Manufacturing Status Review
ASEN 4018 Spring 2018

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Agenda

- Overview
  - Project Purpose & Objectives
  - Baseline Design & Functionality
  - Critical Project Elements & Design Updates from Fall 2017
- Schedule
- Manufacturing
  - Hardware: Mechanical/Electrical
  - Software: Controls/Visual Processing
- Budget
Project Overview
Project Purpose

Amount of orbital debris is set to triple by 2030 (More than 500,000 in orbit today). Consists of:

- Pieces of satellite components
- Satellites at EOL
- Malfunctioning satellites

Project Motivation

Sierra Nevada Corporation:

- ‘Grappling’ feature recognition with an RGB sensor
- Autonomously capture feature with robotic manipulator arm
Project Statement

The KESSLER project will design a system that utilizes visual processing and a robotic arm to autonomously capture space debris. This project will be developed using heritage hardware from the CASCADE capstone project.

<table>
<thead>
<tr>
<th>Level</th>
<th>Shortened Description</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Identify Satellite, articulate arm to closest point on satellite</td>
</tr>
<tr>
<td>2</td>
<td>Identify features on satellite, capture feature via robotic arm</td>
</tr>
<tr>
<td>3</td>
<td>Identify keep out zone, articulate arm on collision avoidance path and capture feature.</td>
</tr>
</tbody>
</table>
Concept of Operations

Baseline Design

0. Demonstration Initiation
Robotic arm positioned in a neutral position and subjected to uniform lighting conditions.
Concept of Operations

1. Identification of Feature

Kinect takes primary image and identifies a feature in Field of View (FOV).
3. Primary Positioning

Robotic arm actuates to the relative position and orientation of the predetermined grappling feature (PGF)
4. Secondary Positioning

- ArduCam Mini takes secondary images to fine tune position of robotic arm
- Robotic arm actuates to the adjusted position and orientation of the PGF
Concept of Operations

5. Capture

Control software commands robotic claw to close on and capture PGF.
Software Flow Diagram

Start → Visual Processing → Controls → End

Visual Processing

Image Acquisition → Image Processing → Location Matching → Location and Orientation Formatting

Controls

Path Planning → Path Instruction Conversion → Execute Path → Execute Grapple → Verification


02/05/2018

KESSLER Manufacturing Status Review
Software Flow

**Software Flow Diagram**

- **Start** → **Visual Processing** → **Controls** → **End**

**Visual Processing**

- **Image Acquisition** → **Image Processing** → **Location Matching** → **Location and Orientation Formatting**

**Controls**

- **Path Planning** → **Path Instruction Conversion** → **Execute Path** → **Execute Grapple** → **Verification**
Critical Project Elements Overview

Three Critical Project Elements

- CPE 1: Feature Recognition
  - Addresses Objectives 1 and 2
- CPE 2: Control Systems
  - Addresses Objective 3 and 4
- CPE 3: Robotic Arm
  - Addresses Objectives 4

KESSLER Project Objectives

1. Take visual data confirming the target object is within FOV.
2. Identify pre-defined grappling feature.
3. Determine prediction path to feature location.
4. Autonomously capture the feature via robotic arm
Updates Since CDR/FFR

- Technical
  - KESSLER will not build a VICON-like system, currently coordinating with on-site VICONTab for access
  - Visual Processing has a new method for feature detection (will be discussed further)
  - Controls has decoupled path planning and trajectory execution (will be discussed further)

- Monetary
  - Robotic Arm (mechanical & electrical) components shipped
  - Satellite Model & MGSE components ordered
  - Visual Processing components delivered

- Logistical
  - Two week schedule delay in manufacturing & hardware-based unit testing (circumvented with initial schedule margin, with margin still remaining)
Project Schedule
KESSLER Manufacturing Status Review

Course Deliverables
- Financial
- Electrical
- Mechanical
- Visual Processing
- Controls
- Multiple Subsystems
- Breaks

~1.5 wk Procurement Delay

~4 day delay after re-baseline

Part Procurement, Ground Support Equipment, Manufacturing

Original Schedule is planned with two week margin.
KESSLER Manufacturing Status Review

Course Deliverables
- Financial
- Electrical
- Mechanical
- Visual Processing
- Controls
- Multiple Subsystems
- Breaks

Machining Ends

~1.5 wk Procurement Delay

Hardware components, Software units

~4 day delay after re-baseline

AIAA Abs.

TRR

Machining Ends
KESSLER Manufacturing Status Review

Course Deliverables
Financial
Electrical
Mechanical
Visual Processing
Controls
Multiple Subsystems
Breaks

~1.5 wk Procurement Delay

AIAA Abs.
Machining Ends
Hardware components, Software units

TRR

MSR

~4 day delay after re-baseline
KESSLER Manufacturing Status Review

Course Deliverables
- Financial
- Electrical
- Mechanical
- Visual Processing
- Controls
- Multiple Subsystems
- Breaks

AIAA Abs.
Machining Ends

~1.5 wk Procurement Delay
~4 day delay after re-baseline

Subsystem specific component/unit integration

Motor Aliveness
Spec Torque Test
Kinect Functionality
Secondary Camera Functionality
Control Loop
Path Planning
ROS Data (ctrl)
Object Detection
Object Location Determination
ROS Data (visual processing)

Subsystem Testing
- Robotic Arm Spec Torque
- Robotic Arm Plane Sweep
- Unit Integration (ctrl)
- Unit Integration (visual processing)
- TRR
Current Schedule is planned with 1.5 week margin.

- 1 week net margin
- 0.5 week conservative scheduling for integration
- Spring Break not counted but usable time (extra week)
System Status Overview

KESSLER efforts are split between Hardware & Software

1/3 Hardware
- **Electrical**: Robotic arm actuators, visual processing sensor interface, electrical ground support equipment.
- **Mechanical**: Robotic arm, mechanical ground support equipment, and simulated satellite.

2/3 Software
- **Visual Processing**: Identification of satellite and grappling feature. Sends position, orientation, and satellite 3D point cloud.
- **Controls**: Path planning and executing robotic arm control.

Subsystem Level of Effort

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02/05/2018
Hardware Status Overview

**KESSLER efforts are split between Hardware & Software**

### Mechanical
- **20% Scale Iridium Satellite**
- **Iridium Satellite**
- **Arm addition/brackets**
- **Robotic Arm MGSE (stand)**
- **Iridium Satellite MGSE (stand)**

### Electrical
- **Actuator Characterization**
- **Arm Assembly Harnessing**
- **Electrical Ground Support Equipment**
- **Secondary Camera Interface Software**
- **Testbed 5**

**Subsystem Level of Effort**

- **1/3 Hardware**
  - **Mechanical**
  - **Visual Proc.**
  - **Controls**

- **2/3 Software**

**Project Overview**

- **Schedule**
- **Mech.**
- **Elec.**
- **Software: Controls**
- **Software: Visual**
- **Budget**

02/05/2018
Manufacturing: Hardware Mechanical
# Mechanical: System Overview

<table>
<thead>
<tr>
<th>Category</th>
<th>Finish</th>
<th>Status</th>
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<tbody>
<tr>
<td>Iridium Satellite</td>
<td>2/16</td>
<td>Behind</td>
</tr>
<tr>
<td>Arm Additions</td>
<td>2/16</td>
<td>Early</td>
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<tr>
<td>Arm Stand</td>
<td>2/23</td>
<td>On Time</td>
</tr>
<tr>
<td>Satellite Stand</td>
<td>2/28</td>
<td>On Time</td>
</tr>
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</table>

**Project Overview**

- **Schedule**
- **Mech.**
- **Elec.**
- **Software: Controls**
- **Software: Visual**
- **Budget**

**Fig. 4 KESSLER Mechanical Design**

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
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<tbody>
<tr>
<td>Height</td>
<td>48.00”</td>
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<tr>
<td>Height</td>
<td>50.00”</td>
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<tr>
<td>Height</td>
<td>23.00”</td>
</tr>
<tr>
<td>Width</td>
<td>12.00”</td>
</tr>
<tr>
<td>Width</td>
<td>12.00”</td>
</tr>
<tr>
<td>Width</td>
<td>12.00”</td>
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</table>
Schedule Status: Behind
- Total Schedule Slip: 1 Week
- Requires Manufacturing in Parallel
- Recovery Date: February 19th

<table>
<thead>
<tr>
<th>Category</th>
<th>Task</th>
<th>Modeling Status</th>
<th>Build Status</th>
<th>Integration Status</th>
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</thead>
<tbody>
<tr>
<td>Model Iridium Satellite</td>
<td>Body</td>
<td>Procured, Machined, Assembled</td>
<td>Inspection, Delivery</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Panels</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Antenna</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>BUS</td>
<td></td>
<td></td>
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</table>
Hardware Status: Robotic Arm

Schedule Status: **Ahead**
- Total Schedule Slip: **0 Weeks**
- Donated Aluminum (AES Dept.)
- COTS Crust Crawler Parts

### Software:
- Controls
- Visual

### Budget

<table>
<thead>
<tr>
<th>Category</th>
<th>Task</th>
<th>Modeling</th>
<th>Build</th>
<th>Integration</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Design</td>
<td>CAD</td>
<td>Cam Model</td>
</tr>
<tr>
<td>Robotic Arm</td>
<td>Girders</td>
<td>✔️</td>
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<tr>
<td></td>
<td>Servos</td>
<td>✔️</td>
<td></td>
<td>✔️</td>
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<tr>
<td></td>
<td>ArduCam</td>
<td>✔️</td>
<td>✔️</td>
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<td>Turntable</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 6 Robotic Arm**

- Modeled
- Built
- Integrated

**Planned 02/05**

**02/05/2018**

KESSLER Manufacturing Status Review
Hardware Status: Support Stands

Schedule Status: **On Schedule**
- Total Schedule Slip: 0 Weeks
- Delivered Before Required Deadline
- Low Time Commitment

<table>
<thead>
<tr>
<th>Category</th>
<th>Task</th>
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<th>Build</th>
<th>Integration</th>
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<tr>
<td></td>
<td>Status</td>
<td>Design</td>
<td>CAD</td>
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<td>Arm Stand</td>
<td>Tubing</td>
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<td></td>
<td>Base</td>
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<tr>
<td>Satellite Stand</td>
<td>Rods</td>
<td></td>
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<td>Base</td>
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**Fig. 7 Support Stands**

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**Project Overview**
- **Schedule**
- **Mech.**
- **Elec.**
- **Software: Controls**
- **Software: Visual**
- **Budget**
Manufacturing: Hardware Electrical
Electrical: Overview

Electronics Hardware Housing and Integration

- ArduCAM / Microcontroller - purchased and received
- Kinect - heritage
- Arm Assembly - heritage, purchased but not received

<table>
<thead>
<tr>
<th>Category</th>
<th>Critical Path Requirement</th>
<th>Status</th>
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<tbody>
<tr>
<td>ArduCam &amp; MCU Assembly</td>
<td>Medium</td>
<td>On Schedule</td>
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<tr>
<td>Kinect</td>
<td>Low</td>
<td>On Schedule (Completed)</td>
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<tr>
<td>Arm Assembly Harnessing</td>
<td>High</td>
<td>On Schedule (Pending Early!)</td>
</tr>
<tr>
<td>Servo Torque Testing</td>
<td>Medium</td>
<td>On Schedule</td>
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</table>

Electrical Status

• Hardware Status: On Schedule

<table>
<thead>
<tr>
<th>Category</th>
<th>Design</th>
<th>Build</th>
<th>Integration</th>
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<tbody>
<tr>
<td>Arm Assembly</td>
<td>Power Line</td>
<td>Procured</td>
<td>Machined</td>
</tr>
<tr>
<td>ArduCam Assembly</td>
<td>Signal Line</td>
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<td>Machined</td>
</tr>
<tr>
<td></td>
<td>Harnessing</td>
<td></td>
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</table>

- Modelled
- Integrated
- Planned 02/05

• Software Status: On Schedule

<table>
<thead>
<tr>
<th>Category</th>
<th>Pseudo Code</th>
<th>Development</th>
<th>Integration</th>
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<tbody>
<tr>
<td>ArduCam Assembly</td>
<td>Flow</td>
<td>SPI</td>
<td>Assembled</td>
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<td></td>
<td>Open Source</td>
<td>I2C</td>
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</tr>
<tr>
<td></td>
<td>Skeleton</td>
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</table>

- Built
- Integrated
- Planned 02/05

Software Status Overview

**KESSLER efforts are split between Hardware & Software**

**Electrical**

**Mechanical**

**Vis. Proc.**

**Controls**

1/3 Hardware

2/3 Software

**Subsystem Level of Effort**

**Controls**

- Software Concept of Operations
- Robot workspace analysis
- Robot orientation analysis
- Robot mech./drifting error analysis
- Robot joint-link configuration
- Control loop/motion planning timing
- CAD to ROS Description

**Visual Processing**

- Image Capture
- Identify Satellite in FOV
- Identify features (RGB)
- Find feature orientation
- Identify Closest Feature
- Determine grappling location
- Send Data to Controls

**KESSLER Manufacturing Status Review**

- **Project Overview**
- **Schedule**
- **Mech.**
- **Elec.**
- **Software: Controls**
- **Software: Visual**
- **Budget**

02/05/2018
Controls System Overview

Path Planning
- Ports Data to Movelt! (x,y,z, yaw, pitch, roll, Arm Definitions)
- Movelt! Plans Path

Path Instruction Conversion
- Trajectory Execution Manager Ports Trajectory
- Control Manager
  - Position Controller
  - Torque Controller

Execution
- USB2Dynamixel
- Servos
- USB2Dynamixel

Joint State Log
- Position
- Velocity
- Torque

Legend
- Complete
- In Progress
- Not Applicable
- Data Transfer
- Command
- Hardware
Controls System Overview

- **ROS**: Software communication framework
- **MoveIt!**: Path planners & motion planners
Controls System Overview

- **Movelt!: Trajectory execution management**

Diagram:

- **Path Planning**
  - Ports Data to Movelt! (x,y,z, yaw, pitch, roll, Arm Definitions)
  - Movelt! Plans Path

- **Path Instruction Conversion**
  - Trajectory Execution Manager Ports Trajectory

- **Control Manager**
  - Position Controller
  - Torque Controller

Legend:

- Complete
- In Progress
- Not Applicable
Controls System Overview

- **Dynamixel Controller**
  - Libraries: Package and send R/W commands to servos
# Software Status

## Project Overview

<table>
<thead>
<tr>
<th>Task</th>
<th>Pseudocode</th>
<th>Development</th>
<th>Testing</th>
<th>Integration</th>
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<tbody>
<tr>
<td>Controller Manager</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Torque Controller</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Position Controller</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Test Framework</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROS Data Network</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Path Planning</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Controller Manager**
  - Pseudocode
  - Developed
  - Tested
  - Integrated
- **Torque Controller**
  - Pseudocode
  - Developed
  - Tested
  - Integrated
- **Position Controller**
  - Pseudocode
  - Developed
  - Tested
  - Integrated
- **Test Framework**
  - Pseudocode
  - Developed
  - Tested
  - Integrated
- **ROS Data Network**
  - Pseudocode
  - Developed
  - Tested
  - Integrated
- **Path Planning**
  - Pseudocode
  - Developed
  - Tested
  - Integrated

### Difficulty
- Most difficult: Controller Manager, Torque Controller, Position Controller, Test Framework, ROS Data Network, Path Planning
- Least difficult: None

### Status
- **Pseudocode**
- **Developed**
- **Tested**
- **Integrated**

### Planned 02/05

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**KESSLER Manufacturing Status Review**

02/05/2018

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• Ensure joint(s) trajectory within limits
• Listen to topics
• Ensure trajectory sequence
• Inspect output packets
• Operate servo
Able to assign controller to servo
Able to switch controller type for servo
Execute dummy trajectory

Legend:
Pseudocode  Developed  Tested  Not tested
• Execute planned trajectory
• Plan + execute trajectory based on visual data
Manufacturing: Visual Processing Software
Previous Software Flowchart

Take image with Kinect (2D and 3D) → Identify satellite in FOV with feature matching → Identify features by feature matching → Find location and orientation data

Reasoning for Change
• Features are too simple for feature detection
• Minimum of 3 points for match

Fig. 8: Feature matching with simple shape

[Red square] Denotes Change
[Yellow square] Denotes No Change
Updated Software Flowchart

1. Take image with Kinect (2D and 3D)
2. Identify satellite in FOV (using feature matching from fall 2017)
3. Identify features by color (set colors for features)
4. Use geometry to find feature orientation (plane detection in MATLAB)
5. Identify closest feature (3D point cloud and found features)
6. Locate specific point to grapple (center of smallest dimension of selected feature)
7. Package location and orientation for controls (toolbox in MATLAB)

Challenging Aspect

Denotes Complete
# Software Status

## Project Overview

<table>
<thead>
<tr>
<th>Task</th>
<th>Pseudocode</th>
<th>Development</th>
<th>Testing</th>
<th>Integration</th>
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<tbody>
<tr>
<td>Plane detection</td>
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<tr>
<td>Color matching</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Closest feature</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grapple location</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Identify satellite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Package Data</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Take image</td>
<td></td>
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</table>

**Most difficult**

- Plane detection
- Color matching
- Closest feature
- Grapple location
- Identify satellite
- Package Data
- Take image

**Least difficult**

**Pseudocode**

- Developed
- Tested
- Integrated

**03/19/2018**

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**KESSLER Manufacturing Status Review**

02/05/2018

**Budget**

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Color Matching

- Color attribute is a 3-dimensional matrix (Red, Green, Blue)
- Unique combination of RGB values correlates to a specific color
- Isolate certain RGB values to isolate features and recolor
  - Known colors for each feature

Solar Panels
- Antennas
- Bus structure

Fig. 9: Colored satellite model
Fig. 10: Color processed satellite model

---|---|---|---|---|---|---
20% Scale model of satellite
3D Point Cloud Feature Identification

- Map color image to 3D point cloud
- Concern: Low density point cloud impedes detailed feature analysis
- Mitigation: Larger model to increases clarity of picture

Fig. 11: Full colored point cloud with features

Fig. 12: Isolated satellite model point cloud
Challenges

- Mechanical delay postpones testing: one week delay
- Mitigation: Testing with 3D point cloud from CAD model: mitigated delay on 2/3/18, back on schedule

Fig. 13: Point cloud of small satellite model
Fig. 14: Point cloud from CAD model

Budget
### Summary & Current Status

#### Starting Budget
- **Budget** $5,000.00

#### Subsystem Costs

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Cost</th>
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<tbody>
<tr>
<td>Mechanical</td>
<td>$1,072.10</td>
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<tr>
<td>Electrical</td>
<td>$23.35</td>
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<tr>
<td>Test &amp; Safety</td>
<td>$742.16</td>
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<tr>
<td>Controls (Software)</td>
<td>$0.00</td>
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<tr>
<td>Visual Processing</td>
<td>$165.12</td>
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<tr>
<td>Misc.</td>
<td>$0.00</td>
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</table>

#### Total Cost
- **Total Cost** $2002.73

#### Remaining Budget
- **Remaining Budget** $2997.27

#### Current Status:
- Nearly all items ordered and/or delivered.

**Updated: 2/3/2018**

### Subsystem Status

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Overall Status</th>
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</thead>
<tbody>
<tr>
<td>Mechanical</td>
<td>All items delivered</td>
</tr>
<tr>
<td>Electrical</td>
<td>Most items available, non-pivotal on order.</td>
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<tr>
<td>Test &amp; Safety</td>
<td>Most items ordered, issues being resolved soon</td>
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<tr>
<td>Controls (Software)</td>
<td>N/A</td>
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<tr>
<td>Visual Processing</td>
<td>All items delivered</td>
</tr>
<tr>
<td>Misc.</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**Updated: 2/3/2018**

**Project Overview**

**Schedule**

**Mech.**

**Elec.**

**Software: Controls**

**Software: Visual**

**Budget**

**Updated: 2/3/2018**

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02/05/2018

**KESSLER Manufacturing Status Review**

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# Updated Cost Plan

<table>
<thead>
<tr>
<th>Subsystem Costs</th>
<th>Previously Spent</th>
<th>Potential Future Expenses</th>
<th>Notes on Potential Future Expenses</th>
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<tbody>
<tr>
<td>Mechanical</td>
<td>$1,072.10</td>
<td>$667.00 + $12.65 S&amp;H</td>
<td>MX-64T servo, MX-28T servo, AX-12A servos (2), 5” Girder, Misc. screws</td>
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<tr>
<td>Electrical</td>
<td>$0.00</td>
<td>$350.00</td>
<td>3 pin DXL cable set, casing, shrink wrap, wire, harnessing</td>
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<tr>
<td>Test &amp; Safety</td>
<td>$742.16</td>
<td>$20.00</td>
<td>Various fasteners</td>
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<td>Controls (Software)</td>
<td>$0.00</td>
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<td>Visual Processing</td>
<td>$165.12</td>
<td>$0.00</td>
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</tr>
<tr>
<td>Misc.</td>
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<td>$0.00</td>
<td></td>
</tr>
<tr>
<td><strong>Total Cost (Previous &amp; Future)</strong></td>
<td></td>
<td><strong>$3,029.03</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Remaining Budget</strong></td>
<td></td>
<td><strong>$1,970.97</strong></td>
<td></td>
</tr>
</tbody>
</table>

**STATUS:** 39% of allowed budget remaining

---

**Updated:** 2/3/2018
Thank You!

Questions?
Backup Links

- Section 1
- Section 2
- Section 3 Mechanical
- Section 3 Electrical
- Section 3 Controls
- Section 3 Visual Processing
- Section 4
Section 1
# Level 1 Success Criteria

**Table 1**: Level 1 Success Criteria

<table>
<thead>
<tr>
<th>Identification</th>
<th>Processing</th>
<th>Command Execution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identify at least two surfaces with varying depths in 3D space.</td>
<td>Identify the distance between the closest point of the satellite and the base of the robotic arm (± 4mm).</td>
<td>Demonstrate end-effector can move to closest point and actuate while facing the parallel plane.</td>
</tr>
</tbody>
</table>

*Three categories decoupled to ensure there is no dependency when meeting mission success criteria*
# Level 2 Success Criteria

**Table 2: Level 2 Success Criteria**

<table>
<thead>
<tr>
<th>Identification</th>
<th>Processing</th>
<th>Command Execution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identify grappling feature recognition on target satellite.</td>
<td>Determine grappling feature location and orientation to within ± 4mm &amp; ± 5 degrees.</td>
<td>Grapple feature in parallel plane to within ± 90 degree of end-effector roll angle.</td>
</tr>
</tbody>
</table>

*Three categories decoupled to ensure there is no dependency when meeting mission success criteria*
Level 3 Success Criteria

Table 3: Level 3 Success Criteria

<table>
<thead>
<tr>
<th>Identification</th>
<th>Processing</th>
<th>Command Execution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identify collision feature on target satellite.</td>
<td>Define keep-out zone to within ± 4mm of collision feature surface, and select grappling feature that causes the smallest collision risk.</td>
<td>Grapple feature in perpendicular plane (demonstrate additional Degree of Freedom).</td>
</tr>
</tbody>
</table>

*Three categories decoupled to ensure there is no dependency when meeting mission success criteria*
Project Purpose

- The simulated target satellite is modeled after the Iridium satellite series.
- Model will be 30% scale
- Features are:
  - Solar Panel Joints
  - Bus Structure Support
  - Antenna
- Features on Iridium are commonly found on other satellites as well.

Fig. 3 Iridium Satellite [3]
Project Description

**Project Assumptions**

- **Satellite Position:**
  - Object is in front of and within reach of robotic arm.

- **Satellite Dynamics:**
  - Object is stationary with respect to robotic arm.

- **Lighting Conditions:**
  - Operations are conducted during Sun-Soak orbital phase.

- **Standard Spacecraft Subsystems:**
  - Are not in scope of KESSLER project (e.g. ADCS, EPDS, CDH, COM).

- **Environment:**
  - Controlled test environment at 1G and atmosphere.

All assumptions are approved by project customer.
## Functional Requirements

<table>
<thead>
<tr>
<th>Req. ID</th>
<th>Requirement</th>
<th>Verification Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>The <strong>visual processing algorithm</strong> shall identify the surface of a satellite in the primary camera’s (RGB) field of view (FOV) and within the robotic arm’s reach.</td>
<td>Imaging Analysis &amp; Visual Inspection</td>
</tr>
<tr>
<td>F2</td>
<td>Control <strong>algorithm</strong> shall <strong>define a path</strong> to the location of a grappling feature.</td>
<td>Path Simulation (Experimental vs. Theoretical Location)</td>
</tr>
<tr>
<td>F3</td>
<td>Robotic arm shall <strong>autonomously navigate</strong> to at least one preselected grappling feature on the satellite.</td>
<td>Demonstration/Test</td>
</tr>
<tr>
<td>F4</td>
<td>The KESSLER system shall have a <strong>total mission</strong> time no greater than <strong>53 minutes</strong>.</td>
<td>Timing Analysis</td>
</tr>
<tr>
<td>F5</td>
<td>KESSLER shall <strong>execute</strong> a total of <strong>3 end to end process operations</strong> and succeed at least twice within the total mission time.</td>
<td>Demonstration/Test</td>
</tr>
</tbody>
</table>
Hardware Interface

Robotic Arm
- AX-12A Servo (Finger 1)
  - MX-64T Servo (Wrist Roll)
  - MX-28T Servo (Wrist Pitch)
  - MX-64T Servo (Roll)
  - MX-64T Servo (Pitch)
- AX-12A Servo (Finger 2)
  - MX-64T Servo (Base 1)
  - MX-64T Servo (Base 2)
- MX-106T Servo (Turn Table)

Visual Processing Hardware
- Primary RGB Camera
- IR Depth Sensor
- Secondary RGB Camera (ArduCam Mini)
  - DC Outlet
  - Arduino Microcontroller
  - USB2Dynamixel
  - 12V, 5A Power Supply

Legend
- USB
- TTL
- Power
- SPI/I2C
- TTL+Power Line

02/05/2018
KESSLER Manufacturing Status Review
Hardware Data I/O

**Hardware**

- **Primary Camera (Microsoft Kinect)**
- **Secondary Camera (ArduCam Mini)**
- **Arm Servos (x10)**

**ROS**

- **Visual Processing**
- **Goal Position Goal Orientation 3D Point Cloud**
- **Controls**

**Legend**

- Important + challenging
- Important
- Implemented + verified
- Not building
Proposed Design

KESSLER Primary Components & Functionality

1. **Primary Camera**: Kinect Mounted to Arm Platform
2. **Secondary Camera**: ArduCAM Mini
3. **Scaled Iridium Satellite on MGSE**
4. **CPU commands motor drivers**
5. **6 DOF Crustcrawler Robotic Arm**

**KESSLER Manufacturing Status Review**
Proposed Design

1. Visual system searches for grappling feature on satellite
2. Algorithm identifies feature on satellite in FOV
3. Algorithm calculates how to grapple
4. CPU commands arm move as necessary to grapple feature
5. Robotic arm receives commands, rotates as necessary to grapple feature

Secondary Camera: ArduCAM Mini

Primary Camera: Kinect Mounted to Arm Platform

Scaled Iridium Satellite on MGSE

CPU conducts visual processing and runs control algorithm

Secondary Camera’s Field of View

6 DOF Crustcrawler Robotic Arm

CPU commands motor drivers
Proposed Design

1. Visual system searches for grappling feature on satellite
2. Algorithm identifies feature on satellite in FOV
3. Algorithm calculates how to grapple
4. CPU commands arm move as necessary to grapple feature
5. Robotic arm receives commands, rotates as necessary to grapple feature

6 DOF Crustcrawler Robotic Arm
Primary Camera: Kinect Mounted to Arm Platform
Secondary Camera: ArduCAM Mini
Secondary Camera’s Field of View
CPU conducts visual processing and runs control algorithm

Scaled Iridium Satellite on MGSE

Primary Camera:
Kinect Mounted to Arm Platform

Secondary Camera:
ArduCAM Mini

Algorithm calculates how to grapple
CPU commands arm move as necessary to grapple feature

Robotic arm receives commands, rotates as necessary to grapple feature

02/05/2018
Proposed Design

1. Visual system searches for grappling feature on satellite
2. Algorithm identifies feature on satellite in FOV
3. Algorithm calculates how to grapple
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Secondary Camera: ArduCAM Mini

Primary Camera: Kinect Mounted to Arm Platform

Scaled Iridium Satellite on MGSE

Crustcrawler Robotic Arm

Secondary Camera’s Field of View

6 DOF

CPU conducts visual processing and runs control algorithm

KeSSLER Manufacturing Status Review
Proposed Design

1. Visual system searches for grappling feature on satellite
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Primary Camera: Kinect Mounted to Arm Platform
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6 DOF Crustcrawler Robotic Arm

Scaled Iridium Satellite on MGSE

CPU commands motor drivers

3. CPU conducts visual processing and runs control algorithm
Proposed Design

1. Visual system searches for grappling feature on satellite

2. Algorithm identifies feature on satellite in FOV

3. Algorithm calculates how to grapple

4. CPU commands arm move as necessary to grapple feature

5. Robotic arm receives commands, rotates as necessary to grapple feature

CPU conducts visual processing and runs control algorithm
Section 2 Back-up
**KESSLER Manufacturing Status Review**

**Work Plan**

**Critical Design Phase**
- CDR Feedback Review
- Fall Final Report Efforts
- Fall Final Report
- FINALS WEEK
- WINTER BREAK

**Manufacturing/Component Dev.**
- Electrical Component Ordering
- Electrical ICD
- Electrical Component Inspection
- Mechanical Drawing
- MGSE Component Ordering
- Robotic Arm Component Manufactur.
- Satellite Manufacturing
- MGSE Manufacturing
- MSR
- Cable Harnessing
- Robotic Arm Integration
- Machining Ends

**Component/Unit Testing**

**Subsystem Testing**

**Integration Testing**

**Project Close-Out**
- SFR Presentation Efforts
- SFR
- SFR Feedback Review
- PFR Efforts
- PFR

---

**Model Completion**

**FFR Operations**

**Part Procurement, Ground Support Equipment, Manufacturing**

**Three step testing progression**

**Schedule is planned with two week margin.**

---

**Schedule**

- Week 1
- Week 4
- Week 10
- Week 15

---

**Course Deliverables**
- Financial
- Electrical
- Mechanical
- Visual Processing
- Controls
- Multiple Subsystems
- Breaks
**Test Plan**

**KESSLER Manufacturing Status Review**

### Critical Design Phase

### Manufacturing & Component Development

**Component/Unit Testing**
- Motor Aliveness
- Spec Torque Test
- Stall Torque Test
- Kinect Functionality
- Secondary Camera Functionality
- Control Loop
- Path Planning
- ROS Data (ctrl)
- Object Detection
- Objection Location Determination
- ROS Data (visual processing)

**Subsystem Testing**
- Robotic Arm Spec Torque
- Robotic Arm Stall Torque
- Robotic Arm Plane Sweep
- Unit Integration (ctrl)
- Unit Integration (visual processing)
- TRR

**Integration Testing**
- CTRL & RA Integration
- VP & CTRL Software Integration
- SPRING BREAK
- Full System Integration
- Testing Complete

**Project Close-Out**

---

**Schedule is planned with two week margin.**

- Course Deliverables
- Financial
- Electrical
- Mechanical
- Visual Processing
- Controls
- Multiple Subsystems
- Breaks

**Test Plan**

Hardware components, Software units

Subsystem specific component/unit integration

Multiple subsystem integration

Testing Complete

TRR

Schedule is planned with two week margin.
Sec 3: Mech
Subsystem: Iridium Satellite

Sub-Assemblies:
- Solar Panels x 2
- Antennas x 3
- BUS Structure x1
- Body x2
Sub-Assembly – Solar Panel

- Solar Panel: Acrylic Sheet
  - 12mm Thickness
  - Dark Blue -- Glossy

- Bar: HDPE Rod
  - ¾” Thickness
  - Grey -- Matte
Sub-Assembly – Antenna

- **Antenna: Acrylic Sheet**
  - 12mm Thickness
  - Black -- Glossy

- **Support: HDPE Rod**
  - ¾” Thickness
  - Grey – Matte

- **Bracket: Aluminum 3030**
  - 45° Angle
  - Aluminum -- Matte
Sub-Assembly – Bus

- Rods: HDPE
  - ¾” Thickness
  - Grey – Matte
  - Bars at 45 Degrees
  - Driven by Body Interior
Sub-Assembly – Body

- Side Pieces: Acrylic Sheets
  - 12mm
  - Grey – Matte
  - 220mm Long
  - Triangular Prism
Subsystem: Mechanical Arm

New Additions:

- MX-64T Wrist
- MX-64T Elbow
- MX-28 Elbow
- ArduCam
- ArduCam Mount
- Girder
- Turntable Bracket

34”
## Design & Functionality

### Performance

<table>
<thead>
<tr>
<th>Actuator</th>
<th>Stall Torque (oz.in.)</th>
<th>Torque Experienced (oz.in.)</th>
<th>Factor of Safety (FOS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MX-64 DA</td>
<td>2,060</td>
<td>1,200</td>
<td>1.7</td>
</tr>
<tr>
<td>MX-64T</td>
<td>1,030</td>
<td>500</td>
<td>2</td>
</tr>
<tr>
<td>MX-28T</td>
<td>440</td>
<td>120</td>
<td>3.6</td>
</tr>
</tbody>
</table>

**Stall Torque:**
- MX-64DA: 2,060 oz.in.
- MX-64T: 1,030 oz.in.
- MX-28T: 440 oz.in.

**MX-64DA**
- 5" Girder
- 1.3 oz.
- 5"

**MX-64T**
- 5" Girder
- 6.0 oz.
- 3.6"

**MX-28T**
- 5" Wrist
- 6.0 oz.
- 3.6"

**MX-64 Wrist, AX Dual Robotic Grappler**
- 3.4 oz.
- 3.0"
- 9.6"
## Mechanical Tolerances

<table>
<thead>
<tr>
<th>Governing Part(s)</th>
<th>Required Tolerance</th>
<th>Achievable Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body Plates/Panels/Antenna</td>
<td>0.10”</td>
<td>0.00025”</td>
</tr>
<tr>
<td>Body Plates</td>
<td>3°</td>
<td>0.05°</td>
</tr>
<tr>
<td>BUS Structure</td>
<td>0.10”</td>
<td>0.001”</td>
</tr>
<tr>
<td>Support Bars</td>
<td>0.10”</td>
<td>0.001”</td>
</tr>
<tr>
<td>Stand Rods</td>
<td>0.5°</td>
<td>0.01°</td>
</tr>
</tbody>
</table>

*All manufacturing and integration tolerances fall within KESSLER requirements*
Sec 3: Elec
Electrical Hardware Block Diagram

**ArduCam**: Harnessing for communication and integration with microcontroller.

**Microcontroller**: USB to MicroUSB, expected location central to PC.

**Kinect**: External DC Power Supply and USB cord management

**Arm Assembly**: Anchors for ArduCam harnessing, removal of heritage force cells, re-harnessing of heritage Dynamixel 3-pin connectors.

**Expected Challenge**: Verifying ArduCam harnessing provides reliable connectivity and does not impede arm execution.
## Electrical Tasks

<table>
<thead>
<tr>
<th>Completed</th>
<th>In Progress</th>
<th>To Be Completed</th>
</tr>
</thead>
</table>

### Visual System
- Microsoft Kinect USB and DC Supply verification
- Microsoft Kinect Software Recognition
- ArduCam Mini Signal Wires
- Microcontroller USB verification

### Robotic Arm
- Actuator Liveliness Characterization
- Actuator Torque Analysis
- Gripper Modification
- Signal Line Verification
- DC Supply Verification
- Girder Harnessing Anchors

02/05/2018
ArduCam Mini

- **Power**
  - 3.3 to 5 VCC and GND

- **SPI**
  - Issues capture command; ArduCam waits for new frame and buffers the entire image data to the frame buffer, sets completion flag bit

- **I2C**
  - Interacts directly with the OV2640 image sensor
Secondary Visual System Software

- Green – Controller positions ArduCam to image capture location
- Yellow – Microcontroller commands image capture and transfer from camera
- Red – Transfer of Image from microcontroller to CPU
- Blue – Microcontroller communicates with Control and Visual algorithm

Software Completion

Cam Setup
- Extensive open source code
- 60%

Serial Image Capture
- Extensive User Guide
- 20%

Image Transfer
- Extensive implementation guide
- 20%

Signal received from Visual Processing for Quad Sweep
  - Initialize ArduCAM
  - Serial Communicate for Image Capture (x4)
  - Serial Communicate for Image Transfer
  - Transfer Image (256 bytes image data to file)
  - Signal sent to Visual Processing (capture complete)
Sec 3: Ctrl
System

Project Overview

Schedule

Mech.

Elec.

Software: Controls

Software: Visual

Budget

02/05/2018

KESSLER Manufacturing Status Review
Trajectory Verification

| D2.2   | The robotic arm path shall be constrained by the arm's joint limitations | Demonstration/Test |
Backup: Functions to Implement

- **MoveIt interface**
  - `setPoseTarget`
  - Getters: `ActiveJoints`, `DefaultPlannerID`, `JointTolerance`, `PositionTolerance`, `OrientationTolerance`, `JointNames`

- **Controller Interface**
  - `sendTrajectory`, `waitForExecution`, `cancelExecution`

- **Actuator Interface**
  - `getState`, `setPosition`, `setTorque`, `initialize`, `detectError`

- **Watchdog**
  - `checkError`, `ESTOP`
## Backup: Timing model verification

<table>
<thead>
<tr>
<th>WU</th>
<th>ID</th>
<th>L</th>
<th>E</th>
<th>Data</th>
<th>CS</th>
<th>Calculations</th>
<th>WU</th>
<th>ID</th>
<th>L</th>
<th>I</th>
<th>Arguments</th>
<th>CS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.00057 s</td>
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<td></td>
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<tr>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td>Up to 0.0179 s</td>
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<td></td>
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<tr>
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<td>0.00144 s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Calculations include:
  - Trajectory processing
  - Data packaging
  - Command packaging
Challenges

- Understanding the sample code
- Understanding MoveIt! structure

- Test safety
  - Mitigation: Limit speed, Verify path planning output

- Error bounds
  - Mitigation: Automatic adjustment
Sec 3: VP
## Software Tools: MATLAB

<table>
<thead>
<tr>
<th>Toolbox</th>
<th>Purpose</th>
<th>Percent written by KESSLER</th>
<th>Level of Difficulty (1-5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image Acquisition Toolbox for Kinect Sensor</td>
<td>Take 2D and 3D images</td>
<td>0%</td>
<td>1</td>
</tr>
<tr>
<td>Computer Vision Toolbox</td>
<td>Feature matching satellite</td>
<td>30%</td>
<td>2</td>
</tr>
<tr>
<td>Computer Vision Toolbox</td>
<td>3D point cloud processing</td>
<td>70%</td>
<td>4</td>
</tr>
<tr>
<td>Robotic System Toolbox</td>
<td>Data formatting for Controls System</td>
<td>30%</td>
<td>3</td>
</tr>
</tbody>
</table>

1: Requires no assistance  
3: Requires individual research  
5: Requires expert support

**Level of Difficulty Scale**

Table #: Visual Processing software tools
Feature Matching Results:

• Varied angles between images: 10 degrees between images is sufficient

• Tested database against satellite at random orientation not included in database

• Minimum of 3 matches needed and results are above that threshold
Identify Closest Point
Plane Detection

- Point cloud of full satellite
- Planes of solar panels
- Planes of bus structure
CPE 1 & Success Criteria

• CPE 1 Feature Recognition
  • Addresses Objective 1 & 2.
  • RGB-based **visual algorithm**
    • Responsible for recognizing stationary pre-selected grappling features at an unknown orientation.
    • Responsible for **identifying** features that may **collide** with mechanical arm
  • This CPE also includes the **imaging and processing hardware** required to execute feature recognition.
## F1: Design Requirements

<table>
<thead>
<tr>
<th>REF ID</th>
<th>Description</th>
<th>Verification Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1.1</td>
<td>The visual processing algorithm shall be capable of detecting a feature at a minimum distance of 20 inches.</td>
<td>Demonstration/Test</td>
</tr>
<tr>
<td>D1.2</td>
<td>The visual processing algorithm shall be capable of identifying the main characteristics of a satellite with a level of confidence greater than or equal to 75%.</td>
<td>Image Analysis</td>
</tr>
<tr>
<td>D1.3</td>
<td>The visual processing algorithm shall identify the position (x,y,z) and orientation (Euler angles) of an object in 3D space.</td>
<td>Image Analysis</td>
</tr>
<tr>
<td>D1.4</td>
<td>The visual system shall be capable of communicating with the control system.</td>
<td>Demonstration/Test</td>
</tr>
</tbody>
</table>
Color Matching

- Color attribute is 3 dimensional matrix (Red, Green, Blue)
- Unique combination of RGB values correlates to specific color
- Isolate certain RGB values to isolate features and recolor
  - Known colors for each feature

![Diagram of a satellite model with labeled components: Solar Panel, Antennas, Bus structure.]

Fig. #: Colored satellite model
Fig. #: Color processed satellite model

20% Scale model of satellite

Software functionality demonstrated for L2-L3 Success Criteria
3D Point Cloud Feature Identification

• Map 2D color image to 3D point cloud
  • Both 2D & 3D sensors: 1920 x 1080 pixels

• Concern: Low density point cloud may not demonstrate 4mm requirement satisfaction capability (Pixel utilization of scale model ~ 390 x 220 pixels)

0.6mm < 4mm requirement
4mm for Full Scale
0.8mm for 20% Scale
0.6mm close to 0.8mm
Visual Processing Timing

Timing Analysis

Trial Number

Time (s)

- Analyze Data Spring
- Analyze Image Spring
- Analyze Data Fall
- Analyze Image Fall
Section 4
## Hardware Status: Mechanical

**Updated: 2/2/2018**

<table>
<thead>
<tr>
<th>Item (Name)</th>
<th>Price (per unit, without tax)</th>
<th>Quantity</th>
<th>Item Total</th>
<th>Shipping, Handling, and any other fees</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>MX-106T</td>
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<td>1</td>
<td>$552.00</td>
<td>$12.65</td>
<td>Delivered</td>
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<tr>
<td>MX-64T Wrist</td>
<td>$364.00</td>
<td>1</td>
<td>$364.00</td>
<td>$0.00</td>
<td>Delivered</td>
</tr>
<tr>
<td>2.5&quot; Girder</td>
<td>$23.00</td>
<td>2</td>
<td>$46.00</td>
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<td>Delivered</td>
</tr>
<tr>
<td>MX-64/106 To MX-28 Adapter</td>
<td>$11.99</td>
<td>2</td>
<td>$23.98</td>
<td>$0.00</td>
<td>Delivered</td>
</tr>
<tr>
<td>Singleaxismount</td>
<td>$15.00</td>
<td>3</td>
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<td>Delivered</td>
</tr>
<tr>
<td>12in. (30.48cm) 3-pin wire extension</td>
<td>$9.49</td>
<td>3</td>
<td>$28.47</td>
<td>$0.00</td>
<td>Delivered</td>
</tr>
</tbody>
</table>
## Hardware Status: Testing

**Updated: 2/3/2018**

<table>
<thead>
<tr>
<th>Item (Name)</th>
<th>Price (per unit, without tax)</th>
<th>Quantity</th>
<th>Item Total</th>
<th>Shipping, Handling, and any other fees</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylic Cement</td>
<td>$19.17</td>
<td>1</td>
<td>$19.17</td>
<td>$30.97</td>
<td>Ordered</td>
</tr>
<tr>
<td>Acrylic Sheets</td>
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<td>$278.40</td>
<td>$42.85</td>
<td>Not yet ordered</td>
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<tr>
<td>Aluminum Frame</td>
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<td>$32.16</td>
<td>$0.00</td>
<td>Ordered</td>
</tr>
<tr>
<td>Brackets (10 pk)</td>
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<td>1</td>
<td>$14.10</td>
<td>$5.99</td>
<td>Ordered</td>
</tr>
<tr>
<td>HDPE Rod</td>
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<td>2</td>
<td>$23.96</td>
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# Hardware Status: Visual Processing

**Updated: 2/2/2018**

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<tr>
<th>Item (Name)</th>
<th>Price (per unit, without tax)</th>
<th>Quantity</th>
<th>Item Total</th>
<th>Shipping, Handling, and any other fees</th>
<th>Status</th>
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<tr>
<td>Arduino Zero</td>
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<td>Lighting</td>
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