Smallsat Connected Optical Positioning Entity

Spring Final Report

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Faculty Advisor: Zoltan Sternovsky

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Motivation

→ Need **relative motion** and **orientation** of nearby spacecraft in **proximity operations**
→ Find **inexpensive**, **autonomous**, and **accurate** solution
Project Objectives

Design, build, and test a proof-of-concept sensor package that collects **relative motion** and **orientation** data of a TARGET satellite for output to the CHASE satellite on-board attitude control system.

**Levels of Success**

**Level 1:** Detect and return data outputs for a target satellite with known markers up to 100m.

**Level 2:** Detect and return data outputs of a target satellite with no markers, but with a known 3-D model up to 100m.

**Level 3:** Detect and return data outputs of an unknown target satellite up to 1 km.
CHASE - Satellite housing design sensor package (SCOPE)

FLOOD - Flash Lidar Object Orientation Determination

FOV - Field Of View

ICP - Iterative Closest Point

IR - InfraRed light

LiDAR - Light Detection And Ranging

LRF - Laser Range Finder

SCOPE - Designed sensor package, housed on CHASE

TARGET - Target satellite to sense with design sensor package (SCOPE)
Mission CONOPS

SCOPE
sensor package

TARGET
Incoming Satellite

CAMERA
Offset in image

Camera origin

Position:
Velocity:
$\phi, \theta, \psi$
$\dot{\phi}, \dot{\theta}, \dot{\psi}$
Mission CONOPS

SCOPE

TARGET

Camera

TRACK

Position: $\hat{\mathbf{w}}$

Velocity: $\hat{\mathbf{w}}$

$<\phi, \theta, \psi>$

$\dot{<\phi, \theta, \psi>}$
Mission CONOPS

Purpose and Objectives

Test Overview

Test Results

Systems Engineering

Project Management

ORIENTATION

Position: 10.0 m \( \hat{u} \)
Velocity: 0.408 m/s \( \hat{u} \)
\( \phi, \Theta, \psi \): \( <260.3^\circ, 0.5^\circ, 0.2^\circ> \)
\( \dot{\phi}, \dot{\Theta}, \dot{\psi} \): \( <2.8^\circ, 0.3^\circ, 0.5^\circ>/s \)
Levels of Success

<table>
<thead>
<tr>
<th>Level 1</th>
<th>Detect and return data outputs for a target satellite with known markers up to 100m.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 2</td>
<td>Detect and return data outputs of a target satellite with no markers, but with a known 3-D model up to 100m.</td>
</tr>
<tr>
<td>Level 3</td>
<td>Detect and return data outputs of an unknown target satellite up to 1 km.</td>
</tr>
</tbody>
</table>
Design Description
Critical Project Elements

Centroid Determination
1. Use Background Subtraction to Detect TARGET.
2. Return Location in FOV for determining ADCS turning angles.

Position and Velocity Determination
2. Return position and velocity of TARGET satellite.

Orientation and Roll rate Determination
1. Return orientation of TARGET within 1 deg of actual.
2. Return angular rates of TARGET within 1% of actual.

1-U Satellite Constraints
1. Mass is less than 1.33[kg]
2. Dimensions fit within 10x10x10[cm]
3. Data is written at a rate faster than 2[Hz]
4. Average power remains below 20W

Four main CPE’s define SCOPES largest challenges
Functional Block Diagram

Purpose and Objectives

- Azimuth and Y-axis rotation to point directly at TARGET
- Relative distance and speed of TARGET
- Transformation matrix and rotational speeds of TARGET

Overview

- Rock64 Microcontroller
  - Determine rotation angles to point directly at SCOPE
  - Determine TARGET centroid location in edited frame
  - Remove background from image pane with Background Subtraction
  - Data smoothing through averaging distance and velocity
  - Calculate instantaneous velocity by change in distance
  - Receive distance from sensor’s face to TARGET
  - Characterize spin with FLOOD algorithm
  - Compare field of data to theoretical 3D model
  - Parse incoming spacial points and assign XYZ relative coordinates

Test Results

- Systems Engineering
- Project Management

Legend

- Wired Data
- Power Connection
- Information
- Sensor FOV/IR Beam
- Command
- Hardware Item

Target

- Optical Camera
- Distance USB 2.0 Finder
- Flash LiDAR Sensor

System Inputs

- Computer generated 3D model of TARGET
- 5V 2A Barrel Jack Adapter
- 3 Prong Wall Connector
- 24V Linear Power Supply
- Regulated 5VDC
- Regulated 24VDC
- Unregulated 120VAC

Satellite BUS

TARGET
Design Description

Purpose and Objectives

Test Overview

Test Results

Systems Engineering

Project Management

10[cm]

10[cm]

10[cm]

Mounting Face

Visual Camera

Flash LiDAR

Laser Range Finder

Rock64 Media board

6 Sided Sensor Housing
Overall Software Flow Chart

ROCK64 Microprocessor Board

- Image Pane
- Background Subtraction Algorithm
- Centroid Data ($<x, y> = [px]$)
- Testbed Turning Angles ($<\alpha, \beta> = [^\circ]$)
- SD Card Memory Space (ADCS)

- Distance and Velocity
- Position ($x = [m]$) + Velocity ($\dot{x} = [m/s]$)
- Initial Position

- Point Cloud (.pcd file)
- Iterative Closest Point
- Orientation ($<\varphi, \theta, \psi> = [^\circ]$) + Roll Rate ($<\varphi, \dot{\theta}, \psi> = [^\circ/s]$)

Legend:
- Raw Data
- Algorithm
- Data Output

Purpose and Objectives, Design, Test Overview, Test Results, Systems Engineering, Project Management
## Acquire Sensor Capabilities

<table>
<thead>
<tr>
<th>Driving Requirement</th>
<th>Design Parameter defined by Requirement</th>
<th>Sensor Capability</th>
<th>Requirement Fulfilled</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR 1.1</td>
<td>TARGET’s volume between 20x20x30[cm] and 1x1x1[m].</td>
<td>A total of 420 pixels are illuminated by TARGET at maximum distance and minimum volume</td>
<td>Yes</td>
</tr>
<tr>
<td>DR 1.2.1</td>
<td>Detect TARGET at a distance of 100[m]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DR 1.4.1</td>
<td>Detect TARGET under favorable lighting conditions</td>
<td>Visual camera → operates best under well-lit conditions</td>
<td>Yes</td>
</tr>
</tbody>
</table>

**DFK Autofocus Camera**
- Resolution: 5MP (2560x1920[px])
- Frame rate: 15 fps

**Aico 25mm Lens**
- FOV: 10.50°V x 14.68°H
**Background Subtraction**

### Assumptions
1. Only one moving object in frame
2. TARGET is always sun-facing

### Results
1. Centroid of object is found for Acquire/Track
2. Return initial centroid within 60s of boot
Background Subtraction in Action

Modelling from blender simulation

Real time acquisition on SCOPE
## Laser Range Finder Capabilities

### SF30-C Laser Rangefinder 100m

<table>
<thead>
<tr>
<th>Driving Requirement</th>
<th>Design Parameter defined by Requirement</th>
<th>Sensor Capability</th>
<th>Requirement Fulfilled</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR 1.2.1</td>
<td>Detect TARGET’s at a range of 100 m</td>
<td>Measurement range +100[m]</td>
<td>Yes</td>
</tr>
<tr>
<td>DR 2.1</td>
<td>Output TARGET’s satellite relative position with an error of less than 1%</td>
<td>Frame rate of 400 [Hz] Accuracy of +/- 10 [cm] Std position 0.0388 [m]</td>
<td>Yes</td>
</tr>
<tr>
<td>DR 3.1</td>
<td>Output TARGET’s satellite relative velocity with an error of less than 1%</td>
<td></td>
<td>No</td>
</tr>
</tbody>
</table>
### LiDAR Sensor Requirement Satisfaction

**IFM Electronics O3D301**

<table>
<thead>
<tr>
<th>Driving Requirement</th>
<th>Design Parameter defined by Requirement</th>
<th>Sensor Capability</th>
<th>Requirement Fulfilled</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR 4.1</td>
<td>Output <code>TARGET</code>’s relative orientation between 1[m] and 10[m].</td>
<td>Measurement range up to 10[m], and background up to 30[m].</td>
<td>Yes</td>
</tr>
<tr>
<td>DR 4.2</td>
<td>Output <code>TARGET</code>’s relative orientation with an error off less than 1[deg]</td>
<td>Individual point accuracy is +/- 2[cm]</td>
<td>Yes</td>
</tr>
<tr>
<td>DR 4.3</td>
<td>Determine orientation of <code>TARGET</code> through comparison with known 3D model.</td>
<td><code>.pcd (point cloud)</code> file output</td>
<td>Yes</td>
</tr>
</tbody>
</table>

**Image:**
- IR LEDs to illuminate target
- IR Camera
Iterative Closest Point ~ FLOOD

Assumptions
1. 3D model of TARGET is known
2. Initial position is known to within 1% of actual
3. Model is within frame of Flash Lidar sensor

Results
1. Outputs quaternion and translation vectors
Visualization of FLOOD algorithm aligning point with 3D model of TARGET to find relative orientation and position
Testing Overview
Test Overview

Adjustable Track

Target Test Stand

Target

Winch

SCOPE test stand

Purpose and Objectives

Design

Test Overview

Test Results

Systems Engineering

Project Management
## Acquire/Track Test Setup

### Requirements Verified

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR 1</td>
<td>The sensor package shall be capable of detecting a target satellite.</td>
</tr>
<tr>
<td>FR 2</td>
<td>The sensor package shall output the target satellite's relative position upon detection.</td>
</tr>
<tr>
<td>FR 3</td>
<td>The sensor package shall output the target satellite's relative velocity upon detection.</td>
</tr>
<tr>
<td>FR 6</td>
<td>The sensor package shall output target satellite data at a set frequency.</td>
</tr>
</tbody>
</table>

![Image of test setup with 105[m] distance]
## Acquire/Track Test Logistics

<table>
<thead>
<tr>
<th>Data Collected</th>
<th>Method of Collection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turning Angles for SCOPE to point at center of TARGET</td>
<td>SCOPE Cam w/ BGSUB through HDMI</td>
</tr>
<tr>
<td>Position and velocity of TARGET with respect to SCOPE body frame.</td>
<td>Acuity LRF vs. SCOPE sensor package</td>
</tr>
</tbody>
</table>

### Purpose and Objectives

- **Test Overview**
- **Test Results**
- **Systems Engineering**
- **Project Management**

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![Test Diagram](image-url)
## Track/Orientation Test Setup

### Requirements Verified

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR 2</td>
<td>The sensor package shall output the target satellite's relative position upon detection.</td>
</tr>
<tr>
<td>FR 3</td>
<td>The sensor package shall output the target satellite's relative velocity upon detection.</td>
</tr>
<tr>
<td>FR 4</td>
<td>The sensor package shall output the target satellite's relative orientation upon detection.</td>
</tr>
<tr>
<td>FR 5</td>
<td>The sensor package shall output the target satellite's relative rotation rate upon detection.</td>
</tr>
<tr>
<td>FR 6</td>
<td>The sensor package shall output target satellite data at a set frequency.</td>
</tr>
</tbody>
</table>
## Data Collected

| Position and velocity of TARGET with respect to SCOPE body frame. | Acuity LRF vs. SCOPE sensor package |
| Orientation and rotation rates about TARGET’s Z axis. | Rotary Encoder placed on TARGET’s rotational motor |

### Purpose and Objectives

- **Design**
- **Test Overview**
- **Test Results**
- **Systems Engineering**
- **Project Management**
Testing Results
### Driving Requirements for **Physical Characteristics**

| DR 1.1: The sensor shall be able to detect a target satellite with volumetric dimensions between 20x20x30 [cm] and 1x1x1 [m]. |
| DR 1.4: The sensor shall be able to detect a target satellite under **favorable lighting conditions**.* |

### Driving Requirements for **Motion Characteristics**

| DR 1.2: The sensor shall be able to detect a target satellite at a range of 100 [m]. |
| DR 3.1: The sensor package shall output the target satellite’s relative velocity with an error of less than 1% with a relative velocity of 0.1[m/s] to 1[m/s]. |
| DR 5.2: The sensor shall be able to detect target satellite rotation rates between 1[deg/s] and 5[deg/s]. |

*Favorable lighting conditions assumes diffusive white light on diffusive white paper.*
Simulated Centroid Determination

### Driving Requirements

<table>
<thead>
<tr>
<th>DR 1.2:</th>
<th>The sensor shall be able to detect a target satellite at a range of 100 [m].</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR 1.3:</td>
<td>The sensor shall detect the target satellite within 60(s) of turn-on.</td>
</tr>
<tr>
<td>DR 1.4:</td>
<td>The sensor shall be able to detect a target satellite under favorable lighting conditions.</td>
</tr>
</tbody>
</table>

All points fed into the Background algorithm were in the target area for both the large and the small target.
Driving Requirements

DR 1.2: The sensor shall be able to detect a target satellite at a range of 100 [m].

DR 1.3: The sensor shall detect the target satellite within 60(s) of turn-on.

DR 1.4: The sensor shall be able to detect a target satellite under favorable lighting conditions.

Instantaneous Centroid Determination
Success Rate = 100%

Centroid Determination
Success Rate = 5/5 trails

Level of Success = Level 2
**Driving Requirements**

**DR 1.2:** The sensor shall be able to detect a target satellite at a range of 100 [m].

**DR 1.3:** The sensor shall detect the target satellite within 60(s) of turn-on.

**DR 1.4:** The sensor shall be able to detect a target satellite under favorable lighting conditions.

**Instantaneous Centroid Determination**
Success Rate = 47.68%

**Centroid Determination**
Success Rate = 3/5 trails

Level of Success = Level 2
Centroid determination is **heavily dependent** on lighting conditions, as seen from small TARGET data.

Calibration of camera’s FOV was difficult with autofocus feature. Solution to move towards **fixed lens**.
Position Determination Results

Driving Requirements

**DR 2.1:** The sensor package shall output the target satellite's relative position with an error of less than 1% up until a relative position of 1[m].

Both simulation and test results followed the following model:

\[ f(x) = \frac{\text{error}}{\text{distance}} \]

<table>
<thead>
<tr>
<th>Result</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Success Rate</td>
<td>72.63%</td>
</tr>
<tr>
<td>Level of Success</td>
<td>Level 3</td>
</tr>
</tbody>
</table>
Driving Requirements

**DR 3.1:** The sensor package shall output the target satellite's relative velocity with an error of less than 1% up until a relative velocity of 0.1[m/s].

Both simulation and test results followed the following model:

\[ f(x) = \frac{\sqrt{2 \text{error}}}{\text{distance}} \]

**Result**

<table>
<thead>
<tr>
<th>Success Rate</th>
<th>9.57%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level of Success</td>
<td>Level 3</td>
</tr>
</tbody>
</table>

Velocity Determination (0.1-1[m/s])

0.1, 0.5, 1 m/s trials
Track Conclusions

**LRF ranging positions**

Oscillations in pivot point yields $4.7\text{cm}$ in error.

<table>
<thead>
<tr>
<th>Error Contribution</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Difference in <em>ranging heights</em> (shown on the left)</td>
<td>Change truth LRF ranging position.</td>
</tr>
<tr>
<td>Beam divergence was about <em>four times larger</em> than expected.</td>
<td>Acquire a better LRF, yet size is a constraint.</td>
</tr>
<tr>
<td>Jerk in translation affecting velocity over time.</td>
<td>Drive train on test stand rather than winch.</td>
</tr>
</tbody>
</table>

0.2° divergence
Driving Requirements

DR 4.1: The sensor package shall output the target satellite’s relative orientation at a starting range of 10[m].

DR 4.2: The sensor package shall output the target satellite’s relative orientation with an error of less than 1[deg].

Success Rate

<table>
<thead>
<tr>
<th>Speed</th>
<th>Success Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 deg/s</td>
<td>22.6%</td>
</tr>
<tr>
<td>3 deg/s</td>
<td>20.3%</td>
</tr>
<tr>
<td>5 deg/s</td>
<td>1.7%</td>
</tr>
</tbody>
</table>

Level of Success: Level 2

Error in Roll Angle Determination

- 10[m]
- 1 deg
- 5 deg/s trial

Level of Success: Level 2
Rotation Rate Results

**Driving Requirements**

**DR 5.1:** The error of the sensor package’s relative rotation rate output shall be less than 1[deg/s].

**DR 5.2:** The sensor shall be able to detect target satellite rotation rates between 1[deg/s] and 5[deg/s].

<table>
<thead>
<tr>
<th>Success Rate</th>
<th>Level of Success</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 deg/s</td>
<td>Level 2</td>
</tr>
<tr>
<td>3 deg/s</td>
<td></td>
</tr>
<tr>
<td>5 deg/s</td>
<td></td>
</tr>
</tbody>
</table>

![Graph showing error in rotation rate determination with success rates for 1 deg/s, 3 deg/s, and 5 deg/s, along with a level of success indicated as Level 2.](image-url)
## Orientation Conclusions

<table>
<thead>
<tr>
<th>Error Contribution</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Stand in field of view of LiDAR</td>
<td>Change testing to use a drop test, or work more on filtering</td>
</tr>
<tr>
<td><strong>Noise</strong> in LiDAR data limits ability of orientation</td>
<td>Tune sensor parameters/Increasing size or budget could allow for purchase of more accurate sensor</td>
</tr>
<tr>
<td><strong>Low resolution</strong> of LiDAR</td>
<td>Combine high resolution visual camera data with accurate depth sensing of LiDAR</td>
</tr>
<tr>
<td>Low <strong>data rate</strong> at close distances</td>
<td>Optimize algorithm at these distances so there is less model movement between frames</td>
</tr>
</tbody>
</table>

Test Stand in field of view of LiDAR change testing to use a drop test, or work more on filtering. **Noise** in LiDAR data limits ability of orientation. **Low resolution** of LiDAR. Low **data rate** at close distances. Optimize algorithm at these distances so there is less model movement between frames.
Overall Power Consumption Fulfilled

**Model Assumptions**

- Highest power consumption during orientation phase (all sensors in operation).
- Peak power reached 10% of time to take one measurement.

**Requirement**

- Average power must remain continuously under 20[W].

**Result**

- Overall power consumption reaches no higher than 11[W].
Driving Requirements

DR 6.1: The sensor shall output target satellite data at a frequency of 2[Hz].

DR 6.2: The sensor may output target satellite data at a frequency of 5[Hz].

Rock64 Board
Quad Core 1.8GHz
4GB DRAM

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Output Frequency [Hz]</th>
<th>Requirement Fulfilled?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background Subtraction</td>
<td>10.0</td>
<td>Yes</td>
</tr>
<tr>
<td>FLOOD</td>
<td>2.0(&lt;6m), 5.0(&gt;6m)</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Mass and Volume Requirements Fulfilled

Driving Requirements

<table>
<thead>
<tr>
<th>DR 7.3: The sensor shall not have a mass exceeding 1.33[kg].</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR 7.1: The dimensions of the sensor package shall not exceed 10[cm]×10[cm]×10[cm] upon launch.</td>
</tr>
</tbody>
</table>

Mass requirement met with a 28% margin.

Volume requirement met, designed within specifications of SolidWorks model.
Requirements Overview

<table>
<thead>
<tr>
<th>FR 1</th>
<th>Capable of detecting a target satellite.</th>
<th>Had trouble with small TARGET.</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR 2</td>
<td>Output the target satellite’s relative position upon detection.</td>
<td>Difficulties inside 10[m].</td>
</tr>
<tr>
<td>FR 3</td>
<td>Output the target satellite’s relative velocity upon detection.</td>
<td>Difficulties under 0.8[m/s].</td>
</tr>
<tr>
<td>FR 4</td>
<td>Output the target satellite’s relative orientation upon detection.</td>
<td>Affected heavily by test setup.</td>
</tr>
<tr>
<td>FR 5</td>
<td>Output the target satellite’s relative rotation rate upon detection.</td>
<td>Met Requirements</td>
</tr>
<tr>
<td>FR 6</td>
<td>Output target satellite data at a set frequency.</td>
<td></td>
</tr>
<tr>
<td>FR 7</td>
<td>Formatted to fit within a 1U platform upon launch.</td>
<td></td>
</tr>
</tbody>
</table>

Overall, many of the requirements were not fully met due to the minimum sized target being too small.
Systems Engineering
Systems Engineering Approach

- **Purpose and Objectives**
- **Design**
- **Test Overview**
- **Test Results**
- **Systems Engineering**
- **Project Management**

**Overview**

- **Concept Development**
  - CDD
- **Requirements Engineering**
  - PDR
- **System Architecture**
  - CDR
- **System Integration**
  - MSR
- **Test & Evaluation**
  - TRR
- **Transition Operation & Maintenance**
  - SFR
Demand in Industry
Need for rendezvous missions that are autonomous and inexpensive. Cube Satellites are perfect solution.

Mission Statement
Design, build, and test a proof-of-concept sensor package that collects relative motion and orientation data of a TARGET satellite for output to the CHASE satellite on-board attitude control system.

Functional Requirement Formation

Functional Requirements written based on customer desires.
Concept of Operations drove FR declaration.
Design Requirement Examples:

- **SCOPE Physical**:
  - Mass < 1.33[kg]
  - Volume < (10[cm] x 10[cm] x 10[cm])
  - Power consumption < 20[W]
  - Data Frequency: 2[Hz]

- **TARGET Detection**:
  - Volume between 20x20x30[cm] & 1x1x1[m]
  - Detection Range: 100[m]
  - Detection of target within 60[s] of turn-on
  - Detection under favorable lighting conditions

- **Position**:
  - Error < 1% up until 1[m]

- **Velocity**:
  - Error < 1% up until 0.1[m/s]

- **Orientation**:
  - Orientation Range: 10[m]
  - Error < 1[deg]

- **Rotation Rate**:
  - Error < 1[deg/s]
  - Rotation Rates between 1[deg/s] & 5[deg/s]

**Testable Design Requirements (DR’s)** were based on physical implementation of FR’s. DR’s were negotiated with the customer based on initial requests, and are decomposed based on levels of success.
Trade studies were conducted for the three major stages of our mission: Acquire, Track, Orientation.

Based on physical parameters, software, implementation difficulty, and cost.

**Orientation Trade Study**

<table>
<thead>
<tr>
<th>Camera Type</th>
<th>Chosen/Not Chosen Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stereo Camera</td>
<td>Not chosen due to low accuracy</td>
</tr>
<tr>
<td>Sweep LiDAR</td>
<td>Not chosen due to low sampling ability.</td>
</tr>
<tr>
<td>3D Flash LiDAR</td>
<td>Chosen due to high accuracy and low latency.</td>
</tr>
</tbody>
</table>
Unit Testing & Subsystem Verification

<table>
<thead>
<tr>
<th>Phase of Mission</th>
<th>Acquire</th>
<th>Track</th>
<th>Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Conducted</td>
<td>Determine centroid within <strong>60[s]</strong> of boot.</td>
<td>Determine position and velocity.</td>
<td>Determine orientation and roll rate.</td>
</tr>
<tr>
<td><strong>Results</strong></td>
<td><strong>Satisfied</strong> for large TARGET (5 out of 5 trials).</td>
<td><strong>Somewhat Satisfied</strong> for position DR. (73% fall within 1% accuracy)</td>
<td><strong>Somewhat Satisfied</strong> for orientation. (~20% fall within 1[deg])</td>
</tr>
<tr>
<td></td>
<td><strong>Somewhat Satisfied</strong> for small TARGET (3 out of 5 Trials).</td>
<td><strong>Not Satisfied</strong> for velocity DR.. (9.57% fall within 1% accuracy)</td>
<td><strong>Satisfied</strong> for rotation rate. (~91% fall within 1[deg/s])</td>
</tr>
</tbody>
</table>

Unit tests were conducted on each subsystem, and were aimed at satisfying Design Requirements (DR’s).

Based on physical parameters, software, implementation difficulty, and cost.
### System Verification & Validation

<table>
<thead>
<tr>
<th>Test</th>
<th>Acquire/Track</th>
<th>Track/Orientation</th>
<th>Physical Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Conducted</td>
<td>Correctly predict centroid, move LRF to centroid position, begin tracking LRF params.</td>
<td>Output LRF Params from 15[m], begin outputting orientation params. At 10[m].</td>
<td>Volume measured, mass taken, and power consumption profiled.</td>
</tr>
<tr>
<td>Results</td>
<td><strong>Partially Successful</strong> (could not keep LRF lock on small target.)</td>
<td><strong>Successful Transition</strong> conducted.</td>
<td></td>
</tr>
</tbody>
</table>

System verification was conducted through transition testing, where the phases of the mission were combined.

Physical parameters were tested for the complete package.
Risk was assessed with an ALARP risk matrix.

Corrections were proposed to handle high-risk areas (if and when they arose in subsystem integration).

Risk mitigation strategies proved helpful (from testing results), but requirements were still not met completely.
### Main Setbacks and Risk Assessment

<table>
<thead>
<tr>
<th>Unforeseen Setback</th>
<th>How it was handled</th>
<th>Successfully Overcome?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unusually high noise in LiDAR and Camera data.</td>
<td>Tested on open field at night.</td>
<td>Yes</td>
</tr>
<tr>
<td>Trouble with encoders (constantly breaking)</td>
<td>Buying new ones and assigning responsibility.</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Unfortunately, the group wasn’t able to mitigate the **data accuracy failure** risk, and most measurements were above their requirements.

This risk was constrained by the ability to acquire sensors within the team’s size constraints.

Risk was assessed with an ALARP risk matrix

Corrections were proposed to handle high-risk areas (if and when they arose in subsystem integration)

Risk mitigation strategies proved helpful (from testing results), but requirements were still not met completely.
Challenges and Lessons Learned

 Initial customer design desires are often infeasible
The shorter a project’s duration, the harder it is to satisfy all requirements. Cost of necessary components can be exuberant. Communication with the customer is key in early project development.

Subsystem integration will not go as smoothly as planned
Underlying hardware/software issues will arise in preliminary testing. Working out operational bugs takes valuable time, and should be carefully documented.

Early risk assessment is key for future prevention of requirement failure(s)
There will be issues in testing that could have been avoided with risk mitigation strategies. Risk identification is tricky - experience is necessary to identify potential risks.

“The customer has no idea what they want, it is up to you [the Systems Engineer] to tell them...”
-Cody Humbargar (Senior SE, Raytheon)
Project Management
1. Develop list of short term and long terms tasks using finish to start approach.

1. Generate group discussion to center focus on common goals.

1. Assign responsibilities based upon group member strengths and interests.

1. Focus on own responsibilities.

1. Continuously assess progress as deadlines approach.
## Project Management Approach

<table>
<thead>
<tr>
<th>Difficulties</th>
<th>Successes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group member developed unique niches so aspects of the project became dependant on them.</td>
<td>Understood project as a whole so was able to access the quality and completeness of subsystem tasks as well as get team members up to speed</td>
</tr>
<tr>
<td>Tasks to be completed always took more time than expected.</td>
<td>Took lessons learned from one deliverable and applied them to the next</td>
</tr>
<tr>
<td>Wasn’t Involved enough in the manufacturing process and software architecture.</td>
<td>Assigned responsibilities and organized meeting times while also developing new technical skills.</td>
</tr>
</tbody>
</table>
Make a “Depth Chart”
(Like in baseball, football… really any sport) detailing the associated group members that are lead/understudy for every key project element for design and testing is essential so unnecessary dependencies are avoided.

Aesthetics are everything
While the project itself consists mainly of real engineering work, if it can’t be properly advertised and sold then it’s just as useless as the Tucker 48, Tivo, Laser Discs…

Success is not relative
Don’t determine your own project’s success based on the success of others. No two projects are created equal and the fact that other projects are struggling or succeeding should in no way be a reflection of project success. Always gauge success by requirements and levels of success.
Purpose and Objectives

Design

Test Overview

Test Results

Systems Engineering

Project Management

Budget Overview

Final | $4,357.16
Marg | $642.84

4453 hours entry level labor ($32.21/hr) | $143,437.98

Overhead (200%) | $286,875.96

Cost of materials | $4357.16

Total Industry Cost | $434,671.10

Raytheon Savings | $414,671.10

Percent Savings | 2,073%
Acknowledgments

We would like to thank Trudy Schwartz, Bobby Hodgkinson, and Matt Rhode for their guidance with the testing design.

We would also like to thank Zoltan Sternovsky for general project guidance.

Thank you to Lee and Tim for presentation practice help and feedback.

And last but certainly not least a special thank you to Steve Thilker, Collin Baukol, and Cody Humbargar from our sponsor Raytheon.
Thank you for your support!

Questions?
References


“OpenCV: Open Source Computer Vision.” https://docs.opencv.org/3.3.0


References


References

http://1.bp.blogspot.com/_SjnNZeKhheo/TTWSPzsl1nl/AAAAAAAAAnl/SpCXSVeDfFU/s1600/Cygnus+approaching+the+ISS.jpg

https://imgur.com/gallery/WNG2lqq - Soyuz docking with ISS GIF

https://www.theimagingsource.com/products/autofocus-cameras/usb-3.0-color/dfkafuj003m12/


http://robotsforroboticists.com/kalman-filtering/

Dynapar, “Quadrature Encoder Overview,” Quadrature Encoder - Dynapar Available:
Sensors and Rock64 Diagrams

Laser Rangefinder

Visual Camera
Sensors and Rock64 Diagrams

Flash LiDAR

Rock64 Microcontroller
Fulfilling Functional Requirements

<table>
<thead>
<tr>
<th>Functional Requirements</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR 1</td>
<td>Transition Test 1</td>
</tr>
<tr>
<td>FR 2</td>
<td>Transition Test 1</td>
</tr>
<tr>
<td>FR 3</td>
<td>Transition Test 1</td>
</tr>
<tr>
<td>FR 4</td>
<td>Transition Test 2</td>
</tr>
<tr>
<td>FR 5</td>
<td>Transition Test 2</td>
</tr>
<tr>
<td>FR 6</td>
<td>Inspection</td>
</tr>
<tr>
<td>FR 7</td>
<td>Inspection</td>
</tr>
</tbody>
</table>
## Acquire/Track Procedure

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1</strong></td>
<td>Offset the pointing of <strong>SCOPE</strong> sensor package to align <strong>TARGET</strong> in the visual camera’s FOV.</td>
</tr>
<tr>
<td><strong>2</strong></td>
<td>Target Rotates about <strong>Z axis</strong> at 1-5[deg/s].</td>
</tr>
<tr>
<td><strong>3</strong></td>
<td>Adjust Pointing of <strong>SCOPE</strong> based on angles outputted from the sensor package and LRF laser in scope FOV on target.</td>
</tr>
<tr>
<td><strong>4</strong></td>
<td>Save data and sync test equipment with <strong>SCOPE</strong>’s microcontroller.</td>
</tr>
<tr>
<td><strong>5</strong></td>
<td>Translate <strong>TARGET</strong> along <strong>Z axis</strong> at 0.1-1[m/s].</td>
</tr>
<tr>
<td><strong>6</strong></td>
<td>Save position and velocity data from LRF and sync with test equipment.</td>
</tr>
<tr>
<td><strong>7</strong></td>
<td>Post-process and analyze data collected.</td>
</tr>
</tbody>
</table>
## Track/Orientation Procedure

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Align the axes of SCOPE and TARGET</td>
</tr>
<tr>
<td>2</td>
<td>Target Rotates about Z axis at 1-5[deg/s].</td>
</tr>
<tr>
<td>3</td>
<td>Adjust Pointing of SCOPE based on angles outputted from the sensor package.</td>
</tr>
<tr>
<td>4</td>
<td>Save position and velocity data from LRF and sync with test equipment.</td>
</tr>
<tr>
<td>5</td>
<td>Translate TARGET along Z axis at 0.1[m/s].</td>
</tr>
<tr>
<td>6</td>
<td>Output orientation data from SCOPE and sync with rotational encoder truth measurement.</td>
</tr>
<tr>
<td>7</td>
<td>Post-process and analyze data collected.</td>
</tr>
</tbody>
</table>
All bodies have constant material properties:

**Component(s):** Shell  
**Material:** 6061 Aluminum Alloy  
**Thermal Conductivity:** 170 W/(m*K)

**Component(s):** Laser Rangefinder  
**Material:** ABS PC  
**Thermal Conductivity:** 0.2618 W/(m*K)

**Component(s):** Rock64 Board  
**Material:** Non-conductive PCB Substrate  
**Thermal Conductivity:** 0.2256 W/(m*K)

**Component(s):** Visual Camera, 03D301 LiDAR  
**Material:** ABS PC/6061 Aluminum  
**Thermal Conductivity:** 85 W/(m*K)

**Contact Resistance:** $2.5 \times 10^{-4} \text{ W*m}^2/\text{K}$

Triangular based mesh
Model uses the following conditions:

**Ambient Temperature:** 290K

**Thermal Emissivity:** 0.12

**Contact Resistance:** $2.5 \times 10^{-4}$ W*m$^2$/K
## Various Power Outputs

<table>
<thead>
<tr>
<th>Component</th>
<th>Low Power</th>
<th>Peak Power</th>
<th>Mean Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock64 Media Board</td>
<td>1.25W</td>
<td>10W</td>
<td>2.5W</td>
</tr>
<tr>
<td>IFM 03D301 Flash LiDAR</td>
<td>5W</td>
<td>48W</td>
<td>10W</td>
</tr>
<tr>
<td>DFK AFUJ003-M12</td>
<td>n/a</td>
<td>5W</td>
<td>1.25W</td>
</tr>
<tr>
<td>SC30-C Laser Rangefinder</td>
<td>n/a</td>
<td>5W</td>
<td>1.25W</td>
</tr>
</tbody>
</table>

**Sources**

- **Rock64**: [https://forum.pine64.org/showthread.php?tid=1220](https://forum.pine64.org/showthread.php?tid=1220)
- **AFUJ003**: [https://www.theimagingsource.com/products/autofocus-cameras/usb-3.0-color/dfkafuj003m12/](https://www.theimagingsource.com/products/autofocus-cameras/usb-3.0-color/dfkafuj003m12/)
- **SC30-C**: [https://www.parallax.com/product/28058](https://www.parallax.com/product/28058)
### Various Operational Temperatures

<table>
<thead>
<tr>
<th>Component</th>
<th>Peak Operational Temperature</th>
<th>Maximum Predicted Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock64 Media Board</td>
<td>65°C</td>
<td>42°C</td>
</tr>
<tr>
<td>IFM 03D301 Flash LiDAR</td>
<td>50°C</td>
<td>30°C</td>
</tr>
<tr>
<td>DFK AFUJ003-M12</td>
<td>45°C</td>
<td>27°C</td>
</tr>
<tr>
<td>SC30-C Laser Rangefinder</td>
<td>40°C</td>
<td>26°C</td>
</tr>
</tbody>
</table>

**Sources**

**Rock64:** https://forum.pine64.org/showthread.php?tid=1220  
**AFUJ003:** https://www.theimagingsource.com/products/autofocus-cameras/usb-3.0-color/dfkafuj003m12/  
**SC30-C:** https://www.parallax.com/product/28058  
**03D301:** https://www.ifm.com/hu/en/product/O3D301
Sensor Calibration

If ●, then the origin of the image frame can be moved to that point.

If ○, then mechanical techniques can adjust camera pointing.

1. Localize offset point with cardboard, decreasing in size.
2. Measure the distance offset and apply correction.
The minimum sized model defines the pointing accuracy to be required as a **20[cm]** vertical and horizontal resolution.

This means that the sensor package must be able to rotate at **0.115[deg]** per step.

The resolution of our **sensor test stand encoders and digital level** give a resolution of **0.01[deg]**.

Therefore, we can measure up to **1.7[cm]** per step.
Sensor Face Offset

All offsets are accounted for in software:

- $R_{lev} = \langle 0, 38, 0 \rangle$ [mm]
- $R_{lrf} = \langle 0, -31, 0 \rangle$ [mm]
- $R_{fl} = \langle -49, -35, 0 \rangle$ [mm]
Error Due to Face Offset

This offset causes error in pointing as the object gets closer.

At 10[m], the closest position in which the laser rangefinder is used, this error (vertical offset) is 2.79[cm].
Analysis:

\[
a = 1.5 \, \text{m/s}^2 \\
m = F_1/a = 2.040 \, \text{kg} \\
F_2 = ma = 3.06 \, \text{N} \\
F_T = F_1 + F_2 = 23.06 \, \text{N} \\
T = F_T r = 1.153 \, \text{Nm} \\
T_F = T \sigma = 1.7295 \, \text{Nm} \\
P_F = F v_{\text{max}} \sigma = 34.59 \, \text{W} \\
\omega_{\text{max}} = v_{\text{max}}/r = 12.5 \, \text{rad/s} = 190.98 \, \text{RPM} \\
\omega_{\text{min}} = v_{\text{max}}/r = 12.5 \, \text{rad/s} = 19.09 \, \text{RPM}
\]

Conclusions:

Need pullout torque at least 2 Nm between ~19 RPM and 190 RPM
Need 34.59 W for power
Test Stand Simulated Load

Tip deflection: \( \approx 4.4\, \text{mm} \)

Induced Angle:
\( \approx 0.25\, \text{deg} \)

Maximum dip: \( \approx 4.28\, \text{mm} \)
Velocity control - FBDs

- CG
- Drag
- Friction
- Weight (W)
- Pulling Force of Winch motor

302.5 mm
378 mm
541 mm
Torque calculations

Givens:

\[ r = 0.0762m \]
\[ F_s = 12.34N \]
\[ ma = 12.5 \times 0.2 = 2.5N \]
\[ D = \frac{1}{2} \rho V^2 C_d A = 0.7989N \]

Analysis:

\[ F_{tot} = -F_s - D + F_p = ma \]
\[ F_p = F_s + D + ma = 15.6289N \]
\[ T = F_p \times r = 1.19Nm \]
\[ at \ v_{max} = 1m/s: \ \omega = v/r = 125RPM \]

Conclusions:

The needed Torque at 125 RPM is 1.19Nm. Looking at the Pullout torque curve one the next slide, it is possible to conclude that the motor will provide sufficient torque for the test stand to move as needed.
Torque vs RPM
If we had to maintain a constant velocity when $v_0 = 0.7$ m/s, this is how we should decrease the angular velocity for the winch.

If instead we maintained a constant angular rotation throughout the whole experiment, starting with our velocity would increase if we started at $v_0 = 0.7$ m/s,
**Analysis:**

- Choose $s = 1$ mm (accuracy at 1 m) one order of magnitude greater than Functional requirement.

- Given:
  - $r = 5$ cm
  - $\theta = s/r = 0.02$ rad
  - $\omega_{max} = 190.98$ RPM
  - $\omega_{min} = 19.09$ RPM

- Calculations:
  - $ppr = 2\pi/\theta = 314.159$
  - $f_{max} = \omega_{max}/\theta = 1000$ Hz
  - $f_{min} = \omega_{min}/\theta = 100$ Hz

**Conclusions:**

- Need at least 314 pulses per rev
- Need a min frequency of 1000 Hz
Givens:
\[
\begin{align*}
  r &= 5 \text{ cm} \\
  \omega_{\text{max}} &= 5 \text{ deg/s} \\
  \omega_{\text{min}} &= 1 \text{ deg/s}
\end{align*}
\]

Analysis:
Choose detection angle to be 0.1 deg (one order of magnitude greater than functional requirement)

Conclusions:
- Need at least 3600 pulses per rev
- Need a min frequency of 50 Hz
Allowable pixel error for background subtraction: 7px
Autofocus capabilities

Two types: Passive and Active
1. Active uses SONAR or IR
2. Passive uses pixel comparison and computer analysis

Passive: Determines blurriness of image → adjusts to find min. Blurriness
- Determines blurriness by contrast of edge pixels
## Flash LiDAR Resolution

### Formulae:

\[ x = 2d \tan \left( \frac{H\text{fov}}{2} \right) \]

\[ z = 2d \tan \left( \frac{V\text{fov}}{2} \right) \]

\[ \text{horizontalpix/m} = \frac{H\text{pxRes}}{x} \]

\[ \text{verticalpix/m} = \frac{V\text{pxRes}}{x} \]

\[ \text{TotalPixelRes m}^2 = \text{horizontalpix/m} \times \text{verticalpix/m} \]

### Table:

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>IFM O3D301</th>
<th>FOV:40X30</th>
<th>RES:176X132</th>
<th>20 x 20 cm</th>
<th>1 x 1 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>492</td>
<td>20.32</td>
<td>20</td>
<td>492</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>596</td>
<td>16.79</td>
<td>24</td>
<td>596</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>735</td>
<td>13.60</td>
<td>29</td>
<td>735</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>931</td>
<td>10.75</td>
<td>37</td>
<td>931</td>
<td></td>
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<tr>
<td>7</td>
<td>1215</td>
<td>8.23</td>
<td>49</td>
<td>1215</td>
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<tr>
<td>6</td>
<td>1654</td>
<td>6.04</td>
<td>66</td>
<td>1654</td>
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</tr>
<tr>
<td>5</td>
<td>2382</td>
<td>4.20</td>
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<td>2382</td>
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</tr>
<tr>
<td>4</td>
<td>3722</td>
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<td>149</td>
<td>3722</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>6617</td>
<td>1.51</td>
<td>265</td>
<td>6617</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>14888</td>
<td>0.67</td>
<td>596</td>
<td>14888</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>59554</td>
<td>0.17</td>
<td>2382</td>
<td>59554</td>
<td></td>
</tr>
</tbody>
</table>
FLOOD Explained

1. Guess initial rotation and translation of Flash Lidar data
2. Compare Point Cloud to 3D model
3. Remove Outliers
4. Calculate and apply ideal rotation and translation
5. Error < Threshold
   - Yes: Output to SD card
   - No: < 10 Iterations
     - Yes: Proceed
     - No: Repeat step 3

1. Faces from 3D model are stored in bins in a k-d tree data structure
   a. Each bin represents a 3D box
2. For each point from our Lidar scan traverse down to bin containing that point
3. Check the distance from point to each face contained in bin
4. Repeat step 3 for neighboring bins if the distance to the edge of that bin is less than the current minimum found distance
Given the two point cloud sets $M$ and $D$, where $D$ is the set produced by the LiDAR scan, and $M$ is the set derived from the model. For each point $d_i \in \mathbb{R}^3$ in $D$, and a rotation $R$ and translation $t$, there is a point $c_i$ such that.

$$c_i = \arg \min_{c_k \in M} \| (Rd_i + t) - c_k \|, \quad \forall i = 1...m$$

(1)

$t$ and $R$ are then calculated using the following error function.

$$\epsilon = \frac{1}{m} \min_{t,R} \sum_{i=1}^{m} \| Rd_i + t - c_i \|^2$$

(2)
FLOOD Timing

- Almost always above 2 Hz minimum
- Add in maximum number of points so algorithm does not have to process 10’s of thousands of points
Blender
Distribution of LRF Mean

\( n = \) number of LRF returns per every system data output
\( \sigma = \) standard deviation of normal distribution for single LRF data output
\( \bar{X} = \) the mean of all LRF data over the course of half a second. It should be noted the the expected value of the mean is the actual distance.

\( CI = \) Confidence Interval
\( Z_{\alpha/2} = \) Normal Distribution Critical value

Important to note that the standard deviation of the mean is \( \frac{\sigma}{\sqrt{n}} \)

Normal distribution of mean of LRF data:

\[
CI : \bar{X} \pm Z_{\alpha/2} \frac{\sigma}{\sqrt{n}} \rightarrow Z_{\alpha/2} \frac{\sigma}{\sqrt{n}} \leq 0.01\bar{X}
\]

For a 99% confidence interval that the LRF is returning data within one percent of actual distance, \( Z_{\alpha/2} = 2.575 \).

\[
(2.575) \frac{\sigma}{\sqrt{n}} \leq 0.01\bar{X} \rightarrow \sigma \leq 0.003883d
\]
Use of Kalman Filtering

Means to use data from multiple sources in order to create a joint probability distribution that can then be used to more accurately predict the correct data parameters.

Our Date Sources:
- Laser Range Finder
- Optical Camera
- LiDar

Our goal using a Kalman filter: to optimize estimation of the state of the TARGET satellite in the Orientation Phase.
Position Error Propagation

Using the standard deviation of the position the standard deviation of the velocity can be calculated with the following equation:

\[ x = a + b - c \quad \sigma_x = \sqrt{\sigma_a^2 + \sigma_b^2 + \sigma_c^2} \]

For velocity error propagation \((\sigma_{\text{pos1}} = \sigma_{\text{pos}})\):

\[ \text{vel} = \text{pos2} - \text{pos1} \quad \sigma_{\text{vel}} = \sqrt{\sigma_{\text{pos1}}^2 + \sigma_{\text{pos2}}^2} = \sqrt{2\sigma_{\text{pos1}}^2} = \sqrt{2}\sigma_{\text{pos}} \]

Based on the velocity error propagation, the standard deviation of the laser range finder needs to be the following to satisfy 1% accuracy. The worst case is at 10m with 10 data returns per half second.

\[ \sqrt{2}\sigma_{\text{pos}} \leq \sqrt{n}(0.003883)d \rightarrow \sigma_{\text{pos}} \leq \sqrt{n/2}(0.003883)d = \sqrt{5}(0.03883) = 0.0868 \]

Therefore the 99% confidence interval can be calculated.

\[ Z_{\alpha/2} \frac{\sigma}{\sqrt{n}} = (2.575)(0.0868/\sqrt{1}) = \pm 0.224m \]
Important to note that the standard deviation of the mean is $\frac{\sigma}{\sqrt{n}}$.
$\sigma_n =$ standard deviation of vertical pointing off center in number of pixels
$\sigma_\psi =$ standard deviation of horizontal pointing off center in meters
$\sigma_\theta =$ standard deviation of vertical pointing off center in meters
d = distance away from camera

$\alpha =$ horizontal full angle
$\beta =$ vertical full angle
$m =$ number of pixels in horizontal direction
$n =$ number of pixels in vertical direction
$\sigma_m =$ standard deviation of horizontal pointing off center in number of pixels

To calculate the standard deviation in terms of meters.

$$\sigma_\psi = \frac{2dtan\left(\frac{\alpha}{2}\right)}{m}(\sigma_m) \quad \sigma_\theta = \frac{2dtan\left(\frac{\beta}{2}\right)}{n}(\sigma_n)$$

A smaller field of view is beneficial, the alpha and beta of the hard found that is the smallest but can still fit the larger possible target in the FOV at the minimum distance of 10 m with a 25mm focal length is $\alpha = 14.68 \text{ and } \beta = 10.5 \text{deg}$

The expected value for the distance returned from the center of the object is zero so in order to construct the normal distributions for horizontal and vertical pointing.

$$\theta = \sigma_\theta Z \quad \psi = \sigma_\psi Z$$