RAVEN: A Test-bed for Visual Cooperative Localization Algorithms

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GPS-denied locations, such as large canyons or dense urban areas, present increasingly difficult challenges for GPS users across the globe. Visual cooperative localization is a novel solution used to circumvent GPS-denial. Visual cooperative localization is defined as the use of state algorithms in conjunction with opportunistic measurements such as visual contact and radio ranging to determine a team member?s location. RAVEN (Rover and Air Visual Environment Navigation) was developed as a data collection test-bed to assist in verifying these visual cooperative localization algorithms. The test-bed consists of three major components: an unmanned aerial vehicle (UAV), an unmanned ground vehicle (UGV), and a ground control station (GCS). RAVEN collects visual tracking data from both vehicles and associated GPS, IMU, and housekeeping sensor measurements, so that both robots can efficiently share GPS-aided INS navigation filter estimates and visual tracking filter estimates with each other via novel decentralized data fusion (DDF) algorithms. This paper will outline the development and completion of the test-bed by describing design methodology, modeling used for the verification of key components, testing to validate the models, and the results of the completed test-bed.

Nomenclature

$RAVEN$	=	Rover and Air Visual Environment Navigation
UAV	=	Unmanned Aerial Vehicle
UGV	=	Unmanned Ground Vehicle
GCS	=	Ground Control Station
DDF	=	Decentralized Data Fusion
$DARPA$	=	Defense Advanced Research Projects Agency
$CONOPS$	=	Concept of Operations
FBD	=	Functional Block Diagram
EPS	=	Electrical Power System
RTK	=	Real-Time-Kinematic
AOV	=	Angle of View
σ	=	Standard Deviation
δ	=	Deviation

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I. Introduction

As GPS-denied locations become more pervasive in the modern world, novel solutions to this problem have begun to be explored. One such method is visual cooperative localization, specifically in the form of decentralized target tracking and localization. Decentralized estimation allows for opportunistic information sharing and increased system scalability as vehicles do not need to report to a centralized server and can be added to the system as needed. Due to the advantages decentralized estimation over more traditional estimation methods, there has been an increase in the use of decentralized estimation systems in uncertain environments such as GPS-denied environments.

To further develop the motivation for decentralized estimation, Fig. 1 depicts a scenario in which a team of robots and humans are in a GPS-denied environment. The goal of this scenario is to localize the team members without reliable GPS. The use of decentralized estimation systems allows for localization of the team members through the use of opportunistic measurements and information sharing between the team members themselves.

The goal of RAVEN is to provide a test-bed for our customer's current research in visual cooperative localization citeNisar. As per customer requirements, RAVEN has developed an Unmanned Aerial Vehicle (UAV) and an Unmanned Ground Vehicle (UGV) pair for the purpose of gathering data for use in our customer's research. However, while the purpose of the visual cooperative localization algorithms is for use in GPS-denied environments, RAVEN does not simulate a GPS-denied environment as it is out of the scope of this project.

Fig. 1 An example of robot and human team members in a GPS-denied environment, image courtesy of DARPA[1]

The vehicles in the test-bed visually track each other while simultaneously collecting and sharing GPS, IMU, and state estimation data. Vehicles also collect a wealth of "housekeeping" data which is either stored on the vehicle or shared with the Ground Control Station (GCS) to allow for situational awareness during system operation. As the system used is decentralized, the GCS does not perform any computational processes for either of the two vehicles and only acts as a method for monitoring the system during operation to ensure accurate data collection.

After this data is delivered to our customer, our customer's visual cooperative localization algorithms will attempt to determine the relative positions of the UAV and UGV from the visual data and evaluate the algorithm's effectiveness by comparing against the test-bed's collected ground truth. The success of RAVEN will allow our customer to further develop their solution for GPS-denied environments.

II. Design Objectives

RAVEN was driven by ten customer-developed and required safety functional requirements. These functional requirements, shown in Tables 1 and 2, provided the foundation for the development of the project objectives.

Functional Requirement	Description
FR 1.0	RAVEN shall perform data collection for 15 minutes. *Motivation: Customer Requirement. Customer requires 15 minutes of data to test their cooperative localization algorithms*
FR 2.0	RAVEN shall have a removable data storage system on both the UAV and UGV. *Motivation: Customer requirement. Allows ease of delivery of data to customer.*

Table 1 Functional Requirements 1 and 2, continued on next page

Functional Requirement	Description
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. *Motivation: Customer requirement. Ensures use with customer algorithms.*
FR 4.0	UAV & UGV visual data shall have a minimum resolution of three inches per pixel at a distance of 30 m. *Motivation: Customer requirement. Ensures use with customer algorithms.*
FR 5.0	RAVEN shall operate outside on a fair-weathered day (i.e., no wind, no precipitation). *Motivation: Customer requirement. Team does not have to design an extremely robust UAV control system.*
FR 6.0	RAVEN shall comply with Army Memorandum (DAMO-AV). (i.e. No DJI products to be used) *Motivation: Customer requirement. Project must align with Army requirements.*
FR 7.0	RAVEN shall utilize the customer-provided Clearpath Jackal UGV. *Motivation: Customer requirement. Team must inferface with customer hardware.*
FR 8.0	The UAV and UGV shall communicate flight and navigation status data to their respective ground stations (GCS) and to each other. *Motivation: Customer and safety requirement. Allows for monitoring of both vehicles during testing.*
FR 9.0	RAVEN shall communicate flight/drive commands from ground stations to and from their respective vehicle over an ISM Radio Frequency. *Motivation: Safety requirement. Ensures required communication with vehicles during testing.*
FR 10.0	Vision system shall use customer specified interfaces. *Motivation: Customer requirement. Ensures use with future customer hardware.*

Table 2 RAVEN's Functional Requirements

To help facilitate the success and organization of RAVEN, specific objectives for the project were developed from the functional requirements and were split into seven major categories: vision, structure, captured data, controls, communications, electronics & software, and management. These project objectives can be mapped directly to the functional requirements. Below is a list of the significant level 3 objectives.

- Vision: A moving UAV shall track the UGV at 10-30 m and be in 90% of frames. A stationary UGV shall track the UAV at 10-30 m and be in 90% of frames. Acquire target in less than 3 seconds.
- Captured Data: Store battery life estimate, package temperature, control input data, GPS/ephemeris data, IMU data, magnetometer data, and barometer data all in ROS bags w/ 20 GB storage margin.
- Controls: UAV will have emergency land switch. Control station displays map overlay of UAV/UGV positions as well as battery status, flight timer, and storage capacity.
- Communications: Vehicles shall share GPS data, visual tracking, and state data with the control stations.
- Electronics/Software: Vehicles shall have 15 min tracking endurance. Management: Project cost shall remain under budget.

Following the creation of the organization and framework of RAVEN through the functional requirements, project objectives, and CPEs, the entire project was put into context through the development of a concept of operations (CONOPS). The CONOPS visualizes the developed framework and is shown in Fig. 2.

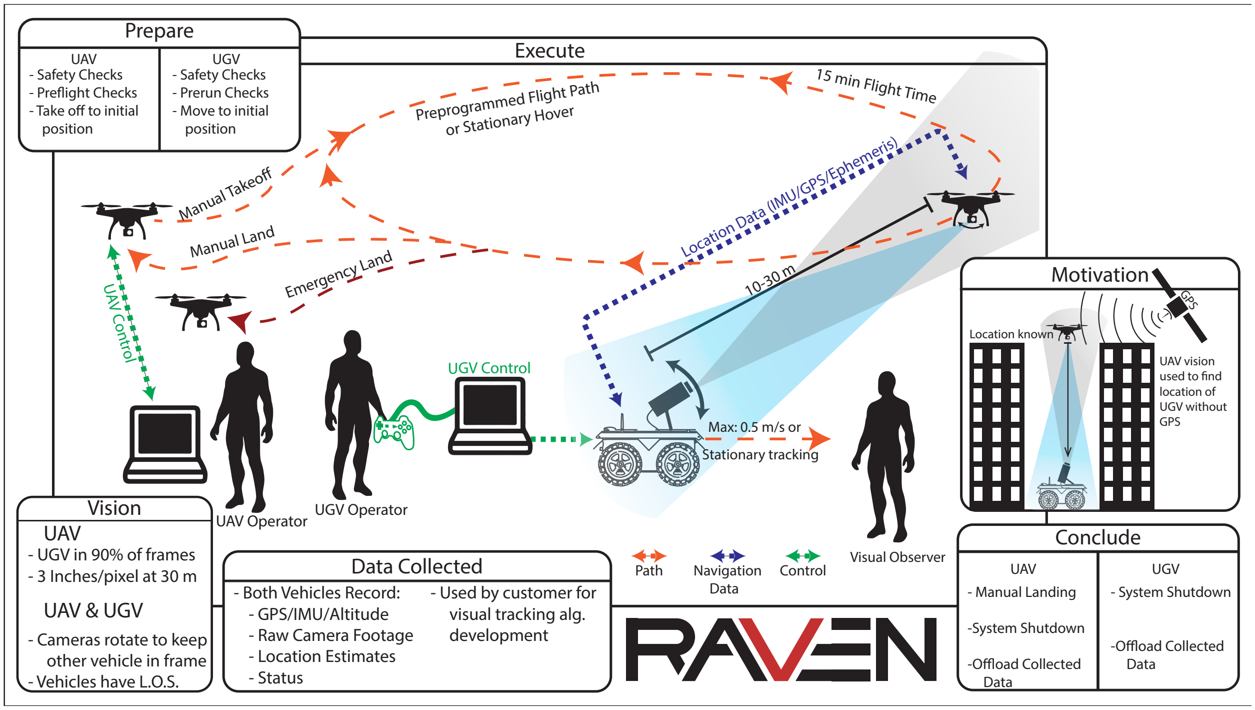

Fig. 2 Concept of Operations for RAVEN system operation

System operation is split into three main phases: prepare, execute, and conclude. The prepare phase starts with safety and pre-operation checks on both vehicles and ends with pilot controlled UAV takeoff into initial position. After the vehicles are in position, the UAV will begin moving along its autonomous flight path and both vehicles will begin collecting data. The vehicles will then share their GPS, IMU, and state estimation data between each other. This shared information will then be used in conjunction with tracking software to point each vehicle's vision system, allowing the vehicles to record image data of the opposing vehicle. To conclude operation, the pilot will take control and land the UAV. Both vehicles will then be shut down, their data offloaded, and the data delivered to the customer for future use.

III. Design Methodology

A. Overall System Design

Using the developed framework and the CONOPS, a more specific system design was explored and diagrammed in the form of a system-level Functional Block Diagram (FBD), seen in Fig. 3.

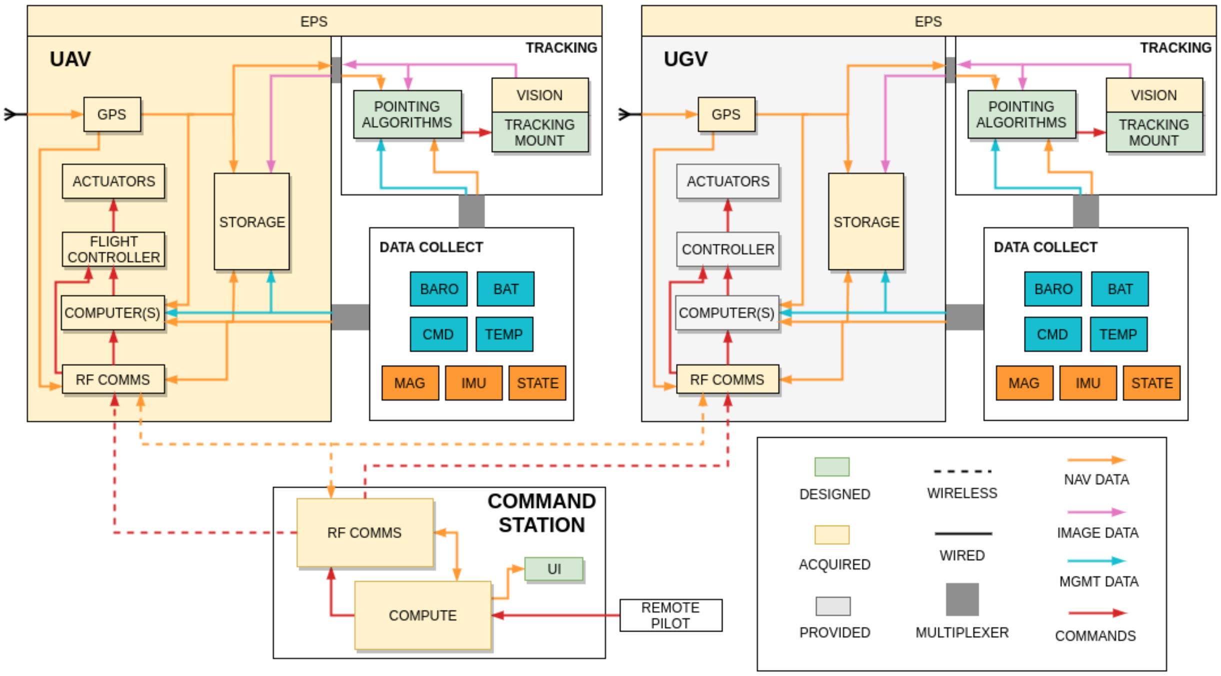

Fig. 3 RAVEN system level functional block diagram

The FBD is split into three main subsystems: UAV, UGV, and GCS. The UAV and UGV subsystems are similar in design, including the electrical power system (EPS), tracking, sensor suite and data collection (includes GPS and storage), RF communications, and vehicle control systems.

UsingRFcommunications, thevehiclessharenavigationdatabetweeneachotherandtheGCS.Thisnavigationdata, markedinorange,

The vehicles share and store management data, marked in blue, which is made up of battery life, storage capacity, controller commands, control status, and battery temperature. The vehicles also store all image data collected by the tracking subsystem.

Finally, the GCS displays the navigation and management data for both vehicles in developed user interfaces.

The FBD also represents which aspects of the project were acquired, provided to RAVEN by the customer, or developed by the team. Yellow represents elements that were acquired from external vendors, grey represents elements that were provided by the customer, and green represents elements that were developed by the team.

B. UGV Subsystem

1. Platform

The platform for the UGV subsystem was decided to be the Clearpath Jackal rover by functional requirement 7.0.

2. Payload

The payload for the UGV subsystem consists of the vision hardware, camera gimbal, and GPS. Vision hardware encompasses the camera and lens used to capture image data. The camera was chosen to fulfill functional requirements 3.0, 4.0, and 10.0. A trade study was performed that determined a machine vision camera with USB 3.0 capabilities and a resolution of 1920x1080 best meets these functional requirements. Additionally, in order to capture image data that is processable for the customer, a lens focal length of 16mm was chosen to pair with the camera. This provides a horizontal angle of view of 37.4 degrees and a vertical angle of view of 28.4 degrees. According to the accuracy derivation derived below, at the closest operating range of the UAV from the UGV of 10 meters and assuming the target of the image must be within frame for 90% of the images, our pointing vectors from the GPS must have a standard of deviation of 0.973 meters from the true value. This limits the necessary accuracy of the GPS for the project.

$$tan\left(\frac{AOV}{2}\right) = \frac{2\delta_{err}}{10m} \tag{1}$$

$$\delta_{err} = \frac{10m}{2}tan\left(\frac{28.4deg}{2}\right) = 1.2466m \tag{2}$$

$$\sigma_{err} = \frac{MaximumError}{90\%Z - score} = \frac{1.24664m}{1.28155} = 0.973m \tag{3}$$

The gimbal configuration used on the UGV must be capable of pointing the camera in any direction within the hemisphere above the UGV in which the UAV will be flying. Because the UGV will track the UAV while stationary on the ground, a 2-axis gimbal configuration was chosen. This allows for 360 degree rotation about the z axis and 180 degree rotation about the axes normal to the z-axis.

GPS

In order to fulfill our requirement of tracking in 90% of frames, the GPS accuracy must be accurate enough to keep both vehicles in the other vehicle's camera's angle of view. Achieving this high accuracy requires Real-Time-Kinematic (RTK) GPS. To justify the use of RTK GPS, a GPS accuracy model was developed. This model, shown in Fig. 4, determined the required GPS accuracy to keep the camera in the required angle of view of 37^o. Using this model, a justification of the RTK GPS was output, shown in Fig. 5. The output from this model shows standard GPS vs. RTK GPS. The results of the model show that using RTK GPS keeps the camera within the required angle of view.

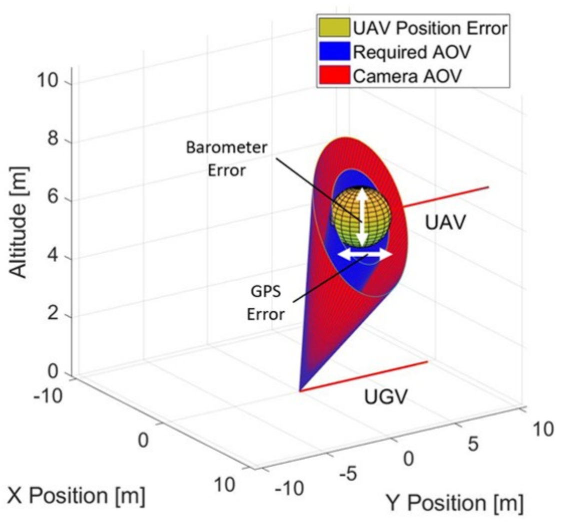

Fig. 4 Comparison of Standard and RTK GPS accuracy

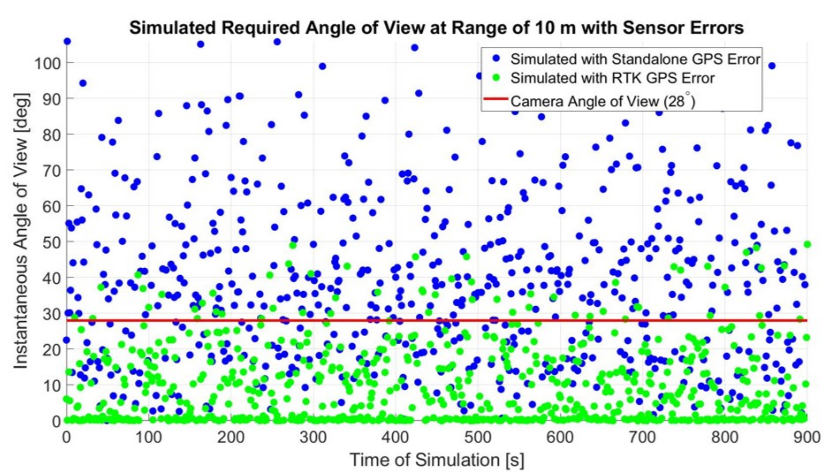

Fig. 5 Comparison of standard and RTK GPS showing RTK GPS

C. UAV Subsystem

1. Platform

A trade study was conducted in the early stages of RAVEN's development to identify the most suitable vehicle platform. The driving condition for this trade study was F.R. 1.0: RAVEN shall perform data collection for 15 minutes; however other factors such as cost and complexity also played a role. The results of the trade study lead the team to choose a multi-rotor vehicle. From this point a more in depth model was required to assist in deciding between a quadcopter or hexacopter platform. The developed model focused on maximum hover endurance, all up weight, maximum amp draw, and what battery size would be ideal. Fig. 6 shows a plot of hover endurance vs. battery size when keeping the drive system constant.

This plot shows that even at its maximum hover endurance, the quadcopter only has 1̃8 minutes of hover endurance. As data collection lasts 15 minutes and set up, take-off, and landing will also take time, the total time that the UAV will be on is 18.15 minutes[3]. Since the quadcopter's endurance is almost exact to this time specification, it cannot be used.

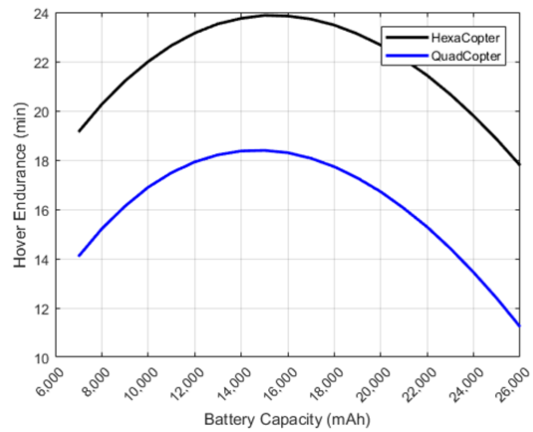

Fig. 6 Hover endurance vs. Battery size for quadcopter and hexacopters

Comparably, the hexacopter has a 24 minute endurance time which gives a reliable safety margin for testing and operation. Another advantage of the hexacopter is that the increased hover endurance time allows for increased mass to be added to the platform, while still being able to reach the 18.15 hover endurance time.

2. UAV Payload

The UAV payload consists of the vision system, including camera and gimbal, as well as GPS. All other sensors and systems are integral for the platform to perform correctly and are considered to be apart of the UAV platform.

The vision system for the UAV is similar in design to the UGV, however the major separation between these two systems is the gimbal that will be used. The UAV will be using a single tilt-axis gimbal for camera control. The use of a single tilt axis gimbal major advantage over the use of a 2 or 3 axis gimbal is the simplicity of the coordinate transformations. The major flaw of the single tilt axis gimbal is the inability to yaw. To make up for this, the entire UAV will yaw during its autonomous pathing. This reduces the complexity of the vision system camera control as yaw can be integrated into the autonomous pathing control. A single tilt axis gimbal also allows for increased camera stability.

Fig. 7 A CAD model of the integrated hexarotor UAV

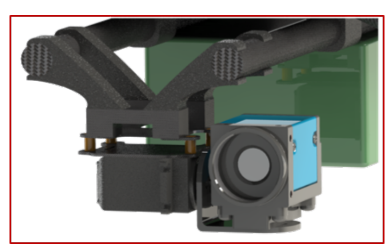

Fig. 8 A CAD model of the single tilt axis gimbal

D. Tracking and Determination Software

RAVEN is a software heavy project. As shown in the FBD, only software was developed by the team, while the hardware was off-the-shelf purchases. The software for this project has been split into three major categories: determine, acquire, and confirm seen in Fig. 9

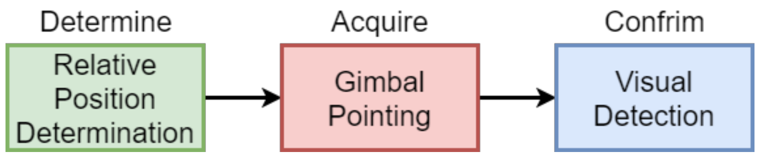

Fig. 9 Determine, acquire, and confirm general layout

Fig. 10, below, is the flowchart for the tracking and determination software used on RAVEN. This is the software that is used for the crux of the project, the collection of visual data from the vehicles.

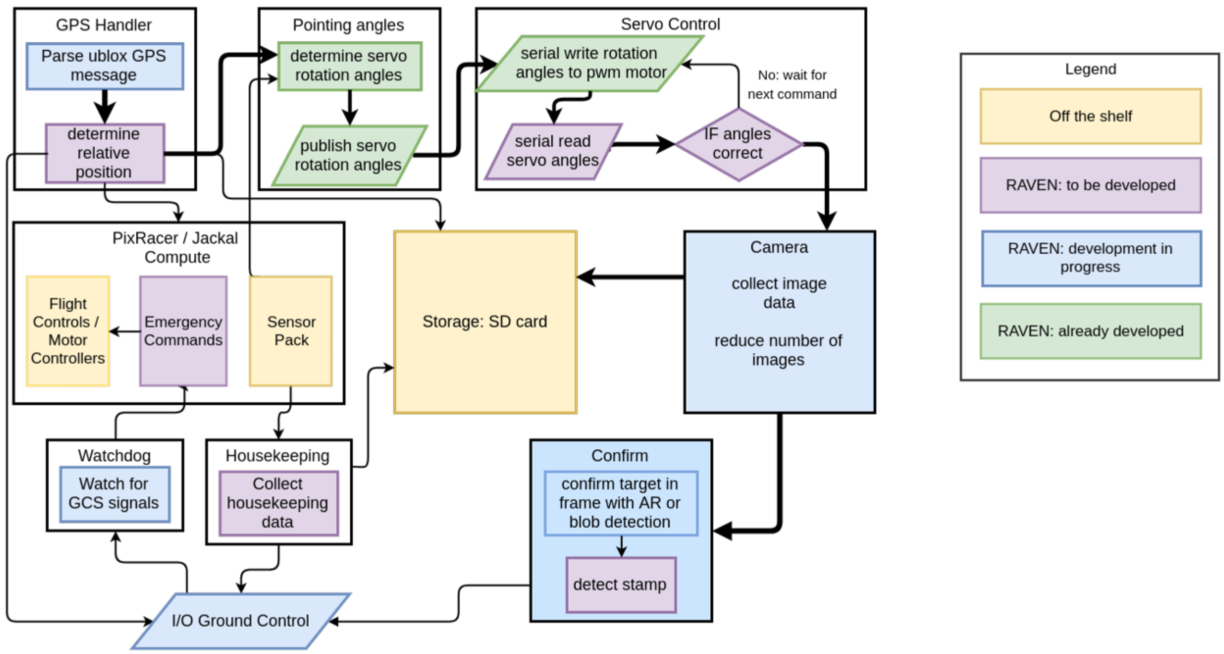

Fig. 10 RAVEN Tracking and Determination Flowchart

The general direction of the software flowchart is in the clockwise direction. First, GPS location is parsed from uBlox/NMEA messages at 1 Hz. The parsed data is then passed to both the on-board flight controller and the relative position software at 1 Hz. The relative position software uses the parsed GPS data, the vehicle state data at 50 Hz, and the barometer data at 1 Hz to determine the vehicle's relative position.

Once the relative position is determined, it is passed to the pointing angle software at 1 Hz to for the determination of required servo angles. These servo angles are passed to the servo control software at 1 Hz, which moves the gimbal to the specified position.

During the previous determination steps, the camera be takes image data at 11 Hz. This image information is passed to the confirmation software. The confirmation software is to ensure that the vehicles are within the required 90% of frames as specified by F.R. 3.0 and prevents pushing the confirmation requirement on to the customer. For the UAV, the vehicle is determined to be in frame by using an AR tag bundle. The UGV uses blob detection to determine if the UAV is in frame. Both the UAV and UGV confirmation software output a confirmation message at 11 Hz which includes an image number stamp, a time stamp, and a positive or negative confirmation. This data is then be used to confirm that the vehicles are within 90% of frames.

ll software overview MSR stuff

IV. Testing Results

The UAV system is undergoing flight tests currently. It has successfully undergone manual flight tests and endurance tests. Results from the battery discharge of the endurance test shows excellent agreement with the expected performace predicted by the power model. After a full mission duration of 18.5 minutes, the experimental results deviated from the model by only 1.03% The battery results can be seen in figure 11.

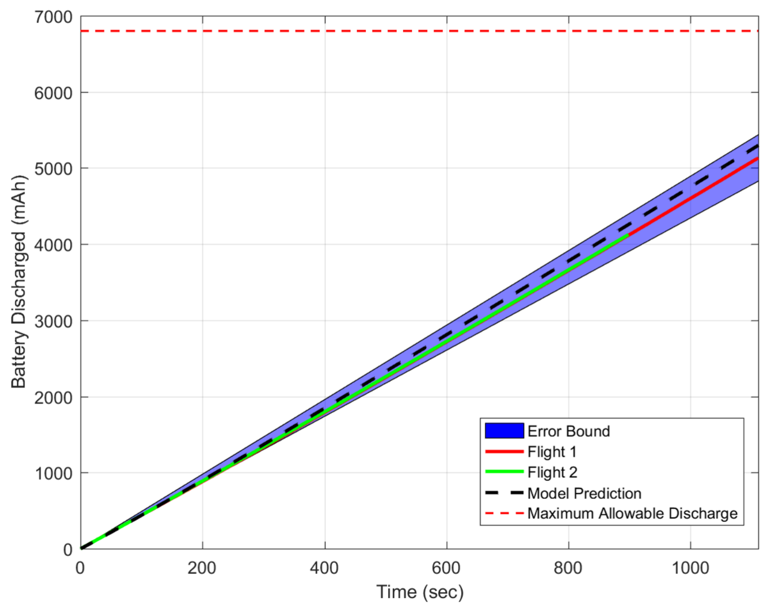

Fig. 11 UAV battery results

Initial results from GPS testing shows that the selected configuration gives very accurate results. Position tests were conducted that concluded the accuracy of the GPS recievers to have an average deviation of just 14cm from the true value with a standard of deviation of 11cm. This is well under the required accuracy predicted from the model in equations 1-3. Thus, the team is fully expecting that the position determination is sufficient for the requirements of the project.

V. Conclusion

Upon successful completion of the testing plan, RAVEN will be ready for full system operation as a test-bed for visual cooperative localization algorithms. The completed system will have met or exceeded all of the functional requirements as well as all level 3 project objectives. The completed system will be able to record visual, navigation, and management data for both vehicles for the desired test length, while still having a margin large enough for continued testing.

The success of the development and testing of the UAV and UGV pair will allow for further development by our customer into novel GPS-denied environment solutions. This test-bed has the potential to be a proof-of-concept for decentralized target tracking and localization and will be a increasingly important benefit to the development of our customer's visual cooperative localization algorithms.

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References

[1] "DARPA Developing Squad level Robotics and sensing technology," The Next Big Future, 2015, Web. https://www.nextbigfuture.com/2015/02/darpa-developing-squad-level-robotics.html

[2] Dourmashkin, Steve, Ahmed, Nisar, et al. "GPS-Limited Cooperative Localization using Scalable Approximate Decentralized Data Fusion" University of Colorado Boulder, Unpublished

[3] "RAVEN Conceptual Design Review", University of Colorado Boulder, 2017, Web. https://www.colorado.edu/aerospace/current-students/undergraduates/senior-design-projects/past-senior-projects/2017-2018/rover-and-air