The Design of an Air-Ground Research Platform for Cooperative Surveillance

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Abstract

This report describes an unmanned systems architecture and platform for performing cooperative autonomy research. The primary research aim of this system is to explore distributed, cooperative, autonomy algorithms for controlling multiple unmanned systems vehicles. The system consists of multiple small, Unmanned Aerial Vehicles (UAVs) and an Unmanned Ground Vehicle (UGV) that can operate autonomously and accept missions from a ground station. The system leverages open standards and off-the shelf technologies, and can be configured to carry different mission payloads. The vehicles communicate with each other and collaborate in a distributed manner. Real time telemetry and sensor updates are displayed on the FalconView based ground station. Over 60 flight demonstrations, as well as UAV-UGV collaborative experiments have been performed using this system.

1 Introduction

In distributed, heterogeneous, multi-agent teams, agents may have different capabilities and types of sensors. Many real world scenarios could benefit from having teams of robots with different capabilities working in a cooperative manner. An example is after an earthquake or hurricane disaster, in which multiple locations need to be searched and surveyed for survivors. Detection of forest fires or chemical spills are other examples. In such dynamic environments, teams of heterogenous agents will need to cooperate in real-time to perform tasks efficiently.

The Georgia Tech Research Institute has developed a system for performing cooperative autonomy research using multiple unmanned vehicle platforms. The system consists of multiple small, Unmanned Aerial Vehicles (UAVs) and an Unmanned Ground Vehicle (UGV), as shown in Figure 1. The vehicles can operate

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Figure 1: UAV-UGV Team: The system includes multiple small UAVs and a UGV.

autonomously and accept missions from a ground station, and are able to communicate with each other in a distributed manner.

A common theme explored in air-ground teaming missions is how to best leverage the differences between the UAV and UGV platforms. Small sized UAVs may be flying at an altitude of 1000 ft. or more, and therefore have a broad field of view. They can cover areas quickly and are not constrained to road networks. However, it is often challenging to localize targets exactly from a moving airframe. Furthermore, because they are moving quickly and at altitude, they cannot get a detailed view of the target as easily as a ground vehicle can.

A UGV on the other hand, can utilize better localization capabilities and get up close to take sensor readings of suspected targets. Furthermore, a UGV can carry additional payloads and sensors, beyond the weight and power limits of the UAV, and can easily perform long missions. However, the UGV in this case is restricted to navigation over road networks and does not have a full view of the environment at any given time.

The vehicles in this system work as a team and are able to leverage the characteristics of the different platforms: The UAVs are used for searching and surveillance, and the UGV is able to get a close-up view of a target. This work describes the architecture for the UAV research platform and mechanisms for communication between air and ground vehicles and the ground station. An example search and surveillance demonstration is also presented.

2 Related Work

Decentralized control of four identical UAVs in a search task is presented by Ryan, et al. (Ryan et al., 2007). The avionics, airframe and mission processor used are also similar to the UAV platform presented here. A similarly sized UAV research platform and software architecture are described by (John Tisdale, 2006). A related theme of their work is the ability to leverage different strengths of the respective platforms: The UAVs had a wide visual field of view, but could not accurately localize a ground target. The UGVs had a very narrow field of view but could localize accurately.

Related to target tracking, UAVs were also used to search for and track a river using visual features using the same platform in the work by Rathinam, et al. (Rathinam et al., 2007). The work by Tisdale, et al.,(Tisdale et al., 2009) uses vision based target tracking as input to both search and localization.

Stentz, et al. also presents a cooperative air-ground vehicle system (Stentz et al., 2002). In that work, a UAV is used to fly-ahead of the UGV's planned path and detect hazards in the terrain. The UAV and UGV were tightly coupled to each other and to the task in those experiments, but it is possible that such task assignments could be more generalized.

Research in cooperation between air and ground vehicles was performed by Grocholsky, et al. (Grocholsky et al., 2006). In that work, a single UAV cooperated with multiple small UGVs to localize a target on the ground. There were multiple UGVs in this case, of a much smaller size (less than 1 meter.)

In other works by Grocholsky, et al.,(Grocholsky et al., 2006) and also Bayraktar, et al.(Selcuk Bayraktar, 2004), the UAV airframe (1/4 scale Piper Cub), avionics (Cloud Cap Piccolo) and configuration are nearly identical to those selected for this paper.

The work in this paper addresses decentralized task assignment and collaboration between multiple UAVs and a car sized UGV in a target detection and surveillance task. This work incorporates on board real-time computer vision, behavior based autonomy, open standards, and heterogeneous mission planning, where the heterogeneity is across platforms, sensors, and autonomy. The focus is agent to agent collaboration, including air-air and air-ground scenarios.

3 System Infrastructure

3.1 UAV Platform

The UAV platform, shown in Figure 2(a), leverages off-the-shelf, readily available components, and is based on a quarter-scale Piper Cub airframe with a base model Piccolo avionics and autopilot system from Cloud Cap Technology (Vaglienti et al., 2009). The airframe has a wingspan of 104 inches. Two airframes have been tested, one with a four-stroke 20 cc gasoline engine, and the other with a two-stroke 26 cc gasoline engine. The different engine configurations allow for either more power or endurance as the mission dictates. The flight duration is up to 90 minutes, depending on mission tasks and payload. There is room available on board for scientific payloads and sensors, configurable to the missions, see Figure 2(b). In addition to the autopilot package, each airframe can carry up to seven lbs of payload or sensors. Over 60 field tests of this platform were performed in 2010, including multi-UAV cooperative autonomy and UAV-UGV teaming demonstrations.

3.1.1 Flight Operations and Safety

During flight operations, a human pilot manually takes off and lands each UAV. A human operator also monitors the UAV health (GPS status, signal strength, speed, engine RPMs, etc.) using the autopilot operator interface component of the ground station. For safety, each UAV is flown at a separate altitude with sufficient separation. Once the vehicle is at the safe altitude, the human pilot switches the vehicle into autonomous operation. At this point the UAV will begin to track toward the first waypoint in its current route. At any time, the flight operator can change the waypoints and upload them to the vehicle. The operator can also send a command to the autopilot to shut down any on-board payload should the need arise. Additionally, the pilot can take over manual control at any point during the flight. In the event that the autopilot system loses communication with the ground station, the UAV will automatically return to the safe waypoint and orbit. Lastly, the platform also includes a homing beacon for emergency recovery.

3.1.2 UAV System Architecture

The UAV system architecture consists of the autopilot system for low level flight control and the autonomy payload for high level mission control. The flight control modules and high level autonomy modules have been logically and physically separated to provide for flight safety and ease of configuration. The logical architecture for the UAV platform and ground station is shown in Figure 3. The autopilot system provides for low level control of the platform and can be given a series of waypoints or control loops using the corresponding operator interface in the ground station. The UAV platform can be flown without the autonomy or other sensor payload, using only the autopilot to follow waypoints. This may be desirable if there is a mission requirement to carry a bulky sensor and gather data for offline analysis.

The autopilot module is self-contained and includes a dedicated communications link, power supply and charging circuit. In addition the platform also carries a dedicated power supply for the engine's ignition. The autopilot system communicates with the ground station via a dedicated 2.4GHz data link. The avionics components include a flight control system (flight computer), a GPS/IMU and barometric altimeter sensor for localization and a waypoint following autopilot for control. Position updates are sent to the ground station at 4 Hz and the core autopilot processes sensor data and controls airframe servos at a rate of 20Hz. In addition a magnetometer is connected to the autopilot to provide for accurate heading estimates.

Higher level mission control is provided by the autonomy payload and mission processor. The mission processor receives sensor data and sends new waypoint and turn rate commands to the autopilot. The mission processor communicates with the autopilot's flight control system over a serial port. The autonomy payload includes: an onboard PC-104 Intel Atom 1.6GHz mission processor running the Linux operating system, a USB digital camera with a 1/3" CCD sensor and interchangeable lenses (8mm, 16mm and 25mm for wide angle and zoom views), and a Digi 900Mhz radio. This radio serves as the mission-level communications link for and agent-agent communications. Each of the UAVs and UGV can use this link to send messages directly to each other or to the ground station. The autonomy payload is self contained and can easily be removed to perform experiments with different sensor or payload configurations. For example, in other experiments an infrared camera payload was carried to gather sensor data from two different IR cameras for offline analysis.

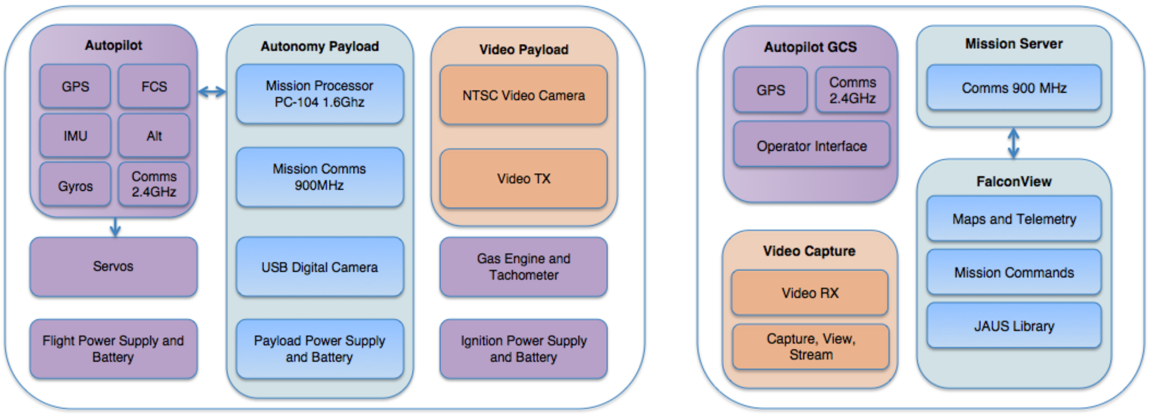
The vehicle is also equipped with an analog color video camera that transmits video to the ground over a separate link. This video is captured by the ground station and stored in digital format for use by the base station operators and for after-action reports. An example video frame is shown in Figure 4(a).

(a) UAV Platform (b) Payload

Figure 2: UAV Platform: a) The UAV platform is configurable for different mission requirements, payloads and sensors. b) The basic research payload (on the right) includes a mission processor, data link, and digital camera. The mission processor connects to the autopilot (small box on the left) over the serial port.

The UAV mission processor's software architecture is open and extensible, and includes the use of open-source technologies and tools. Software processes are loosely coupled and communicate using a publish-subscribe messaging architecture, LCM (Albert S. Huang, 2010), as shown in Figure 5. Some of the lower level processes and libraries are written in C++, such as the computer vision processes, and high level autonomous behaviors are written in Java. Both custom and 3rd party low level libraries and drivers are used to encapsulate access to hardware and standards.

As an example of interprocess communication using LCM, the image processing software component uses pose information to stamp images with position and to perform target localization. The avionics process handles messages coming from the autopilot and publishes a pose message (containing position and attitude



(a) UAV Platform

(b) Ground Station

Figure 3: System Architecture: a) The UAV platform's autopilot and payloads contain separate power and communications links. The payloads can be replaced with different capabilities and sensors as the mission requirements dictate. b) The ground station contains operator interfaces for the autopilot and also for payload operation. Vehicle positions are displayed over the maps in the FalconView^{TM}display. Video and sensor feeds are also captured, displayed and stored on the ground.

(a) UAV Video Feed

(b) UGV Video Feed

Figure 4: Analog Video Feeds: a) The UAV platform captures video during flights and transmits it to the ground station. b) The UGV platform also streams video to the ground station operators.

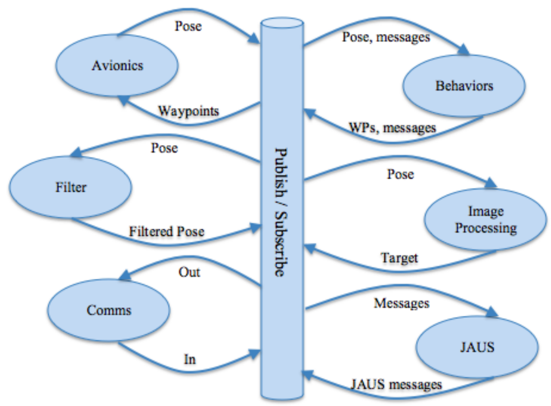


Figure 5: UAV Logical Software Architecture: The UAV Software Architecture uses a publish/subscribe mechanism for passing messages between processes and is easily extensible.

information). Other processes, such as filter or image processing, can subscribe to these messages and use them, while posting messages of their own. The use of a publish subscribe mechanism allows new processes and sensors to be more easily integrated onto the platform. For example, a new sensor could include a process that reads data from the sensor and consumes the pose messages from the existing system. The sensor could post new messages that additional behaviors could consume, or replace existing message types (such as a target-found message.)

3.1.3 Aerial Target Detection and Localization

An important component of the system is aerial target localization. The UAV platform currently uses a computer vision based mechanism for target detection; although additional techniques or sensors could easily be integrated into the system. Aerial Target Detection and Localization combines the ability to capture images from the air, process them using computer vision to find a target in the image, and to calculate the location of that target on the ground, given the position of the UAV.

The UAV's on-board digital camera is affixed to the underside of the fuselage and points down at a target on the ground. The UAV and the camera each have their own coordinate frame. The vision system combines the ability to: (1) capture images while in the air, (2) process them in real-time using computer vision for target detection, and (3) compute the estimated GPS ground location of the detected target. Figure 7 displays a sample image of ground features from Ft. Benning. The image contains the colored tarps that are used as a sample target. Target detection is achieved using color based recognition methods that rely on a trained model of color thresholds. The UAV's pose is recorded when the image is snapped and is defined by the UAV's position (latitude, longitude, elevation) and attitude (roll, pitch, yaw). In combination with the position and orientation of the camera's coordinate frame with respect to the UAV (extrinsic parameters) and knowledge of the camera's sensor size, lens configuration, and pixel resolution (intrinsic parameters), along with the detected target's pixel coordinates in the image, the target's estimated coordinates in the real world may be computed, i.e., localized.

3.1.4 Behavior Based Autonomy

Mission level autonomy is designed to work in a behavior based framework, in which behavioral autonomy components are encapsulated into reusable modules or behaviors. Various sets of behaviors can be developed and unit tested before being incorporated into the system. Behaviors can encapsulate simple low level control, such as flying a search pattern or commanding waypoints, or higher level operations, such as performing a

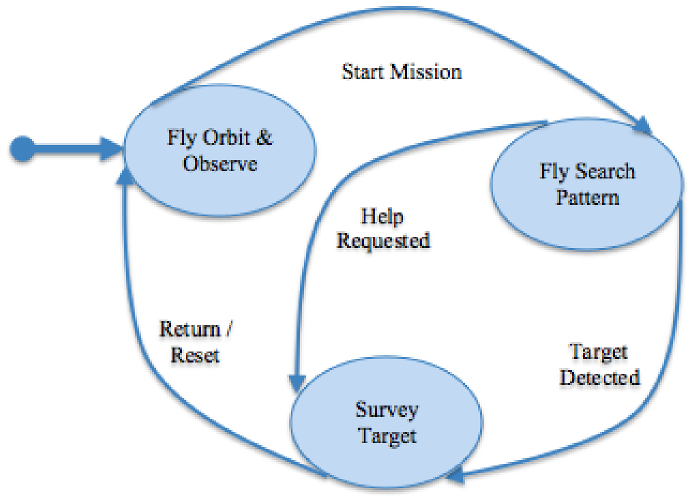


Figure 6: Behavior Based Autonomy: A behavior based autonomy approach is used to encapsulate higher level autonomy into reusable components. Behaviors are connected together in a state machine.

cooperative task.

In this architecture, bevaviors are connected using a control state machine that defines the states or behaviors that are possible, and the events or triggers that cause the robot to change from one behavior to another. Different inputs available to the behaviors could be used by the triggers to force a behavior change, such as the location of targets or through other events such as receiving a message from team members.

Consider the example behavior state machine, as shown in Figure 6, which is used on this platform to perform a cooperative target search and detection mission. After the UAVs are safely at altitude and switched to autonomous operation, the UAVs enter the $Fly - Orbit$ behavior. In this behavior, the mission processor simply gathers and logs data from the sensors, but does not send commands to the autopilot. When the ground station mission operator sends a $Start - Mission$ command, the behavior state machine switches to the $Fly - Search - Pattern$ behavior. At this point the behavior commands the autopilot to follow a predetermined search pattern (defined by a set of waypoints.) However, a similar behavior could be written to provide low level bank angle commands if desired. While the UAV performs the search pattern, the behavior is listening for messages from the other UAVs and UGV on the team (the $Help - Requested$ message). It is also listening for messages from the sensors indicating that a target was found ($Target - Detected$ message). If the computer vision process locates the target or one of the other UAVs locates the target and sends a request for help over the communications link, the current behavior becomes the $Survey - Target$ behavior. At this point, the behavior will send new waypoints to the autopilot, dynamically commanding it to fly a new path around the target location. The UGV runs a similar state machine internally, waiting for help requests from one of the UAVs before navigating autonomously to the requested location.

3.2 UGV Platform

The UGV platform consists of a 2006 Porsche Cayenne SUV automobile that has been modified for autonomous operation, shown in Figure 1. This vehicle was developed as Georgia Tech's entry into the DARPA Urban Challenge.[1] The vehicle is equipped with stereo vision for lane navigation and LIDAR and radar sensors for obstacle detection. The vehicle performs autonomous waypoint navigation using the filtered GPS and IMU sensor output. The system uses a standard D* algorithm for graph based path planning over a list

[1] http://www.darpa.mil/grandchallenge/TechPapers/Sting_Racing.pdf

of ordered waypoints. The vehicle starts with a known map of the navigable environment, a Route Network Definition File (RNDF), which contains metadata about points that define road segments. The vehicle can be given a set of waypoints to visit in advance or can be sent a current waypoint using the JAUS standard messages. The LIDARs and radar are used to detect static and moving obstacles in the environment and provide 360 degree coverage around the vehicle. The UGV also is equipped with the same Digi 900 Mhz radio as the UAVs for agent-agent communications. The vehicle also carries an analog video camera and transmitter. A sample video frame is shown in Figure 4(b). This platform can be configured to carry different sensors as mission requirements dictate. For example, in one experiment, the UGV carried a chemical sensor as part of an ammonia detection mission, and sent sensor readings back to the ground station.

The vehicle navigates using a hybrid approach of behavior-based reactive control which references an internal, local map and a graph-based planner that references the RNDF road network. The reactive controllers, similar to the behavior based controllers described in (Wooden et al., 2007), keep the vehicle clear of obstacles, while the high level planner provides a route to the waypoint locations.

(a) 8mm lens at 300 meters

(b) 16mm lens at 250 meters

Figure 7: UAV On-board Computer Vision: The mission processor processes images from the on-board digital camera in real time. The target location is at the colored tarps in the center of the images. The UGV navigated to the target location after the target was detected from the UAV. Images are shown from each of the 2 UAVs, with different camera lenses and flying at different altitudes.

3.3 JAUS Standard

In support of collaborative autonomy, the vehicles must have a common capability to request assistance from each other when a target of interest is located. The Joint Architecture for Unmanned Systems (JAUS) is a standard that allows for greater interoperability between unmanned systems. As an example, each of the vehicles in the system and also the base station, can send JAUS GO-TO-WAYPOINT messages to the team or a specific vehicle to request that they navigate to a new area. The standard includes a message set, protocol, and was originally an initiative of the U.S. Department of Defense for facilitating open architectures for unmanned systems. Interoperability is an important focus area for future unmanned systems, as vehicles of different types and from different vendors will need to cooperate with each other.

The vehicles in this system can each exchange JAUS messages with the other vehicles and the ground station. The benefit of the JAUS messaging capability on this platform is that vehicles from other vendors that also implement JAUS may be easily integrated into this system for performing joint field tests. This project uses the OpenJAUS[2] implementation for creating JAUS standard messages between the air and ground platforms.

[2]http://www.openjaus.com

Figure 8: Using the FalconView^{TM}based ground station, multiple UAVs and UGVs can be displayed, with video overlays and system status.

3.4 Ground Station

The system also includes a FalconView^{TM}based ground station, as shown in Figure 8. FalconView^{TM}is widely used by the U.S. Department of Defense for its aircraft mission planning and mapping capabilities. The open-source version of FalconView^{TM}is now freely available.[3] FalconView^{TM}provides for application extensions through a plug-in framework. The vehicles in this system communicate to the FalconView^{TM}application plug-in through a ground station mission server to display vehicle position and telemetry information in real time, using JAUS standard messages. The ground station can also be used to send JAUS messages to the vehicles and to send other waypoint and mission based commands. As the vehicles in the system perform the mission, the vehicles' behavioral state (such as *Search* or *Survey*) are displayed on the FalconView^{TM}map, along with the vehicle positions. Detected target locations are updated on the map as well.

4 Field Experiments

4.1 Cooperative Target Detection and Surveillance

In one type of a cooperative scenario, all vehicles participate in a search, detection and surveillance mission. For example, a team of UAVs and a UGV can perform target surveillance over a wide area by flying a set of predefined waypoints, with the UGV waiting in standby. When one of the UAVs locates the target, it sends a message to team members with the target location. At that time, the team members can all navigate to the target location and perform surveillance.

This field experiment was performed in October 2010, at the McKenna site at Ft. Benning, GA, shown in Figure 4(a). The test location includes a network of roads and a long runway, along with a village or Military Operations on Urban Terrain (MOUT) setting. The purpose of this experiment was to demonstrate air-ground cooperation. Two UAVs autonomously flew search patterns covering the road networks and the village, with the UGV in standby mode at the far end of the test site. A fixed target, consisting of colored tarps, was placed inside the village. The UAV mission computers processed 2-3 image frames per second on

[3]http://www.falconview.org

board, using basic color thresholds, to detect the target, as shown in Figure 7.

When the first UAV spotted the target on the ground, the mission processor sent new waypoint commands to the autopilot and it autonomously changed course to survey the target. It also requested help from the other UAV and UGV by sending a JAUS message to each vehicle. In this case, the vehicles were setup to re-send the JAUS messages until an acknowledgement was received from each team member. The other UAV received the message and also autonomously changed course to survey the target. The UGV was given the target location and navigated autonomously to the target area to perform more detailed surveillance. After all of the vehicles jointly surveyed the target for several minutes, the mission was completed.

5 Conclusion and Future Work

This paper presented the design of a reusable and configurable UAV-UGV research platform for performing joint air to air and air to ground cooperative missions. The system can process sensor data on board and run high level autonomy algorithms for performing collaborative, autonomous missions. This platform has been field tested in multiple flight configurations, including a demonstration of a cooperative detection and surveillance task involving two UAVs and a UGV.

Future experiments will involve additional experiments between multiple UAVs and UGVs operating simultaneously and autonomously. For instance, given a set of tasks to accomplish, an area to explore is how the vehicles can negotiate among themselves to divide up the tasks in a way that reduces the overall system resource expenditures. An example of this approach, currently being investigated, is the use of an auction algorithm in which vehicles place bids on tasks to determine task assignments. An area that will be explored further is the cost metric that is used to generate bids for the auctions. As part of this, cost methods that include true (rather than straight line) paths, and include wind and other environmental conditions will be investigated. Finally, additional target detection algorithms and sensor configurations are being investigated.

Acknowledgments

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