Rover and Air Visual Environment Navigation

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CUSTOMER: NISAR AHMED

ADVISOR: TORIN CLARK
## Agenda

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<th>Ryan Wall and Rolf Andrada</th>
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<td>Ryan Blay</td>
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Acronyms

- AOV: Angle of View
- AR: Augmented Reality
- AUW: All Up Weight
- CEP: Circular Error Probable
- CPU: Central Processing Unit
- EPS: Electrical Power System
- ESC: Electronic Speed Control
- FC: Flight Controller
- FOV: Field of View
- GCS: Ground Control Station
- GPS: Global Positioning System
- IMU: Inertial Measurement Unit
- ISM: Industry Science Medicine
- LiPo: Lithium Polymer
- LOS: Line of Sight
- MCU: Microcontroller Unit
- MP: Megapixel
- PWM: Pulse Width Modulation
- RF: Radio Frequency
- RTK: Real Time Kinematics
- UAV: Unmanned Aerial Vehicle
- UGV: Unmanned Ground Vehicle
- UI: User Interface
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 and UAV/UGV pair to customer.
Concept of Operations

**Prepare**
- UAV: Safety Checks, Preflight Checks, Take off to initial position
- UGV: Safety Checks, Pre-run Checks, Move to initial position

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

**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

**Vision**
- UAV: UGV in 90% of frames, 3 inches/pixel at 30 m
- UAV & UGV: Cameras rotate to keep other vehicle in frame, Vehicles have L.O.S.

**RAVEN**

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

**UGV Control**
- UAV Operator
- UGV Operator

**Path**
- Navigation Data
- Control
- Visual Observer
Concept of Operations

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

**Execute**
- Preprogrammed Flight Path or Stationary Hover
- 15 min Flight Time
- Location Data (IMU/GPS/Ephemeris)
- Max: 0.5 m/s or Stationary tracking
- 10-30 m

**Vision**
- UAV in 90% of frames
- 3 inches/pixel at 30 m
- UAV & UGV
  - Cameras rotate to keep other vehicle in frame
  - Vehicles have L.O.S.

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

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

**Conclude**
- UAV
  - Manual Landing
  - System Shutdown
  - Offload Collected Data
- UGV
  - System Shutdown
  - Offload Collected Data

RAVEN
Concept of Operations
## Functional Requirements

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<th>Functional Requirement</th>
<th>Description</th>
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<tr>
<td>FR 1.0</td>
<td>RAVEN shall perform data collection for 15 minutes.</td>
</tr>
<tr>
<td>FR 2.0</td>
<td>RAVEN shall have a removable data storage system on both the UAV and UGV.</td>
</tr>
<tr>
<td>FR 3.0</td>
<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>
</tr>
<tr>
<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>
</tr>
<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>
<tr>
<td>FR 10.0</td>
<td>Vision system shall use customer specified interfaces.</td>
</tr>
</tbody>
</table>

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### Project Overview

- Tracking
- Power
- Communication
- Conclusion
Baseline Design Choices and CPEs

- **BAROMETER (1)**
- **GPS (3)**
- **2-AXIS GIMBAL (1)**
- **CPU (4), EPS (2), SENSORS (1)**
- **2.4 GHz (3)**

- **GPS (3)**
- **2-AXIS GIMBAL (1)**
- **CPU (4)**
- **FC (1)**
- **3-AXIS GIMBAL (1)**
- **LIPO (2)**

2.4 GHz, 915 MHz (3)

**Project Overview**

1. **Tracking Systems**
2. **Power Systems**
3. **Communications**
4. **Data Collection**

UAV/UGV gimbals, GCS Models courtesy of GrabCAD
UGV model courtesy of ClearPath Robotics
Tracking Method

FR 3.0 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.

FR 4.0 UAV and UGV visual data shall have a minimum resolution of three inches per pixel at a distance of 30 m.
Relative Position Determination

Collect
Collect position data using sensor suite

Share
Share position data between vehicles*

Determine
Determine relative position using shared information

*Will be focused on in communications section

Project Overview  Tracking  Power  Communication  Conclusion
### Relative Position Determination: Collect

#### Vehicle Sensors

<table>
<thead>
<tr>
<th>State Variable</th>
<th>GPS*</th>
<th>Barometer</th>
<th>IMU</th>
<th>Magnetometer</th>
</tr>
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<tbody>
<tr>
<td>x</td>
<td>✔</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>y</td>
<td>✔</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>z</td>
<td></td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Φ (Roll)</td>
<td></td>
<td></td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>Θ (Pitch)</td>
<td></td>
<td></td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>Ψ (Yaw)</td>
<td></td>
<td></td>
<td>✔</td>
<td></td>
</tr>
</tbody>
</table>

*DGPS with RTK engine provides high (cm) accuracy for relative positions*
Relative Position Determination: Determine

\[ \mathbf{x}_{rel} = \mathbf{x}_{UAV} - \mathbf{x}_{UGV} \]

Relative Position
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
Vehicle Location Error Model (cont.)

- UAV location error based on GPS and barometer
- Assumption: error has Gaussian distribution
- NEO-M8P u-blox M8 High Precision GNSS Module with RTK [1]
  - Listed Error: 0.025 m CEP
- MS5611 Barometer [2]
  - Listed Max Error: ±0.5 mbar
Vehicle Location Error Model – Required AOV

- RTK-GPS results in >90% within AOV constraints

Simulated Required Angle of View at Range of 10 m with Sensor Errors

- Simulated with Standalone GPS Error
- Simulated with RTK GPS Error
- Camera Angle of View (37°)
Vehicle Location Error Model – Required AOV

- RTK-GPS results in >90% within AOV constraints
Camera Pointing

Input collected sensor data (with relative position computed) → Compute coordinate transformations → Point camera
Camera Pointing – Gimbal Model

- **UAV: 3-axis gimbal**
  - Control Yaw, Pitch, Roll

- **UGV: 2-axis gimbal**
  - Control Yaw, Pitch
  - UGV on "level" surface

- Need:
  - Relative Position (GPS, Barometer, AR)
  - Attitude (IMU and Magnetometer)
Pointing Model

- Quaternion rotation scheme
  - Vehicle body to camera frame
  - One axis of rotation and rotation angle

- Break down rotation into Euler angles:
  - UAV: 3-2-1
  - UGV: 3-2

- Gimbal Lock (+Pitch 90° on UAV)
  - UAV gimbal will be prevented from pointing straight down
  - FOV will handle overhead pointing
Pointing Simulation

- Pointing using quaternions

- Legend (body frame):
  - Black – camera pointing vector
  - Red – x
  - Green – y
  - Blue – z

\[ V_d = 1.8258 \, \text{m/s}, \, \theta_d = 89.4443^\circ \]
\[ V_r = 0.5 \, \text{m/s}, \, \theta_r = 304.6228^\circ \]
\[ n = 1 \]
Pointing Simulation

- Pointing using quaternions

- Legend (body frame):
  - Black – camera pointing vector
  - Red – x
  - Green – y
  - Blue – z

Project Overview  Tracking  Power  Communication  Conclusion
Visual Detection – Verification

- Visual detection is used to verify target is within image frame
- Visual detection methods are susceptible to environmental conditions, e.g. lighting
- Camera resolution will need to be high enough to meet FR 4.0
- Visual detection split into two groups: ground to air, and air to ground
  - Air to ground validation accomplished with AR tags
  - Ground to air validation accomplished with blob detection
Resolution Model

- **Purpose:**
  - Feasibility of camera and lens choice
  - Satisfy FR 4.0 (3 in/pix at 30 m)
  - Latency impact

- **FLIR Blackfly 2.3 MP & 12 mm lens[3]:**
  - Resolution: 1920 x 1200
  - Focal Length (f): 12 mm
  - Sensor Type: 1/1.2” (10.67 mm x 8 mm)

- **Pixel Density:**
  - Compute by dividing FOV by resolution
  - At 30 m: **0.467 in/pix**

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

\[
FOV = 2d \cdot \tan\left(\frac{AOV}{2}\right)
\]
Resolution Model

Flight Model with FOV Cone

Y Position [m]  X Position [m]

UAV

Flight Model with FOV Cone

Y Position [m]  X Position [m]

UAV

Project Overview  Tracking  Power  Communication  Conclusion
Resolution Model

Flight Model with FOV Cone

Y Position [m]  X Position [m]

UAV

DGV

Flight Model with FOV Cone

Y Position [m]  X Position [m]

UAV

DGV
AR Tag Proof of Concept

- High-contrast binary patterns with unique features
- Robust to lighting changes
- Implementations exist in ROS packages
- Able to estimate position and orientation from tags
AR Tag Proof of Concept

Project Overview

Tracking

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Conclusion
AR Tag Required Size Estimate

- Trial Run (Laptop Webcam):
  - Resolution: 640 x 480
  - AOV: ~64°
  - Identified: 5.5 cm AR tags up to 2.5 m range

- Implies:
  - Tracking limit: 11 pixels per linear dimension of the tag
  - Tag size: ~18 cm (7 in) for 2.3 MP sensor (extrapolating linearly assuming no distortion effects)
AR Tag Required Size Estimate

- **Trial Run (Laptop Webcam):**
  - Resolution: 640 x 480
  - AOV: ~64°
  - Identified: 5.5 cm AR tags up to 2.5 m range

- **Implies:**
  - Tracking limit: 11 pixels per linear dimension of the tag
  - Tag size: ~18 cm (7 in) for 2.3 MP sensor (extrapolating linearly assuming no distortion effects)
Ground to Air Detection

- AR tags would be too large to attach to the UAV
- 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: identify clusters of pixels with similar characteristics, e.g. color, intensity
Ground to Air Detection (cont.)

- Similar method used by Krukowski et al. [4]
- OpenCV libraries for blob detection, pre and post-processing steps [5]
  - Eases implementation
Similar method used by Krukowski et al. [4]

- OpenCV libraries for blob detection, pre and post-processing steps [5]
  - Eases implementation
UAV Power Requirements

FR 1.0  RAVEN shall perform data collection for 15 minutes.
Power

- Assumptions:
  - 85% Battery Discharge
  - Voltage Linearly Depends on Charge
  - Wire Resistance Negligible
  - Payload Current Draw Constant (6A)
  - Wires 5% of All Up Weight
  - Flying at 5280 ft, 60°F
  - No Airframe Drag

\[
T = \frac{1}{2} \rho A V^2
\]

\[
V_{air} = \sqrt{\frac{2T}{\rho A}}
\]

\[
P_{prop} = TV_{air}
\]

\[
P_{mech} = (V_{batt} - R_{motor} I_{motor})(I_{motor} - I_0)
\]

\[
V_{air} = \omega \times \text{pitch} \times \left( \frac{0.0254}{60} \right)
\]

\[
I_{tot} = \text{NumMotors} \times I_{motor} + I_{payload}
\]
# Quad vs HexaCopter

<table>
<thead>
<tr>
<th></th>
<th>QuadCopter</th>
<th>HexaCopter</th>
</tr>
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<tbody>
<tr>
<td>Max Hover Endurance</td>
<td>18 min</td>
<td>24 min</td>
</tr>
<tr>
<td>Mixed Flight Endurance</td>
<td>15.3 min</td>
<td>20.4 min</td>
</tr>
<tr>
<td>All Up Weight</td>
<td>4.3 kg</td>
<td>4.65 kg</td>
</tr>
<tr>
<td>Controllable with rotor failure</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Max Amp Draw</td>
<td>80 A</td>
<td>113 A</td>
</tr>
<tr>
<td>Ideal Battery</td>
<td>5s – 14,000 mAh</td>
<td>5s – 16,000 mAh</td>
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</table>

## Hover Endurance Vs Battery Size
Keeping Drive System Constant

![Hover Endurance Graph](graph.png)
UAV Configuration

<table>
<thead>
<tr>
<th>Configuration</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Rotors</td>
<td>6</td>
</tr>
<tr>
<td>Hover Endurance</td>
<td>24 (min)</td>
</tr>
<tr>
<td>Battery</td>
<td>5s-16000 mAh Li-Po</td>
</tr>
</tbody>
</table>

Electronics not included

![Graph showing endurance vs. added mass](image)

- **Project Overview**
- **Tracking**
- **Power**
- **Communication**
- **Conclusion**
## UAV Configuration

<table>
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![Drone Image](image-url)

---

**Graph:**

- **Endurance (min)** vs **Added Mass (g)**

---

**Project Overview**

**Tracking**

**Power**

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**Conclusion**

---

**FEASIBLE**
## Communication

| FR 2.0 | RAVEN shall have a removable data storage system on both the UAV and UGV. |
| FR 8.0 | The UAV and UGV shall communicate flight and navigation status data to their respective ground stations (GCS) and to each other. |
| FR 9.0 | RAVEN shall communicate flight/drive commands from ground stations to and from their respective vehicle over an ISM radio frequency. |
## Data Storage Feasibility

<table>
<thead>
<tr>
<th>Name</th>
<th>Data Rate</th>
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</thead>
<tbody>
<tr>
<td>Camera</td>
<td>114 MB/s</td>
</tr>
<tr>
<td>IMU</td>
<td>~4 kB/s</td>
</tr>
<tr>
<td>GPS</td>
<td>2.4 kB/s</td>
</tr>
<tr>
<td>Barometer</td>
<td>~0.13 kB/s</td>
</tr>
<tr>
<td>Total Data Rate</td>
<td>115 MB/s</td>
</tr>
<tr>
<td>USB 3.0 Flash Write Speed</td>
<td>150 MB/s</td>
</tr>
</tbody>
</table>

**Storage Time** | **Storage Needed** | **Storage Capacity**
900 s (15 min)  | 101.1 GB          | 128 GB

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Data Sharing

<table>
<thead>
<tr>
<th>Item</th>
<th>Data rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preview Image</td>
<td>2.50 Mbits/s</td>
</tr>
<tr>
<td>Navigation Data</td>
<td>75 kbits/s</td>
</tr>
<tr>
<td>Management Data</td>
<td>20 kbits/s</td>
</tr>
<tr>
<td><strong>Total Data Rate</strong></td>
<td><strong>2.51 Mbits/s</strong></td>
</tr>
<tr>
<td><strong>Maximum Throughput</strong></td>
<td><strong>11 Mbits/s</strong></td>
</tr>
</tbody>
</table>

Data Sharing 2.4 GHz 802.11b/g/n
Max Data Rate: **11 Mbits/s**
Est Data Rate: **2.51 Mbits/s**

Groundstations Receive:
Location Data, Management Data and Preview Image

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Data Sharing

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Data Sharing 2.4 GHz 802.11b/g/n
Max Data Rate: **11 Mbits/s**
Est Data Rate: **2.51 Mbits/s**

Groundstations Receive:
Location Data, Management Data
and Preview Image

UAV Companion CPU

GPS, IMU, Barometer

Jackal Celeron

Project Overview | Tracking | Power | Communication | Conclusion
Commands

### Project Overview

- **Tracking**
- **Power**
- **Communication**
- **Conclusion**

### Overview

#### Component Manufacturer Range

<table>
<thead>
<tr>
<th>Component</th>
<th>Manufacturer</th>
<th>Range</th>
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</thead>
<tbody>
<tr>
<td>FS-i6 Controller</td>
<td>SiK Telemetry</td>
<td>1.0 km</td>
</tr>
<tr>
<td>915 MHz SiK Telemetry</td>
<td></td>
<td>500 m</td>
</tr>
<tr>
<td>2.4 GHz WiFi 802.11</td>
<td></td>
<td>125 m</td>
</tr>
</tbody>
</table>

#### Hardware Overview

- **FS-i6 RC Controller AFHDS 2A 2.4 GHz**
- **UART Connection**
- **UAV Companion CPU**
- **Jackal Celeron**
- **Jackal Micro Control**
- **USB**
- **Game Controller**
- **2.4 GHz WiFi Data Sharing 802.11b/g/n**
## Conclusions

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<th>Objective</th>
<th>Requirement</th>
<th>Verified?</th>
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<tr>
<td>Tracking Method</td>
<td>Sensor requirements for state determination</td>
<td>✔</td>
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<tr>
<td></td>
<td>Camera pointing, gimbal actuation, and camera resolution</td>
<td>✔</td>
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<tr>
<td></td>
<td>Visual detection methods</td>
<td>✔</td>
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<tr>
<td>UAV Power</td>
<td>Requirement of hexacopter baseline decision</td>
<td>✔</td>
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<td></td>
<td>Endurance capabilities of baseline design</td>
<td>✔</td>
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<tr>
<td>Communications</td>
<td>Data storage requirements</td>
<td>✔</td>
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<tr>
<td></td>
<td>Data sharing</td>
<td>✔</td>
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<tr>
<td></td>
<td>Command sharing</td>
<td>✔</td>
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</table>
Schedule to CDR
Schedule to CDR

Project Overview

Tracking

Power

Communication

Conclusion
<table>
<thead>
<tr>
<th>System</th>
<th>Cost</th>
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<tbody>
<tr>
<td>Cameras</td>
<td>$1,000.00</td>
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<tr>
<td>Lenses</td>
<td>$500.00</td>
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<tr>
<td>T-Motor Brushless Motors</td>
<td>$450.00</td>
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<tr>
<td>C94-M8P GPS Units</td>
<td>$400.00</td>
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<tr>
<td>Batteries</td>
<td>$400.00</td>
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<tr>
<td>UAV Frame/Hardware</td>
<td>$350.00</td>
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<tr>
<td>Gimbal/Mounts</td>
<td>$350.00</td>
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<td>Wifi Receivers</td>
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<td>UAV Computer</td>
<td>$150.00</td>
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<td>UAV Flight Controller</td>
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<td>Removable Storage</td>
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<td>Structural Hardware</td>
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<td>UAV Controller</td>
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<td>Speed Controllers</td>
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<td>Telemetry Radio</td>
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<td>Remaining Funds</td>
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<tr>
<td>Total</td>
<td>$5,000.00</td>
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Questions?
References

1. NEO-M8P u-Blox M8 High Precision GNSS Module.” High Precision GNSS Modules, u-Blox.
5. Lady, M H. “Blob Detection With Python and OpenCV.” MakeHardware, 19 May 2016.
Index (Presentation)

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Required AOV
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Gimbal Control Diagram
Pointing Simulation

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AR Tag Proof of Concept
AR Tag Size Estimate
Ground to Air Detection
UAV Power Requirements
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Data Sharing
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- UGV Link Budget Model
Detailed Baseline Design Choices

‣ UAV
  ▶ 3 Axis Brushless Gimbal
  ▶ Lithium Polymer Battery
  ▶ External Computer
  ▶ Vision System
    ▶ Global Shutter Camera
    ▶ Monocular
    ▶ Color
    ▶ Prime Lens
  ▶ Communication Bands
    ▶ 2.4 GHz Navigation
    ▶ 915 MHz Controls
  ▶ External Integrated GPS Board
  ▶ Multirotor Frame

‣ UGV
  ▶ 2 Axis Servo Gimbal
  ▶ Vision System
    ▶ Global Shutter Camera
    ▶ Monocular
    ▶ Color
    ▶ Prime Lens
  ▶ Communication Bands
    ▶ 2.4 GHz Navigation & Command

‣ Ground Station
  ▶ Dual Ground Station
Motivation

As long as there are GPS denied environments there will be a need to circumvent GPS denial. In these situations, precise localization must be maintained by other means. To deliver precise location data, a cooperative localization method using aerial drones and ground units has been developed. The drone is able to access GPS signal by flying out of the denied zone and transmitting its location to any ground units. The relative position of the drone can then be found using cooperative localization.
Reacquisition of Target

Data: Image

VISUAL DETECTION

TARGET IN FRAME?

NO

TARGET REACQUISITION

YES

RELATIVE LOCATION DETERMINATION

Save location data

LOCATION DATA BUFFER

Data: Relative vector and orientations

CAMERA POINTING

Data: Save pointing data

Use buffered location and pointing data

NEGATIVE DETECT

INCREASE SEARCH FRAME SIZE

ATTEMPT DETECTION

NEW LOCATION DATA

BUFFERED LOCATION DATA

USE LOCATION DATA TO MOVE IMAGE PATCH

POINT CAMERA TO NEW LOCATION
Sensor Error Calculations and Assumptions

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

- **MS5611 Barometer**
  - Max Total Error Band with Autozero at Pressure Point, at 25°C = ±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
  - $\sigma = \frac{5}{3}$ (Gaussian Distribution at 99.7%)
  - Both barometers operate in similar environments
    - Barometer drift due to environment ignored for relative altitude

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

\[
h_{alt} = \left(1 - \left(\frac{P_{sea}}{1013.25}\right)^{0.190284}\right) \times 145366.45
\]
Data Filter Considerations

- Considered using an Extended Kalman Filter (EKF)

- Advantages:
  1. Useful for estimation and prediction of future states
  2. Useful for sensor fusion of multiple sensors for single metric
  3. Useful to clean noisy sensor data in real time

- Disadvantages
  1. Difficult to implement
  2. Computationally costly
Data Filter Considerations

- Considered using an Extended Kalman Filter (EKF)

- Advantages:
  - Useful for estimation and prediction of future states
  - Useful for sensor fusion of multiple sensors for single metric
  - Useful to clean noisy sensor data in real time

- Disadvantages
  - Difficult to implement
  - Computationally costly

- State Estimation was considered to account for latency in relative position transmission
- Latency of 0.5 seconds would still allow UAV to be In-View*
Data Filter Considerations

- Considered using an Extended Kalman Filter (EKF)

- Advantages:
  - Useful for estimation and prediction of future states
  - Useful for sensor fusion of multiple sensors for single metric
  - Useful to clean noisy sensor data in real time

- Disadvantages
  - Difficult to implement
  - Computationally costly

- No state variables are being measured by multiple sensors
- Therefore weighted sensor fusion using a Kalman filter is not necessary

<table>
<thead>
<tr>
<th>State Variable</th>
<th>GPS</th>
<th>Barometer</th>
<th>IMU</th>
<th>Magnetometer</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>✔</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>y</td>
<td></td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>z</td>
<td></td>
<td></td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>Φ (Roll)</td>
<td></td>
<td></td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Θ (Pitch)</td>
<td></td>
<td></td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Ψ (Yaw)</td>
<td></td>
<td></td>
<td></td>
<td>✔</td>
</tr>
</tbody>
</table>
Justification of Requirement of RTK Capable GPS

- Error of NEO-M8P GNSS Module:
  - Standalone: 2.5 m CEP
  - RTK: 0.025 m CEP
- Assumptions:
  - Gaussian Distribution of Error
  - UGV is Stationary
  - Constant Velocity Circular UAV Orbit at 10 m (Closest mission range)
  - No latency in pointing
Justification of Requirement of RTK Capable GPS
Vehicle Location Error Model (cont.)

- UAV location error based on GPS and barometer
  - Assumption: error has Gaussian distribution
- NEO-M8P u-blox M8 High Precision GNSS Module with RTK [1]
  - Listed Error: 0.025 m CEP
  - \( \sigma = 0.025/0.6745 \)
  - (0.025 m at 0.6745 \( \sigma \))
  - Gaussian Distribution at 50%
- MS5611 Barometer [2]
  - Listed Max Error: \( \pm 0.5 \) mbar
  - \( \sigma = 5/3 \) (5 m at 3 \( \sigma \))
  - Gaussian Distribution at 99.7%
Justification of Requirement of RTK Capable GPS Module (cont.)
## UAV Mass Budget

<table>
<thead>
<tr>
<th>Object</th>
<th>Mass (g)</th>
<th>Qty</th>
<th>Total (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airframe</td>
<td>1050</td>
<td>1</td>
<td>1050</td>
</tr>
<tr>
<td>Motors</td>
<td>70</td>
<td>6</td>
<td>420</td>
</tr>
<tr>
<td>ESCs</td>
<td>23</td>
<td>6</td>
<td>138</td>
</tr>
<tr>
<td>Batteries</td>
<td>1800</td>
<td>1</td>
<td>1800</td>
</tr>
<tr>
<td>Propellers</td>
<td>32.5</td>
<td>6</td>
<td>195</td>
</tr>
<tr>
<td>GPS Module</td>
<td>160</td>
<td>1</td>
<td>160</td>
</tr>
<tr>
<td>Auxiliary Computer</td>
<td>38</td>
<td>1</td>
<td>38</td>
</tr>
<tr>
<td>Flight Controller</td>
<td>34</td>
<td>1</td>
<td>34</td>
</tr>
<tr>
<td>Camera + Lens</td>
<td>160</td>
<td>1</td>
<td>160</td>
</tr>
<tr>
<td>Gimbal</td>
<td>160</td>
<td>1</td>
<td>160</td>
</tr>
<tr>
<td>Wiring</td>
<td>5% AUW</td>
<td>1</td>
<td>188</td>
</tr>
<tr>
<td><strong>AUW</strong></td>
<td></td>
<td></td>
<td><strong>4153</strong></td>
</tr>
</tbody>
</table>

### Weight Breakdown

- **Airframe** 26%
- **Batteries** 38%
- **GPS Module** 4%
- **Camera + Lens** 4%
- **Gimbal** 4%
- **Weight Breakdown**
- **Flight Controller** 1%
- **Auxiliary Computer** 1%
- **Propellers** 5%
- **Wiring** 5%
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 Flir Blackfly 2.3MP, a 12mm lens gives a 37 degree vertical AOV and a 48 degree horizontal AOV.
Chosen GPS Receiver: C94-M8P

- The C94-M8P integrates the Ublox's high-precision NEO-M8P chip with UHF antennas and an RTK engine.

- The UHF antennas allow Differential-GPS to obtain cm-level accuracy (0.025 m + 1 ppm CEP).

- Only $400 for two integrated boards and associated hardware.

- However, it will add 160 grams and the antenna will require to be elevated on a ground plane.

https://www.u-blox.com/en/product/c94-m8p
GPS is greatly impacted from noise that can result from the camera system as well as the EPS.

To mitigate, it is necessary to keep the GPS receiver and antenna as far from the camera and battery as possible.

Insulating the camera and cables in a low-cost solution such as Aluminum foil will act as a Faraday cage and reduce interference.

Having a ground plane isolates the GPS receiver and improves the signal-to-noise ratio and satellites it can acquire.
In order to feel confident in the ability to visually track, the latency should be within constraints. The big question is: Is our system fast enough?

<table>
<thead>
<tr>
<th>Capture Data</th>
<th>Process Data</th>
<th>Transmit/Receive</th>
<th>Process Data</th>
<th>Use Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS/IMU</td>
<td>Parse Lat/Long &amp; raw ephemeris. Calculate state estimates.</td>
<td>Send data &lt;30 meters</td>
<td>Calculate relative location and angle to turn camera.</td>
<td>Activate servos to turn camera.</td>
</tr>
<tr>
<td>100 ms (10 Hz)</td>
<td>10 ms</td>
<td>20 ms</td>
<td>TBD ms</td>
<td>TBD ms</td>
</tr>
</tbody>
</table>
Latency Model

- Calculated Latency is time between pointing states
- Includes position transmission, processing, pointing commanding, and actuation
Latency Model

\[
D = V \cdot t \\
t - t_0 = t_{lat} \\
D = V \cdot t_{lat} \\
D = 2 \cdot 10m \cdot \sin\left(\frac{\theta}{2}\right) = 2 \cdot 10m \cdot \sin\left(\frac{AOV}{2}\right) \\
V \cdot t_{lat} = 2 \cdot 10m \cdot \sin\left(\frac{AOV}{2}\right) \\
t_{lat} = \frac{2}{V} \cdot 10m \cdot \sin\left(\frac{AOV}{2}\right)
\]
Calculating Transmit/Receive Latency

- This latency boils down to the time it takes to deliver a message.
  - \( \text{Packet Delivery Time} = \text{Transmission Time} + \text{Propagation Delay} = 10 \text{ ms} + 250 \text{ ns} = 10 \text{ ms} \)
  - \( \text{Roundtrip Time} = 2*\text{Packet Delivery Time} + \text{Processing Delay} = 2*10 \text{ ms} + 20 \text{ ms} = 40 \text{ ms} \)
  - \( \text{Network Throughput} = \frac{\text{Window Size}}{\text{Roundtrip Time}} = \frac{32 \text{ Kbit}}{40 \text{ ms}} = 800 \text{ bit/ms} \)
  - \( \text{Message Delivery Time} = \frac{\text{Message Size}}{\text{Network Throughput}} = \frac{19.2 \text{ Kb}}{800 \text{ bit/ms}} = 24 \text{ ms} \)
ROS Overview

- The Robot Operating System (ROS) is a abstraction for data communication between machines.
- Data is packaged as messages based on primitive data types.
- Chunks of code can be made Nodes, which Publish messages to and Subscribe to receive messages from Topics.
- Topics are a kind of message exchange for one type of message.
- Any Node can Subscribe to any topic, and Publish to any topic.
- Does not matter if Nodes are on the same machine or different machines.
- Custom messages can be created using other message types.
## Communications Data Rate Calculations

<table>
<thead>
<tr>
<th>Name</th>
<th>Data Size</th>
<th>Event Rate</th>
<th>Data Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camera</td>
<td>1920x1200 [pixels]*(1.3-2.0) [bytes/pixel in RAW] = 2.8-4.4 MB/frame</td>
<td>41 frames/s</td>
<td>114-180 MB/s</td>
</tr>
<tr>
<td>IMU</td>
<td>20 [values]*16 [bit/value] = 320 bits</td>
<td>I2C Connection Dependent 100 Hz</td>
<td>~4.0 kB/s</td>
</tr>
<tr>
<td>GPS</td>
<td>Ublox NMEA output: 19.2 kbits</td>
<td>1 Hz</td>
<td>19.2 kbits/s</td>
</tr>
<tr>
<td>Barometer</td>
<td>7 bits</td>
<td>I2C Connection Dependent 100 Hz</td>
<td>~1 kbit/s</td>
</tr>
<tr>
<td>Preview Image</td>
<td>160x160 pixel jpeg image: 20 kB (rough estimate)</td>
<td>4 Hz/vehicle</td>
<td>1.25 Mbits/s</td>
</tr>
</tbody>
</table>

*SD cards limited to about 90 MB/s write speed: alternates are high speed USB 3 Flash drives @ 150-300 MB/s - needs to be verified. Or Removable SSD. [FlashDrive](#) [SD Card](#) [RemovableSSD](#)
## RF Link Budget model

<table>
<thead>
<tr>
<th>Connection Name</th>
<th>Frequency</th>
<th>Protocol</th>
<th>Data Type</th>
<th>Estimated Data Rate</th>
<th>Max Data Rate</th>
<th>Transmitter Power</th>
<th>Receiver Sensitivity</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>UAV Controller</td>
<td>2.408 ~ 2.475 GHz</td>
<td>AFHDS 2A</td>
<td>Manual Controller Commands to FC</td>
<td>N/A</td>
<td>N/A</td>
<td>19 dBm</td>
<td>-105 dBm</td>
<td>1 km</td>
</tr>
<tr>
<td>SiK Telemetry Radio</td>
<td>915 MHz</td>
<td>FHSS</td>
<td>MAVLink GCS1 to FC</td>
<td>Varies: N/A</td>
<td>250 Kbits/s</td>
<td>100mW (20 dBm?)</td>
<td>-117dBm</td>
<td>500 m</td>
</tr>
<tr>
<td>Data Network</td>
<td>2.4 GHz</td>
<td>802.11g/n</td>
<td>*</td>
<td>2.75 Mbits/s</td>
<td>54-&gt; 11 Mbits/s</td>
<td>14 dBm</td>
<td>-68 dBm</td>
<td>125 m</td>
</tr>
</tbody>
</table>

* UAV - UGV [GPS, IMU, Bar, State Estimation]
UAV-GCS1 [GPSx2, IMUx2, Barx2, State Estimationx2, Housekeeping, Preview Image, Control Relay]
UGV-GCS2 [GPSx2, IMUx2, Barx2, State Estimationx2, Housekeeping, Preview Image, UGV Manual Controls]
Camera Specifications

- Flir Blackfly 2.3MP Color:
  - Resolution: 1920x1200
  - Weight: 36 g
  - Size: 29 x 29 x 30 mm
  - FPS: 41
  - Power consumption: < 3 W
  - Cost: $495
  - Interface: USB 3.1 gen 1
  - Global Shutter
  - 10 bit and 12 bit ADC
Quaternion Rotation Calculation

- Determine relative position and attitude of vehicle
- Cross relative position vector and body x-axis for rotation axis
- Determine desired angle by taking the inverse cosine of the dot product of the relative position and body x-axis divide by the product of their magnitudes
- Calculate quaternion with unitized rotation vector and rotation angle
- Determine 3-2-1 Euler Sequence for gimbal control (3-2 for UGV)
Simulation Rotation Scheme

- Takes quaternion \((q)\) and calculates rotation matrix \((R)\)
- Multiply \(R\) with vehicle x-axis to get pointing vector

\[
R = \begin{bmatrix}
1 - 2(q_2^2 + q_3^2) & 2(q_1 q_2 - q_0 q_3) & 2(q_0 q_2 + q_1 q_3) \\
2(q_1 q_2 + q_0 q_3) & 1 - 2(q_1^2 + q_3^2) & 2(q_2 q_3 - q_0 q_1) \\
2(q_1 q_3 - q_0 q_2) & 2(q_0 q_1 + q_2 q_3) & 1 - 2(q_1^2 + q_2^2)
\end{bmatrix}
\]
Avoiding Gimbal Wire Wrap

- Vehicles should yaw around body z-axis if approaching gimbal yaw limit (gimbal dependent)

- Skid steering on UGV, manually controlled

- Should not be an issue due to low vehicle speeds (no jerking motion to yaw)
Power

Assumptions:
- 85% Battery Discharge
- Voltage Linearly Depends on Charge
- Wire Resistance Negligible
- Payload Current Draw Constant (6A)
- Wires 5% of All Up Weight
- Flying at 5280 ft, 60° F
- No Airframe Drag

\[
T = \frac{1}{2} \rho A V^2
\]

\[
V_{\text{air}} = \sqrt{\frac{2T}{\rho A}}
\]

\[
P_{\text{prop}} = TV_{\text{air}}
\]

\[
P_{\text{mech}} = (V_{\text{batt}} - R_{\text{motor}}I_{\text{motor}})(I_{\text{motor}} - I_0)
\]

\[
V_{\text{air}} = \omega \times \text{pitch} \times \left( \frac{0.0254}{60} \right)
\]

\[
I_{\text{tot}} = \text{Num Motors} \times I_{\text{motor}} + I_{\text{payload}}
\]

Component | Efficiency
--- | ---
ESCs | 97%
Motors | 80% (hovering)
Propellers | 70% (hovering)
## UAV Configuration

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Rotors</td>
<td>6</td>
</tr>
<tr>
<td>Hover Endurance</td>
<td>24 (min)</td>
</tr>
<tr>
<td>Battery</td>
<td>5s-16000 mAh Li-Po</td>
</tr>
<tr>
<td>Motor</td>
<td>~400-500 kV, 250+ Watt</td>
</tr>
<tr>
<td>Propeller</td>
<td>18x5.5 Carbon Props</td>
</tr>
<tr>
<td>Max Current Draw</td>
<td>120 (A), 19 Amp/motor</td>
</tr>
<tr>
<td>Hover Current Draw</td>
<td>6 Amp/Motor</td>
</tr>
<tr>
<td>Max Wattage</td>
<td>1500 Watts</td>
</tr>
<tr>
<td>Hover Wattage</td>
<td>550 Watts</td>
</tr>
<tr>
<td>Full Throttle Endurance</td>
<td>9 min</td>
</tr>
<tr>
<td>Battery Discharge Rating</td>
<td>23C+</td>
</tr>
<tr>
<td>All up Weight</td>
<td>4.65 (kg)</td>
</tr>
</tbody>
</table>

![Graph showing endurance vs. added mass](image)
Mass Budget Calculations

![Graph showing battery mass in grams versus battery capacity in mAh for 3, 4, 5 cell configurations.](image)

- **3 Cell**
- **4 Cell**
- **5 Cell**
Mass Budget Calculations

![Graph showing the relationship between ESC Mass (g) and ESC Rating (Amps). The graph includes a fitted curve.](image-url)
Power Graphs

\[ T = \frac{1}{2} \rho AV^2 \]

\[ V_{air} = \sqrt{\frac{2T}{\rho A}} \]

\[ P_{prop} = TV_{air} \]

\[ P_{mech} = (V_{batt} - R_{motor} I_{motor})(I_{motor} - I_0) \]

\[ V_{air} = \omega \times \text{pitch} \times \left( \frac{0.0254}{60} \right) \]

\[ I_{tot} = \text{NumMotors} \times I_{motor} + I_{payload} \]
### UGV Power

<table>
<thead>
<tr>
<th>At Max Power Draw</th>
<th>Power Draw</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onboard Computer</td>
<td>60 W</td>
</tr>
<tr>
<td>Drive System</td>
<td>500 W @ Full throttle</td>
</tr>
<tr>
<td>Payload</td>
<td>50 W max</td>
</tr>
<tr>
<td>Total</td>
<td>610 W</td>
</tr>
<tr>
<td>Endurance</td>
<td>~25 Min</td>
</tr>
</tbody>
</table>

### Stationary Tracking

<table>
<thead>
<tr>
<th>Power Draw</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onboard Computer</td>
</tr>
<tr>
<td>Payload</td>
</tr>
<tr>
<td>Drive System</td>
</tr>
<tr>
<td>Total</td>
</tr>
<tr>
<td>Endurance</td>
</tr>
</tbody>
</table>

Note: Power Consumption occurs when rover is driving top speed while spinning gimbal at full speed and stress testing CPU simultaneously. Not representative of RAVENs use of the system, expecting more than 2 hrs of battery life while testing.

Courtesy of Clearpath Robotics
### Internal UGV Link Budget Model

#### Property | Estimate | Limit
--- | --- | ---
Storage Write Speed | 115 MB/s | 150 MB/s
Output Network Data Rate | 2.25 Mbits/s | 54 Mbits/s: Network Pend
Incoming Network Data Rate | 0.06 Mbits/s | 54 Mbits/s: Network Depend

#### RF Component | Purpose
--- | ---
Bluetooth PlayStation Controller | Pre-installed manual control remote. (Not used)
2.4 GHz 802.11g/n | Receive nav data from UAV. Send nav & state data to GCS.
# Internal UAV Link Budget model

<table>
<thead>
<tr>
<th>Property</th>
<th>Estimate</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage Write Speed</td>
<td>115 MB/s</td>
<td>150 MB/s</td>
</tr>
<tr>
<td>Output Network Data Rate</td>
<td>1.30 Mbits/s</td>
<td>54 Mbits/s: Network Pend</td>
</tr>
<tr>
<td>Incoming Network Data Rate</td>
<td>0.06 Mbits/s</td>
<td>54 Mbits/s: Network Depend</td>
</tr>
</tbody>
</table>

## RF Component

<table>
<thead>
<tr>
<th>RF Component</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>915 MHz GCS Path Command</td>
<td>Upload flight path to FC from GCS</td>
</tr>
<tr>
<td>2.412 GHz AFHDS 2A</td>
<td>Upload Manual Commands Directly to FC</td>
</tr>
<tr>
<td>2.4 GHz 802.11g/n</td>
<td>Receive nav data from UGV, Send nav &amp; state data to GCS.</td>
</tr>
</tbody>
</table>