effector[8].

4.2.3 Dry Adhesives

The invention of *dry adhesives* at the end of the 20th century has lead to many new innovations since. Dry adhesives are a reusable adhesive nanotechnology material based of the structures on the bottom of a gecko foot[9]. The material uses pressure to create molecular forces, such as the van der Waals force, to adhere to surfaces[9]. In a study between NASAs JPL and Stanford University, this material had a prototype for the use of capturing small objects in space. This technology used multiple dry adhesive surfaces along with both spring and pulley systems to create a gripping device for a force of up to 50 N[10].

As shown in figures 12 and 13 the gripping device must have a method of pulling the dry adhesive surfaces toward one another, in this case using a tendon attached to a pulley or constant spring. The shear forces of this motion cancels out and all that is left is a normal adhesive force. To turn off the the device the force pulling the surfaces together is released, and two other tendons are used on the outside of the surfaces to pull them off the surface using a moment force. Actuators are used between various surfaces to allow for the release and tightening of the tendons attached to the grippers.

Dry adhesives have been tested in a complete vacuum at -60 deg C for 30,000 separate gripper commands[10]. This shows that dry adhesives are a reusable and reliable end effector for missions in space. The nanotechnology has been tested on rough and smooth, as well as wet and dry surfaces. This means gripper doesn't need a very specific location to grip to, just a flat surface. Creating this contact could only be done with the use of a robotic arm, or by using a boom along with very precise orbital maneuvers. The volume and mass of dry adhesive material is very small relative to the payload restraints, the material itself is similar to strips of sandpaper. The device to implement the adhesives would likely weight much less than 15 kg as it is mostly made of small springs, pulleys and linear actuators. The pros and cons of dry adhesives discussed above are shown in table 9.

Table 9. Pros and Cons of a dry adhesive end effector.

Pros	Cons
Volume and mass of system easily fit in payload.	More moving parts than a claw (pulleys, springs, linear actuators).
Approach for capture somewhat simple (only 1 surface of contact).	More cost than a simple claw or clamp.
Tested on a solar panel with no damage.	Maintaining grip after capture may require moments applied by the satellite or robotic arm.
Tested in vacuum to be very reliable (30,000 ON/OFF cycles).	

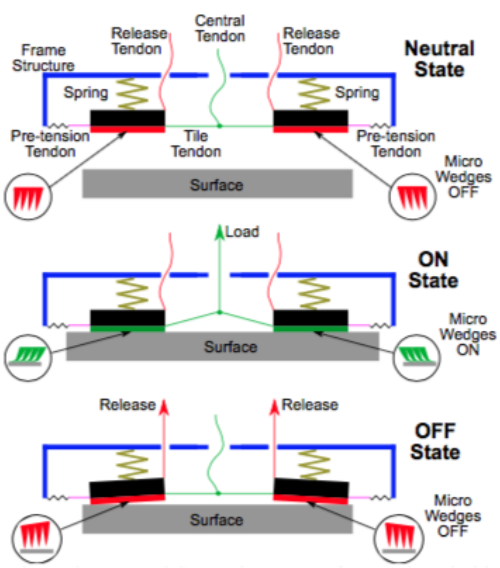

Figure 12. One concept for the use of dry adhesive nanotechnology, 2 pads[10].

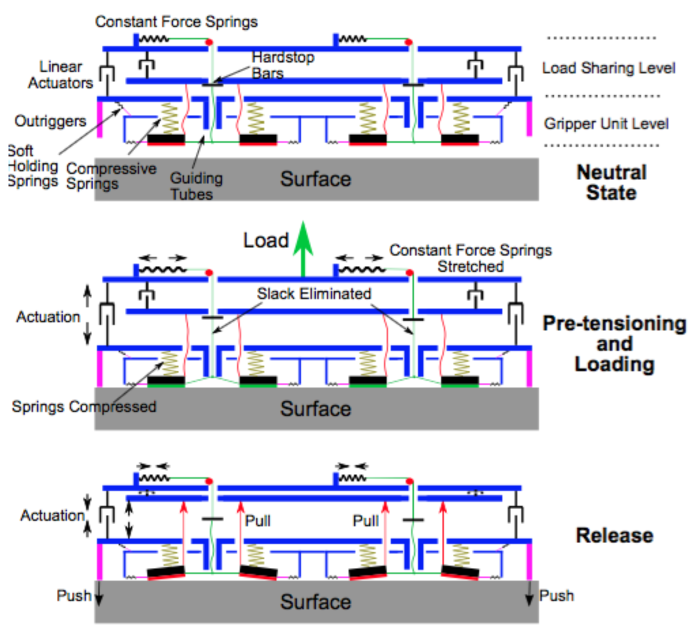

Figure 13. One concept for the use of dry adhesive nanotechnology, 4 pads[10].

4.2.4 *Electrostatic Adhesion*

Electrostatic adhesion has been used in industry for a number of years, NASA has considered the technology for a variety of uses from a gripper for satellites to the bottom of astronaut feet for walking on the space shuttle. This technique uses two electrodes to induce opposite charges on adjacent planes, which induce opposite charges on the target surface, which causes an electrostatic force between the electrodes and the target surface. This technology is possible with both conductive and non non-conductive surfaces. For conductive surfaces, Coulomb forces are applied, and for non-conductive surfaces the force is due to dielectric polarization [11]. Gripping and release is done very quickly by turning the electrodes on and off. Electrostatic adhesion can also be achieved for a variety of shapes and textures, since the electrodes can be encased in a form-fitting polymer.

Implementing an electrostatic end effector allows for a less precise approach to an object, since the electrodes ionize the surface of the object an attractive force will pull the two together. An electrostatic effector required around 1-5 kV, but only about 10-20 nA per Newton to operate [11]. Since power is voltage multiplied by amperage, the power requirement is very low, about 10-100 μW per Newton. The volume and mass would be more than that of a simple claw mechanism, but still well under the volume and mass limitations.

The downside of using electrostatic adhesion is the difficulty cost of manufacturing. Since the physics of an electrostatic end effector are different in space expensive calibration and testing facilities are needed. The humidity of a lab under the pressure of the atmosphere requires more complex design for the electrodes, and calibration must be done inside a vacuum chamber. The gripper pads must be machined very carefully, with many added safety features, to prevent any coronal discharge or arcing across electrodes. Electrostatic pads are also much more efficient at pulling in shear, parallel to the surface, in opposed to pulling perpendicular from the surface. The pros and cons of electrostatic adhesion discussed above are shown in table 10.

Table 10. Pros and Cons of an electrostatic gripper.

Pros	Cons
Can adhere to a variety of different shapes and textures.	Difficulty of manufacturing
Approach is somewhat simple since device enables electrostatic attraction.	Cost of facilities for calibration and testing.
Low power, mass, and volume.	Ionizing the CubeSat may cause sensor damage depending on CubeSat payload.
	Safety concerns (arcing and coronal discharge)

4.3 Testbed Configuration: Single Axis Translation

The following design options propose four fundamentally different methods for designing a Testbed to achieve translational motion between the CubeSat and the capture device. Because it is only the relative motion that is important in this problem, all four design options consider a translating CubeSat with a stationary capture device. Each design option is independent of which object is translating and could feasibly work in the swapped configuration, with the capture device translating and the CubeSat stationary. However, the bottom line is that the CubeSat will most likely be smaller, less bulky, and lighter weight - making it by far the easier object to translate. Thus, this is the configuration depicted in each design option. If an unforeseen issue arises with this configuration, steps can be taken to use the same fundamental method of translation while swapping the roles of the objects in terms of translation. It is worth noting in advance that one of the tradable criteria in deciding upon one of these options is how well the method of translation represents the unrestrained motion encountered in the space environment. It is not a requirement that the Testbed used in this demonstration be representative of the space environment in terms of dynamics. However, as this technology is obviously geared toward space applications, the readiness with which the method of translation replicates the dynamical environment of space is noted in each design description and later traded upon.

4.3.1 Air Table

This air table design involves creating a test table that is similar to an air hockey table in that it is capable of floating the CubeSat platform on a cushion of air, thereby mimicking a frictionless surface that closely resembles planar translational motion in the space environment. With this option, the relative translational motion between the CubeSat and the capture device would be achieved by having a thruster or propeller system on the CubeSat platform. The biggest drawback to this option is the imprecision in controlling the motion of the CubeSat platform. Imperfections in table construction and airflow, combined with an imperfect propulsion system could well bring the translational motion below the required tolerance determined by the capture device. Different design variations could be implemented to mitigate this problem, such as adding guide rails to the table. However, those sorts of modifications would restrain the main benefit of this option, which is that it provides nearly frictionless translation.

Table 11. Air table pros and cons

Pros	Cons
Frictionless surface is representative of planar motion in the space environment	Additional component to design and manufacture - most likely no COTS options available
Allows for more translational degrees of freedom - capability of being used for higher level testing	Imprecise velocity and directional control
Capable of being manufactured out of cheap, common materials (i.e. 2x4's and plywood)	

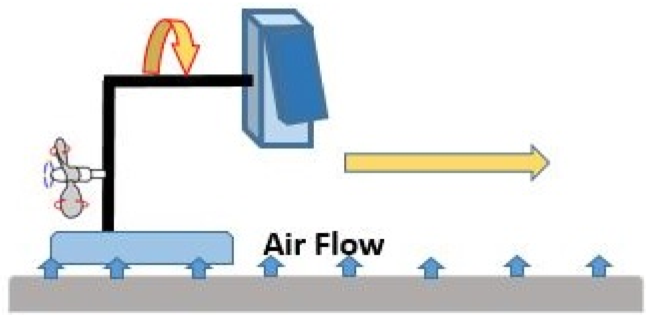

Figure 14. Air Table Configuration

4.3.2 Linear Drive System

The linear drive design uses a to-be-determined linear motion system to move the CubeSat platform to the capture device. The setup would be similar to that of the air table shown in Figure 4.3.1, with a structure holding the CubeSat in place for rotation about an axis parallel to the linear rail. This structure would then be mounted on to a base plate that interfaces with the linear drive system, such as in Figure 4.3.2. The system would also feature a motor along with a method of converting rotational motion into translational motion, such as a belt drive, a ball screw, or a rack and pinion. Although the linear drive system does not provide translation over a frictionless surface, and thus does not replicate translation in the space environment, steps can be taken from a control design standpoint to mitigate this issue and still demonstrate the functionality of the capture device with the development toward space capture technology in mind. The main advantage to this system is that it restrains the Testbed to 1 axis of translation, which is all that is required. Thus, no additional control need be implemented to ensure that the relative translation occurs in a single direction. Again, a further trade study shall be conducted to evaluate which of the previously mentioned options will be implemented. At this stage of design, the options mentioned, in addition to other linear actuators, all function in the same way from a conceptual perspective. Choosing one will eventually come down to interface requirements and cost.

Table 12. Linear drive system pros and cons

Pros	Cons
Simple design - constrains the testbed to linear translation so no directional control is required	Not frictionless - does not accurately represent the space environment
COTS systems and components are available	Higher cost

Figure 15. Linear Drive System [12]

4.3.3 Cable-Hung CubeSat

This design involves the CubeSat hanging from a cable that runs through a pulley which is attached either to the ceiling or to an external structure. The capture device sits directly below it on the ground and translational motion is achieved by lowering the CubeSat via the pulley system. Because gravity acts in the direction of translation, this option does not represent space dynamics along the capture path. However, it is the simplest design from a materials and manufacturing standpoint. This also leads into it being the cheapest design. The complexity that comes into this design is that with the CubeSat rotating, it will be very difficult, if not impossible to hang it in such a way that minimizes wobble. Adding a large amount of wobble to the CubeSat rotation is not desirable because it adds an uncontrollable degree of rotational motion to the problem that is not conducive to creating a controlled demonstration that mirrors the levels of success of the project.

Table 13. Cable-Hung CubeSat pros and cons

Pros	Cons
Simple design	Facility constraints
Low cost	CubeSat can wobble

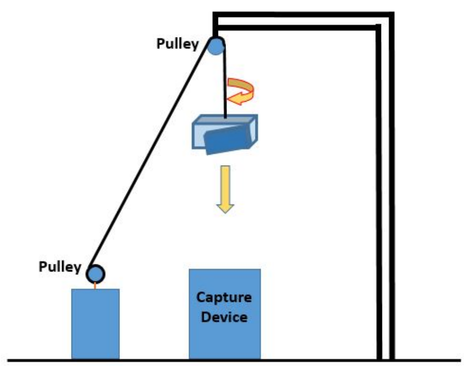

Figure 16. Cable-Hung CubeSat Configuration

4.3.4 Magnetic Levitation

The final design option uses the concept of magnetic levitation, also known as a linear induction motor [13], to suspend the CubeSat platform in the air as well as apply a magnetic force in order to propel the CubeSat forward toward the capture device. This design requires both the CubeSat platform and the track to be equipped with electromagnets that induce repelling magnetic forces, thereby suspending the platform above the track. Translational motion is achieved by controlling the current through the electromagnets in order to change the magnetic force in such a way that linear acceleration is achieved. Like the air table, this is a frictionless system, and like the linear rail, it is constrained to one axis of translation. In some ways, it is the best of both worlds from the air table and the linear rail. However, cost and lack of expertise limit the feasibility of this design.

Table 14. Magnetic levitation pros and cons

Pros	Cons
Frictionless translation	High cost
Constrained to one axis of translation - no directional control required	New technology - not a lot of expertise or resources available

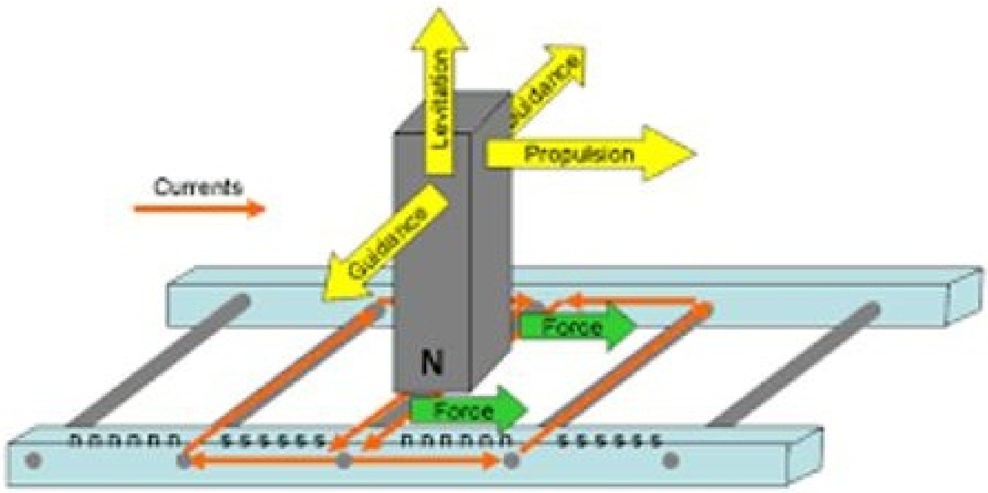

Figure 17. Magnetic Levitation Configuration [14]

4.4 Testbed Configuration: 1 Degree Rotational Motion

This section of the testbed configuration focuses on having two functions: to spin up the CubeSat and to maintain the rotational speed of at most 3 deg/s during the test phase. The four design options below offer methods to satisfy these two functions. These design options are chosen such that they offer flexibility in its interface with the CubeSat; thus, there are not any predetermined configurations.

4.4.1 Electric Stepper Motor

Electric stepper motors [15] are rotary DC motors that contain several coils of wire that surround the rotor. The rotor has a permanent electric magnet and interacts with the magnetic field that the coils create such that the rotor rotates in steps. By energizing the coils in sequence, the rotor will rotate one step at a time and spin just like an ordinary motor. It is also possible to obtain more resolution by taking half steps or quarter steps. Fig. 18 displays an image of the internal components of a stepper motor.

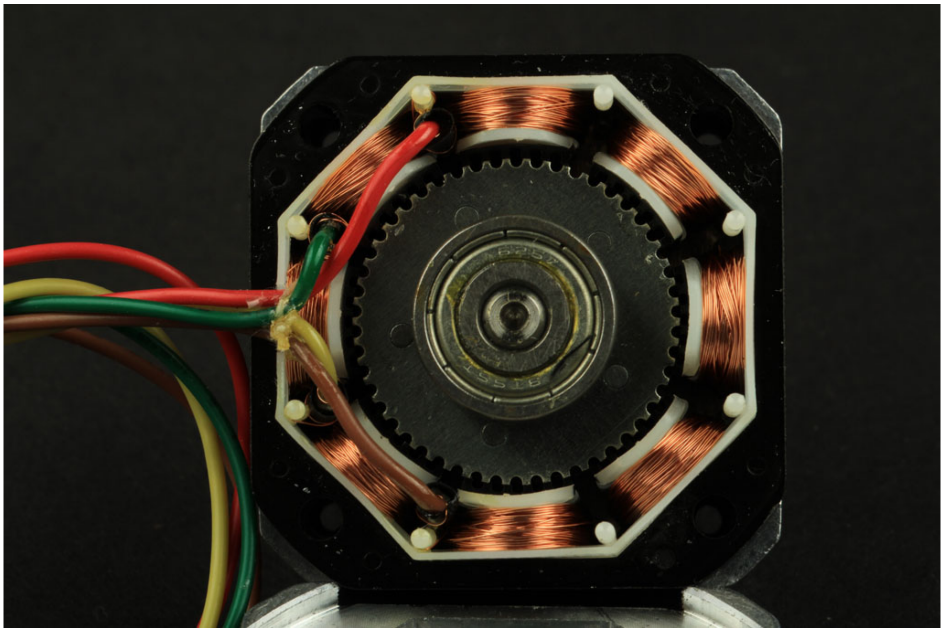

Figure 18. Internal View of a Stepper Motor [15]

Stepper motors are designed to operate at low RPMs. With a controller, the stepper motor can offer precise pointing, precise speed control, and high torque levels at low RPMs. This will allow the ability to spin up the 3 kg CubeSat and overcome any unnecessary friction of outside torque. Stepper motors are widely used in different applications and are developed by several manufacturers; from high end motors to toy motors. With a wide and experienced market, stepper motors offer a safe and reliable option. The downside to the stepper motor is that they are susceptible to resonance [16]; this occurs when the input pulse frequency matches the natural frequency of the motor. If not careful, the chances of missing steps are higher; which creates difficulty in maintaining the desired RPM. Another downside is stepper motors lose accuracy with increasing loads. In order to maintain a 3 deg/s rotational speed, it is desirable to obtain high step accuracy. To obtain high accuracy, torque capability will have to be lowered. Thus, stepper motors can start to get expensive and power extensive for high torque and accurate motors. Table 15 lists the advantages and disadvantages that are mentioned above.

Table 15. Electric Stepper Motor Advantages & Disadvantages

Advantages	**Disadvantages**
Simple & easy to setup	Power extensive
Can be operated with an open loop system	Susceptible to resonance
Great online resources & wide market	Accuracy reduces with increasing loads

4.4.2 Electric Geared Motor

This option is similar to the stepper motor but utilizes the use of a gear system [17] that interfaces with an ordinary electric motor. A base DC motor (brushless or brushed) turns a rotor that interfaces with a gear system; which can increase torque capability in exchange for rotational speed capability. Fig. 19 displays an image of the internal components of an electric gear motor.

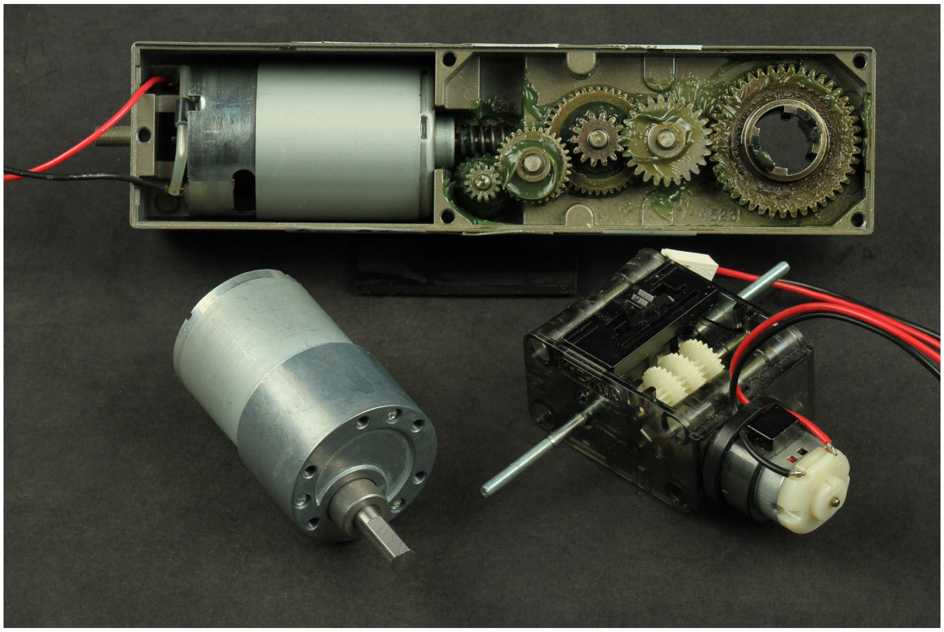

Figure 19. Internal View of a Gear Motor[17]

Geared DC motors are widely used in several applications and have a huge market. Electric geared motors are considered to be smoother than a stepper motor. Due to its simple technology, it is also possible to design an optimal gear system for this project; however, that will require additional time and resources. The downside of the geared motor is that friction can limit the functionality of the motor. Extra resistance in the gear system can cause the electric to be unresponsive at low voltages; thus, a stronger and more expensive electric motor may be needed to enough torque to surpass static friction. Another downside is that geared motors are susceptible to backlash, where the gaps between each gear can cause a loss of motion which reduces the precision of the motor. This is not a significant problem for unidirectional rotation; but, it can possibly occur within the Testbed design. Tab. 16 lists the advantages and disadvantages that are mentioned above.

Table 16. Electric Geared Motor Advantages & Disadvantages

Advantages	**Disadvantages**
Simple & more design space	More mechanical parts
Low cost	
Great online resources & wide market	

4.4.3 Magnetorquer

This option utilizes a magnetic torque rod within the CubeSat and applies a one directional torque onto the structure by interacting with a static external magnetic field. A torque rod consists electromagnetic coils[18] that create a magnetic field, similar to a permanent magnet, when current runs through the coils. A torque is created due to the misalignment between the fields of the rod and environment. By varying the amount of current within the coils, the magnitude of the torque can be varied. Fig. 20 displays an image of a magnetic torque rod.

Figure 20. Electromagnetic torque rod[19]

This provides the advantage of producing torque without the use of moving mechanical parts. The downside is that an external support such as an air bearing or ceramic frictionless bearing will need to the hold the CubeSats weight. Torque rods are simple enough to be designed and manufactured; but will require resources and time to create. With a low friction support and torque rod, it is possible to obtain slow rotational speeds in a low friction environment; thus, it will be easier to obtain a free spin on the CubeSat. The huge drawback with this design is that several components are needed such as: an artificial magnetic field (possibly a simplified Helmholtz cage[20]) that creates a strong and varying magnetic field, a bearing, and the torque rod itself. The market for these components is still growing; thus, it will be hard to obtain pre-made components. Pre-constructed torque rods are space grade and very expensive. Tab. 17 lists the advantages and disadvantages that are mentioned above.

Table 17. Magnetorquer Advantages & Disadvantages

Advantages	**Disadvantages**
No moving mechanical parts	Require time to design, build, and calibrate
	Little resources and knowledge
	Can get expensive quick

4.4.4 Reaction Wheel

This option utilizes a reaction wheel[21] that is mounted onto the CubeSat to rotate the CubeSat through angular momentum exchange. The reaction wheel consists of an electric motor and a circular mass attached to the rotor. By fixing the motor to the CubeSat, a torque on the CubeSat can be created by spinning up the circular mass; in an action-reaction manner. Fig. 21 displays an image of a reaction wheel.

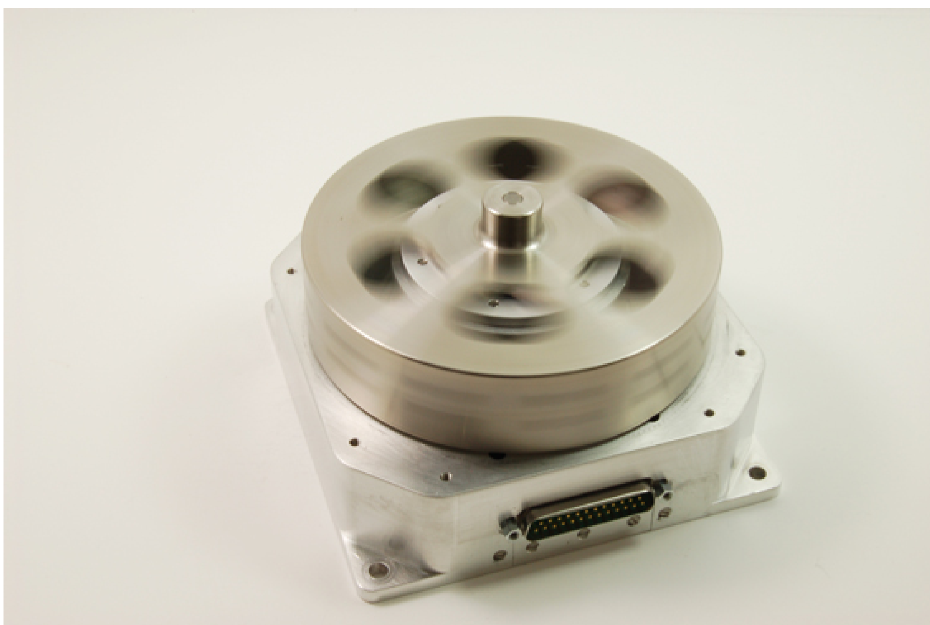

Figure 21. Reaction Wheel Example[22]

Similar to the magnetorquer, the reaction wheel will need to be used in conjunction with an external support to hold the weight of the CubeSat such as an air bearing or ceramic frictionless bearing. Reaction wheels are commonly used in space applications for attitude control and are simple enough to design. The downside is that vibrations can occur and will need to be mitigated. Another difficulty is that the motor will need to be continuously engaged; thus having the wheel spin at all times. In order to maintain a rotational speed, the motor will need apply a constant torque onto the CubeSat to counter frictional torque, which constantly spins up the reaction wheel. This introduces the problem of saturation, where the system reaches its max capable momentum exchange. This will have to be taken into consideration within the design phase. Tab. 18 lists the advantages and disadvantages that are mentioned above.

Table 18. Reaction Wheel Advantages & Disadvantages

Advantages	Disadvantages
Higher capability for design & optimization	Run time limited by saturation
Simple to design	Vibrations can occur

4.5 Hardware Interface for Testbed

In order to run the demonstration, some electronics interface will be required to run the capture algorithm while taking inputs from the numerous sensors and sending out signals to the actuators. This generally requires analog and/or digital I/O ports, signal conditioning, and of course a processor to run the algorithm. Two options are being considered for this: A PC& microcontroller (or multiple microcontrollers), a System-On-Chip (SOC), and a National Instruments DAQ-LabView interface.

4.5.1 Microcontroller

The primary advantage of of using a PC and a microcontroller is the amount of flexibility there is to a system. The microcontroller would act as an interface for the motors and servos while the computer does the computational work required. This is needed because most microcontrollers do not have the processing power to run complex algorithms with floating point math, but they do have the peripherals necessary to send and receive signals. There are numerous microcontrollers that can be used as the interface such as the PIC family, Arduinos, and others. A drawback to this option is that it would almost certainly require a separate signal conditioning circuit to filter out noise and regulate voltage and current from input signals and to output signals.

Arduinos are cheap, programmable devices that are readily available and have a lot of documentation and support. The Arduino comes with multiple digital I/O pins, analog input pins, serial ports, and a USB port for connection to a PC. The Arduino is based on user interface, as it uses its own development system and hides a lot of ”under-the-hood” operations from the user.

The PIC family of microcontrollers are similar to the Arduinos, except that they can be better tailored to their specific application. This is because the PIC is a ”bare” microcontroller that allows the user more access to memory registers and special functions, allowing it more flexibility for a custom solution. The PIC family is low cost but slightly more difficult to program than the Arduino.

Table 19. Hardware interface pros and cons

Advantages	Disadvantages
I/O directly to peripherals	More difficult to program
Cheap	Limited on memory and processing power for some applications

4.5.2 System-On-Chip

Sysem-On-Chip solutions include options like the Rasberry Pi and BeagleBone Black. These are not classified as microcontrollers, as they are inexpensive single-board computer that contain a multicore processor which runs on a Linux or Windows operating system. While microcontrollers typically run off of an 8-bit or 16-bit single core processor, a Rasberry Pi runs off of a 32-bit or 64-bit quad core processor that is similar to what most smart phones have. The board also contains general I/O pins, display connectors, wireless capabilities, and other features that would feasibly allow it to interact with the Testbed sensors and actuators. Because of this, an SOC solution would be capable of running the demonstration alone, as it has the processing power to run the algorithm and the peripherals to interface with the Testbed components. Like the previous option, the SOC would also require a separate signal conditioning circuit between it and the Testbed sensors and actuators.

4.5.3 LabView & DAQ

Labview (Laboratory Virtual Instrument Engineering Workbench) is a graphical environment where programs can be created by using a graphical user interface instead of coding various functions. This option allows a PC to handle all of the processing by running LabView while a separate Data Acquisition (DAQ) device handles the interface with the sensors and actuators. The DAQ offers multiple digital and analog I/O ports, analog to digital and digital to analog converters, and is capable of executing all of the signal conditioning needed to regulate current and voltage as well as reduce signal noise. The DAQ communicates with the PC via USB where the LabView program is run. This option is beneficial because it does not require a separate signal conditioning circuit and it allows a PC to run the capture algorithm, which is guaranteed to have enough processing power. Additionally, there is endless support for LabView and DAQ systems within the aerospace department as this is the method of data collection for almost all of the undergraduate lab experiments.

4.6 Object Tracking Sensors

Team CASCADE's primary means of measuring the displacement and angular velocity of the moving CubeSat is through the use of the Research and Engineering Center for Unmanned Vehicles. This facility is free of cost and only requires reserving the facility.

4.6.1 RECUV (Research and Engineering Center for Unmanned Vehicles)

The Research and Engineering Center for Unmanned Vehicles (RECUV) is a research facility dedicated to the development of unmanned vehicle systems for atmospheric use. RECUV uses 8-16 Vantage V5 Vicon cameras for motion capture. The Vantage V5 is capable of five types of motion capture. The three pertaining to this project will be discussed. The first type is optical-passive, a technique that uses retro-reflective markers tracked by Vicon infrared capability. The second is markerless motion sensing which relies on software to track the motion of the object. The third type is inertial motion sensing which does not require camera but uses the VICON as a localization tool[23]. Sensors are place on the moving object, these sensors then transmit data to a computer. Figure 22 shows an image and Table 20 provides information on the advantages and disadvantages of using the RECUV facility.

Table 20. RECUV Pros & Cons

Pros	**Cons**
Facility Provided by the University (Free of Costs)	May be difficult to secure a reservation
Highly reliable data displacement and angular displacement data	Unfamiliarity using the Tracker software.
Motion and tracking sensing capability greater than 1m	

Figure 22. VICON Camera used in RECUV[23]

4.6.2 Lidar Rangefinder

The Lidar Rangefinder is a powerful, scalable laser based measurement solution that is capable of measuring distance, velocity and signal strength with targeting range of 0 to 40m[24]. The laser rangefinder operates on the time of flight principle by sending a single stripe laser pulse towards the object and measuring the time delay between the transmission of an optical signal and its reception. The range finder sensor has a lightweight and compact design that can be easily mounted on the Testbed and serve the purpose of sensing the CubeSat. The rangefinder has a really low power consumption with capability of 1cm resolution and accuracy of +/- 2.5cm[24]. A higher resolution is essential for an autonomous closed loop control system to increase probability of successful capture. The signal processing algorithm for the rangefinder is really straightforward and it encapsulates all the required functions providing distance and velocity measurements in a small device. Figure 23 shows an image of such a device. Table 21 provides information on the advantages and disadvantages of using the the Lidar Rangefinder.

Table 21. Lidar Rangefinder Pros & Cons

Pros	**Cons**
Capable of measuring both distance & velocity	Low resolution & accuracy
Long range measurement	
Operational Safety	

Figure 23. Lidar Rangefinder[24]

4.6.3 LVDT(Linear Variable Displacement Transducer)

A linear variable displacement transducer, LVDT, is an electrical transducer that capable of measuring linear position. It is used to convert mechanical motion into electrical signals. A typical LVDT has three solenoid coils lined end-to-end, surrounding a rod. The primary coil is located between the other two coils which are located at the top and bottom of the transducer. The object of position measurement is attached to the cylindrical core, and slides along the axis of the tube. Alternating current drives the primary coil causing voltage induced in the two secondary coils. Movement of the core triggers the linkage from primary to both the secondary coils, thus changes the induced voltages. An output voltage can be related to the displacement by using a synchronous detector. The LVDT can output both analog or digital signals and it interfaced with serial or parallel digital output protocol to ensure signal processing ability. The LVDT is capable of measuring positions up to 0.762 meters and the accuracy deviates proportionally to the measuring range. The LVDT sensor can have as high as 0.5mm resolution which provides an accurate approach to the CubeSat[25]. Figure 24 shows an image of such a device. Table 22 provides information on the advantages an disadvantages of using the Linear Variable Differential Transducer.

Table 22. LVDT Pros & Cons

Pros	**Cons**
High resolution	Expensive
Environmentally Robust	Short sensing range

Figure 24. Linear Variable Displacement Transducer[25]

4.6.4 Arduino Ultrasonic Range Detection Sensor

An Arduino Ultrasonic Range Detection Sensor is a module that provides 2cm to 400cm non-contact measurement function, with an ranging accuracy of 3mm[26]. Ultrasonic transmitters, receiver and control circuit are included into the module. It works by sending out a burst of ultrasound and listening for the echo when it bounces back from the targeting object. The Ultrasonic sensor has 2 openings on its front, one opening transmits ultrasonic waves, and the other receives them. By knowing the speed of sound in the air, the ultrasonic sensor can use this information along with the time difference between sending and receiving the sound pulse to determine the distance to an object. The ultrasonic range detection sensor is an accessible module that really easy to implement with an Arduino and it is programmable. Figure 25 shows an image of the device. Table 23 provides information on the advantages and disadvantages of using the Arduino Ultrasonic Range Detection Sensor.

Table 23. Arduino Ultrasonic Detection Sensor Pros & Cons

Pros	**Cons**
Programmable	Sensitive to temperature
Low cost	High signal to noise ratio

Figure 25. Arduino Ultrasonic Range Detection Sensor[26]

4.6.5 9 DOF- Razor IMU

The 9 Degrees of Freedom - Razor IMU by Sparkfun incorporates three sensors. A ITG-3200 digital output MEMs triple-axis gyroscope. This sensor is responsible for providing the digital output X,Y,Z axis angular rates. The second sensor is the HMC883L magnetometer used to provide low field magnetic sensing. The third sensor is the ADXL345 triple axis accelerometer. This sensor will measure the static and dynamics acceleration of gravity due motion, shock or tilt. The outputs of the sensors is processed by an on-board ATmega328 which is then sent to a serial SPI or I2C interface which can easily be integrated into any hardware including the CRST. The Sensor stick does have a reset switch, on or off switch and a built in I2C interface[27]. Figure 26 shows the board. Table 24 provides information on the advantages and disadvantages of using such a device.

Table 24. 9 DOF Pros & Cons

Pros	Cons
Low Cost	Has a magnetometer which is not needed
Can provide attitude and translational data	Data may not reflect current time
Open source software readily available online	

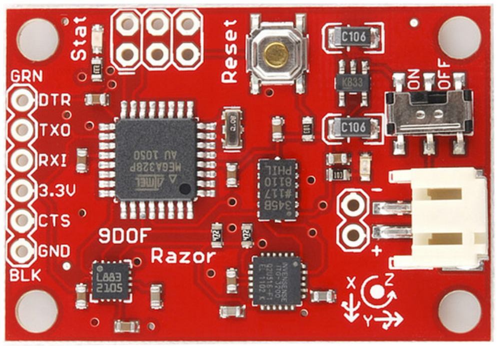

Figure 26. 9 DOF -Razor IMU[27]

4.6.6 CruizCore XG1300L

The XG1300L is a digital MEMS gyroscope and accelerometer. It contains an accelerometer and a single axis MEMs gyroscope. It is capable of measuring rotational speed, attitude, tilt, acceleration and track relative position. This sensor has a wide measurement range to include a (+/-) 100 to degrees per second input dynamics range and (+/-) 2 to 8 Gs of selectable acceleration measurement range[28]. Figure 27 shows an the device. Table 25 provides information on the advantages and disadvantages of using the the CruizCore gyroscope/accelerometer.

Table 25. CruizCore XG1300L Pros & Cons

Pros	Cons
Programmable	Sensitive to temperature
Very compact	High signal to noise ratio
Selectable Output (Angular rate,attitude,acceleration)	Will have to buy several sensors
Low Cost	

Figure 27. CruizCore XG1300L[28]

4.6.7 Rotary Encoder (1024 P/R (Quadrature)

The rotary encoder can be used as a angular position sensor. Attaching such a device to a motor will correspond to a linear position. This optical device converts angular position of a built in rotating shaft into an analogue or digital code. The rotary encoder trade studied will be the (1024 P/R (Quadrature). The unit output for this encoder is in gray code which is the standard output for most encoder. Gray code is a reflected binary code. Gray code enables one to tell how much the built in shaft has turned and in which direction. A microcontroller will then be used to interpret the binary data. This encoder is especially effective in providing the CRS the feedback data needed to capture the CubeSat[29]. Figure 28 shows an the device. Table 26 provides information on the advantages and disadvantages of using the Rotary Encoder.

Table 26. Rotary Encoder Pros & Cons

Pros	Cons
Low cost	Will need an interface module
Can provide attitude and translation data	Gray code output will need to be interpreted
Effective for position feedback	

Figure 28. Rotary Encoder[29]

4.6.8 Summary of All Design Options

The purpose of the sensor trade study is to determine the best sensors that will determine the angular positional, and velocity displacement of the CubeSat. These displacement parameters will serve as inputs to a feedback algorithm such that commands can be generated resulting in knowing the relative position. Section 5.5 shows the results of the sensor trade study. Within the trade are a wide array of sensors that could be used including the RECUV facility which will use VICON cameras to track the angular and translational position and velocity. The data collected from this facility can be used to compare to the sensors used in a less controlled environment to have multiple sources of data, compare and verify this data. Based on the research conducted during the trade study the Arduino Uno microprocessor or Rasberry Pi are options. The cost of these additional parts will be considered in the trade study. Table 27 shows the performance specifications of each sensor references from manufacturer data sheets. The performance specifications will be explained in section 5.5 in detail. The comparison of these specifications are what will drive the trade study and result in the necessary sensors that meet the CRS's needs.

Table 27. Sensor Trade Study Performance Values

Design Option	Classification	Procurement Cost	Additional Cost	Resolution	Integration	Calibration	Accuracy
Lidar Range Finder	Position Sensor	$149.99	Arduino Uno 25−50	1cm	I2C or PWM	Erroneous data at greater than 18cm	0.025m
9 DOF - Razor IMU	Position sensor	$74.95	FTDI Basic Breakout $14.95	3-bit resolution, 16g, triple-axis accelerometer	Output pins match up with FTDI Basic Breakout, Bluetooth Mate, XBee Explorer	Calibrate ITG-3200, ADXL345, HMC5883L	Function of user algorithm
Ultrasonic Sensor HC-SR04	Position Sensor	$10.99	Arduino Uno 25−50	0.3cm	Pins:(VCC, Input, Echo, GND) Arduino	Erroneous data at greater than 40cm	Function of user algorithm
CruizCore XG1300L	Gyroscope, triple-axis accelermometer	$110.00	Arduino Uno 25−51	+/- 100 deg/s (continuous)	I2C	10 deg/hr	Full floating point precision
Rotary Encoder (1024 P/R (Quadrature)	Position Sensor	$34.99	Microcont. (price varies)	1024 pulse/rotation	Microcont.	manual shaft adjustment	6000rpm
ADISI6060 Digital Gyroscope	Gyroscope, triple-axis accelermometer and Magnometer	$74.95	FTDI Basic Breakout $14.96	3-bit resolution, 16g, triple-axis accelerometer	I2C/SPI	Calibrate ITG-3200, ADXL345, HMC5883L	Function of user algorithm
LVDT(Linear Variable Displacement Transducer)	Position Sensor	$250	Signal Conditioner $400	Millionth of an inch	LVDT signal conditioning equipment	N/A	Function of user algorithm
VICON Camera (RECUV	Translation and angular motion	Through Reservation	RJ45 ($0.25), Tracker Software (available)	16Megapixels	Cat5e/RJ45	Active Wand	Function of user algorithm

5 Trade Study Process and Results

In the following sections, the design option candidates with the highest potential were compared for feasibility and tendency to produce the best outcome for the project. Each section has its own criteria, which were selected by evaluating the requirements and breaking down what was needed to achieve these requirements. The risk and cost of each option were evaluated separately from the other criteria, as these do not directly govern the capabilities of each design. Plots were then generated to compare the weighted criteria against the risk and cost involved to give an overall picture of the feasibility of each design.

5.1 Capture Device Deployment

Selection of the capture device deployment is critical for bridging the gap between the capture device and the CubeSat. Approaching an object in space that is rotating and translating requires a careful approach, and keeping everything clear of the target aside from the capture device is critical for ensuring the safety of all entities involved. With this in mind, the criteria for the deployment device depend heavily on ensuring safety.

5.1.1 Deployment Device Criteria

- **Performance**:
  - *Control*: Control accounts for the degrees of freedom (DOF) that each deployment device provides. This dictates the amount of "flexibility" the device has to complete the approach, and indicates what additional factors might be needed (i.e. attitude corrections) for capture.
  - *Implementation*: Implementation is a measure of the complexity of the algorithms necessary for the deployment device to function. This includes software and programming aspects as well as an estimate to the level of understanding of the spacecraft dynamics that is needed to perform a successful capture. There is a trade-off between control and implementation and a high score in one category typically corresponds with a low score in the other.
  - *Reliability*: Reliability suggests that the device could be reused. An item scoring low in reliability would likely not be able to endure multiple cycles, for example, a device that would not retract easily.
- **Constraints**:
  - *Mass Budget*: Although a majority of the payload mass will be contained within the deployment device, mass does not seem to be of great concern overall. It will still be considered within the trade at a low weight in case of unforeseen issues.
  - *Volume Budget*: The payload volume should provide sufficient space for each of the design choices, but selection of the end effector will limit the available space for the deployment device.
  - *Power Budget*: Power is the biggest constraint concern. Robotic arms can overshoot the allowable power, so careful selection will be necessary if this device is selected.
- **Risk:**
  - Risk is a measure of the safety concern associated with each capture device. For a capture to be successful, the device must be able to attach and release without incurring damage to the device or the CubeSat, and may not create space debris.
- **Cost:**
  - Cost evaluates various costs associated with the manifestation of the device. This includes procurement costs, material costs, and the time required to manufacture.

5.1.2 Deployment Device Trade Study Metric Definitions

Table 28 shows the description of each criteria for evaluating within the trade study. Table 29 shows the cost and risk estimates associated with each deployment device.

Table 28. Metrics for Criteria of Deployment Device

Criteria	5	4	3	2	1
Mass	Very Light	Light		Heavy	Very Heavy
Volume	Minimal Volume				Maximum Volume
Power	No Power Required	Minimal Power		High Power	Exceeds Power Limit
Control	6 DOF	5	3-4	2	1 DOF
Implementation	Simple Algorithm		Moderate		Complex Algorithm
Reliability	Repeatable for many cycles		Likely repeatable for a few cycles		No guarantee of repeated performance

Table 29. Cost and Risk Metrics

	1	**2**	**3**	**4**	**5**
Cost Metric	< $500	$500 – $1000	$1000 - $1500	$1500 - $2000	> $2000
Risk Metric - Success Probability	80 - 100%	60 - 80 %	40 - 60 %	20 - 40 %	< 20%

5.1.3 Trade Study Results

Table 30 shows the overall benefit of the device. Note that the performance criteria were weighted heavier than the physical constraints, with control receiving the highest weight. After evaluating the benefit, each option was given a risk and cost score to be plotted in Figures 29 and 30.

- **Ranking Explanations**
  - *Mass Budget:* The mass of each design option was evaluated based on research of common devices used in industry for similar applications. Overall, mass was not a significant concern because of the allowable payload mass budget of 15kg. Devices in space applications are commonly designed to be lightweight as a trade-off with cost. The robotic arm and tether scored high due to concepts that suggested masses under 33% of the allowable mass budget. A boom would require more mechanical parts that would increase mass, suggesting a lower score.
  - *Volume Budget:* Similar to the mass budget, volume was of low concern overall. The payload volume is large enough such that the devices would fit with a significant margin. The boom scored lowest here as well. A telescoping structure would require several stages each with significant volume for a robust design.
  - *Power Budget:* A high performance robotic arm could draw power over the allowable 100W Orbital Average Power, while mid-range performance ones could perform with a 20-40% margin. The tether scored high due to researched concepts that indicated low volume implementation. The boom was given a score in the middle, as the power required would heavily depend on the selected design.
  - *Control:* Higher degrees of freedom are preferred for the capture device to allow for flexibility in the capture approach. Ideally, capture would be completed without a need for attitude corrections from the spacecraft the device operates from to save fuel. The robotic arm scored highest due to the six degrees of freedom available from affordable options. A boom or tether device would required additional manipulation to increase the available degrees of freedom.

- *Implementation:* The implementation measures the complexity of the algorithms needed to operate the device. The scores in this category nearly reflect the opposite of control. A robotic arm with six degrees of freedom would require complex software to implement properly, resulting in a low score. On the other, the boom and tether deploy in a single degree of freedom which would simplify the software aspect of these devices.
- *Reliability:* For the device to be reliable, it must be able to operate for multiple missions due to a requirement for the device to be reusable. None of the design options scored particularly low. However, the boom would be comprised of multiple moving parts that would be subject to wear and tear and diminishing structural integrity.

Table 30. Results of Deployment Device Trade Study

Capture Mechanism Trade		Robotic Arm		Boom		Tether	
Criteria	%	Raw	W	Raw	W	Raw	W
Mass	0.1	4	0.4	3	0.3	5	0.5
Volume	0.1	4	0.4	3	0.3	4	0.4
Power	0.1	1	0.1	2	0.2	4	0.4
Control	0.3	5	1.5	2	0.6	2	0.6
Implementation	0.2	2	0.4	4	0.8	4	0.8
Reliability	0.2	4	0.8	3	0.6	4	0.8
TOTAL			3.6		2.8		3.5

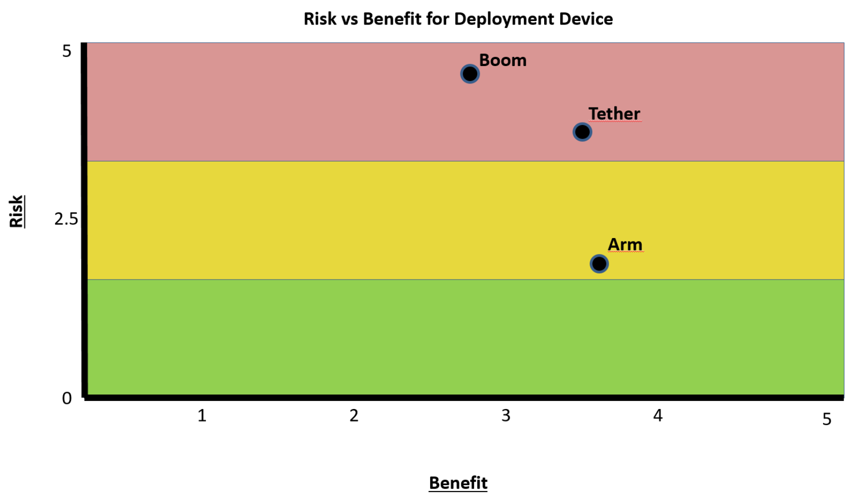

Figure 29. Risk-Benefit analysis for Deployment Device

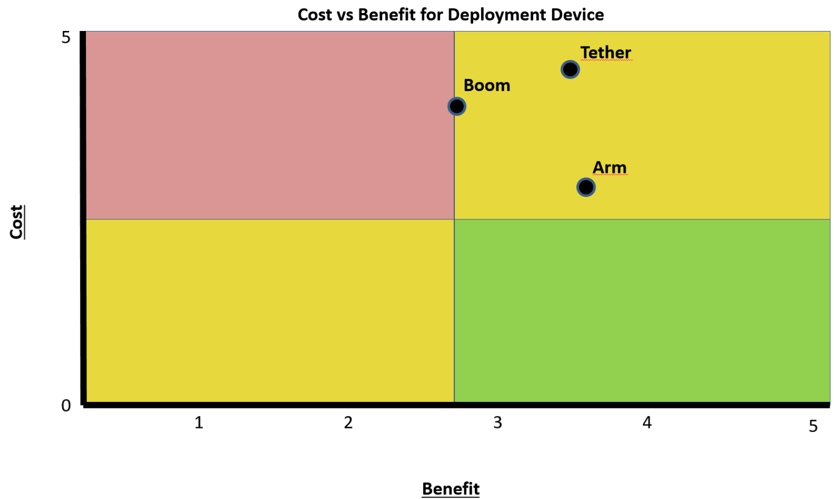

Figure 30. Cost-Benefit analysis for Deployment Device

5.2 Capture Device Effectors

Choosing an appropriate end effector is one of the main focuses of CASCADE. Autonomously gripping to the surface of a rotating and translating object is not simple, especially without a well designed end effector. This trade study was used to determine the most simple, and yet effective end effector that can be developed within the budget and time constraints of the project. The four design options for end effectors were outlined in Section 4.2.

5.2.1 End Effector Criteria

- **Performance**: The performance of the chosen end effector is possibly the most important aspect to having a successful capture. In the performance aspect of the end effector there were two criteria that were most vital for the success of the mission.
  - *Release Ability*: Being able to release the CubeSat is necessary to complete the goal of the mission, demonstrating the ability to re-purpose the CubeSat.
  - *Approach Difficulty*: Proximity operations for completing a successful capture can be very complex, so minimizing this requirement as much as possible is desired. By the use of a well designed end effector the approach can be simplified. For example, a claw will need to very carefully grab onto at least two sides of the CubeSat with precise timing, while an engulfer can simply be maneuvered so that the entire CubeSat is captured at once.
  - *Reliability*: The end effector should be designed to last throughout many successful captures. The CubeSat capture system will be expensive, so it should be able to carry out a large number of operations. Effectors with more chance of breaking or becoming useless are considered much less reliable.
- **Constraints**:
  - *Mass Budget*: While mass is important since there is a given mass budget, end effectors are relatively small compared to the 15 kg limit. However, some of mechanisms that make the end effector work may turn out to be large, and it is typical for mass to become larger than expected as the manufacturing and building phase is completed.
  - *Volume Budget*: The volume of the effector is important to account for considering both the deployment method and capture system vision system would all need to fit in the payload volume as well. However, the volume of all the aforementioned effectors are very small considering they would only need to be slightly larger than the width of the CubeSat, which fits well within the volume itself.

5.2.2 *Effector Trade Study Metric Definitions*

Table 31. Metrics for judging the criteria for end effectors.

Criteria	5	4	3	2	1
Mass	Very Light	Light		Heavy	Very Heavy
Volume	Minimal volume				Maximum volume
Release Ability	Ability to release with simple ON/OFF		Release is possible but difficult to implement		Release not possible
Approach Difficulty	Approach for contact on specific side not necessary	Approach for contact on one side necessary	Approach for contact on two sides necessary	Approach for contact on three sides necessary	Approach for contact on four sides necessary
Reliability	Will complete a very large number of successful captures.		Will complete a medium number of successful captures.		Will complete a very low number of successful captures.

Table 32. Cost and Risk Metrics

	1	**2**	**3**	**4**	**5**
Cost Metric	< $500	$500 – $1000	$1000 - $1500	$1500 - $2000	> $2000
Risk Metric - Success Probability	80 - 100%	60 - 80 %	40 - 60 %	20 - 40 %	< 20%

5.2.3 *Trade Study Results*

The results of the trade study are shown below in Table 33. The mass and volume are weighted the least since the end effector should be relatively small. Release ability is necessary for mission completion so it is weighted heavily. Approach difficulty adds a large amount of complexity to the capture algorithm, and affects the overall difficulty of the mission. Reliability is also somewhat heavily weighted due to the fact that the capture system should be able to complete a lot of missions, or it would be a waste of money. Below are explanations for the criteria rankings shown in Table 33.

- **Ranking Explanations**:
  - *Mass Budget*: The mass budget for effectors was easy to evaluate since all the effectors were relatively small. The claw was given the highest ranking since it requires no additional parts for operation. Dry adhesive and the engulfer were ranked a 4 since both require additional parts for operation, such as springs and pulleys, or compressed air and a drawstring mechanism. electrostatics was assumed to have the most mass due to the complicated electrical system necessary for operation.
  - *Volume Budget*: The volume of each of the effectors was researched and the options were ranked against one another. An engulfer got the highest rank since it was deployable on a small CubeSat, before deployment it only took 1U of volume. A claw would take up little volume, it only needs to be at max the width of the CubeSat. The electrostatics would have more volume due to the electronics involved; along with the dry adhesive due to the linear actuators, pulleys, and springs.
  - *Release Ability*: The release ability was simple to judge, all of the effectors were able to release with a simple command other than the engulfer. The engulfer has a high probability of the CubeSat becoming stuck. There is the possibility of redesigning the engulfer to incorporate some sort of film to allow for release, but this option has a lot of risk.

– *Approach Difficulty*: Approach difficulty was ranked according to the number of sides needed to come in contact with. For an engulfer there is no specific side to approach from, it would simply need to position in the path of the CubeSat. For dry adhesives and electrostatics they only need one side to grip onto. Also, dry adhesive has been tested on a solar panel, expanding the surface area possible for the contact. Electrostatics also has the added benefit of attracting objects by electrostatic force, which means the approach doesn't have to be precise. A claw would require at least two surfaces of contact, and the timing would need to be very precise. Otherwise one end of the claw will come in contact with the surface before the other creating an impulsive moment on the CubeSat surface.

– *Reliability*: Each of the design options was evaluated the ability to be reused a large number of times. Dry adhesive and electrostatics were the top ranked options for re-usability. Electrostatics are low power and can be supplied power through use of solar panels. The gripper itself can be made to be form fitting with little moving parts, which indicated it would not be damaged easily. Dry adhesives have been tested on a solar panel for 30,000 cycles in a vacuum which proves that the material is extremely reliable. The lifetime of dry adhesives would likely outlive the amount of fuel available for performing capture missions. For a claw there are moving parts, such a servo joints, which would be more susceptible to damage due to the nature of which a claw must perform a capture. The claw must be able to handle the torque of the CubeSat since it grapples from both sides, while other options are made to attach from only one side. Finally, the engulfer runs the risk of entangling the CubeSat making it only useful for one capture. The engulfer also has to fully stop the motion of the object with just an impact, which has higher risk for damaging the capture device as well as the CubeSat.

Table 33. Results of the end effector trade study.

End Effector Trade		Claw		Dry Adhesive		Engulfer		Electrostatics	
Criteria	%	Raw	W	Raw	W	Raw	W	Raw	W
Mass	0.1	5	0.5	4	0.4	4	0.4	3	0.3
Volume	0.1	4	0.4	3	0.3	5	0.5	3	0.3
Release Ability	0.3	5	1.5	5	1.5	1	0.3	5	1.5
Approach Difficulty	0.3	3	0.9	4	1.2	5	1.5	4	1.2
Reliability	0.2	3	0.6	5	1	1	0.2	5	1
TOTAL			3.9		4.4		2.9		4.3

After the benefit analysis was conducted for each of the end effectors, the risk of each option was considered. This was done by considering both the probability of success as well as the risk of any damage resulting to the capture device and the CubeSat. For a claw the risk was relatively high, considering the approach must be very precise and the claw has to grab onto the surface with precise timing and commands. The claw would also increase the risk of damage somewhat since the moving parts are very rigid. Electrostatics would be simple for approach and capture of objects, but working with charges to grip to the surface of a CubeSat would introduce the risk of interfering with and possibly damaging sensors on board. An engulfer makes the probability of capture high, but success is defined by both capture and release ability. Since the release ability for an engulfer is questionable this runs the risk of the CubeSat becoming stuck in the device, which would bring both satellites to the end of operations. Dry adhesives were determined to have the least risk due to the fact that they have been tested on a variety of surfaces, even solar panels, for many gripping maneuvers. This means that the risk of damage would be fairly low as long as the dry adhesive effector made contact with a relatively low speed. The approach using dry adhesives is also less complex, meaning the probability of success should be more high.

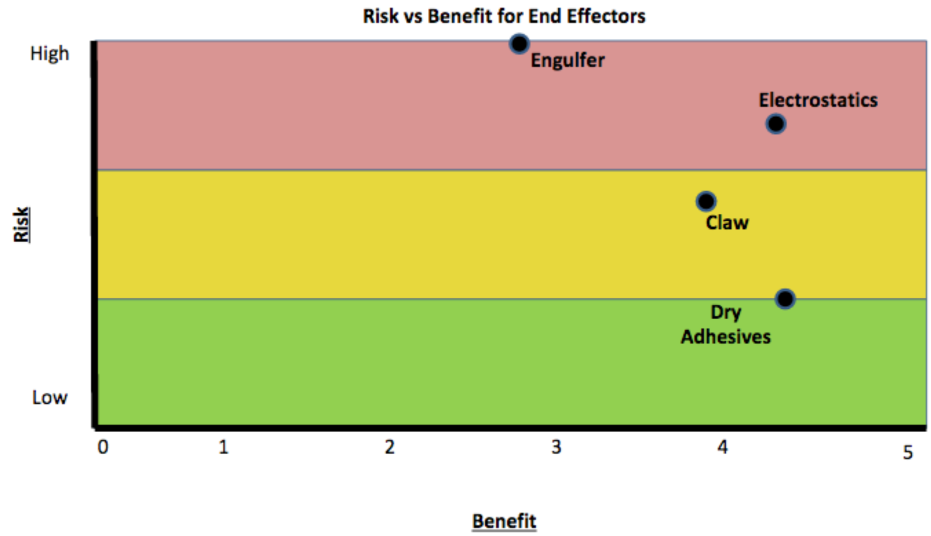

Figure 31. Risk-Benefit analysis for end effectors

Using the benefit scores from the trade study results a cost-benefit analysis was done. This was done by comparing the relative costs of the design options, by looking at a rough estimate of the cost of material, and the overall difficulty and costs related to the manufacturing process. For an electrostatic gripper it was determined that the cost of manufacturing would be extremely high. Designing the electrode layouts, and the surface for the electrostatic gripper would require testing and calibration within a very low pressure vacuum. Manufacturing an engulfer would be more feasible, it was done by the LEOPARD senior projects team a few years ago. An engulfer would not need very expensive material, especially for a ground-based prototype. However, the costs of an engulfer stem from manufacturing and testing much more since not many concepts exist for this sort of device, and none exist for a device capable of release. Dry adhesives are now manufactured and available for procurement through a company called *nanoGriptech*. The cost of dry adhesives is more based on the cost and manufacturing of the moving parts required to make the adhesive work. Finally, the claw is the best option since a claw effector can simply be procured online. Even if the claw were manufactured from scratch, there are many resources available for the team to learn how to make a claw, and the parts required would be inexpensive.

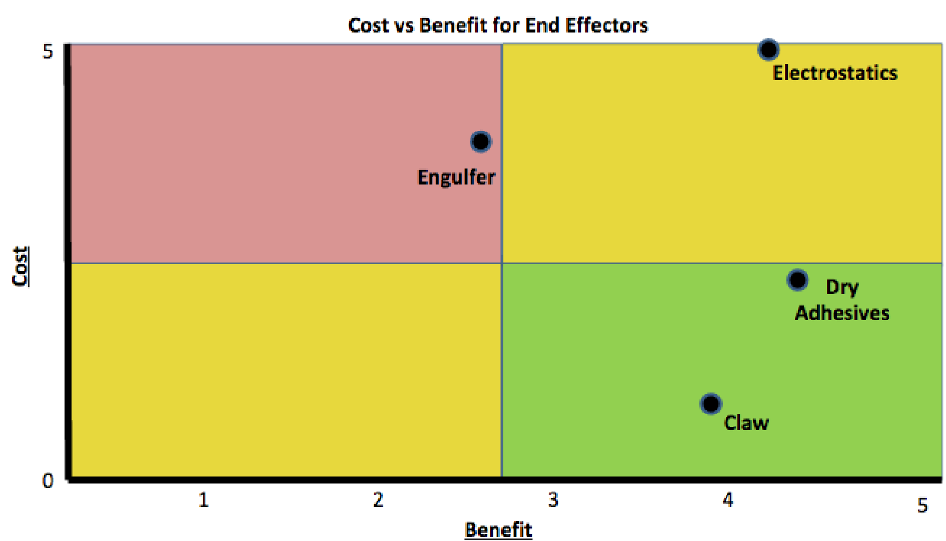

Figure 32. Cost-Benefit analysis for end effectors

5.3 Testbed Configuration: Single Axis Translation

Although linear motion is not at all the main thrust of this project, it is an essential part to demonstrating the successful capture of a CubeSat. The goal of this trade study is to decide upon a relatively simple, cost-effective method for translation that performs well and is not a hassle logistically. The four design options included in the trade study are detailed in Section 4.3.

5.3.1 Trade Study Criteria

- **Performance**: The performance of the method of translation within the demonstration is a large aspect the trade study. For further clarity, performance is broken down into two sub-criteria.
  - *Representation of Space Environment (in terms of dynamics only)*: As mentioned earlier, designing and building a demonstration that represents the space environment from a dynamics standpoint is not a specific design requirement, as it is not readily testable or feasible in this course. However, it is a consideration in designing the method of translation for the Testbed, as the capture device is focused on space applications, and thus it is desirable for the Testbed to be capable of demonstrating feasibility for the capture device to be used in space.
  - *Precision of Translational Motion*: This is an essential criteria for demonstrating capture along one axis of translation, the reason being that demonstrating capture is not possible without a certain degree of accuracy in linear motion. Some capture devices may require linear motion within a tighter tolerance than others (i.e. claw vs engulfer), but a higher precision method of translation is nonetheless desirable.
- **Logistics**: The logistics of the translation method has been broken down into the three sub-criteria below.
  - *Setup Flexibility*: This criteria is useful in determining the level of planning and risk mitigation that might go into each design option, specifically in terms of available facilities. Some options might be a quick setup that can be done in any given space that is large enough, whereas others might require a week to setup in addition to a facility with specific features. This is specifically valuable in evaluating whether or not the setup allows for the possibility of using the RECUV motion detection lab for the demonstration, which is an option for object tracking.
  - *Knowledge Base*: This criteria encompasses the knowledge base relating to the specific capture method, both on the team as well as from external sources.
  - *Ease of Manufacturing/Procurement*: This criteria specifies the difficulty in obtaining the hardware for single axis translational motion. This includes procurement and/or manufacturing. Note however, that this does not encompass cost, which will be looked at as part of a cost-benefit analysis.
- **Design Simplicity**: This criteria refers to the complexity of the design in terms of the number of moving parts, actuators, complex components, etc. It is useful to the team to choose a simple design, as the project as a whole has a lot of aspects to it that will all require a lot of time.

5.3.2 *Trade Study Metric Definitions*

Table 34 explains how each score is defined for each of the given criteria. Table 35 defines the cost and risk metrics used in the cost-benefit and risk-benefit analyses.

Table 34. Single Axis Translation Trade Study Criteria Metrics

Criteria	**5**	**4**	**3**	**2**	**1**
Rep. of Space	Zero resistance in all directions		Resistance force along translational axis limited to drag		Restrictive normal force in all directions
Precision	Straightness tolerance within 5mm over 1m	Straightness tolerance within 5-10mm over 1m	Straightness tolerance within 10-20mm within 1m	Straightness tolerance within 20-50mm within 1m	Straightness tolerance greater than 50 mm within 1m
Setup Flexibility	Can be set up anywhere		Specific facility requirements limit setup locations but there are options on campus		No available locations on campus for setup due to facility requirements
Knowledge Base	The team is very familiar with method	The team has some familiarity and there are a lot of resources at CU	The team has no familiarity but there are a lot of resources at CU	The team has no familiarity and resources at CU are hard to come by, but there are sources available online	No one has ever done this
Ease of Manufacturing/Procurement	100% COTS and can be shipped in 1 week or less	Can be procured in 2 weeks or less	Can be procured in 2-4 weeks	Can be procured in 4-6 weeks	Will take 6+ weeks to procure
Design Simplicity	Extremely simple	Simple	Neutral	Complex	Extremely Complex

Table 35. Cost and Risk Metrics

	5	**4**	**3**	**2**	**1**
Cost Metric	< \$500	\$500 – \$1000	\$1000 - \$1500	\$1500 - \$2000	> \$2000
Risk Metric - Success Probability	80 - 100%	60 - 80 %	40 - 60 %	20 - 40 %	< 20%

5.3.3 Trade Study Results

The results of the single axis translation trade study are shown in Table 36, along with the subsequent risk-benefit and cost-benefit plots. The two highest weighted criteria were precision and design simplicity. Precision is necessary to limit the relative translation to a single axis and ensure that the demonstration is repeatable. Design simplicity was given a heavy weight due to the amount functions that need to happen throughout the demonstration. A simple design mitigates the risk of having to spend too much time troubleshooting the linear translation system. Ease of manufacture and representation of the space environment were each given a weight of 0.75, as each are in a way, added bonuses to the design. Setup flexibility and knowledge base can each be overcome with research and planning, but are nonetheless important aspects to consider. Explanations of the score given to each option are detailed below.

- **Ranking Explanations:**
  - *Representation of Space:* The highest scores in this category were the air table and magnetic levitation, as each option allows for frictionless motion. The cable-hung system has gravity and a tension force acting in the direction of translation, but is unforced in other directions, allowing it to reflect transverse disturbances to a certain degree by assuming small displacements. The linear drive system has restrictive normal forces acting in the transverse directions, and friction acting in the capture direction, making it not at all reflective of free-space motion.
  - *Precision:* Linear drive systems offer extremely precise linear motion, and can be used to accurately control the velocity of the moving object. Magnetic levitation is also capable of precise motion, as it is essentially a linear rail with no rail when designed correctly. The air table is much less precise, as any imperfections are going to lead to uncertainties in the direction of motion. This includes propulsive inefficiencies, the table not being perfectly level, drafts in the room, imperfect hole sizes for flow up through the table, etc. The cable-hung system is capable of precise translation, but it is prone to disturbances and would be nearly impossible to keep the CubeSat from wobbling, which would add an additional rotational degree of freedom.
  - *Setup Flexibility:* The air table would require a large amount of space and would be extremely difficult to move, limiting it's flexibility to be used in different places. The cable-hung system has similar difficulties because it requires a large, external structure to hang the CubeSat from. The linear drive and magnetic levitation systems each involve more compact setups.
  - *Knowledge Base:* The team has a fair amount of experience with pulley systems and with linear rail systems, and there are resources all over the place. Manufacturing an air table is not something that anyone on the team has done, but the concepts are well understood and help could be found quite easily at CU. With magnetic levitation, the team has no knowledge. There may be resources at CU, although the team is not yet aware of any.
  - *Ease of Manufacture:* Magnetic levitation would be one the most difficult options to procure, as it essentially requires making a ”unrolled” induction motor, and there are no off-the-shelf options available. Although the air table can be made out of common materials, it would require a large amount of time to manufacture. COTS linear drive systems are available, though some parts may need to be machined in order to reduce cost. However, it is reasonable to assume that everything needed for a linear drive system could be shipped and machined in 2-4 weeks. The cable-hung system is the simplest design, would require minimal machining and could most likely be put together in the shortest amount of time.
  - *Design Simplicity:* The linear drive and cable-hung systems can each be done with one actuator and involve simple motion. The air table is a bit more complex in that it requires airflow from a fan as well as a nontrivial propulsion system. The magnetic levitation option is extremely complex in that it uses electromagnets to make something levitate and propel it forward. There is a reason that this is new technology that is not readily available.

Table 36. Single Axis Translation Trade Study Results

Translation Trade		Air Table		Linear Drive System		Cable-Hung		Magnetic Levitation	
Criteria	%	Raw	W	Raw	W	Raw	W	Raw	W
Rep. of Space	0.15	4	0.6	2	0.3	3	0.45	4	0.6
Precision	0.3	2	0.6	5	1.5	2	0.6	4	1.2
Setup Flexibility	0.1	2	0.2	4	0.4	3	0.3	3	0.3
Knowledge Base	0.1	3	0.3	4	0.4	4	0.4	2	0.2
Ease of Manufacture	0.15	2	0.3	3	0.45	4	0.6	1	0.15
Design Simplicity	0.2	3	0.6	4	0.8	4	0.8	1	0.2
TOTAL			2.6		3.85		3.15		2.65

Shown in Figure 33 is a risk-benefit plot of the different linear translation methods. The benefit of each option is taken directly from its score in Table 36. The risk was evaluated based on research of current technology, complexity of the design, and a reflection of team expertise to ultimately predict the probability of success. Magnetic levitation was given the highest risk, as modern linear induction motors are still under research and development. Designing a linear induction motor for magnetic levitation would be a huge undertaking and the probability of success for the team is very low, given that linear translation is only a small part of the project. The success probability of the air table was rated at just under 50%, giving it a higher risk. This is due to the difficulty in manufacturing it and producing enough airflow to lift the CubeSat platform, as well as designing a feasible method for propelling the CubeSat forward in a controlled direction at a precise speed. So, there is a lot that goes into the air table and therefore a lot that could go wrong. The cable-hung and linear drive systems were the lowest risk, as each use simple designs and are easy to control with minimal uncertainty. There is not a lot that could go wrong with either option, as both methods utilize proven linear motion techniques that are intuitive to understand. The cable-hung system is rated at slightly higher risk because of the wobble in rotation that would need to be mitigated.

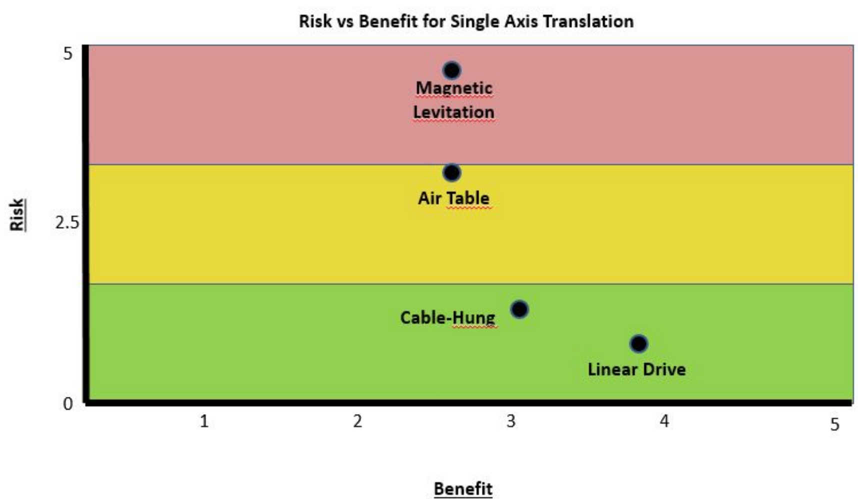

Figure 33. Risk-Benefit analysis for single axis translation

Figure 34 shows the cost-benefit analysis of the translation design options. Magnetic levitation was again the worst option at high cost and low benefit. The reason for this is that the complex electromagnets and coils required to construct a linear induction motor could easily be upwards of $5000, which would put the team well over budget. The linear drive system could also be quite expensive, but it offers the largest benefit. COTS linear drive systems that are at least 1 meter long typically cost somewhere between $2000 and $4000. However, this cost could be reduced by manufacturing some of the components rather than buying them. The team can also apply for additional funding in order to relax budget constraints. The air table is close to neutral as far as cost goes, meaning that it could be manufactured for around $1000. The biggest cost of the air table setup is the high-volume fan, which would likely cost $400-$600. The remaining materials would be relatively inexpensive, as the table can mostly be manufactured out of 2x4's and plywood. The cable-hung system is the cheapest option as it simply requires a pulley, a cable, and a motor. The motor would be the most expensive item, but would probably be available for around \$200-\$400.

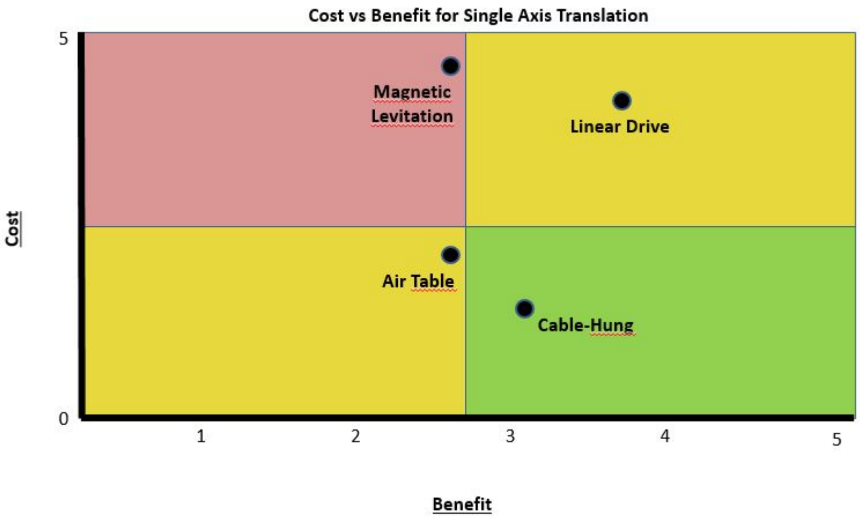

Figure 34. Cost-Benefit analysis for single axis translation

5.4 Testbed Configuration: Single Axis Rotation

The goal of this trade study is similar to the previous trade study on translation. The four design options included in the trade study are detailed in Section 4.4.

5.4.1 Trade Study Criteria

- **Performance**: The performance of the method of rotation within the demonstration is a large aspect for the trade study. For further clarity, performance is broken down into two sub-criteria.
  - *Accuracy and Precision of Rotational Motion*: This criteria specifies the actuator's ability to maintain its rotational speed. This is an important factor in verifying the capture device. By mocking a space environment, this will increase the success of the capture device in space; thus, the motion of the CubeSat on the Testbed shall mimic the motion of any CubeSat in space. This requires the rotational motion to be as smooth as possible and precise at all times during the testing phase. This also requires the actuator to not interfere with the capture device, such that it can either disengage or remain within some interference margin.
  - *Torque Capability*: This criteria specifies the actuator's ability of providing torque. It is best to have a higher torque capability during all times of the testing phase. This allows the ability to spin up the spacecraft and maintain its spin within any desirable spin rate. The rotational actuator must account for any physical changes to the CubeSat that affects the inertia of the CubeSat, and overcome any external forces such as friction.
- **Logistics**: The logistics of the rotational method has been broken down into the two sub-criteria below.
  - *Knowledge Base*: This criteria specifies the amount of knowledge and research that is available on campus and online pertaining to the actuator.
  - *Ease of Manufacturing/Procurement*: The criteria specifies the difficulty in obtaining hardware for a rotation actuator. This includes either obtaining the whole actuator itself and/or any needed manufacturing. Within a restricted schedule, it is best to obtain the actuator quickly for calibration and testing.
- **Design Simplicity**: This criteria specifies the amount of time and expertise that is needed to have a completed rotation actuator that satisfies the two functions of spinning up and maintaining a free spin. This pertains to designing, building, calibrating, and interfacing the actuator to the CubeSat.

5.4.2 Trade Study Metric Definitions

Table 37. Single Axis Rotation Trade Study Criteria Metrics

Criteria	**5**	**4**	**3**	**2**	**1**
Accuracy/Precision	Rotational speed within 0.2 deg/s	Rotational speed within 0.4 deg/s	Rotational speed within 0.6 deg/s	Rotational speed within 0.8 deg/s	Rotational speed within 1 deg/s
Torque Capability	Constant extra spin up torque		Extra spin up torque		Minimal spin up torque
Knowledge Base	The team is very familiar with method	The team has some familiarity and there are a lot of resources at CU	The team has no familiarity but there are a lot of resources at CU	The team has no familiarity and resources at CU are hard to come by, but there are sources available online	No one has ever done this
Ease of Manufacturing/Procurement	100% COTS and can be shipped in 1 week or less	Can be procured in 2 weeks or less	Can be procured in 2-4 weeks	Can be procured in 4-6 weeks	Will take 6+ weeks to procure
Design Simplicity	Extremely simple	Simple	Neutral	Complex	Extremely Complex

Table 38. Cost and Risk Metrics

	5	**4**	**3**	**2**	**1**
Cost Metric	< \$500	\$500 – \$1000	\$1000 - \$1500	\$1500 - \$2000	> \$2000
Risk Metric - Success Probability	80 - 100%	60 - 80 %	40 - 60 %	20 - 40 %	< 20%

5.4.3 Trade Study Results

The results of the trade study are shown below in Table 39. Design simplicity and accuracy/precision are ranked the highest. Simplicity affects the probability of success and the amount of time that is needed to complete the Testbed rotation actuator. Accuracy/precision affects the validity of the Testbed; higher accuracy/precision results in a better model of a spinning CubeSat in space. Knowledge base and ease of procurement/manufacturing are less important since they depend on the ability to obtain resources; it is better to have many resources within reach to lower the amount of time for completion. Torque capability is ranked the lowest because all the actuators can be designed to fit within the required amount of torque to meet the functional Testbed requirements; however, the maximum capability is the important factor. Below are explanations for the criteria rankings shown in Table 39.

- **Ranking Explanations**:
  - *Accuracy/Precision*: The electric stepper motor can provide high accuracy and precision of around 0.36 degrees per step with high torque; higher resolution results in smoother low rotation speeds. The electric gear motor can also provide a high amount of resolution depending on the gear ratio. The reaction wheel can also provide a high amount of resolution depending on the spinning inertia and motor specifications. The magnetorquer will have the highest accuracy and resolution due to its use of the electromagnetism; where the rotation actuation is almost immediate compared to the other mechanical options.
  - *Torque Capability*: The magnetorquer has a more noticeable cap of on its torque capability compared to the other options. The ratio of torque and required electrical power is huge and puts a limit of the amount of torque the rod can produce. The reaction wheel has a varying cap on its torque capability due to

saturation. Depending on the design, the reaction wheel will always have a decreasing amount of torque that it can provide. The stepper motor is more lenient on limited torque. Even though it can produce a constant amount of torque, it must sacrifice torque capability for higher resolution. The electric gear motor is ranked the highest because it is a device that has none of the disadvantages above. It is worth noting that the torque available for the motor is dependent on the rate at it spins. Due to a slow rotation speed, this can be neglected.

– *Knowledge Base*: The electric gear motor has an extensive amount of digital and physical resources and has been around since the mid 1850s. The reaction wheel and electric stepper motor also have been around for some time; but have smaller amounts of resources compared to the gear motor. The magnetorquer is not as popular compared to its ground-based opponents and have a smaller knowledge base.

– *Ease of Procurement/Manufacturing*: The electric stepper motor and electric gear motor have a huge market in their respective category. Most motors are delivered in almost-ready-to-use condition with some motors having optional additions such as encoders and drivers. The reaction wheel has a huge market in its motor component; and with advanced manufacturing, its spinning inertia can be manufactured to the right specifications. The magnetorquer has a very limited market where most torque rods are space grade and very expensive. Torque rods can require a lot of time and a huge amount of wire to create.

– *Design Simplicity*: With the right driver and proper calibration, the stepper motor can be used in a quick fashion; however, its interface with the CubeSat to model a free spin will be difficult. A detachment mechanism such as a clutch will need to be created to disengage the motor from the CubeSat, to separate the mechanics of the motor. The electric gear motor has more mechanical parts and has a similar problem to the stepper motor. The magnetorquer is the most complex because it involves several key components for it work such as an artificial magnetic field; but, it easy to obtain a free spin. The physics behind electromagnetism be can difficult to model and understand. The reaction wheel is right in between the three options since it has an easier interface than the electric motors and will require less time to develop than the magnetorquers.

Table 39. Single Axis Rotation Trade Study Results

Rotation Trade		Electric Stepper Motor		Electric Gear Motor		Magnetorquer		Reaction Wheel	
Criteria	%	Raw	W	Raw	W	Raw	W	Raw	W
Accuracy/Precision	0.3	4	1.2	4	1.2	5	1.5	4	1.2
Torque Capability	0.1	4	0.4	4	0.4	3	0.3	3	0.3
Knowledge Base	0.15	4	0.6	5	0.75	2	0.3	4	0.6
Ease of Procurement /Manufacture	0.15	4	0.6	4	0.6	1	0.15	4	0.6
Design Simplicity	0.3	3	0.9	3	0.9	1	0.3	4	1.2
TOTAL	1		3.7		3.85		2.55		3.9

Figure 35 displays the risk-benefit visual for the rotation actuators. The risk is similar to the linear translation section above.The magnetorquer has the highest risk due to the complexity and amount of time required to create its components. With little few experience in electrical physics and few online resources, this method of producing rotation can be daunting with a lower probability of success. The benefit is great in such that it provides the better representation of how a satellite would rotate in space, and also due to its future use. The reaction wheel has a lower risk due to the experience of the team with previous labs; however, it is more complex than an ordinary electric motor. The reaction wheel has a great benefit because it is an actuator that a satellite would use in space; thus can provide great future use. The electric gear motor and electric stepper have the lowest risk due to its simplicity and extensive resource. The gear has the least benefit due to its great amount of friction and mechanical parts, which is not desirable for spacecraft Testbeds.

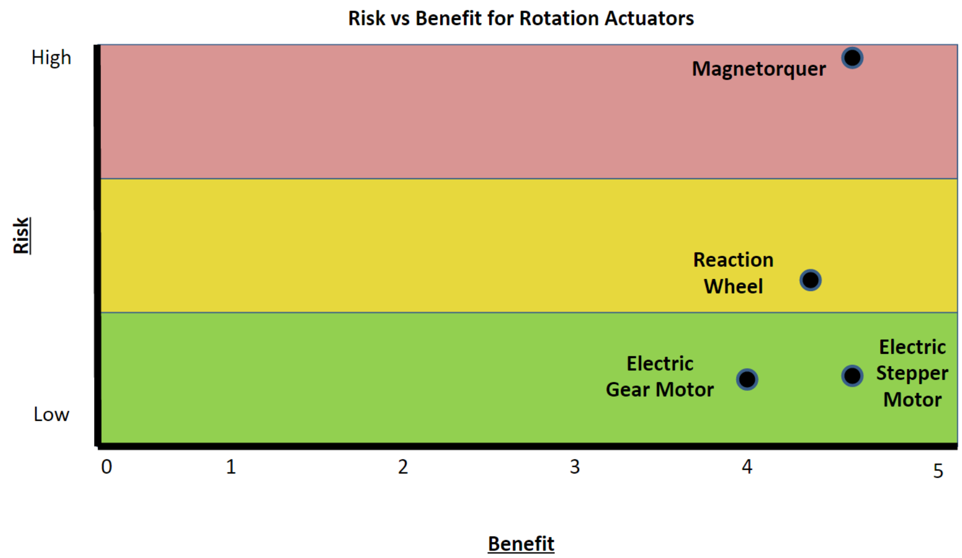

Figure 35. Risk-Benefit analysis for single axis rotation

Figure 36 displays the cost-benefit visual for the rotation actuators. The magnetorquer has the highest cost due to the amount and cost of hardware that is needed to complete the actuator. Torque rods consists of many coils of electrical wire with low resistance; depending on the required magnetic strength (about 1-2 G is that norm), the cost of wire can add up quickly. In addition to power supplies, construction material, and controllers, the cost exceeds $ 2000. The electric stepper motor has a lower cost due to the reduction of components that it needs; such that it only needs one controller. However, the cost can get expensive depending on the precision needed.

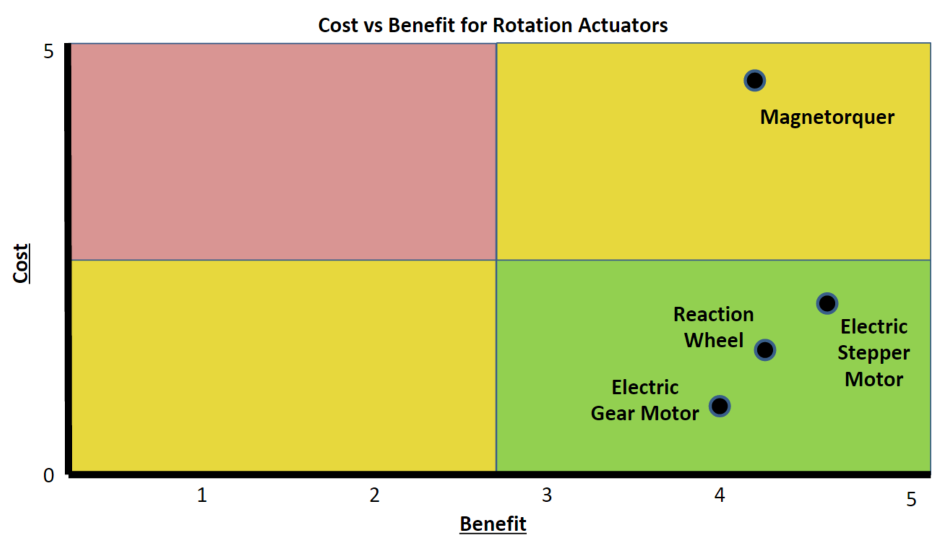

Figure 36. Cost-Benefit analysis for single axis rotation

5.5 Object Tracking Sensors

The goal of this trade study is to determine the most effective method for tracking the motion and orientation of the CubeSat throughout the capture demonstration.

5.5.1 Trade Study Criteria

- **Procurement**: The cost criteria considers procurement towards a sensor or multiple sensor and how that procurement affects the allotted budget.Multiple sensors may be used for the position and angular velocity data so additional component cost will be considered. If multiple sensors are used then integrating these sensors will only increase the cost. The allotted budget is $5000.
- **Additional Components** The criteria also includes the cost of any additional components needed to interface the sensors.
- **Resolution**: The ability for sensors to detect changes in the motion of the CubeSat within 1m is an important criteria. A high sensor resolution will enable the the capture device to sense if the CubeSat motion is translating or rotating. The capture device will depend on the sensor resolution to make the proper adjustment to fulfill its objective of capturing the CubeSat.
- **Integration**: The sensors used must be able to integrate and possibly synthesize data, interface with the hardware and supplement the tracking algorithm that will be used to capture the CubeSat. Integration of the sensors within the CubeSat Recovery System will play a crucial role because it provides the necessary data for system feedback.
- **Calibration**: A sensor with high accuracy and precision will require little to no calibration. Calibration or lack thereof will determine the error between expected data and the actual data provided by the sensor. The ability to easily correct for that data is the calibration criteria.
- **Accuracy**: The accuracy is a property of the sensor that will determine the quality of the data. The accuracy is ratio between the output signal and the minimum input that will produce and output. Accuracy can be slope measured in mV/V. If the capturing device is unable to track and capture the CubeSat a source of error will measure as a lack of accuracy and will be corrected for through calibrating the sensor.

5.5.2 Trade Study Metric Definitions

The trade study metric definitions for the object tracking criteria are given in Figure 40.

Table 40. Object Tracking Sensor Trade Study Criteria Metrics

	0	1	2	3	4	5	Heuristic
Procurement	>$500	>$200	>$100	50−100	0−50	$0	Low Cost Sensors will get the higher weight.
Additional Components	>$150	>$100	>$50	$25-50	0−25	$0	Cost of Additional Components should be at a minimum
Resolution	1m	3bit	>1cm	1mm-3mm (8bit)	<1mm (8gs for accelerometers) (16bit for DSP)	Infinitesimal	Sufficient for CubeSat Capture. Less than 1m
Integration	Requires Operating System	Requires Microprocessor	Purchase of Additional Parts	I2C or SPI	I2C/SPI/Open source software	Built In Interphase	Integration should be easy and require little to know additional parts or software.
Calibration	No Calibration Capability	Software / hardware calibration of multiple parts.	Software calibration of multiple parts.	Software based and requires only user inputs to calibrate.	Calibration error tolerable	No Need to Calibrate within operational range	There should be no need to Calibrate for Error
Accuracy	N/A	N/A	N/A	N/A	A function of algorithm	<0.025m (Full floating point precision)	Sensor should be able to detect any changes in CubeSat position or orientation.

5.5.3 Ranking Explanations

- **Cost Criteria[35%]**:
  - **Procurement[15%]**: Generally sensors that measure position and angular rates are cheap and readily available. Allocating funds toward the purchase of sensors will not total up to a percent of our total budget. It is also important to consider that there is no RECUV procurement if a reservation is secured.
  - **Additional Component[20%]**: One sensor may not be able to measure all the parameters so additional sensors may to be needed. Purchasing multiple sensors increases procurement cost and so additional components will be considered heavily during the purchase of the first sensor.
- **Performance[65%]** The performance of the sensors will enable the capture device to capture the CubeSat autonomously given the appropriate data. The criterion used to decide on a sensor that will enable system autonomy are listed below. :
  - **Resolution[15%]**: The sensors within this trade study all have the capability to identify a 3U CubeSat with a protruding solar array. Also CubeSat motion has been defined to be 1DOF translation and rotation so there will be minimal changes in position. A relatively low weight is assigned.

– **Integration[25%]**: Integration is assigned a relatively high weight because the sensor must be compatible with the capture device. The sensor output data must be interpreted by the capture feedback algorithm to enable autonomy. Most sensors have a standard 3-wire DC type. USB will be considered for data transfer.

– **Calibration[10%]**: This criterion is given the lowest weight because of lack of change to the surrounding environment that may interfere with sensor collecting data.

– **Accuracy[15%]**: Accuracy is given a moderately low weight because it is the sensor specification that will not change. A sensor with a high sensitivity will enable the capturing device to achieve it requirement of capture and release. If the sensor accuracy is insufficient then a new sensor can be purchased.

5.5.4 Trade Study Results

Shown in Figure 41, is the result of the trade study for the tracking object trade study. The top three results are RECUV tracking, Encoders, and the HC-SR04.

Table 41. Tracking Trade Results

Tracking Trade		RECUV		LIDAR		RAZOR IMU		HC-SR04		XG1300L		LVDT		Encoder	
Criteria	%	Raw	W	Raw	W	Raw	W	Raw	W	Raw	W	Raw	W	Raw	W
Procurement	0.15	5	0.75	2	0.3	3	0.45	4	0.6	3	0.45	1	0.15	5	0.75
Add. Components	0.2	5	1	2	0.4	4	0.8	4	0.8	3	0.6	1	0.2	3	0.6
Resolution	0.15	5	0.75	5	0.75	2	0.3	3	0.45	5	0.75	5	0.75	5	0.75
Integration	0.25	4	1	4	1	1	0.25	4	1	2	0.5	2	0.5	5	1.25
Calibration	0.1	5	0.5	5	0.5	3	0.3	4	0.4	4	0.4	5	0.5	3	0.3
Accuracy	0.15	5	0.75	5	0.75	5	0.75	5	0.75	5	0.75	5	0.75	5	0.75
TOTAL			4.75		3.7		2.85		4		3.45		2.85		4.4

Shown in Figure 37 is the risk-benefit analysis done on the object tracking design options. It is clear that both the Rotary Encoder option and the RECUV option maximize benefit with minimal risk. The RAZOR IMU Gyroscope and LVDT are high risk with low benefit, and will therefore not be considered as options for the baseline design.

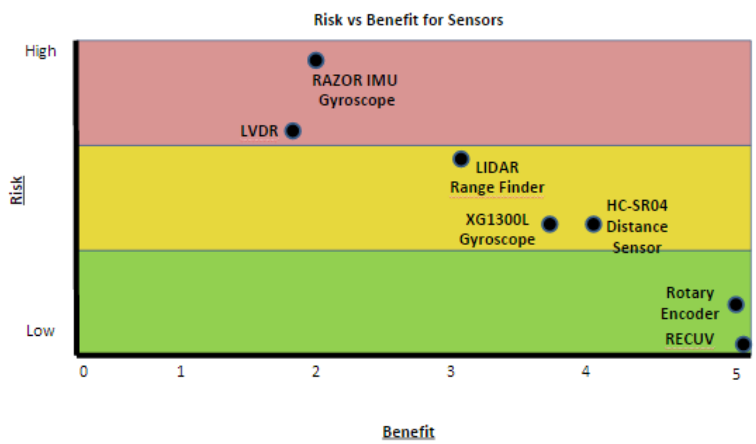

Figure 37. Risk-Benefit analysis for the Sensors

The cost-benefit analysis for the object tracking design options is shown in Figures 38. In agreement with the risk-benefit analysis, the rotary encoder and RECUV facilities are the optimal design options.

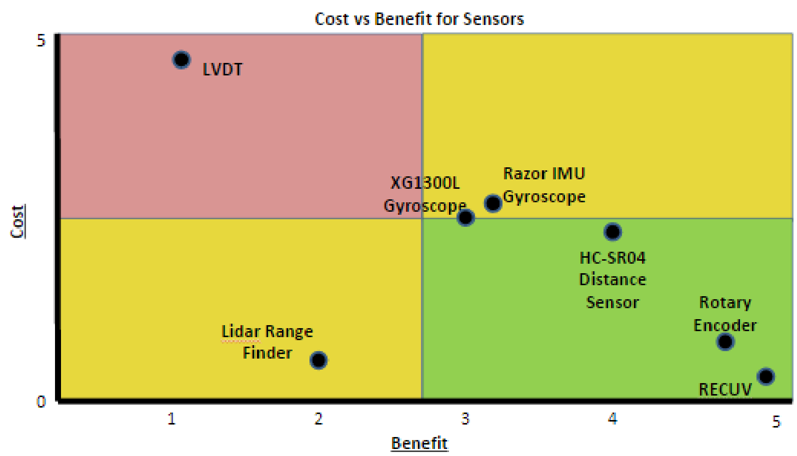

Figure 38. Cost-Benefit analysis for the Sensors

Since the RECUV facility is busy and availability is limited, it will be the primary and the rotary encoder will be the secondary in the event access is not given.

6 Selection of Baseline Design

6.1 Summary

Overall, the baseline design is attained through a collapsible approach. First, the selection of the capture device deployment and end effector made it easier to narrow the available design space for the Tesbed; this allows the determination of the best approach to verify the success of the capture device. Next, the selection of the Testbed configuration narrows the available design space for the sensors; thus, sensors are selected to best accommodate the Testbed.

In the end, the baseline design consists of a robotic arm with a claw, or dry adhesives(as availability permits), that will be tested with a linear rail and a reaction wheel on the CubeSat, with encoders, or RECUV lab(as availability permits), as sources for feedback.

6.2 Deployment Device

The robotic arm is the leading option for a deployment device as it presents the lowest cost, lowest risk option at the highest performance. These claims are justified by extensive research showing that a robotic arm could be procured at an affordable cost with the capabilities needed to achieve the mission objective. For the team to implement this device, it will need to develop a comprehensive understanding of the software package that the device operates on so that the correct commands can be sent to the robotic arm to perform a capture. By selecting this device, the risk of error within the system preventing capture at the target location is reduced and can be compensated for by the arm. The robotic arm would also be compatible with either of the end effectors that are to be carried forward as explained below, and can do so with high precision.

6.3 End Effector

For the end effector selection it was decided to move forward with both the claw and the dry adhesive options. The claw was a suitable selection for the end effector, while it did not provide the lowest risk, it did have a low cost for development. Dry adhesives proved to have the lowest risk, but the cost involved was ranked higher due to the manufacturing required as well as the questionable availability due to never coming in contact with *nanoGriptech Inc.*. Both of these options are feasible for development within the time constraints of senior projects design. Dry adhesives would be preferred due to the simple approach and the low risk to the CubeSat structure including the solar panel, which also opens up the options for available gripping locations. Dry adhesives have also been tested for a large number of grips, up to 30,000, showing they will easily last for many captures.

6.4 Testbed Configuration: Single Axis Translation

After conducting a trade study on the method of linear translation, the decision was made to move forward with the linear drive system. This configuration involves the CubeSat translating horizontally on a linear rail or ball screw device. The big advantages to this system are that it is precise, reliable, simple, and easy to set up. Direction control is eliminated, as linear rails can be manufactured to straightness tolerances on the order of tenths of millimeters. Additionally, accurate velocity control is guaranteed with the right motor selection. The main drawbacks to the linear drive system are that it does not in any way represent dynamics in space and that it is one of the more expensive options. As explained earlier, it is not a requirement that the demonstration be representative of the space dynamics. Although this project is geared toward space applications, the goal is to demonstrate the functionality of the capture device and the capture algorithm, which can be done most effectively with a linear drive system as the method of translation. As far as the cost goes, the linear drive system is not going to put the project severely over budget, and therefore the issue can be mitigated by manufacturing certain components rather than buying them off the shelf, as well as applying for additional funding.

6.5 Testbed Configuration: Single Axis Rotation

In the end, the optimal rotation actuator in the Testbed is the reaction wheel. The reaction wheel scored the highest in the trade study with acceptable cost and risk. The reaction wheel is mainly chosen due to its flexibility in design space and in the interface with the CubeSat. With a flexible interface, the CubeSat can be oriented either vertically or horizontally; and with a wide design space, a high resolution in rotation can be achieved (at minimum 3 deg/s). With a support surface such as a frictionless bearing, the reaction wheel provides a method of applying torque onto the CubeSat while allowing the CubeSat to spin freely. To accomplish this, the reaction wheel will need to be attached to the center of gravity of the CubeSat. Even with a small displacement error, the reaction wheel can account for the unwanted gravitational torque and still provide control on the angular rate.

6.6 Object Tracking Sensors

The wide array of sensors involved in this study are all capable of meeting the CRS's need for measuring displacement, velocity and acceleration. The sensor that meets that need most according to the trade study is the rotatory encoder. The encoder is capable of serving as a both a displacement and velocity transducer by placing it on the motor that generates linear translation and using the angular velocity and displacement measurements to back out linear translation. Furthermore, it is the one sensor that can be used within the capture device and the proposed linear drive system that will be used to move the CubeSat. The resolution of the encoder at 6000rpm is less than that of other sensors but in the low rpm application that will be seen in the capture demonstration, it will provide accurate data. Of course, the best scoring design option was the RECUV motion detection facility, as it is extremely accurate, low risk, and free. However, its availability cannot be counted upon. Therefore, both the RECUV motion detection facility and the rotary encoder sensor are being moved forward through the baseline conceptual design. The encoders will be used as the primary motion sensing source while the RECUV facility will be used as an extra source of validation for the CubeSat capture demonstration if it is available.

7 Bibliography

[1] Nanosatellite Database. (n.d.). Retrieved August 31, 2016, from http://www.nanosats.eu

[2] Brändle, Markus. ”Robotic Arm Motion Planning”. Swiss Federal institute of technology Zurich. 2008

[3] LaValle, Steven M. ”Planning Algorithms”, 1^{st}ed. University of Illinois. 2006.

[4] ”7Bot Arm.” 7Bot. N.p., n.d. Web. 26 Sept. 2016.

[5] Bourrec, Lionel, Lauren Bernabe, Victor Pires, and Sylvain Trimolieres. TELESCOPIC BOOM FOR SPACE APPLICATIONS ENGINEERING MODEL. N.p., n.d. Web. 22 Sept. 2016.

[6] ”Deployable Booms.” European Space Agency. N.p., n.d. Web. 26 Sept. 2016.

[7] Hoyt, Robert. The μTORQUE Momentum-Exchange Tether Experiment. Tethers Unlimited. Web. 15 Sep. 2016.

[8] Hoyt, Rob. ”GRASP.” GRASP. Tethers Unlimited, n.d. Web. 26 Sep. 2016.

[9] Metin Setti and Ronald S. Fearing. ”Synthetic Gecko Foot-Hair micro/nano-structures as dry adhesives”. Journal of Adhesion Science and Technology (2003). Web. 12 Sep. 2016.

[10] Hao Jiang, Elliot W. Hawkes, Vladimir Arutyunov, Jacob Tims, Christine Fuller, Jonathan P. King, Carl Seubert, Herrick L. Chang, Aaron Parness, and Mark R. Cuthosky. ”Scaling Controllable Adhesives to Grapple Floating Objects in Space”. Standford University, NASA JPL/Caltech (2014). Web. 13 Sep. 2016.

[11] Tom Bryan, Todd Macleod, Larry Gagliano, Scott Williams, Brian McCoy. Innovative Electrostatic Adhesion Technologies. NASA Marshall Space Flight Center, SRI International. Web. 16 Sep. 2016.

[12] Linear Motion, Linear Actuator,& Linear Bearing Solutions, Linear Bearings, Linear Motion, Linear Guides & Rails, Linear Actuators, Roller Bearings Available: http://www.pbclinear.com/.

[13] Kumar, C. (2013). Static Test Study on Linear Induction Motor. IJCEE International Journal of Computer and Electrical Engineering, 251-255.

[14] Battery and Energy Technologies, Electric Drives Available: http://www.mpoweruk.com/motorsspecial.htm.

[15] Earl, Bill. ”What is a Stepper Motor?.” All About Stepper Motors. Adafruit, 5 May 2014. Web. 20 Sept. 2016. https://learn.adafruit.com/all-about-stepper-motors/what-is-a-stepper-motor

[16] ”Basics of Step Motors.” Basics of Motion Control. Orientalmotor, n.d. Web. 21 Sept. 2016. http://www.orientalmotor.com/technology/articles/step-motor-basics.html#types

[17] Earl, Bill. ”Geared Motors.” Adafruit Motor Selection Guide. Adafruit, 21 May 2014. Web. 26 Sept. 2016. https://learn.adafruit.com/adafruit-motor-selection-guide/geared-motors

[18] Savala, C., Designing a Magnetic Torque Rod for a CubeSat Available: http://www.nps.edu/academics/institutes/cebrowski/stem/doc/christineposter.pdf

[19] NSS Magnetorquer Rod. CubeSatShop, 2009. Web. 22 Sept. 2016. http://www.cubesatshop.com/product/nss-magnetorquer-rod/

[20] Meghan Prinkey. ”CubeSat Attitude Control Testbed Design: Merritt 4-Coil per axis Helmholtz Cage and Spherical Air Bearing”, AIAA Guidance, Navigation, and Control (GNC) Conference, Guidance, Navigation, and Control and Co-located Conferences, (AIAA 2013-4942) http://dx.doi.org/10.2514/6.2013-4942

[21] Schaub, Hanspeter, and John L. Junkins. Analytical Mechanics of Space Systems. Reston: American Institute of Aeronautics and Astronautics, Inc., 2003. 151. Print.

[22] Nanosatellites heading for space. ClydeSpace, n.d. Web. 22 Sept. 2016. http://www.maxonmotor.com/maxon/view/application/Nanosatellites-heading-for-space

[23] Vicon. ”Motion Capture Systems.” VICON. N.p., n.d. Web. 26 Sept. 2016. https://www.vicon.com

[24] Robot Shop. N.p., 2016. Web. 22 Sept. 2016. http://www.robotshop.com/en/lidar-lite-2-laser-rangefinder-pulsedlight.html

[25] "LVDT Tutorial." TE Connectivity. N.p., n.d. Web. 26 Sept. 2016. http://www.te.com/usa-en/industries/sensor-solutions/insights/lvdt-tutorial.html

[26] Support:, Tech. Ultrasonic Ranging Module HC - SR04 (n.d.): n. pag. Micropik. Web. http://www.micropik.com/PDF/HCSR04.pdf

[27] "9 Degrees of Freedom - Razor IMU." - SEN-10736. N.p., n.d. Web. 26 Sept. 2016. https://www.sparkfun.com/products/10736

[28] "Ultrasonic Ranging Module HC-SR04." MICROINFINITY. N.p., n.d. Web. 26 Sept. 2016. http://www.minfinity.com/eng/page.php?Main=1&sub=1&tab=5

[29] "Rotary Encoder - 1024 P/R." - COM-11102. N.p., 26 Sept. 2015. Web. 26 Sept. 2016. https://www.sparkfun.com/products/11102