University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018
Cubesat Active Systematic CApture DEvice (CASCADE)
Project Definition Document (PDD)
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1. Problem Statement

With the recently emerging market for CuebSat 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 extensive attitude control and maneuvering systems. 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.

The mission of CASCADE is to design and build a CubeSat capture system that could be used as a functional payload aboard the SN-50 MicroSat platform developed by Sierra Nevada Corporation (SNC). This capture system, dubbed “Bell”, after the classical Greek hero Bellerophon who captured Pegasus, will be used to capture a 6U CubeSat, dubbed “Pegasus”. The full rigid body spaceflight dynamics pertaining to the successful capture of Pegasus will be simulated using computer software. Additionally, the functionality of Bell will be tested by replicating the approach and capture process with a physical testbed. The simulation and physical testbed will both include an approach from a TBD distance from Bell to Pegasus and the capture of Pegasus. Sierra Nevada Corporation will provide definitions of the electrical, mechanical, software, and thermal interfaces between Bell and the SN-50 MicroSat. The specific details upon which success will be measured are presented in Section 3 of this document. Upon success, CASCADE shall deliver video documentation of the demonstration as well as documentation for the Flight Software.

As mentioned, many CubeSats do not have an attitude determination and control system[2] (ADCS), and almost none are equipped with a propulsion system. The CubeSats that do have attitude control are typically used to keep instruments pointing in one direction, and thus are capable of spinning about a single axis for stabilization. Taking this into consideration, the lowest level of success for this project is marked as simulating and demonstrating the capture of a non-rotating CubeSat. In this situation, the only relative motion between Bell and Pegasus is one degree of translation. This applies to capturing CubeSats that are able to control their spin rate, and assumes that they are capable of setting their spin rate to zero during capture operations. Higher levels of success are defined as capturing a CubeSat with a specified spin rate about the stable axis, thus increasing the range of CubeSats that can be captured. The major limitation to this project is the capture of dead or tumbling CubeSats. Incorporating this level of complexity into a testbed was deemed infeasible due to time and budget constraints. However, it should be noted that CubeSats without an ADCS typically only have missions that span months to a few years before failing. Thus, these are disposable and have been excluded from the scope of this project.

2. Previous Work

The capture and recovery of satellites is a problem that has been studied by the aerospace industry for decades. The Massachusetts Institute of Technology (MIT) and the National Space Development Agency of Japan (NASDA) embarked on a five-year concept study from 1995 to 2000 on space robotic missions for capturing stray objects. The research findings of these two aerospace institutions determined that one to ten ton expensive satellites spinning and tumbling were suitable targets for capture and recovery[4] . The recovery effort would use a chaser satellite with two robotic arms. The two-arm manipulator configuration used three finger end effectors and upon approach locked onto handles on the target satellite.[3] The chaser satellite would then use thrusters to reorient the satellites attitude[4].

NASDA then went on to conduct live experiments in 1997 with other aerospace institutions to include The European Space Agency and the German Aerospace Center. Together they launched ETS-VII, a robotic system that consisted of a robotic arm mounted on a satellite, an on-ground robot control system and a communication network to connect the ground control system to ETS-VII. Results showed that ETS-VII performed best when using coordinated satellite attitude control, a control scheme to synchronize the attitude of a pair of satellites by having one satellite estimate the angular momentum of the other[5].

A solution for the capture device configuration that does not involve the use of a robotic arm is a net or tether device[6]. This kind of device may use inflatable tubes to deploy a net around the object being captured and then pulls the object in by deflation of the tubes and collapsing the net. This method has been successful in capturing objects with less sensitivity to error than something such as the two-arm manipulator.

3. Specific Objectives

The primary objective of CASCADE is to design, build and demonstrate a robotic capture system. The levels of success pertaining to the project are present in Table 1. 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 1. Levels of Success. Each higher level assumes success of lower level has taken place unless specifically noted.

Success Levels	**Software Simulation (space environment)**	**Testbed Demonstration**	**Capture Device**
Level 1	-Simulation of approach and capture using Flight Software within 30 minutes. -Stabilize system after capture (less than 0.01 deg/s angular velocity in all three axes).	-Demonstrate approach and initial capture of Pegasus from initial TBD approach distance. -No visual damage -ONLY 1 DOF Translation	-Maintain hold for 5 minutes. -Mass: 15 kg -Volume: 24"x28"x17" payload bay. -Power: 100 W
Level 2	Visualization of pre-capture simulation	ONLY 1 DOF rotation	Demonstrate the ability to release Pegasus safely after capture
Level 3	Visualization of post-capture stabilization	1 DOF rotation AND translation	

4. Functional Requirements

Shown in Figure 1, is the concept of operations (CONOPS) for CubeSat recovery mission.

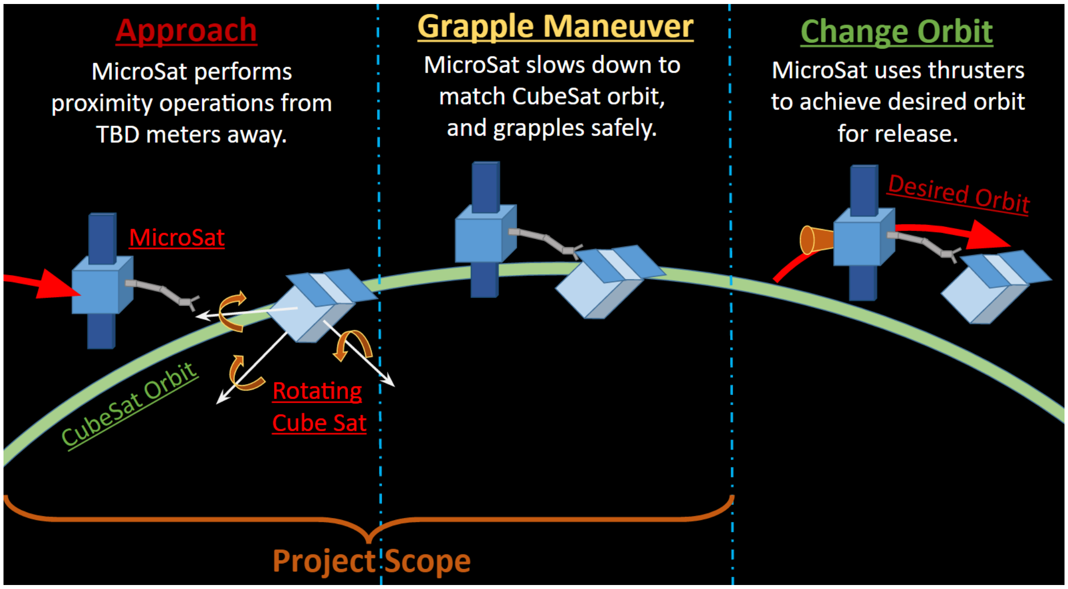

Figure 1. CASCADE Mission CONOPS

Bell shall begin from an initial TBD distance where the on-board *vision system* shall determine the relative position between Bell and Pegasus. This data shall be sent to the flight software on Bell for determining the optimal trajectory for capture. Once Bell is in position (aligned with the rotation axis of Pegasus), Bell's capture device shall capture Pegasus and stabilize the resulting two-body system. Once stabilized, Bell will move into another orbit to be repurposed. Once in the new orbit, Bell will release Pegasus and continue to another mission.

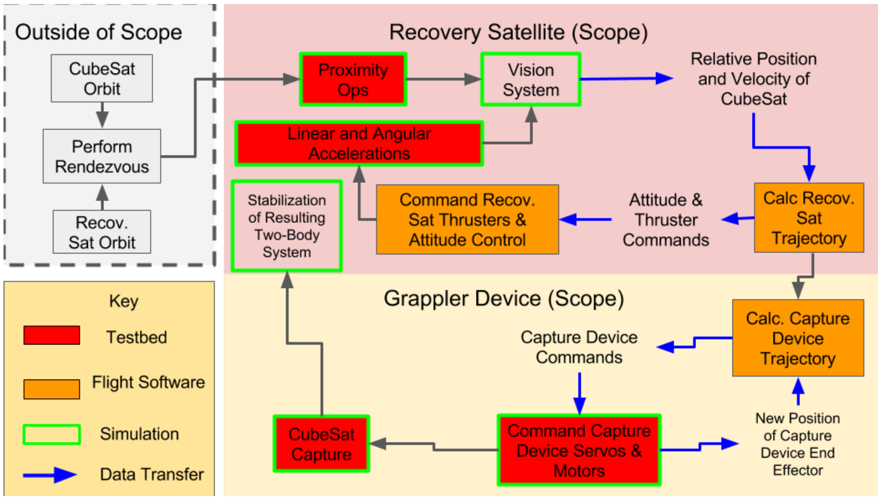

Figure 2. Functional Block Diagram

The project scope is defined by the proximity operations associated with capture and stabilization. Figure 2 shows the functional block diagram for the Bell satellite and capture system. The *vision system* is not within the scope of this project, so instead, the data from such a system will be mocked using Newtonian mechanics to propagate the relative motion of the two satellites from their initial states. The vision system data shall be passed to the flight software and be used to determine the trajectory for Bell as it makes its way to capture Pegasus. The spacecraft's thrusters and attitude control system shall be utilized to get Bell in position to capture Pegasus. After Pegasus is captured, Bell attitude control shall stabilize the system. The entire project scope will be simulated in software, while the testbed will only demonstrate up to the moment of capture, and omit post-capture operations.

Figure 3 shows the concept of operations for the testbed which will be used to test the capture of Pegasus. The dynamics calculated in the simulation will be converted with software and controllers so that the same relative motion is mirrored on the testbed for demonstration. The test shall be conducted using simulation to model the capture using Newtonian physics and Bell's ADCS and propulsion capabilities. Next, motors will be used to allow Pegasus to translate in one direction along a track, as well as rotate along the same axis. The testbed will model the relative motion of Bell as it approaches Pegasus by moving all the dynamics of Bell onto Pegasus until the capture device is close enough for capture. The capture mechanism will then be sent commands to capture Pegasus. Finally, the successful capture of Pegasus will be visually inspected to ensure both satellites are undamaged.

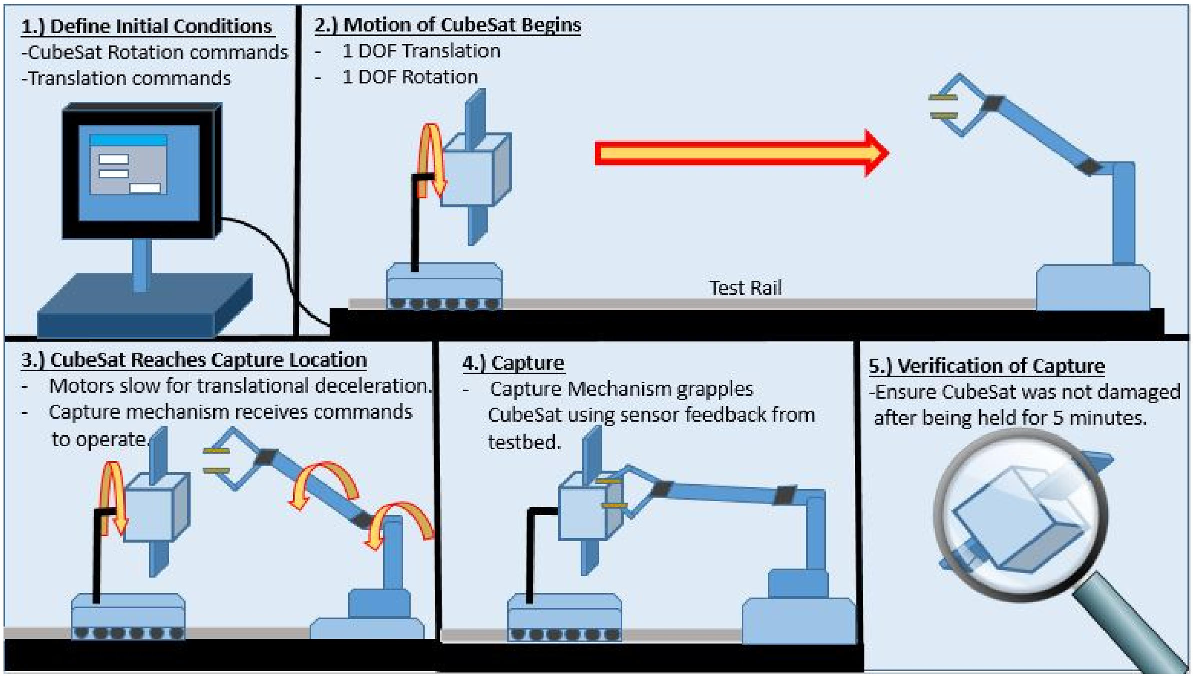

Figure 3. Testbed CONOPS

5. Critical Project Elements

The critical project elements categorized below identify those aspects of the project that are critical to its success. Their relevance on this list is also justified by the team's skill set presented in Section 5.

	Technical	
T1	Approach and Capture Algorithm	Algorithm may require high level math and optimization techniques in order to characterize capture mechanism dynamics and develop the optimal path of capture. The team has little experience with trajectories and path optimization functions.
T2	Translation of Motion from Sim to Testbed	In order to demonstrate the effectiveness of the capture mechanism in space, an innovative testbed shall be developed in addition to a method for relating space dynamics & control to the dynamics & control of the testbed. A large part of the project shall be designing, modeling, and testing the mechanisms used to simulate space dynamics on earth, as well as developing a software package that will link the two together.
T3	Capture Device Implementation	Possibly the biggest design choice of this project will be deciding on the method of capture. This shall require a trade study to determine the best option. Once a choice is made, rigorous modeling and testing shall be required to fully characterize the capture device. It will then need to be integrated with the testbed along with the capture algorithm for effective autonomous control. This integration is a CPE because it will require expertise in numerous areas.
T4	Pegasus Spin Axes Requirement	Designing and building a method for rotating Pegasus about 1 axis with feedback control will require a significant amount of time and money. This system also needs to be interfaced with the capture device software and control in order to ensure the testbed dynamics demonstrate the space dynamics simulation.
T5	Post Capture Operations Testing	Post Capture operations can be simulated on a computer, but a feasibility study will need to be conducted in order to determine whether or not time and budget constraints would allow for the physical testing and demonstration of post capture maneuvers. The post capture maneuvering will add complexity to the testbed.
	Logistical	
L1	Capture Device Procurement	As the capture device is the main part of the project, its procurement is critical, and shall be part of the trade study in determining the best capture method. Buying an off-the-shelf component would save time and decrease the workload, but could lead to budget and integration issues. Designing and building a capture device from scratch could save money, but increase the complexity of the overall project.
	Financial	
F1	Testbed Mechanical & Sensor Procurement	The testbed requires many components and sensors outside of the capture device. Designing a feasible testbed and procuring all of the necessary hardware while staying under budget will be challenging.

6. Team Skills and Interests

The table below describes the areas of expertise and/or interests of the team members and how they relate to the critical project elements identified in Section 5.

Name	Individual Skills/Interests	CPE
Zack Allen	Past Experience: Software Lead at Sunlight Photonics, Mars OASIS Automated Habitat Module Software: C/C++, Python, MATLAB, Java, LabView	T1, T2, T3, T4, T5
Chad Eberl	Relevent Coursework: Space Systems Engineering Past Experience: Mechanical Design and Manufacture; CAD; DAQ Software : MATLAB, C, LabView	T2,T3,L1,F1
Matthew Fromm	Past Experience: Manufacturing and Modeling, Software Development, Agile Process Management Software: MATLAB, Python, Java, Javascript Interests: Structural Design, Mechanical Systems	T2, T3, L1
Andrew McBride	Relevent Coursework: Micro-controllers, Systems Past Experience: Electrical Lead on HASP 2014 Proposal team and Intern at Civil Engineering Professionals Software: MATLAB, C, Python, Proscessing	T1, T2, T3, T4,
Haoyu Li	Past Experience: Lidar remote sensing, instrumentation and applications on various platforms; Gravational wave and PMC studies Software: MATLAB, C, C++, Python, LabView	T1, T3,L1
Tony Ly	Relevent Coursework: Spaceflight dynamics Past Experience: Testbed development for a spin deployed spacecraft Interests: Orbital mechanics, controls	T1, T2, T4, T5
Noel Puldon	Relevent Coursework: Controls, Systems Engineering Leadership and organizational skillset. Software: MATLAB & C	T1, T2, T4, L1, F1
Keegan Sotebeer	Relevent Coursework: Automatic control, Microcontrollers. Past experience: CAD and Mechanical Design. Software: MATLAB, C, C++	T2, T3, T4
Morgan Tilong	Relevent Coursework: Aerospace and Electrical Past experience: Electrical Engineering Intern. Software: MATLAB & Ruby	T2, T3, L1

7. Resources

The table below describes the resources beyond team interest/skills needed to address the critical project elements defined in Section 5. The table also identifies the sources of each resource and are not limited to: specialized equipment, software, facilities, or outside expertise, and any additional financial support needed beyond the $5,000 project funds.

Critical Project Elements	Resource	Source
T2, T4	• Machine Shop • CAD Software	Matt Rhode, Bobby Hodgkinson
T3, T4	• Electrical Hardware	Trudy Schwartz, Bobby Hodgkinson, Lad Curtis, PAB
T2, T3, L1,	• Construction Materials	Matt Rhode, Bobby Hodgkinson, PAB
L1, F1	• Funding for Sensor Hardware	Joan Wiesman, PAB

References

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

[2] CubeSat Attuitude Control using micronewton eletrospray thrust actuation. Retrieved September 11, 2016 from `http://dspace.mit.edu/handle/1721.1/90806`

[3] Capture of a Non-Cooperative Object Using a Two-Arm Manipulator. Retrieved August 31, 2016, from `http://arc.aiaa.org/doi/pdf/10.2514/6.IAC-04-A.5.06`

[4] Space Robotic Mission Concepts For Caturing Stray Objects. Retrieved September 4th, 2016, from `http://robots.mit.edu/publications/recent%20pubs/ists_paper.pdf`

[5] Space robot experiments on NASDA's ETS-VII satellite, Dr Mitsushige Oda. Retrieved in September 4th, 2016. `ieeexplore.ieee.org/document/772555/`

[6] Grapple, Retrieve, And Secure Payload (GRASP) Technology for Capture of Non-Cooperative Space Objects. Retrieved August 31, 2016, from `http://www.tethers.com/GRASP.html`