

**Cooperative Tracking of Moving Targets
by Teams of Autonomous Unmanned Air Vehicles**

Final Report

FA9550-04-C-0107

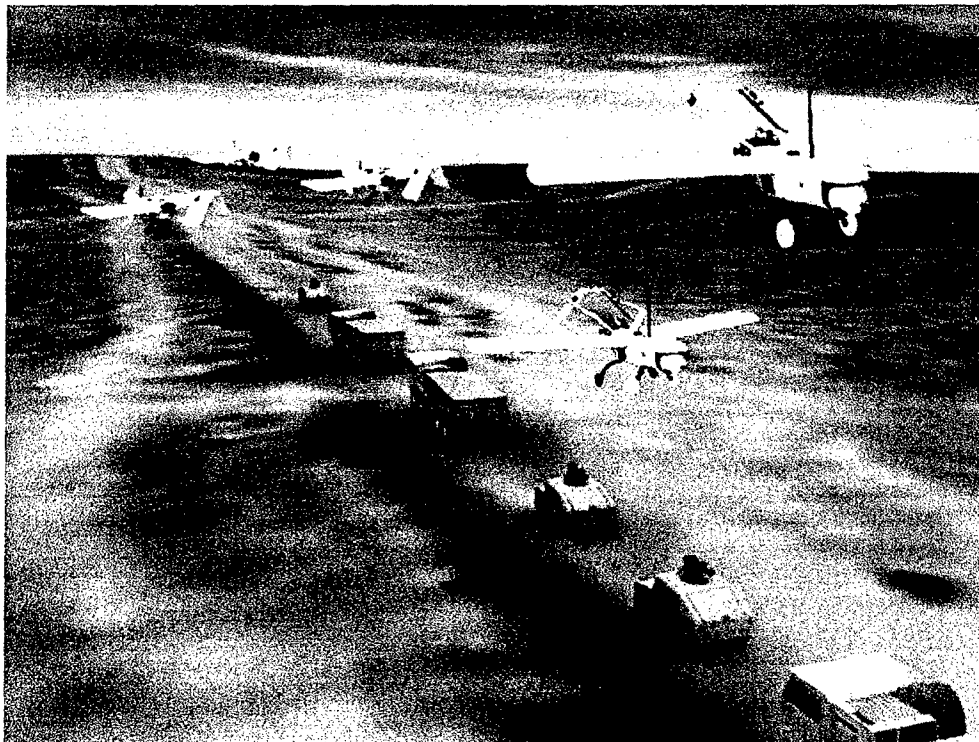
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July 14, 2005



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1 Introduction

This report summarizes work by the MLB Company (industry partner) and the Research and Engineering Center for Unmanned Vehicles at the University of Colorado at Boulder (CU) (research institution partner) on the cooperative tracking of moving targets by teams of autonomous unmanned air vehicles. This work was performed between September 2004 and July 2005.

The following future scenario provides the motivation for this work: A ground vehicle moves at high speed along a mountain road, away from a town where it committed a hit-and-run attack on a group of civilians. The US military forces want to find the attackers and follow them to their hideout. Multiple unmanned aerial vehicles (UAVs) are sent to the area where the attackers were reported to have retreated. One of the UAVs identifies the attackers' vehicle based on reports from the civilians and notifies nearby UAVs of its location. The UAVs alter their flight paths relative to that point, with some moving ahead of the vehicle and others maintaining position near it – without attracting attention from the attackers. As the attackers move through the region, responsibility for direct sensing passes from one UAV to another to always keep the target in sight. Through collaboration, autonomous unmanned air vehicles were able to complete tasks that each could not have done alone.

Teams of low cost unmanned aerial vehicles (UAVs) with autonomous behaviors will be capable of performing inexpensive, persistent, distributed sensing functions such as the one described in the preceding scenario. One application of interest is the use of UAV teams to perform Cooperative Search, Acquisition and Tracking (CSAT) of moving ground targets in a stealthy manner. Current state-of-the-art for autonomous control of UAV teams enables the collaborative tracking of friendly (i.e. vehicles that provide their GPS location and velocity and are not attempting to evade) ground vehicles, such as in the context of a convoy protection scenario.

This report describes the UAV platform, control algorithm, and sensor hardware that, based on our research, is best suited to demonstrate cooperative tracking of moving targets.

2 UAV Platform and Sensor System

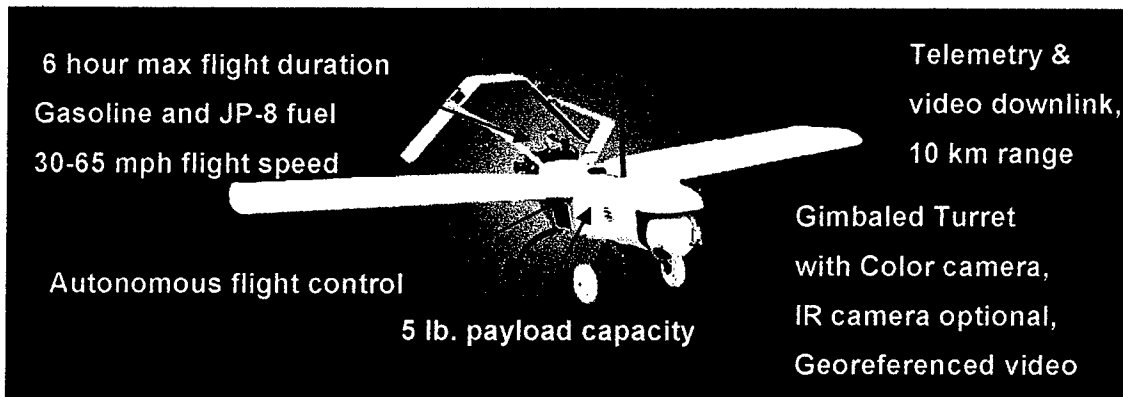


Figure 1. MLB Bat UAV System.

The MLB Bat 3 is a small, low cost, UAV system that includes an integrated, automatically aimed, gimbal camera sensor. The Bat 3 is capable of fully autonomous flight operation from launch through landing, has a 6 hour duration, and has been in production since Fall 2000. The Bat 3 is launched from a car top bungee-powered catapult and lands autonomously in a clearing 100 x 50 yards in size. The complete system sells for \$42,000 and replacement aircraft (with gimbal sensor) sell for \$25,000. For these reasons we have chosen the Bat 3 as the platform for cooperative tracking simulations and flight demonstrations. MLB has 6 DOF dynamics models for the Bat 3 already developed and extensive flight experience with the system (over 500 hours logged).



Figure 2. Bat operational footprint, complete system shown here.

MLB's gimbal camera system has 3 axis DOF and can carry both E/O and IR sensors which are aimed along a common boresight. The gimbals are commanded by the autopilot to hold the boresight on specified locations (moving or fixed) by using the on-board attitude and position sensors to aim the turret. The entire system weighs 2.5 lbs (with E/O and IR cameras) and is a standard feature on the Bat 3 UAV. For this program MLB plans to upgrade this sensor system to perform automatic tracking of image pixels and to provide digitally stabilized imagery in the downlinked video. The current camera aiming is based only on inertial information, but for tracking moving vehicles it is necessary to close the tracking loop based on optical information as seen by the cameras. MLB has identified hardware manufactured by OCTEC Inc. that can be carried by the Bat 3 and will enable pixel tracking of objects in the video imagery.

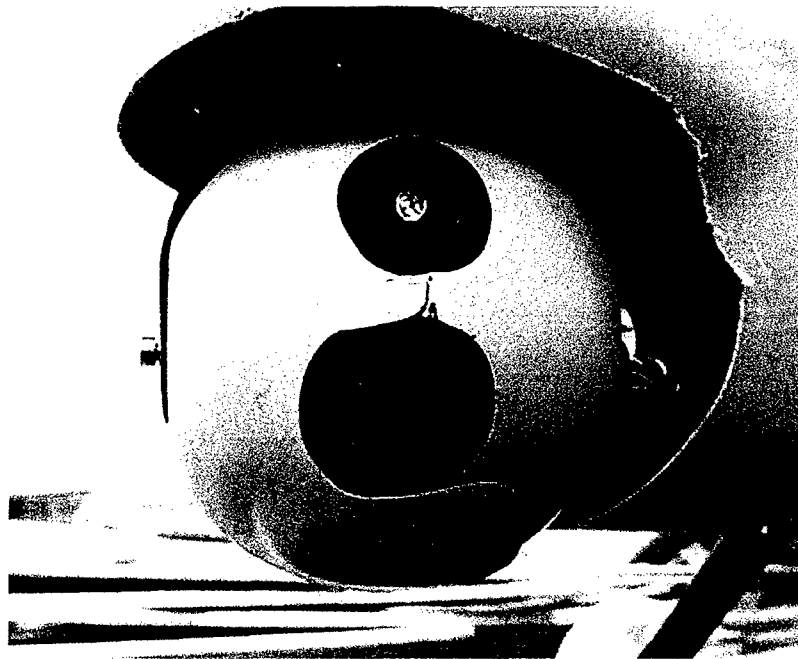


Figure 3. 3-axis gimbal camera turret with E/O and IR sensors installed

3 Cooperative Convoy Escort Using Teams of UAVs

For the purpose of demonstrating cooperative tracking of moving targets using teams of UAVs, MLB and UC Boulder decided to focus on the problem of escorting a convoy along an unknown route. In the current Iraq conflict convoys carrying troops and supplies are routinely attacked by insurgents in an attempt to instill fear and disrupt the ability of American forces to operate in the region. Attacks are usually carried out by small groups of individuals that create an ambush for the convoy in an attempt to create a "kill zone". Any advanced warning of approaching suspect vehicles or unusual activity ahead of or around the convoy will greatly aid the troops in protecting the convoy and avoiding ambushes. Smaller convoys use high-speed as a means of defense and often travel at speeds above 100 mph. Larger convoys are restricted to lower speeds (<50 mph) and must make numerous stops to maintain formation and navigate through cities. MLB has discussed this problem and demonstrated our convoy escort system to the Marine Corps Warfighting Lab, the US Army Transportation School, and several private security firms operating convoys in Iraq. There is unanimous agreement among these warfighters that an escort system using UAVs would greatly enhance the safety of the convoy.

The basic convoy escort mission is to provide continuous live imagery from around and ahead of the convoy while maintaining the ability to task some of the UAVs to track suspicious targets when needed. Our work will focus on developing the algorithms for coordinating and controlling the teams of UAVs along with the system upgrades needed for the Bat UAV to perform this mission.

Convoy Escort Mission Description and Goals

- 1) Follow “friendly” vehicles along a known route and provide imagery that can answer the question: Is the road ahead/behind and sides clear?
- 2) Friendly vehicle’s location and speed is telemetered to the UAV.
- 3) Friendly vehicle’s route is not known to the UAV.
- 4) UAV may be slower and less agile than convoy.
- 5) Must search sufficiently far ahead of convoy to give ample warning of road status.
- 6) Convoy personnel can alter the footprint of the UAV escort
- 7) Must track an unfriendly moving target when requested.
- 8) UAVs must account for terrain changes and obstructions to viewing
- 9) Ideally, all imagery is georeferenced and assembled into an easy to use display /control station.

Our goal for phase 2 of this work is to demonstrate a team of 5 (or more) UAVs that accomplish this mission.

4 Known Challenges for Convoy Escort

Between February and July of 2004 MLB developed and demonstrated a convoy escort capability for the Bat 3 UAV that enables a single UAV to coordinate its flight path and camera aiming to automatically track a ‘friendly’ vehicle (Fig. 4 and Fig. 5).

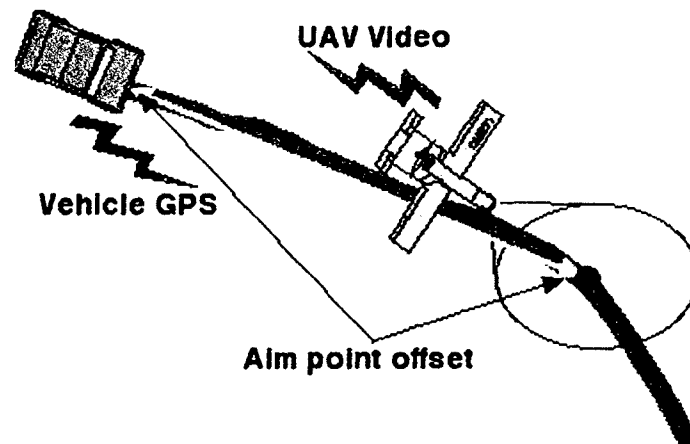


Figure 4. Tracking of a "friendly" vehicle with coordinated motion of the UAV and its sensors.



Figure 5. Imagery from Bat 3 UAV. Tracking of a "friendly" vehicle, convoy protection demonstration at Blackwater Security, Moyock, NC in August 2004.

The 'friendly' convoy vehicle shares its GPS information with the UAV so that the aircraft can track it without relying on a visual target fix. The route of the convoy is not known ahead of time and the UAV uses pre-programmed strategies for following the convoy based on its ground speed and location. During the course of testing several shortcomings were discovered in the ability of a single UAV to provide adequate convoy escort coverage:

Convoy Escort Problems using Single Bat 3 UAV

1) Failure of UAV to anticipate ground vehicles turn direction and resulting loss of image tracking

The Bat UAV flies a circle trajectory around the ground vehicle when the ground speeds are so low that they prevent the aircraft from following in a straight line. Once the circling begins it is possible for the ground vehicle to outmaneuver the UAV by turning sharply or changing speed abruptly when the UAV is moving away from the vehicle. Because the UAV is less agile in speed and turn radius than the ground vehicle, this can result in loss of target track for up to one minute while the UAV repositions itself. Using multiple UAVs for escort would reduce the chances of this problem occurring because UAVs could be positioned to minimize loss of track when the convoy moves slowly.

2) UAV's lack of maneuvering agility

As mentioned above, ground vehicles can outmaneuver most fixed-wing UAVs because the UAV can not "stop" quickly or turn as sharply as the ground vehicle. The gimbal mounted sensor system reduces the impact of the maneuvering disparities between the vehicles, but there are significant trade-offs in what the gimbal sensor can accomplish and the cost of the UAV system. For example, a UAV with a highly stabilized sensor system with long range zoom capability can fly at farther slant range to the image target and thereby minimize the gimbal angle excursions needed to track the target. This type of system is typically larger and more costly than most mini-UAVs and requires a large infrastructure tail to support it. Flying high or far away from the target is not always an option because of obstacles that may block the line of site and possibly weather (cloud, fog, etc.) that prevent viewing at a great distance. Flying closer to the target requires a larger range of motion from the gimbal for tracking, but reduces the need for exceptional gimbal stability and therefore reduces system size and cost. Ultimately, a solution that uses teams of UAVs to keep the target in view is preferred because this allows low-cost less agile UAVs to perform the mission effectively.

3) Terrain or obstacle obstruction of line of site to target

Terrain or vegetation along the route can often block the region of interest from view during convoy escort. Loss of line of site can also disrupt telemetry to and from the UAV. This is often a problem when the convoy travels along tree-lined roads or through urban

canyons. Using multiple aircraft in different locations can provide different viewing angles and minimize this problem.

4) Mechanical limits of the sensor's gimbal system

The Bat 3 gimbal system has a mechanical range of ± 135 deg yaw, ± 20 deg roll, and $+20$ -120 deg in pitch. During tests it is not uncommon to lose target track for up to 15 seconds while the aircraft reorients itself for proper gimbal aiming. By properly spacing the UAV team around the area of interest this problem will be reduced because multiple views of the same region are available if an aircraft reaches its gimbal's mechanical limits.

5) Maintaining RF link with moving vehicles

Our tests so far have not used directional tracking antennas on the ground vehicles during convoy operations and when line of sight is lost with the UAV the video signal will often drop out. We have seen signal loss when operating along tree lined streets with the UAV flying on one side of the convoy such that trees absorb the RF video signal. It may be necessary for the UAV team to perform communication relay tasks in addition to imaging for optimal convoy protection.

6) Simplified UAV user interface and data presentation for convoy operators

Having UAV operators located inside moving convoys creates a new paradigm for information gathering and is one that has not been fully tested. Our initial experiments indicate that the interface between the operator and the UAV must be very simple to avoid operator overload. Similarly, the tools used to display information gathered by the UAVs must be simple to use and intuitive, or else the situation ahead of the convoy can not be adequately assessed in time.

7) Maintaining an appropriate lead distance ahead of the convoy

The lead UAV(s) must fly far enough ahead of the convoy to allow proper assessment and planning based on the data received. In order to provide a lead-time of one minute at highway speeds the UAV must fly at least 1 mile ahead of the convoy. When flying

along an unknown route this often results in the UAV being off course because the aircraft doesn't know what "1 mile ahead" really means when the convoy may turn at any moment. The convoy route is typically known when traveling at high speeds and this information could be shared with the UAV team to properly position the lead planes. Multiple UAVs flying ahead of the convoy will provide better coverage than using a single aircraft for the case of unknown routes.

In most all cases, teams of cooperating UAVs provide a solution to these known challenges in the convoy escort mission. Cooperation will also allow the team to perform multiple tasks such as convoy escort and tracking of suspicious vehicles. Listed below is a summary of factors that encourage cooperation between UAVs while escorting or tracking.

Factors that encourage cooperation between UAVs while tracking:

- 1) Terrain/vegetation (obstruction of target)
- 2) Gimbal limits (lost track)
- 3) Stand-off tracking (stealth, detection)
- 4) Target maneuvers faster than imaged zone (lost track)
- 5) Multiple simultaneous views of target (stereo, mapping/mosaicing)
- 6) Maintain RF link (form RF relay)
- 7) Track physically large moving targets (convoys)
- 8) Multiple objectives (tracking, searching, relaying, etc.)

We have placed a video on our web server that shows an example of the problems encountered during a convoy escort experiment at Blackwater Security in July 2004:

<http://www.spyplanes.com/convoy.mpg>

In this video we see the live video feed from a single Bat UAV as it attempts to follow a "friendly" convoy vehicle (a gold-colored van) traveling at speeds below 35 mph along a tree lined 2-lane road. The aircraft is autonomously following and aiming its camera at the vehicle based on the vehicles GPS position and speed which is telemetered to the

UAV. In this short video many of the convoy escort problems are readily visible. Listed below is a synopsis of what is shown on the video and the problems encountered.

Event	Run time(minutes.seconds)
1) Van and truck moving on dirt road (<30 mph) while UAV is circling in left hand orbit.	0.00
2) UAV is circling left as van turns right and picks up speed. UAV is now travelling opposite van's direction	0.90
3) Gimbal reaches mechanical limits while vehicles travel in opposite directions.	0.20
4) UAV is turning towards van, but van is now 1/4 mile further down the road and line-of-site is blocked by the tree line. Video reception is poor and van is not visible.	0.40
5) UAV flies towards van to reacquire, but LOS is still blocked by trees.	1.00
6) Van is reacquired and UAV is regaining its proper position relative to vehicle.	1:24
7) UAV is in position.	1:40
8) LOS blocked by trees while tracking	1:50

It is interesting to note that a few seconds of bad planning on the part of the UAV can result in a large separation distance between the UAV and the convoy vehicle. It can take a single UAV up to 1 minute or more to recover from these seemingly minor mistakes.

5 Pixel-Based Tracking of Moving targets in Live Video

Pixel-based tracking of moving targets from the UAV's live video is a necessary capability for tracking suspicious vehicles in the convoy escort mission. The Bat UAV has not demonstrated this capability yet and MLB has begun investigating hardware/software solutions to enable this functionality. OCTEC Ltd. is a company in England that manufactures a single board video processor that can track designated regions in a video image. MLB contacted OCTEC and they agreed to analyze recorded video from a Bat UAV to see if tracking of moving targets would be feasible. Small UAVs like the Bat are more susceptible to turbulence because of their low wing loading ($< 3 \text{ lb/ft}^2$) and this can create unwanted motion in the video that the gimbal system is too slow to correct for. OCTEC took a sample of Bat video and successfully demonstrated tracking of moving targets in spite of the jitteriness. An example of the processed video can be see on our web site at:

<http://www.spyplanes.com/OCTEC.mpg>

MLB plans to integrate the OCTEC hardware into the Bat UAV in phase 2 of this work.

6 Convoy Escort Strategies and Simulation Results

Cooperative control is realized through a hierarchical, hybrid control architecture. The control system is separated into three layers (Fig. 6): the low level autopilot on each individual vehicle, a hybrid controller on each vehicle that generates command inputs for the low-level controller, and a team coordinator that assigns every vehicle to a particular task or mode. Details of each layer follow.

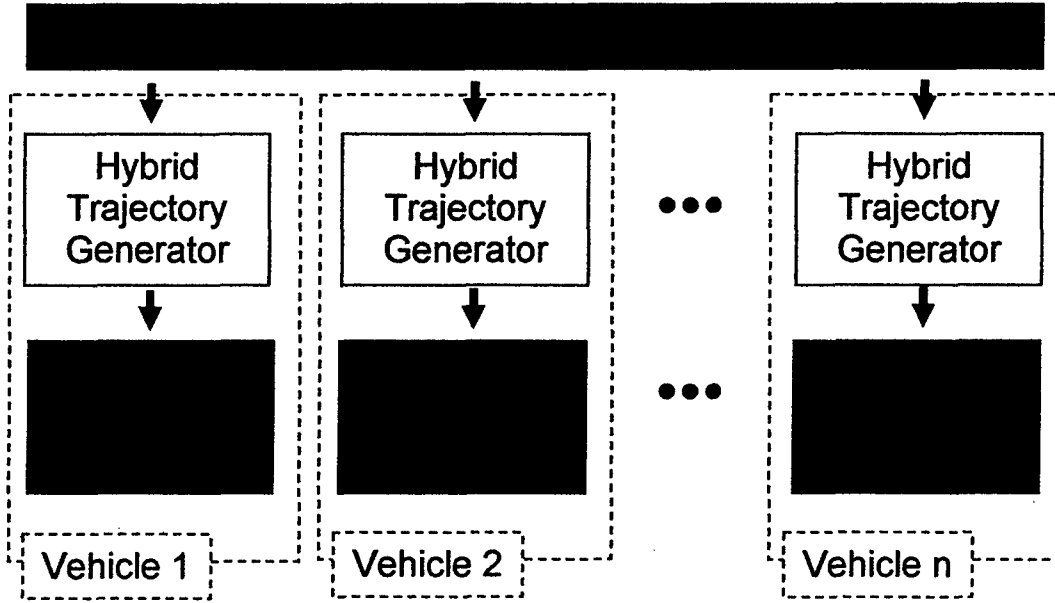


Figure 6. Hierarchical, hybrid control architecture for cooperative vehicle tracking by a team of unmanned aircraft.

6.1 System Models

6.1.1 Low-level Flight Control

The MLB Bat Flight Control System (FCS) provides low-level guidance and control. The FCS provides roll, pitch, and yaw stability of the aircraft as well as velocity- and altitude-hold functions. For aircraft guidance, the FCS accepts four-state waypoint commands (three-dimensional position plus speed) or explicit speed, altitude, and turn rate commands. The FCS uses gain scheduling to maintain flight performance over the entire speed envelope. Using the latter command structure, the system model presented to the hybrid control layer is a kinematic “unicycle model”:

$$\begin{aligned}
 \dot{x} &= u_1 \cdot \cos(\psi) + W_x \\
 \dot{y} &= u_1 \cdot \sin(\psi) + W_y \\
 \dot{\psi} &= u_2(t - T_d) \\
 \dot{h} &= u_3
 \end{aligned}
 \quad
 \begin{aligned}
 0 \leq v_{\min} \leq u_1 \leq v_{\max} \\
 |u_2| \leq \omega_{\max} \\
 |u_3| \leq \dot{h}_{\max}
 \end{aligned}
 \quad (1)$$

where $[x, y, h]^T$ is the three-dimensional position of the aircraft, ψ is the aircraft heading, $[W_x, W_y]^T$ is the background wind velocity, T_d is the time delay in the turning

rate command that accounts for the roll dynamics of the aircraft, and $[u_1, u_2, u_3]$ are the commanded speed, turning rate, and climb rate, respectively. For this work the climb rate command is given by simple proportional feedback $u_3 = -k_h(h - h_{des})$ where h_{des} is the task-specific desired height.

6.1.2 Gimbaled Camera Sensing

The MLB Bat UAV provides a gimbaled camera sensor that is used for all target tracking. It is assumed here that the gimbaled unit can sweep through its range of motion with sufficient speed. Therefore the coverage region of the unit is modeled as a single camera with a field of view defined by gimbal limits. Given UAV altitude h above the ground and gimbal field of view θ , the sensor traces out a circle of radius $r_d = h \cdot \tan(\theta)$ below the UAV. Thus, objects are considered detected if they come within the distance r_d of any UAV.

6.1.3 Terrain Line of Sight Restrictions

In order to consider the effects of terrain line of sight restrictions without the need to employ complicated ray-tracing algorithms, certain circular regions E_m of the environment are defined as “non-viewable”. The motion of the ground vehicles and aircraft is not impeded by these regions; however, no UAV can detect or sense a target in these regions.

6.2 Team Coordination Layer

The team coordinator is responsible for assigning each UAV in the group to one of the modes in the hybrid controller. Current modes include: Loiter, Search, Follow, Support_Follow, Protect, and Support_Protect. The Follow mode is applied to UAVs that are assigned to track a ground vehicle that is adversarial or unclassified. The Protect mode refers to UAVs assigned to track “friendly” ground vehicles, i.e. perform convoy protection. The coordinator has access to all sensor information and can communicate to every UAV (i.e. the coordination layer is a centralized supervisor). At specified intervals the coordinator assigns all UAVs based on the current state of the global world model.

This model includes the position of all sensed targets, the states of each UAV, and the area of interest. The coordinator makes assignments in the following order:

- Each target object is Followed or Protected by one UAV
- Each UAV in Follow/Protect mode is Supported by one UAV
- Remaining UAVs are assigned to Search.

6.2.1 Follow, Protect, and Support Assignment

The team coordinator's first step is to assign at least one UAV to Protect or Follow each target by using binary integer programming to minimize

$$\sum_{i=1}^n \sum_{j=1}^m t_{ij} \cdot x_{ij} \quad (2)$$

subject to

$$\forall j, \sum_{i=1}^n x_{ij} = 1 \quad \forall i, \sum_{j=1}^m x_{ij} \leq 1 \quad m \leq n \text{ or} \quad (3)$$

$$\forall j, \sum_{i=1}^n x_{ij} \leq 1 \quad \forall i, \sum_{j=1}^m x_{ij} = 1 \quad n \leq m \quad (4)$$

where m is the number of targets, n is the number of UAVs, t_{ij} is an estimate of the time needed by UAV_{*i*} to intercept target_{*j*}, and x_{ij} is an assignment variable that is equal to 1 if UAV_{*i*} is assigned to target_{*j*} and zero otherwise. In the current version of the team coordinator, friendly and adversarial/unclassified ground vehicles are treated equally in the assignment process. Priority can be given to one set over the other by performing the assignment task twice, once for the higher priority group and then once for the other group. If the friendly and unclassified targets are treated equally, UAVs in the Follow or Support_Follow modes are switched to the Protect or Support_Protect modes if an unclassified target is later classified as friendly (and in need of tracking).

After the coordinator assigns UAVs to Follow/Protect each target, the remaining UAVs are assigned to Support the UAVs in Follow/Protect mode using the same procedure described above.

6.2.2 Search Assignment

After the Follow, Protect, and Support assignment step, all remaining UAVs are assigned to the search mode. The team coordinator assigns each remaining UAV to a different region within the total area of interest. The supervisors onboard the UAVs translate the assigned regions into waypoints in order to generate lawnmower search patterns.

The team coordinator breaks the total area of interest into equally sized regions. The number of regions equals the number of UAVs in the search mode. Using the same integer programming procedure described above, the coordinator assigns UAVs to regions based on the distance between the UAV and the center of the regions.

An alternative approach is based on a search map that is used to fuse the sensor coverage of each UAV. The total search area is discretized into a set of rectangular regions. Each region is assigned a single value to represent coverage. In the current scheme, coverage is represented by the time since the most recent visit. This variable approximates the accuracy of any information gleaned from that region during the previous visit. After this value increases past a minimum threshold the region is considered uncovered. The coverage value is reset to zero whenever a certain percentage of any UAV's individual sensor footprint enters the region. Fig. 7b shows the search map for a search task performed by 5 UAVs. In this map, black indicates recent coverage and white indicates no coverage.

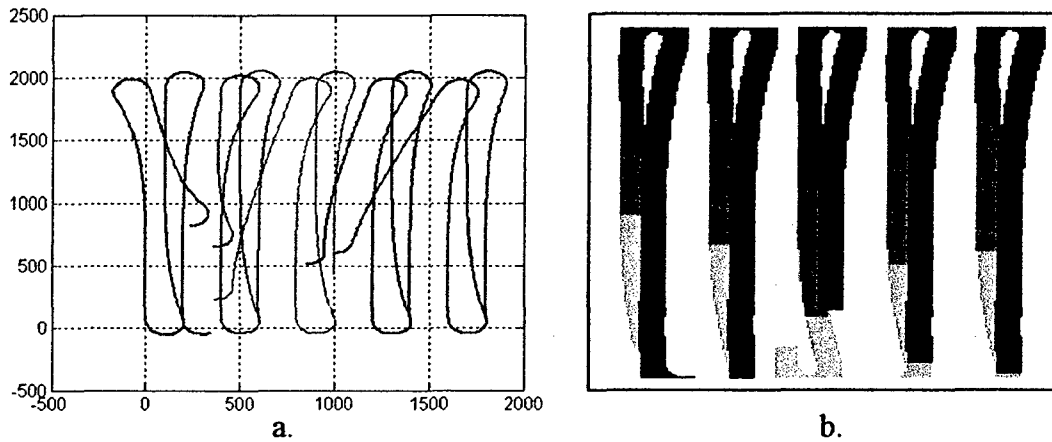


Figure 7. Area search conducted by 5 UAVs. a.) Lawnmower patterns followed by each UAV (indicated by different colors). b.) Coverage map of UAV sensors. Black indicates recently visited space while white signifies no recent coverage.

From the fused map, each UAV assigned to the Search task performs a graph search over a limited planning horizon in order to determine its motion. The optimization cost for the receding horizon control combines the coverage achieved by each aircraft with a proximity cost that keeps UAVs separated. The advantage of this approach over the lawnmower search method is that UAVs in the Search mode will not overlap regions recently swept by UAVs in other modes, thus improving the overall coverage by the team.

6.2.3 Loiter Assignment

UAVs are assigned to the Loiter mode only after the UAV they are tracking enters the un-viewable region E_{nv} . When this occurs, the target object is replaced in the assignment process by the center of the un-viewable region it just entered. The assignment procedure continues as if these regions were objects. Rather than assign UAVs to Follow or Support these new targets, UAVs are assigned to loiter around their perimeter until the target is reacquired.

6.3 Hybrid Trajectory Generator

Using the kinematic system model, the hybrid controller generates command inputs for the low-level flight control. The hybrid controller consists of a set of discrete modes and

a set of (possibly) different continuous controllers for each mode. In its current configuration the control has the modes described in Section 6.2. The switching logic between modes is controlled by an onboard supervisor and by commands from the higher-level team coordinator. Commands from the team coordinator take precedence over all onboard supervisor commands.

6.3.1 Loiter and Follow Controllers

The Loiter, Follow, and Support controllers are all based on a Lyapunov vector field approach in which the unmanned vehicle circles about a designated point $[x_l, y_l]^T$ that may be stationary or moving. The control maneuvers occur at a commanded altitude h_{des} (which may vary for each mode) with a commanded nominal speed $u_1 = V_0$ and radius R_0 . The motion is controlled using a Lyapunov vector field to calculate the desired planar velocity $[\dot{x}_d, \dot{y}_d]^T$ and then using proportional feedback from the heading angle error to command the turning rate. The Lyapunov function $V(x, y) = (r^2 - r_d^2)^2$, where $r = \sqrt{(x - x_l)^2 + (y - y_l)^2} = \sqrt{\Delta x^2 + \Delta y^2}$ is the radial distance of the UAV from the loiter position, leads to the guidance vector field

$$\bar{f}(x, y) = \begin{bmatrix} \dot{x}_d \\ \dot{y}_d \end{bmatrix} = \left(\frac{-V_0}{r} \right) \cdot \begin{bmatrix} \Delta x \cdot \frac{r^2 - r_d^2}{r^2 + r_d^2} + \Delta y \cdot \frac{2 \cdot r \cdot r_d}{r^2 + r_d^2} \\ \Delta y \cdot \frac{r^2 - r_d^2}{r^2 + r_d^2} - \Delta x \cdot \frac{2 \cdot r \cdot r_d}{r^2 + r_d^2} \end{bmatrix}. \quad (5)$$

The desired heading ψ_d is calculated from Equation (5) and the heading angle error is fed back to the turn rate command

$$\psi_d = \arctan\left(\frac{\dot{y}_d}{\dot{x}_d}\right), \quad (6)$$

$$u_2 = -K \cdot (\psi - \psi_d). \quad (7)$$

Stand-off tracking of a moving ground vehicle is accomplished using the Lyapunov vector field approach in the frame of reference attached to a moving point, i.e. relative to the position of the ground vehicle. If the velocity of the moving target is known or estimated, the controller can be modified to ensure that the UAV remains outside of the

stand-off radius. A new command is calculated by adding the target's velocity to the Lyapunov guidance vector. The scaling of the guidance vector is calculated in order to maintain the desired UAV speed. Given the guidance direction vector $\vec{f} = [L_x, L_y]^T$, the target velocity $[T_x, T_y]^T$, and a scale factor α , the velocity of the UAV in global coordinates is:

$$\vec{V} = \begin{bmatrix} V_x \\ V_y \end{bmatrix} = \begin{bmatrix} T_x + \alpha \cdot L_x \\ T_y + \alpha \cdot L_y \end{bmatrix}. \quad (8)$$

Taking the norm of Equation (8) and setting it to the desired speed V_o leads to the following expression for the scale factor:

$$\alpha^2 \cdot (L_x^2 + L_y^2) + \alpha \cdot 2 \cdot (L_x \cdot T_x + L_y \cdot T_y) + (T_x^2 + T_y^2) - V_o^2 = 0 \quad (9)$$

Equation (9) is solved for α , which is substituted back into Equation (8) to determine the desired velocity and heading.

Fig. 8 shows an example of UAV behavior in the Loiter mode. The UAV begins at position (800, 800) meters and is commanded to loiter around the origin with a speed of 20 m/s at a stand-off radius of 300 meters. Fig. 9 shows the guidance vector field generated for this example.

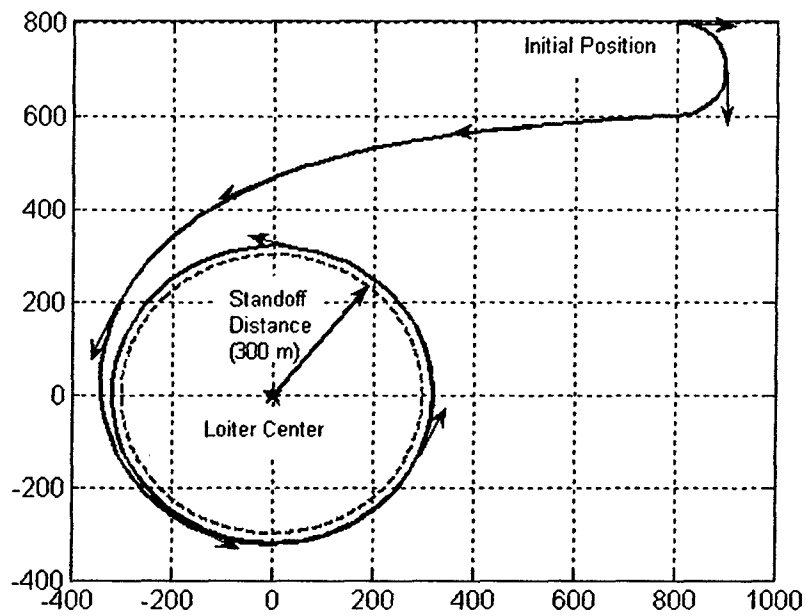


Figure 8. Example Loiter maneuver. The UAV begins at (800,800) meters and is commanded to loiter around the origin with a radius of 300 meters and a speed of 20 m/s.

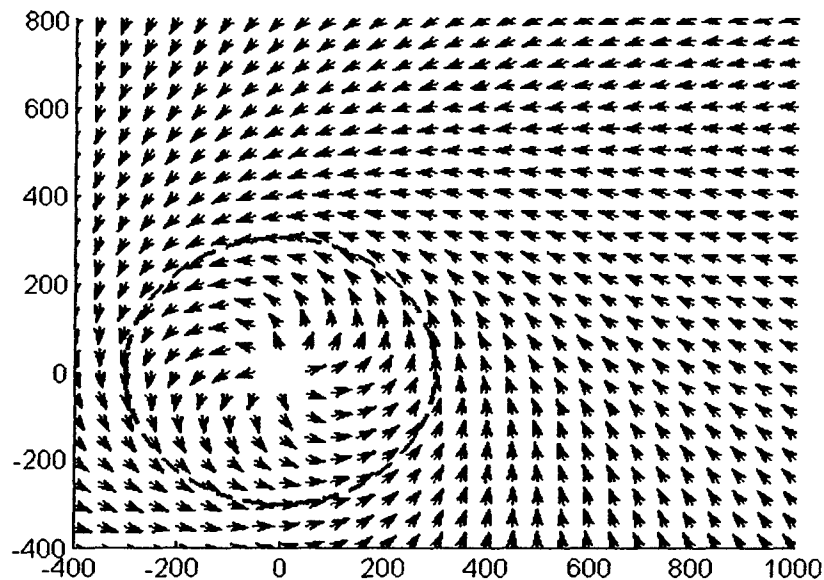


Figure 9. Lyapunov vector field loiter maneuver around the origin with a radius of 300 meters (dashed line).

An example Follow task when the target velocity is unknown is illustrated in Fig. 10 and Fig. 11. The UAV is commanded to follow a ground vehicle moving with a velocity of $(0, 10)$ m/s. The UAV attempts to maintain a 300 meter stand-off distance while traveling

at a speed of 20 m/s. Fig. 10 shows the path of the UAV in a fixed coordinate system while Fig. 11 shows the path of the UAV relative to the moving target.

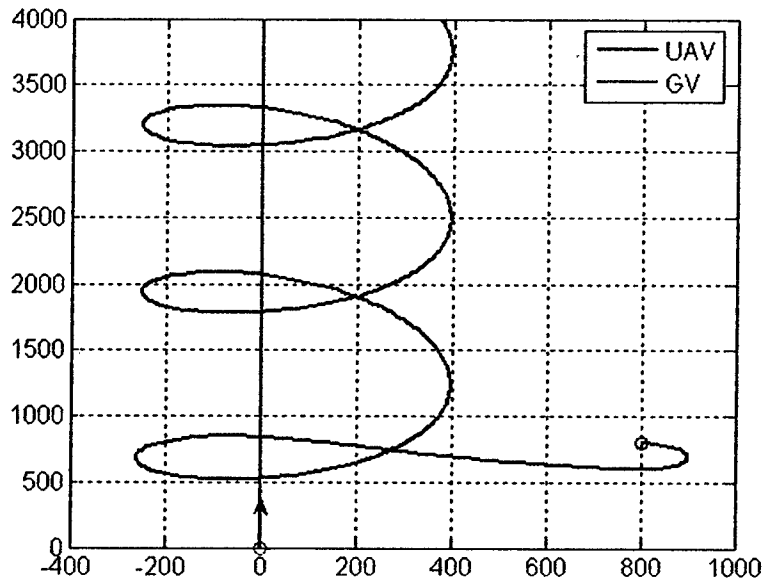


Figure 10. Example Follow maneuver. The UAV begins at (800,800) meters and is commanded to follow a ground vehicle (GV) starting at the origin with a velocity of (0, 10) m/s. The UAV is commanded to maintain a stand-off radius of 300 meters and a speed of 20 m/s.

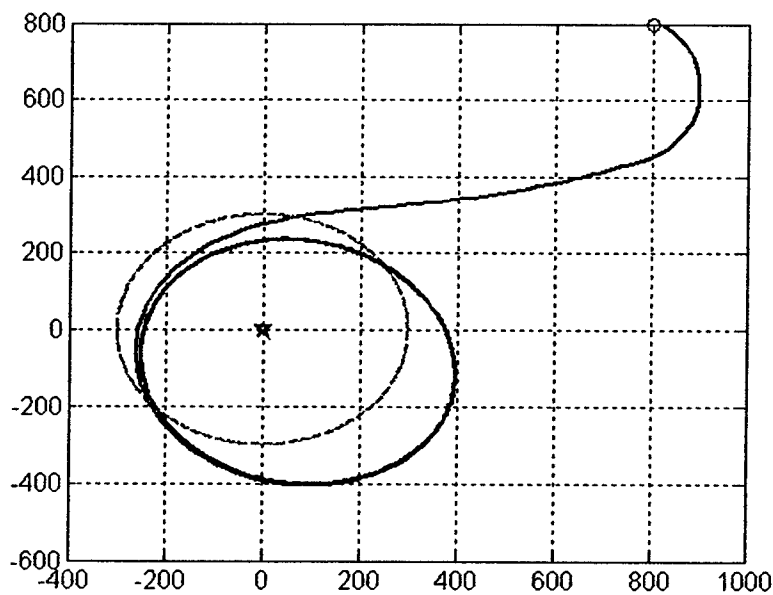


Figure 11. Position of UAV relative to the GV during Follow maneuver. The dashed line indicates the commanded stand-off radius.

Fig. 12 shows the results of the same scenario above while including the target's velocity. This velocity can be attained by communication with a "friendly" vehicle or by filtering the position measurements obtained by onboard sensor processing.

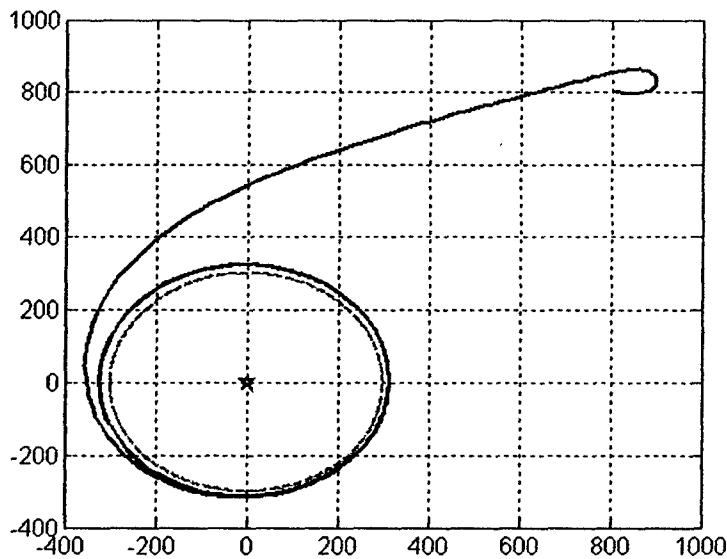


Figure 12. Position of UAV relative to the GV during Follow maneuver using the GV velocity. The controller keeps the UAV outside stand-off radius (dashed line).

The Follow control algorithm applies as long as the ground vehicle velocity is less than or equal to the velocity of the UAV. Otherwise the UAV cannot keep up with the moving target. Fig. 13 and Fig. 14 show an example Follow task with a ground vehicle moving at a velocity of $(0,18)$ m/s.

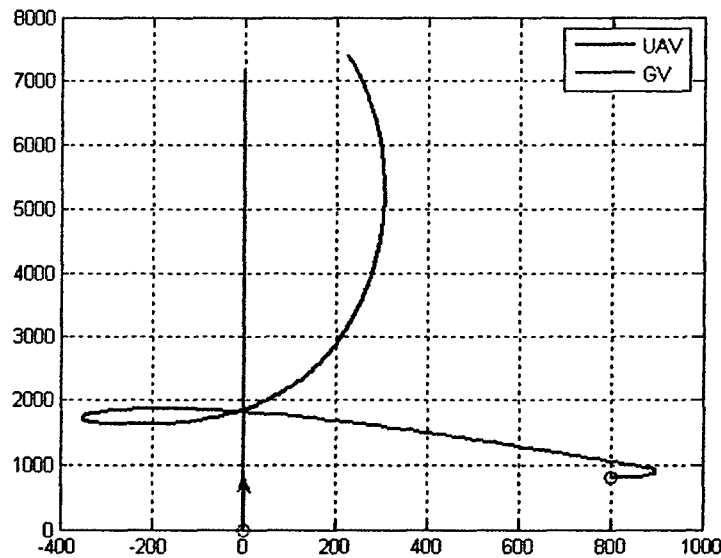


Figure 13. Example Follow maneuver. The UAV begins at (800,800) meters and is commanded to follow a ground vehicle (GV) starting at the origin with a velocity of (0, 18) m/s. The UAV is commanded to maintain a stand-off radius of 300 meters and a speed of 20 m/s.

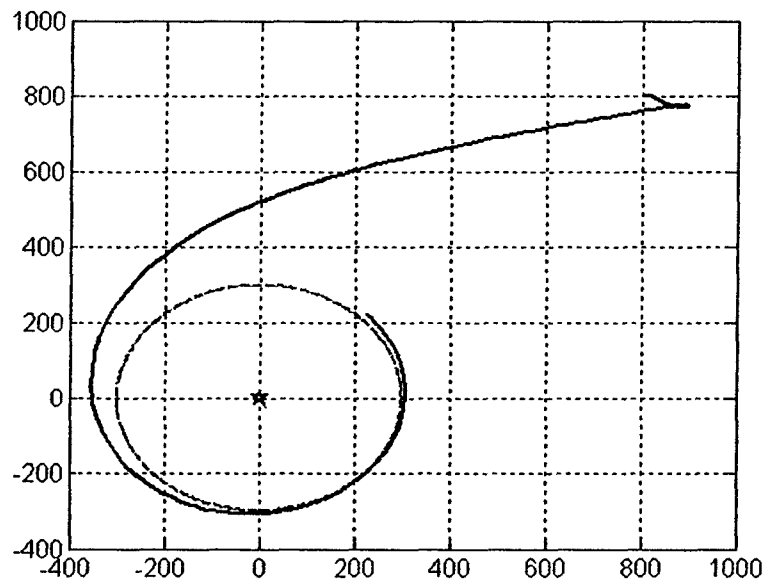


Figure 14. Position of UAV relative to the GV during Follow maneuver. The dashed line indicates the commanded stand-off radius.

6.3.2 Support Mode: Coordinated Stand-off Tracking by Two Vehicles

When a team of vehicles are assigned to follow a single target, i.e. one UAV is assigned to Support another, coordination between UAVs is necessary to avoid collisions and to

maximize sensor coverage of vehicle motion. Team tracking can improve sensor coverage when the target vehicle is uncooperative, or is highly agile, such that estimates of its position and velocity are poor. The idea is to distribute UAVs in the group uniformly in phase on the tracking loiter circle, so that unpredicted changes in vehicle motion can be observed and followed at least by the UAV in the most advantageous position.

Phase coordination is produced by a second Lyapunov guidance law, which adjusts the speed of the vehicles (within limits) to maintain desired relative phase on the loiter circle provided by the first Lyapunov law (Equation 4). The resulting speed commands are then processed through the correction algorithm (Equation 7) to maintain the desired standoff distance to the moving target.

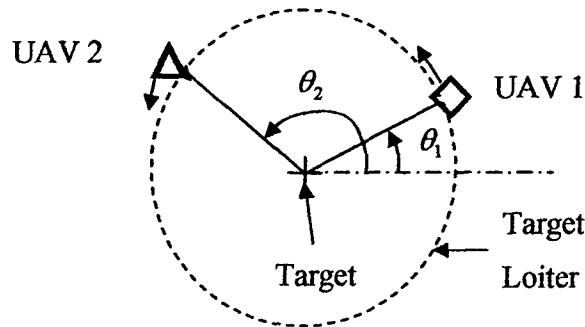


Figure 15. Phase angles for a team of UAVs tracking a single target.

Fig. 15 shows a two-UAV tracking team, with corresponding phase angles θ_1 and θ_2 defined relative to the instantaneous tracking loiter circle. The phasing Lyapunov function is

$$V_p = (\theta_2 - \theta_1 - \theta_D)^2 \quad (10)$$

whose rate of change is

$$\frac{d}{dt}V_p = 2(\theta_2 - \theta_1 - \theta_D)(\dot{\theta}_2 - \dot{\theta}_1). \quad (11)$$

Choosing the angular speed commands

$$\dot{\theta}_1 = k(\theta_2 - \theta_1 - \theta_D) + V_0 / R_0 \quad (12)$$

$$\dot{\theta}_2 = -k(\theta_2 - \theta_1 - \theta_D) + V_0 / R_0 \quad (13)$$

results in

$$\frac{d}{dt}V_P = -4kV_P, \quad (14)$$

which produces exponential convergence of V_P to zero, i.e. convergence of the relative angle $\theta_2 - \theta_1$ to the desired phase offset θ_D . The corresponding speed commands to the flight control subsystems are then

$$\begin{aligned} u_{1,1} &= k(\theta_2 - \theta_1 - \theta_D)R_0 + V_0 \\ u_{1,2} &= -k(\theta_2 - \theta_1 - \theta_D)R_0 + V_0 \end{aligned} \quad (15)$$

In the case of a two-UAV team, we choose the offset θ_D to be an odd multiple of π radians. It is interesting to note that the multiple of π chosen determines which UAV is phased ahead of the other. For example, choosing the odd multiple of π closest to the initial angular offset of the UAVs preserves their initial ordering in phase on the loiter circle. Choosing a different multiple of π causes one UAV to overtake the other, switching the phase order before settling to the desired 180 degree relative offset.

Fig. 16 shows the results of the overall control scheme, where two UAVs act in a team to follow a moving target, maintaining a desired standoff distance as well as a desired loiter circle phasing. The left plot shows UAV paths (blue and green) in global coordinates, where the vehicle to be tracked followed the red line, moving with constant velocity along the Y-direction. The right plot shows the view of this same motion in a coordinate system attached to the tracked vehicle ('x'). Here it is clear that the UAVs are attracted to a loiter circle about the GV, and maintain the desired standoff distance (dashed circle). Fig. 17 shows the standoff distance and phase angle separation of the vehicles versus time.

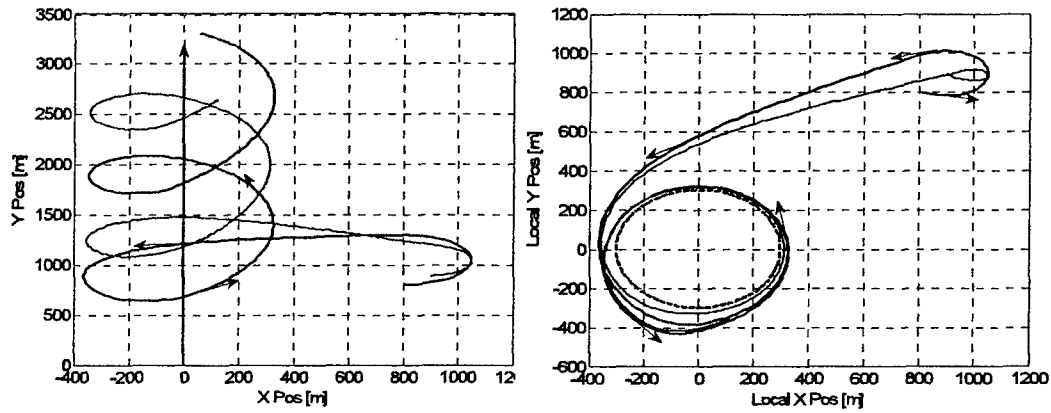


Figure 16. Two-UAVs tracking a moving target, shown in global coordinates (left) and local coordinates (right).

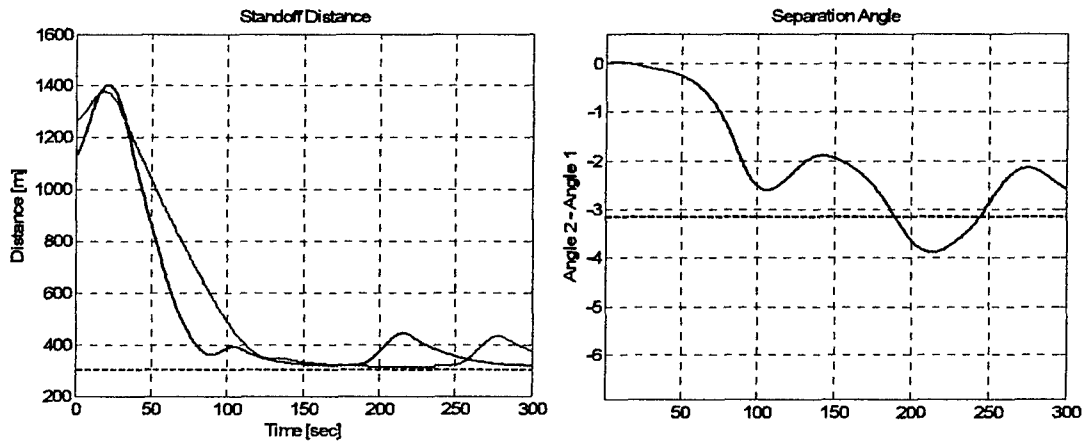


Figure 17. Coordinated team tracking performance for the moving target scenario: standoff distance (left) and angular separation (right).

This simulation also enforced constraints on turn rate and airspeed, as seen in Fig. 18. The velocities of the UAVs were restricted to $V_0 - 5m/s \leq u_{1,i} \leq V_0 + 5m/s$ and a maximum turn rate was enforced $|\dot{\mu}_2| \leq 0.1rad/s$. These constraints prevent the UAV from precisely following the Lyapunov vector fields, hence stand-off distance and phase offsets do not converge to their desired values. However, the resulting behavior is seen to be robust to these perturbations, producing good stand-off distances and reasonable phase separation in tracking a moving target.

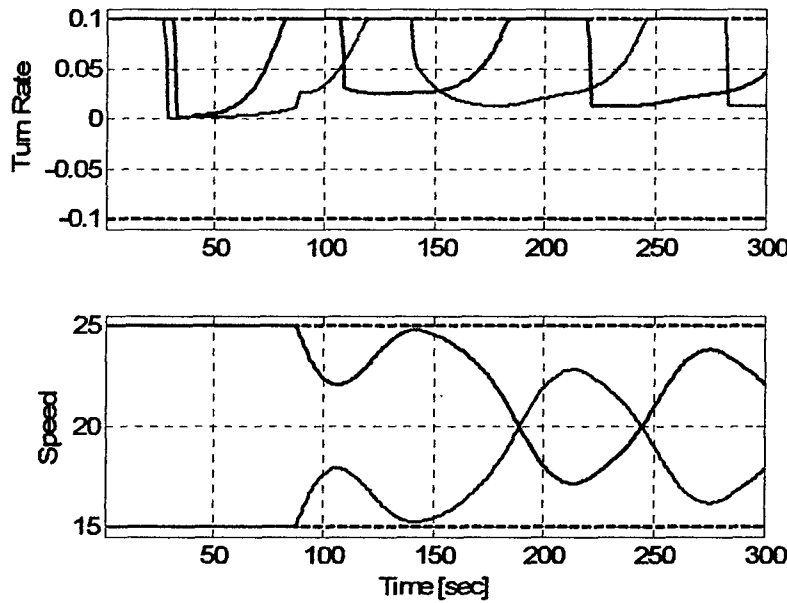


Figure 18. Turn rate and airspeed constraints enforced in the moving target, team-tracking scenario.

6.3.3 Protect Mode: Convoy Protection

Ground vehicle tracking for convoy protection is achieved by modifying the Lyapunov control used for the Loiter and Follow modes. In particular, the circular pattern relative to the ground vehicle is expanded in order to include two straight-line segments along the direction of travel of the ground vehicle. The new pattern is defined by four parameters, the straight-line distance D_f to cover in front of the ground vehicle, the straight-line distance D_b to cover behind the ground vehicle, the radius R_t of the turn made at either end of the pattern, and the fractional offset f_{off} of the pattern from the ground vehicle center. The pattern relative to the ground vehicle (at the origin, moving in the x-direction) is illustrated in Fig. 19.

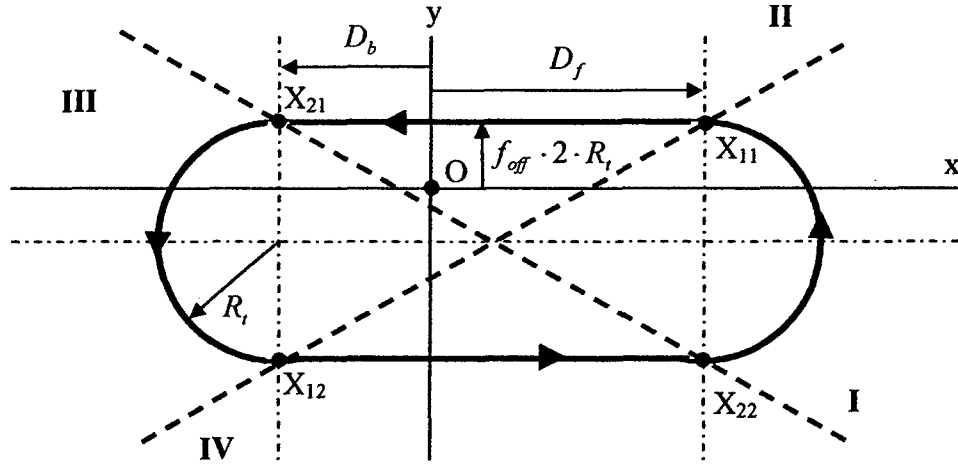


Figure 19. Tracking pattern of a single UAV in (Convoy) Protect mode.

For convoy protection, the UAV controller divides the region around the ground vehicle into four quadrants (Fig. 19) defined by the lines through $\{X_{11}, X_{12}\}$ and $\{X_{21}, X_{22}\}$. In quadrant I the controller uses the Lyapunov algorithm (Equation 4) described above. In quadrant II the controller aims the UAV at point X_{21} . Quadrant III returns to the Lyapunov approach and in quadrant IV the controller aims at point X_{22} .

When two UAVs are assigned to track a friendly vehicle (i.e. one vehicle is in Protect mode and the other is in Support_Protect mode) Equation 13 is used to maintain relative phasing and separation. Fig. 20 shows two UAVs following a friendly vehicle traveling with a speed of 10 meters per second. Fig. 20a shows the paths of the UAVs relative to the ground vehicle. The parameters used to define the tracking pattern are $D_f = 1000m$, $D_b = 300m$, $R_t = 300m$, and $f_{off} = 0.5$. Fig. 20b depicts the global paths of the UAVs.

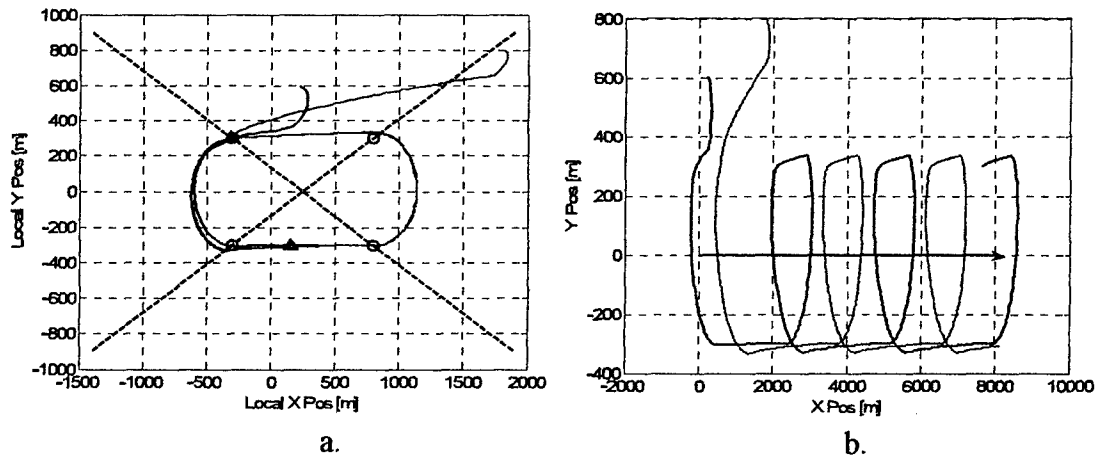


Figure 20. Two UAVs performing Convoy Protection. a.) Paths of the UAVs in the coordinate system relative to the ground vehicle. b.) Paths of the UAVs in the global coordinate system.

6.3.4 Cooperative Tracking of Fast Moving Ground Vehicles

Preliminary work has begun to enable the cooperative tracking of fast moving ground vehicles, where *fast* is defined to be faster than the maximum possible speed of the UAVs. In order to maintain coverage of the fast ground vehicle, the UAV team must coordinate its motion such that the ground vehicle enters the sensing range of one UAV as it leaves range of the other.

Upon initially detecting a fast moving ground vehicle, a single UAV is assigned to intercept it. The time to intercept (TTI) is calculated for each UAV and the one with the minimum TTI is assigned to intercept. Based on the speed of the ground vehicle and the intercept path of the UAV, the point along the ground vehicle path where the first UAV will lose contact of the ground vehicle is calculated. The closest UAV to this point is then assigned to loiter at this location until the ground vehicle arrives. The same step is continued until all UAVs are assigned a location along the ground vehicle route. Fig. 21 shows plots of a team of 5 UAVs with maximum speed of 20 meters per second tracking a ground vehicle moving with a speed of 30 meters per second. Fig. 21a shows the paths of each UAV and the ground vehicle. Fig. 21b depicts the separation distance between the ground vehicle and the closest UAV as a function of time. The sensors were modeled with a range of 800 meters (indicated by the green dashed line in Fig. 21b). By

cooperating, the UAV team kept the ground target in view for over 500 seconds, compared to just 75 seconds of sensor coverage by the first UAV.

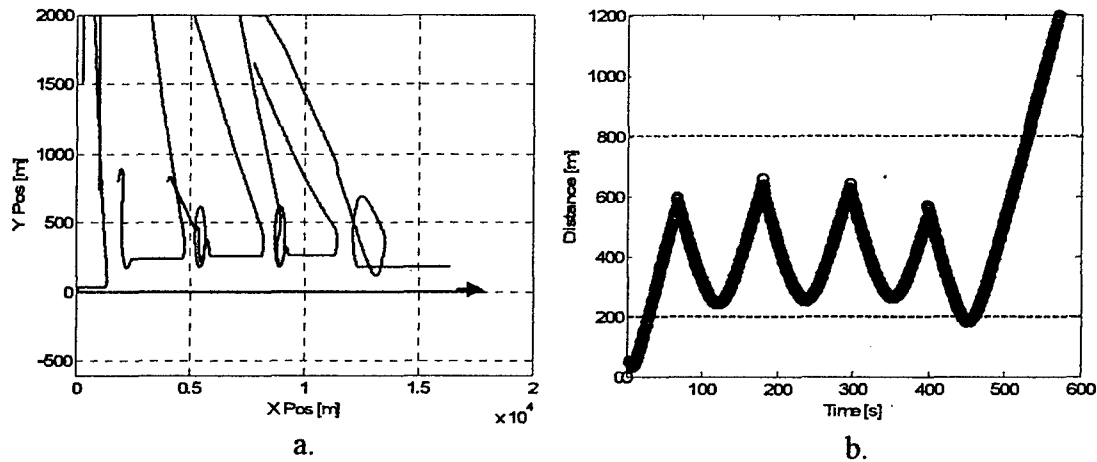


Figure 21. The UAV team maintains sensor coverage of a ground vehicle moving with a speed greater than the maximum speed of the UAVs. a.) Paths of the UAVs and ground vehicle. b.) Separation distance between the ground vehicle and the nearest UAV. Dashed lines represent stand-off distance and sensor range.

7 Simulation Results

This section presents the results of two simulations. Initial UAV positions are selected randomly for each example. The first scenario includes 6 UAVs and 3 unclassified/adversarial ground vehicles. Thus, one UAV is assigned to Follow each ground vehicle, and one UAV Supports each UAV in Follow mode. In the second example, 1 of the ground vehicles is classified as a friendly and the two UAVs tracking it are re-tasked to provide convoy protection. Movies of the simulations may be found at <http://recuv.colorado.edu/~frew/cooptrack.html>.

The current simulations use a sensor range of 800 meters and a stand-off radius of 200 meters. The UAVs have a nominal speed of 20 meters per second with a maximum deviation of ± 5 meters per second. The UAVs also have a maximum turn rate of 0.2 radians per second. For the purposes of task assignment, ground vehicles are always detected once they have been introduced into the world.

The environment used for the simulations presented in this section is the Table Mountain Radio Quiet Zone in Boulder, CO. This area serves as a test range for the CU Boulder AUGNet project and other UAV projects. The flight range is approximately 3600 meters by 4200 meters. In the simulations presented below the vehicles follow the roads on the Table Mountain facility. The UAVs do not make use of knowledge of the roads in their planning.

7.1 Scenario 1: Three Unclassified Ground Vehicles

Fig. 22 depicts the paths of the 6 UAVs and the 3 ground vehicles in scenario 1. The colored lines represent the UAVs while the solid black lines denote the moving ground vehicles. Each UAV begins in the search mode and is eventually assigned to track one of the three ground vehicle. Fig. 23 shows a plot of the separation distance between each ground vehicle and the two UAVs assigned to track it. After converging to the specified loiter circles, the UAVs maintain a stand-off distance between 200 – 250 meters. The commanded stand-off distance is violated (e.g. at approximately 450 seconds) only when the ground vehicle changes direction. Even then, the UAV responds quickly and moves away from the target.

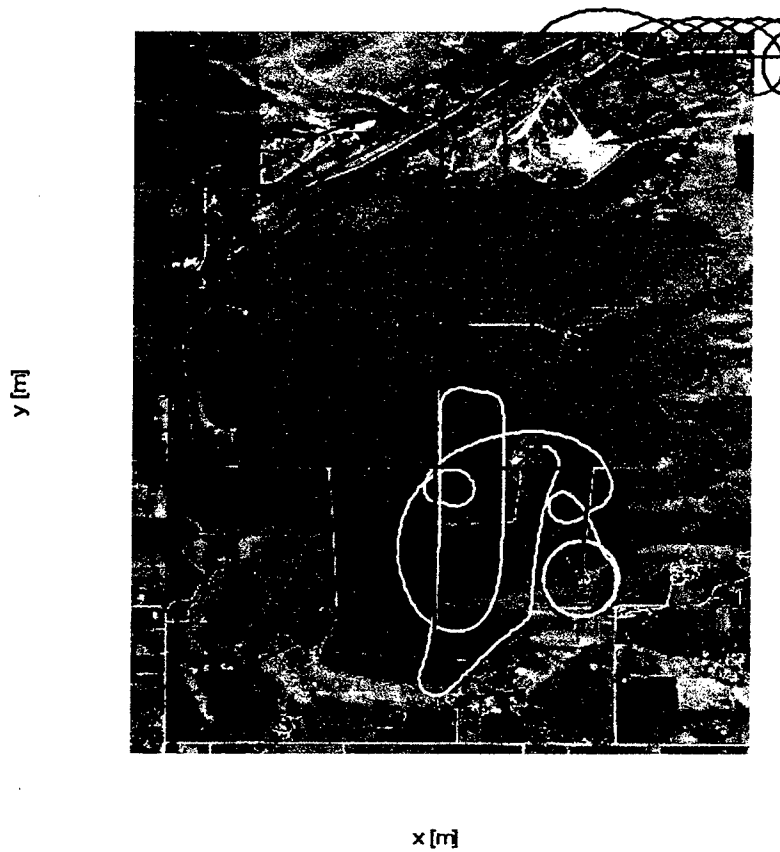


Figure 22. Paths of 6 UAVs (colored lines) tracking 3 moving ground vehicles (solid black lines).

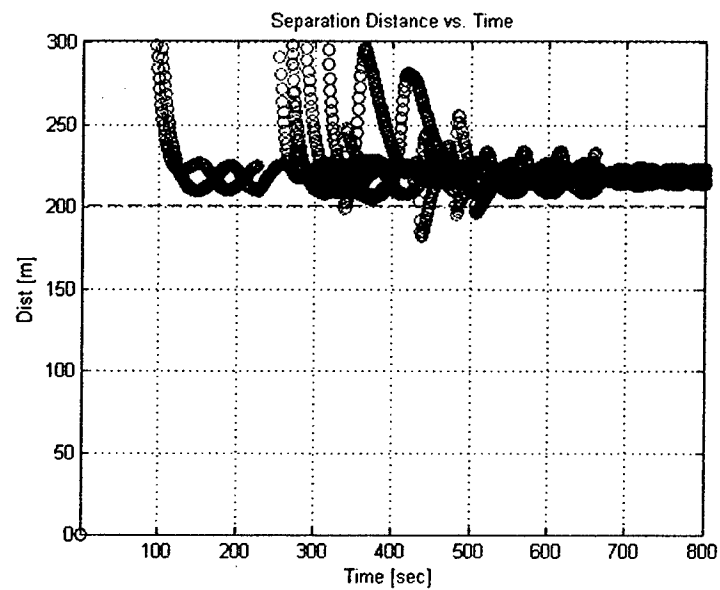


Figure 23. Separation between UAVs and ground vehicles. The dashed line denotes the stand-off distance of 200 meters.

Fig. 24 - Fig. 26 show the state of the world at times 51 sec, 226 sec, and 251 sec, just after each ground vehicle is detected. In Fig. 24, each UAV is searching a different region of the environment when the first vehicle is detected. UAV1 is closest to the target and is assigned to Follow. UAV4 is the next closest and is assigned to Support UAV1. The remaining UAVs are assigned new search regions. Fig. 25 depicts the state of the team at 226 seconds when the second ground vehicle is detected. UAV6 is assigned to Follow the second ground vehicle and because UAV4 is close to the second ground vehicle it is re-assigned to Support UAV6. UAV5 is then assigned to support UAV1, taking the place of UAV4. Fig. 26 shows a sequence of steps during this re-assignment process. Finally, Fig. 27 shows the detection of the third ground vehicle. UAV2 and UAV3 are closest to the target and assigned to Follow and Support respectively.

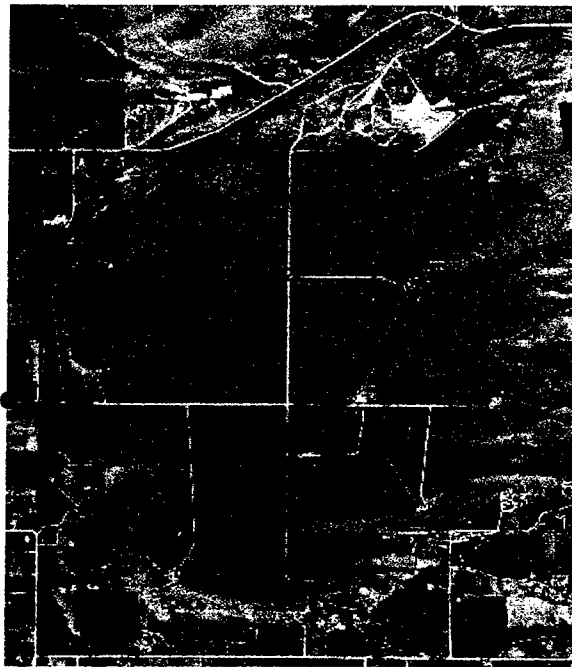


Figure 24. The first ground vehicle enters the region of interest at time 51 seconds.

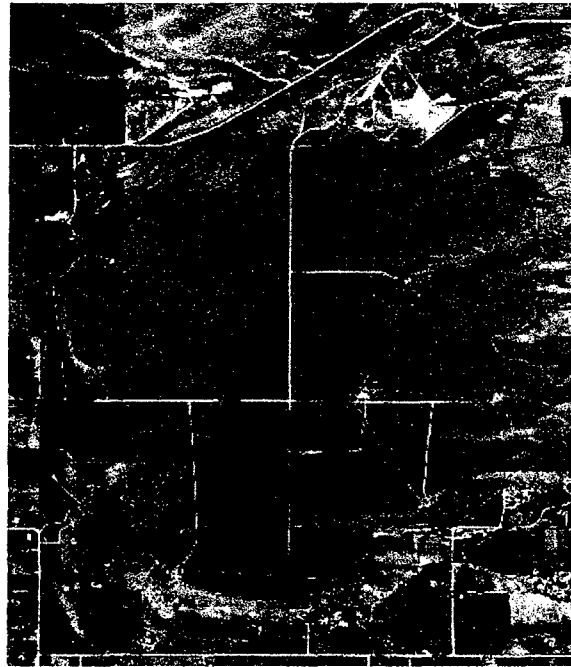


Figure 25. The second UAV is detected at time 226 seconds.

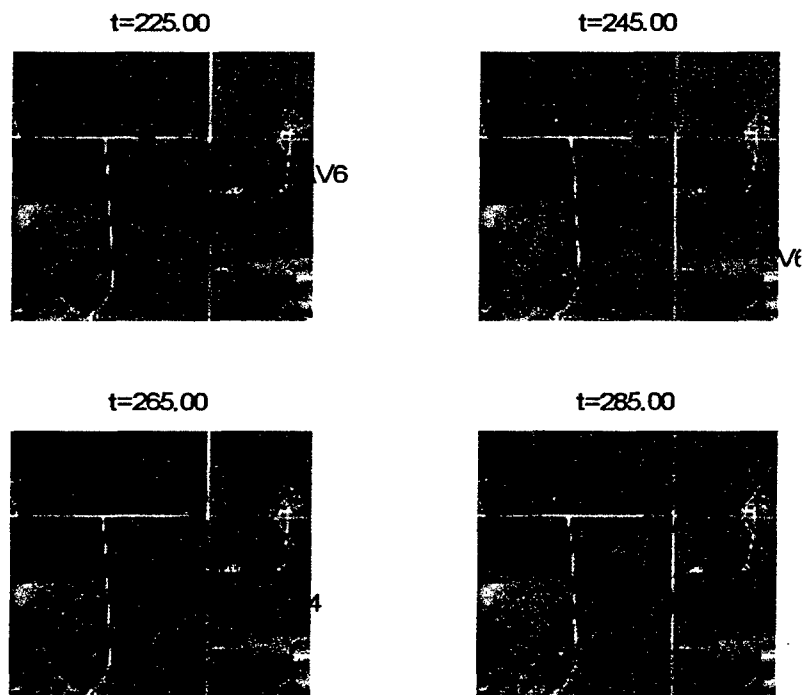


Figure 26. Sequence of plots show (re)assignment of UAVs after the second ground vehicle is detected.



Figure 27. The final ground vehicle appears at time 251 seconds.

7.2 Scenario 2: Two Unclassified, One Friendly Ground Vehicle

In this scenario six UAVs track three ground vehicles. Unlike Scenario 1, the third ground vehicle is classified as a friendly vehicle so UAV2 and UAV3 enter Protect and Support_Protect modes instead of Follow and Support Follow. Fig. 28 shows the paths of each UAV and ground vehicle throughout the simulation. Fig. 29 shows the paths of UAV2 and UAV3 as well as their sensor trace. Here, a sensor radius of 200 meters is used in order to simulate the field of view of the gimbaled camera on the MLB Bat, compared to the 800 meter sensor radius used in Section 4.2.4 to describe the full range of the gimbal unit. Fig. 30 shows the UAVs and ground vehicle at several different times throughout the scenario. In every case the sensor coverage extends beyond the current location of the ground vehicle. This illustrates the coverage of the environment around the UAV in order to provide significant advance warning for possible threats.

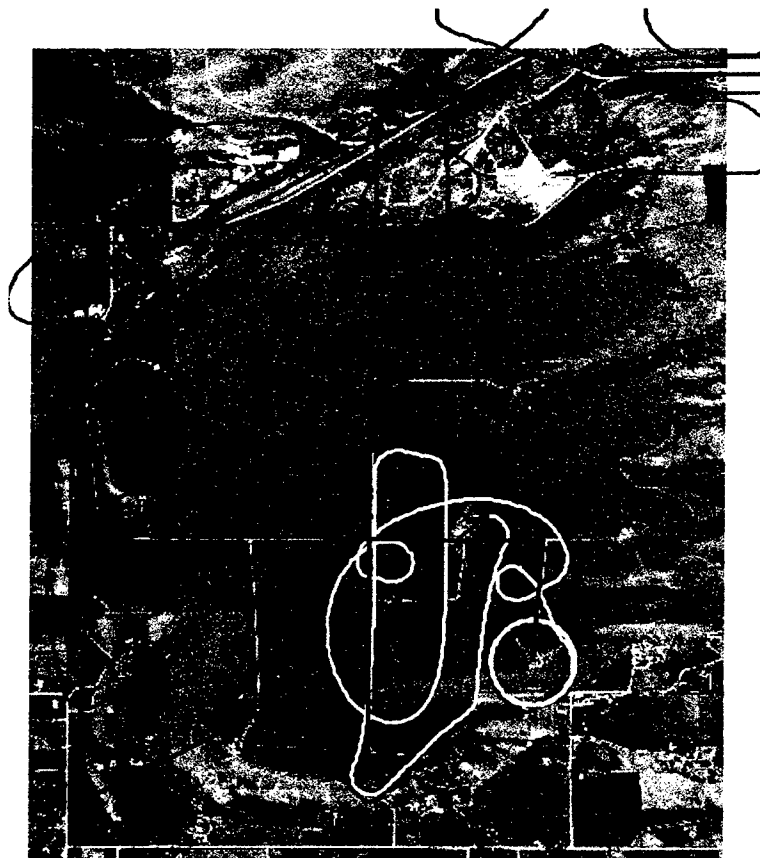


Figure 28. Paths of six UAVs (color lines) and three ground vehicles (black lines).

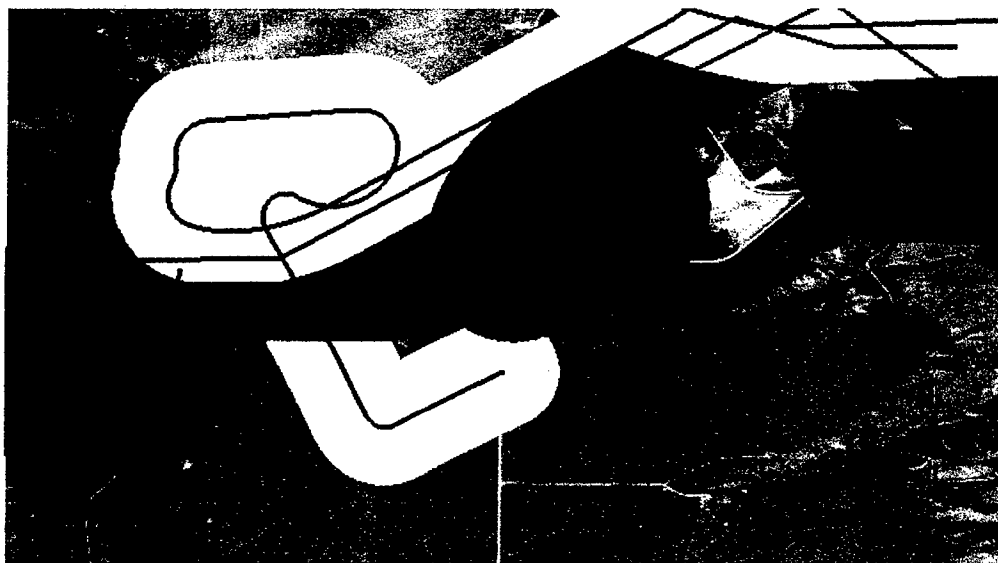


Figure 29. Path of two UAVs in Convoy Protection mode above friendly ground vehicle. The colored region represents the ground trace of the UAV's sensors.

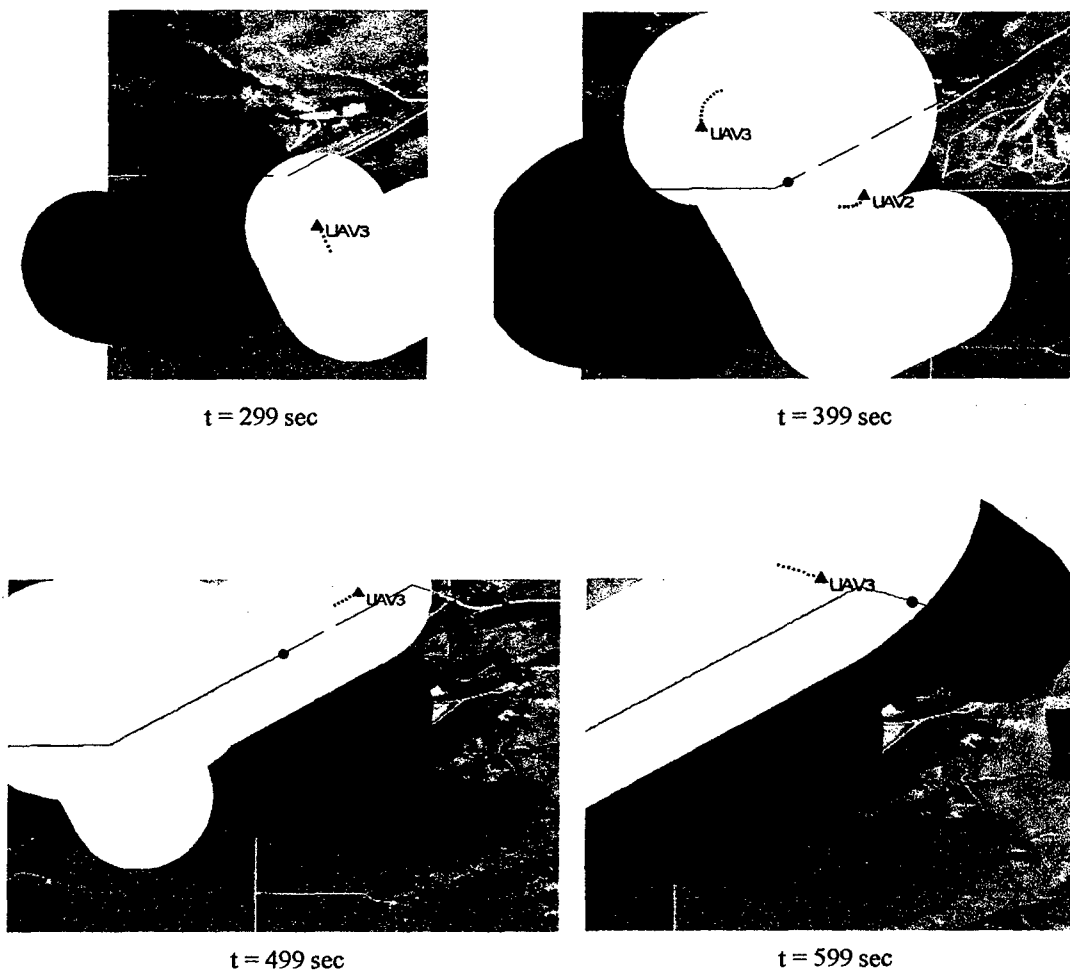


Figure 30. Sequence of images of convoy at various times during scenario.

7.3 Scenario 3: Two Unclassified, One Friendly Ground Vehicle, Limited Sensor Coverage and Terrain Obstruction

This simulation incorporates height control, sensor coverage limitations, and terrain obstructions. Unlike the previous two examples, unclassified targets are only detected if they come within the sensor coverage of a UAV. In contrast, friendly vehicles are detected once they enter the environment. The gimbal camera system is modeled with a field of view of 120 degrees. Different heights are commanded for the different tasks: Search and Loiter modes are assigned a desired height of 1000 meters, giving the greatest sensor coverage on the ground; Follow, Protect, and Support_Protect are assigned heights of 500 meters, giving more accurate tracking of ground targets; and Support is assigned a height

of 750 meters in order to maintain greater coverage at the expense of worse resolution. Two un-viewable regions are included that lie on the roads in the simulation environment. These regions have radii of 350 and 400 meters. Fig. 31 shows the paths of each ground vehicle and UAV in this simulation. The shaded circles represent regions of zero sensor visibility.

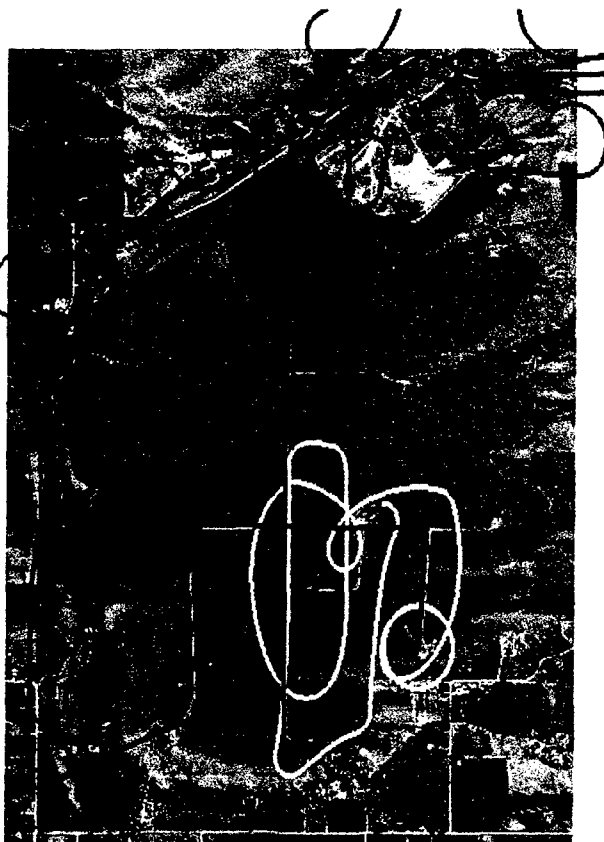


Figure 31. Paths of six UAVs (color lines) and three ground vehicles (black lines). The shaded circles represent regions of zero sensor visibility.

Fig. 32 – Fig. 33 depicts the simulation at 61 seconds, 239 seconds, and 272 seconds when each ground vehicle is first detected. Compared to the previous example, the first two targets are detected 10 seconds and 13 seconds after they first appear in the environment. UAV1 and UAV4 are assigned to the first target since they are closest to it upon detection. Fig. 33a depicts the UAVs when the second target is detected. At this time UAV1 and UAV4 have descended to their commanded heights in order to track GV1. The sensor ground coverage is reduced for these UAVs since they have descended

from their Search heights. Fig. 33b depicts the environment when the third ground vehicle, a friendly vehicle, enters the environment and is detected.



Figure 32. UAVs at time 61 seconds when first ground vehicle is detected. Shaded circles represent regions of no sensor visibility and unfilled circles denote coverage of UAV sensors.

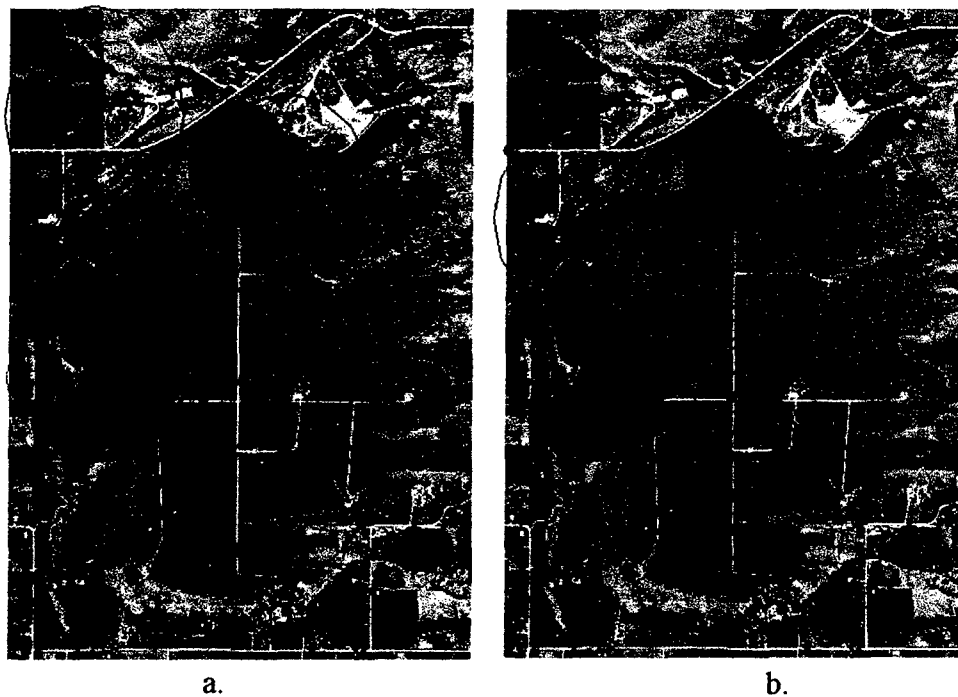


Figure 33. UAVs at time a.) 239 seconds and b.) 272 seconds when the second and third target are detected.

Fig. 34 depicts a sequence in which UAV 1 and UAV 4 track GV1 through a region of zero-visibility. The UAVs track the target until it enters the zero-visibility region and disappears from view ($t=105.00$). The two UAVs then take up loiter positions around the zero-visibility region. Like the Follow/Support modes, the UAVs separate themselves 180 degrees in phase. As they circle, their sensors cover most of the region boundary. As the target emerges from the region and is detected again, the UAVs continue following.

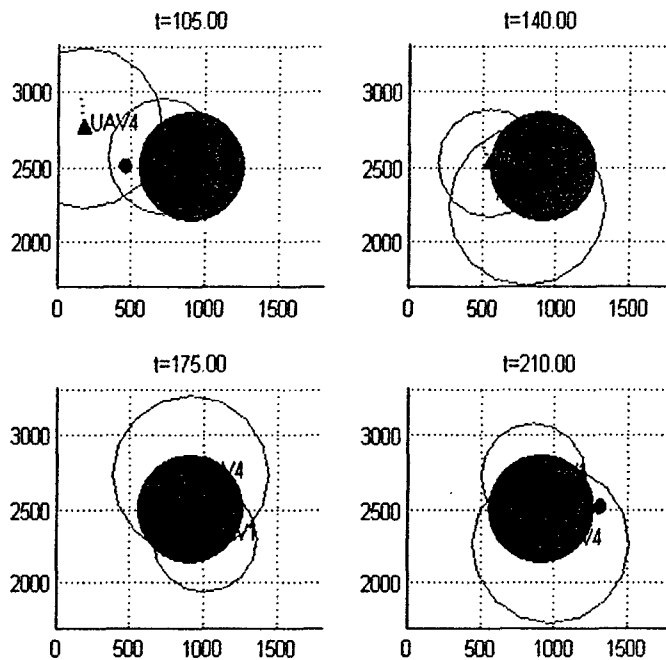


Figure 34. Two UAVs track the target through a region of zero visibility.

8 Conclusion

This effort has identified hardware and developed new control methods that will enable the demonstration of collaborative tracking of mobile targets using teams of small UAVs. Listed below is a summary of tasks accomplished in this research effort.

Tasks accomplished in this effort:

- 1) Identified UAV and sensor hardware appropriate for demonstrating collaborative control of teams of UAVs. Performed extensive flight tests of the hardware.
- 2) Investigated challenges encountered when a single UAV tracks a friendly vehicle by performing flight test experiments in real-world settings.
- 3) Identified hardware that will enable pixel-based tracking of unfriendly targets and tested its performance using flight video.
- 4) Identified and chose the convoy escort mission as the primary focus for this effort.
- 5) Developed a hybrid control method for managing teams of UAVs enabling collaborative tracking of mobile targets. The method can be adapted into a

decentralized control scheme with the addition of ad-hoc network communication hardware.

- 6) Tested the hybrid control scheme in a nonlinear simulation. The simulation includes the effects of multiple UAVs, friendly and unfriendly vehicles, terrain obstacles, and sensor motion constraint parameters.
- 7) Developed methods for coordinated control that provides collision avoidance, terrain avoidance, terrain obstruction of sensors, and maintains stand-off distance while tracking.

REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-05-

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions, Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork

0327

1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE	3. REPORT TYPE AND DATES COVERED FINAL REPORT
4. TITLE AND SUBTITLE COOPERATIVE TRACKING OF MOVING TARGETS BY TEAMS OF AUTONOMOUS UNMANNED AIR VEHICLES			5. FUNDING NUMBERS FA9550-04-C-0107
6. AUTHOR(S) DR. HENRY JONES			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) MLB Company 2551 Casey Ave, Suite B Mountain View, CA 94043			8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Office of Scientific Research 875 North Randolph Street Suite 325, Room 3112 Arlington, VA 22203 Lt Col Sharon Heise			10. SPONSORING/MONITORING AGENCY REPORT NUMBER
11. SUPPLEMENTARY NOTES			
12a. DISTRIBUTION AVAILABILITY STATEMENT Approved for public release, distribution unlimited			12b. DISTRIBUTION CODE
13. ABSTRACT (Maximum 200 words) This effort has identified hardware and developed new control methods that will enable the demonstration of collaborative tracking of mobile targets using teams of small UAVs. Listed below is a summary of tasks accomplished in this research effort.			
14. SUBJECT TERMS			15. NUMBER OF PAGES
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT

8-4-05