Ground Moving Target Engagement by Cooperative UAVs

Corey Schumacher

Air Vehicles Directorate

Air Force Research Laboratory (AFRL/VACA)

Wright-Patterson AFB, Ohio 45433

Corey.Schumacher@wpafb.af.mil

Abstract— The purpose of this tutorial paper is to present an application example for the MultiUAV cooperative control simulation. MultiUAV has been used to simulate a Cooperative Moving Target Engagement (CMTE) scenario, with a team of UAVs acting as a sensor and communication network to cooperatively track and attack moving ground targets. This scenario illustrates the utility of MultiUAV for cooperative control applications requiring heterogeneous vehicles with varied sensor, communication, dynamic, and weapon capabilities. A human supervisor designates one or more moving ground targets for the vehicles to attack. The vehicle agents must then autonomously and cooperatively determine which vehicles will perform the required tasks, when the tasks will be performed, and what flight paths will be used. This requires assigning time-dependent cooperative and joint tasks, where multiple sub-elements of the primary task must be accomplished by different vehicles, for any of the tasks to have value. This tutorial focuses on the unique requirements of the CMTE scenario and how they are addressed in the MultiUAV simulation.

I. INTRODUCTION

The scenario under consideration is one of Cooperative Moving Target Engagment (CMTE), in which a stand-off Unmanned Aerial Vehicle (UAV) with a wide-area Ground Moving Target Indication (GMTI) radar and several smaller UAVs with small-area GMTI radars and GPS-guided ground-attack weapons must cooperatively track and prosecute moving ground targets. A very large number of potential targets could be simultaneously tracked by the stand-off vehicle, but this paper will focus on the cooperative task planning required to track and attack the targets, with the assumption that specific targets to be prosecuted are nominated to the UAV team by a human supervisor or outside agent.

The stand-off vehicle has a large-area Ground Moving Target Indication (GMTI) Doppler radar that continually monitors the Region of Interest (ROI). This radar detects targets based on differences in the velocity between the target and the background. The stand-in UAVs can similarly track ground targets using a GMTI radar, with much smaller area coverage, and also release a weapon on a target. Sensor data from all vehicles cooperatively tracking a particular moving ground target is fused on a single vehicle, forming a high quality target track. This track information is sent via a radio data link to a GPS-guided weapon, which is used to destroy the target. This system allows the prosecution of moving targets with cheap, sensorless weapons. Maintaining a high quality target track is critical at all times, requiring continuous tracking by multiple vehicles for the duration of an attack mission. Because the GMTI sensors are Doppler-based, a moving ground target can only be detected and tracked if the velocity component of the ground target's velocity, relative to the terrain, in the direction of the standoff vehicle, is above the required minimum detection velocity.

This paper discusses the implementation of the CMTE scenario in MultiUAV, a MatLab-based simulation used for cooperative control research. Detailed information about MultiUAV structure, capabilities, and background can be found in [1]. The CMTE scenario exhibits extensive timing constraints and task coupling, and the computation of an efficient set of task assignments and corresponding vehicle paths must be automated for practical implementation. Due to the time-sensitive nature of the mission, the combined task assignment and path planning problem must be solved very quickly. This cooperative task assignment problem is solved in MultiUAV using a suboptimal Mixed Integer Linear Program formulation that addresses task timing constraints, agent dynamic constraints, joint tasks, and agent availability time windows, and which can be solved very rapidly for typical problem sizes. See [2] for details. MultiUAV has a modular design enabling easy modification of simulation elements, allowing a variety of cooperative control scenarios and algorithms to be studied with a single simulation.

II. SCENARIO DEFINITION

The CMTE scenario requires a high level of cooperation between team members and has the additional complexities of nonlinear agent dynamics and sensor constraints. CMTE requires that two or more UAVs track a moving (ground) target with Doppler radar while an additional UAV launches a GPS-guided munition. The sensed target positions and associated error ellipses from each tracking UAV are fused to form a precise, updated GPS location of the target, which is continuously sent to the munition. In order to reduce the error in the location of the moving target, the UAVs tasked to perform the tracking must have different line-of-sight angles to the target, preferably near orthogonal views. In addition, a moving target can only be detected and tracked if the UAV has a line-of-sight view to the target within some offset angle, γ, from the heading of the moving target, ψ. The size of the offset angle γ depends on the magnitude of the velocity vector of the target. Figure 1 shows the heading

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of the target and the associated regions in which UAVs can be located to detect its motion.
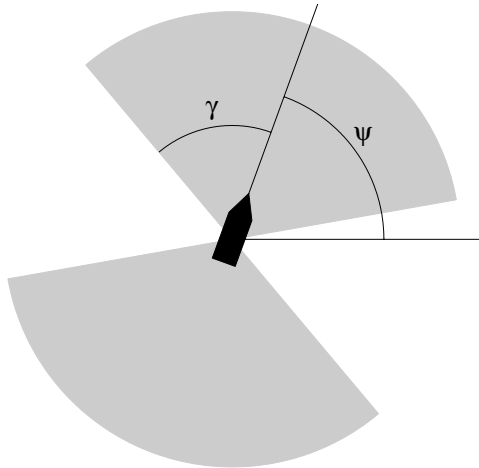

Fig. 1. Region of detectability based on target heading.

Complicating matters further, each UAV has a sensor footprint in which targets must be located to be tracked. The footprint has minimum and maximum ranges and bearings and, due to the configuration of the radar antenna array, is pointed out the wing of the UAV. Figure 2 shows a UAV tracking a target and the associated sensor footprint relative to the orientation of the UAV. The sensor can scan on either side of the UAV, but not both at the same time.
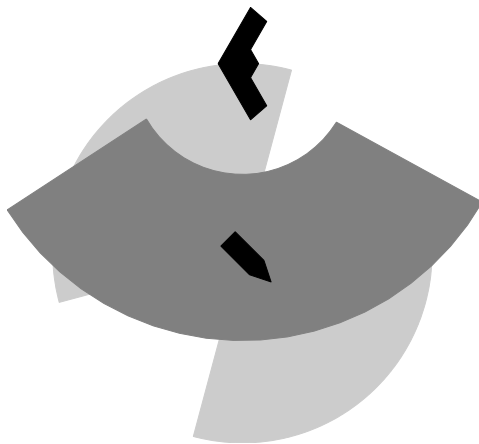

Fig. 2. UAV sensor footprint (dark gray region).

The team of UAVs designated to track and prosecute targets in the ROI are also supported by an additional stand-off team member which remains at a safe distance and has a wide-area sensor with an assumed 360-degree sensor footprint able to view the entire field. UAVs inside the ROI can cooperatively track a target with the off-board vehicle, or with another stand-in team member. Because the error in the estimate of the position of the moving target can best be reduced by multiple sensors with well-separated line-of-sight angles to the target, we restrict the difference

in bearing angles of the UAVs to the target to be greater than 45 degrees. This restriction partitions the detectability region of the target further into regions that satisfy both the target detectability requirement and the angle offset requirement. For fixed target heading and position and fixed stand-off vehicle position, regions where a target can be cooperatively tracked can be identified and used to develop path-planning routines of the UAVs to complete the mission.

While the bulk of the complexity in the CMTE scenario comes from the cooperative tracking of targets, the attack on the target must also be considered. All UAVs inside the ROI can track targets and drop weapons. To be in position to attack, a UAV must be headed toward the target and be between the minimum and maximum launch ranges. Once the weapon is launched, the attacking UAV is free to perform other tasks, but the tracking UAVs must continue to track the target for the duration of the weapon flight. This also leaves them in position to image the target after weapon impact to perform bomb damage assessment (BDA).

III. SCENARIO MODELING

The primary players in the CMTE scenario, and a summary description of how they are modelled in MultiUAV follows:

1. Stand-off UAV. This vehicle is assumed to have 360-degree sensor coverage with a Doppler GMTI radar. This vehicle is also assumed to orbit around a fixed location, and can maintain constant surveillance of the ROI. The stand-off UAV's sensor is capable of detecting and tracking any moving ground target within the ROI, as long as the minimum detectable radial velocity threshold is met. At present, stand-off UAV dynamics are not included in MultiUAV. Although only moderate modifications would be required to make the stand-off UAV one of the active players in the simulation, that would be of limited value, as its flight plan is not subject to modification.

2. Stand-in UAVs. The smaller, stand-in Combat UAVs are modelled with representative six degree-of-freedom nonlinear dynamics, with appropriately-tuned autopilots and waypoint-generation algorithms. Their sensors are modelled as GMTI radars with minimum and maximum ranges, and limited sensor sweep angles, centered sideways out of the aircraft wing. See Fig 2 for a graphical depiction of the sensor footprint. Any ground target within the footprint with a radial velocity component larger than the minimum threshold is assumed to be tracked. Communications between the UAVs can be assumed to be perfect and instantaneous, or a delay model included in the simulation can be used. Fuel is not considered a constraint during the relatively short duration of a target prosecution, so fuel limitations are not modelled. The UAVs carry a limited number of GPS-guided munitions.

3. Weapons. The GPS-guided weapons used to attack targets are modelled very simply. They are assumed

to fly at a constant speed to the target, with some assigned Probability of Kill P_k based on the target type. Updated GPS coordinates of the target are assumed to be communicated to the munition from the UAV that performs the sensor data fusion and maintains target tracks. These weapons have minimum and maximum allowable launch ranges and require the firing vehicle to be pointed at the target when a weapon is dropped.

4. Targets. Targets are also modelled relatively simply. Different target types can have different priority levels, different probability of being killed if attacked P_k, and different maximum velocities. Targets can also act as threats, and attempt to shoot down the UAVs. However, in the CMTE scenario, we have not yet used that capability. Target motion is scripted, and does not react to the UAVs, except when a target is destroyed.

MultiUAV simulates the key aspects of the scenario that are required to model the dynamic and sensor coverage constraints. This allows a detailed examination of the cooperative task assignment problem for this scenario. Substantial extensions to the simulation would be required to include higher fidelity sensors models, although the simulation structure allows for such modifications.

IV. TASK ASSIGNMENT COMPLEXITY

The CMTE scenario exhibits strict timing constraints between tasks, and thus requires extensive cooperation between team members. UAV dynamics impose constraints on flyable paths to achieve tracking and attacking positions. Sensor and weapon limitations further constrain the problem. This complexity makes the CMTE scenario an excellent problem for studying time-dependent cooperative assignment methods. To reduce the complexity of the CMTE task assignment and scheduling problem to a more reasonable level, the following assumptions and restrictions were added:

1. Targets have constant heading and speed.
2. Targets have fixed position (since the UAVs have large sensor footprints relative to the distance a target could travel in typical scenarios, this is a reasonable assumption for path planning, as long as the sensor footprint edges are not used). For purposes of sensor detection, we assign a velocity vector to the target, but the actual (simulated) target position remains constant.
3. Tracking of targets occurs along arcs of a circle centered at the target with radius so as to place the target in the center of the sensor footprint (see Fig. 2).
4. Weapons are launched at a fixed distance from the target and flight time of the weapon is known so as to fix the amount of time after an attack has occurred that the target must be tracked.

These restrictions and assumptions simplify the complexity of path planning needed to accomplish a CMTE mission. Additional complexity could be added without changing the method of assignment as long as the interface between the nonlinear path planning and the assignment algorithm remains abstracted to the specification of windows of availability of team agents.

V. MULTIUAV SIMULATION EXAMPLE

This section illustrates the use of MultiUAV to simulate the CMTE scenario, using an example with 5 vehicles and 3 targets. UAVs and targets were randomly distributed over an ROI 110 km wide and 170 km long with the stand-off vehicle fixed directly north of the area of interest. Figure 3(a) shows the initial positions of the targets and in-area UAVs. Each target is shown with an associated detectability region (outlined in black) and cooperative tracking region (solid wedge). Recall that the cooperative tracking region is the intersection of the detectability region with the line-of-sight angles greater than 45 degrees different from the off-board vehicle line-of-sight. Task time availability windows are computed based on computing minimum time trajectories to these regions. The task assignments and paths were calculated using the Mixed Integer Linear Program approach described in detail in [2].

The CMTE scenario is rich in timing complexity making visualization difficult without animation. Figures 3(a)-3(d) show the progression of the simulated scenario at 4 distinct points in time. Figure 3(b) shows that UAV 1 is assigned to track target 1 in cooperation with the off-board vehicle while UAV 5 attacks. The sensor footprint of the tracking UAV is shown to validate that the UAV is in position to track the target. Because UAV 1 is in the cooperative tracking region of target 1, no other UAVs are needed to track this target. This represents one iteration of the assignment algorithm. During the next iteration, UAVs 2 and 3 are assigned to cooperatively track target 2. Figure 3(c) shows the instant in time when UAV 4 releases a weapon to attack target 2. Note that the assignment algorithm correctly assigned 2 UAVs to track this target due to the distance needed for UAV 2 or 3 to reach a cooperative tracking region with sufficient room to track the weapon for the entire weapon flight. Also note that UAV 3 extended its path to arrive at the correct position and time to track the target. Since the algorithm ensures that the target prosecution time falls in the availability time windows of each UAV, no vehicle will be given requirements that violate underlying dynamic constraints. The final target is attacked by UAV 4 with UAV 2 assigned to track in cooperation with the off-board vehicle (Fig. 3(d)).

VI. CONCLUSION

MultiUAV is a powerful and flexible simulation tool that can be used to study UAV cooperative control for complex scenarios. This paper describes the Cooperative Ground Moving Target Engagement scenario as it is represented in MultiUAV. The simulation results presented here illustrate that MultiUAV can be effective for scenarios involving severe timing constraints and extreme task coupling. With relatively minor changes to vehicle, sensor, and target
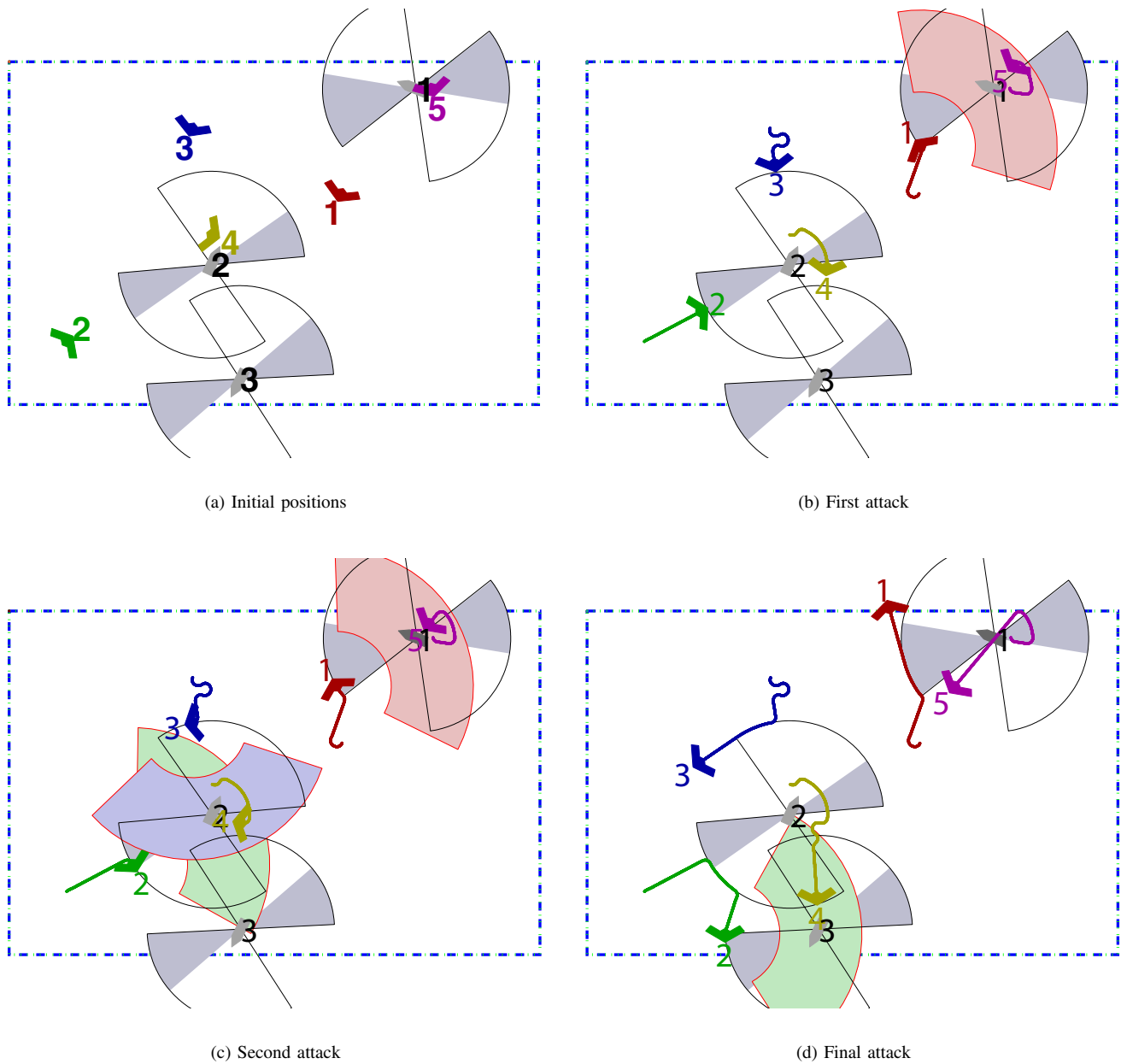
(a) Initial positions

(b) First attack

(c) Second attack

(d) Final attack

Fig. 3.   Simulated CMTE scenario.

characteristics, many potential UAV cooperative control scenarios could be studied using this tool.

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