Proximity Identification, characterization, and neutralization by thinking before acquisition (PIRANHA)

Test Readiness Review

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• Overview
• Schedule
• CPEs and Testing Scope
• Critical Testing
• Budget
PIRANHA Design

Heritage Debris Capture System

Software and Computing Hardware

PIRANHA

Rangefinder

Camera

Laser beam

Tilt axis of rotation

Pan axis of rotation

Servos

2-DOF Gimbal Assembly

University of Colorado Aerospace Engineering Sciences

8/24/2014
Space Operations Simulation Center

DETECT & RANGE

THINK

POSITION FINDING

CAPTURE

Debris centered in camera FOV
Laser/rangefinder ranges debris

DCS
PIRANHA

6-DOF Robot

Power
Robot Interface

$\mathbf{r_{rel}}$

J2000 position/attitude

Debris

$\mathbf{J2000}$ position/attitude
Levels of Success

Space Operations Simulation Center

Stage 1

- Purpose: Gain confidence in PIRANHA

Stage 2

- Purpose: Test PIRANHA/SOSC communication

Stage 3

- Purpose: Test closed-loop attitude control

PIRANHA

USB1

r_{rel} q

SOSC Robot

10Hz

Power

Robot Interface
Work Plan

Software Phase II Testing
- Integrate all C code from Software Phase I into one source code
- Add logic algorithms & checks
- Test source code outputs give simulated inputs

Power Board Test
- Tested board with full load single board computer
- Waiting on ATX power supply to be procured (EDA: Mar. 7th)
- Have alternate power supply for now so no delay in tasks

Validation in SOSC
- Attempt 3 Levels of Success in one day

SOSC Fit Check
- Successfully Mounted DCS to 6DOF robot
- Ran through capture scenario & Captured ~500 images (Static & Dynamic) of debris

HWIL Phase I
- Communicated with:
  - Rangefinder (triggered & received)
  - Servos (commanded & received)
  - Camera (triggered & received)
  via the single board computer

SOSC Comms & Camera
- Successfully transmitted entire capture scenario at 20Hz
- Successfully characterized size of debris in all images
- Successfully sent one data structure via Ethernet

Software Phase II
- Full load Power Board Test
- HWIL Phase II Testing
- Validation in SOSC

SOSC Mar. 21st

** Post TRR **

SOSC Troubleshooting Interpretation Software

*** Contingency Date: Mar. 31st ***

Hardware Component Tests
- Verify precision of rangefinder
- Verify pixel count & FOV of camera
- Verify precision of servos
- Verify gimbal free of binding

Software Phase I
- Integrate all C code from Software Phase I into one source code
- Add logic algorithms & checks

Hardware Component Testing
- Verify precision of rangefinder
- Verify pixel count & FOV of camera
- Verify precision of servos
- Verify gimbal free of binding

Systems Test
- Class Milestone

Electrical
- Mechanical/Manufacturing
- Software

PIRANHA Milestone

SOSM Mar. 21st

HWIL Phase II
- Verify correct attitude calculation

Added Software Task
- Ethernet program with interrupt @ > 10Hz

Completed since MSR

Software Component Testing
- Mechanical/Manufacturing
- SOSC Fit Check
- Software Phase II Testing
- HWIL Phase I Testing
- SOSC Comms & Camera

** Post TRR **

Contingency Date: Mar. 31st

SOSM Mar. 21st

Mechanical/Manufacturing
- Manufactured gimbal assembly
- Manufactured electronics box
- Manufactured plate to mount PIRANHA to DCS

Software Phase I
- Convert MATLAB/Simulink code to C
- Image processing
- Centroiding
- Quaternions
- Verify outputs from C code are the same as outputs from MATLAB/Simulink

Electrical
- Manufactured gimbal assembly
- Manufactured electronics box
- Manufactured plate to mount PIRANHA to DCS

Mechanical/Manufacturing
- Successfully transmitted entire capture scenario at 20Hz
- SOSC troubleshooting interpretation software
- Captured ~100 usable dynamic photos with PIRANHA’s camera

Spring Break

SOSC Fit Check
- Successfully Mounted DCS to 6DOF robot
- Ran through capture scenario & Captured ~500 images (Static & Dynamic) of debris

SOSC Troubleshooting Interpretation Software

*** Contingency Date: Mar. 31st ***

SOSC Troubleshooting Interpretation Software

*** Contingency Date: Mar. 31st ***
CPE.1 Software-Hardware Interfacing  
-Addressed through HWIL Phase I testing  
-All hardware talks to single board computer

CPE.2 Servo Pointing & Control  
-Addressed through Software Phase I testing  
-Simulated images of debris yield servo commands

CPE.3 Detect & Size

CPE.4 SOSC Testing  
*External facility in which we are not priority*
Purpose:

• **Software**, **Hardware-In-the-Loop (HWIL)**, and **Hardware Component** tests will unit test hardware, software functions, and the hardware-software interfaces.

• **SOSC testing will validate the design**

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**Needs:**
1) Model for comparison
2) Functioning PIRANHA-SOSC interface
3) Thorough test plan

3 levels of success in SOSC

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**Software Tests**

**HWIL Tests**

**Hardware Component Test**

**SOSC Test**

**Tests Worked Concurrently**
PIRANHA Performance Model

- Rangefinder Precision
- Servo Performance
- Software Timing

Updating Model

1. Predicted Quaternions
   - Q3
   - End of Scenario Q3 Limits

2. Time (s)
   - Start
   - Turn Begins ~1m
   - Finish

Values:
- Before turn to capture

3. Predicted Vector from PIRANHA to Debris

4. Compare to SOSC measurements

5. Debris:
   - (R, θ)

6. Start
   - [R, θ]
   - Finish

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**HWIL Phase II Testing Will Verify:**

DES.5.1 – PIRANHA shall output trajectory and attitude, which define SOSC 6-DOF robot motion, at a rate of no less than 10 Hz

CMP.4.2.1 - PIRANHA shall output debris relative position vectors.

Attitude Output In SOSC Phase II will be dependent on measured vectors from PIRANHA to the debris. 3 distinct “zones” in the capture scenario for attitude calculation:

1) Prior to initiating turn to capture debris
2) During turn to capture debris
3) After turn to capture debris
Verify Measurements Made (Requirement)

Gimbal, servos, camera, rangefinder

Final Debris Position

Motor

Laptop

Debris, actuated with fishing line and electric motor calibrated to pull at 8cm/s

Black Background

Debris, actuated with fishing line and electric motor calibrated to pull at 8cm/s

Flat Surface

Initial Debris Position

Motor

Final Debris Position

Black Background

Electronics box

Gimbal, servos, camera, rangefinder

Compare

Start

Finish

Predicted Vector from PIRANHA to Debris

[R, θ]

Predicted Quaternions

Start

Finish

Verify Attitude and Trajectory Output at min 10 Hz (Requirement)
SOSC Validation Stage 1

Setup & Power ‘ON’:

Start Up Script Executed on Boot Up

If installed(USB1) && Notinstalled(eth2) && Notinstalled(USB2)
   Execute SOSC Scenario 1
End

Post Process Data via MATLAB:

Compare trend between calculated and ideal $r_{rel}$ & quaternion

SOSC Start Capture Scenario:

Stage 1: Requirements Verified: DES 3.1

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SOSC Validation Stage 2

Setup & Power ‘ON’:

Start Up Script Executed on Boot Up

\[\text{If}\ \text{installed}(\text{USB1}) && \text{installed}(\text{eth2})\]
\[\text{&&}\ \text{Notinstalled}(\text{USB2})\]
\[\text{End}\]

\[\text{Execute SOSC Scenario 2}\]

Post Process Data via MATLAB:

Time Range PanServo TiltServo Q1 Q2 Q3 Q4

Predicted Vector from PIRANHA to Debris

Predicted Quaternions

Stage 2: Requirements Verified:
- CMP 3.1.1
- DES. 4.1
- DES 4.1.1
Setup & Power ‘ON’:

Start Up Script Executed on Boot Up

\[
\text{If } \text{installed(USB1) } \&\& \text{installed(eth2)} \\
\&\& \text{installed(USB2)} \\
\text{End}
\]

Execute SOSC Scenario 3

Post Process Data via MATLAB:

Time Range PanServo TiltServo Q1 Q2 Q3 Q4

Ethernet connected to SOSC

Compare calculated and ideal \( r_{rel} \) & quaternion at time stamp

Predicted Quaternions

Predicted Vector from PIRANHA to Debris

Stage 3: Requirements Verified: DES. 5.1.2

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**Setup**

- Arrive at SOSC
- Attach DCS to robot & connect +15V
- Configure robot
- Hang debris from crane hook
- Stage spotlight
- Focus camera with laptop

**Stage 1**

- Power ‘ON’ DC power supply remotely
- Inform SOSC to start scenario
- Hang debris from crane hook
- Stage spotlight
- Focus camera with laptop

**Stage 2**

- Attach Ethernet cable
- Cycle DC power supply remotely
- PIRANHA start scenario
- Eject USB flash drive and post process collected data

**Stage 3**

- Attach USB2 flash drive
- Cycle DC power supply remotely
- PIRANHA start scenario
- Eject USB flash drive and post process collected data
Expenses Since MSR ($410):
• Single board computer needed to be repurchased with additional HW
  • Under warranty and has been returned to vendor for inspection
  • Miscellaneous HW was purchased

Known Future Costs $175
• Poster
• Final Report Printing

The team has secured an additional $500 from the Deans office for travel to the AIAA conference
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Purpose:

- **Phase I** – Verify each software function behaves as expected based on requirements
- **Phase II** – Verify the PIRANHA program, constructed from Phase I functions, behaves as expected based on requirements
- Mitigate risks associated with software algorithms and integrating multiple software functionalities into one system

### Software Phase I

**Individual Software Functionalities**

- Servo Command Calculation
- DCS Attitude Calculation
- Image Processing (Filtering, Centroiding, Sizing)

### Software Phase II

**Integrated Software Functionality**

- PIRANHA “main” program

---

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Solution</th>
<th>CPEs</th>
<th>Requirements</th>
<th>Risks</th>
<th>V&amp;V</th>
<th>Planning</th>
</tr>
</thead>
</table>

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Purpose: Verify that the algorithm used to calculate the appropriate attitude quaternion to output to the SOSC robot does so correctly based on requirements. This test also will mitigate risk of the DCS capturing the debris in a manner outside of its capture alignment limits.

Diagram:

- Servo Model
- Rangefinder Model
- Capture Scenario Trajectory Model
- Euler Angle
- Logic
- Quaternion Calculation Algorithm
- DCS Attitude Quaternion Calculated
- Compare
- Desired Attitude Quaternion
Summary of Measurements:

<table>
<thead>
<tr>
<th>Measurement</th>
<th>How the Measurement is Verified</th>
<th>Expected Result</th>
<th>Related Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated DCS Attitude Quaternion</td>
<td>Capture Model Quaternion</td>
<td>Turn begins within 1/6th second, final angle within 0.14 degrees</td>
<td>DES.4.1.1</td>
</tr>
</tbody>
</table>

Required Materials/Facilities:

- Computer which runs Simulink for preliminary test, or single board computer running chosen environment for secondary test in C
- Capture Model
**Quatetion Function Test Results**

<table>
<thead>
<tr>
<th>Metric</th>
<th>Experimental Value</th>
<th>Expected Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Turn Begin Time) - (Ideal Turn Begin Time)</td>
<td>0.1668 [s]</td>
<td>1/6 [s]</td>
</tr>
<tr>
<td>(Final Angle) – (Ideal Final Angle)</td>
<td>2.9*10^-3 [deg]</td>
<td>Less than 1*10^-2 [deg]</td>
</tr>
</tbody>
</table>

**Lessons Learned:**

- Function performs as expected based on the capture scenario model.
- Set up for easy evaluation of errors. Timing of the scenario can be changed to simulate computation time, and range and measured camera angle errors can be introduced.
**Purpose:** To verify the image processing algorithm in the SOSC environment at varying ranges. This was done utilizing a camera, rangefinder, and image processing software. Designed to mitigate risks of errors in size characterization during full scale test by adjusting variables in code to match SOSC environment.

**Summary of Measurements:**

<table>
<thead>
<tr>
<th>Measurement</th>
<th>How it was completed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Debris Diameter</td>
<td>String around circumference</td>
</tr>
<tr>
<td>Range to Debris</td>
<td>SOSC Robot Position Data</td>
</tr>
<tr>
<td>Camera FOV</td>
<td>Given by SOSC</td>
</tr>
<tr>
<td>Size of Debris</td>
<td>Image processing algorithm</td>
</tr>
</tbody>
</table>

**DES.2.1:** Ability to detect 10 – 40cm diameter debris at 20m
**DES.3.1:** Ability to determine size to ±2cm
- Size calculated for over 500 photographs over the capture scenario

- All sizes within requirement of knowing the debris size to within ±2 cm
Software Phase I: Servo Control

**Purpose:** Verify servo pointing commands can be derived from debris centroid found from images using C code. Helped to address critical project element concerning pointing and tracking the debris throughout capture scenario.

**Procedure:** Generate images with known simulated debris position using Simulink, and generate centroid with centroiding function. From centroid and camera field of view, find the desired servo angles. Compare MATLAB results for the same Simulink generated images.
Residual MATLAB-C Servo Angle

Residuals [deg]

Time [s]
**Software Flow Diagram of Capture Process:**

- **Inner loop** represents initialization procedure (range >= 20m).
- **Outer loop** represents capture procedure, inner loop will remain active (20m > range > 1m).
- Interrupt running in parallel with capture procedure loop.
Software Phase II Test Setup

Image Setup

Debris Centroid

Size

Range

Simulated Images

Image Processing

Edges

Debris Edges

Centroid Detection

Debris Centroid

Size Characterization

Debris Size

Calculate Rotation Angles

Pan and Tilt Angles

Save to file

Compare to values used to create images

Test Setup

Initialization

Capture Process

20 Images where debris drifts toward center of image frame
Range = 20m

100 Images where debris drifts toward center of image frame
20m > Range > 0.5m
Software Phase II Testing – Results

- This test is used to verify that the Software can:
  - Properly pass values between individual functions
  - Sense the debris has been centered in the image frame
  - Determine debris is closer than 1m and initiate capture phase (Software only calculates quaternions)
Interrupt and Ephemeris Data Testing

- Tested 50ms Interrupt with counter in the loop
- Tested 50ms Interrupt with hardware in the loop
- Tested sending entire data set over Ethernet with a 50ms Interrupt with counter in the loop
- Tested sending entire data set over Ethernet to the S.O.S.C. with a 50ms Interrupt with counter in the loop
- Test sending entire data set over Ethernet with a 50ms Interrupt with hardware in the loop
- Tested sending data structure over Ethernet
Purpose:

- **Commercial Off-The-Shelf** – Verify hardware performs as required

- **Custom Fabricated** – Verify team manufactured components, coupled with COTS hardware, performs as required

- **Mitigate risks** associated with COTS component performance, and validate the design of custom fabricated components
• **Purpose:** Verify the rangefinder can accurately range targets within the tolerances specified at the ranges needed for testing in the SOSC. Test will mitigate possibility of failure due to defective rangefinder.

• **Diagram:**

Distance = increments of 1 m

Student Laptop

Acuity Accu Range 1000 - Rangefinder
Summary of Measurements:

<table>
<thead>
<tr>
<th>Measurement</th>
<th>How the Measurement is Verified</th>
<th>Expected Accuracy</th>
<th>Related Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range (m)</td>
<td>Truth distance is measured with meter tape</td>
<td>+/- 3 mm (AR1000 Data Sheet)</td>
<td>DES.2.1, DES.4.1</td>
</tr>
</tbody>
</table>

Required Materials/Facilities:

- Wall
- Meter tape
- Laptop capable of interfacing with rangefinder
- Steady surface for rangefinder
Rangefinder Test Results

<table>
<thead>
<tr>
<th>Measurement</th>
<th>1 (m)</th>
<th>2 (m)</th>
<th>3 (m)</th>
<th>4 (m)</th>
<th>5 (m)</th>
<th>20 (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial 1</td>
<td>0.951</td>
<td>1.951</td>
<td>2.953</td>
<td>3.953</td>
<td>4.950</td>
<td>20.102</td>
</tr>
<tr>
<td>2</td>
<td>0.951</td>
<td>1.951</td>
<td>2.953</td>
<td>3.953</td>
<td>4.950</td>
<td>20.102</td>
</tr>
<tr>
<td>3</td>
<td>0.951</td>
<td>1.951</td>
<td>2.953</td>
<td>3.953</td>
<td>4.950</td>
<td>20.102</td>
</tr>
<tr>
<td>4</td>
<td>0.951</td>
<td>1.951</td>
<td>2.953</td>
<td>3.953</td>
<td>4.950</td>
<td>20.102</td>
</tr>
<tr>
<td>Distance from tape #1</td>
<td>0</td>
<td>1</td>
<td>2.002</td>
<td>3.002</td>
<td>3.999</td>
<td>-</td>
</tr>
</tbody>
</table>

LESSONS LEARNED:
-Rangefinder has precision stated in data sheet

-Reasonable ranges returned at just over 20 m

-Rangefinder model does not need to be updated.

-Must calibrate range prior to operation with PIRANHA to get required accuracy.
Purpose: Verify that the chosen servos (MX-64T) are capable of performing as required when subject to loading characteristic of the PIRANHA instrument.

Required Materials/Facilities:
- Servo
- Mass representing PIRANHA loading
- Computer for communication with servo
- Variable angle servo mount

Comparison of Commanded and Resulting Angular Position

Summary of Measurements:

<table>
<thead>
<tr>
<th>Measurement</th>
<th>How the Measurement is Verified</th>
<th>Expected Result</th>
<th>Related Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Servo Final Position</td>
<td>Comparison with servo command</td>
<td>Within 0.088 degrees</td>
<td>TSR.2.2</td>
</tr>
</tbody>
</table>

Diagram

- Green = Mass Characteristic of PIRANHA Load on Servo
- Grey = Servo
- Dashed line = Rotation Axis
- Dotted line = Vertical Reference

$\theta$ varied from 0 to 30 degrees
- 2 cases, servo shaft bending moment loading and shaft lateral loading.
- Lateral loading results most interesting

- With loading incremented from 0 to 1.62 kg the servo was commanded to move to the position outlined in red.

<table>
<thead>
<tr>
<th>Load [kg]</th>
<th>Discrepancy Between Commanded and Measured Position [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.177</td>
</tr>
<tr>
<td>0.5</td>
<td>1.408</td>
</tr>
<tr>
<td>1.62</td>
<td>4.484</td>
</tr>
</tbody>
</table>

**LESSONS LEARNED**
- Must test the assembled system to understand servo response.
- Possible solutions: Add bias to the control software, or increase servo voltage
Purpose: Verify that camera gimbal system provides two degree of freedom motion with the pointing accuracy given by the component requirements. The test is designed to mitigate the risk of camera pointing errors by measuring the accuracy of the system performance.

Required Materials/Facilities:
- Camera gimbal assembled according to design
  - Two manufactured gimbal brackets
  - Two servos
  - Large mounting plate
- Servo controller (computer with USB to RS-485 converter)
- Communication cables (USB and RS-485)

Comparison of Commanded and Resulting Angular Position

Summary of Measurements:

<table>
<thead>
<tr>
<th>Measurement</th>
<th>How the Measurement is Verified</th>
<th>Expected Accuracy</th>
<th>Related Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical servo angular position</td>
<td>Comparison with input</td>
<td>± 0.088°</td>
<td>CMP.2.1.1.1</td>
</tr>
<tr>
<td>Horizontal servo angular position</td>
<td>Comparison with input</td>
<td>± 0.088°</td>
<td>CMP.2.1.1.1</td>
</tr>
</tbody>
</table>

Diagram
### V&V: Gimbal System Test Results

<table>
<thead>
<tr>
<th>Commanded Angle [˚]</th>
<th>Actual Angle [˚]</th>
<th>Δ [˚]</th>
</tr>
</thead>
<tbody>
<tr>
<td>225</td>
<td>224.998</td>
<td>0.002</td>
</tr>
<tr>
<td>265</td>
<td>264.998</td>
<td>0.012</td>
</tr>
<tr>
<td>245</td>
<td>244.949</td>
<td>0.051</td>
</tr>
<tr>
<td>225</td>
<td>224.998</td>
<td>0.002</td>
</tr>
<tr>
<td>205</td>
<td>204.959</td>
<td>0.041</td>
</tr>
<tr>
<td>185</td>
<td>184.921</td>
<td>0.079</td>
</tr>
<tr>
<td>225</td>
<td>224.998</td>
<td>0.002</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Commanded Angle [˚]</th>
<th>Actual Angle [˚]</th>
<th>Δ [˚]</th>
</tr>
</thead>
<tbody>
<tr>
<td>180</td>
<td>179.999</td>
<td>0.001</td>
</tr>
<tr>
<td>200</td>
<td>199.862</td>
<td>0.138</td>
</tr>
<tr>
<td>190</td>
<td>189.930</td>
<td>0.070</td>
</tr>
<tr>
<td>180</td>
<td>179.999</td>
<td>0.001</td>
</tr>
<tr>
<td>170</td>
<td>169.979</td>
<td>0.021</td>
</tr>
<tr>
<td>160</td>
<td>159.872</td>
<td>0.128</td>
</tr>
<tr>
<td>180</td>
<td>179.999</td>
<td>0.001</td>
</tr>
</tbody>
</table>

**LESSONS LEARNED:**

- Initial Δ’s with no integral control were >1˚

- After fine-tuning the built-in servo integral control gain, gimbal system has ±0.14˚ accuracy required (CMP.2.1.1.1)

- Gains required to achieve required accuracy:

<table>
<thead>
<tr>
<th>P Gain</th>
<th>I Gain</th>
<th>D Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>32</td>
<td>0</td>
</tr>
<tr>
<td>16</td>
<td>16</td>
<td>0</td>
</tr>
</tbody>
</table>

- Gimbal system must also be tested with mounting board inclined to simulate DCS attitude during capture scenario

- Gimbal system mounted on board

- Board clamped to table
**Purpose:** Verify all voltage and current levels are correct to ensure correct operation of all critical components to the project. Designed to mitigate risk of frying components before and while they are connected. Voltage levels will be checked prior to hooking up sensors to verify correct voltage regulation.

**Setup:** Voltage and current measurements will be taken at the points marked in red. All voltage measurements will be in reference to ground.

<table>
<thead>
<tr>
<th>Expected Value</th>
<th>Camera</th>
<th>SBC</th>
<th>Servo</th>
<th>Rangefinder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (± 2mv)</td>
<td>12V</td>
<td>5V</td>
<td>12V</td>
<td>15V</td>
</tr>
<tr>
<td>Max Current</td>
<td>0.21A</td>
<td>2.31A</td>
<td>1.00A</td>
<td>0.13A</td>
</tr>
</tbody>
</table>

**Materials:**
- Multimeter
- Oscilloscope (voltage regulation)
- Power PCB
- Electronic components in circuit
Power Board Full Load Test

- All components powered except Single Board Computer
- Check that proper voltages are maintained on all output pins
  - Voltages on all output pins measured in reference to board ground pin (ground pin referenced to power supply ground)
- 15V power supply

Single Board Computer

- Will be powered off of power board utilizing a commercial PSU
  - Input of 12V from power board
  - Attaches to 20 pin ATX connector

<table>
<thead>
<tr>
<th>Description</th>
<th>Ground</th>
<th>Laser Rangefinder</th>
<th>Camera</th>
<th>Servo 1</th>
<th>Servo 2</th>
<th>Fan for Heat sink</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output Pin</td>
<td>GND</td>
<td>RNG</td>
<td>CAM</td>
<td>SER1</td>
<td>SER2</td>
<td>FAN</td>
</tr>
<tr>
<td>Expected (V)</td>
<td>0</td>
<td>15</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Measured (V)</td>
<td>0.07</td>
<td>15.01</td>
<td>12.00</td>
<td>12.04</td>
<td>12.03</td>
<td>11.96</td>
</tr>
</tbody>
</table>
**Purpose:** Verify the camera operates with the FOV and pixel count specified in data sheet. Test will mitigate the possibility of failure due to defective camera, or the incorrect FOV and pixel count entered into software algorithms.

**Diagram:**

- Measured distance to calculate FOV
- Known distance
- Image Processing Software for pixel count
- Verify pixels and FOV
Summary of Measurements:

<table>
<thead>
<tr>
<th>Measurement</th>
<th>How the Measurement is Verified</th>
<th>Expected Result</th>
<th>Related Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel Count</td>
<td>Data Sheet</td>
<td>Identical, 1928 x 1448</td>
<td>DES.2.1, DES.3.1</td>
</tr>
<tr>
<td>FOV (deg)</td>
<td>Lens Specification</td>
<td>30°</td>
<td>DES.2.1, DES.3.1</td>
</tr>
</tbody>
</table>

Required Materials/Facilities:
- Test board with PCB attached
- PointGrey Flea 3.0 with lens
- Laptop to interface with camera
- Image processing software
- Tenma 72-6910 power supply set to 14.97V
- Clamp to secure test board
- Meter stick
Camera tested both horizontally and vertically to get FOV in each direction

Results:

<table>
<thead>
<tr>
<th></th>
<th>FOV [°]</th>
<th>Pixel Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical</td>
<td>21.46</td>
<td>1928 x 1448</td>
</tr>
<tr>
<td>Horizontal</td>
<td>29.72</td>
<td>1928 x 1448</td>
</tr>
</tbody>
</table>

**LESSONS LEARNED:**
- Camera returns intelligible photos
- Image is size specified by data sheets (1928 x 1448)
- FOV can be easily adjusted if necessary using lens lever
- FOV set to 21.46° x 29.72°
Purpose: To verify all hardware required to mount the DCS to the 6DOF robot is available, verify the capture scenario enables the DCS to approach the debris against a dark background, verify Ethernet transmission of data structure, and capture static and dynamic photos of debris throughout capture scenario that can be used for further testing the image processing C function.

Setup: (Mounting DCS & Executing Capture Scenario)

Setup: (Ethernet Communication)
Materials:
• DCS
• 10.2cm Debris
• Laptop
• DCS and Debris J2000 Attitude & Ephemeris files
• Ethernet C program
• Image Processing C program

Facility:
• SOSC

Summary of Measurements:
<table>
<thead>
<tr>
<th>Measurement</th>
<th>How it was completed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Debris Diameter</td>
<td>String around circumference</td>
</tr>
<tr>
<td>Range to Debris</td>
<td>MATLAB file of robot position vs. time &amp; known position of debris in facility</td>
</tr>
<tr>
<td>Camera FOV</td>
<td>Given by SOSC</td>
</tr>
<tr>
<td>Size of Debris</td>
<td>Image processing algorithm</td>
</tr>
</tbody>
</table>

Image Process Results:
Size determination by C image process algorithm:

![Debris size for dynamic photos](image)

- **Required Upper Limit**: 12.5 cm
- **Required Lower Limit**: 8.5 cm
- **Actual Size of debris**: 10 cm

Comparison of Ethernet Communication

**Transmitted Data Structure** ➔ **Ethernet** ➔ **Received Data Structure** ➔ Compare

**Ethernet Result:**
A data structure containing test values was successfully transmitted and received by the SOSC computer via a laptop PIRANHA provided.
Purpose: Verify single board computer can transmit entire capture scenario via Ethernet UDP/IP protocol at a rate of 20Hz and capture images using PIRANHA’s camera to verify the appropriate lens was purchased for the camera given the lighting conditions of the scenario. Verify debris greater than 40 cm is characterized correctly with image processing software.

Setup: (Camera)

Setup: (Ethernet Communication)
Materials:
• Point Grey Flea 3 camera
• Laptop
• 65cm debris
• DCS and Debris J2000 Attitude & Ephemeris files
• Ethernet 20Hz C program
• Image Processing C program

Summary of Measurements:

<table>
<thead>
<tr>
<th>Measurement</th>
<th>How it was completed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Debris Diameter</td>
<td>Meter stick</td>
</tr>
<tr>
<td>Range to Debris</td>
<td>MATLAB file of robot position vs. time &amp; known position of debris in facility</td>
</tr>
<tr>
<td>Camera FOV</td>
<td>Camera hardware component test</td>
</tr>
<tr>
<td>Size of Debris</td>
<td>Image processing algorithm</td>
</tr>
</tbody>
</table>

Facility:
• SOSC

Image Process Results:

Size determination by C image process algorithm:

The plot illustrates the size was not characterized accurately. It is speculated the FOV originally measured is incorrect. Further research will be conducted.

Comparison of Ethernet Communication

The entire capture scenario was transmitted to the SOSC and interpreted correctly by their computers. There was however an error in their software that converts the J2000 coordinates to the SOSC fixed coordinate system. The z coordinate and quaternion was not correctly rotated into the SOSC fixed frame. SOSC engineers are troubleshooting their software.
- Need appx. 1.5° accuracy in servo pointing to capture with proper DCS attitude, and 0.24 Hz sample rate to complete turn at 3°/s

- Have theoretically 0.14° pointing accuracy and 1.59 Hz sample rate
**Pixel Smear: Derivation**

**Relative Attitude**

\[ \frac{d\beta}{dt} = \alpha \]

\[ \beta = \text{Angle from DCS longitudinal axis to debris} \]

\[ \frac{d\beta}{dt} = \alpha = \text{Angular rate of change of } \beta \]

\[ \alpha_{\text{max}} = \text{maximum angular rate throughout the scenario} = 0.06 \, ^\circ/s \]

\[ \gamma = \text{Half of total field of view of camera} \]

\[ r = \text{Range to debris} \]

\[ d = \text{Distance across an image at a specified range} \]

\[ n_p = \text{Number of pixels across an image} \]

\[ l_p = \text{Length of one pixel} \]

\[ l_o = \text{Length across the debris} \]

**Camera View**

\[ d = 2r \tan \gamma \]

\[ \frac{l_p}{n_p} = \frac{d}{n_p} \]

\[ d_p = r \tan(\alpha_{\text{max}} t_s) \]

\[ \rho = \frac{d_p}{l_p} \]

\[ l_p \rho = r \tan(\alpha_{\text{max}} t_s) \]

\[ t_s = \frac{\tan^{-1}(l_p \rho)}{\alpha_{\text{max}}} \]

\[ n_o = \frac{l_o n_p}{d} \]

\[ \% \text{smear} = \frac{\rho}{n_o} \]
Pixel Smear: Results

- $\rho = 0.2$ (1/5 of a pixel is smeared before camera is able to take a picture)
  - Need $t_s = 5.4$ms
  - Percent smear of object pictured in figure

- Camera has a shutter time of $30\mu s$ which is much faster

- In worst case, with $t_s = 5.4$ms and a 10cm debris at 20m smear is only about 1.2% of the object.
• Camera attached to 6-DOF robot such that it could see debris throughout rendezvous
• Robot moved along same trajectory that will be used for actual capture scenario
• Camera saved images at rate of 2Hz
• Images processed using C functions to detect debris and calculate size
• Range at each image found by correlating timestamp on image to data file with inertial position of camera
Initialize camera context and image variable → Open Ethernet port → Connect to camera → Establish Receive Buffer for Images → Send software trigger to acquire image → Begin streaming images → Create image structure in image variable → Save image to receive buffer → Stop streaming images → Raw Image → PIRANHA Main Code

Initialization procedure

Trigger Camera
Laser Rangeﬁnder Interface Flow Diagram:

- Triggering rangefinder to get range rather than picking range of stream of measurements to decrease processing time

Servo Interface Flow Diagram:

- Sample data packet: \{0xFF, 0xFF, ID, Length, Instruction, Address, Low value, High value, Checksum\}
- Must send DCS and debris inertial attitude and position to command robots
  - Rate of 20Hz
  - Specific data structure
- Ethernet Interface
  - UDP/IPv4
- Status:
  - Successfully sent data structure over Ethernet from laptop to SOSC computers (single frame)
  - Can send entire scenario over Ethernet and write results to data file for comparison
    - Need to test in SOSC still
    - Will be used for HWIL Phase II testing
Assembly of Gimbal System

- Smooth assembly
- Few minor adjustments (longer fasteners)
- Original pin was too small, allowed play between the brackets
- New pin fits tightly, system feels smooth, no binding in the tilt servo

Gimbal System with Original Pin

Play between the two brackets – centers of ball bearings not aligned

Pan axis of rotation

Laser beam

Press fit bearings with pin

Tilt axis of rotation
Camera/Rangefinder Bracket

Gimbal Corner Bracket

F = W_{Range} + W_{Cam/Rangefinder bracket}

\delta_{max} = \frac{Fd^3}{3EI}

Max. Deflection (Ti-6Al-4V) = 0.55 \mu m
Max. Deflection (6061 T6 Al) = 0.75 \mu m

F = W_{Range} + W_{Cam} + W_{Cam/Rangefinder bracket} + W_{Corner bracket} + W_{Tilt servo}

\delta_{max} = \frac{Fb(l^2 - b^2)^{\frac{3}{2}}}{9\sqrt{3EI}}

Max. Deflection (Ti-6Al-4V) = 0.28 nm
Max. Deflection (6061 T6 Al) = 0.41 \mu m
## Bracket Strength

<table>
<thead>
<tr>
<th>Ti-6Al-4V</th>
<th>Technical Data Sheet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate Bearing Strength</td>
<td>1380 – 2070 MPa</td>
</tr>
<tr>
<td>Yield Strength</td>
<td>825 – 895 Mpa</td>
</tr>
<tr>
<td>Shear Strength</td>
<td>480 – 690 MPa</td>
</tr>
</tbody>
</table>

\[
\sigma_y = \frac{F_n}{A} \rightarrow \frac{ma}{A} \rightarrow a = \frac{\sigma_y A}{m} \\
\tau_y = \frac{F}{A} \rightarrow \frac{ma}{A} \rightarrow a = \frac{\tau_y A}{m}
\]

If all the mass of the entire system was placed on the narrowest surfaces and the material failed at the low end of the material index, the system would need to see accelerations that are very unrealistic for the SOSC.
Empirical Equation:

\[ h_c = 10.45 - v + 10v^2 \]

\[ h_{c,fan} = 18.8 \, W/m^2K \]

SBC – Operates between 20° and 60° C

\[ Q = h_c (T_s - T_\infty) \rightarrow Q_{fan} = 17.88 \, W \]

\[ Q_{hs} = \frac{T_s - T_\infty}{1/h_cA_s} = 4.26 \, W \]

\[ \bar{h}_c = \text{heat transfer coefficient} \]

\[ Q = \text{heat transfer by convection} \]

\[ v = \text{velocity} \]

\[ T = \text{temperature} \]

The fan can remove four times as much heat as the heat sink puts out.
### Electronics

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Board Computer</td>
<td>$404.01</td>
</tr>
<tr>
<td>SBC repurchase</td>
<td>$314.80</td>
</tr>
<tr>
<td>Power Board</td>
<td>$50.44</td>
</tr>
<tr>
<td>USB to RS-485 Converter</td>
<td>$30</td>
</tr>
<tr>
<td>Electronics Enclosure</td>
<td>$39.17</td>
</tr>
<tr>
<td>Power Board Components</td>
<td>$35.18</td>
</tr>
<tr>
<td>Power adapter</td>
<td>$4.95</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$878.55</strong></td>
</tr>
</tbody>
</table>

### Instruments

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range Finder</td>
<td>$1282.50</td>
</tr>
<tr>
<td>PointGrey Flea3 Camera</td>
<td>$1085</td>
</tr>
<tr>
<td>Camera Lens</td>
<td>$115.46</td>
</tr>
<tr>
<td>2 x MX-64 Servos</td>
<td>$611.80</td>
</tr>
<tr>
<td>2 Servo Brackets</td>
<td>$50.79</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$3285.55</strong></td>
</tr>
</tbody>
</table>

### Mechanical HW

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bearings</td>
<td>$21.66</td>
</tr>
<tr>
<td>Pins for bearings</td>
<td>$12.57</td>
</tr>
<tr>
<td>Screws/Test eq.</td>
<td>$20.86</td>
</tr>
<tr>
<td>Additional HW</td>
<td>$2.81</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$57.90</strong></td>
</tr>
</tbody>
</table>

### Miscellaneous

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFR Printing</td>
<td>$44.59</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$44.59</strong></td>
</tr>
</tbody>
</table>

**TOTAL = $4,266.59**
Safety Concerns: SOSC

• Primary safety concern is ladder fall
  • Will be mitigated by inspecting ladder before use

• Secondary safety concern is robot motion
  • Will be mitigated by communication prior to robot motion: Team members within the robot range of motion will be verified to be ‘ready’ verbally prior to motion. Motion will be preceded by the shout “MOTION.”
**NON-SOSC Testing**

- CMP.2.1.1.1: Gimbal Hardware Test
- CMP.4.2.1: HWIL Phase II
- CMP.4.2.1.1: HWIL Phase II
- DES.5.1: HWIL Phase II

*All other requirements are check box type, or will be verified in calibration of rangefinder*

**SOSC Testing**

- DES.2.1: Comm. Check and Phase I
- DES.3.1: Stage I-III
- CMP.3.1.1: Stage II-III
- DES.4.1: Stage II-III
- DES.4.1.1: Stage III