University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018
Project Definition Document
Kinesthetic Engineered Solution to Space Litter and Exhausted Resources

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Approvals

	Name	Affiliation	Approved	Date
Customer	Josh Stamps	Sierra Nevada Corporation		9/18/17
Course Coordinator	Dale Lawrence	CU/ AES		

Project Customers

Name: Josh Stamps Email: josh.stamps@sncorp.com Phone: 720-407-3178

Team Members

Name: Glenda Alvarenga Email: glal4280@colorado.edu Phone: 720-277-6053	Name: Abdiel Agramonte-Moreno Email: abag5006@colorado.edu Phone: 702-321-4546
Name: Thanh Cong Bui Email: thbu0442@colorado.edu Phone: 303-547-614	Name: Christopher Choate Email: Christopher.Choate@colorado.edu Phone: 509-951-3118
Name: Lauren Darling Email: Lauren.Darling@colorado.edu Phone: 817-676-6154	Name: Sergey Derevyanko Email: sede1371@colorado.edu Phone: 720-300-1107
Name: Cassidy Hawthorne Email: Cassidy.hawthorne@colorado.edu Phone: 330-242-1411	Name: Abigail Johnson Email: abjo5441@colorado.edu Phone: 720-883-6608
Name: Nick Thurmes Email: nith2593@colorado.edu Phone: 720-600-4666	Name: Jannine Vela Email: jave9878@colorado.edu Phone: 720-448-4416
Name: Taylor Way Email: taylor.way@colorado.edu Phone: 720-290-8211	

I. Problem Statement

A. Project Motivation

In recent years the Low Earth Orbit (LEO) environment has been subjected to an increase in orbital debris, which is predicted to triple by 2030[1]. This percentage is continuously increasing due to various reasons, including: pieces of satellite components that have broken off or become detached, satellites without propulsion at the end of their mission life, disabled/malfunctioning satellites, launch vehicle upper stages, and other miscellaneous man-made space junk. In April of 2016, a small piece of orbital debris impacted and cracked a window on the International Space Station (ISS), which had a crew of six on-board[2]. Although the damage caused by this debris was not catastrophic, it demonstrates how orbital debris can jeopardize high cost assets as well as the invaluable lives of astronauts.

B. Project Overview

Sierra Nevada Corporation (SNC), in collaboration with the Ann H.J Smead Aerospace Engineering Department undergraduate senior design team at the University of Colorado at Boulder, seeks to address this issue by developing technologies that demonstrate the capability to remove space debris using a low-cost small satellite with a robotic arm. The concept of this integrated robotic arm satellite has three operational objectives: (1) perform rendezvous with the space debris, (2) grasp the space debris with the robotic arm, and (3) use one of several methods to de-orbit the space debris or move the debris to a different orbit. The Kinesthetic Engineered Solution to Space Litter and Exhausted Resources (KESSLER) project will address the second operational objective. A successful project will demonstrate grappling a simulated space-debris object (spacecraft) using a 6-degree-of-freedom (DOF) robotic arm and visual imagery to identify a physical feature on the spacecraft to grapple and predict an approach path to the feature. In particular, this project will be aiming to grapple a small satellite with sturdy physical features (i.e. electronics box, star tracker, and antennas), each of which is a type of the many 4000 objects in LEO whose size is several centimeters. [3] The final product will be another step towards achieving low-cost in-orbit servicing, docking, and space cleaning.

This project is a follow-on effort from the 2016-2017 senior design project CASCADE, which demonstrated the capability to grapple a spinning satellite using a five degree-of-freedom Crustcrawler arm, as well as an external imaging facility to track the dynamics of the spinning satellite (See Sec. 2.2). KESSLER will improve the existing range of motion of the arm, as well as implement a visual imaging module integrated to the arm system itself (to remove the need of the imaging facility), in order to identify both the target location to grapple as well as predict and execute a path to grapple the target location (while avoiding undesired collisions with the spacecraft). This project will be conducted in a controlled lab space at the University of Colorado (1g, non-vacuum environment) and will not require space-qualified hardware or standards.

II. Previous Work

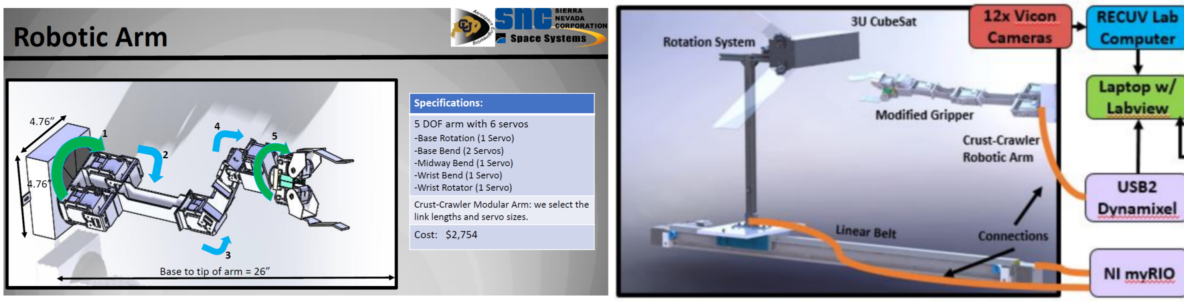
A. Industry Efforts

Satellite rendezvous-and-capture is a need in the orbital environment to reduce risk of collisions with debris and to repair, refuel, or re-orient spacecraft. The Restore-L spacecraft is set to launch in mid-2020. This spacecraft is intended for satellite servicing; however, it also involves the autonomous rendezvous and grappling of satellites[4]. This design will use two arms, each with seven degrees-of-freedom, including a "three-axis shoulder, a pitch actuator at the elbow, and a three-axis spherical wrist"[5]. While not explicitly stated on the Satellite Servicing Projects Division website, it appears in the Restore-L Concept of Operations video that one arm is used to grasp the satellite, while the other arm is used to perform maintenance on the satellite[6]. While a second arm may be useful for maintenance, it is not necessary for grasping or grappling a satellite, which is a focus of KESSLER (the other is the vision system).

Little information is available about the vision system of the Restore-L. However, a precursor to the Restore-L is Raven. "Raven features a visible light camera, an infrared camera and a 3D flash LiDAR sensor on a pan-tilt gimbal able to independently track ISS Visiting Vehicles..."[7]. It has been indicated that this will be similar for the Restore-L, and algorithms will involve range, bearing, and pose to rendezvous and grasp satellites[8]. Further information appears to be unavailable. However, the precursor to the Raven was the Argon module, which "runs the algorithms that match the data against pre-loaded software models of the target" in order to track targets[9]. This method may be useful for this project.

B. Design Heritage: CASCADE

As mentioned in Section 1, the KESSLER project is building upon the heritage efforts of the CASCADE project. The satellite-capture system included an arm mechanism with 5 degrees of freedom (DOF), a vision system, and the autonomous capture software. The vision system includes VICON, a collection of infrared cameras and software that continuously feed inertial position and Euler angles of the targets in the field of view to LabView, and a Light Detection and Ranging (LIDAR) sensor that obtains proximity data of the CubeSat. LabView then determines the axis of rotation (AOR) of the target, which is vital for the end-effector (grappler) to successfully capture the CubeSat. The vision data from the sensors were inputs to an algorithm that calculates the desired position of the end-effector. Currently, the arm is capable of capturing a rotating 3U CubeSat that is placed at a flushed position to the plane of the grappler. Figure 1 shows both the DOF achieved by CASCADE, as well as an overview of the primary components integrated to build the CRST system.



(a) Crustcrawler Arm Indicating the 5 DOF for CASCADE

(b) The CASCADE CRST System Primary Components

Figure 1: CASCADE Assembly Overview

For KESSLER, recognition of predefined grappling features on the target as well as the an algorithm for predicting a path to execute will be developed. The Artificial Intelligence (AI) as well as the mechanism will be expanded to grapple features at an angle that is not flush with the plane of the grappler (additional DOF). The sensor package to recognize the grappling features will utilize Red Green Blue (RGB) cameras in addition to the previously integrated LIDAR, this will enable the test-bed to no longer require the VICON lab to identify the grappling location.

III. Specific Objectives

As discussed in Sec. 1, the purpose of this project is to address the second operational objective of SNC, which is to grasp the space debris with a robotic arm. Two driving assumptions have been defined that will bound the function of this project, as seen below:

1. The target object is in front and within reach of the robotic arm; this entails that this scenario is valid if the target object and the chase vehicle (spacecraft with arm) are in the same orbit and in proximity to each other.
2. The target object is stationary with respect to the robotic arm; this entails that the scenario is valid if the target object is 3-axis stabilized.

With this entry criteria, the primary objectives of the project are to: (1) take visual data of the target object, (2) identify pre-defined grappling features (PGFs) on the target object with an unknown orientation and a prediction path to the target, and (3) autonomously execute commands via the robotic arm based on processed visual data. Objectives (1) and (2) are defined by demonstrating the ability to recognize a PGF among several on a stationary object with an unknown orientation. Objective (3) is defined by autonomously grappling the object with the robotic manipulator arm designed previously.

SNC has asked for more specific objectives based on the work previously done by CASCADE; this can be seen below:

- Modification of the existing robotic arm to include additional degrees of freedom necessary to grapple from a variety of approach angles.
- Incorporation of an RGB sensor into the existing machine vision system that currently uses only a LIDAR distance sensor.
- Incorporation of machine learning algorithms to enable autonomous recognition of the designated grappling feature.

The additional DOF has initially been chosen to be a rotation capability at the midway bend (see Figure 1.a for reference) - this will enable the arm to grapple objects that are not in the same plane as the base plate. This will be further investigated after creating trade studies for potential solutions.

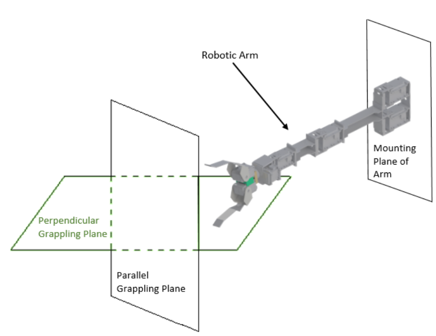


Figure 2: Grappling Plane Definitions

Based on the needs of the customer, the PGFs will be defined as physical structural items that protrude on the spacecraft that can be used to grapple (these will be simulated). Table 1 below defined the various levels of success for the three major aspects of this project. Note that the term "location command" refers to the inertial positions and Euler Angles of the spacecraft feature. Planes are defined to be with respect to the mounting of the arm versus the plane of the end-effector (see Figure 2 to view mounting with respect to the arm's end-effector, this is an example of them being parallel). Perpendicular planes would be any plane that intersects the normal plane (i.e. Figure 2 only shows one perpendicular case). The remaining orientations are what are considered angled planes.

Table 1: Preliminary Level Definitions

	Process Visual Data	**Command Definition**	**Command Execution**
Level 1 Success	Identification of target satellite.	Define perimeter of target spacecraft in parallel plane (+- TBD cm)	Trace perimeter of target spacecraft via the end-effector of the arm. (Demonstrate ROM)
Level 2 Success	Identify grappling feature recognition on target satellite.	Define grappling location on feature to within +- TBD cm	Grapple feature in parallel plane.
Level 3 Success	Identify collision features on target satellite.	Identify optimal grappling location and path to within +- TBD cm	Grapple feature in perpendicular plane. (Demonstrate additional ROM)

IV. Functional Requirements

A. Functionality

Once mounted on to the Mechanical Ground Support Equipment (MGSE), the Crustcrawler arm will be supported on a platform allowing the mobility for six degrees of freedom (DOF) in a 1G environment. Power will be provided to both the central processing unit (CPU) and electrical components mounted on the fixture, including spacial positioning and thermal sensors located on the end-effector of the arm. A user will initiate the Attitude Determination and Control System (ADCS) algorithm run on a PC to initiate a TBD range/depth sensor to determine the proximity of the mechanical arm to a defined object in the line of sight of the TBD camera(s), as well as the use of an inertial measurement unit (IMU) to determine its orientation with respect to the object. The algorithm will use the cameras mounted on the mechanical arm to capture images of the object within a TBD range using on-board depth perception and positioning sensors to identify physical features common among satellites in LEO.

The positioning data and sensors relaying the health and status of the mechanical arm will be collected using the National Instruments myRio Data Acquisition System (DAQ) and relayed back to the CPU for data processing. The algorithm will determine if said features are within the limitations of the mechanical arm to acquire and send commands to the arm to rotate accordingly. The algorithm will continue to take images and relay commands to the arm until it is within the bounds of grappling the feature. The algorithm will command the motor drivers to actuate and rotate the mechanical arm to a nominal grappling position and close for capture. Force sensors on will relay information back to the CPU and the algorithm will verify successful capture. Additionally a thermal control system will be included due to the lessons learned from CASCADE with regards to the actuators overheating during operation of the arm. A depiction of this process is shown in Figure 3.

1. Functional Requirements

Functional requirements are identified as follows:
1. Robotic arm shall utilize visual processing system to locate target object in its line of sight within a TBD distance.
2.The robotic arm shall identify at least one pre-selected grappling feature on target object.
3. Positioning algorithm shall provide a path for target location to capture target object.
4. The robotic arm shall autonomously grasp feature on target object.

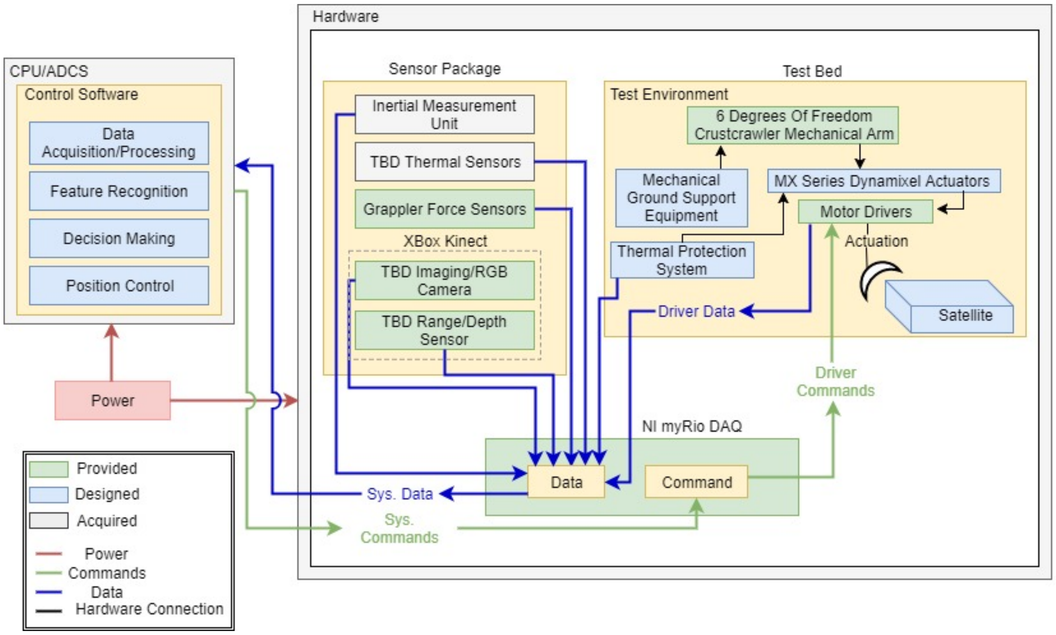


Figure 3: Functional Block Diagram

B. Concept of Operations

There are three steps needed in order to remove space debris from orbit: (1) perform rendezvous with the space debris, (2) grasp the space debris with the robotic arm, and (3) perform maneuver to de-orbit space debris. This general CONOPS is found in Figure 4.

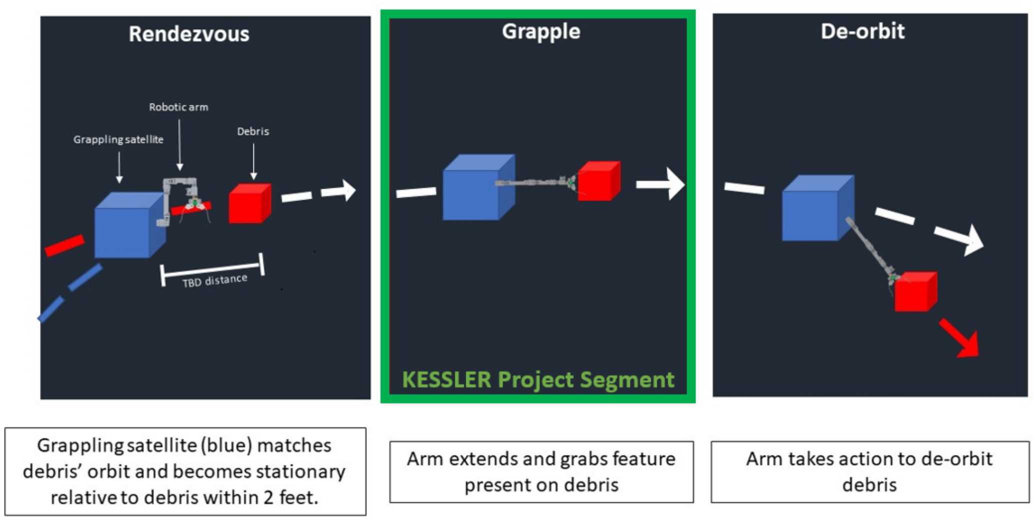


Figure 4: Mission Overview: KESSLER will address the Grappling Segment

For this project, only the second objective will be addressed. There are multiple scenarios that need to be taken into account. Since one specific feature will be grappled, and the orientation of the space debris is unknown, the arm must be able handle a case in which the feature is initially out of sight of the camera.

In the event that the feature is on the part of the debris which faces the robotic arm, the arm will run a visual scan, identify the desired feature, decide the best path for the end-effector to get there, and then grapple the object at that feature. A software logic flow chart can be seen in the appendix.

If the feature is not seen on the first visual scan, a search algorithm is run which moves the end-effector around about 90 degrees to the right or left (depending on the shape of the debris). If the feature is found and it is accessible to the grappling arm it will be grabbed. If the feature is still not found or it is too hard to reach with the arm, the arm will suggest to be moved 90 degrees with respect to the satellite (depending on the location of the feature and shape of the debris). This is shown below as Figure 5.

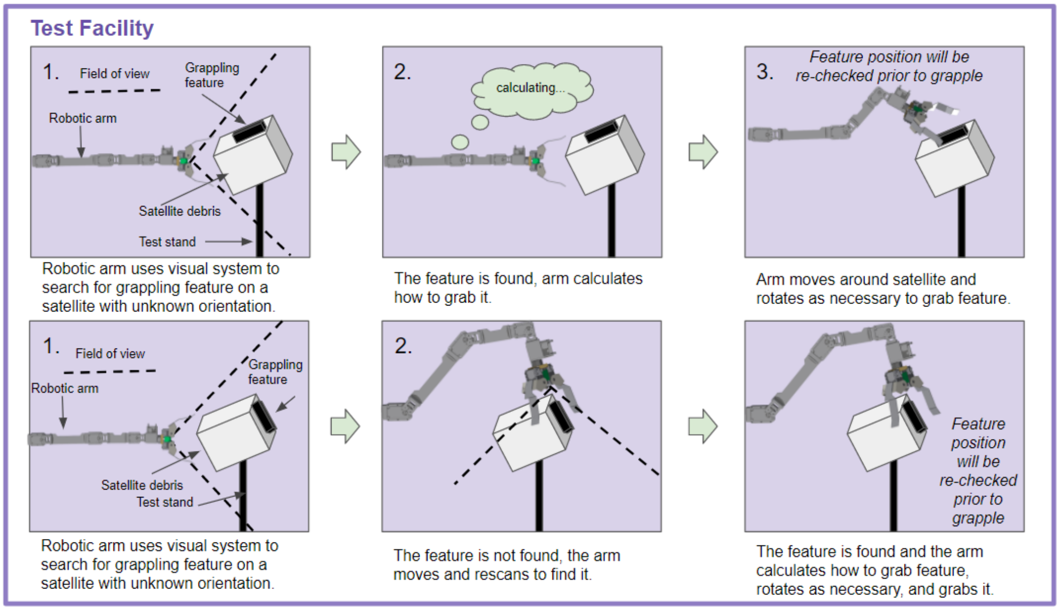


Figure 5: KESSLER Ground Based Concept of Operations

V. Critical Project Elements

KESSLER is comprised of 4 main Critical Project Elements (CPEs) which enable at the least Level 1 Success. The Robotic Arm (RA) and Image Processing (IP) aspects of the project are key constraints required of the system.

CPE 1: Mechanical (RA) - The arm must demonstrate its mechanical capability to grapple a stationary object in from a pre-determined feature and hold on to said object until it is instructed to let go. The arm operates with 6 DOF in order to maximize its range of capture so that it may grab features on the object at arbitrary angles. The arm will also be able to re-position to get more complete data and recognize features that may not be visible from the initial position.

CPE 2: Control Software (RA): The control software will have two major tasks as the project progresses. The first will be to resturn the arm to working condition by handling repair and integration of code into the arm. The second is to add on to the existing software an understanding of the position of obstacles and pathing that will allow the arm to avoid it.

CPE 2.1: Arm Manipulation It was brought up that a major issue with using the system acquired from the CASCADE group is that the current software running with the arm has inherent issues when commanding it to accuate from a tilted position. This is something that will have to be addressed while getting the arm into functioning condition. Additionaly it may need to be revisited later once the Feature Recognition Software has been developed in the event that there are any hiccups in integration.

CPE 2.2: Pathing of the Arm In addition to repairing any issues that may exist with the pre-existing software, new software will need to be developed to help the arm understand that it cannot always directly path to the point of interest but in some scenarios will need to have a basic awareness of where it is in respects to various obstacles it will need to avoid, such as Solar Panels on the side of the target spacecraft. It is not suspected that developing the recognition of these objects and avoidance of them is expected to be difficult and will require a fair amount of the effort in this section.

CPE 3: Electrical (RA/IP): This element is comprised of key support electrical equipment as well as any necessary electrical design required for the image processing subsystem. Key electrical harness, connections, and critical electrically driven components that take command input from software and actuate the desired motion (i.e. motor drivers, motors, etc.). A significant challenge of this system is the flex cable design which contains all electrical wiring throughout the arm and must support the ROM of the arm. Additionally, if the image processing subsystem requires high-speed image processing capabilities on a micro-controller/processor this may require custom designed hardware and/or COTs electrical interface control.

CPE 4: Feature Recognition (IP): RGB visual sensor(s) will image and recognize key features on an object. This encompasses key imaging sensor (i.e. camera(s)), image sensor support equipment (i.e. image processor board), and image processing software. It will determine the location of a feature to be grappled and pass this data to the Control Software.

VI. Team Skills and Interests

Critical Project Element	Team Members and Associated Skills/Interests
Mechanical (RA)	• **Abdiel Agramonte-Moreno**: Previous experience in mechanical design of robotic arms and CubeSats, SolidWorks experience. • **Christopher Choate**: UAS design, test and manufacturing, software, SolidWorks and ANSYS experience. • **Jannine Vela**: Previous experience in mechanical design, manufacturing, integration and test on small satellites. SolidWorks experience. • **Taylor Way**: Interest in electronics with relevant coursework in progress, experience with software (Matlab, C, assembly) and SolidWorks.
Control Software (RA)	• **Abby Johnson**: Software development, integration and test for flight software. Experience with virtual simulation testing, hardware/software integration, and fault detection, identification, and response algorithms. • **Cong Bui**: Interest in controls. Experience with test procedures,lab operations, software and electronics integration. • **Sergey Derevyanko**: CSCI classes: Data Structures, Discrete Structures, Currently in Algorithms. Video game development. • **Nick Thurmes**: Significant experience in Python, experience in C/C++, experience in microcontrollers, interest in control systems
Electrical (RA)	• **Lauren Darling**: Minor in Electrical Engineering and Astrophysics. Experience with configuration management, design engineering process, customer consulting. • **Taylor Way**: Interest in electronics with relevant coursework in progress, experience with software (Matlab, C, assembly) and SolidWorks. • **Cong Bui**: Experience with test procedures,lab operations, software and electronics integration. • **Sergey Derevyanko**: CSCI classes: Data Structures, Discrete Structures, Currently in Algorithms. Video game development.
Feature Recognition (IP)	• **Cassidy Hawthorne**: Previous and current experience in ADCS design and test, interest in algorithms (APPM minor), experience with Altium Designer, software experience (C, C++, Matlab, assembly). • **Jannine Vela**: Interest in learning about image processing with some software experience in C and C++ • **Glenda Alvarenga**:Interest in learning about image processing, computer science minor complete (Matlab, C, C++), some embedded systems programming experience, experience with Altium Designer.

VII. Resources

Critical Project Element	Resources Needed	Resources Available
Mechanical (RA)	Access to previous designs and relevant test results. SolidWorks (or similar) CAD Design software, manufacturing facilities, and test-bed compatible location	Aerospace Machine Shop (staff and equipment), ITLL Machine Shop (staff and equipment), SolidWorks Student License, CASCADE Team Members,
Control Software (RA)	Software from previous design, workstations compatible with previous environment, control theory mentoring	Professors: Nikolaus Correll, Dale Lawrence, Jacob Segil, Eric Frew, Hanspeter Schaub
Electrical (RA)	Electronics lab space, access to Altium Designer or similar PCB design software	ASEN Electronics Lab, ITLL Electronics Lab, Professors/Staff: Tim May, Bobby Hodgkinson, Trudy Schwartz, Robert Marshall, Dennis Akos
Feature Recognition (IP)	Test-bed compatible location (precise imaging for feature characterization)	VICON Lab, Professors/Staff: William Emery, Dallas S. Masters, Albin Gasiewski, John Crimaldi, Carol Cogswell

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VIII. Appendix

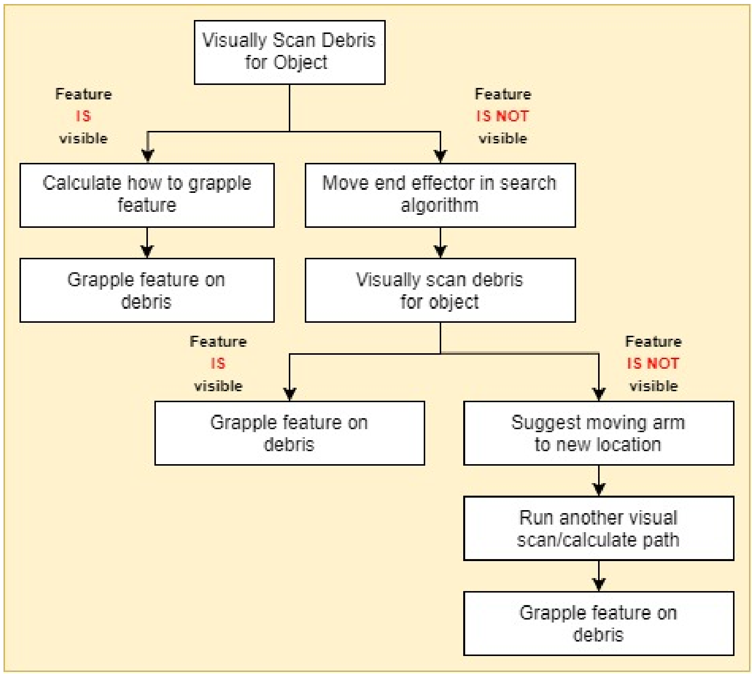

Figure 6: KESSLER Preliminary Software Logic Flow Diagram