University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018

Project Definition Document - MEGACLAW

Mechanically **E**ngineered **G**rappling **A**rm to **C**apture **L**itter and **A**tmospheric **W**aste

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Approvals

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1. Problem Statement

1.1. Project Motivation

As space is becoming more accessible, altitudes near Low Earth Orbit (LEO) are increasingly crowded with retired satellites, launch vehicle upper stages, and miscellaneous orbital debris. Currently, there are an estimated 13,000 objects of diameter greater than 10 [cm], 100,000 of diameter greater than 1 [cm], and tens of millions of objects with diameter less than 1 [cm] in aimless orbits throughout LEO.[4] Furthermore, in the coming years, there are plans to launch hundreds of CubeSats, as well as entire satellite constellations, into this environment.[5] So, with satellite launches showing no signs of slowing down, and space debris threatening to impact huge U.S. government and private assets at speeds exceeding 17,500 [mph], something must be done to manage this imposing problem before space becomes inaccessible.

1.2. Project Introduction

To mitigate this situation, Sierra Nevada Corporation (SNC), alongside the Ann and H.J. Smead Aerospace Engineering Sciences Department undergraduate senior projects team at the University of Colorado Boulder, shall develop a satellite-mounted robotic grappling-arm debris capture system. Success for this mission includes debris identification, capture and neutralization, with the purpose of either de-orbiting or salvaging said debris. As in previous iterations of this project, this team will develop the MEGACLAW to carry out capture and neutralization procedures. MEGACLAW shall use a sensor on a CrustCrawler robotic arm to identify both the target object and the arm's end-effector, and adjust in real-time to execute the arm's path to a defined capture point. This shall be achieved through the use of a closed-loop sensor feedback control software package. SNC will handle all structural, electronic, and thermal interfacing between the MEGACLAW and its bus to support this capturing process. The target object in this mission will have no rotational or translational motion relative to the arm, dimensions that allow full view of the debris from the arm's viewpoint, and a capture point designed for grappling tests.

Much credit is due to SNC's past two senior projects, CASCADE[2] and KESSLER[1] (described in Sections 2.1 and 2.2) from years 2016-2018. CASCADE developed rigid body dynamics models in MATLAB, designed a robotic arm with five degrees of freedom (DOFs), and, using an external vision system, demonstrated success in capturing "active" CubeSats rotating about a single stable axis. KESSLER improved upon this design by developing a 7 DOF arm with an integrated vision system using a Kinect V2, capturing a scaled Iridium satellite by executing an open-loop arm path planning system. MEGACLAW will build upon these innovations to improve the vision system, software processing, and arm actuation efficiency in order to adjust the arm's path during capture execution using real-time feedback from the vision system. The lowest level of success for this mission will include the construction of ground support equipment (GSE) capable of holding a grappling target, as well as the arm, stationary. Furthermore, low-level success will be determined by the development of a closed loop system capable of continually identifying the debris and actuating the arm toward the best capture position, and around any obstacles presented by the grappling target, as a live response. For high-level success, see Specific Objectives (Section 3).

2. Previous Work

2.1. CASCADE

In collaboration with Sierra Nevada Corporation, the 2016-2017 Smead Aerospace Engineering Sciences Senior Projects team designed and built CASCADE, a **C**ubesat **A**ctivated **S**ystematic **CA**pture **DE**vice, along with a corresponding GSE setup. CASCADE consisted of a robotic arm and vision system with the purpose of identifying and capturing a rotating, free-floating object. The vision system included several IR cameras and a LIDAR system. Both systems were processed autonomously in LabVIEW. From this information, the kinematic state of the object was determined with respect to the capturing arm, and both the destination and path of the end-effector were computed.

2.2. KESSLER

In 2017-2018, another Aerospace Engineering project group built upon CASCADE's original design and system to implement an optical system in order to autonomously capture space debris. The **K**inesthetic **E**ngineered **S**olution to **S**pace **L**itter and **E**xhausted **R**esources, also known as KESSLER sought to actually grasp the object previously identified in the CASCADE project. Changes were made to both the image identification and the arm motion, and the group was ultimately successful in achieving an error of less than 1mm at a distance of 1 meter from the camera. This was achieved by changing the optics system to an XBOX Kinect camera and using MATLAB for visual processing. Additional changes were made to the control algorithms and the power of the actuators was tweaked for better control.

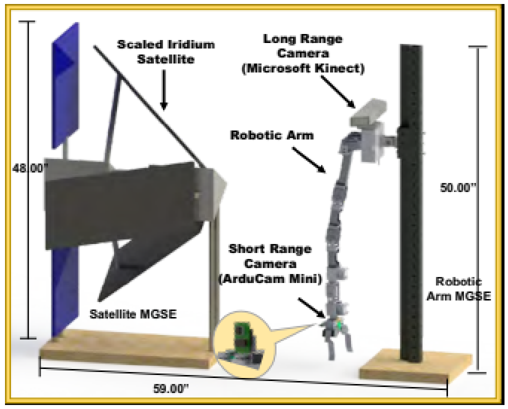

Figure 1. The original concept given for the KESSLER project

2.3. General Space Debris Collection Solutions

Apart from the efforts made by the aerospace engineering seniors in collaboration with SNC, many other private companies have begun to create their own solutions to removing space junk. One very exciting project is a system known as RemoveDEBRIS. RemoveDEBRIS was sent to the ISS this April onboard SpaceX's Falcon 9 rocket. The system will have 2 different mechanisms for collecting the junk, a rejectable harpoon to stab the object, or collection via a net. RemoveDEBRIS will also utilize lasers in order to track the desired object.

Another debris removal innovation comes from a Japanese company called "Astroscale". They have developed a satellite to track and create an orbital debris map. Using this map they then hope to launch ELSA (End of Life Service by Astroscale). ELSA plans on using magnets to collect debris in space, which is an interesting idea considering most spacecraft and satellite are constructed using titanium and aluminum, both of which do not exhibit magnetism. However it will be very exciting to see how ELSA progresses as time goes on.

Although the talk of space debris has quickly become an important problem to solve, there is still a lot of uncertainty towards what will actually work most effectively. Other possible ideas that have been popular throughout the discussion of space debris removal include, lasers to destroy the debris, satellites with sticky attachments, giant space trash cans, and even self destructing satellites. All of these ideas will help MEGACLAW build off of it's current design and improve the collection and elimination of space debris.

3. Specific Objectives

As discussed above, the motivation for this grappling arm design, to clear orbital debris, is of utmost importance to help protect future spacecrafts. While the previous group (KESSLER) developed a successful grappling mechanism and achieved their design requirements, the project operates under the simplifying assumption that the orbital debris was stationary relative to the grappling arm. As such, KESSLER implemented an open loop system to grapple the target object based on preliminary sensor data. Though the aforementioned design has its uses, the majority of orbital debris is characterized by some rotational and translational movement. As such, using an open-loop system is not optimal to serve the ultimate purpose of the problem statement.

In order to mitigate the effects of orbital debris, MEGACLAW will implement a closed-loop control system, in combination with a CrustCrawler robotic grappling arm, to track, approach, and capture a mock-up TBD satellite. The control system's closed-loop shall be dependent on sensor data collected by a TBD sensing system, from which the relative positions and orientations of the robotic arm's end-effector, as well as a given (TBD) grappling point, will be computed. Upon receiving the aforementioned state data from the sensing system, the control software package shall determine the most optimal path for the end effector to follow in order to reach the target's grappling point at a desired orientation and will command the arm to proceed along that path - until it receives updated positions from the sensor system (which shall collect new readings and update the control system at TBD rate) and modifies the path accordingly. Upon reaching the grappling point on the target, the end effector shall secure the target.

To more specifically define the scope of this project, two discrete areas are identified as crucial in measuring the project's success. Under each area, three measurable levels of success are set. If in one of these areas the project achieves, for example, level 3 success, but in the other area achieves only level 1 success, then the entire project will only be said to have reached level 1. The two areas for which success shall be quantified are as follows:

- The system's spatial sensing system, which shall operate in a closed-loop, such that (1) the onboard camera collects data at a frequency of TBD Hz, (2) identifies and tracks objects in its field of view (and at higher success levels, a special grapple point of predetermined TBD shape), and (3) output data to a control system that will determine an updated position for the end effector to move to in order to most efficiently rendezvous with the target.
- The grappling arm, which shall (1) receive input commands from control software based on positional data found, (2) actuate corresponding motion to approach object, and (3) ultimately grapple the object.

With these two discrete areas, levels of success were determined for each benchmark of the project. The resulting objectives and their levels of success are displayed below in Table 1.

	Closed Loop Sensing	**Arm Actuation**
Level 1 Success	Identify and report end-effector location at TBD rate	end-effector accurately responds to given controlled input
Level 2 Success	Identify and report grapple location and end-effector location at TBD rate	End-effector contacts with grapple point on object, at TBD speed, with a predetermined orientation as dictated by sensor system input
Level 3 Success	Identify, predict and report grapple location and end-effector location at TBD rate	Successful acquisition of target object

Table 1. Success Levels

4. Functional Requirements

4.1. Requirements

4.1.1. Grappling arm shall receive commands from the closed loop algorithm.

4.1.2. Grappling arm shall follow continuously updated commands given by closed-loop algorithm.

4.1.3. Control software package shall use feedback data to compute relative position points for end-effector pathing.

4.1.4. Ground support equipment shall be redesigned to minimize movement due to torque from the arm's actuation.

4.1.5. Grappling target used in system GSE shall have no translational or rotational motion. However, the control software shall be written such that these motions can be accounted for in the future.

4.1.6. All systems shall be operational in a 1G testing environment.

4.1.7. End-effector shall have ability to release object upon command.

4.1.8. Grappling arm shall avoid contact between debris and all of its components excluding end-effector.

4.1.9. Grappling arm shall avoid contact with host vehicle.

4.2. Concept of Operations

The task that MEGACLAW will help accomplish is shown in the Figure 2 CONOPS. A satellite will rendezvous with space debris, MEGACLAW will capture the space debris, and finally the client can either perform maintenance or de-orbit the debris. The capture phase of this task is the scope of the MEGACLAW project. It is assumed that the satellite has rendezvoused to a constant relative position and orientation to the space debris. The MEGACLAW project has not been tasked to perform operations after capturing the debris. In order to simplify the problem, the client has specified that the capture can be assumed to occur during a 30 minute eclipse in the orbit. This will require MEGACLAW to provide an external light source that will be known and provided to the closed loop software as compared to the changing natural lighting of the sun during orbit.

Figure 2. Big picture concept of operations

Within MEGACLAW's scope, the CONOPS is shown in Figure 3. The main task for this project is to develop a closed-loop algorithm to continuously compute a path for the CrustCrawler arm to follow to a given point on the target object to be grappled. The software flow diagram displays the basic logic of this algorithm. The sensors onboard will continuously detect the relative positions and orientations of the grapple point (GP) and arm end-effector (EE), and compute a path for the arm to follow. The arm will then capture the debris at the target grapple point.

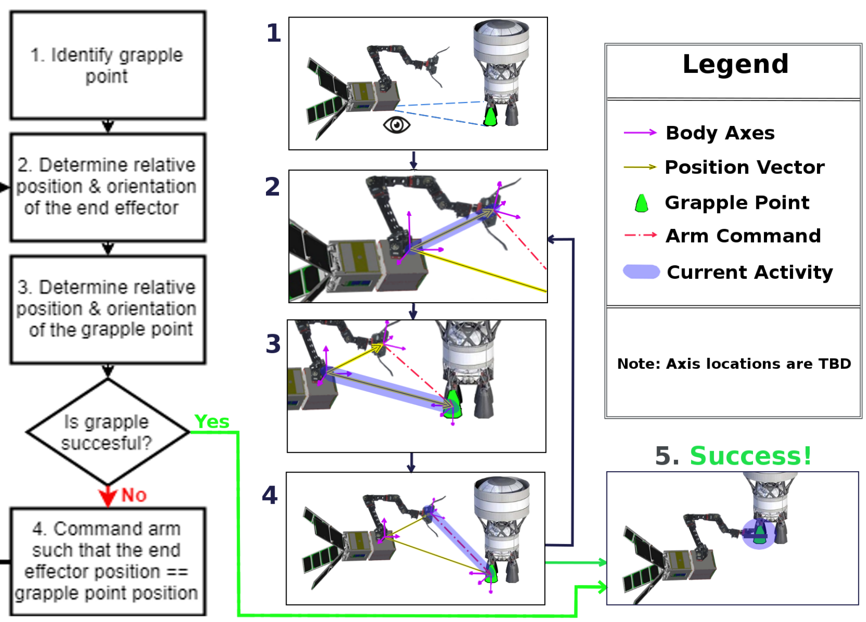

Figure 3. Concept of Operations

4.3. Functional Block Diagram

The FBD (Functional Block Diagram) shown in Figure 4 shows the functionality of the MEGACLAW system. The GSE hardware will include mounts for the CrustCrawler arm, target object, external lighting, and sensor packages. The arm and target object mounts will remain stationary. External lighting will provide a constant, known light source for the sensors. Sensors will send position and orientation data to the DAQ, which will communicate reference data to the CPU. Here, the closed-loop software will process said data, and compute a valid path for the arm to take to the target grapple point. Commands will be sent from the CPU to the DAQ. The DAQ will communicate these commands to the arm, which will move according to said commands until it has reached the target point, at which point it will capture the object. The closed loop software will complete this cycle at a TBD frequency to provide a continuously updated path to the arm, in order to improve upon the accuracy and flexibility of an open-loop control system.

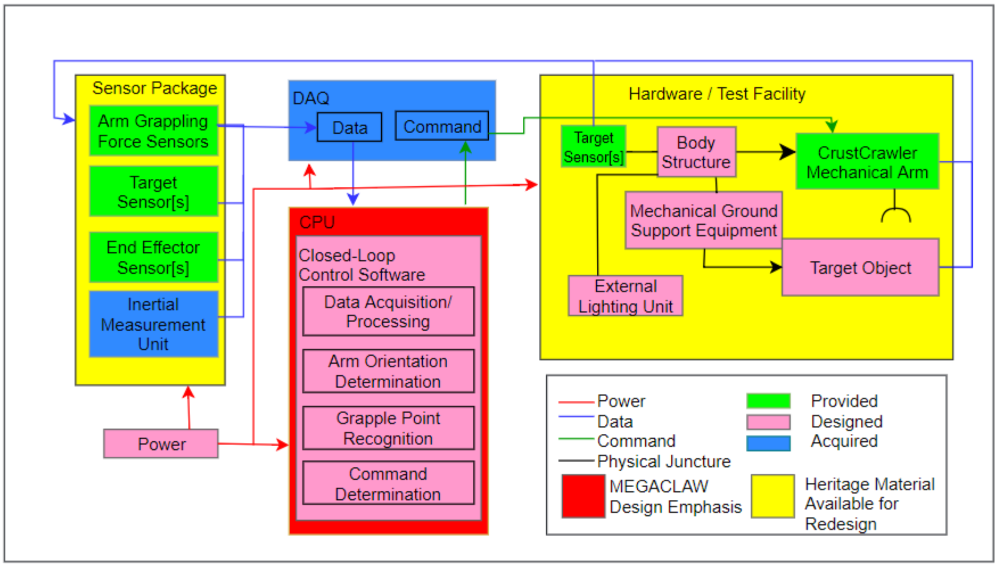

Figure 4. Functional Block Diagram

5. Critical Project Elements

The critical project elements have been determined as elements that are crucial for succeeding the aforementioned level 1 specific objectives. These objectives focus on closed loop feedback to control the robotic arm. The primary categories for the critical project elements are the grappling arm, control software, sensors, and GSE. These categories are further described in Table 2.

Critical Element	Details	Justification
Grappling Arm	Response to Closed-loop Feedback	Although KESSLER's CrustCrawler arm proved responsive to commands based on feedback system in an open loop, the mechanical system's response must accurately update the arm's course at a TBD rate, which may pose a challenge.
	Component Reliability	Project KESSLER had reliability issues with servo motors in the CrustCrawler arm. Should the servos or any of the existing components prove unreliable or functionally insufficient to fulfill the project's objectives, aspects of the arm may need to be redesigned and rebuilt, adding significant cost/complexity.
Control Software	Closed Loop Feedback	As implementing a closed-loop control system is the central aspect of this project, the control software package is a primary concern, especially given the team members' limited knowledge base of both control implementation and integration software.
Sensor Processing	Position of End-Effector	Given significant error accumulation throughout the CrustCrawler hardware in prior projects, the customer has suggested that the control loop be closed externally from the arm. As such, it shall be crucial to track the end-effector's position rather than relying on errant measurements based on hardware geometry.
	Position of Grappling Point	Along with end-effector position, accuracy of the grappling point's relative position must be sufficient for a successful grappling procedure.

Table 2. Critical Project Elements

6. Team Skills and Interests

Team Member	Skills and Interests	Critical / Primary Elements
Luke Beasley	MATLAB, SolidWorks, FEM Analysis, 3D Printing, STK, Mechanical and Structural Design, Systems Engineering	Grappling Arm, Ground Support Equipment
Joseph Beightol	Software Experience (MATLAB, C, Unix, Linux, LabVIEW), SolidWorks experience, Design, STK and GMAT experience. Interested in manufacturing and software development.	Control Software, Sensor Processing
Benjamin Elsaesser	Software (Python, MATLAB, C, Bash, ROS, C++, Arduino), circuit design, testing. Interested in control systems and estimation.	Grappling Arm, Control Software
Sheridan Godfrey	3D Printing, 3D Scanning, Prototyping, CAD (SolidWorks and Onshape), MATLAB, Manufacturing, Design, Testing, Engineering Management, Interest in electronics and optics	Grappling Arm and Sensor Processing
Caleb Inglis	Software (MATLAB, LabVIEW, C, C++, Arduino, some Python), Engineering Management, Technical Writing; Interest in Software, Control Systems, Design, and Manufacturing	Control Software, Grappling Arm, Ground Support Equipment
Jack Isbill	Software (MATLAB, VBA, Python, SolidWorks, LabVIEW), Engineering Management, Interests in Propulsion and Dynamic Environments	Sensor Processing
Andy Kain	Software (MATLAB, LabVIEW, SolidWorks, Altium, C, C++), 3D printing (Lulzbot, Markforged), 3D scanning (Picza), FEM, and circuit design.	Sensor Processing, Grappling Arm
Cedric Leedy	Software (MATLAB, LabVIEW, SolidWorks), 3D-Printing, Design, and Manufacturing. Interested in Software Development and Systems Engineering.	Grappling Arm and Sensor Processing
Christopher Leighton	Software (MATLAB, C, C++, Python, Arduino), enrolled in Microavionics, interest in control systems and 3D modeling.	Sensor Processing, Control Software
Daniel Mastick	Optics, Software Development (MATLAB, C, Python, Bash) Manufacturing	Sensor Processing
Bailey Topp	Software (MATLAB, LabVIEW, C), Technical Writing, Financial Analytics and Statistics, Quality Assurance. Interested in Programming Controls Systems in Python, C	Control Software, Grappling Arm

7. Resources

Critical Project Element[s]	Resource[s] - Source[s]
Grappling Arm	CrustCrawler hardware (multiple sets) - SNC, actuators
Control Software	ITLL stations/shops/machinery, Dr. Bradley Hayes, Dr. Nikolaus Correll, Trudy Schwartz and Bobby Hodgkinson
Integration Software	ITLL stations/shops/machinery, heritage software - KESSLER and CASCADE
Sensors	XBOX Kinect - SNC, Dr. Bradley Hayes, Dr. Nikolaus Correll, Trudy Schwartz and Bobby Hodgkinson
GSE	Prototype GSE (hardware) - SNC, testing environment location TBD

References

[1] Alvarenga, Glenda, et al. KESSLER Spring Final Review. Aerospace Engineering Sciences Senior Design Projects, University of Colorado Boulder

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[5] Tech Times: *ESA Calls for Sustainable Future in Space, Cites Growing Problem of Orbital Debris*
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