DECENTRALIZED COLLABORATION BETWEEN HETEROGENEOUS AGENTS IN COMBINED AIR AND GROUND MISSIONS

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This paper presents the results of experiments using collaborative autonomy and control algorithms in recent demonstrations. Experiments were performed using two small unmanned aerial vehicles (UAVs) and an unmanned ground vehicle (UGV). The UAVs and UGV collaborate to perform autonomous target tracking and distributed sensing missions. The system incorporates JAUS open messaging standards to communicate. Real time telemetry and sensor updates are displayed on the FalconView™ based ground station. The system architecture leverages open standards and inexpensive hardware and allows for ease of payload configuration and algorithm development.

INTRODUCTION

Aerial and ground robots have different capabilities and likely carry different sensor technologies. Air and ground robot teams can leverage these characteristics in cooperative tasks. This paper describes the use of collaborative autonomy algorithms for multiple agents to cooperate on a shared task. 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 autonomously and accept missions from a ground station. The vehicles communicate and collaborate 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 use vision based sensors to perform target search tasks, can move quickly, and can cover the entire area if necessary. Furthermore, multiple UAVs may divide tasks among themselves. However, the UAVs will have difficulty localizing targets exactly, and because they are moving quickly and at altitude, they cannot get a detailed view of the target.

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 limits of the UAV. However, the UGV in this case is restricted to navigation over roads and does not have a full view of the environment at any given time.

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Figure 1. Unmanned Vehicles: The test platform consists of multiple small UAVs and a UGV. The UAVs are capable of autonomous flight and can carry different scientific payloads. The Georgia Tech “Sting” UGV is capable of autonomous navigation and obstacle avoidance.

RELATED WORK

Decentralized control of four identical UAVs in a search task is presented by Ryan, et al. The avionics, airframe and mission processor used are also similar to the UAV platform presented here. The decentralized algorithm used here incorporates similar market based auction methods to those presented here for dividing the search area among available UAVs.

Research in cooperation between air and ground vehicles was performed by Grocholsky, et al. 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.)

Stentz, et al. also presents a cooperative air-ground vehicle system. 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.

Kraus presents an excellent summary of negotiation in multi-agent environments. However, many of the algorithms are more relevant for competitive multi-agent scenarios. This paper focuses more on cooperative agent scenarios, in which market economies work well as strategies.

In works by Grocholsky, et al., and also Bayraktar, et al., the UAV airframe (1/4 scale Piper Cub), avionics (Cloud Cap Piccolo) and configuration are nearly identical to those selected for this paper. 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. The work by Tisdale, et al., uses vision based target tracking as input to both search and localization.

The work in this paper addresses decentralized task assignment and collaboration between multiple UAVs and UGVs in a target localization 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 and uses advances in market-based methods for task allocation.

**SYSTEM INFRASTRUCTURE**

The test system consists of multiple small UAVs and a UGV, as shown in Figure 1. The system also includes a ground station for displaying the vehicles’ telemetry information and for sending mission commands.

**UAV Platform**

The UAV platform, shown in Figure 2, 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.\(^9\) The avionics system performs low level flight control, and communication with the ground station via a dedicated 2.4GHZ data link. The avionics components include a GPS/IMU and barometric sensor for localization and a waypoint following autopilot for control. Position updates are sent to the ground station at 1HZ and the core autopilot processes sensor data and controls airframe servos at a rate of 20HZ. In addition, the avionics system is connected to the high level mission processor over a serial port. The mission processor receives sensor data and sends new waypoint commands to the autopilot.

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 flight duration is up to 90 minutes, depending on mission tasks and payload. In addition to the avionics package, each airframe can carry up to 7 lbs of payload.

There is room available on board for scientific payloads and sensors, configurable to the missions, see Figure 3. Currently, each UAV carries the following payloads: an onboard PC-104 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 for mission and agent-agent communications. The vehicle is also equipped with an analog color video camera that streams video to the ground for use by the base station operators and for after-action reports. An example video frame is shown in Figure 4.
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, 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.

Figure 3. UAV Platform: a) The UAV platform is configurable for different mission requirements, payloads and sensors. The payload can occupy the area of the removable box. b) The basic research payload includes a mission processor, data link, and digital camera.

UGV Platform

The UGV platform consists of a 2006 Porsche Cayenne SUV automobile that has been modified for autonomous operation. This vehicle was developed as Georgia Tech’s entry into the DARPA Urban Challenge.* The vehicle is equipped with stereo vision and LIDAR sensors for obstacle detection and performs GPS waypoint navigation. The UGV also is equipped with the same Digi 900 Mhz radio as the UAVs for agent-agent communications. The system uses a standard D* algorithm for graph based path planning over a list of ordered waypoints. The vehicle starts with a known map of the 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 SICK LIDARs are used to detect static and moving obstacles in the environment and provide 360 degree coverage around the vehicle.

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 keep the vehicle clear of obstacles, while the high level planner provides a route to the waypoint locations.

Ground Station

The system also includes a FalconView™ based ground station, as shown in Figure 6. FalconView™ is widely used by the U.S. Department of Defense for its aircraft mission planning and mapping capabilities. The open-source version of FalconView™ is now freely available.† FalconView™ provides

*http://www.darpa.mil/grandchallenge
†http://www.falconview.org
Figure 4. UAV Video: The UAV captured video during test flights and streamed it to the ground.

Figure 5. UAV Logical Software Architecture: The UAV Software Architecture uses a publish-subscribe mechanism for passing messages between processes and is easily extensible.
for application extensions through a plug-in framework. The vehicles in this system communicate to the FalconView™ application plug-in through a ground station 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. In addition, the ground station displays sensor data (such as streaming video from the UAVs) in real time, as shown in Figure 6(a).

![Image](image_url)

(a) Base Station

(b) Geo-rectified Image in FalconView™

Figure 6. The FalconView™ based Ground Station. a) Multiple UAVs and UGVs can be displayed, with video overlays and system status. b) Multiple images taken from the UAV platform were stitched and geo-rectified offline to be loaded into the FalconView™ based ground station. This provides the most recent imagery for the Ground Station operators.

**METHODOLOGY**

**Aerial Target Detection and Localization**

An important component of the system is aerial target localization. This 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 schematic in Figure 7 shows the on-board digital camera affixed to the underside of the UAV and looking 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 8(a) displays a sample image of ground features from Ft. Benning. The image contains the blue canopy square that is used as a sample target. Target detection is achieved using color based recognition methods that rely on a trained model of color thresholds. Figure 8(b) shows the result of a successful detection of the blue target at specific pixel coordinates. The UAV’s pose is recorded when the image is snapped and is defined by the UAV’s position (latitude, longitude, elevation) and pose (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.
Figure 7. Target Localization: The UAV camera coordinate frames used in the target localization task.

Figure 8. Target Detection: A sample image is shown from flight tests at Ft. Benning. The image is tagged with the UAV’s position and pose during image acquisition. a) The potential targets in this frame are the blue canopies. b) The detected target is found in the processed image. Pixel coordinates are used to compute world coordinates in the target localization process.
Direct Cooperation

In a direct cooperation mode, all vehicles perform a default operation until a request for help is received from another vehicle. At that time, all vehicles change tasks and plan to assist the requesting vehicle. In a simple example, a team of UAVs and a UGV can perform target surveillance over a wide area by flying a set of predefined waypoints. When one of the UAVs locates the target, it can send a message to team members with the target location. At that time, the team members can navigate to the target location and perform surveillance.

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 standard 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. This project uses the OpenJAUS* implementation for creating JAUS standard messages between the air and ground platforms.

Cooperation through Auctions

In addition to the above, this work also investigates market, or auction, based approaches to distributed, cooperative, task assignment. There are many different methods for performing distributed cooperation, including optimization algorithms and game theoretic techniques. However, auction based approaches have the benefits of being simple to implement and understand, and can easily be modified as mission requirements dictate. In addition, auction based algorithms generally have low communication requirements (agents coordinate tasks through bid messages), and therefore, are well suited to environments with communication constraints. Finally, auctions can perform computations in parallel and the methods take advantage of the local information known to each agent. For instance, a UAV would not need to communicate a low fuel state to the entire team for allocating tasks, but could implicitly include this knowledge in their own task selection through cost-based bidding.

Using a basic auction algorithm, similar to the work performed by Zlot et al., multiple UAVs and the UGV can divide a set of tasks among themselves without intervention from a central agent or human. As a simple example, each vehicle may have a set of predefined waypoints that it needs to visit to perform reconnaissance, and each vehicle will request that others participate in those tasks by auctioning them, as well as simultaneously responding to requests from others.

In the basic auction approach, each vehicle bids on the task using a simple metric, the time based cost that it would take for that vehicle to visit that location. The two UAVs have different engines and fly at different speeds. Furthermore, the UGV is restricted to navigation over roads. Also, the vehicles will be spaced out over the test area to be covered. In this case, the time metric uses the insertion cost heuristic to determine what the additional cost would be if the new task were awarded and added to the list of existing tasks. It is expected that for a cooperative visit-waypoint task, the

*http://www.openjaus.com/
global end cost to cover all of the tasks using the auction based method will be less than the total cost if each vehicle were to perform all of their own tasks without cooperation.

EXPERIMENTS

Air-Ground Direct Cooperation

The first experiment demonstrates UAV - UGV collaboration to perform target surveillance at the McKenna site at Ft. Benning, GA, shown in Figure 4. 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 direct message based cooperation using message passing. A UAV autonomously flew a fixed waypoint route covering the road networks and the village, with the UGV in standby mode at the far end of the test site. A fixed target, a 6x9 ft. blue tarp, was placed inside the village. The UAV processed up to 3 image frames per second on board, using basic color thresholds, to detect the target, as shown in Figure 9. Once the UAV spotted a target on the ground, the mission processor sent new waypoint commands to the autopilot and it autonomously changed course to survey the target, shown in Figure 10, and requested help from the UGV by sending a JAUS message. The UGV received the JAUS message, planned a route to the target location, and began navigating autonomously to the target area, see Figure 11.

Cooperative Waypoint Auction

A cooperative waypoint auction experiment was performed in a Software in the Loop (SIL) simulation and also in a case where one UAV flew autonomously while a 2nd UAV participated in the experiment, but remained on the ground. Initially, each UAV was given a set of waypoint-visit tasks and set into a predefined orbit at opposite ends of the test location. The waypoints to be visited by each UAV overlapped with those belonging to the other vehicle, and covered the entire test area of approximately 500m x 1000m. At the start of the experiment, each UAV began to auction their waypoint-tasks one at a time, and in parallel. The bid for each task is based on the "profit", the reward for visiting the task minus the cost, where the reward for each task was constant in this scenario. The cost for the UAV to visit the task is calculated from the shortest path insertion into its existing task list, using a Euclidean, straight line distance calculation between tasks to compute the
Figure 10. Autonomous Waypoint Generation and Following. On-line autonomous behaviors generated new waypoints on the fly for the UAV to follow as a result of auction and target tracking behaviors.

Figure 11. UAV-UGV Collaboration: The UAV sent a JAUS new Waypoint message to the UGV. The UGV is shown here performing autonomous waypoint navigation. a) The UGV replans over the road network and heads to the target area. b) The UGV enters the village on the way to the target location.
additive cost. The estimated cost is then the amount of time that it takes the UAV to fly that distance (the UAVs fly at different speeds).

In these initial experiments, when the UAVs did not cooperate, the total distance required for both UAVs to visit all of the waypoints was over 3200 meters. However, when the UAVs cooperated, using auctions to divide their tasks, the team cost decreased to about 1800 meters, as shown in Figure 12.

![Figure 12. A cooperative auction for coordinating visits to waypoints. a) Each UAV has a predefined set of waypoints to visit, red dots for UAV1 and green stars for UAV 2. The waypoints overlap and the team effort to visit them all is high. b) If the vehicles cooperate to divide up the waypoints, they can be visited more efficiently.](image)

CONCLUSION AND FUTURE WORK

Future experiments will involve collaborative task allocation 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. In addition, heterogeneous auctions that include different sensors across team members, as well as air-ground auction experiments are planned. Finally, the team will continue to incorporate JAUS and also STANAG-4586 standards into the platform and architecture.

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REFERENCES


