# Collaborative Coordination and Control for an Implemented Heterogeneous Swarm of UAVs and UGVs


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## ABSTRACT

Over the last few years, cooperative autonomous systems have become a more popular solution for accomplishing tasks that are otherwise performed by human operators. Several strides have been made with homogeneous systems of vehicles in areas of localization, formation behaviors, path planning, task allocation, and vehicle controls. This paper describes both work completed and the future goals in the Machine Intelligence Lab (MIL) on the development of a heterogeneous system of platforms consisting of unmanned ground vehicles (UGS) and unmanned aerial vehicles (UAVs) that cooperatively work together to accomplish tasks such as search and rescue in an outdoor environment. The Robot Operating System (ROS) is used between and within each vehicle to handle cooperative high level planning and task allocation, as well as control each vehicle's individual capabilities, specializing in identification or classification. High level planning between vehicles includes formation behaviors, heterogeneous path planning and task allocation, and basic levels of localization. A description of the system and a planned implementation in a practical testing environment is also given.



## Keywords

Cooperative Robotics, Swarm Intelligence, Heterogeneous Swarm, Sensor Fusion, Centralized and Decentralized Control, Robot Operating System, Localization, Multirotor Vehicles


## 1. INTRODUCTION

Recently, unmanned systems have come to the forefront of technology being developed for military, civilian, and research purposes. This is in part due to their growing economic feasibility, ease of use, as well as the ability to travel to locations humans are unable to reach. These systems are also able to safely and effectively handle situations without putting humans lives at risk. This ability to create a safer environment in dangerous situations has created a push in both the private and public sector to make these tools more accessible. One main push of this focus is to replace manned aerial and ground capabilities with unmanned aerial vehicles (UAV), unmanned ground vehicles (UGV), unmanned underwater vehicles (UUV), and unmanned surface vehicles (USV).

Furthermore, a focus has been placed on the increased autonomy of these systems to make decisions and accomplish tasks with minimal user input, freeing up manpower for other uses. This is highly useful in a system where more than a single vehicle is used to search and gather information. For instance, in a search and rescue scenario, it is best to maximize the search with as many unmanned vehicles and humans as possible. Freeing up human operators from controlling vehicles allows more agents to perform the search. Beyond simply building autonomous unmanned vehicles, research goals have looked into the benefits of using homogeneous, i.e. similar nature and type vehicles, or heterogeneous, which uses varying types of vehicles, possibly in different planes of operation.

### 1.1 Motivation

This research aims to design a system of multiple autonomous unmanned ground and aerial vehicles to form a heterogeneous cooperative swarm to accomplish goals and missions such as search and rescue in an outdoor environment. The work is a continuation of previous work performed here at the University of Florida in homogeneous swarms of UGVs [4] and further development on planned heterogeneous collaborative swarm work [29]. Though some examples of fully heterogeneous systems exist, this is the first time, as far as we know, that a system on this level will be created. A group of UGVs and UAVs will be created to work independently of each other. Each vehicle will be capable of being completely autonomous using waypoint navigation and mission arbitrator that exists within the Robot Operating System (ROS) environment. Though each vehicle is independent, they will have the capability to cooperatively plan their desired tasks to complete the mission. Vehicles will split the field of operation into sections based on the number of vehicles in the group and will then split off into a leader/follower system. Using a follow-the-leader method, the UAVs will begin an identification phase, in which they travel the field ahead of UGVs to mark low-confidence targets of interest as well as obstacles that should be avoided. UGVs will then perform a search behind UAVs to detect targets of interest with high-confidence levels while avoiding obstacles found by the UAV or the UGV sensors. When targets of interests have been determined, a classification phase will then be started in which a specialized group of UGVs will mark targets of interest to classify the target as needing attention by a human operator or to be ignored. Other mission types may be explored; two such possibilities are area survey and clearing missions, where vehicles will travel in random search patterns, but in formations to cover much larger areas.

## 2. BACKGROUND

Over the past few years the state of the art for homogeneous and heterogeneous groups of vehicles have been researched. Duan and Liu [8] found various projects that have advanced techniques in flocking, formation, and network control, which were used in various mission types for demonstration [3]. Specifically they

**Figure 1. UAV Blimp and UGV vehicles used in earlier GRASP Lab Research**

found groups, such as the University of Pennsylvania, looked into systems of UGVs and UAVs that work cooperatively to accomplish tasks by creating formations. They also found a strong push to create systems utilizing the Mobile Ad-Hoc Networks (MANET) feature which turns UAVs into network repeaters for UGVs. More so, they discuss the mission types these systems are being built to work within, such as Searching and Localization, or Tracking and Pursuit-Evasion systems.

A more in-depth review of the these findings as well as well as other projects and their developments has been given below.

## 2.1 University of Pennsylvania

The University of Pennsylvania General Robotics, Automation, Sensing, and Perception (GRASP) Lab has been working on the development of collaborative systems over the past decade. During early development, the GRASP Lab focused on formation control of ground vehicles using a system of UGVs that coalescing into formations around a shepherding UAV, or blimp as shown in Figure 1 [2], [3], [24]. Focus was then placed on using Expected Maximization statistical and pattern recognition methods for generating Gaussian distributions of vehicles on the ground, then using these distributions in order to split the groups into formations per UAV. The overall goal of this system was to show how multiple UAVs could be used to collect information on a group of UGVs, then using this information they command groups of UGVs to first establish a formation, and then guiding the group from waypoint to waypoint.

UPenn also developed a system for performing reconnaissance and tracking in an urban environment using UAVs and UGVs [12], [23], [16]. In this system UAV planes outfitted with an Inertial Measurement Unit (IMU), control package, and camera package are tasked with flying into an urban area and planning their own path to search and collect ground feature data. Once coverage is complete, the UAVs travel back to a base where the data is off-loaded, processed, and used to create an a priori map of features for UGVs to use. Once generated, this map is sent to a group of UGVs, which are then commanded to enter the field of operation and perform search and tracking behaviors according to targets of interest on the map.

One such demonstration shows the UGVs locating a building that holds a target of interest and then tracking/following that target outside the field of operation. A major focus for this system was how to use a priori information to localize targets in the area so that ground vehicles are able to efficiently collect data.

More recently, UPenn has become famous for their various videos of cooperation between UAV quadrotors performing formation flights, aerial dances, grasping and moving objects, building structures, and various other cooperative tasks. Kumar and Michael described how micro UAVs, specifically quadrotors, offer a new area of opportunity in research and application for systems such as UPenn's previous work [18]. One of the first projects applied to this theory was the use of a group of AscTec Hummingbird Quadrotors UAVs collectively moving from point to point in a tight formation (shown in Figure 2). Given precise pose information, Turpin *et al.* described how a formation is created using parameters given through a shape matrix [27]. Each UAV plans its own trajectory, using both the given parameters and a motion sensing camera to estimate the state of other UAVs and plan accordingly. Mellinger *et al.* developed a system of quadrotors that cooperatively grab and move wood blocks of varying size throughout a three-dimensional environment [22]. Most of the focus of these systems has been placed on the non-linear control and trajectory planning for each vehicle in a controlled environment. All of the above work is performed in a controlled environment with multiple motion capture cameras by Vicon. Although vehicles within these systems know their exact pose in the environment, a limitation due to the use of these cameras will not allow operation outside of a strictly controlled environment.

**Figure 2. GRASP Lab AscTec quadrotor swarm**

## 2.2 ETH Zurich

ETH Zurich is another university gaining notoriety for their use of UAV multirotor vehicles. Through a research partnership with AscTec, they use Hummingbird, Pelican and Firefly UAVs to cooperatively accomplish tasks. One such project incorporates a Swarm of micro FLYing robots (sFLY) for use in search and rescue mission where UAVs attempt to find victims in a GPS-Denied environment [1].

ETH Zurich details a system where multiple UAVs are used to collect imagery via a single camera, which is then fused with vehicle state information to form a global map with highlighted areas of interest [31], [6]. The focus of this work is to perform localization by creating a map that is used to extract locations of objects in the area to develop a pose, and then locating objects of interest in relation to the vehicles own understanding of the environment. Though initial testing was performed in a controlled environment, they have since moved to outside environments and shown that their method is still effective.

As an example of their efficient control of quadrotors, ETH Zurich's Flying Machine Arena lab developed algorithms that allow quadrotors to cooperate in playing acrobatic games. One such algorithm, as defined by Ritz *et al.*, allows a fleet of quadrotors to play catch with a ball [26]. This work has advanced into a system where quadrotors balance poles on the top of their frame and then have the ability to "toss" the pole between vehicles. This work follows closely to the University of Pennsylvania with the focus on controls and trajectory tracking of UAV solely operates by use of a motion capture camera system.

## 2.3 Stanford University

In 2001, Stanford University created a project known as the "Stanford Testbed of Autonomous Rotorcraft for Multi Agent Control" or STARMAC [13]. Using both centralized and decentralized control, their research focused on the use of small UAV quadrotors using waypoint navigation, with a goal of developing a testbed system in outdoor environments in order to show the validity of using multi-agent algorithms in a real-world situation. Later projects developed a trajectory tracking control system that create a path from given waypoints and velocities allowing a UAV quadrotor to navigate through a cluttered environment [14]. The system was built for a singular UAV and tested in an indoor environment, with eventual goals of placing the system technique into a group of UAVs for improved control.

## 2.4 Smaller Collaborative Projects

Several other groups have also created systems for cooperative vehicles, and though on a smaller scale than those projects previous mentioned, significant advancements have still been made. At Carnegie Mellon University, for instance, Vandapel *et al.* worked on the development of a system using a single UAV and multiple UGVs [28]. Though the system did not cooperatively work with each other in real time, a system was created in which a UAV could be used to travel into a field of operation and collect imagery localization data. Once processed this data would be used by the UGVs to understand an environment before driving into it.

Another example of work focusing on quadrotor controls and trajectory tracking in formation has been in development at the Massachusetts Institute of Technology. Called RAVEN (Real-time indoor Autonomous test ENvironment), this system, which used Vicon motion capture camera systems, performed robust coordination algorithms for a group of quadrotors to further develop vision-based sensing systems that both detected and guided the vehicles. How *et al.* describes the systems purpose as a way to simplify and handle multivehicle coordination and control at a lower level, therefore allowing high-level behaviors to be implemented quickly [15].

A more controlled, but larger heterogeneous swarm project was developed between vehicles called eye-bots and foot-bots. Ducatelle *et al.* and Mathews *et al.* both describe a system made of small track/wheel ground vehicles (foot-bots) and five thruster air vehicles (eye-bots) that solve tasks within a controlled indoor environment. Eye-bots are setup to fly through the environment and attach themselves magnetically to a ceiling. Though eye-bots are described as capable of flight, all tests explain that each is manually placed in a grid pattern to assist foot-bots in navigating between two targets in a foraging task system that closely mimics ant colony movement [9], [10]. Other focuses of the research show how eye-bots assist foot-bots in traversing a gap clearing environment [20], using a single eye-bot to assist foot-bots in traveling over a hill in terms of angle steepness and calculating group formation in order to traverse an angle too steep for a single vehicle to climb [21].

Another example of focus in localization is given by De Silva *et al.* who describe a heterogeneous system, in which UAVs use a combination of visual and acoustic data to localize position with a ground vehicle within a closed environment [5]. A bearing sensor uses imagery data from a pinhole camera on the UAV to lock onto a ground vehicle and calculate the generated heading. A ranging sensor, or Time of Flight (TOF) sensor, uses an acoustic source and receiver between the UAV and UGV. The amount of time for the source to travel through air gives the distance between the two targets. A combination of the two sensors gives a statistically accurate relative location between the two vehicles.

**Figure 3. Obstacle Avoidance using UAV and UGV**

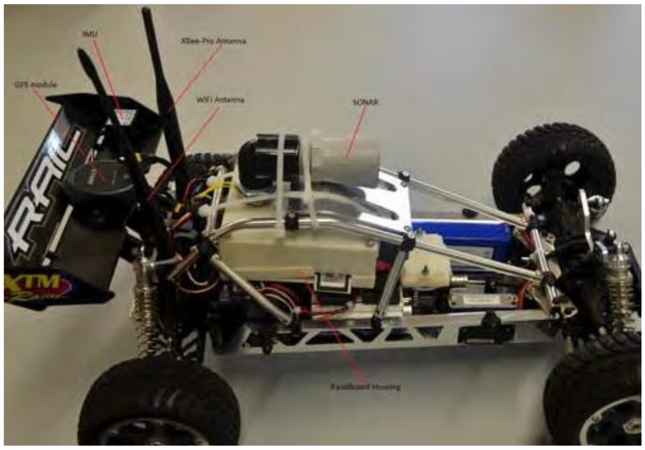


**Figure 4. UGV Modified RC XTM Rail**

More recently Garzón *et al.* developed a heterogeneous cooperative system between a single UAV and UGV (Figure 3) [11]. A UAV was manually flown above an autonomous UGV with the requirement that the UGV stay in the field of view durin g the entire flight. Aerial imagery was collected and processed to supply the UGV with obstacle data in the forward direction of the UGV. Using this information, a UGV could then traverse a path in an outside environment safely given that the UAV accurately portrayed the environment.

## 3. COOPERATIVE SYSTEM HARDWARE

Descriptions of each agent that makes up the ground and air components of the system as well as basic description of the base station are given below.

### 3.1 UGV Description

UGVs used in the cooperative system are modified XTM Rail RC racing vehicles, as shown in Figure 5, that houses all control electronics inside of a protective roll cage. These vehicles were first used in work with homogeneous swarms [4], but have since been further modified. Each vehicle houses an upgraded quad-core ARM ODROID-X2 board installed with Linux Ubuntu and the Robot Operating System (ROS) for handling control and sensor processing.

The vehicle design uses waypoint navigation handled by an ArduPilot-Mega (APM) 2.5. The APM is an open-source autopilot control board used in both unmanned aerial and ground vehicles. It houses an Inertial Measurement Unit (IMU) with magnetometer, accelerometer, gyroscope sensors, and a barometer for altitude information. The software suite loaded on the APM is a modified version of their ground vehicle control software to control an Anderson based steering vehicle such as the XTM Rail. The APM is directly interfaced with the ODROID-X2 to allow sensor information swap as well as single waypoint transmission and control commands.

Beyond the APM, the sensor suite consists of sonar for obstacle avoidance, a Hokuyo URG-04LX-UG01 LIDAR for obstacle and target identification, and a PointGrey FireFly MV usb camera for computer vision classification methods. Sonar is used on each vehicle, however, the LIDAR and cameras are split between vehicles to allow for a local heterogeneous group of ground vehicles with different capabilities.

**Figure 5. AscTec Pelican Side View**

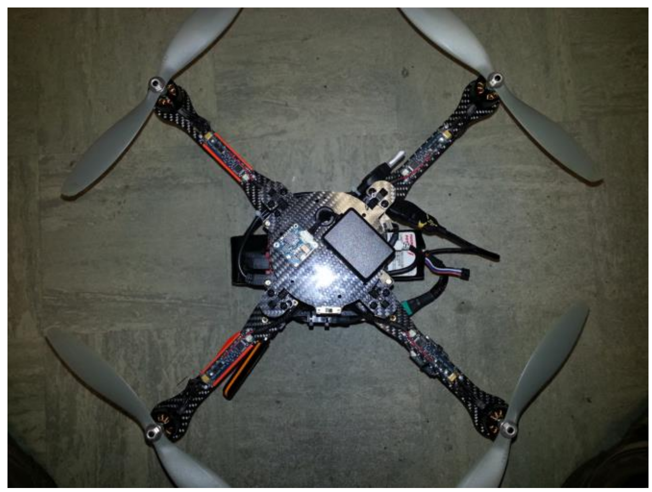

**Figure 6. AscTec Pelican Top View**

Communication is handled by both XBee RF devices as well as wireless N WiFi. WiFi is used when in range of the base station to transmit high bandwidth imagery and other data that may be useful to the base station for control decisions or human observation. WiFi is also used between vehicles to share localization and environment data within the ROS environment. RF communication is used as a backup in terms of vehicle state and target information in the event of a main WiFi ROS communications drop.

### 3.2 UAV Description

Multiple types of UAVs are used within the cooperative system. One such vehicle is an AscTec pelican that was used for a single autonomous UAV, Android, and ROS system that was developed in the Machine Intelligence Lab [30]. Various other quad and hex framed multirotor vehicles (e.g., Flamewheel F450 and F550 models) will also be added to the cooperative system with the help of the APM autopilot control board. Open-source software with attitude, altitude, and waypoint control has been implemented for these types of vehicles. Control and sensor processing abilities is given to UAVs by way of a quad-core ARM ODROID-U2 installed with Linux Ubuntu and ROS. The ODROID-U2 is a smaller version of the CPU used on the UGVs.

The main sensor of the aerial vehicles is a PointGrey FireFly MV camera which is used for computer vision, obstacle, and target identification purposes. Aerial vehicle communication follows the same structure as the ground vehicles.

### 3.3 Base Station

A base station is used for collecting and processing data for the swarm of vehicles. The base station is comprised of a computer comparable to a high power desktop with communication capabilities that mimic the UGVs and UAVs. The primary purpose of the base station is as a central hub for all information on agents within the cooperative system as well as a method for control for the system. Chosen missions are passed to the base station which in turn decides how to pass the mission to agents in the group. Specifically during centralized control missions, the base station decides how the mission is divided, however, in decentralized control missions, details are simply passed to the agents for them to decide what to do.

The ROS environment is installed onto the base station and is the primary source for information collection and process. All collected data on the various agent's state and mission progress may be viewed on the base station through an external computer connection or tablet. Mission parameters, such as objectives, vehicle tasks, and overall commands, may be sent to the base station using these observing connections.

### 3.4 System Assumptions

There are a few assumptions to be made for the cooperative system to function as intended. First, the proposed outdoor environment is to be an open field with no high structures that could cause collision issues with the UAVs. The first tests will be performed in a completely open field as to focus more on group behaviors versus UAV obstacle avoidance. This is an issue being solved by other research and is not a focus of this proposed research. Further testing is desired in a more cluttered environment, in which trees and other obstacles may obstruct a UAVs view of the ground. In these cases, the UAVs will be flown high enough to avoid these obstacles.

Next, obstacles in the field of operation will be controlled. The vision used in the proposed research will not follow computer vision or pattern recognition techniques to perceive complex objects, but will instead be used to detect objects of specific shapes and colors. These different objects will pertain to either obstacles or targets of interest depending on the technique used. Along with the obstacles in the field, special patterns and colors will be used for tracking the agents to assist in localization.

## 4. ENVIRONMENT AND ARCHITECTURE

The cooperative system is made of various vehicles that must communicate with each other and be controlled in a similar manner. To handle this aspect, the Robot Operating System (ROS) environment was chosen, due to the open source nature of the software, which allows various sources of code to be used or for code developed in this research to be easily shared. ROS also allows an easy method for all code to be duplicated and moved to multiple vehicles, and is used throughout the various levels in the heterogeneous cooperative system.

### 4.1 ROS Environment on Individual Agents

ROS is installed on each agent to supervise control within the vehicle as well as interface sensors into the system. Each vehicle is setup as a ROS Master given that the network is prone to connection drops. Since all nodes created are started with and must have access to a ROS Master, a loss of connection in a system that relies on a ROS Master located elsewhere would result in all nodes and controls shutting down, effectively stopping the vehicle from functioning.

Individually, a single node, *AscTec_Drivers*, is created to handle manual control, waypoint navigation, and status message posting to ROS. *AscTec_Drivers* is derived from a node created by Community College of New York for their 3D indoor mapping research [7], [25]. The node originally held manual control and status message component for ROS, however, through our previous work [30], waypoint navigation was added. The node is made to control the AscTec Pelican, while a related node, *APM_Drivers*, is created to handle the same behavior and control except for the ArduPilot-Mega (APM) autopilot control board.

Another node, *Agent_Control*, was created to handle communication and control with the APM or the AscTec. The node allows for sensor data such as IMU, battery, and GPS information to be retrieved from the APM and shared to the ROS database. Subsequently, the node also allows information such as waypoints and commands to be sent to the APM, instigating launching, landing, or movement between path planned points. This node is made generally, therefore only small changes have to be made to either control an air or ground vehicle. Through a combination of the APM and ROS, control may be added to many types of multirotor aerial vehicles or nonholonomic ground vehicles.

Still on the individual agent level, various sensor nodes are made to drive and receive information from the sonar, LIDAR, and camera sensors. These nodes collect the desired information from the source, process the data as desired, and place the information within the ROS database. For example, in terms of sonar and LIDAR finding obstacles, the information is processed in terms of the vehicle's known location within the global map. This information is then published onto the ROS database for use by either the vehicle's obstacle avoidance or obstacle identification algorithms. Camera nodes are used to first drive receipt of imagery from the camera, as well as perform computer vision algorithms made for use in the identification of obstacles. The computer vision nodes are made with the use of Open Source Computer Vision (OpenCV) libraries that exist within ROS.

### 4.2 ROS Environment between Agents

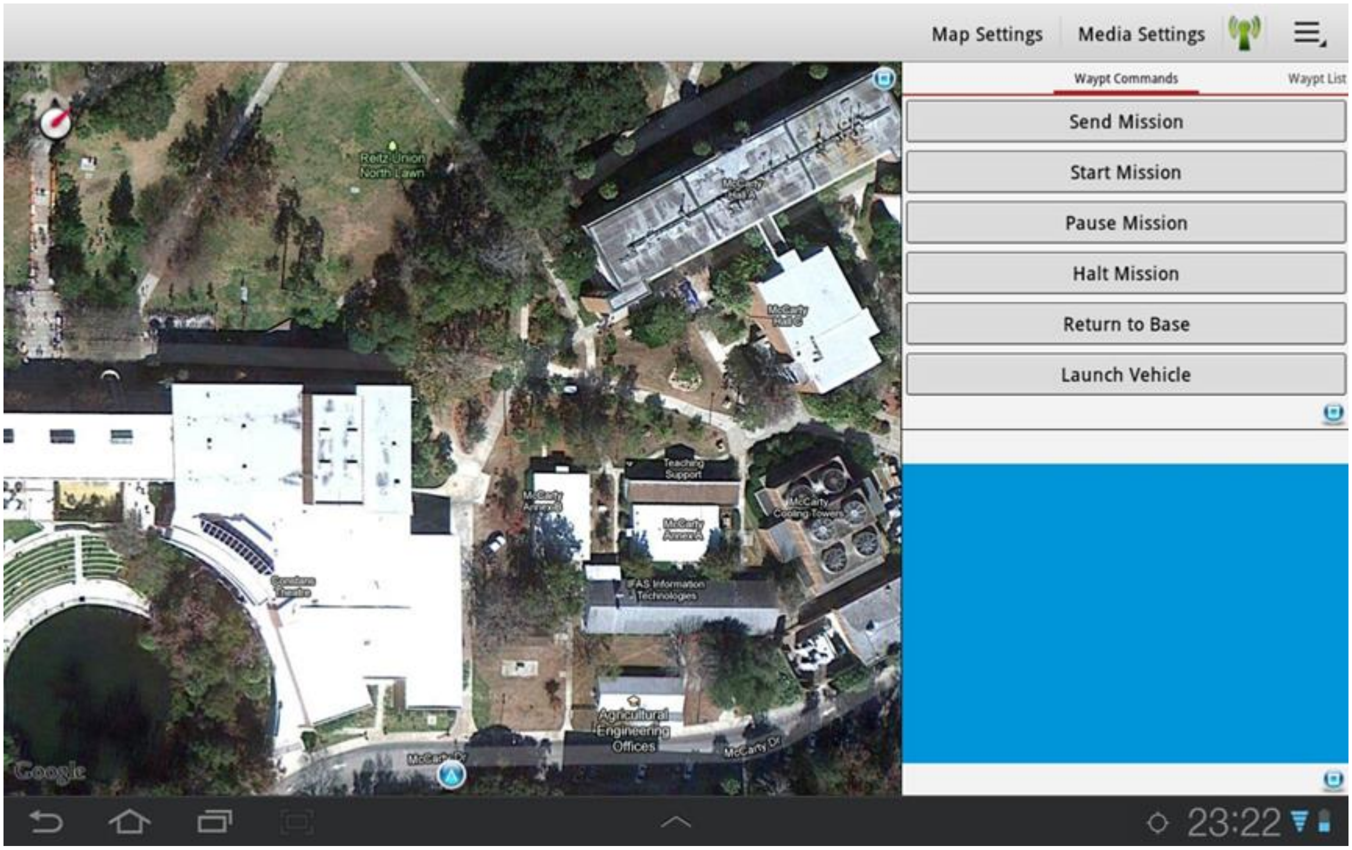


**Figure 7. Android Application for Mission Control**

Following the agent level control of vehicles, ROS is used to allow intercommunication between vehicles. Each ROS Master is bridged between vehicles to share information in terms of vehicle name. Through this connection, information collected from agents is shared with other agents as well as the base station, and in turn, any human observer. Mission parameters may be sent from an external source through ROS to the base station where it will either be split into various tasks or passed directly to each agent.

## 4.3 Control with ROS in Android and Ubuntu

Applications in Android and Ubuntu are used as an external source of control and observation for human operators. First, the application made in Android for our previous work [30], shown in Figure 7, is used as an infield control and observation device. The device may connect to the base station to retrieve state information about the mission or detailed information about the vehicles. The device may also be used to directly connect to an agent within the cooperative group and override its current task with a user controlled task. All information collected from the vehicle during this override is still shared with the group.

The application made in Ubuntu acts as a ground station device to be used by a user to select the overall mission parameters, receive feedback on mission progress, and change mission parameters or agent tasks during the mission. The application is made only to connect to the base station through ROS either directly or remotely as it did in the Google Application.

# 5. CURRENT STATE AND FOCUSES

All vehicles are in the final stages of being updated to new hardware as well as final software being written. Control has been tested between the Android application and both the UGVs and UAVs through ROS. Single vehicle missions have already been performed where a user decides a path for the vehicle to travel and then starts the mission.

The primary goal for these vehicles is to be used with cheap, open source hardware. This allows a combination of the autopilot board and a CPU with ROS to be added to various ground or air vehicles, thus bringing them into the system.

During further development of the system, certain focuses will be reviewed and developed when needed to better control the system. These focuses, as well as testing and mission plans are given below.

## 5.1 Future Focus Developments

### *5.1.1 Behaviors*

Various behaviors will be used to control the vehicles as they travel through the field of operation. A more complex obstacle avoidance behavior will allow vehicles to avoid objects that it senses directly in the field of movement as well as objects known to it through the global map. Using known locations of obstacles found in the environment as well as locations of other agents on the same plane of operation, an agent will attempt to move away from these objects when they intrude into a threshold area of safety for the agent. Current behaviors that allow for the avoidance of other agents has already been created.

Behaviors that handle tracking, following, and formation building will be created to handle UAV tracking and acknowledgment of UGV agents. In various cases of missions, such as leader/follower aspects, the UAV must know where the UGVs are located and may rely on imagery rather than GPS locations. These behaviors will follow some of the same aspects of formation building as the University of Pennsylvania did with their blimp and UGV formations [2], [3], [24].

Behaviors that handle the identification or classification of an object of interest will be created. In these cases, certain patterns may have to be made around an object to collect more detailed information. These behaviors may be used on either UAVs with cameras or UGVs with LIDAR or cameras. Other aspects of this behavior may follow localization techniques in developing GPS tagged locations of objects of interest as discovered by the UAV.

#### *5.1.2 Localization*

Localization will be a major factor in how the cooperative group behaves when carrying out their individual tasks. Position of the vehicle severely depends on data received through GPS and how the inertial navigation system portrays movement while completing tasks. Relative Localization concepts such as those created by De Silva *et al.* and Garzón *et al.* could possibly be used to better know the location of vehicles as well as obstacles in the vicinity [5], [11].

A localization method described by De Silva *et al.* uses both vision and acoustic data to decipher a relative location of other vehicles detected by a UAV. This method may be used and filtered with each vehicle's expected position to triangulate and improve the accuracy of vehicle positions in the environment. Along with this, Garzón *et al.* work may be used in conjunction with leader/follower components of the cooperative group. Specifically, if a UAV is being used to lead a formation of ground vehicles, the information received via imagery from the UAV could be used to give detailed information on obstacles that the formation of UGVs may want to avoid.

#### *5.1.3 Task Allocation and Path Planning*

As both task allocation and path planning are major components of any cooperative system, further research and review will be performed in order to ensure the most effective and efficient methods. Lacroix and Besnerais, through their review of current homogeneous and heterogeneous systems, discuss that task allocation and path planning is still a major issue in such systems [19]. With that in mind, a major focus of the proposed research will involve using a centralized control scheme to decide mission task allocations for each agent. The base station will be aware of all agents within the cooperative group and will perform an orchestration algorithm to compute paths for each agent. The algorithm will handle costs of maximizing coverage, minimizing time and effort, and also handling possible lost communications during agent travel.

Alternately, a decentralized control scheme will also be reviewed, in which communication loss with the base station is not a detrimental event, given that each vehicle is capable of making its own decisions in task allocation. Vehicles will communicate with each other and the base station to reach a consensus on how the mission should be split between agents given type and capability of vehicle. A combination of nearest neighbor algorithms and cost functions may be used on deciding how the vehicles split up tasks. Zengin and Dogan method of developing a cost function to handle adversarial situations will be a good point to build on when developing a cost function for the initial path planning and updates under travel [32].

Furthermore, some consideration in path planning may be made when developing a leader/follower system. In missions where UGVs may use UAVs as a leader to travel from point to point, methods such as described by the University of Pennsylvania or by Tanner and Christodoulakis, which use a system of nearest neighbor rules to coordinate velocities around the centroid of the group could be applied. A leader/follower system will have use in a heterogeneous system given the added benefit of using an aerial vehicle to assist a small group of ground vehicles in covering an area and avoiding objects while traveling.

A final consideration in mission planning may be in the use of vehicles to perform a fast, low confidence search over an area to build an a priori map. Kelly *et al.* explains path planning techniques that focuses on perception in an environment, specifically, in reference to work performed by Carnegie Mellon Universities PerceptOR group and their work using a "flying eye" that gathers data to provide information in the form of a map to ground vehicles [17].

#### *5.1.4 Communication*

Although not a chief concern of our work, serious consideration will be placed on effective and reliable communication protocols. For the scale of the system currently being developed, standard Wireless-N WiFi and XBee RF networks are expected to be able to handle all required communication between the base station and vehicles. WiFi connections will be handled through TCPIP with in the ROS framework, and, when applicable, P2P connections may be used to send direct vehicle imagery to a connecting vehicle or the base station.

Given the data load that a system of multiple vehicles could have on a single WiFi network, a hybrid RF and WiFi network will be used for a scalable decentralized control scheme. A communication leader of each group will request followers to start a local Ad-Hoc network that will be used to share data and information within the group. The leader will use its' RF network to communicate between other group leaders and the base station. The RF communication channel will control the transmission of relevant information such as targets of interest, task changes decided upon by vehicles, or asset request commands. Handshaking when publishing information may be used to reduce communication loss.

There are two possible solutions for a centralized control scheme that will be reviewed. One possible solution will closely mimic the decentralized control scheme. The RF channel will still be used to update all vehicles as well as share information between each group and the base station, however, the command decisions will originate directly from the base station.

The second possible solution proposed will channel all communication control to the base station. All data is held by the leaders of each group until the base station requests it. Once received, the base station will then choose to either update mission parameters or request data from the next leader in line. Although the method is much slower, more control over data transmission is gained allowing for less data overlap and loss.

### 5.2 Overall Mission and Testing

A major focus of this research will be the culmination of all work into a single implemented system to be tested in a practical environment. A system consisting of five UAVs, six UGVs, a base station, and tablets will form the cooperative swarm and be tested within various mission scenarios. In all mission types, however, vehicles will be split into Identification UAVs, Identification UGVs, and Classification UGVs. Tablets will be used as observer units that will allow users direct control of a vehicle or to modify objectives during a mission. All testing is expected to be performed during 2013.

The most recent planned test will consist of manual missions being planned for each vehicle. Once missions are planned, all vehicles will be given the mission and the mission will begin. This test is to confirm that the system works as expected as well as collect data from each vehicle in terms of vision, LIDAR data, and state data. After this test, further development will be made in furthering the system's capability of planning its own missions.

Once basic tests are completed, further testing will focus on the systems capability to complete specific missions. The first mission is Area Survey, in which case a scenario for either a centralized or decentralized control system will be tested to initiate ground and air vehicles to randomly travel over a specified field of operation. Identification based vehicles will separately search the area for targets of interest, while classification vehicles would travel to found targets of interest to classify the object. Another option is to have vehicles create leader/follower formations based on the type of vehicles and search the field of operation randomly, but cooperatively. It is expected that this option may prove more useful due to a wider field of coverage as well as the added benefit of using aerial vehicles to help sense the area with ground vehicles.

The primary area of use the system is intended for is Search and Rescue. In this scenario, a zone is defined as an area where targets of interest, such as a person in danger, are being sought. Either a centralized or decentralized system will decide tasks individually for each vehicle, or simply pass mission parameters to the vehicles and let them decide on the mission. During the decision process, it is likely that a small portion of available air vehicles may fly ahead and build a fast terrain and target map to be used in path planning. Expectations are that the decision is made to split the vehicles into groups to accomplish the tasks. Number of groups and group size will be decided based on number of agents in the cooperative group as well as size of area to be covered.

Once the agent's tasks are decided, they will travel to the beginning points of the search. UAVs will fly ahead of UGVs, attempting to keep at least one UGV in visual range for localization purposes. UAVs will be used to identify targets of low confidence as well as obstacles to be avoided. Identification UGVs will follow the UAVs path performing a high confidence search to locate targets of interest. If required, closer inspection for identification will be performed. During the search, if either UAV or UGV decides a target is a high confidence target of interest, a classification UGV will be dispatched to perform a classify behavior on the object. Either the classification UGV will decide the target should be rescued or ask a human observer to review information and decide. The mission is complete once coverage of the field is within an acceptable margin and all targets have been classified.

Coverage rate based on vehicle capabilities, cost functions based on energy used and distance traveled to perform the mission, and accuracy in completing mission objectives, such as target identification or avoidance, are the primary metrics to be used to describe the system's capability. Other possible metrics explored will be formation creation and control, planning and task allocation behavior analysis, data loss and overlap, which will be used to improve the system's abilities.

# 6. CONCLUSIONS

In this paper we described the development of a heterogeneous system of UGVs and UAVs that cooperate in a real outdoor environment to complete certain tasks or missions. We detailed specifics on design for each agent as well as the software architecture for the system as it works in the Robot Operating System. We described the current state of the system in the ability to travel and perform waypoint navigation, while also detailing the future testing plans of the system. We also detail various focuses that will be reviewed and further researched during development.

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