Proximity Identification, Characterization, And Neutralization by tHinking before Acquisition (PIRANHA)

Critical Design Review

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Team: Aaron Buysse, Chad Caplan, Matt Holmes, Colin Nugen, Kevin Rauhauser, Ryan Slabaugh, Rebecca Travers

Advisor: Dr. Jelliffe Jackson

8/24/2014
Purpose
Solution
Critical Project Elements (CPE)
Requirements & Satisfaction
Risks
Verification & Validation
Planning
Facts

• Millions of pieces of debris in orbit\(^1\)
• GOCE satellite reentered atmosphere on November 10\(^{th}\), 2013\(^2\)
• No active measures taken to reduce debris

Artist Rendition of Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) Satellite.\(^2\)
Space Operations Simulation Center

**DETECT & RANGE**
- Debris centered in camera FOV
- Laser rangefinder ranges debris

**THINK**
- TOO BIG
- TOO SMALL
- Fits in DCS

**POSITION FINDING**
- $r_{rel}$

**CAPTURE**
- Laser rangefinder

Debris Camera detects debris centered in camera FOV. Laser rangefinder ranges debris, determining if debris is too big or too small and fits in DCS.
Space Operations Simulation Center

**Stage 1**

**PIRANHA:**
- Calculates, stores debris relative position vector and DCS attitude

**SOSC Robot:**
- Runs trajectory using pre-canned attitude & ephemeris data stored on SOSC computer

**Stage 2**

**PIRANHA:**
- Calculates, stores position & attitude
- **Transmits pre-canned attitude & ephemeris data to robot**

**SOSC Robot:**
- Runs trajectory using pre-canned attitude & ephemeris data transmitted from PIRANHA

**Stage 3**

**PIRANHA:**
- Calculates, stores position & attitude
- **Transmits pre-canned ephemeris**
- Calculates, transmits **real-time attitude data to robot**

**SOSC Robot:**
- Runs trajectory using pre-canned ephemeris and real-time attitude data transmitted from PIRANHA
Design Solution

PIRANHA

Heritage Debris Capture System

Dimensions:
- 56 cm width
- 20 cm height
- 62 cm height
- 90 cm width
Design Solution: PIRANHA

- Rangefinder
- Camera
- 2-DOF Gimbal Assembly
- Servos
- Software and Computing Hardware
**Camera**

<table>
<thead>
<tr>
<th>Point Grey Flea3 GigE³</th>
<th>Pixels</th>
<th>2.8 MP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interfacing</td>
<td>Ethernet</td>
<td></td>
</tr>
<tr>
<td>Color Depth</td>
<td>12 bit</td>
<td></td>
</tr>
<tr>
<td>Size</td>
<td>29mm x 29mm x 30mm</td>
<td></td>
</tr>
<tr>
<td>Price</td>
<td>$995</td>
<td></td>
</tr>
</tbody>
</table>

**Rangeﬁnder**

<table>
<thead>
<tr>
<th>Acuity AR1000 Laser Distance Sensor⁴</th>
<th>Precision</th>
<th>± 3mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Range</td>
<td>0.1 m</td>
<td></td>
</tr>
<tr>
<td>Sample Rate</td>
<td>6 Hz</td>
<td></td>
</tr>
<tr>
<td>Size</td>
<td>195mm x 96mm x 50mm</td>
<td></td>
</tr>
<tr>
<td>Price</td>
<td>$1250</td>
<td></td>
</tr>
</tbody>
</table>
Design Solution: Gimbal System

Gimbal system

- 2-DOF
- Camera at center of rotation

Servos

<table>
<thead>
<tr>
<th>Dynamixel MX-64R</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>0.088˚</td>
</tr>
<tr>
<td>Stall Torque</td>
<td>6 N.m (at 12V, 4.1A)</td>
</tr>
<tr>
<td>Rate</td>
<td>58 rpm (at 11.1V)</td>
</tr>
<tr>
<td>Position Finding</td>
<td>Magnetic encoder, cable connection</td>
</tr>
<tr>
<td>Price</td>
<td>$305 (each)</td>
</tr>
</tbody>
</table>

FNC.2: Detect debris at 20m

DES.4.2: Pointing & Tracking during entire capture scenario

FNC.4: Pointing & Tracking Debris

CMP.2.1.1: Camera shall have 2DOF independent of DCS

CMP.2.1.1.1: Pointing accuracy shall be a minimum of ±0.14˚

Dynamixel MX-64R

- 0.088˚ resolution
- Stall Torque: 6 N.m at 12V, 4.1A
- Rate: 58 rpm at 11.1V
- Position Finding: Magnetic encoder, cable connection
- Price: $305 (each)

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Gimbal brackets

• 3D printing at Lockheed Martin
  • Ti-6Al-4V – electron beam melting
• Will manufacture brackets if necessary
  • 6061 T6 Al
Single Board Computer

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCM-9362 Intel Atom⁶</td>
<td></td>
</tr>
<tr>
<td>Processing Frequency</td>
<td>1.66 GHz</td>
</tr>
<tr>
<td>Interfacing</td>
<td>Ethernet, USB 2.0,</td>
</tr>
<tr>
<td></td>
<td>RS-232/422/485</td>
</tr>
<tr>
<td>Random Access Memory</td>
<td>1 GB</td>
</tr>
<tr>
<td>Size</td>
<td>146mm x 102mm</td>
</tr>
<tr>
<td>Price</td>
<td>$273</td>
</tr>
</tbody>
</table>

FNC.4: Output relative position of debris
FNC.3: Characterize debris
TSR.2.1: Camera
TSR.2.2: Servos
TSR.3.1: Rangefinder
TSR.3.2: Image processing
CMP.4.1.1: Interface with camera, rangefinder, and servos
Removal of Optical Rim Sensor

Ideal Case

Top View of DCS (Looking Down into DCS)

Multiple Concerns with Optical Rim Sensor
- Tight tolerances
- Can detect extrusion via image processing

Propagation of 1° Error on First Mirror

Inside of DCS Top View

Final Reflector would have to be 9.54cm long

Size Characterization Algorithm Results

Calculated Size 49.5cm

Algorithm computes size assuming debris is circular

Simulated Debris with Extrusion

Actual Size 50.0cm

Top View of DCS
- Transmitter
- Receiver
- Reflectors

DCS Rim

Transmitter

Receiver

Reflectors with 1° error

Reflectors

DCS Rim

Simulated Debris

Original Picture
FNC.2 PIRANHA shall detect the presence of debris within 20mi proximity of the DCS.

FNC.3 PIRANHA shall characterize objects based on their size and shape.

FNC.4 PIRANHA shall output the position of the debris relative to the DCS vector (pointing and tracking telemetry).

FNC.5 PIRANHA shall be testable via interface with the SOSC testbed.
Critical Project Elements

CPE.1 Interfacing

CPE.2 Pointing & Control

CPE.3 Detect & Size

CPE.4 SOSC Integration
SOSC Experiment

Goal: Characterize debris within ±2cm

Setup:

\[ x \equiv \text{Distance between camera & debris} \]

Results:

- DES.3.1: Software calculated size to within ±2cm
- Distance to debris = 20.30m
- Actual Size = 10.2cm

Calculated Size = 9.00cm

FNC
- FNC.2, FNC.3
  - Detect and Size characterization

CPE
- CPE.3
  - Detect at 20m & Characterize to ±2cm

TSR
- TSR.3.2
  - Image Processing

CMP
- CMP.3.2.1
  - Size w/ Minimum 16 pixels

DES.3.1: Software calculated size to within ±2cm
Electrical: DC Power Supply:
- AMETEK DLM-60-10-M130
- 0-60V±2mV and 0-10A (600W)

Data: Ethernet
- 10, 100, and 1000 megabit options

Mechanical: Mounting
- L-bracket connections
- Already available

Provide: Data Structure
- Inertial Ephemeris and Attitude Quaternions of Debris and DCS

Screenshot of STK Scenario

Debris & DCS are to scale

Ephemeris & Attitude Verified in STK and by SOSC Engineers
### Functional Requirements
- FNC.2: Detect & Range
- FNC.3: Determine Size
- FNC.4: Determine Position
- FNC.5: Interface with SOSC

### Trade Study Results
- Camera
- Rangefinder
- Servos
- Single Board Computer
- Ethernet

### Critical Project Element
- CPE.1: Ability to interface all components from trade study results
### Interfacing – Power

#### Power Schematic

![Power Schematic Diagram](image)

#### Component Power Table

<table>
<thead>
<tr>
<th>Component</th>
<th>Voltage (V)</th>
<th>Current (A)</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camera</td>
<td>12</td>
<td>0.21</td>
<td>2.50</td>
</tr>
<tr>
<td>Single Board Computer</td>
<td>5</td>
<td>2.31</td>
<td>11.55</td>
</tr>
<tr>
<td>Servos</td>
<td>12</td>
<td>0.96*</td>
<td>11.48</td>
</tr>
<tr>
<td>Rangefinder</td>
<td>15</td>
<td>0.13</td>
<td>1.88</td>
</tr>
</tbody>
</table>

*Servo current based on max torque experienced with safety factor added

#### Regulator Specifications

<table>
<thead>
<tr>
<th>Regulator</th>
<th>KA278R12CTU</th>
<th>LT323AT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage</td>
<td>15V</td>
<td>15V</td>
</tr>
<tr>
<td>Output Voltage</td>
<td>12V</td>
<td>5V</td>
</tr>
<tr>
<td>Max Output Current</td>
<td>Rated 2A</td>
<td>Expected 1A</td>
</tr>
<tr>
<td></td>
<td>Rated 3A</td>
<td>Expected 2.3A</td>
</tr>
<tr>
<td>Max Power Dissipation</td>
<td>15W</td>
<td>3W</td>
</tr>
<tr>
<td></td>
<td>30W</td>
<td>23W</td>
</tr>
</tbody>
</table>
**Interfacing – Hardware**

**Component Interface Diagram**

- **SOSC Interface**
- **Power Supply**
- **RS-232 Communication**
- **RS-485 Communication**
- **Data Storage**
- **Flash Drive**
- **Robot Interface**
- **Images Stored to RAM**
- **Ephemeris & Attitude Quaternion Sent from RAM to Flash Drive**
- **Relative Vector from Debris to DCS & DCS Attitude Quaternion from RAM to Flash Drive**

**Purpose**
- Laser Rangefinder
- Single Board Computer
- Camera
- Servos
- SOSC Interface

**Solution**
- Laser Rangefinder Hardware
- Camera Hardware
- Servo Hardware
- SOSC Interface
- Data Storage

**CPEs**
- Single Board Computer
- Ethernet Communication

**Requirements**
- Laser Rangefinder
- Single Board Computer
- Camera
- Servos
- SOSC Interface

**Risks**
- Range stored to RAM
- Image stored to RAM
- Ephemeris & Attitude Sent from RAM to robot interface via Ethernet

**V&V**
- RS-232 Communication
- RS-485 Communication

**Planning**
- Single Board Computer
- Ethernet Communication
- Power Supply
- Single Board Computer
- Robot Interface

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Purpose: Interfacing – Software

Solution:

- Laser Rangefinder

CPEs:

- ACUIY AR1000

Requirements:

- Hardware interrupt routine
- Laser rangefinder

Risks:

- Protocol: RS-232 8N1 9600 baud rate
- Range stored in DDR2 (RAM)
- Updated at 6Hz

V&V:

- Planning
Interfacing – Software

Camera

SERVOS

time

\[ t = 0 \text{s} \]
\[ t = 0.2 \text{s} \]
\[ t = 0.4 \text{s} \]
\[ t = 1.1 \text{s} \]
\[ t = 1.2 \text{s} \]
Interfacing – Software

**SOSC Interface**

- **Send Ephemeris and Quaternion to S.O.S.C. at a Rate of 20Hz**
- **Interrupt Time < 1ms**
- **Software Interrupt Routine: Ephemeris and Quaternion**

**Protocol:**
- Ethernet
- 1 Gb bandwidth

**Purpose**

**Solution**

**CPEs**

**Requirements**

**Risks**

**V&V**

**Planning**

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Interfacing – Software

Purpose

Solution

CPEs

Requirements

Risks

V&V

Planning

Servos

Camera

LOOPS WHILE RANGE IS GREATER THAN 1 METER

TRIGGER CAMERA

STORE IMAGE 1928 x 1448 MATRIX IN DDR2

IMAGE PROCESSING FUNCTION

CAMERA CONTROL FUNCTION

CHECK RANGE

SIZE FUNCTION

END LOOP

CALCULATE RELATIVE POSITION VECTOR AND QUATERNION

STORE DATA IN RAM WITH TIME STAMP.
Goal: Track and range debris throughout rendezvous

\[ \theta_c \equiv \text{critical pointing angle} \]

\[ \theta_c = \tan^{-1} \left( \frac{0.05m}{20m} \right) = 0.14^\circ \]
Image Processing:
- Median Filter – Removes noise from image
- Sobel Filter – Detects edges in image
- Centroid computed as average of edge points

Servo Model:
- 1% settling time of 0.3 seconds to step input
\[ \tan(\theta) = \frac{x_p \lambda}{d} \]

\[ \theta = \tan^{-1}\left( \frac{x_p \lambda}{d} \right) \]

\[ \tan\left(\frac{FOV}{2}\right) = \frac{h_p \lambda}{2d} \]

\[ d = \frac{h_p \lambda}{2 \tan\left(\frac{FOV}{2}\right)} \]

\[ \gamma = \tan^{-1}\left( \frac{2 y_p}{v_p} \tan\left(\frac{FOV}{2}\right) \right) \]

\[ \lambda \equiv \text{physical size per pixel} \]

\[ x_p \equiv \text{horizontal pixels from center} \]

\[ h_p \equiv \text{total horizontal pixels} \]
Debris occupies more pixels as DCS approaches.
**Pointing & Control – Simulink Model**

**CMP.4.2.1.1:** Command Servo at a rate greater than 0.4Hz

**CMP.4.2.2:** Shall be able to point with an accuracy of $\pm 0.14^\circ$
## Project Risks

<table>
<thead>
<tr>
<th>Risk Level</th>
<th>Minor Consequence</th>
<th>Moderate Consequence</th>
<th>Major Consequence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Degradation of results but overall mission success</td>
<td>Partial mission failure but most objectives still met</td>
<td>Complete or nearly complete mission failure</td>
</tr>
<tr>
<td><strong>Very Likely</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Moderate Likelihood</strong></td>
<td>3D printing errors • Error in range finding • Error in detection software</td>
<td>Failure to properly determine attitude for capture at rotation • Pointing and tracking errors</td>
<td>Unfamiliar programming language and operating sensor</td>
</tr>
<tr>
<td><strong>Unlikely</strong></td>
<td>• Gimbal pointing error</td>
<td>• Unable to test in SOSC • Servo shaft bending moment</td>
<td></td>
</tr>
</tbody>
</table>
Purpose:

- Software, Hardware-In-the-Loop (HWIL), and Hardware Component tests will verify requirements and investigate failure modes
- SOSC testing will validate the design
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 Control Law
DCS Attitude Calculation
Debris Size Characterization
Image Processing (Filtering & Centroiding)

Software Phase II
Integrated Software Functionality

PIRANHA “main” program

Purpose
Solution
CPEs
Requirements
Risks
V&V
Planning
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:

- **HWIL Phase I** – Verify hardware components are capable of being commanded by and interfaced with Single Board Computer (SBC), and perform as required. Also, verify servo control law performs as expected.

- **HWIL Phase II** – Verify SBC is capable of handling all Phase I components integrated as an entire system, and the whole performs as required

- Mitigate risks associated with a new coding language/environment, timing, and hardware-software interfacing

### HWIL Phase I

**Hardware Control & Communication**

- Servo Control Law
- Commanding Servos
- SBC/Camera Communication
- SBC/Laser Communication
- SBC/Servo Communication

### HWIL Phase II

**Entire PIRANHA instrument**

- PIRANHA Software
- Computer
- Servos
- Rangefinder
- Camera

**V&V: HWIL Testing – 2 Phase Approach**
Purpose:

- **Stage 1** – Verify performance relative to requirements in the intended operational environment, the SOSC
- **Stage 2** – Verify ability to transmit data to SOSC (first-step towards closed-loop operations)
- **Stage 3** – Validate instrument aides in debris capture by automating a portion of the process
- Mitigate risk associated with SOSC interfacing

**Purpose**:  
- **Stage 1** – Verify performance relative to requirements in the intended operational environment, the SOSC  
- **Stage 2** – Verify ability to transmit data to SOSC (first-step towards closed-loop operations)  
- **Stage 3** – Validate instrument aides in debris capture by automating a portion of the process  
- Mitigate risk associated with SOSC interfacing

**Solution**

- **CPEs**
- **Requirements**
- **Risks**
- **V&V**
- **Planning**
**Purpose:** Validate PIRANHA instrument aides in capturing debris by calculating and sending real-time attitude commands with pre-determined inertial ephemeris to robot interface.

**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>Attitude Data Structure</td>
<td>Compare to pre-canned attitude</td>
<td>Max attitude error 2.18°</td>
<td>DES.5.1.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>DES.5.1.2</td>
</tr>
</tbody>
</table>

**Comparison of Attitude Data Structure**

**Diagram**

**Ephemeris & Attitude Downlink**

**Required Materials/Facilities:**

- SOSC Facility
- Ephemeris & Attitude data files
- Ethernet cable
- PIRANHA & DCS

**Diagram**

**Ephemeris & Attitude Downlink**
Purpose: Verify that the algorithm used to calculate servo pointing commands is able to do so within requirements:

- Difference between desired angle and actual angle will be no larger than 0.14 degrees
- The control system shall be able to update pointing commands to the servos at a rate greater than 0.4 Hz.

This test will also help mitigate risk of PIRANHA failing due to control law design errors.

Diagram:
### 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 Pointing Angle</td>
<td>Commanded Pointing Angle</td>
<td>Under the 0.14 degree requirement</td>
<td>CMP.2.1.1.1</td>
</tr>
<tr>
<td>Servo Pointing Angle Update Rate</td>
<td>Direct Comparison with Requirement</td>
<td>Better than 3.33 Hz</td>
<td>CMP.4.2.1.1</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

### Results

**CMP.4.2.2:** Shall be able to point with an accuracy of ±0.14°
**Purpose**

Software Phase I, Component Testing, Power Board Fabrication, Initializing SBC, Manufacturing Gimbal

**Solution**

3D Print Brackets, Order Components, Design & Order Power PCB

**CPEs**

- HWIL Phase I,
  - Manufacture Gimbal Brackets if 3D print fails

**Requirements**

**Risks**

**V&V**

**Planning**

- Week 1: SOSC Testing
- Week 5: Software Phase I, HWIL Phase I, Verify Requirements
- Week 10: Mechanical, Electrical, Software, Systems, Test, Milestone, Uncertainty
- Week 15: SOSI Spring Symposium, Final Presentation
Purpose

Solution

CPEs

Requirements

Risks

V&V

Planning

Critical Path

Week 1

Week 5

Week 10

Week 15

Purchasing Components

Hardware Component Testing

HWIL Testing Components on SBC

Machining Gimbal Brackets

HWIL Testing Entire Functionality

SOSC Testing

Mechanical

Electrical

Software

Systems

Test

Milestone

Uncertainty

CDR

Week 2

Week 3

Week 4

Week 6

Week 7

Week 8

Week 9

Week 11

Week 12

Week 13

Week 14

Week 16

Week 17

Week 18

Week 19

Week 20

Week 21

Week 22

Week 23

Week 24

Week 25

Week 26

Week 27
### Cost Plan

- Purchases confident in as of clearing CDR ~ $3200
- Budget Margin ~ $1800
- Margin to repurchase any single component in case of accidents
- Margin could allow for registration to AIAA conference if accepted

<table>
<thead>
<tr>
<th>Hardware</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acuity AccuRange 1000 (Rangefinder)</td>
<td>$1250</td>
</tr>
<tr>
<td>Point Grey Flea with lens (Camera)</td>
<td>$995</td>
</tr>
<tr>
<td>Two MX-64R Actuators (Servos)</td>
<td>$610</td>
</tr>
<tr>
<td>PCM – 9362 (Single Board Computer)</td>
<td>$273</td>
</tr>
<tr>
<td>RAM &amp; ROM</td>
<td>$44</td>
</tr>
<tr>
<td>3D Printed Bracket</td>
<td>$0</td>
</tr>
<tr>
<td>Electronics Box</td>
<td>$30</td>
</tr>
<tr>
<td>Printed Circuit Boards</td>
<td>$65</td>
</tr>
<tr>
<td>Mechanical hardware (metals, bolts, etc.)</td>
<td>$50</td>
</tr>
<tr>
<td>Wiring (USB, Ethernet, interface cords, etc.)</td>
<td>$20</td>
</tr>
<tr>
<td>Shipping Estimates</td>
<td>$60</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$3397</strong></td>
</tr>
</tbody>
</table>
**Specialized Facilities Required:**
- Space Operations Simulation Center at Lockheed Martin
- Allotted 11 days for testing
  - Expecting 2-3 days required for testing
References


Camera/Rangefinder Bracket

Gimbal Corner Bracket

Cantilever Beam

\[ F = W_{\text{Range}} + W_{\text{Cam/Range bracket}} \]

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

\[ \delta_{\text{max}} = \frac{F l^3}{3E I} \]

Beam Cross Section

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

\[ I = 1.559 \times 10^{-7} \text{m}^4 \]

\[ E_{\text{Ti-6Al-4V}} = 113.8 \text{ GPa} \]

\[ E_{\text{6061 T6 Al}} = 68.9 \text{ GPa} \]

\[ d = 0.1305 \text{ m} \]

\[ l = 1.111 \times 10^{-5} \text{ m}^4 \]

\[ a = 0.0625 \text{ m} \]

\[ b = 0.0417 \text{ m} \]

\[ l = 0.1042 \text{ m} \]
Gimbal Bracket Torque Margins

Tilt Servo

\[ T = F_{\text{tilt}} d \]
\[ F_{\text{tilt}} = W_{\text{Range}} + W_{\text{Cam}} + W_{\text{Cam/Range bracket}} \]

Req. Torque (Ti-6Al-4V) = 1.77 Nm
Req. Torque (6061 T6 Al) = 1.48 Nm

At 11.1V, 3.9A, servo stall torque is 5.5 Nm (>2x any required torque)

Pan Servo

\[ T = F_{\text{pan}} d \]
\[ F_{\text{pan}} = W_{\text{Range}} + W_{\text{Cam}} + W_{\text{Cam/Range bracket}} + W_{\text{Corner bracket}} + W_{\text{Tilt servo}} \]

Req. Torque (Ti-6Al-4V) = 2.08 Nm
Req. Torque (6061 T6 Al) = 1.83 Nm

d = 0.1305 m

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Bending Moment on Pan Servo Shaft

Moment: 1.73 N-m

- Will order servos early for testing
- Will manufacture “panning” bracket if necessary
  - Bending moment will be held by bracket
  - Only torque on servo shaft

Bearings
- Combination of ball and thrust bearings
- Support radial load on servo shaft
- Allow free panning rotation

Pan axis of rotation
Slide Intentionally Left Blank

Slides here after are backup V&V slides illustrating various tests that will be performed.
**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.

**Summary of Measurements:**
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
**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)

**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**

![Diagram](image)
**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**

![Diagram](image)

**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 Rotation Rate</td>
<td>Comparison with capture scenario model</td>
<td>Greater than 200 deg/s for all scenarios</td>
<td>TSR.2.2</td>
</tr>
</tbody>
</table>

**Diagram**
- Green = Mass Characteristic of PIRANHA Load on Servo
- Gray = Servo
- Dashes = Rotation Axis
- Dashes = Vertical Reference

Θ varied from 0 to 30 degrees
**Purpose:** Verify PIRANHA is able to accurately calculate and store attitude and the relative position vector of the debris at a rate no less than 10Hz as it moves through a pre-determined STK scenario. This test will mitigate risks associated with PIRANHA not being able to determine the position of the debris relative to the DCS accurately, attitude of the DCS accurately, or at the required rate.

**Diagram**

---

**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>Debris relative position calculated by PIRANHA</td>
<td>Comparison with debris relative position &amp; Attitude from STK scenario</td>
<td>± 0.045m</td>
<td>DES 4.1 DES 4.2</td>
</tr>
</tbody>
</table>

**Required Materials/Facilities:**
- SOSC Facility
- Ephemeris & Attitude data files
- PIRANHA & DCS

**Comparison of Debris Relative Position Vectors**
- Debris Relative Position & Attitude Calculated by PIRANHA
- Debris Relative Position & Attitude from STK Scenario
- Compare
**Purpose:** Verify PIRANHA is able to output an ephemeris & attitude data structure at a rate of no less than 10Hz. This test will mitigate risks associated with PIRANHA not being able to communicate with the SOSC robot.

**Diagram**

---

**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>Data transfer Rate</td>
<td>Analyze data post Ethernet transmission</td>
<td>Transfer rate &gt; 10Hz</td>
<td>DES.5.1</td>
</tr>
</tbody>
</table>

**Required Materials/Facilities:**
- SOSC Facility
- Ephemeris & Attitude data files
- Ethernet cable
- PIRANHA & DCS

**Comparison of Ephemeris & Attitude Data Structure**

- Transmitted Ephemeris & Attitude File
- Ethernet
- Received Ephemeris & Attitude
**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:**

```
Capture Scenario Trajectory Model

Logic

Euler Angle

Servo Model

Rangefinder Model

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 $1/6^{\text{th}}$ 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
**Purpose:** To verify the capability of detecting an object in the S.O.S.C. environment. This authenticates that our image processing function can detect an object between 1 and 20 meters, with a diameter of 10 cm. This test verifies that the algorithm developed can satisfy FNC.2, DES.2.1, and TSR.2.1: Detection of 10 cm diameter at 20m with a camera.

**Diagram of Test Set-Up:**

- **Physical Test Set-Up:**
  - **Image**
  - **Range**
  - **Diameter**
  - **Object Detected?**
  - **Compare**
  - **Given diameter and range, should object be detected?**

---

*Image Processing Function Diagram*
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>Binary, Detected of Not?</td>
<td>Physical dimensions of test set up</td>
<td>Objects of 10 cm diameter are detected at a range of 20 m</td>
<td>FNC.2, DES.2.1, TSR.2.1</td>
</tr>
</tbody>
</table>

Required Materials/Facilities:
- SOSC
- White sphere of 10 cm diameter
- Computer running MATLAB, or eventually single board computer running C and chosen environment
Purpose: To verify the software size characterization 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>Handheld Laser Rangefinder standing under camera and debris</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
Results: 10.2cm Diameter Debris at a range of 4.20m

Calculated Size = 9.22cm

<table>
<thead>
<tr>
<th>Test</th>
<th>Distance [m]</th>
<th>Calculated Size [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.30</td>
<td>9.0</td>
</tr>
<tr>
<td>2</td>
<td>4.20</td>
<td>9.22</td>
</tr>
<tr>
<td>3</td>
<td>20.12 &amp; 19.82</td>
<td>8.63</td>
</tr>
<tr>
<td>4</td>
<td>15.16</td>
<td>8.87</td>
</tr>
<tr>
<td>5</td>
<td>10.00</td>
<td>8.93</td>
</tr>
<tr>
<td>6</td>
<td>5.46</td>
<td>–</td>
</tr>
</tbody>
</table>

Size characterization was within ±2cm requirement for each test

Materials:
- MATLAB
- Camera
- Rangefinder

Facilities:
- SOSC
- Maneuverable Robot

Actual Size of Debris → Image Processing → Calculated Size → Compare
**Purpose:** Verify all software components, when put together, function in line with expectations and requirements. The test will also provide additional insight into the possibility of PIRANHA failing due to software function interfaces.

**Diagram:**

- Image of Simulated Debris (from camera and capture models)
- Range (from range and capture models)
- Simulink Block containing PIRANHA “main”
  - Camera Pointing Commands
  - Relative Vector to Debris
  - Quaternion for SOSC
  - Compare
- Debris Size Characterization
  - Compare
- Capture Scenario Model
## 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>Camera Pointing Commands</td>
<td>Comparison with input</td>
<td>Within 0.14 degrees of capture scenario geometry</td>
<td>CMP.2.1.1.1, CMP.4.3.1.1</td>
</tr>
<tr>
<td>Vector to Debris</td>
<td>Comparison with input</td>
<td>Angle within 0.14 degrees, magnitude within 0.045 m</td>
<td>CMP.4.3.1, DES.4.1</td>
</tr>
<tr>
<td>Quaternion to SOSC</td>
<td>Capture Scenario Model, input</td>
<td>Identical to capture scenario model</td>
<td>DES.4.1.1, DES.4.3</td>
</tr>
<tr>
<td>Debris Size Characterization</td>
<td>Input</td>
<td>Reflects simulated image of debris</td>
<td>DES.3.2</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
- Camera, rangefinder, capture scenario models
Purpose: This test is to verify that the laser rangefinder’s output data can be collected and stored by the single board computer. This will help mitigate risk of PIRANHA failing due to the software algorithm being unable to access range measurements.

Diagram of Test Set-Up:

Summary of Measurements:

<table>
<thead>
<tr>
<th>Measurement</th>
<th>How the Measurement is Verified</th>
<th>Related Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Rangefinder output range stored on SBC</td>
<td>Compare physical range of LRF to data transfer range</td>
<td>CMP.4.1.1</td>
</tr>
</tbody>
</table>

Required Materials/Facilities: Requires the PCM-9362 (SBC) with Linux and use of GCC compiler, AR1000 (LRF), DC power supplies of 5V and 15V, Computer monitor,
**Purpose:** This test is to verify that the camera can be trigger via software and an image can be stored on board the single board computer. This will help mitigate risk of PIRANHA failing due to the software algorithm being unable to access images.

**Summary of Measurements:**

<table>
<thead>
<tr>
<th>Measurement</th>
<th>How the Measurement is Verified</th>
<th>Related Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image stored on SBC</td>
<td>Image viewed on computer monitor</td>
<td>CMP.4.1.1</td>
</tr>
</tbody>
</table>

**Required Materials/Facilities:** Requires the PCM-9362 (SBC) with Linux and use of GCC compiler, Point Grey Flea, DC power supplies of 5V and 12V, Computer monitor
**Purpose:** This test is to verify that a servo can be instructed via software to move to a position and then have the final position returned to the single board computer. This will help mitigate risk of PIRANHA failing due to the software algorithm being unable to point the rangefinder/camera, or read off angle measurements for the relative position vector.

**Diagram of Test Set-Up:**

<table>
<thead>
<tr>
<th>Measurement</th>
<th>How the Measurement is Verified</th>
<th>Related Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Send and receive data from servo</td>
<td>Compare output position from servo to command position</td>
<td></td>
</tr>
</tbody>
</table>

**Required Materials/Facilities:** Requires the PCM-9362 (SBC) with Linux and use of GCC compiler, MX-64 Servo, DC power supplies of 5V and 12V, Computer monitor
**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 = 1, 5, 10, 15, 20 meters
- 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
**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>Pixels</td>
<td>Pixel count</td>
<td></td>
<td>DES.2.1, DES.3.1</td>
</tr>
<tr>
<td>FOV (deg)</td>
<td>Distance for field of view known at 20 meters</td>
<td>Depends on Lens</td>
<td>DES.2.1, DES.3.1</td>
</tr>
</tbody>
</table>

### Required Materials/Facilities:

- Wall
- PointGrey Flea 3.0
- Image Processing Software
**V&V: HWIL Control Law**

**Purpose:** Verify that the control law, when connected with the camera, centers an object in the field of view in the manner stated by project requirements. The test will also help in mitigating the risk of PIRANHA failing due to inability of the debris to be ranged.

**Required Materials/Facilities:**
- Camera gimbal assembled according to design
  - Servos, camera, rangefinder attached
- Single Board Computer
- Communication cables (USB and RS-485)
- 2 white spheres, 10 and 40 cm in diameter
- Black Sheet

**Comparison of Object Position in FOV with Ideal**

<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>Calculated Centroid offset from Field of View Center</td>
<td>Comparison with control law software test</td>
<td>± 0.14° maximum</td>
<td>CMP.2.1.1.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>CMP.4.2.1.1</td>
</tr>
</tbody>
</table>

**Summary of Measurements:**

**Diagram**
**Purpose:** Verify that in a capture-like scenario, PIRANHA is capable of tracking, ranging characterizing debris, and outputs quaternion and ephemeris data in a form acceptable by the SOSC. The test will also verify that all hardware and software is interfacing correctly, and will help in mitigating risk of failure associated with running all software and hardware concurrently.

**Diagram:**

- Camera sees where debris is on the table
- Fishing Line to Move Debris
- PIRANHA Measured Debris Position
- Compare
- Debris Size Characterization
- Quaternion/Ephemeris Compared to required format

Debris less than 1 meters verified to begin the DCS turn

Table
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>Relative Position Vector</td>
<td>Known Relative Position via Camera and Table Markings</td>
<td>+/- 3 mm (AR1000 Data Sheet), pointing within 0.14 degrees</td>
<td>FNC.4, DES.4.1, CMP.4.2.1.1</td>
</tr>
<tr>
<td>Relative distance at which Quaternion Output Changes</td>
<td>Known Relative Distance via Camera and Table Markings</td>
<td>+/- 3mm</td>
<td>DES.4.2</td>
</tr>
<tr>
<td>Ephemeris and Quaternion Format and Rate</td>
<td>SOSC Known Requirements</td>
<td>Identical</td>
<td>FNC.5, DES.5.1</td>
</tr>
<tr>
<td>Debris Characterization</td>
<td>Simulated Debris Measurement</td>
<td>Reflects Test Case Ball Size</td>
<td>CMP3.1.1.1, DES.3.2</td>
</tr>
</tbody>
</table>

Required Materials/Facilities:
- Table with minimum dimensions 2x1 [m]
- Paper on which to create position reference for debris, or graph paper
- Secondary camera (808 # 16 camera already available, or cell phone)
- Timer with visible digits
- PIRANHA
- Sphere to simulate debris, 10-40 cm
- Fishing Line