| Agenda |

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</table>
Mission Statement: RAVEN will develop a testbed that will collect image, position, and sensor data to be used by the customer for the verification of customer developed cooperative localization algorithms.

- Provide the customer with an **UAV and UGV pair testbed**.
- Record **image, position, and sensor** data.
- **Deliver** recorded information, including **collected GPS data**, and UAV/UGV pair to customer.
Motivation

- **Scenario:** Teams of humans and robots in a GPS-denied environment
- Localize team members without reliable GPS
- However, RAVEN will not be simulating a GPS-denied environment

Squad X concept, courtesy DARPA
Concept of Operations

Prepare
- UAV - Safety Checks
- Preflight Checks
- Take off to initial position
- UGV - Safety Checks
- Prerun Checks
- Move to initial position

Execute
- Manual Takeoff
- Manual Land
- Emergency Land
- Preprogrammed Flight Path or Stationary Hover
- Location Data (IMU/GPS/Ephemeris)
- 15 min Flight Time
- 10-30 m

Data Collected
- Both Vehicles Record:
  - GPS/IMU/Altitude
  - Raw Camera Footage
  - Location Estimates
  - Status
- Used by customer for visual tracking alg. development

Conclusion
- UAV
  - Manual Landing
  - System Shutdown
  - Offload Collected Data
- UGV
  - System Shutdown
  - Offload Collected Data

Motivation
- UAV vision used to find location of UGV without GPS
- Location known

Project Purpose
Design Solution
CPEs
Design Reqs.
Project Risks
Validation
Project Planning
<table>
<thead>
<tr>
<th>Functional Requirement</th>
<th>Description</th>
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</tr>
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<td>RAVEN shall have a removable data storage system on both the UAV and UGV.</td>
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<td>UAV and UGV visual data shall contain the other vehicle in 90% of frames and shall not take more than three seconds of frame data without the other vehicle in frame.</td>
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<td>FR 4.0</td>
<td>UAV &amp; UGV visual data shall have a minimum resolution of 3 inches per pixel at a distance of 30 m.</td>
</tr>
<tr>
<td>FR 5.0</td>
<td>RAVEN shall operate outside on a fair-weathered day (i.e., no wind, no precipitation).</td>
</tr>
<tr>
<td>FR 6.0</td>
<td>RAVEN shall comply with Army Memorandum (DAMO-AV).</td>
</tr>
<tr>
<td>FR 7.0</td>
<td>RAVEN shall utilize the customer-provided Clearpath Jackal UGV.</td>
</tr>
<tr>
<td>FR 8.0</td>
<td>The UAV and UGV shall communicate flight and navigation status data to their respective ground stations (GCS) and to each other.</td>
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<tr>
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<td>RAVEN shall communicate flight/drive commands from ground stations to and from their respective vehicle over an ISM Radio Frequency.</td>
</tr>
<tr>
<td>FR 10.0</td>
<td>Vision system shall use customer specified interfaces.</td>
</tr>
</tbody>
</table>
Design Solution
Functional Block Diagram
Functional Block Diagram
UAV Hardware

- GPS Antenna
- Camera/Gimbal
- Battery
- Flight Controller
- Onboard Computer
- GPS Receiver

Project Purpose
Design Solution
CPEs
Design Reqs.
Project Risks
Validation
Project Planning
UAV Electronics Wiring

Connection Legend

- USB 3.0
- Others

915 MHz SIK Telemetry
FlySky RC Receiver

ESC 1
ESC 2
ESC 3
ESC 4

Flight Controller Pixracer

FTDI

GPS
USB Splitter
WIFI Transceiver

SD Card

I2C to PWM Board
Brushless Gimbal Controller

MP
MR
MT

5V Voltage Regulator

Battery 6s (22.2V) 8000 mAh

Onboard Computer ODROID XU4

Camera

Project Purpose  Design Solution  CPEs  Design Reqs.  Project Risks  Validation  Project Planning
UAV Electronics Wiring

Flight Controller Pixracer
- 915 MHz SIK Telemetry
- FlySky RC Receiver
- 5V Voltage Regulator
- Battery 6s (22.2V) 8000 mAH

Onboard Computer ODROID XU4
- SD Card
- USB Splitter
- WIFI Transceiver
- I2C to PWM Board

Connection Legend
- PWM Signal
- Others

Connection Points:
- ESC 1
- ESC 2
- ESC 3
- ESC 4
- M1
- M2
- M3
- M4
- M5
- M6
Functional Block Diagram
UGV Hardware Overview

- Antennas
- Camera/Gimbal
- GPS Receiver (under rail)
- AR Tags on Aluminum Plates
- Extruded Aluminum Rail

Project Purpose
Design Solution
CPEs
Design Reqs.
Project Risks
Validation
Project Planning
UGV Electronics Wiring

Connection Legend:
- Ground
- 5V
- PWM Signal
- 2 Line I2C Signal
- USB 3.0 Connection

Diagram showing connections between Pan Servo, Tilt Servo, Compass, Arduino Mini Microcontroller, Barometer, Camera, GPS, and Clearpath Jackal UGV.
Functional Block Diagram
Communications

Project Purpose

Design Solution

CPEs

Design Reqs.

Project Risks

Validation

Project Planning
Robot Operating System (ROS)

- Open-source meta-operating system that provides:
  - Tools and libraries for interfacing with robotic systems and their components
  - Communication framework for distributed computing over network
Determine
- Use GPS to find relative vector between vehicles.

Acquire
- Point Gimbal using GPS data to command servo.

Confirm
- UAV and UGV detection using AR tag and blob detection
GPS receivers on each vehicle will communicate with each other and use **Differential-GPS (DGPS)** and **Real-Time Kinematics (RTK)** to reduce error considerably.

- **DGPS** - method of removing shared errors from both GPS receivers.
- **RTK** - ability to converge to a much higher precision using carrier-phase tracking (requires DGPS).
Critical Project Elements
Critical Project Elements Breakdown
Critical Project Elements Breakdown

- Command and Data Sharing
- Platform and Payload Integration

- Vehicle and GCS Communication
- UAV Endurance
- Platform Mounting
Critical Project Elements

Breakdown

- Project Purpose
- Design Solution
- CPEs
- Design Reqs.
- Project Risks
- Validation
- Project Planning
Design Requirements and Satisfaction
## Payload and Platform Integration

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![Functional Requirements Diagram]

- **Tracking and Determination**
  - Confirm
  - Acquire
  - Determine
  - Camera Configuration
- **Command and Data Sharing**
  - Vehicle and GPS Communication
- **Platform and Payload Integration**
  - UAV Endurance
  - Platform Mounting
Platform Mounting

<table>
<thead>
<tr>
<th>Design Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR 1.2</td>
<td>UAV payload shall mount to UAV platform.</td>
</tr>
<tr>
<td>DR 7.1</td>
<td>UGV payload shall mount to 5 mm diameter holes spaced 120 mm x 120mm.</td>
</tr>
<tr>
<td>DR 7.4</td>
<td>UGV payload shall weigh less than 44 lbs.</td>
</tr>
</tbody>
</table>

Vehicle Specifications → Payload Mount

Project Purpose → Design Solution → CPEs → Design Reqs. → Project Risks → Validation → Project Planning
UGV Specifications

Project Purpose

Design Solution

CPEs

Design Reqs.

Project Risks

Validation

Project Planning
UGV Mounting Rails Specifications

*Dimensions in mm

Extruded aluminum used to mount the gimbal and AR tag plates

Project Purpose
Design Solution
CPEs
Design Reqs.
Project Risks
Validation
Project Planning
UGV Gimbal Specifications

**Dimensions in mm**

- 120 ± 10
- 28 ± 10
- 60 ± 10
- 120 ± 1

Aluminum servo and camera mounts

*Project Purpose*

*Design Solution*

*CPEs*

*Design Reqs.*

*Project Risks*

*Validation*

*Project Planning*
UGV AR Plate Specifications

180 x 180 tags
5 ± 1
250 ± 10
320 ± 10

*Dimensions in mm

4 aluminum sheets to house the 4 AR tags
UAV Specifications

- Design
- Solution
- CPEs
- Design Reqs.
- Project Risks
- Validation
- Project Planning
## UAV Endurance

<table>
<thead>
<tr>
<th>Design Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR 1.1</td>
<td>EPS shall provide power to all electronic subsystems for a minimum of 15 minutes.</td>
</tr>
</tbody>
</table>

![Mass Budget to Power Budget Diagram](image-url)

**Legend:**
- **Project Purpose**
- **Design Solution**
- **CPEs**
- **Design Reqs.**
- **Project Risks**
- **Validation**
- **Project Planning**
### Mass Budget

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame</td>
<td>600 g</td>
</tr>
<tr>
<td>Driving Components</td>
<td>709 g</td>
</tr>
<tr>
<td>Battery</td>
<td>956 g</td>
</tr>
<tr>
<td>Payload</td>
<td>531 g</td>
</tr>
<tr>
<td>Wiring</td>
<td>139 g</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2935 g</strong></td>
</tr>
<tr>
<td>Max Takeoff Weight</td>
<td>3516 g</td>
</tr>
<tr>
<td>Margin</td>
<td>581 g</td>
</tr>
</tbody>
</table>

**Conclusion:**
- 17% mass margin
- DR 1.1 satisfied
Power Budget

- Battery: Turnigy 8,000 mAh 6S Li-po
- 18.15 minute endurance required

<table>
<thead>
<tr>
<th>Component</th>
<th>Amperage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camera</td>
<td>0.25 A</td>
</tr>
<tr>
<td>Computer</td>
<td>1.00 A</td>
</tr>
<tr>
<td>GPS</td>
<td>0.50 A</td>
</tr>
<tr>
<td>Flight Controller</td>
<td>0.50 A</td>
</tr>
<tr>
<td>Gimbal</td>
<td>0.15 A</td>
</tr>
<tr>
<td>Propulsion</td>
<td>16.0 A</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>18.4 A</strong></td>
</tr>
</tbody>
</table>

Conclusion:
- 25% charge margin after 18.15 min mission
- DR 1.1 satisfied

UAV Current and Mission Time

Conclusion:
- 25% charge margin after 18.15 min mission
- DR 1.1 satisfied
## Command and Data Sharing

<table>
<thead>
<tr>
<th>Functional Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR 8.0</td>
<td>The UAV and UGV shall communicate flight and navigation status data to their respective ground stations (GCS) and to each other.</td>
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<tr>
<td>FR 9.0</td>
<td>RAVEN shall communicate flight/drive commands from ground stations to and from their respective vehicle over an ISM Radio Frequency.</td>
</tr>
</tbody>
</table>

### Diagram

- **Tracking and Determination**
  - Acquire
  - Determine
  - Camera Configuration
- **Command and Data Sharing**
  - Vehicle and GPS Communication
- **Platform and Payload Integration**
  - UAV Endurance
  - Platform Mounting

### Project Phases

- **Project Purpose**
- **Design Solution**
- **CPEs**
- **Design Reqs.**
- **Project Risks**
- **Validation**
- **Project Planning**
<table>
<thead>
<tr>
<th>Design Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR 9.2</td>
<td>Shall be able to transmit user pilot controls to the UAV and UGV.</td>
</tr>
<tr>
<td>DR 9.2.1</td>
<td>Vehicles shall be piloteable by generic controllers</td>
</tr>
</tbody>
</table>
UGV Control

- To satisfy DRs 9.2 & 9.2.1 within test area, UGV must be controllable within 40 meters.
- Bluetooth game controller (provided with Jackal) tested to have range of 45.7 meters.
- Backup is to piggyback controller signal over WiFi data network.

<table>
<thead>
<tr>
<th>Req. Range</th>
<th>Control Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 m</td>
<td>45.7 m</td>
</tr>
</tbody>
</table>

Conclusion:
- Satisfies DR 9.2, 9.2.1
- UGV will be controllable in operation area
UAV Control

- To satisfy DRs 9.2 & 9.2.1 within test area, UAV must be controllable within 65 m of the user.
- Transmitter: Turnigy i6s 2.4 GHz

<table>
<thead>
<tr>
<th>Req. Range</th>
<th>Control Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>65 m</td>
<td>1000 m</td>
</tr>
</tbody>
</table>

Conclusion:
- Satisfies DR 9.2, 9.2.1
- UAV will be controllable in operation area
## Data Sharing

<table>
<thead>
<tr>
<th>Design Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR 8.1</td>
<td>Both vehicles shall communicate navigation data to their respective ground station.</td>
</tr>
<tr>
<td>DR 8.2</td>
<td>Vehicles shall be able to share data between each other</td>
</tr>
<tr>
<td>DR 8.3</td>
<td>Both vehicles shall communicate visual tracking data to GCS.</td>
</tr>
<tr>
<td>DR 8.4</td>
<td>Vehicles shall share live GPS data.</td>
</tr>
<tr>
<td>DR 8.5</td>
<td>Vehicles shall share live IMU, magnetometer and barometer data</td>
</tr>
</tbody>
</table>

![Diagram showing data sharing distribution]
Data Sharing Speed

- To satisfy DRs 8.1 – 8.5:
  - The data sharing network (using IEEE 802.11 b standard) must have the bandwidth to carry all aforementioned data.
  - UAV, UGV, and CGS must all be connected to the data sharing network.

### Table: Data Rates

<table>
<thead>
<tr>
<th>Item</th>
<th>Data Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preview Image</td>
<td>3.05 Mbits/s</td>
</tr>
<tr>
<td>Navigation Data</td>
<td>153.6 kbits/s</td>
</tr>
<tr>
<td>Management Data</td>
<td>25 kbits/s</td>
</tr>
<tr>
<td>Total Data Rate</td>
<td>3.231 Mbits/s</td>
</tr>
<tr>
<td>802.11 b Maximum Throughput</td>
<td>11 Mbits/s</td>
</tr>
<tr>
<td>Margin</td>
<td>7.769 Mbits/s</td>
</tr>
</tbody>
</table>

### Table: Connections

<table>
<thead>
<tr>
<th>Connection</th>
<th>Device</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network Hub</td>
<td>Netgear Nighthawk AC1750 WiFi Router</td>
</tr>
<tr>
<td>UGV Connection</td>
<td>Built-in WiFi adapter</td>
</tr>
<tr>
<td>UAV Connection</td>
<td>ODROID WiFi Module 3</td>
</tr>
<tr>
<td>Ground Stations</td>
<td>Ethernet</td>
</tr>
</tbody>
</table>

Conclusions:
Total network demand is less than the network throughput and all nodes connected to network, satisfying DR 8.8.
Data Sharing Range

- To satisfy DR 8.1 – 8.5:
  - The data sharing network must function within the entire test area (radius of 30 m)
  - Testing done using consumer grade hardware: ZyXEL C1100Z Router, Intel integrated WiFi adapter

<table>
<thead>
<tr>
<th>Required Range</th>
<th>Estimated Range</th>
<th>Distance</th>
<th>Strength</th>
<th>Share Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 m</td>
<td>55 m</td>
<td>1 m</td>
<td>-20 dBm</td>
<td>Stable</td>
</tr>
<tr>
<td></td>
<td></td>
<td>55 m</td>
<td>-64 dBm</td>
<td>Stable</td>
</tr>
<tr>
<td></td>
<td></td>
<td>118 m</td>
<td>-80 dBm</td>
<td>Slight Delay</td>
</tr>
</tbody>
</table>

To satisfy DR 8.1 – 8.5:
- The data sharing network must function within the entire test area (radius of 30 m)
- Testing done using consumer grade hardware: ZyXEL C1100Z Router, Intel integrated WiFi adapter
Tracking and Determination

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<tr>
<td>FR 4.0</td>
<td>UAV and UGV visual data shall have a minimum resolution of 3 in/pixel at a distance of 30 m.</td>
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Diagram:
- Tracking and Determination
- Command and Data Sharing
- Platform and Payload Integration

Legend:
- Confirm
- Acquire
- Determine
- Camera Configuration
- Vehicle and GPS Communication
- UAV Endurance
- Platform Mounting

Project Purpose → Design Solution → CPEs → Design Reqs. → Project Risks → Validation → Project Planning
Camera Configuration

### Design Requirement

<table>
<thead>
<tr>
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<th>Description</th>
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</thead>
<tbody>
<tr>
<td>DR 4.1</td>
<td>Camera resolution shall be greater than 1920x1080 with at least a 25 mm focal length (35 mm equivalent)</td>
</tr>
</tbody>
</table>

- DFK 33UX249 and 16mm lens:
  - Resolution: 1920 x 1200
  - AOV: 28 x 36.8 degrees
- Pixel Density:
  - At 30 m: 0.451 in/pix

**Conclusion:**
- Camera has a pixel density less than 3 in/pixel @ 30 m
- DR 4.1 satisfied
## Determination of Location

<table>
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</thead>
<tbody>
<tr>
<td>DR 3.2</td>
<td>UAV mounted vision tracking system shall be able to track UGV at ground speed of 0.5 m/s and range of 10 m.</td>
</tr>
<tr>
<td>DR 3.4</td>
<td>UGV mounted vision tracking system shall be able to track UAV at ground speed of 0.5 m/s and range of 10 m.</td>
</tr>
<tr>
<td>DR 8.4</td>
<td>Vehicles shall share live GPS data.</td>
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### Flowchart

1. GPS Solution
2. Error Model
3. RTK Accuracy

### Project Diagram

- Project Purpose
- Design Solution
- CPEs
- Design Reqs.
- Project Risks
- Validation
- Project Planning
Chosen GPS Solution

- GPS Receiver: NEO-M8P integrated on C94-M8P application boards

- C94 boards can communicate with each other over UHF (ultra-high frequency) to communicate DGPS corrections

- The receivers use RTK (Real-time Kinematic) that allow cm-level relative accuracy
Vehicle Location Error Model

- **Purpose**
  - Gaussian distributed error based on sensor datasheets
  - Determine required Angle of View accounting for sensor errors
  - Justification of RTK capable GPS

- **Assumptions**
  - Constant velocity orbit
  - Circular orbit
  - Constant altitude
Over 90% of simulated RTK data points are within angle of view.
### Design Requirement

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**Diagram:**

1. **Gimbal Software**
   - **Rotation Angle Calcs.**
   - **Servo Limitations**
   - **Gazebo Overview**
   - **Gimbal Demo**

---

**Process Flow:**

- **Project Purpose**
- **Design Solution**
- **CPEs**
- **Design Reqs.**
- **Project Risks**
- **Validation**
- **Project Planning**
Gimbal Software Flowchart

UGV

/lugv/gps
read raw gps messages from receiver

parse message

publish geodetic point locations

UAV

/luav/gps
read raw gps messages from receiver

parse message

publish geodetic point locations

/convert

read geodetic point locations

transform geodetic to ECEF

determine relative position vector

transform ECEF to ENU

determine servo rotation angles

publish servo rotation angles

GCS

/read servo angles

serially send servo angles to Arduino

Arduino

serially receive servo angles

command servos
Calculating Servo Rotation Angles

- **Goal**: convert inertial geodetic coordinates into East-North-Up coordinates to determine gimbal rotation angles

- **Step 1**: convert inertial geodetic to Earth centered Earth Fixed (ECEF)

\[
N = \frac{a}{\sqrt{1 - e^2 \sin^2(\phi)}}
\]

\[
\begin{bmatrix}
  x \\
  y \\
  z
\end{bmatrix} = \begin{bmatrix}
  (N + h) \cos(\phi) \cos(\lambda) \\
  (N + h) \cos(\phi) \sin(\lambda) \\
  (1 - e^2) N + h \sin(\phi)
\end{bmatrix}
\]
Calculating Servo Rotation Angles Cont.

- **Step 2:** convert ECEF to ENU using direction cosine matrix (DCM)

\[
DCM = \begin{bmatrix}
-sin(\lambda) & -cos(\lambda)sin(\phi) & cos(\lambda)cos(\phi) \\
-cos(\lambda) & -sin(\lambda)sin(\phi) & sin(\lambda)cos(\phi) \\
0 & cos(\phi) & sin(\phi)
\end{bmatrix}
\]

- **Step 3:** calculate servo rotation angles using projections

\[
\theta_p = tan^{-1}\left(\frac{r_n}{r_e}\right)
\]

\[
\theta_t = tan^{-1}\left(\frac{r_u}{\sqrt{r_e^2 + r_n^2}}\right)
\]
Accounting for Servo Limitations

- “Figure 8” method
  - Pan servo resets to initial position (like a sprinkler)
  - Tilt servo flips to the other side
- Solves wire wrap issue from using continuous rotation
- Maneuver completes within a single second
Gazebo Overview

- ROS Simulation Tool
- Provides 3D visualization of systems
- Allows sensor emulation
- Simulates reasonable approximations of dynamics
- Allows prototyping of RAVEN network
Gazebo Assumptions

- Sensors are emulated
  - Sensor traits are not yet configured
  - Sensor data source will change

- Physical characteristics
  - Magnitude of losses are unknown
  - Can change with environment
UGV Gimbal Demonstration
### Design Requirement

<table>
<thead>
<tr>
<th>Design Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>UAV mounted vision tracking system shall be able to identify presence of UGV in frame.</td>
</tr>
<tr>
<td>3.3</td>
<td>UGV mounted vision tracking system shall be able to identify presence of UGV in frame.</td>
</tr>
</tbody>
</table>

**Diagram:**

UAV to UGV

- Augmented Reality Tags

UGV to UAV

- Blob Detection

**Timeline:**

- Project Purpose
- Design Solution
- CPEs
- Design Reqs.
- Project Risks
- Validation
- Project Planning
Augmented Reality (AR) Detection

Overview:
- Orientable high contrast binary patterns.
- Robust to lighting changes.
- Easily implemented in ROS. (ar_track_alvar)
- AR tag bundle improves accuracy.

Testing:
Need:
- Characterize the maximum AR detection range.
Method:
- Testing performed with Flir Flea3 Machine vision camera.
- 10cm tags and 18cm tags used.
Performance Metric:
- Number of pixels per linear tag dimension.
AR Testing Results

<table>
<thead>
<tr>
<th>Test</th>
<th>AR Tag Size</th>
<th>Max Detection Range</th>
<th>Pixels per tag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Webcam (PDR) 5.5cm</td>
<td>5.5 cm</td>
<td>2.5 m</td>
<td>27.9 pix</td>
</tr>
<tr>
<td>Flea 3</td>
<td>10 cm</td>
<td>25.3 m</td>
<td>29.7 pix</td>
</tr>
<tr>
<td>Flea 3</td>
<td>18 cm</td>
<td>35.6 m</td>
<td>37.7 pix</td>
</tr>
<tr>
<td>DFK 33UX249 w/ 16mm lens</td>
<td>18 cm</td>
<td>&gt;30 m</td>
<td>39.9 pix (@ 30 m)</td>
</tr>
</tbody>
</table>

- DFK 33UX249 with 16 mm lens using 18 cm tags
  - Will have more pixels per tag than Flea 3
  - Detection threshold is exceeded.
Blob Detection - Overview

- Blob (binary large object) detection: identify clusters of pixels with similar characteristics, e.g. color, intensity
- OpenCV libraries for blob detection, and processing steps
- Assumptions made to constrain problem:
  - High contrast between target and background
  - Accurate information about target location and motion relative to camera
  - Background features are connected to edges of image frame (e.g. trees, buildings)
Blob Detection -- Process

Initial image
Blob Detection -- Process

Convert to grayscale
Blob Detection -- Process

Threshold for binary image
Blob Detection -- Process

Find contours

Diagram showing the process of blob detection with steps including Project Purpose, Design Solution, CPEs, Design Reqs., Project Risks, Validation, Project Planning.
Blob Detection -- Process

Find center and mark detection
Conclusions:
► For blue sky, and sun in frame:
► DR 3.3 satisfied
Project Risks
## Significant Project Risks

<table>
<thead>
<tr>
<th>Risk</th>
<th>Description</th>
<th>Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>UAV stability is poor</td>
<td>Incremental build up with proxy masses</td>
</tr>
<tr>
<td>2</td>
<td>Field of view is insufficient</td>
<td>Lens and camera combination FOV will be determined before integration via testing</td>
</tr>
<tr>
<td>3</td>
<td>Noise affecting GPS accuracy</td>
<td>Antenna design and electronics placement will reduce interference</td>
</tr>
<tr>
<td>4</td>
<td>Pulse Width Modulation not working</td>
<td>PWM motor control will be ground tests</td>
</tr>
<tr>
<td>5</td>
<td>Communication between Ardupilot and ODROID fails</td>
<td>Confirmation in testing of serial to USB data transfer</td>
</tr>
<tr>
<td>6</td>
<td>Lead times for products</td>
<td>Suppliers have been contacted to check stock, parts have been identified so ordering can occur immediately</td>
</tr>
</tbody>
</table>

### Conclusions:
- Quantify GPS accuracy early to facilitate project success
- Lead times must be accounted for by ordering before break
- Communication between hardware must be confirmed as soon as possible
Testing, Verification & Validation
Testing Methodology/Approach

- Incremental Test Buildup to minimize risks
  - Using weights to simulate payload when not needed
- Indoor testing whenever possible
  - RECUV indoor flight Space ( Allows more testing flexibility)
- Parallelize platform from payload to allow multiple teams to work on hardware at the same time
Conclusions:
- Critical intermediary testing must begin soon
- Rigorous scheduling to keep testing on track
- Able to parallelize platform and payload effectively
## Verification Methods

<table>
<thead>
<tr>
<th>FR</th>
<th>Summary</th>
<th>Verification Method</th>
<th>Testing Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>Collect for 15 min</td>
<td>UAV Endurance, Full System Test</td>
<td>✅</td>
</tr>
<tr>
<td>2.0</td>
<td>Removable Storage System</td>
<td>Inspection</td>
<td></td>
</tr>
<tr>
<td>3.0</td>
<td>Other vehicle in 90% of frames, no more than three seconds without other vehicle in frame</td>
<td>GPS Characterization, Full System Test</td>
<td>✅</td>
</tr>
<tr>
<td>4.0</td>
<td>Minimum resolution of 3 inches/pixel</td>
<td>Camera Characterization</td>
<td>✅</td>
</tr>
<tr>
<td>5.0</td>
<td>Operate on a fair weathered day</td>
<td>Full System Test</td>
<td>✅</td>
</tr>
<tr>
<td>6.0</td>
<td>Do not use any DJI products</td>
<td>Inspection</td>
<td></td>
</tr>
<tr>
<td>7.0</td>
<td>Use Clearpath Jackal</td>
<td>Inspection</td>
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</tr>
<tr>
<td>8.0</td>
<td>Communicate flight and navigation data to ground stations</td>
<td>Communications test, Full system test</td>
<td>✅</td>
</tr>
<tr>
<td>9.0</td>
<td>Communicate over ISM frequencies</td>
<td>Inspection</td>
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</tr>
<tr>
<td>10.0</td>
<td>System shall use customer specified interfaces</td>
<td>Inspection</td>
<td></td>
</tr>
</tbody>
</table>

**Conclusion:**

Full system test and GPS characterization critical to system success
GPS Characterization

► Executed on the business field
► Verify GPS error model
  ► DRs: 3.1, 8.4
► Overview:
  ► Two modules on a cart, moving across field
  ► Modules are a known, fixed distance apart (4 ft)
  ► Both logging GPS location

► Measuring:
  ► GPS Location (1 Hz)
  ► Distance Between modules (Ruler)

► Allows relative position error to be measured using known difference in position.

Conclusions:
► Validate GPS error model
► Verify DGPS/RTK operation
Full System Test

- Executed at CU Boulder South Campus
- UGV placed in operation area
- Integrated system is validated against mission profile
- Collecting:
  - Flight Time (Stopwatch)
  - GPS (1 Hz)
  - Vision Data (10 Hz)
    - Must have vehicle in frame 90% of time
  - Status (1 Hz)
  - Navigation Data (10 Hz)
Approx time: Operation
T – 10:00 UGV Powered and positioned
T – 5:00 Payload Powered on (FR 4.0)
T – 2:30 Operation area live
T – 2:00 Transmission Begins (FR 8.0,9.0)
T – 1:00 UAV Takeoff
T + 0:00 Data Collection Begins (FR 3.0)
T + 15:00 Data Collection Ends
T + 15:30 UAV Lands
T + 16:00 All Stop
T + 17:00 All Safe Call

Data offloaded (FR 2.0)

Verify data collected meets requirements

Conclusions:
► Full System Test able to verify operation of system
► Test site available
► Detailed procedure in work
# Major Testing Risks

<table>
<thead>
<tr>
<th>Risk</th>
<th>Description</th>
<th>Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>UAV crash with major damage</td>
<td>Incremental Build Up and testing, Spare structural carbon rods</td>
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<tr>
<td>1.2</td>
<td>UAV crash with catastrophic damage, irreparable damage to the UAV system or payload</td>
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<tr>
<td>2.0</td>
<td>Component damage</td>
<td>Payload installed only when required</td>
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<tr>
<td>3.0</td>
<td>Testing takes too long</td>
<td>Margin in testing schedule</td>
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<tr>
<td>4.0</td>
<td>Li-Po damage</td>
<td>Observed charging, charging in Li-Po sack</td>
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</table>

## Conclusions:
- Flying UAV is inherently risky
- Some components are irreplaceable due to budget
- Project must be able to pivot testing strategies if failure occurs
Project Planning
Work Breakdown Structure - Overview

RAVEN

Software
- Vision
- Controls
- Modeling
- Network

Hardware
- Electronics
- Sensors
- Manufacturing
- Platforms
- Payloads

Logistics
- Testing
- Finance and Procurement
- Safety
### Work Flow - Logistics

#### Project Purpose
- Design
- Solution

#### CPEs
- Design Reqs.
- Project Risks
- Validation
- Project Planning

#### Logistics
- Spring Semester
- Procurement
  - ETAR/ITAR Checks
  - Part Ordering
  - Shipment Monitoring
- Finance
  - Standard Development
  - Rule Development

#### Finance Tracking
- Safety Validation
  - Alexander Swindell
- Rule Development
  - Alexander Swindell

#### Project Risks

#### Validation

#### People Assigned

#### % Complete

#### Timeline
- Jan 2018
- Feb 2018
- Mar 2018
- Apr 2018
- May 2018
## Work Flow - Hardware

<table>
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<tr>
<th>RAVEN</th>
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</tbody>
</table>

**Project Purpose**
- Design

**CPEs**
- Design Req's
- Project Risks
- Validation
- Project Planning
# Work Flow – Software

## RAVEN

<table>
<thead>
<tr>
<th>People Assigned</th>
<th>% Complete</th>
<th>Jan 2018</th>
<th>Feb 2018</th>
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<th>Apr 2018</th>
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<tbody>
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<td><strong>Hardware</strong></td>
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</tbody>
</table>

---

## Project Purpose

- Design

## Design Solution

- CPEs

## Design Reqs.

- Project Risks

## Validation

- Project Planning
**Financial Summary**

<table>
<thead>
<tr>
<th>System</th>
<th>Cost</th>
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<tbody>
<tr>
<td>Cameras (x2)</td>
<td>$990.00</td>
</tr>
<tr>
<td>Batteries (x2)</td>
<td>$600.00</td>
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<tr>
<td>Lenses (x2)</td>
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<tr>
<td>T-Motor Brushless Motors (x3)</td>
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<tr>
<td>C94-M8P GPS Units (x2)</td>
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<td>Carbon Rods (x4)</td>
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<td>UAV Frame</td>
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<td>Router</td>
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<td>Propellers (x18)</td>
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<td>Voltage Regulators</td>
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<td>Ethernet Cables</td>
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**RAVEN Budget Breakdown**

EEF grant: $1000
Questions?
References

- NEO-M8P u-Blox M8 High Precision GNSS Module.” High Precision GNSS Modules, u-Blox.
- “SS CAP ALTIMETER PRESSURE SENSOR.” Board Level Pressure Sensors, TE Connectivity.
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“Bumper, 33/64 In., Black, Rubber, PK10." Grainger, 20 Aug. 2015, www.grainger.com/product/18AH59?cm_mmc=PPC%3A%2BGoogle%2BPLA&s_kwcid=AL%21212966%213%21166594954253%21%21%21s%2182128346557%21&ef_id=WgDoQwAAK4OZ%3A20171202012750%3As&kwid=productads-adid%5E166594954253-device%5Ecplaid%5E82128346557-sku%5E18AH59-adType%5EPLA.


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- UGV Hardware
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- ROS Overview
- Tracking Method Overview
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- Integration
- UAV Endurance
- Command and Data Sharing
- Vehicle Controls
- Data Sharing
- Tracking and Determination
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- Chosen Tracking Solution
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- Blob Detection – Overview
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- Cost Plan
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Back up Slides
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- Sensor overview & error
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- UAV hardware detail
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- Gazebo simulation detail
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- Testing DRs and models
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- Test breakouts
- Test cards
- Testing risk breakdown & cards
Acquisition Overview

- ODROID XU4 sends PWM commands to Feiyu-Tech 3-axis gimbal controller

- Arduino Mini 05 sends PWM commands to 2 x 180° servos
  - Hitec HS-7950TH servos
  - Implement “Figure 8” method due to 180° limit
Communications System Test

- Conducted at South Boulder Campus
- Verify data/telemetry/command range
  - DR 8.2, 8.3, 8.5
- Validate data models
  - DR 9.1, 9.2
- Assess flight ready status of communications system

Overview:
1. Props off, UGV on blocks
2. UAV moved to >30 m from GCS and UGV
3. UAV commanded to take off
4. Auto flight sequence commenced
5. Auto/Manual flight toggled
6. Emergency land command sent
7. UAV moved and sequence repeated until COMMS unreliable or ROS node failure

Data collection performed by RAVEN natively, external data collection systems unnecessary

Conclusions:
- Assess flightworthiness of comms
- Verify operational range of system
## Project Development: Communications

### Table: Project Development

<table>
<thead>
<tr>
<th>Design</th>
<th>PDD</th>
<th>CDD</th>
<th>PDR</th>
<th>CDR</th>
<th>Decision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground Control</td>
<td>-</td>
<td>2 ground stations</td>
<td>-</td>
<td>-</td>
<td>Team Provided</td>
</tr>
<tr>
<td>Network Configuration</td>
<td>-</td>
<td>2.4 GHz and 902 MHz</td>
<td>2.4 GHz, 2.4 GHz, and 915 MHz</td>
<td>-</td>
<td>Sik Telemetry Radio V2 TG Yi 6s</td>
</tr>
<tr>
<td>GPS</td>
<td>-</td>
<td>Integrated Board</td>
<td>Integrated RTK GPS boards</td>
<td>-</td>
<td>C94-M8P-2</td>
</tr>
<tr>
<td>Ground UI</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>QT</td>
<td>QT</td>
</tr>
<tr>
<td>Storage</td>
<td>Micro SD</td>
<td>Micro SD</td>
<td>Micro SD / Flash USB</td>
<td>Micro SD</td>
<td>EVO Select</td>
</tr>
</tbody>
</table>
## Project Development: Vehicle Hardware

<table>
<thead>
<tr>
<th>Design</th>
<th>PDD</th>
<th>CDD</th>
<th>PDR</th>
<th>CDR</th>
<th>Decision</th>
</tr>
</thead>
<tbody>
<tr>
<td>UAV Frame</td>
<td>-</td>
<td>Quadrotor</td>
<td>Hexarotor</td>
<td>-</td>
<td>TAROT FY 690s</td>
</tr>
<tr>
<td>UAV Gimbal</td>
<td>-</td>
<td>3 axis, brushless</td>
<td>-</td>
<td>-</td>
<td>FY MiNi 3D Pro</td>
</tr>
<tr>
<td>Onboard CPU</td>
<td>-</td>
<td>External</td>
<td>-</td>
<td>-</td>
<td>Odriod XU4</td>
</tr>
<tr>
<td>UAV Battery</td>
<td>-</td>
<td>LiPo</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>UGV</td>
<td>Customer Provided</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Clearpath Jackal</td>
</tr>
<tr>
<td>UGV Gimbal</td>
<td>-</td>
<td>2 axis, servo</td>
<td>-</td>
<td>-</td>
<td>In House</td>
</tr>
<tr>
<td>Flight Controller</td>
<td>-</td>
<td>Autonomous</td>
<td>-</td>
<td>-</td>
<td>Pix Racer</td>
</tr>
</tbody>
</table>
## Project Development: Vision System

<table>
<thead>
<tr>
<th>Design</th>
<th>PDD</th>
<th>CDD</th>
<th>PDR</th>
<th>CDR</th>
<th>Decision</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Camera Shutter</strong></td>
<td>-</td>
<td>Global Shutter</td>
<td>-</td>
<td>-</td>
<td>DFK 33Ux249</td>
</tr>
<tr>
<td><strong>Camera Configuration</strong></td>
<td>-</td>
<td>Monocular</td>
<td>-</td>
<td>-</td>
<td>&quot; &quot;</td>
</tr>
<tr>
<td><strong>Color Response</strong></td>
<td>-</td>
<td>Color</td>
<td>-</td>
<td>-</td>
<td>&quot; &quot;</td>
</tr>
<tr>
<td><strong>Lens</strong></td>
<td>-</td>
<td>Prime Lens</td>
<td>12 mm Prime Lens</td>
<td>-</td>
<td>M112FM12</td>
</tr>
<tr>
<td><strong>UAV Tracking Method</strong></td>
<td>-</td>
<td>GPS, Sensor, and Visual Tracking</td>
<td>Combined w/ AR Tags</td>
<td>-</td>
<td>Combined w/ AR Tags</td>
</tr>
<tr>
<td><strong>UGV Tracking Method</strong></td>
<td>-</td>
<td>GPS, Sensor, and Visual Tracking</td>
<td>Combined w/ Blob Detection</td>
<td>-</td>
<td>Combined w/ Blob Detection</td>
</tr>
</tbody>
</table>
## Critical Project Elements

<table>
<thead>
<tr>
<th>Integration</th>
<th>Communications</th>
<th>Tracking and Detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Payload &amp; Platform Hardware Integration</td>
<td>• Command and Data Sharing</td>
<td>• Determine</td>
</tr>
<tr>
<td>• Hardware Compatibility</td>
<td></td>
<td>• Acquire</td>
</tr>
<tr>
<td>• Software Architecture</td>
<td></td>
<td>• Verify</td>
</tr>
</tbody>
</table>
Critical Project Elements

Integration
- Payload & Platform Hardware Integration
- Hardware Compatibility
- Software Architecture

Communications
- Command and Data Sharing

Tracking and Detection
- Determine
- Acquire
- Verify
## Critical Project Elements

<table>
<thead>
<tr>
<th>Integration</th>
<th>Communications</th>
<th>Tracking and Detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Payload &amp; Platform Hardware Integration</td>
<td>• Command and Data Sharing</td>
<td>• Determine</td>
</tr>
<tr>
<td>• Hardware Compatibility</td>
<td></td>
<td>• Acquire</td>
</tr>
<tr>
<td>• Software Architecture</td>
<td></td>
<td>• Verify</td>
</tr>
</tbody>
</table>
WBS - Software

- Vision
  - AR Tags
  - Blob Detection

- Controls
  - PID Tuning

- Modeling
  - Sensor Emulation
  - ROS Network
    - Gimbal Control Prototype
    - Blob Detection Prototype
    - Platform Pathing

- Network
  - UI
  - Safety Commands
Work Breakdown Structure - Software

- Controls
  - Flight Controller and PID Control
    - PID control tuning
      - UAV Platform
    - Testing
      - UAV Platform Test Procedure
    - Increase Performance Robustness
      - UAV Platform Test Procedure
    - Validation
      - UAV Platform Test Procedure
Work Breakdown Structure - Software

Network

UI
- Build UI in pi with Qt5 and matplotlib
  - Sensor emulation
- Integrate UI with Gazebo
  - Gazebo
- Integrate with hardware
  - Full integration
  - Test
    - Test Procedure
      - Full integration
- Increase robustness
  - Full integration
  - Validation
    - Test Procedure
      - Full integration

Safety
- Develop platform safety commands
  - Platforms
  - Test
    - Test Procedure Platforms
  - Increase robustness
    - Platforms
    - Validate
      - Test Procedure Platforms
WBS - Hardware

- **Electronics**
  - Uninstalled Assembly
  - Platform Integration

- **Sensors**
  - MGMT Sensor Integration
  - GPS Integration
  - Interference Reduction

- **Manufacturing**
  - UGV Mounting
  - UGV Gimbal
  - Prototyping
  - UAV Proxy Masses

- **Platforms**
  - UAV Assembly
  - PID Rate Tuning

- **Payloads**
  - Sub-System Assembly
  - Platform Integration
Work Breakdown Structure - Hardware

- Hardware
  - Platforms
    - Receive hardware
    - UAV assembly
    - UAV PID rate tuning
  - Electronics
    - Receive hardware
    - Pre-integration tests
    - Uninstalled test assembly
    - Assembly test
      - Test Procedure
    - Platform integration
      - Platforms
      - Test Procedure
      - Platforms
  - Sensors
    - MGMT sensor integration
      - Platforms
    - GPS integration
      - Platforms
    - Sensor configuration
      - Platforms
    - Interference reduction
      - Platforms
  - Payloads
    - Receive hardware
    - Manufacture hardware
    - Uninstalled tests
      - Test Procedure
    - Platform integration
      - Platforms
      - Test Procedure
      - Platforms
    - Platform testing and validation
      - Platforms
      - Test Procedure
      - Platforms
WBS - Logistics

- Logistics
  - Testing
    - See Testing Section
  - Finance
    - Procurement
    - Financial Tracking
  - Safety
    - Rule Development
    - Safety Command Verification
Work Breakdown Structure - Logistics

- Logistics
  - Finance
    - ETAR/ITAR
    - Procurement
    - Finance Tracking
  - Safety
    - Rule definition and procedures
    - Safety validations
  - Testing
    - See testing section
UAV Electronics Wiring
UAV Electronics Wiring

- 915 MHz SIK Telemetry
- FlySky RC Receiver
- Flight Controller Pixracer
- SD Card
- Onboard Computer ODROID XU4
- Battery 6s (22.2V) 8000 mAh
- 5V Voltage Regulator
- Camera
- WIFI Transceiver
- USB Splitter
- I2C to PWM Board
- Brushless Gimbal Controller
- Connection Legend
  - 3 Line AC Motor Output
  - Others

Project Purpose
Design Solution
CPEs
Design Reqs.
Project Risks
Validation
Project Planning
UAV Electronics Wiring

Connection Legend
- 6 Line Telemetry Port
- Others

Flight Controller Pixracer

915 MHz SIK Telemetry
FlySky RC Receiver

Onboard Computer ODROID XU4
GPS
USB Splitter
I2C to PWM Board

Brushless Gimbal Controller

SD Card

Battery
6s (22.2V)
8000 mAH

5V Voltage Regulator

Camera

ESC 1
ESC 2
ESC 3
ESC 4
ESC 5
ESC 6
M5
M6

Project Purpose
Design Solution
CPEs
Design Reqs.
Project Risks
Validation
Project Planning
UAV Electronics Wiring

Connection Legend
- **PPM Signal**
- **Others**

Project Purpose
Design Solution
CPEs
Design Reqs.
Project Risks
Validation
Project Planning
UAV Electronics Wiring

Connection Legend
- 2 line I2C signal
- Others

Diagram showing electrical components and connections:
- 915 MHz SIK Telemetry
- FlySky RC Receiver
- GPS USB Splitter
- WIFI Transceiver
- Onboard Computer ODROID XU4
- I2C to PWM Board
- Brushless Gimbal Controller
- FTDI
- Flight Controller Pixracer
- SD Card
- M1, M2, M3, M4
- ESC 1, ESC 2, ESC 3, ESC 4
- ESC 5, ESC 6
- 5V Voltage Regulator
- Battery 6s (22.2V) 8000 mAH
- Camera
Mass Breakdown

Vehicle Gross Weight
- Frame: 600 g
- Propellers: 145 g
- Motors: 396 g
- ESCs: 156 g
- Batteries: 956 g
- Wiring: 139 g
- Payload: 531 g

Payload Weight Breakdown
- Camera: 129 g
- Gimbal: 167 g
- GPS: 125 g
- Flight Controller: 11 g
- Auxiliary Computer: 65 g
- RF Comms: 34 g

Total Weight: 2,935 g

Citations: Frame, Battery, Propellers, Motors, ESCs, Camera, Lens, Gimbal, Odroid, PixRacer, GPS Main Module, GNSS Antenna, UHF Antenna, Control Receiver, Nav Receiver, Nav Antenna
## Detailed Mass Breakdown

<table>
<thead>
<tr>
<th>Item</th>
<th>Part</th>
<th>Mass</th>
<th>Quantity</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame</td>
<td>Tarot FY680S</td>
<td>600 g</td>
<td>1</td>
<td>600 g</td>
</tr>
<tr>
<td>Battery</td>
<td>Turnigy, 8,000 mAh 6S Li-po</td>
<td>956 g</td>
<td>1</td>
<td>956 g</td>
</tr>
<tr>
<td>Propellers</td>
<td>APC MR 13x5.5</td>
<td>24.1 g</td>
<td>6</td>
<td>144.6 g</td>
</tr>
<tr>
<td>Motors</td>
<td>T-Motor Antigrav 4006, 380 kV</td>
<td>66 g</td>
<td>6</td>
<td>396 g</td>
</tr>
<tr>
<td>ESCs</td>
<td>Hobbywing, 40 A 2-6 S ESC</td>
<td>26 g</td>
<td>6</td>
<td>156 g</td>
</tr>
<tr>
<td>Gimbal</td>
<td>FY Mini 3D Pro</td>
<td>167 g</td>
<td>1</td>
<td>167 g</td>
</tr>
<tr>
<td>Flight Controller</td>
<td>PixRacer</td>
<td>10.9 g</td>
<td>1</td>
<td>10.9 g</td>
</tr>
<tr>
<td>GPS</td>
<td>uBlox C94-M8P</td>
<td>125 g</td>
<td>1</td>
<td>125 g</td>
</tr>
<tr>
<td>RC Receiver</td>
<td>Redcon CM 703</td>
<td>12 g</td>
<td>1</td>
<td>12 g</td>
</tr>
<tr>
<td>Data Receiver</td>
<td>ODROID WiFi Module 3</td>
<td>14 g</td>
<td>1</td>
<td>14 g</td>
</tr>
<tr>
<td>Telemetry Radio</td>
<td>3DR Telemetry Kit</td>
<td>14 g</td>
<td>1</td>
<td>14 g</td>
</tr>
<tr>
<td>Camera</td>
<td>DFK 33UX249</td>
<td>65 g</td>
<td>1</td>
<td>65 g</td>
</tr>
<tr>
<td>Lens</td>
<td>TAMRON M112FM12</td>
<td>64 g</td>
<td>1</td>
<td>64 g</td>
</tr>
<tr>
<td>Aux Computer</td>
<td>ODROID XU4</td>
<td>65 g</td>
<td>1</td>
<td>65 g</td>
</tr>
<tr>
<td>Wiring Mass</td>
<td>5% AUW</td>
<td>139 g</td>
<td>1</td>
<td>139 g</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>2928 g</strong></td>
</tr>
</tbody>
</table>
Negligible Drag Validation

1 Airframe drag on props

\[ D_V = \frac{C_d F_{\text{prop}} S}{A_{\text{disk}}} \]  

(1)

Where

\( D_V \) = Vertical Drag
\( C_d \) = Total fuselage drag coefficient
\( F_{\text{prop}} \) = Propeller thrust
\( A_{\text{disk}} \) = Propeller disk area
\( S \) = Projected area of affected components

\[ F_{\text{prop}} = \frac{mg}{N} \]  

(2)

\( m \approx 3.166 kg \)
\( g = 9.81 \, m/s^2 \)
\( N = \) number of propellers (6)
\( C_d \approx 0.2 \)

\( S \) is calculated using the motor diameter of 44.35mm, so \( S \approx 0.00154482 \, m^2 \). 
\( A_{\text{prop}} \) is calculated using the propeller radius and has a value of 0.0410433 \( m^2 \) for the 4.5” props and 0.0506707 \( m^2 \) for the 5.5” props. Plugging these values into the vertical drag equation above we get \( D_V < 0.04N \), which is negligible.
Battery Life

![Graph: Current Draw (Amps) vs. Time (sec)]

- **Total Current**
- **Drive System Current**
- **Payload Current**

![Graph: Voltage vs. Percentage]

- Data
- Fitted curve
Calculate moments of inertias via SolidWorks’ mass evaluation tool, in order to characterize stability

- **Desired:** center of mass below propeller plane
- Achievable from SolidWorks center of mass viewer
UAV Stability Properties

Mass = 2794.25 grams
Volume = 1797243.37 cubic millimeters
Surface area = 1247463.35 square millimeters

Center of mass: (millimeters) X = 13.78 Y = 4.76 Z = 14.52

Principal axes of inertia and principal moments of inertia: (grams * square millimeters)
Taken at the center of mass.

\[
\begin{align*}
I_x &= (-0.05, -0.02, 1.00) & P_x &= 54613492.77 \\
I_y &= (1.00, 0.01, 0.05) & P_y &= 62719545.61 \\
I_z &= (-0.01, 1.00, 0.02) & P_z &= 104795258.94
\end{align*}
\]

Moments of inertia: (grams * square millimeters)
Taken at the center of mass and aligned with the output coordinate system.

\[
\begin{align*}
L_{xx} &= 62699632.99 & L_{xy} &= 378729.63 & L_{xz} &= -424409.54 \\
L_{yx} &= 378729.63 & L_{yy} &= 104767875.86 & L_{yz} &= -1100133.13 \\
L_{zx} &= -424409.54 & L_{zy} &= -1100133.13 & L_{zz} &= 54660788.47
\end{align*}
\]
# UAV Product Choices Overview/TOC

<table>
<thead>
<tr>
<th>UAV Hardware</th>
<th>See next slide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camera</td>
<td>DFK 33UX249</td>
</tr>
<tr>
<td>Lens</td>
<td>TAMRON M112FM12</td>
</tr>
<tr>
<td>Gimbal</td>
<td>Feiyu Tech FY MiNi 3D Pro</td>
</tr>
<tr>
<td>Processor</td>
<td>ODROID XU4</td>
</tr>
<tr>
<td>Flight Controller</td>
<td>Pix Racer</td>
</tr>
<tr>
<td>IMU</td>
<td>Included in FC</td>
</tr>
<tr>
<td>Barometer &amp; Magnetometer</td>
<td>Included in FC</td>
</tr>
<tr>
<td>GPS</td>
<td>C94-M8P-2</td>
</tr>
<tr>
<td>2.4 GHz Channel 1 (data)</td>
<td>Steve provided</td>
</tr>
<tr>
<td>2.4 GHz Channel 2 (controller)</td>
<td>DSMX receiver/transmitter</td>
</tr>
<tr>
<td>915 MHz Channel (Mavlink)</td>
<td>SIK telemetry radio</td>
</tr>
</tbody>
</table>
| Props     | 6x High Pitch – 13x5.5" APC  
          | 6x Low Pitch – 13x4.5" APC   |
|-----------|-------------------------------|
| Motors    | Antigravity 4006 KV380 by T-MOTOR |
| Battery   | Multistar 8000mAh 6S            |
| ESC       | 2-6S 40A                       |
| Micro SD (Storage) | Samsung Evo Select |
## Camera: DFK 33UX249

<table>
<thead>
<tr>
<th>Specification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>$1,920 \times 1,200$ (2.3 MP)</td>
</tr>
<tr>
<td>FPS</td>
<td>48</td>
</tr>
<tr>
<td>Interface</td>
<td>USB 3</td>
</tr>
<tr>
<td>Lens mount</td>
<td>C/CS</td>
</tr>
<tr>
<td>Current Consumption</td>
<td>$\sim 250$ mA @ 5 VDC</td>
</tr>
<tr>
<td>Dimensions</td>
<td>H: 29 mm, W: 29 mm, L: 43 mm</td>
</tr>
<tr>
<td>Mass</td>
<td>65 g</td>
</tr>
<tr>
<td>Mounting</td>
<td>Mounting plate included, 29x43mm</td>
</tr>
<tr>
<td>Price</td>
<td>$127$</td>
</tr>
</tbody>
</table>
**Lens: M112FM12**

<table>
<thead>
<tr>
<th>Mount Type</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>H: 7.5cm, W: 10cm, L: 10cm</td>
</tr>
<tr>
<td>Mass</td>
<td>64 g</td>
</tr>
<tr>
<td>Price</td>
<td></td>
</tr>
</tbody>
</table>
## Gimbal: Feiyu Tech FY MiNi 3D Pro

<table>
<thead>
<tr>
<th>Feature</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working Voltage</td>
<td>7-17V (8.4V)</td>
</tr>
<tr>
<td>Dimensions</td>
<td>H: 130 mm, W: 74 mm, L: 50 mm</td>
</tr>
<tr>
<td>Mass</td>
<td>167 g</td>
</tr>
<tr>
<td>Mounting</td>
<td>Mounting hooks included (53.4mm width apart)</td>
</tr>
<tr>
<td>Price</td>
<td>$203.15</td>
</tr>
<tr>
<td>Interfaces</td>
<td></td>
</tr>
</tbody>
</table>
## Processor: ODROID XU4

<table>
<thead>
<tr>
<th>Power Source</th>
<th>5V/4A DC Power Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>H: 20 mm, W: 58 mm, L: 83 mm</td>
</tr>
<tr>
<td>Mass</td>
<td>65 g</td>
</tr>
<tr>
<td>Mounting</td>
<td>Holes in corners for screws/bolts</td>
</tr>
<tr>
<td>Ports</td>
<td>eMMC – Boot loader USB 3 – Camera USB 3 – Data Channel USB 2 – GPS Ethernet HDMI 1.4a 42 pins – 12 for FC</td>
</tr>
<tr>
<td>OS</td>
<td>Linux Kernel 4.9 LTS, ARM compatible</td>
</tr>
<tr>
<td>Price</td>
<td>$59.00</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Operating voltage</td>
<td>5 VDC</td>
</tr>
<tr>
<td>Dimensions</td>
<td>H: ~ mm, W: 36 mm, L: 36 mm</td>
</tr>
<tr>
<td>Mass</td>
<td>10.54 g</td>
</tr>
<tr>
<td>Mounting</td>
<td>Screw holes in corners</td>
</tr>
<tr>
<td>Price</td>
<td>$99.00</td>
</tr>
<tr>
<td>Interfaces</td>
<td>See site</td>
</tr>
</tbody>
</table>
### GPS: C94-M8P-2

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module Mass</td>
<td>35g</td>
</tr>
<tr>
<td>GNSS Antenna</td>
<td>Tallysman TW2406 (35g)</td>
</tr>
<tr>
<td>UHF Antenna</td>
<td>Included in package (50g)</td>
</tr>
<tr>
<td>Ground Plane</td>
<td>5g</td>
</tr>
<tr>
<td>Price</td>
<td>$400</td>
</tr>
</tbody>
</table>
## UAV Sensor Overview

### Assumptions:
- Error is Gaussian
- Specific characteristics such as drift and bias must be determined experimentally

<table>
<thead>
<tr>
<th>State Variable</th>
<th>Sensor</th>
<th>Listed Accuracy</th>
<th>Std. Dev.</th>
<th>Units</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x, y )</td>
<td>uNEO-M8P u-blox M8 High Precision GNSS Module</td>
<td>0.025 m CEP</td>
<td>0.037</td>
<td>m</td>
<td>With RTK</td>
</tr>
<tr>
<td>( z )</td>
<td>MS5611 Barometer</td>
<td>Max Total Error Band w/ Autozero @ 25°C = ±0.5 mbar</td>
<td>1.667</td>
<td>m</td>
<td>From PixRacer Autopilot</td>
</tr>
<tr>
<td>( \phi, \theta )</td>
<td>MPU-9250 Nine-Axis (Gyro) MEMS MotionTracking™ Device</td>
<td>Total RMS noise = 0.1 deg/s RMS</td>
<td>0.1</td>
<td>°/s</td>
<td>From PixRacer Autopilot</td>
</tr>
<tr>
<td>( \psi )</td>
<td>u3-Axis Digital Compass IC HMC5983</td>
<td>1° to 2° Compass Heading Accuracy</td>
<td>0.66667</td>
<td>°</td>
<td>From PixRacer Autopilot</td>
</tr>
<tr>
<td>( \dot{x}, \dot{y}, \dot{z} )</td>
<td>MPU-9250 Nine-Axis (Accelerometer) MEMS MotionTracking™ Device</td>
<td>Total RMS noise 8 mg-rms</td>
<td>0.008</td>
<td>g</td>
<td>From PixRacer Autopilot</td>
</tr>
<tr>
<td>( \dot{\phi}, \dot{\theta}, \dot{\psi} )</td>
<td>MPU-9250 Nine-Axis (Gyro) MEMS MotionTracking™ Device</td>
<td>Total RMS noise = 0.1 deg/s RMS</td>
<td>0.1</td>
<td>°/s</td>
<td>From PixRacer Autopilot</td>
</tr>
</tbody>
</table>
### UGV Sensor Overview

<table>
<thead>
<tr>
<th>State Variable</th>
<th>Sensor</th>
<th>Listed Accuracy</th>
<th>Std. Dev.</th>
<th>Units</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x, y$</td>
<td>uNEO-M8P u-blox M8 High Precision GNSS Module</td>
<td>0.025 m CEP</td>
<td>0.037</td>
<td>m</td>
<td>With RTK</td>
</tr>
<tr>
<td>$z$</td>
<td>Adafruit BMP280 I2C or SPI Barometric Pressure Altitude Sensor</td>
<td>Typical Abs. Acc. = ±1 hPa</td>
<td>3.2333</td>
<td>m</td>
<td>Integrated w/ I2C to Arduino</td>
</tr>
<tr>
<td>$\phi, \theta$</td>
<td>MPU-9150 Nine-Axis (Gyro) MEMS MotionTracking™ Device</td>
<td>Total RMS noise = 0.06deg/s RMS</td>
<td>0.06</td>
<td>°/s</td>
<td>Standard on Jackal</td>
</tr>
<tr>
<td>$\psi$</td>
<td>Honeywell HMC5883L Digital Compass IC</td>
<td>1° to 2° Compass Heading Accuracy</td>
<td>0.666666</td>
<td>°</td>
<td>Integrated w/ I2C to Arduino</td>
</tr>
<tr>
<td>$\dot{x}, \dot{y}, \dot{z}$</td>
<td>MPU-9150 Nine-Axis (Accelerometer) MEMS MotionTracking™ Device</td>
<td>Total RMS noise 4 mg-rms</td>
<td>0.004</td>
<td>g</td>
<td>Standard on Jackal</td>
</tr>
<tr>
<td>$\dot{\phi}, \dot{\theta}, \dot{\psi}$</td>
<td>MPU-9150 Nine-Axis (Gyro) MEMS MotionTracking™ Device</td>
<td>Total RMS noise = 0.06deg/s RMS</td>
<td>0.06</td>
<td>°/s</td>
<td>Standard on Jackal</td>
</tr>
</tbody>
</table>

- Assumptions: Error is Gaussian
- Specific characteristics such as drift and bias must be determined experimentally
Sensor Error Calculations and Assumptions

- **NEO-M8P u-blox M8 High Precision GNSS Module**
  - Standalone: 2.5 m CEP → $\sigma = 2.5/0.6745 = 3.706$ (Gaussian Distribution at 50%)
  - RTK: 0.025 m CEP → $\sigma = 0.025/0.6745 = 0.003706$ (Gaussian Distribution at 50%)

- **MS5611 Barometer**
  - Max Total Error Band with Autozero at Pressure Point, at $25^\circ\text{C} = \pm 0.5$ mbar
  - Pressure at 5450 ft = 828.901 mbar [6]
  - Pressure Altitude at 828.901 + 0.5 mbar = 5433.95 ft
  - Error of ~ 17 ft ~ 5 m
  - $\sigma = 5/3 = 1.66667$ m (Gaussian Distribution at 99.7%)
    - Barometer drift due to environment ignored for relative altitude

- **Adafruit BMP280 I2C or SPI Barometric Pressure Altitude Sensor**
  - Typical absolute accuracy from 0-40°C = ±1 hPa
  - Pressure at 5450 ft = 828.901 mbar = 828.901 hPa
  - Pressure Altitude at 828.901 + 1 hPa = 829.901 hPa = 829.901 mbar = 5417.9 ft
  - Error of ~ 32 ft ~ 9.7 m
  - $\sigma = 9.7/3 = 3.2333$ m (Gaussian Distribution at 99.7%)
Sensor Error Calculations and Assumptions

- **3-Axis Digital Compass IC HMC5983 [7]**
  - 1° to 2° Compass Heading Accuracy
  - \( \sigma = \frac{2}{3} = 0.66667° \) (Gaussian Distribution at 99.7%)

- **Honeywell HMC5883L Digital Compass IC**
  - 1° to 2° Compass Heading Accuracy
  - \( \sigma = \frac{2}{3} = 0.66667° \) (Gaussian Distribution at 99.7%)

- **MPU-9250 Nine-Axis (Gyro) MEMS MotionTracking™ Device**
  - Total RMS noise = 0.06 °/s - rms
  - \( \sigma = 0.1° \)

- **MPU-9250 Nine-Axis (Accelerometer) MEMS MotionTracking™ Device**
  - Total RMS noise = 8 mg – rms
  - \( \sigma = 0.008 \text{ g} \)

- **MPU-9150 Nine-Axis (Gyro) MEMS MotionTracking™ Device**
  - Total RMS noise = 0.06 °/s - rms
  - \( \sigma = 0.06° \)

- **MPU-9150 Nine-Axis (Accelerometer) MEMS MotionTracking™ Device**
  - Total RMS noise = 4 mg – rms
  - \( \sigma = 0.004 \text{ g} \)
Interference

- RAVEN testing location at CU South Campus is 400+ meters from any houses, mitigating residential WiFi interference.
Pixracer Connection

Pinouts
TELEM1, TELEM2+OSD ports
Serial (TTL Level)

<table>
<thead>
<tr>
<th>Pin</th>
<th>Signal</th>
<th>Volt</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (red)</td>
<td>VCC</td>
<td>+5V</td>
</tr>
<tr>
<td>2 (blk)</td>
<td>TX (OUT)</td>
<td>+3.3V</td>
</tr>
<tr>
<td>3 (blk)</td>
<td>RX (IN)</td>
<td>+3.3V</td>
</tr>
<tr>
<td>4 (blk)</td>
<td>CTS (IN)</td>
<td>+3.3V</td>
</tr>
<tr>
<td>5 (blk)</td>
<td>RTS (OUT)</td>
<td>+3.3V</td>
</tr>
<tr>
<td>6 (blk)</td>
<td>GND</td>
<td>GND</td>
</tr>
</tbody>
</table>
Extra Electronics 1

- Arduino Micro
- I2C Barometer
- Sik Telemetry Radio
- 3 Axis Gimbal
Extra Electronics 2

- Servo Motor Driver
- Voltage Regulator
- Turnigy RC Receiver
- Servo Motor
Extra Cables

- FTDI Cable
- USB Splitter
UI + ROS Demonstration
UI + ROS Demonstration
UI Planning
Camera Image size approximation:

- Flea image size: 1,314,816 bytes
- Flea Resolution: 1280 *1024
- Total # of pixels: 1310720
- Flea bytes per pixel: 1.003
- Cam resolution: 1920*1200=2304000
- Size of image file: 2310912 bytes /10^6 =
- 2.311 MB/image
Preview Image approximation

- 384*240 = 92160 pixels
- Worst case scenario, no compression: 1.033 bytes/pixel
- Image size = 95 kB = 761 kb/image
- 11mb/761kb = 6.9% (approx 0.069 seconds to send one preview image over network)
## Controller Power

<table>
<thead>
<tr>
<th>Transmitter Name</th>
<th>Protocol</th>
<th>Frequency</th>
<th>Sensitivity</th>
<th>Output Power (max)</th>
<th>Estimated Range</th>
<th>Hardware Connection</th>
<th>Data Rate</th>
<th>Error Tolerance</th>
<th>Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiK Telemetry Radio</td>
<td>FHSS</td>
<td>900 MHz</td>
<td>-121 dBm</td>
<td>20 dBm</td>
<td>300+ m (out of box)</td>
<td>6 pin (UART + I2C)</td>
<td>250 kbps</td>
<td>25%</td>
<td></td>
</tr>
<tr>
<td>TGY-i6 Transmitter Radio</td>
<td>AFHDS</td>
<td>2.4 GHz</td>
<td>20 dBm</td>
<td>1 km</td>
<td>N/A</td>
<td>6</td>
<td></td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>Netgear R6700 WiFi Router</td>
<td>802.11 b</td>
<td>2.4-2.4835 GHz</td>
<td>14 dBm</td>
<td>90 m</td>
<td>11 mb/s</td>
<td>13</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bluetooth Controller</td>
<td>2.4 GHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>19.2 kB/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ublox GPS Radio</td>
<td>1.5 GHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
- Robot Operating System
- Open-source communication framework
  - Commonly used in robotics research
- Distributed network of independent processes
  - Processes called “nodes”
- Synchronous communication over “services”
- Asynchronous communication over “topics”
All nodes register with the master node.

1. Publisher registers with Master

2. Node subscribes to topic /uav/gps

3. Master provides address(es) of publisher(s)
Subscribers and publishers communicate directly, messages sent when a topic published to.

```
/uav_nav
(Publisher)
```

```
/ugv_nav
(Subscriber)
```

Master Node

Master continues to update

Subs and Pubs establish communication
ROS Overview

- Physical node locations do not matter, but all nodes must be on the same network.
ROS Overview

UGV Computer

/uav_nav (Publisher)

Master Node

UAV Computer

/ugv_nav (Subscriber)
ROS Overview

- ROS topic monitoring can be used to determine data rates used by individual topics.
- ROS Bags subscribe to topics and provide a record of sent data
  - This will be utilized to store all sensor, navigation, image and housekeeping data.
The GPS receiver will output following UBX messages:

- **GPS Fix:** UBX-NAV-HPPOSLLH
- **GPS Raw Ephemeris:** UBX-NAV-ORB
- **Satellite Geometric Quality (DOP):** UBX-NAV-DOP
- **Relative position in NED frame:** UBX-NAV-RELPOSNED
- **Velocity in NED frame:** UBX-NAV-VELNED
- **Time of GPS Fix:** UBX-NAV-TIMEUTC

Update Rate of 1 Hz at 19200 Baud.
GPS Interference

- To combat noise from camera and electronics:
- Antenna will be elevated with ground plane.
- Camera and electronics will be wrapped with aluminum to act as a faraday cage.
Pointing Potential Improvements/Changes

- GPS Unit could potentially send messages with ECEF coordinates.
- If GPS update rate is too slow then path prediction will need to be implemented using velocity solutions from the GPS unit.
- Further UGV gimbal development to minimize size and jitter for the selected camera.
Simulated Camera and Mount

- Gazebo plugin for camera
  - Parameters
    - View distance
    - Resolution
    - Field of view

- Gazebo plugin for mount control
  - Modeled by two intersecting cylinders
  - Manually command pan and tilt joints to angles
  - Still to implement: mount tracks UAV by sharing GPS, more realistic model for camera and mount
Gazebo Playback

- A ROS Bag records ROS messages for topics that the bag is subscribed to, as well as a time record of the message.
- Using ROS playback, tools these messages can be played back in real time.
- Utilizing the Gazebo model, and replaying all ROS messages, the test conditions and results can be played back.
  - There are some limitations, based on the time difference between when a topic was published to, and when the value was processed.
## Gazebo Simulation Orbit Parameters

<table>
<thead>
<tr>
<th></th>
<th>Pointing</th>
<th>Blob Detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance</td>
<td>21.2 m</td>
<td>14.1 m</td>
</tr>
<tr>
<td>Radius</td>
<td>15 m</td>
<td>10 m</td>
</tr>
<tr>
<td>Altitude</td>
<td>15 m</td>
<td>10 m</td>
</tr>
<tr>
<td>Speed</td>
<td>3.93 m/s</td>
<td>0.873 m/s</td>
</tr>
</tbody>
</table>
Camera Distortion Model

- Correction matrix created by checkerboard and Brown-Conrady model.
- Tangential distortion assumed zero.
  \[
  \begin{align*}
  \tilde{x} &= x + x[k_1(x^2 + y^2) + k_2(x^2 + y^2)^2] \\
  \tilde{y} &= y + y[k_1(x^2 + y^2) + k_2(x^2 + y^2)^2]
  \end{align*}
  \]  

- Model corrects for radial distortion.
- Corrected Image will have parallel lines.

*Courtesy SWARD Camera Calibration Toolbox*
Camera Calibration

- Camera matrix:

\[ P = K[R] - RC \]

- Intrinsic matrix multiplied by the Extrinsic matrix.
- Extrinsic matrix can be expressed as:

\[ [R \mid t] = \begin{bmatrix} r_{1,1} & r_{1,2} & r_{1,3} & t_1 \\ r_{2,1} & r_{2,2} & r_{2,3} & t_2 \\ r_{3,1} & r_{3,2} & r_{3,3} & t_3 \end{bmatrix} \]

- Where the right block is camera rotation relative to world coordinates and left block is camera translation in world coordinates.
- World coordinate origin is target.
Camera Matrix

A “principal point” is assumed the center of the distortion.

\[
K = \begin{pmatrix}
  f_x & s & x_0 \\
  0 & f_y & y_0 \\
  0 & 0 & 1
\end{pmatrix}
\]

- $f_x$ and $f_y$ are the focal lengths for the sensor (assumed equal).
- $x_0$ and $y_0$ are offsets for principal point.
- $S$ is axis skew or distortion, or a shear.
AR Tag Test Video
Camera Solution

► DFK 33UX249 (1920x1200).
► Tamron M112FM16 16mm lens.
► Second choice from trade study.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Angle of View</td>
<td>28 degrees</td>
</tr>
<tr>
<td>Horizontal Angle of View</td>
<td>36.8 degrees</td>
</tr>
<tr>
<td>Maximum fps</td>
<td>48 fps</td>
</tr>
<tr>
<td>Lens Mount</td>
<td>C/CS</td>
</tr>
<tr>
<td>Sensor Format</td>
<td>1/1.2&quot;</td>
</tr>
</tbody>
</table>

*Courtesy of rmaelectronics.com and theimagingsource.com
Angle of view is calculated from the sensor dimension, $d$, and the focal length of the lens, $f$

$$AOV = \tan^{-1}\left(\frac{d}{2f}\right)$$

$$FOV = 2d \cdot \tan\left(\frac{AOV}{2}\right)$$

For the 1/1.2” sensor (10.67 x 8.00 mm) on the DFK 33UX249, a 16mm lens gives a 28 degree vertical AOV and a 36.8 degree horizontal AOV.
Testing Improvements

- Camera calibration with larger checkerboard.
- Precise spacing and printing of tags.
- Focus calibration.

*Courtesy of Image Engineering*
OpenCV Blob Detection – Tunable Parameters

- OpenCV library class
  SimpleBlobDetector

- Parameters available to tune for optimal performance
  - Color/threshold – define desired intensity range
  - Area (blobs detected will be between min and max area) in pixels
  - Circularity
  - Inertia ratio (measure of eccentricity of blobs, min and max)
  - Convexity

Courtesy of learnopencv.com
Blob Detection Demo Parameters

- **Threshold (intensity 0 – 255)**
  - Minimum value: 0
  - Maximum value: 127
- **Area of blobs (pixels)**
  - Minimum value: 100
  - Maximum value: 10000
Blob Detection Flowchart -- PDR

PRE-PROCESSING

TRANSFORM PREDICTED LOCATION TO IMAGE COORDS

CROP IMAGE AROUND PREDICTED LOCATION

CONVERT TO GRAYSCALE

ADAPTIVE THRESHOLDING

POST-PROCESSING

PARAMS. AREA

IGNORE BLOBS CONNECTED TO IMAGE FRAME

RETURN DETECTION YES/NO

CAPTURE IMAGE

BLOB DETECTION
Detection of small target
Testing Design Requirements and Models

<table>
<thead>
<tr>
<th>Subsystem Test</th>
<th>Design Requirements</th>
<th>Model to Validate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camera Pointing</td>
<td>DR 3.1</td>
<td>AOV Model</td>
</tr>
<tr>
<td>GPS Accuracy</td>
<td>DR 3.1, 8.4</td>
<td>GPS Error</td>
</tr>
<tr>
<td>Tracking</td>
<td>FR 3.0</td>
<td>Gazebo</td>
</tr>
<tr>
<td>UAV Manual Flight</td>
<td>DR 5.1</td>
<td>-</td>
</tr>
<tr>
<td>UAV Auto Flight</td>
<td>DR 9.3</td>
<td>-</td>
</tr>
<tr>
<td>UAV Endurance</td>
<td>DR 1.1, 7.1, 7.4</td>
<td>Power Model</td>
</tr>
<tr>
<td>Comms Test</td>
<td>DR 8.2, 8.4</td>
<td>Range</td>
</tr>
<tr>
<td>Full System Test</td>
<td>DR 4.1</td>
<td>Gazebo</td>
</tr>
</tbody>
</table>

Conclusions:
- Gazebo model contains many project elements
- Many UAV tests required to build up to test readiness
<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Cause</th>
<th>Likelihood</th>
<th>Effect</th>
<th>Severity</th>
<th>Total</th>
<th>Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Testing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>##############################################################################</td>
</tr>
<tr>
<td>- UAV Crash: No Damage</td>
<td>User Error or Code Failure</td>
<td>10</td>
<td>Reset Test</td>
<td>2</td>
<td>20</td>
<td>Incremental Build Up, Spare carbon structural rods for quick repairs</td>
</tr>
<tr>
<td>- UAV Crash: Minor Damage</td>
<td>User Error or Code Failure</td>
<td>10</td>
<td>Repair Damage Reset Test</td>
<td>4</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>- UAV: Crash Major Damage</td>
<td>User Error or Code Failure</td>
<td>8</td>
<td>Repair Damage Reset Test</td>
<td>8</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td>- UAV Crash: Catastrophic</td>
<td>User Error or Code Failure</td>
<td>4</td>
<td>Re-factor testing plans</td>
<td>10</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>- Li-Po Damage</td>
<td>Operator Error</td>
<td>4</td>
<td>Use other batteries</td>
<td>4</td>
<td>16</td>
<td>Properly plan testing for efficiency, plan for schedule slip due to weather</td>
</tr>
<tr>
<td>- Testing takes too long to</td>
<td>Long Prep Times</td>
<td>4</td>
<td>Schedule Slide</td>
<td>4</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>complete</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>##############################################################################</td>
</tr>
<tr>
<td>- UGV Crash</td>
<td>Operator Error</td>
<td>2</td>
<td>Reset Test</td>
<td>2</td>
<td>4</td>
<td>Only authorized personnel drive vehicle</td>
</tr>
<tr>
<td>- ODROID doesn't meet</td>
<td>Underestimation of the complexity of</td>
<td>6</td>
<td>Change visual detection</td>
<td>2</td>
<td>12</td>
<td>Scale the image processing</td>
</tr>
<tr>
<td>performance requirements</td>
<td>algorithms</td>
<td></td>
<td>strategy</td>
<td></td>
<td></td>
<td>##############################################################################</td>
</tr>
<tr>
<td>- Unable to meet endurance</td>
<td>Model Inaccuracies</td>
<td>2</td>
<td>Mission duration</td>
<td>2</td>
<td>4</td>
<td>Connect two cells in parallel</td>
</tr>
<tr>
<td>requirement</td>
<td></td>
<td></td>
<td>shortened</td>
<td></td>
<td></td>
<td>##############################################################################</td>
</tr>
<tr>
<td>- Bad Data</td>
<td>Incorrect sensor selection, too much</td>
<td>2</td>
<td>Implement filtering,</td>
<td>6</td>
<td>12</td>
<td>Characterize sensors to determine what filtering needs to occur</td>
</tr>
<tr>
<td></td>
<td>sensor noise</td>
<td></td>
<td>refactor data collection strategy</td>
<td></td>
<td></td>
<td>##############################################################################</td>
</tr>
<tr>
<td>- Camera Breaks</td>
<td>UAV Crash, operator error</td>
<td>2</td>
<td>Transfer camera to UAV,</td>
<td>10</td>
<td>20</td>
<td>Payload only installed when required</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>continue testing without UGV camera</td>
<td></td>
<td></td>
<td>##############################################################################</td>
</tr>
<tr>
<td>- Short Electronics</td>
<td>Operator Error</td>
<td>2</td>
<td>Replace broken</td>
<td>6</td>
<td>12</td>
<td>Order spare ODROID and build from schematics</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>electronics</td>
<td></td>
<td></td>
<td>##############################################################################</td>
</tr>
<tr>
<td>- Testing doesn't</td>
<td>Insufficient testing, incorrect test plans</td>
<td>2</td>
<td>Refactor testing plan,</td>
<td>8</td>
<td>16</td>
<td>Peer review test plans among team and faculty</td>
</tr>
<tr>
<td>substantiate claims</td>
<td></td>
<td></td>
<td>retest system</td>
<td></td>
<td></td>
<td>##############################################################################</td>
</tr>
</tbody>
</table>
## Risks

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Cause</th>
<th>Likelihood</th>
<th>Effect</th>
<th>Severity</th>
<th>Total</th>
<th>Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardware</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Too heavy</td>
<td>Inaccurate weight estimates</td>
<td>2</td>
<td>UAV may crash or have reduced endurance</td>
<td>8</td>
<td>16</td>
<td>UAV will be flown with proxy weights for testing.</td>
</tr>
<tr>
<td>- Payload doesn't mount</td>
<td>Insufficient modelling</td>
<td>2</td>
<td>Will have to redesign mounting solution</td>
<td>4</td>
<td>8</td>
<td>Solidworks modelling to ensure payload will mount</td>
</tr>
<tr>
<td>- C/G Stability is poor</td>
<td>Payload weight is not correctly distributed</td>
<td>6</td>
<td>UAV may crash</td>
<td>8</td>
<td>48</td>
<td>Incremental build up with proxy masses.</td>
</tr>
<tr>
<td>- Field of View</td>
<td>Lens and camera combination result in insufficient field of view</td>
<td>4</td>
<td>Target vehicle will not be in image</td>
<td>8</td>
<td>32</td>
<td>Lens and camera combination FOV will be determined</td>
</tr>
<tr>
<td>- Jitter</td>
<td>Gimbal mount not manufactured properly</td>
<td>2</td>
<td>Target vehicle will not be in frame</td>
<td>4</td>
<td>8</td>
<td>Machining gimbal mount from aluminum.</td>
</tr>
<tr>
<td>- Compression</td>
<td>ODROID does not have computational power to compress images</td>
<td>2</td>
<td>Data storage solution will not store all images from tracking run.</td>
<td>2</td>
<td>4</td>
<td>Confirm ODROID has builtin hardware JPEG encoder.</td>
</tr>
<tr>
<td>- Endurance</td>
<td>Extra weight, insufficient battery capacity or motor power</td>
<td>4</td>
<td>System will not fulfill 15 minute tracking requirement.</td>
<td>4</td>
<td>16</td>
<td>Incremental build-up to confirm endurance.</td>
</tr>
</tbody>
</table>
## Risks

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Cause</th>
<th>Likelihood</th>
<th>Effect</th>
<th>Severity</th>
<th>Total</th>
<th>Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electronics</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Splitting GPS data flow between ODROID and transmitter</td>
<td>Ardupilot data transfer capabilities are poor.</td>
<td>2</td>
<td>GPS data may not be recorded or shared between vehicle</td>
<td>4</td>
<td>8</td>
<td>Data transfer will be incrementally tested to determined thresholds.</td>
</tr>
<tr>
<td>- GPS noise affecting accuracy</td>
<td>Pointing system not accurate enough</td>
<td>6</td>
<td>Target vehicle will not be in frame.</td>
<td>8</td>
<td>48</td>
<td>Antenna design and electronics placement will reduce interference.</td>
</tr>
<tr>
<td>- Pulse Width Modulation does not work</td>
<td>Incorrect motor controller design</td>
<td>4</td>
<td>UAV may crash</td>
<td>6</td>
<td>24</td>
<td>PWM motor control will be ground tests.</td>
</tr>
<tr>
<td><strong>Communications</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- WiFi range is not sufficient</td>
<td>UAV moves out of range of GCS station during test</td>
<td>4</td>
<td>Lose control over UAV, data communication would fail</td>
<td>2</td>
<td>8</td>
<td>UAV will fly within predetermined constraints to maintain range within limits.</td>
</tr>
<tr>
<td>- UGV bluetooth connection fails</td>
<td>UGV moves out of range of GCS</td>
<td>2</td>
<td>Lose control over UGV</td>
<td>2</td>
<td>4</td>
<td>UGV will operate within predetermined constraints to maintain range within limits.</td>
</tr>
<tr>
<td>- Preview image does not get communicated to GCS</td>
<td>Communication system does not have bandwidth to send image in real time</td>
<td>4</td>
<td>GCS will not have preview image for operator</td>
<td>2</td>
<td>8</td>
<td>Preview image will be compressed and scaled down before transmission.</td>
</tr>
<tr>
<td>- Interference</td>
<td>Electrical components result in interference with communications system.</td>
<td>2</td>
<td>Realtime data sharing during test is impacted</td>
<td>2</td>
<td>4</td>
<td>Electronics organization in payload is organized to mitigate interference.</td>
</tr>
<tr>
<td>- Communication between Ardupilot and ODROID fails</td>
<td>Protocol miscommunication</td>
<td>4</td>
<td>Flight data will not be shared with rest of network, resulting in failure to track.</td>
<td>8</td>
<td>32</td>
<td>Confirmation in testing of serial to USB data transfer</td>
</tr>
<tr>
<td>Failure Mode</td>
<td>Cause</td>
<td>Likelihood</td>
<td>Effect</td>
<td>Severity</td>
<td>Total</td>
<td>Mitigation</td>
</tr>
<tr>
<td>--------------</td>
<td>------------------------------------------------------------------------</td>
<td>------------</td>
<td>------------------------------------------------------------------------</td>
<td>----------</td>
<td>-------</td>
<td>------------</td>
</tr>
<tr>
<td>Tracking</td>
<td></td>
<td></td>
<td>90% frame requirement will not be automatically verified; will have to be verified with manual review.</td>
<td>2</td>
<td>12</td>
<td>Blob/AR detection are not critical to tracking algorithm</td>
</tr>
<tr>
<td>- Blob detection / AR detection fail</td>
<td>Environmental factors cause detection to fail, or algorithms are not refined enough</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Logistics</td>
<td></td>
<td></td>
<td>Parts do not show up on time resulting in physical integration and testing schedule being pushed back</td>
<td>8</td>
<td>32</td>
<td>Suppliers have been contacted to check stock, and parts have been identified so ordering can occur immediately.</td>
</tr>
<tr>
<td>- Lead times for products</td>
<td>Shipping errors or stocking issues</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test</td>
<td>Required Equipment</td>
<td>Personnel</td>
<td>Date</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------------------</td>
<td>---------------------------------------------------------</td>
<td>-------------------------</td>
<td>---------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unmounted Tracking</td>
<td>Gimbal, camera, GPS Units</td>
<td>R. Andrada, N. Levigne, R. Blay</td>
<td>1/20/17-1/31/17</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GPS Test</td>
<td>2x GPS Units</td>
<td>R. Blay, C. Charland</td>
<td>1/12/17-1/18/17</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UAV Manual Flight</td>
<td>UAV System, Transmitter</td>
<td>C. Charland, A. Swindell</td>
<td>2/5/17</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UAV Auto Flight</td>
<td>UAV System, Transmitter</td>
<td>C. Charland, A. Swindell</td>
<td>2/19/17</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GCS Test</td>
<td>GCS, UAV, UGV</td>
<td>C. Charland, A. Swindell, I. Loefgren</td>
<td>3/20/17</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COMMS Testing</td>
<td>COMMS system, UAV, UGV, GCS, Payload</td>
<td>C. Charland, A. Swindell</td>
<td>3/5/17-3/10/17</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mock Systems Test</td>
<td>UAV, UGV, GCS, Payload</td>
<td>C. Charland, A. Swindell</td>
<td>3/17/17</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full Systems Test #1 &amp; #2</td>
<td>UAV, UGV, GCS, Payload</td>
<td>C. Charland, A. Swindell</td>
<td>4/6/17-4/8/17</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
# Test Equipment & Facilities

<table>
<thead>
<tr>
<th>Equipment/Facility</th>
<th>Status/Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>South Boulder Campus</td>
<td>Available for use on 48 hour notice</td>
</tr>
<tr>
<td>RECU VICON Space</td>
<td>Available for scheduling after safety brief</td>
</tr>
<tr>
<td>Measurement Tools</td>
<td>Purchased or borrowed from AES department</td>
</tr>
<tr>
<td>Sensors</td>
<td>Purchased, some borrowed from customer/ AES department for fall semester testing</td>
</tr>
<tr>
<td>Generator</td>
<td>Borrowed</td>
</tr>
<tr>
<td>UGV Gimbal Mount</td>
<td>Machined</td>
</tr>
<tr>
<td>UAV System Components</td>
<td>Purchased</td>
</tr>
<tr>
<td>UGV</td>
<td>On loan from customer</td>
</tr>
</tbody>
</table>
VICON System

- Motion capture system owned by RECUV
- Operational in indoor flight space (RIFLE)
- Allows precise position capture using multiple IR cameras and reflective tags affixed to vehicle
- Can convert position to UTM+13 (Universal Transverse Mercator)
  - Compatible with EME system used in RAVEN
- Low Latency data generation
- Act as a stand in for GPS data
- Build RAVEN to work with both GPS and VICON
Safety

- Safety when flying UAV is biggest concern
  - Follow American Modeler Associations Guidelines
  - Safety Line when flying the UAV
  - Pilot must be AMA certified
  - Props off whenever possible
  - Arming plug for UAV
  - Follow CU Flight Operations Manual

- Li-Po safety
  - Observed charging of Li-Po batteries
  - Charging in Li-Po sack
  - Low voltage alarms to avoid over discharging

- PPE when handling hazardous materials, e.g. cutting carbon fiber
Moving Forward

- Create detailed test procedures for testing
- Walk through testing with faculty
- Safety brief for the VICON space
- Complete preliminary testing with borrowed hardware
Payload Subsystem Test Breakouts

<table>
<thead>
<tr>
<th>TEST</th>
<th>Level of Success</th>
<th>FR</th>
<th>Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gimbal Control</td>
<td>Vision L2</td>
<td>FR 3.0</td>
<td>Gimbal Model</td>
</tr>
<tr>
<td>Gimbal Pointing</td>
<td>Vision L2</td>
<td>FR 3.0</td>
<td>Gimbal Model</td>
</tr>
<tr>
<td>Camera Characterization</td>
<td>Vision L1</td>
<td>FR 4.0</td>
<td>-</td>
</tr>
<tr>
<td>IMU error</td>
<td>Captured Data L1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>GPS Lock Time/Position Error</td>
<td>Controls L1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Data Collection/Compression</td>
<td>Captured Data L1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CPU Overhead</td>
<td>Electronics L3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Data volume</td>
<td>Captured Data L1</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
# Platform Subsystem Test Breakouts

<table>
<thead>
<tr>
<th>TEST</th>
<th>Level of Success</th>
<th>FR</th>
<th>Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>UAV manual flight and stability</td>
<td>Vision L1</td>
<td>FR 1.0</td>
<td>Gazebo Model</td>
</tr>
<tr>
<td>UAV Auto flight and stability</td>
<td>Controls L3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>UAV endurance</td>
<td>Electronics L1</td>
<td>FR 1.0</td>
<td>UAV Power Model</td>
</tr>
<tr>
<td>GPS signal to ODROID</td>
<td>Captured Data L1</td>
<td>FR 8.0</td>
<td>-</td>
</tr>
<tr>
<td>GPS signal to flight controller</td>
<td>Captured Data L1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Flight controller to ODROID</td>
<td>Controls L3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Data logging</td>
<td>Captured Data L1</td>
<td>FR 2.0</td>
<td>Data Rates</td>
</tr>
</tbody>
</table>
## COMMS Subsystem Test Breakouts

<table>
<thead>
<tr>
<th>TEST</th>
<th>Level of Success</th>
<th>FR</th>
<th>Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>UAV → Ground</td>
<td>COMMS L1</td>
<td>FR 8.0</td>
<td>Data Rates/ Gazebo</td>
</tr>
<tr>
<td>UGV → Ground</td>
<td>COMMS L1</td>
<td>FR 8.0</td>
<td>Data Rates/ Gazebo</td>
</tr>
<tr>
<td>UAV → UGV</td>
<td>COMMS L2</td>
<td>FR 8.0</td>
<td>Data Rates/ Gazebo</td>
</tr>
<tr>
<td>Telemetry Radio</td>
<td>Controls L1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Bluetooth to UGV</td>
<td>Controls L3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>GPS UHF</td>
<td>Electronics L1</td>
<td>-</td>
<td>DGPS Model</td>
</tr>
</tbody>
</table>
## Vision Subsystem Test Breakouts

<table>
<thead>
<tr>
<th>TEST</th>
<th>Level of Success</th>
<th>FR</th>
<th>Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blob detection</td>
<td>Vision L3</td>
<td>-</td>
<td>Gazebo</td>
</tr>
<tr>
<td>AR Tag detection</td>
<td>Vision L2</td>
<td>FR 3.0</td>
<td>Gazebo</td>
</tr>
<tr>
<td>UAV on a Stick</td>
<td>Vision L1</td>
<td>-</td>
<td>Gazebo</td>
</tr>
</tbody>
</table>
## GCS Subsystem Test Breakouts

<table>
<thead>
<tr>
<th>TEST</th>
<th>Level of Success</th>
<th>FR</th>
<th>Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>UI</td>
<td>Comms L1</td>
<td>FR 8.0</td>
<td>UI Mockup</td>
</tr>
<tr>
<td>Emergency Land</td>
<td>Controls L1</td>
<td>FR 9.0</td>
<td>-</td>
</tr>
<tr>
<td>Preview Image</td>
<td>Comms L3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Location Data</td>
<td>Comms L3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mode Switching</td>
<td>Controls L1</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Gimbal Pointing

OBJECTIVE

- Show gimbal can be pointed
- Quantify pointing error

Required Hardware:

- Gimbal
- Arduino
- Power Supply

Required Software:

- Pointing Algorithms
- Command Generator
- Pointing Model

FR: 3.0

Risks:

- Gimbal Damage
- Loaned Gimbal not representative of flight hardware

Environment:

- Lab Environment
- Gimbal mounted to table

Outcome:

- Able to quantify pointing error in gimbal commands
- Verify Pointing algorithms
Unmounted Tracking

**OBJECTIVE**

- Verify Operation of tracking using real hardware
- Identify Issues early

**Required Hardware:**

- Gimbal + Gimbal Controller
- Arduino
- AR Tags or Blob detect or 2x GPS Units
- Camera
- Power Supply

**Required Software:**

- GPS Decoding or Blob or AR Detection
- Pointing Control
- Camera Drivers

**Outcome:**

- Gimbal assembly able to track accurately
- Tracking error not a significant risk to project

**FR: 3.0**

**Risks:**

- Break Equipment

**Environment:**

- Lab Environment
  - or:
  - Outside (GPS) (On Campus)
UAV Manual Flight

OBJECTIVE

- UAV System is controllable and stable

Required Hardware:

- UAV System without payload installed
- Transmitter
- UAV Safety System

Required Software:

- Flight Controller Configs

Risks:

- UAV Crash/Damage
- Li-Po Damage
- Injury to personnel

Environment:

- RECUV VICON Space

Outcome:

- UAV able to hover for mission duration
- UAV able to orbit for mission duration
- UAV is stable during flight
UAV Auto Flight

**OBJECTIVE**
- Verify Auto-Flight Capability
- Hover/Orbit for mission duration
- Toggle between manual and automatic control

**Required Hardware:**
- UAV System without payload

**Required Software:**
- Flight Controller configured
- Flight path definition
- GPS Decoding
- Auto/Manual Toggle

**Outcome:**
- UAV flies autonomously for mission duration
- Switching between auto/manual modes
- Smooth flight

**FR: 1.0, 5.0**

**Risks:**
- UAV Crash Damage
- Li-Po Damage
- Weather Schedule Slippage

**Environment:**
- Outside, Clear Calm Day
GCS Test

OBJECTIVE

- Verify operation of GCS
- Verify:
  - ROS Package
  - COMMS
  - Visual Data
  - GPS Delivery
  - Pose Delivery
  - ISM Band

Required Hardware:

- GCS
- Fully integrated UAV/UGV

Required Software:

- GCS Software
- ODROID Running
- ROS Network

FR: 8.0, 9.0

Risks:

- Unable to reliably validate GCS
- Schedule Slippage

Environment:

- Lab Space

Outcome:

- Reliable GCS
- Checks all verify boxes in objective
COMMS Test

OBJECTIVE
- Ensure Comms system is flight ready
- ROS works
- Comms are reliable

Required Hardware:
- Router
- UGV/UAV
- GCS

Required Software:
- GCS
- ROS Nodes
- Comms Network

Outcome:
- All ROS Nodes can communicate
- Data latency does not pose risk to project
- Comms range is large enough to facilitate operation

FR: 8.0, 9.0, 10.0

Risks:
- Environment:
  - Lab Environment
Mock Systems Test

OBJECTIVE
- Determine Preparedness for FST

Required Hardware:
- Fully Integrated UAV/UGV
- GCS
- Full System Ready

Required Software:
- UAV (Autopilot, Camera, ROS)
- UGV (Controls, Camera, ROS)
- GCS

FR: 1.0, 3.0, 5.0, 6.0, 8.0, 9.0

Risks:
- Schedule Slide
- Integration Failures

Environment:
- RECUV VICON Space

Outcome:
- Ready for FST #1
- All systems Go
Full System Test #1 & #2

OBJECTIVE
- Show full system effectiveness
- Test both Scenarios

Required Hardware:
- Fully integrated UAV, UGV
- GCS
- Generator
- Router

Required Software:
- Completed system software

FR: All

Risks:
- System Damage
- Bodily Harm
- Weather Delays

Environment:
- South Boulder campus
- Calm, Clear day

Outcome:
- System works and satisfies functional requirements
## Testing Risk Detailed Breakdown

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Cause</th>
<th>Likelihood</th>
<th>Effect</th>
<th>Severity</th>
<th>Total</th>
<th>Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>UAV Crash</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- No Damage</td>
<td>User Error or Code Failure</td>
<td>10</td>
<td>Reset Test</td>
<td>2</td>
<td>20</td>
<td>Incremental Build Up, Spare carbon structural rods for quick repairs</td>
</tr>
<tr>
<td>- Minor Damage</td>
<td>User Error or Code Failure</td>
<td>10</td>
<td>Repair Damage Reset Test</td>
<td>4</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>- Major Damage</td>
<td>User Error or Code Failure</td>
<td>8</td>
<td>Repair Damage Reset Test</td>
<td>8</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td>- Catastrophic</td>
<td>User Error or Code Failure</td>
<td>4</td>
<td>Re-factor testing plans</td>
<td>10</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td><strong>Li-Po Damage</strong></td>
<td>Operator Error</td>
<td>4</td>
<td>Use other batteries</td>
<td>4</td>
<td>16</td>
<td>Properly plan testing for efficiency, plan for schedule slip due to weather</td>
</tr>
<tr>
<td><strong>Testing Takes too Long</strong></td>
<td>Long Prep Times</td>
<td>4</td>
<td>Schedule Slide</td>
<td>4</td>
<td>16</td>
<td>Only authorized personnel drive vehicle</td>
</tr>
<tr>
<td><strong>UGV Crash</strong></td>
<td>Operator Error</td>
<td>2</td>
<td>Reset Test</td>
<td>2</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Odroid doesn't meet performance requirements</td>
<td>Underestimation of the complexity of algorithms</td>
<td>6</td>
<td>Change visual detection strategy</td>
<td>2</td>
<td>12</td>
<td>Scale the image processing</td>
</tr>
<tr>
<td><strong>Unable to meet endurance requirement</strong></td>
<td>Model Inaccuracies</td>
<td>2</td>
<td>Mission duration shortened</td>
<td>2</td>
<td>4</td>
<td>Connect two cells in parallel</td>
</tr>
<tr>
<td><strong>Bad Data</strong></td>
<td>Incorrect sensor selection, too much sensor noise</td>
<td>2</td>
<td>Implement filtering, refactor data collection strategy</td>
<td>6</td>
<td>12</td>
<td>Select sensors to</td>
</tr>
<tr>
<td><strong>Camera Breaks</strong></td>
<td>UAV Crash, operator error</td>
<td>2</td>
<td>Transfer camera to UAV, continue testing without UGV camera</td>
<td>10</td>
<td>20</td>
<td>Payload only installed when required</td>
</tr>
<tr>
<td><strong>Short Electronics</strong></td>
<td>Operator Error</td>
<td>2</td>
<td>Replace broken electronics</td>
<td>6</td>
<td>12</td>
<td>Order spare Odroid, build from schematics</td>
</tr>
<tr>
<td><strong>Testing doesn't substantiate claims</strong></td>
<td>Insufficient testing, incorrect test plans</td>
<td>2</td>
<td>Refactor testing plan, retest sys</td>
<td>8</td>
<td>16</td>
<td>Peer review test plans among team and faculty</td>
</tr>
</tbody>
</table>
UAV Crash
- No Damage

Description:
- UAV crash that requires repair
- New props or minor fixes

Rating: 20
Likelihood: 10

Mitigation:
- Payload not installed when not needed
- UAV Safety system
- Spare Props and carbon rods

Impact: 2
**UAV Crash - Minor Damage**

**Description:**
- UAV crash that requires repair
- New props or minor fixes

**Rating:** 40

**Likelihood:** 10

**Mitigation:**
- Payload not installed when not needed
- UAV Safety system
- Spare Props and carbon rods

**Impact:** 4
UAV Crash
- Major Damage

Description:
- UAV crash that requires complex repair
- New parts that aren’t on hand

Rating: 64
Likelihood: 8

Mitigation:
- Payload not installed when not needed
- UAV Safety system
- Spare Props and carbon rods
- Spare companion computer
- Follow AMA Guidelines

Impact: 8
UAV Crash
- Catastrophic Damage

Description:
- UAV crash that cannot be repaired

Rating: 40
Likelihood: 4
Impact: 10

Mitigation:
- Payload not installed when not needed
- Switch testing plans
- Build contingency testing plans
Camera Breaks

Description:
- Camera breaks due to UAV crash or operator error
- Would force removal of camera from UGV for use on UAV

Mitigation:
- Camera payload will only be installed when required for testing
- Only certified pilot will fly UAV

Rating: 20
Likelihood: 2
Impact: 10
UAV Stability is Poor

Description:
- UAV flight stability is poor due to poor weight distribution or C.G. location
- Would increase likelihood of a crash

Mitigation:
- Incremental build-up of components on UAV
- UAV testing with proxy weights

Rating: 48
Likelihood: 6
Impact: 8
Field of View Insufficient

Description:
- Lens and camera combination result in an insufficient field of view
- Could result in failure to track target vehicle in 90% of frames

Mitigation:
- Lens and camera combination angle of view will be confirmed through testing

Rating: 32
Likelihood: 4
Impact: 8
Noise affecting GPS accuracy

Description:
- Electronic equipment and environment worsen accuracy.
- High accuracy is required for tracking system

Mitigation:
- Electronics in payload will be arranged to minimize interference

Rating: 48
Likelihood: 6
Impact: 8
Communication between ArduPilot and ODROID fails

Description:
- Protocol communication or bandwidth limitations prevent data transfer
- Tracking will fail without data sensor data

Mitigation:
- Testing of serial to USB protocol will confirm communication compatibility.

Rating: 32  
Likelihood: 4  
Impact: 8
Description:
- Shipping errors or product being out of stock could occur
- Would result in physical integration and testing schedule being pushed back.

Mitigation:
- Specific components have been identified and are ready for order
- Suppliers have been contacted to confirm availability
UAV Crash - Minor Damage

Description:

- UAV crash that requires repair
- New props or minor fixes

Mitigation:

- Payload not installed when not needed
- UAV Safety system
- Spare Props and carbon rods

Rating: 40

Likelihood: 10

Impact: 4
UAV Crash
- Major Damage

**Description:**
- UAV crash that requires complex repair
- New parts that aren’t on hand

**Rating:** 64

**Likelihood:** 8

**Mitigation:**
- Payload not installed when not needed
- UAV Safety system
- Spare Props and carbon rods
- Spare companion computer
- Follow AMA Guidelines

**Impact:** 8
UAV Crash
- Catastrophic Damage

**Description:**
- UAV crash that cannot be repaired

**Rating:** 40

**Likelihood:** 8

**Mitigation:**
- Payload not installed when not needed
- Switch testing plans
- Build contingency testing plans

**Impact:** 8
Li-Po Damage

Description:

- Cell Damage from:
  - Over discharging
  - Physical damage
  - Improper charging

Mitigation:

- Observed charging
- Charging in Li-Po sack
- Low voltage monitoring on UAV
- Team training on battery safety

Rating: 16

Likelihood: 4

Impact: 4
Testing Takes Too Long

Description:
- Testing Takes longer than expected
- Software not complete when needed
- Testing space not available

Likelihood: 4

Mitigation:
- Schedule Margin for testing issues
- Parallelize testing as much as possible

Rating: 16

Impact: 4
UGV Crash

**Description:**
- UGV crashes into stationary object

**Rating:** 4

**Likelihood:** 2

**Impact:** 2

**Mitigation:**
- Trained operators use UGV
- UGV not operated in spaces with many unmoving objects
ODROID does not meet performance requirements

Description:
- ODROID incapable of running required tasks
- ODROID processing not fast enough
- Unable to write to disk fast enough

Rating: 12

Likelihood: 2

Mitigation:
- Remove visual detection from ODROID
- Move gimbal control to Arduino
- Remove preview image downsampling

Impact: 6
UAV Crash - Catastrophic Damage

Description:
- UAV crash that cannot be repaired

Rating: 40
Likelihood: 8

Mitigation:
- Payload not installed when not needed
- Switch testing plans
- Build contingency testing plans

Impact: 8