Convoy protection using multiple unmanned aerial vehicles: Organization and coordination

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Convoy Protection using Multiple Unmanned Aerial Vehicles: Organization and Coordination

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Abstract— **This paper addresses the problem of how to use a given set of possibly heterogeneous unmanned aerial vehicles (UAVs) to provide protection to a moving convoy of ground vehicles. By protection, we mean providing video or sensor coverage of a moving region around the convoy. A hierarchical system design is described that addresses how convoy protection missions may be organized and how those missions might fit into a larger context. The system encompasses task generation and allocation, flight path generation and tracking, and synchronization between cooperative tasks.**

Task allocation is posed as a constraint satisfaction problem. The design of two classes of orbital flight paths, lateral and longitudinal, is discussed. A coordination algorithm is described that allows the aircraft to synchronize their motions to provide improved sensor coverage. Results of a hardware-in-the-loop simulation are shown.

Index Terms- **Cooperative Systems, Mobile Robots, Surveillance, Tracking**

I. INTRODUCTION

An active area of research for both military and civilian applications is the use of small UAVs to provide useful services [7], [11]. At this point, much of the work available in the literature [5], [8], [9] deals with motion control of vehicles, usually in the form of waypoint following or trajectory tracking. Hardware developments [1], [4] are making it more feasible for ideas to be validated experimentally. Work is also being done in applying ideas from multiagent systems and distributed problem solving in the physical domain [2], [3]. Advances in wireless communications are enabling multiple UAVs to work together cooperatively.

In this paper, we present a framework for the coordinated operation of multiple UAVs in a convoy protection application. Both [5] and [9] looked at the problem of convoy protection using fixed-wing UAVs. In [5], a path generation technique based on sine waves was used to allow a relatively fast-moving UAV to track a ground vehicle that could move at much lower speeds. In [9], an orbit-based approach was introduced and was extended to a formation of aircraft. In this paper, we build on the previous work and employ multiple aircraft flying in various combinations of orbits. The proposed system is organized hierarchically. The lowest layers of the hierarchy consist of continuous controllers interacting with sensors and actuators to produce the required aircraft motions. The upper layers operate in discrete time, providing task generation and allocation, vehicle supervision, and coordination between vehicles and tasks.

The paper is organized as follows. In section II, we present the organization of the system, including a brief description of the problem domain and an example mission scenario. In section III, we discuss the design of the various components that make up the system. In section IV, we present a hardware-in-the-loop (HIL) simulation. Finally, we draw conclusions and discuss future work in section V.

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II. SYSTEM ORGANIZATION

Problem Domain and Terminology

By a convoy, we mean a group of ground vehicles organized to travel as a single column, with or without an escort, and proceeding together under a single command or using the same route [10]. Typical convoy speeds and vehicle spacing depend on many variables, including road and traffic conditions, and the speed of the slowest vehicle. Typical speeds are 15 mph (24km/h) in cities or built-up areas, 25 mph (40 km/h) on two lane roads, 40 mph (66 km/h) on separated expressways, and 5 mph (8 km/h) in blackout conditions [12]. One standard means of protection is the Convoy RAT Pack (CRP), "an advance [manned] security element that precedes a convoy, thereby reconnoitering the route, providing overwatch, and possibly preventing the convoy from being destroyed" [10].

In convoy protection using multiple UAVs, the aim is to use a group of UAVs to patrol the region ahead of and to the sides of the convoy, providing local as well as over-the-horizon visual coverage by transmitting video or other sensor data back to the convoy for examination. The problem we consider is that of how to utilize a given set of possibly heterogeneous aircraft to perform this mission most effectively. The motion of the convoy is unrestricted, and is not know in advance. The UAVs are fixed-wing aircraft with constraints on airspeed and turn-rate. Fixed-wing aircraft are desirable because they are typically simpler, cheaper, and have longer flight durations than rotary-winged aircraft.

Example Mission Scenario

As motivation for what follows, an example mission scenario is given below. This is an example of a more general set of capabilities and represents only one of many ways to use the system. A convoy about to travel through a

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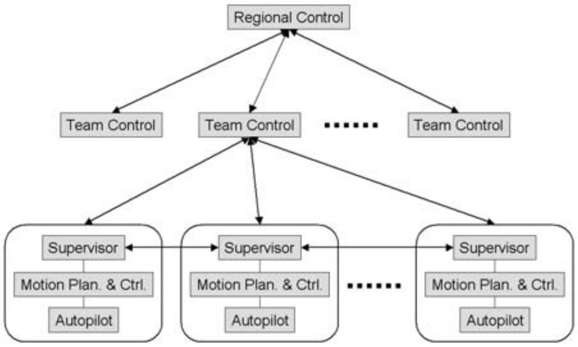

Fig. 1. Hierarchical control architecture

dangerous area requests UAV protection. A convoy protection mission is created, and from the UAVs available in the region, three are assigned to the mission. The aircraft have video cameras onboard, in addition to air-to-ground and air-to-air wireless communication systems. One of the UAVs (UAV1) has an infrared sensor in addition to his video camera. All UAVs have good "health" (fuel levels are high, all sensors and actuators are working) at startup. A plan is generated that includes three tasks: two of the UAVs must patrol the region ahead of the convoy (longitudinal orbits, left and right, termed Tasks 1 and 2), and one of the UAVs will patrol the region on either side of the convoy (lateral orbit, Task 3). The human operator approves the plan. The preferred configuration involves having two different sensors performing the longitudinal orbits. The plan contains the constraint that one of the longitudinal orbits must be performed by an aircraft equipped with an infrared sensor. A team controller determines a task distribution that satisfies the constraints and is optimal in some sense (perhaps based on flight capabilities, fuel levels, etc...). The following solution is obtained: UAV1 is assigned to Task 2 (longitudinal right orbit), UAV2 is assigned to Task 3 (lateral orbit), and UAV3 is assigned to Task 1 (longitudinal left orbit). Feasible flight paths (orbits) are generated onboard each aircraft, based on the position, speed and heading of the convoy, and also on the aircraft's characteristics and capabilities. The two longitudinal orbits are coordinated so that the planes are "out-of-phase", which maximizes the refresh rate of the imagery of the road ahead to the human operator. UAV1 detects a suspect object and alerts the human operator, who confirms that it is a worthwhile target. UAV1 starts tracking the suspect object, and UAV3 and UAV2 reconfigure and both perform longitudinal (look-ahead) orbits.

Outline of Proposed Solution/Architecture

We start with an overview of the proposed solution. A multi-layer hierarchy, shown in Fig. 1, that moves from discrete to continuous signals, is used to organize the system.

The top layer, termed the regional layer, provides each aircraft with a mission assignment. We define a team as one or more aircraft assigned to the same mission. During a given mission, aircraft tasks are dictated by a team/mission control layer. A motion planning and control layer produces safe motion based on the task assignment and coordination with other vehicles in the team.

This organization largely parallels the Intelligent Vehicle Highway System (IVHS) architecture proposed in [13]. In that work, the top layer, termed the network layer, provides a routing to each vehicle entering the system. The routing assigns the vehicle to a travel through a sequence of links (corresponding to road segments). The vehicle path (lane assignment sequence) on any given link is dictated by a link layer. Onboard each vehicle, motion planning and regulation blocks produce safe vehicle motion based on the assignment from the link layer and coordination with other vehicles.

The layers in Fig. 1, from top to bottom, can be described as follows:

Layer 5: Regional control. The regional control layer is responsible for managing UAV assets in some fairly large geographical region. It handles admission and removal of aircraft from the region and assigns aircraft within the region to missions within the region. Normally, admissions would be of freshly fueled aircraft and would occur just after takeoff; removals would be downed aircraft, or damaged or depleted aircraft landing for maintenance.

Layer 4: Team control. The team control layer is responsible for managing the successful conduct of a mission using the team of aircraft assigned to that mission. For missions involving multiple aircraft, this layer decomposes the mission into a set of feasible tasks and allocates these tasks to the team members. This layer may also accept input from human operators who are associated with the mission.

Layer 3: Vehicle supervisor. Each vehicle has a supervisor layer that manages the behavior of the vehicle, monitors its status, and interacts with the team control layer and with the supervisors of other vehicles. Interactions with the team control layer include accepting task assignments, reporting aircraft status, and reporting task status. Interactions with other vehicle supervisors may be used to obtain coordinated behavior of two or more vehicles. The supervisor layer may also provide a manual override capability to human operators.

Layer 2: Motion planning and control. This layer is responsible for producing motion commands that satisfy the requirements of the mission and avoid collisions with obstacles or other aircraft. This layer will include blocks for trajectory generation, obstacle and collision avoidance, and path-tracking. Depending on the degree of motion coordination required, this layer may use information from other team members, whether sensed or communicated.

Layer 1: Autopilot. At the lowest-level of control, this layer deals with continuous signals, and interfaces directly with the vehicle hardware. It contains estimation and control algorithms, sensor processing, and aircraft monitoring.

The regional control layer would likely reside at a headquarters building to allow for interaction with human

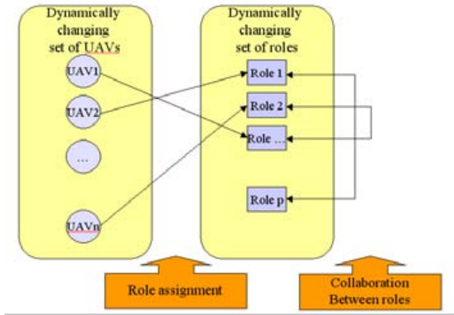

Fig. 2. Role assignment and coordination

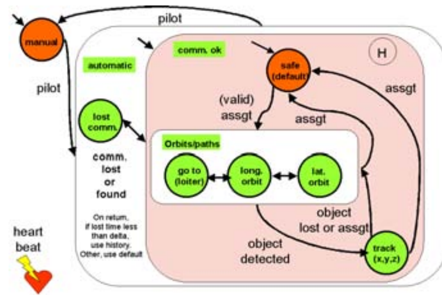

Fig. 3. Vehicle Supervisor

decision makers regarding distribution of assets throughout the region. Communication with teams would occur at relatively low frequency, possibly via satellite. The team control layer would reside on a selected team member or on another node associated with the mission, communicating with team members via a local wireless connection. The remaining layers exist on each aircraft.

III. CONTROL SYSTEM DESIGN

In this section we descibe the design and implementation of a UAV convoy protection system within the multi-layered control architecture outlined above.

Team Control: Task Generation and Allocation
A set S of n UAVs is assigned to a mission. The UAVs can be heterogeneous (that is, have different capabilities, such as onboard sensors, flight time and/or communication range). The set S may change dynamically (UAVs may be lost or reassigned, or new vehicles may join the team). Each vehicle sends profile information to the team controller. The team controller (in this application, located in one of the convoy vehicles) generates a plan P, containing p tasks, or roles, and a set of constraints C. Some of the constraints reflect that a certain sensor configuration is preferable for a particular task, and some of the constraints reflect the fact that several vehicles will have to collaborate to perform a given task (at a minimum, have compatible communication equipment with sufficient range, or, perhaps, carry complementary sensor packages). The plan P is regenerated if the set S changes, the capabilities of some of the UAVs change, or the mission goals change. A human operator may approve or modify the plan.

For every new plan P, a task allocation algorithm is run in which tasks are allocated to UAVs based on their qualifications and task utility values (see Fig. 2). Initially, a constraint satisfaction problem (CSP) is solved, which generates a feasible assignment that satisfies the constraints C [6]. The feasible assignment may then be optimized with respect to a specified cost function, with the restriction that the solution must remain feasible. This step may result in a reshuffling of the task assignments. Once an assignment is obtained, it is broadcast to all vehicles in the set S.

Vehicle Supervisor
The mode-switched vehicle supervisor, shown in Fig. 3, is presented next. The initial default mode for our UAVs is manual control. The pilot makes the decision to switch from automatic to manual and back.

In automatic mode, if communications are lost, the vehicle goes to a "lost communications" waypoint. If the communication loss is short, the system may return to its previous state in the "comm. ok" state using the history feature (the last mode is kept in memory). If the communication loss lasts longer than a pre-designated time period, the vehicle remains at the "lost-communication" waypoint until the pilot takes over. If the pilot has selected automatic operation and the communications are functioning, each vehicle starts by going to a "safe" waypoint. Each vehicle then expects a (valid) assignment from the automated task generation/allocation system. In our convoy protection example, the vehicle can be given one of several orbits or paths to track. The vehicle can be sent to a point, where it will loiter while awaiting further instructions. Or the vehicle can perform either longitudinal or lateral orbits about the convoy. Orbit and path generation is the topic of the next section. If an object of interest is detected, the vehicle switches to tracking that object (so it is not lost), until either the object is lost or the vehicle is reassigned.

Orbital Trajectories
In this section, we describe orbital trajectories that allow a UAV with a limited range of flight speeds and limited turn rate to track a point which moves arbitrarily. These trajectories generate a feasible path for the UAV that will "slow it down" and allow it to track the point, in the sense that it stays within a certain distance of the point and passes over it periodically. In the convoy protection application, the point could be a specified ground vehicle, the centroid of an entire convoy, or a point that stays some distance ahead of or behind the convoy. Here, we will assume that the point is attached to a truck at the head of a convoy. Two types of orbit are discussed: lateral orbits, which emphasize flight over the regions on either side of the target point, and longitudinal orbits, which emphasize flight over the future path of the target point.

Assuming steady (constant-velocity) motion of the truck,

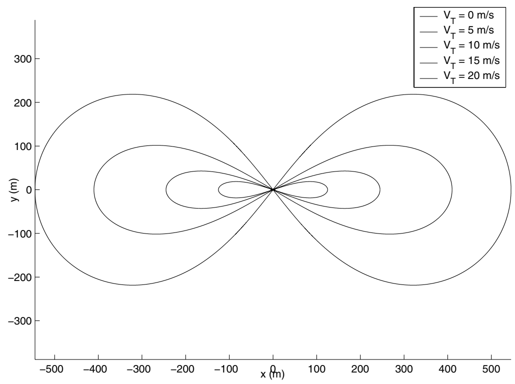

Fig. 4. Lateral orbits for various V_T, with V_P = 20 m/s

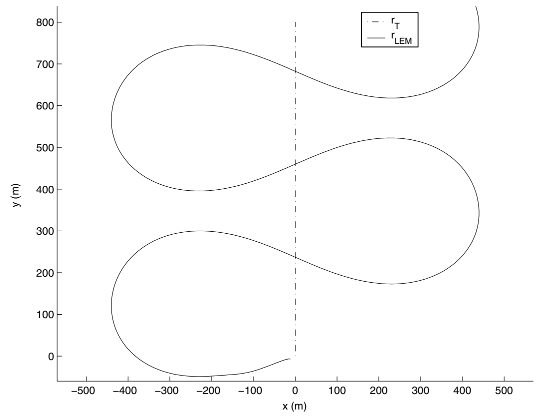

Fig. 5. Ground trace, V_T = 4 m/s, V_P = 20 m/s

we define two reference frames, A, and B. Frame B is a right-handed frame, fixed in the truck, with its y-axis aligned with the vehicle heading and its z-axis pointing up. Frame A is an earth-fixed frame with its axes parallel to those of B.

Lateral Orbits

As described in [9], the lateral orbits are defined as a two parameter family of figure-eight curves in a reference frame which moves with the truck and has its positive y-axis aligned with the velocity vector of the truck.

The orbits are defined using the equation for a lemniscate curve:

$$r = A\sqrt{\cos p\theta} \tag{1}$$

In this equation, r and θ are cylindrical coordinates in frame B, with θ being the angle from the local x-axis. The parameters A and p determine the amplitude and shape of the curve and are to be chosen based on desired trajectory properties.

Denoting the speeds of the aircraft and the truck by V_P and V_T respectively, for each V_P and V_T, parameters p and A are determined such that the constraints on amplitude, return time T, and aircraft turn rate are satisfied, where return time is defined as the time between each pass over the truck. Note that the existence of p and A are dependent on the choice of a return time which is achievable for a given aircraft.

A sample of the resulting orbital trajectories that were chosen for our application are shown in Fig. 4. V_T is varied while V_P is held constant at 20 m/s. It is evident that the amplitude decreases as the speed of the point increases. Also, p increases as V_T increases, which is apparent through the narrowing of the trajectory. At V_T = 20 m/s, the trajectory becomes a point.

Fig. 5 illustrates the resulting ground trace for a truck speed (V_T) of 4 m/s and a UAV speed (V_P) of 20 m/s.

Longitudinal Orbits

In addition to the lateral orbits, a parameterized family of asymmetric longitudinal orbits are defined. Fig. 6 shows these orbits for several values of the speed ratio $\sigma :=$

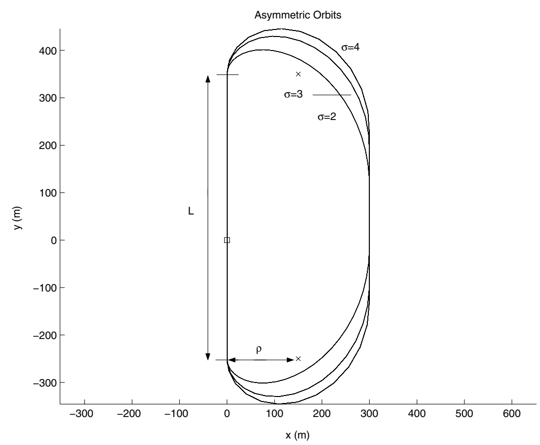

Fig. 6. Longitudinal orbits , V_T = 10 m/s

V_P/V_T, with a truck speed V_T = 10 m/s. These orbits are postioned on the right hand side of the truck, which is at the origin, placing the primary (longest) segment of the orbit over its future path. Corresponding left hand orbits are constructed by reflection about the y axis. Fig. 7 shows a ground trace for $\sigma = 2$.

The longitudinal orbits are parameterized by length L and turn radius ρ, with ρ chosen to be greater than or equal to the minimum turning radius of the aircraft. Position within the frame is also specified. The curved portions of the orbits are sheared semi-circles, with the maximum shear distance Δ given by

$$\Delta = \frac{\rho\pi}{\sigma} \tag{2}$$

This leads to the length constraint

$$L \geq 2\Delta \tag{3}$$

The length $L = 2\Delta$ results in the UAV flying a circle of radius ρ between the end and the beginning of the primary segment.

Tracking Control

The tracking control law that the UAV uses to follow the

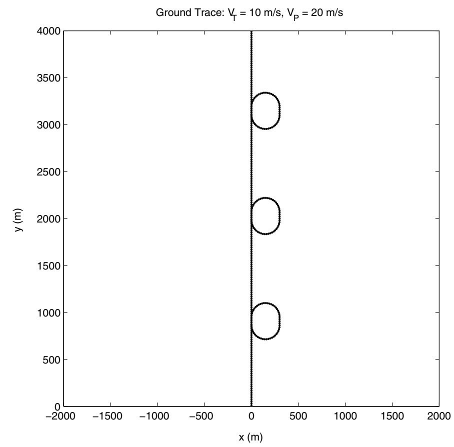

Fig. 7. Longitudinal ground trace, V_T = 10 m/s, V_P = 20 m/s

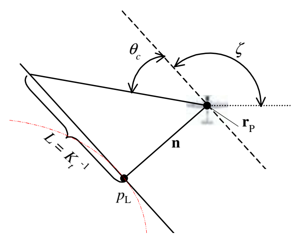

Fig. 8. Control law diagram for a UAV following an orbit trajectory

trajectory is defined in terms of the trajectory's tangent line. Given a point on the orbit, the unit tangent vector, $\mathbf{t}$, is calculated as

$$\mathbf{t} = \frac{\frac{d\mathbf{r}}{d\theta}}{|\frac{d\mathbf{r}}{d\theta}|} \tag{4}$$

where θ is an arbitrary parameter of the orbit curve.

Given the current aircraft position, we seek a tracking point, p_L, on the trajectory, such that the vector $\mathbf{n}$ from p_L to the aircraft is orthogonal to the trajectory tangent vector at p_L. This is shown in Fig. 8. Depending on the aircraft position, the trajectory may have several such points. Therefore, some logic is required to ensure that the correct point is chosen. For the longitudinal orbits, tracking point choice is based on the region that the aircraft is in. For the lateral orbits, it is based on which quadrant the aircraft should be in or be heading towards, combined with choosing the point closest to the origin if two are found in the predicted quadrant.

Once p_L is found, the control angle, θ_c, is calculated using

$$\theta_c = \arctan(K_t|\mathbf{n}|) \tag{5}$$

where K_t is a controller gain. Intuitively, $K_t = 1/L$, where L is the distance from p_L, along the tangent line, to a point that we steer the plane towards.

Once the desired direction of travel in frame B is determined, the desired earth-fixed velocity and aircraft turn rate command can be computed.

Left-Right Coordination

In this section, we describe an orbit synchronization mechanism that may be used to adjust the phase relationship between a pair of aircraft flying longitudinal orbits. In-phase flying will result in simultaneous coverage of the look-ahead zone, while out-of-phase flying will minimize the time between flyovers of the look-ahead zone.

Associated with each longitudinal orbit is a nominal return time (flyover period) T. For two UAVs flying left and right longitudinal orbits, we would like their flyover times to be equal for in-phase flight and to differ by $T/2$ for out-of-phase flight.

This can be accomplished using a form of mutual adjustment, which involves a sequence of information exchanges between the aircraft, with each aircraft both informing the other of its intended flyover schedule and modifiying its own schedule to achieve the desired return time and phase difference.

Denoting the two aircraft A and B, the algorithm for aircraft A is as follows. As the aircraft flies its orbit, it periodically computes a flyover schedule, consisting of a finite sequence of n future flyover times, $\boldsymbol{\tau}_A$, based on minimizing a cost function

$$J = \sum_{i=1}^{n} w_i(\boldsymbol{\tau}_{A,i} - \boldsymbol{\tau}_{A,i-1} - T)^2 + \sum_{i=1}^{n} z_i(\boldsymbol{\tau}_{B,i} - \boldsymbol{\tau}_{A,i} \pm \Delta)^2 \tag{6}$$

where T is the nominal flyover period, Δ is the desired time difference between right and left flyovers, $\boldsymbol{\tau}_B$ is the current plan of aircraft B, and the w_i and z_i are weights.

The schedule $\boldsymbol{\tau}_A$ is subject to constraints. The first time, $\boldsymbol{\tau}_{A,1}$ must be achievable given the current position of aircraft A. All the other times must differ by at least T_{min}, the minimum achievable return time. It may also be desirable to specify a maximum time difference T_{max}.

This leads to a quadratic program with inequality constraints which can be solved for $\boldsymbol{\tau}_A$. Orbit lengths are then increased or decreased to acheive the flyover times in $\boldsymbol{\tau}_A$.

An example of a coordination sequence is shown in Fig. 9. The goal is to have a flyover period for each aircraft of 100 seconds and to have 50 seconds between left and right flyovers. In the example, the initial aircraft schedules are seperated by only ten seconds, corresponding to closely spaced flyovers. By the tenth iteration, the adjusted schedules are very close to achieving the desired time relationships, especially for the later flyovers. The two lowest lines represent previous flyovers and so are not adjustable.

Autopilot

The Cloudcap Piccolo avionics package [1], is currently used to provide lower-level flight control. The system is interfaced to an onboard PC-104 which provides higher level supervisory and planning functions. We have used this system successfully in a number of flight demonstrations.

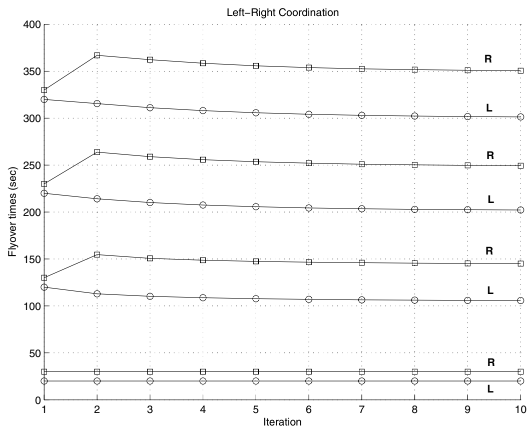

Fig. 9. Coordination Sequence

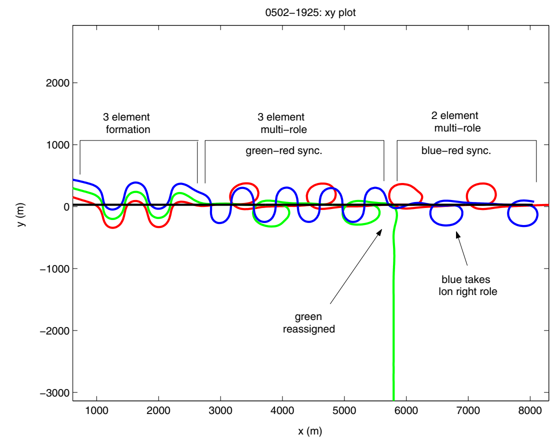

Fig. 10. HIL simulation results

IV. HARDWARE-IN-THE-LOOP RESULTS

To demonstrate the performance of the overall system, we present a hardware-in-the-loop (HIL) simulation for part of a convoy protection mission. The scenario considered matches the one described in the example mission scenario.

The Piccolo autopilot system provides a convenient HIL simulation capability. In HIL mode, each autopilot unit is connected to a laptop PC that runs an aircraft flight simulation. The simulator receives control input commands from the Piccolo, and the Piccolo receives sensor data from the simulator. All other aspects of the system (software, ground station, communications, etc.) are exactly as they are during actual flight tests. The aircraft flight simulation is based on our test UAVs, which are modified Sig Rascal 110 model airplanes. These have a wingspan of 110”, a payload of 8-10 lbs., and a take-off weight of 22-24 lbs.

Fig. 10 is a ground trace plot, showing (x, y) positions in meters. Three UAVs, flying in formation, fly to and begin tracking the convoy. At approximately (3000,0) the UAVs start performing multi-role convoy protection - two of the UAVs perform synchronized right and left orbits, while one UAV performs lateral orbits. Roughly at point (5800, 0), the UAV that was performing longitudinal-right orbits is reassigned, and the UAV that was performing lateral orbits takes up the now vacant longitudinal position.

V. CONCLUDING REMARKS

We have proposed an approach for convoy protection using multiple UAVs. A hierarchical system design was described that addresses how particular missions may be organized, and how those missions might fit into a larger context. The mission organization is based on a team controller, which manages mission decomposition and task assignments. Special emphasis was placed on the generation of feasible UAV flight paths and how they might be coordinated to provide improved sensor coverage properties. The system has been implemented and tested on a hardware-in-the-loop simulation in order to validate the design. Initial flight tests have been conducted and more are planned.

Future work in this area may include decentralized mission organization and optimization of flight paths and flight path combinations.

VI. ACKNOWLEDGMENTS

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