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Swarming Unmanned Air and Ground Systems for Surveillance and Base Protection

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The emergence of various risks to global security and stability is a motivation to develop remote sensing and monitoring systems that can be deployed on Unmanned Vehicles (UxVs). This requires the development of robust autonomous control technologies that can reliably coordinate large numbers of networked heterogeneous systems cooperating on a common mission objective. This paper describes a promising approach to addressing this challenge by using swarm intelligence to coordinate multiple heterogeneous vehicles and remote sensors in realistic applications. We describe a class of stigmergic algorithms based on digital pheromones to control and coordinate the actions of heterogeneous unmanned air and ground systems in two applications: broad area surveillance and base protection. An Operator System Interface was developed to evaluate techniques for enabling a single operator to monitor and manage multiple unmanned vehicles and unattended sensors of different types. The results from recent demonstrations of the technology using air and ground platforms are reported.

Nomenclature

Φ_Θ	=	Uncertainty pheromone	θ	=	Uncertainty tuning constant
Φ_r	=	Sensor Request pheromone	ρ	=	Sensor Request tuning constant
Φ_t	=	Target Tracking pheromone	τ	=	Target tracking tuning constant
Φ_x	=	No-go pheromone	χ	=	No-go tuning constant
Φ_v	=	Vehicle Path pheromone	υ	=	Vehicle Path tuning constant
ϕ	=	Cost factor tuning constant			

I. Introduction

The emerging risks to global security affect the entire infrastructure for production and transportation of material, energy, and information. The sheer number and size of these facilities precludes the use of conventional means of protection. Unmanned remote sensing and monitoring systems offer a promising means to extend protection with limited human resources. Current unmanned systems typically require multiple operators for each vehicle which is labor intensive. Future systems will require a single operator to monitor and manage dozens of platforms[1]. This requires the development of innovative technologies in autonomous control, coordination, communication, and operator interfaces.

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We describe a class of stigmergic algorithms based on digital pheromones for autonomous control. Examples from natural systems[2] show that stigmergic systems can generate robust, complex, intelligent behavior at the system level even when the individual agents are simple and non-intelligent. Digital pheromones are modeled on the pheromone fields that many social insects use to coordinate their behavior. In this paper we describe the use of digital pheromones to control and coordinate the actions of unmanned air and ground sensor systems in two applications: broad area surveillance and facility protection. These swarming algorithms are designed to autonomously and dynamically adapt to a variety of intrusion tactics as well as changes in the configuration of the sensor assets.

In the following sections of this paper we introduce the surveillance and security problem and the requirements it places on the control system; briefly review approaches to swarming control; describe the pheromone algorithms used; describe the operator system interface; review the two demonstrations of the swarming system; and finally we offer some observations and conclusions.

II. Description of the Problem

Currently there are increased demands on security systems and personnel. Advanced sensor suites can provide support for all aspects of the security task including finding, fixing, tracking, targeting, engaging, and assessing (F2T2EA) intruders. But the sheer number and size of the areas to be protected restrict the number of expensive sensor assets that can be economically deployed. Similarly manning all these sensors is problematic. It is well documented that human vigilance begins to fall off after about 30 minutes of monitoring a sensor[3]. Having humans monitor all the video cameras and sensor feeds required to protect a large area 24-7 is prohibitively expensive. In the future successful security systems will need to make better use of scarce sensor assets and rely less on human monitoring of raw sensor feeds. Autonomous sensor platforms can take over the dull, dirty, and dangerous aspects of surveillance and facility security reducing operator overload. Intelligent swarming control of those platforms can maximize their effectiveness by better managing the limited sensor assets to protect against an intelligent adversary.

Autonomous surveillance and patrol impose several requirements on the control algorithms for the surveillance platforms. For the swarming algorithm this means directing the right sensor, to the right location, with the right attitude to the target so the sensor can collect the data necessary for F2T2EA.

A. A Facility Protection Scenario

In a typical configuration, aerial sensors on towers, tethered balloons, and Unmanned Aerial Vehicles (UAVs) provide broad area coverage in the vicinity of the protected area. Ground sensors or intrusion detection sensors may be deployed around the outside perimeter of a protected area to signal breaches. Visible/IR cameras and radar sensors are used to identify and track intruders. Human, animal, and Unmanned Ground Vehicle (UGV) patrols cover the area inside the protected area.

A trip from a ground sensor indicates a potential intruder. Ground sensors provide an approximate location and target type. Additional information must be obtained from the nearest sensor with the ability to more accurately measure location, heading, and speed and make a more positive identification of target type. Other sensors may be necessary to positively identify the target as friendly or enemy and to continuously track the target. Multiple simultaneous intrusions from different directions make the scenario even more complex as the sensors need to coordinate among multiple competing tasks with varying priorities. At some point they may be overloaded and need to trade off identification and tracking to ensure the most critical targets are identified, tracked, and engaged. Finally weapon systems (unmanned and manned) may need to be deployed to deter or neutralize the threat.

B. Surveillance Sensor and Platform Constraints

The sensors and platforms used in surveillance place a number of requirements on the software that controls them.

Multiple types of sensors and sensor capabilities. Surveillance systems include some combination of optical (visible and infrared spectrum), seismic, acoustic, or radar sensors. Additionally Chemical, Biological, Radiological, Nuclear, and Explosive (CBRNE) sensors may be deployed to detect specific types of hazards. Each sensor type has different resolution, detection, and location capabilities, varying performance capabilities for different targets in different terrain and weather conditions, and different requirements for optimal acquisition (distance, speed, orientation, time-on-target, etc.). Sensor fusion detection algorithms may require the coordinated configuration of multiple sensors maintaining specific orientation or temporal constraints. The control algorithms need to be able to manage all these complexities in controlling a wide variety of sensor assets.

Multiple types of sensor platforms and platform capabilities. Sensors may be deployed on mobile ground, air, or marine vehicles or located on fixed or pan-tilt platforms (such as surveillance cameras). The platforms have varying capabilities for speed, altitude, mobility, endurance, and different restrictions for operating in adverse weather and terrain. Ideally all the sensor platforms should be coordinated by a common control algorithm.

Varying communications capabilities. Sensor data need to be processed and important time-critical data needs to be communicated quickly to a base station. Additionally communications is required among the platforms to effect the coordination of each of the nodes. Sensor platforms have widely varying communication capabilities and power constraints. Unattended ground sensors may communicate over short ranges due to power and terrain. Air platforms typically have longer, line-of sight communications ranges. In addition to managing the complex task of configuring and coordinating the sensors for the primary objective of optimizing collection and detection, the swarming algorithms may also need to configure mobile nodes in the swarm to ensure that persistent and timely communication links are maintained to all the sensors in the network.

Whatever deployment of sensor nodes is used, the system must be capable of dealing with a determined, intelligent, and ever adapting adversary intent on identifying and exploiting the weaknesses in the system. They will utilize all forms of Camouflage, Concealment, Deception & Obscurants (CCD&O) to bypass security barriers. If greater autonomy is given to the security system for monitoring and identifying potential intruders then it must be capable of adapting to multiple intrusion strategies.

Previous experience with developing highly adaptive surveillance and patrol algorithms controlling real Unmanned Vehicles (UxVs) identified and resolved issues related to communications constraints, mobility restrictions, and no-go areas delineating hard boundaries for maneuver[4]. For this work we also identified and addressed the following issues:

- **Safety issues.—** Collision with other UxVs, and collision with other entities in the air or on the ground must be avoided. Additional safety factors must be incorporated in the design of the algorithms when hardware methods alone are insufficient.
- **Hardware and Software Failures.—** Failures need to be accommodated and backup and recovery procedures put in place. The algorithms must be designed to be robust in the face of different kinds of failures.
- **Hardware Errors.—** Errors in communication and positioning can lead to dropped messages, missed updates, and inaccuracies in computing vehicle and target locations. This complicates the navigation, collision avoidance, and target acquisition functions requiring strategies to accommodate these errors.
- **Energy Usage.—** Often one of the last items of concern to a researcher is the conservation of energy critical to small distributed platforms. Turns and climbs consume more energy decreasing the effective range and time on station for the UxV. The swarming algorithm needs to consider the energy cost in making its decisions.

III. Approaches to Surveillance and Perimeter Protection

The study of swarming control for surveillance and patrol has been very active. Parunak[5] reviews the major classes of algorithms that have been applied to this problem. There is abundant literature on centralized control schemes, but surveillance and security applications with widely distributed nodes and limited connectivity require distributed, decentralized computation. Some work has been done on developing decentralized versions of centralized control strategies (such as distributed model predictive control[6]), but most of the work in distributed vehicle control involves various kinds of field-based mechanisms. In field-based systems a scalar field is generated by a combination of attracting and repelling elements, and the agents respond to those forces or follow gradients in this field. Within this class of algorithms are particle systems based on Reynold's model[7,8], potential fields based on physics models[9-12], and digital pheromones based on insect models[13-17]. Digital pheromones are similar to potential fields, but they more naturally lend themselves to decentralized computation than potential fields. They have been used to support a variety of surveillance functions described above including path planning[18,19] and coordination for unpiloted vehicles[20,21], positioning multi-sensor configurations[22], surveillance, target tracking and trailing, and maintaining line of sight communications in mobile ad hoc networks[23].

All field-based methods rely on *stigmergy*, a term coined in the 1950's by the French biologist Grassé [24] to describe a broad class of multi-agent coordination mechanisms that rely on information exchange through a shared environment. Examples from nature demonstrate that stigmergic systems can generate robust, adaptive, intelligent behavior at the system level even when the agents are simple and individually non-intelligent. In a stigmergic system, intelligence resides not in a single distinguished agent (as in centralized control) nor in each individual agent (the intelligent agent model), but in the interactions among the agents and the shared dynamical environment.

There has been much research performed on these differing approaches. They have been used to solve various standard benchmark problems (such as n-queens, Travelling Salesman Problem, Iterated Prisoner's Dilemma, RoboCup Soccer, RoboCup Rescue, and Trading Agent Competition). However, these benchmark applications do little to convince security personnel of the value of a particular technology to solving their problem. Rather than using standard benchmarks this paper evaluates the use of digital pheromones in realistic scenarios relevant to the surveillance and security domains. In particular we demonstrate these capabilities using hardware appropriate for security systems: Pan, Tilt, Zoom (PTZ) cameras, ground sensors, small UGVs, and UAVs.

IV. Description of the Swarming Algorithm

This section describes the digital pheromone swarming algorithm developed to control unmanned sensor platforms used in surveillance and security. The swarming algorithm is responsible for positioning and orienting the sensor to collect the necessary data as required by the application. Digital pheromones[17,25] are modeled on the pheromone fields that many social insects use to coordinate their behavior. A digital pheromone represents information about the system and its environment. Different "flavors" of pheromones convey different kinds of information. The following sections define the flavors of pheromones used and the evaluation function for the path planning algorithm.

A. Pheromone Flavors

Each sensor platform maintains its own version of a pheromone map. The map covers the region of space that the platform is currently operating in called the Area of Interest (AOI). There are five primary classes of pheromones involved in the control of the sensor platforms:

1. Φ_Θ Search (or Uncertainty) pheromone attracts a sensor to areas that need to be searched. In a mature application this is a formal measure of the uncertainty about an area. Different flavors of Uncertainty pheromone can be used to model different types of uncertainty remaining in a surveyed area. For example, uncertainty about the presence of a moving entity in an area may be low based on ground sensors in the area, but our uncertainty about the type and identity of that entity remains high until a different sensor can take a look. High uncertainty (Φ_Θ) attracts sensors that can reduce the level of uncertainty about the presence or absence of targets in that area.
2. Φ_r Sensor Request pheromones are deposited by one sensor that has detected a possible target but needs additional sensor assets to complete the identification task. Different request pheromones recruit specific sensor capabilities to the tasks of identifying and tracking the target. It is used by other sensors to determine whether their capabilities are needed to support the detection, recognition, or tracking tasks.
3. Φ_t Target Tracking pheromone is deposited by a sensor while tracking a particular target of interest. Normally one sensor is dedicated to tracking a target's location, heading, and speed. This pheromone repels other sensors from the area so that duplication of effort is avoided.
4. Φ_x No-go pheromone is deposited in areas that represent no-fly zones for UAVs or no-go zones for UGVs.
5. Φ_v Vehicle Path pheromone is deposited along the planned path for each vehicle.

These pheromones are deposited on a gridded map representing a region of space. New deposits of the same pheromone flavor are added to previous deposits of the same flavor. On a regular cycle a certain fraction of the pheromone at each cell in the grid is propagated to each of the neighboring cells in the map and a certain fraction of the pheromone is removed or *evaporated* using standard equations[4]. Regular deposits followed by propagations and evaporation will eventually lead to a persistent and stable pheromone field. These two pheromone maintenance operations enable the propagation of information and help ensure that only current information is maintained in the map.

B. Path Planning

The sensor platform plans the areas to be covered by its onboard sensor(s). Each sensor has a footprint that identifies what area of the space it covers. For an overhead camera this is roughly a trapezoid defined by the orientation of the camera to the ground and modulated by terrain features. For a ground-based PTZ camera this area is a wedge constrained by terrain features and other structures obstructing the view.

The swarming algorithm plans where the sensor should collect data next. For an unmanned vehicle the path consists of a set of waypoints which are broadcast to other platforms in its vicinity. The path is used to estimate what area will be covered by the sensor platform as it traverses that path. The length of the path is long enough so that potential collisions can be detected and corrective measures taken.

The unmanned vehicle evaluates different potential paths against the following high-level objectives:

1. Move quickly to areas where there is the most need for my sensor: highest uncertainty of a type my sensor can address or possible target detected that requires additional confirmation my sensor can provide.
2. Prefer to move in straight lines to conserve fuel (UAVs) or time (UGVs).

3. Prefer to move at optimal airspeeds (UAVs) or more slowly (UGVs) to conserve energy.
4. Prefer to fly at constant altitude or move on level ground to conserve energy.
5. Prefer to fly at optimal ground speed for Automatic Target Recognition (UAVs). In high winds this and objective #3 leads to a preference to fly cross wind to maintain constant ground speed near the optimal airspeed.
6. Stay away from other vehicles and planned paths to avoid collisions and duplication of effort.
7. Stay away from no-go zones.

These high level objectives are translated into a more precise Cost to Benefit formula that can drive swarming decisions. A simple way to calculate the benefit for a path (objective 1) is the sum of the expected change in Search pheromone and Sensor Request pheromone in all the cells $\aleph$ within the field of view of the sensor along the path:

$$B_p = \sum_{\aleph} \left(\theta \Delta \Phi_{\Theta} + \rho \Delta \Phi_r \right) \tag{1}$$

where θ and ρ are tuning constants. The expected change in Search pheromone and Sensor Request pheromone depends on the sensor's capabilities and its ability to reduce uncertainty or to improve the confidence in the identification of a target. For example, if the uncertainty remaining in an area is distinguishing whether the target recognized is friendly or hostile and the sensor onboard cannot make that distinction, then the expected change in Φ_{Θ} pheromone would be zero and the UxV would not be attracted to that area. In our surveillance demonstration a simplified Automatic Target Recognition (ATR) algorithm onboard the UAVs identified targets from images taken by the UAV's camera. Once a potential target was recognized the UAV would deposit Sensor Request Φ_r pheromone at that location. UGV's were attracted to Φ_r pheromone since they could take a close-up image of the target to identify it as friendly or hostile. In the facility protection scenario ground sensors deposited Sensor Request pheromone to attract a nearby available PTZ camera that would identify and track the target.

While attempting to maximize the benefits, the swarming algorithm must also attempt to minimize the costs (objectives 2-7). The cost for a path has three elements: (1) energy used, (2) potential for collision and duplication, and (3) proximity to no-go zones. The energy cost C_f includes the energy cost for speed, heading change, change in altitude or elevation, and movement parallel or perpendicular to the wind. This is dependent on the platform. The other two costs are designed to support (but not enforce) the rules that there be no collisions and no violation of the no-go zones. The Vehicle Path pheromone Φ_v and Target Tracking pheromone Φ_t describe where sensors in the area are planning on surveying in the future so that other sensors can avoid searching those areas. They are used to calculate the cost for a potential collision and duplication of search effort and help support the no collision rule. The No-go pheromone Φ_x is deposited in the no-go zones and propagates a short way into the go zones. It is used to calculate the cost of proximity to a no-go zone and helps support the rule forbidding violation of that space. This pheromone provides a "soft" boundary so that UxVs can sense when they are nearing a no-go boundary and can begin planning maneuvers to avoid it. These three pheromones are summed along with the energy cost for each segment of the move $\Im$ to arrive at a total cost for the path:

$$C_p = \sum_{\Im} \left(\phi C_f + \tau \Phi_t + \upsilon \Phi_v + \chi \Phi_x \right) \tag{2}$$

where ϕ, τ, υ, and χ are tuning constants. The evaluation function for a path is then:

$$\mathrm{T}_p = \frac{\sum_{\aleph} \left(\theta \Delta \Phi_{\Theta} + \rho \Delta \Phi_r \right) + k}{\sum_{\Im} \left(\phi C_f + \tau \Phi_t + \upsilon \Phi_v + \chi \Phi_x \right) + k} \tag{3}$$

where k is a constant to avoid irregularities when the benefit or cost evaluate to zero.

When a new path is required, a search is performed to find the best path. Different exploration strategies can be employed. One approach repeatedly applies Eqn (3) to random cells reachable within a certain radius of the current waypoint in the path (and the constraints of the turning radius of the vehicle) and either picks the best point as the next waypoint or selects one stochastically using a weighted roulette wheel. This is repeated to identify each waypoint in the path. Multiple paths are evaluated in their entirety using Eqn (3) to select the best path. Paths that end up leading to a collision with other UxV planned paths or that enter no-go zones are eliminated from consideration. The application of this rule is one example of how the emergent properties of this algorithm can be managed to enforce hard constraints imposed on the system.

The tuning constants in the path evaluation function can be varied to improve the mission effectiveness of the system based on key performance parameters. Tuning can be performed manually using a Design of Experiments approach and simulation studies. Preferably the constants are tuned using an optimization algorithm such as the genetic algorithm described in previous work[26]. In this study the constants were manually modified from the tuned results of previous work. Experience has shown that the swarm performs well over a wide range of values for the tuning constants. Once the constants of Eqn (3) are tuned they are suitable for a number of applications.

C. Maintenance of the Distributed Pheromone Maps

Since each sensor platform maintains its own pheromone map, information needs to be exchanged to ensure that the maps remain reasonably synchronized. Sensor platforms broadcast the following information to their peers:

Current location, heading, and speed – Used to locate all the other UxVs and human patrols in 3D space. Receiving UxVs deposit Vehicle Path Φ_v pheromone at that location.

Planned path – The current UxV path plan as described above. Receiving sensor platforms deposit Φ_v pheromone along the entire path.

Area Covered – Each sensor collection event is broadcast to peers with a polygon describing the field of view of the sensor and the type of data collected. This message updates the relevant uncertainty for all those cells. Receiving sensor platforms remove Uncertainty Φ_Θ pheromone in proportion to the reduction of uncertainty reported. In the demonstration PTZ, UAV, and UGV cameras would all report Area Covered messages when they had taken a picture.

Sensor Request – When a sensor makes an initial target detection it can recruit additional sensor assets to help complete the identification task by sending this message. This causes a deposit of Sensor Request Φ_r pheromone on each platform's pheromone map. The type of sensor request indicates what kind of confirmation is required. Sensors capable of taking the target detection to a higher level of confidence and specificity will be attracted to that Sensor Request pheromone. In the demonstration, UAVs and ground sensors would recruit any ground camera for video confirmation. This was followed by a tracking request that only the fixed and UGV PTZ cameras could satisfy.

Target Tracked – when a sensor capable of target tracking decides to track a target (based on a Sensor Request for tracking an identified target) it broadcasts this message regularly with updated target positions. Receiving platforms deposit Target Tracking Φ_t pheromone so they neither decide to track that target nor survey in that area.

The pheromone fields of all sensor platforms are initialized with $\Phi_\Theta = 1$ (except in no-go zones), $\Phi_v = 0$, $\Phi_t = 0$, and $\Phi_r = 0$. The No-go pheromone, Φ_x is initially deposited in the no-go areas and propagated a short way into the adjacent cells. After that Φ_x remains static unless the user makes a change in the no-go areas. The evaporation and propagation factors for Φ_x are set to 1 and 0 respectively so it neither evaporates nor propagates. Uncertainty pheromone is regularly deposited on the pheromone map until an area is surveyed. The pattern of deposits is determined by the application as discussed below. This pheromone is removed when a sensor covers that location.

V. Description of the Operator System Interface

The Operator System Interface (OSI) was developed to evaluate techniques for enabling a single operator to monitor and manage multiple sensor platforms of different types in a surveillance application. The OSI is a geospatially based control and display system that allows for operator input and displays a visual representation of the location and status of all the entities in the system. The OSI displays advisories, cautions, and warnings; system status; time-stamped events; imagery from PTZ cameras and the cameras aboard the UAVs and UGVs; and a scalable bird's-eye view of the area of interest. This bird's-eye view includes the real-time position of all UxVs, ground sensors, PTZ cameras, and human patrols as well as targets as they are located and identified (see Figure 1). The OSI also provides audio cues when events occur, such as system health issues or intruder detections. The OSI is designed with human factors in mind, such that the operator needs to perform a minimal set of tasks to maintain the swarm and to configure the interface itself.

The user has considerable flexibility in configuring and customizing the OSI. The asset selection tree governs what information is placed on the display. Right clicking on entities in the map-based display window provides a list of commands and information that is available for that unit. Several key features of the OSI that promote speed and accuracy for control and display actions, high situation awareness, and general ease-of-use, are discussed below.

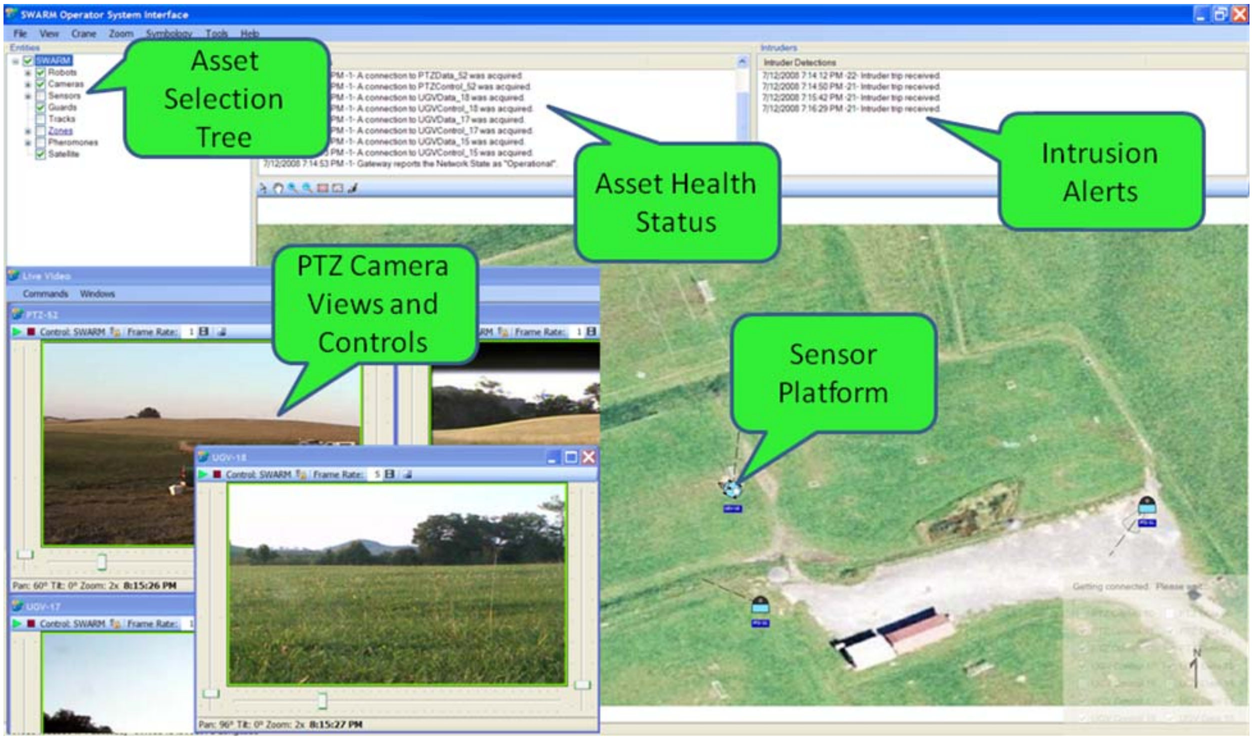

Figure 1. Graphical Operator System Interface overhead view

Simple Drop-Down Menus – The number of drop-down menu headings was limited to seven, and each heading is only one layer deep. This simplicity allows users to quickly get to all functions without having to navigate through many menu layers. This simplicity should also help the user to quickly learn the system's features. Finally, and perhaps most importantly, this simplicity should enhance the operator's ability to learn and remember where a function resides in the menu hierarchy, even if workload and time pressures become high.

Point and Click Control-Display Compatibility – The OSI takes full advantage of the inherent and excellent control-display compatibility afforded by using a mouse and cursor on a geospatial display. For example, if the operator wants to take control of a particular camera, he/she simply clicks on the corresponding camera icon on the display. A pop-up window then appears, allowing the user to control pan, tilt, zoom, and frame rate parameters.

Goal-Based Zoom Capability – The OSI incorporates a traditional point and click display zoom capability, wherein the user can manipulate the mouse and mouse wheel to center, zoom in or out, and/or drag the displayed area. In addition to this capability, the OSI includes a "goal-based" zoom capability. This feature allows the operator to quickly scale the display to show all entities or areas of interest. For example, if the user's goal is to see where all of the ground vehicles are, he/she can click on the "Zoom" pull down header, and can then click on "Ground Vehicles" within that layer. Thus with only two clicks the user is assured that all ground vehicles are displayed. Other zoom-to options are "area of interest", "cameras", "ground sensors", "tracks" and "all entities".

Symbology Flexibility – The OSI was designed to have extreme flexibility in displaying different symbol sets. Symbology standardization is a major issue with unmanned vehicle control stations. Different services, and different communities within the services, use different symbology sets for their interfaces. Ideally, a standard symbology set will eventually be chosen and agreed upon. When that choice is made, the OSI will be able to accept and display it. Currently the OSI can display MIL-STD-2525B, MIL-STD-1787C, MIL-STD-1477C, and a custom designed symbol set. The operator can switch between these symbol sets on-the-fly with just two mouse clicks.

VI. Surveillance Flight and Ground Tests

This section describes the test scenario, vehicles, systems, interfaces for the initial test and demonstration. This demonstration occurred at NASA's Wallops Island test range in July 2007.

A. Unmanned Vehicle Systems Demonstrated

The AAI Aerosonde Mk 4.1 UAV was chosen as the air platform (Figure 3). This UAV cruises at 25 m/s, carries a maximum payload of 5 kg, can operate over 30 hours and has a minimum turning radius of roughly 140 meters.

Figure 3. AAI Aerosonde Mk 4.1 UAV

The nominal operating altitude for the aircraft in this test was 230 meters. The UAVs were equipped with a Canon PowerShot S80 color camera to capture high resolution still images.

Modified Pioneer 3-AT robots were used for the ground vehicles (Figure 2). They can move at 3 kph, climb 45^o grades, carry 30 kg of payload, operate 3-6 hours, and turn in a 40 cm radius. The UGV is equipped with 8 fore acoustic proximity sensors, GPS, digital compass, video camera, and a simulated target confirmation sensor (an RF receiver).

Figure 2. Pioneer 3-AT ground robot

Both the UAV and the UGV were equipped with an Augusta Systems SensorPort payload computer utilizing a 1.4 GHz, low voltage, Pentium-M processor module running Windows XP Embedded on a 1 GB Compact Flash. A MeshNetworks WMC6300 2.4 GHz subscriber card providing a 1.5 Mbps (6 Mbps burst rate) ad-hoc mesh network supported communications of command and control and imagery data with the ground stations. A single laptop on the MeshNetwork is used as a "payload control station" for monitoring the vehicles and providing manual control in emergencies. A second laptop was used for the Operator System Interface to demonstrate techniques for human systems integration.

Augusta Systems developed the software to interface the swarming algorithms with the other system components including the cameras, the MeshNetwork communications network, the autopilot, the robot microcontroller, the GPS, and the payload control station. NewVectors developed the swarming algorithms operating on the payload computer and software for visualizing the pheromones and status of the swarming algorithms on the payload control station. Figure 4 shows the architecture of the systems and the communications links among the components.

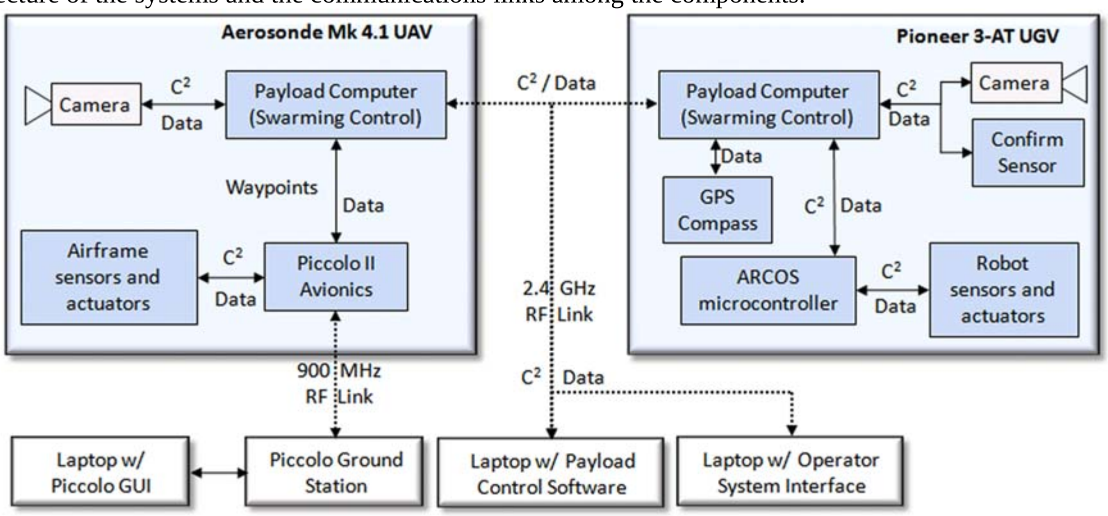

Figure 4. UAV and UGV System Architecture for Surveillance Demonstration

B. Surveillance Demonstration

The flight tests were held at NASA's Wallops Island test range in July 2007. Two Aerosonde UAVs were launched and placed under the control of the swarming algorithm along with four Pioneer UGVs. The UAVs were responsible for a 2.5 km by 1 km playbox, while the UGVs were responsible for a smaller 250 meter by 75 meter portion of that playbox (see Figure 5). Four targets were placed within the UGV playbox and two targets just outside that playbox but still within the UAV playbox.

Both the UAVs and UGVs executed the swarming algorithm described above except that the C_f cost factors were not included since they were not required for the demonstration. A simplified ATR algorithm was implemented on the UAVs. When a UAV or UGV sensor viewed an area the Search pheromone was removed and the regular deposits were stopped. When 80% of the area had been surveyed regular deposits of Search pheromone were restarted. When the ATR on the UAV identified a friendly target (a white circle, see Figure 6) the target location was designated with a box and the image sent to the OSI. When the UAV's ATR detected an unknown target (a white cross) it deposited Sensor Request pheromone at the detected target's location. This attracted the UGVs which possessed the necessary target identification sensor: an RF receiver detecting an RF transmitter embedded in the targets. UGVs needed to be within 6-8 feet of the target to pick up the RF signal to identify the target. Once a UGV identified a target it was reported to the OSI and the rest of the swarm so that further sensor hits on that target would be ignored. The UAV's ground projection of target location was within 50 meters of the actual location, a function of GPS error and UAV avionics error. This error wasn't a problem since the Sensor Request pheromone would propagate and the UGVs would survey around the location estimate until it found the actual target.

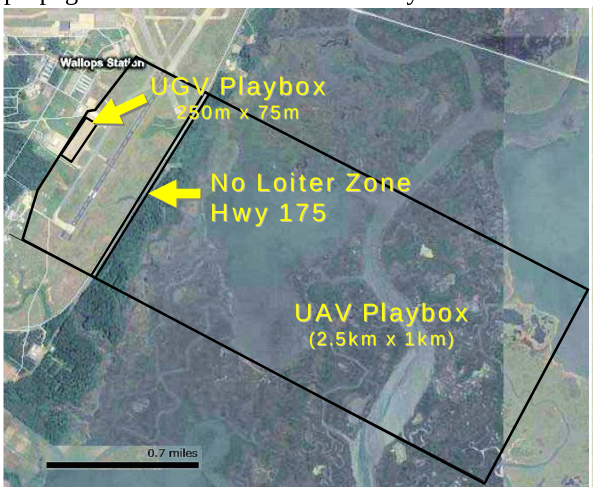

Figure 5. UAV and UGV playboxes

Figure 6. Image from UAV detecting friendly target

For safety reasons, pilots on the ground reviewed all the flight paths planned by the swarming algorithm. If they did nothing the plans were loaded into the autopilot for execution. If the plan was rejected the swarming algorithm would generate a new plan. NASA safety engineers also requested that time spent over a highway cutting through the UAV playbox be minimized (Figure 5). We accommodated this requirement by defining a new class of No-go pheromone called a No-loiter pheromone. It was evaluated the same as the boundary No-go pheromone in Eqn (3) for building flight paths, but flight paths were allowed to cross through the No-loiter pheromone without being rejected. By placing No-loiter pheromone across the road, the waypoint algorithm would tend to pick waypoints that resulted in crossing the road at a near-right angle (Figure 7) thus minimizing time spent directly over the highway.

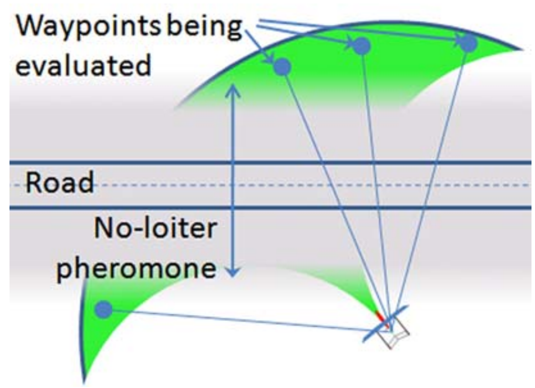

Figure 7. No-Loiter Pheromone minimizes time UAV spends overflying highway

On the day of the demonstration the swarming algorithm had to deal with a few new surprises. All six UxVs were successfully launched, but payload communications with one of the UAVs failed. Without any human intervention the second UAV automatically adapted to the missing UAV and surveyed the area by itself. However, due to the size of the UAV playbox that had to be covered by the one remaining UAV and the need to stay 200m away from the edge of the UGV playbox due to NASA safety constraints, the UAV missed the targets in the UGV playbox. Still, without the expected help of the UAV, the UGVs' normal swarming activity brought them within the requisite range of 6-8 feet to find and identify three out of the four targets placed within the 200,000 square foot playbox. Finally, prior to the demonstration, the acoustic collision detection sensors on the UGVs started generating spurious contacts. The sensors were turned off for the demonstration so the collision prevention function of the swarming algorithm was entirely responsible for guaranteeing that no two robots collided during the demonstration further demonstrating the robustness of the algorithm to hardware failures.

VII. Perimeter Protection Tests

A second test and demonstration was held the following year adding ground sensors, human patrols, and fixed ground and aerial PTZ cameras, but without the UAVs, to evaluate a suite of sensors for perimeter protection. A

Hostile Environment Airfield Protection (HEAP) OPerational SITuation (OPSIT) scenario was used. In this scenario an airfield is to be protected against penetration by hostile forces through the employment of a distributed, intelligent, and largely autonomous base perimeter protection system comprised of unattended sensor systems, unmanned vehicles, and an advanced network infrastructure. The system needed to be capable of complementing the limited number of personnel available for patrolling and monitoring the security of the base's perimeter.

As part of this test, the system software for integrating the hardware components was updated to a platform based architecture utilizing Augusta Systems' EdgeFrontier technologies within a new message framework enabling improved control of message flow, avoidance of congestion, and simplified system maintenance.

A. Description of the Hardware

Pioneer 3 ground robots were updated with new motors and control software running on an Asus EeePC – a small form factor laptop PC. With the new motors and control software speeds were increased from 3 kph to 29 kph. They were outfitted with either Axis 213 or 215 PTZ cameras. A SensorPort computer hosted the EdgeFrontier communications software and the swarming control logic. The same 2.4 GHz MeshNetwork communications system was employed for inter-swarm and base station communications. Two robots were used in the demonstration.

Figure 8. Modified Pioneer 3-AT Robot for Facility Patrol

A moored balloon carrying an Axis 213 PTZ camera was also planned for the demonstration, but an accident during testing destroyed the camera and it was not used for the final test.

Two fixed ground PTZ cameras provided additional surveillance capabilities. One of the fixed PTZ cameras was an AXIS 232D, a network dome color camera that outputs motion JPEG and MPEG-4 video and full PTZ control over an IP network. It features an 18x optical zoom and autofocus lens. It is capable of continuous 360^o pan and 90^o tilt operation. The second fixed PTZ camera was a Pelco Spectra III. It is a dome color camera with 16x optical zoom, autofocus lens with full 360^o pan and 90^o zoom. Status and commands are sent through an RS-422 link and video is transmitted over coaxial cable to an Axis 241 video server that served as a frame grabber and gateway to an IP network for transmitting the images to the Sensor Port control station.

Figure 9. Axis 213 and 232D PTZ cameras

A Crane MicroObserver ground sensor network was used for the perimeter intrusion sensors. Twenty MicroObserver 1045 acoustic and seismic sensors were wirelessly connected to the MicroObserver gateway. This in turn communicated over an IP network with the SensorPort control computer. The ground sensors were placed roughly 12 meters apart since each had a reliable detection range of 6 meters. The system is capable of creating tracks from multiple sensors, but this requires a higher density of sensor nodes and it can be confused when multiple intruders are involved. Instead the swarming algorithm just listened to individual sensor trips and relied on the PTZ cameras to track targets.

Figure 10. Crane MicroObserver gateway and 1045 acoustic and seismic sensor

Finally human patrols were outfitted with a Garmin GPS tracking system that communicated wirelessly to a base station connected to a laptop computer. Though not under swarming control, the human patrols were integrated into the swarming logic. The reported location of a patrol was broadcast to the autonomous swarm entities that would deposit Vehicle Path Φ_v pheromone at those locations in their pheromone maps. The propagation radius estimated the ground area visible to the human patrols so that other sensors would avoid duplicating the human surveillance activity. In this way the swarm was able to easily coordinate its autonomous surveillance tasks with available human patrols.

The UGVs, PTZ cameras, and ground sensor gateway were each connected to SensorPort computers running the communications and swarming control software. The SensorPort is a Windows XP embedded computer platform equipped with a 1.4 GHz low-voltage Pentium-M processor, 1 GB RAM, data storage, and I/O ports. The SensorPorts are connected over a 2.4 GHz wireless MeshNetwork. Figure 11 shows the architecture of the systems and the communications links among the components.

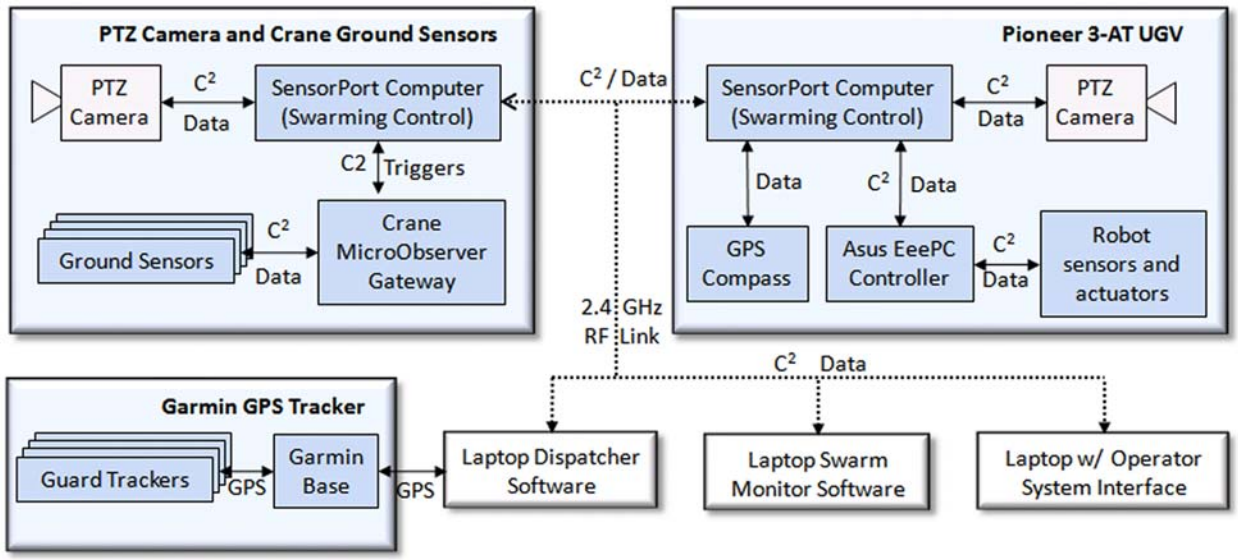

Figure 11. UGV, Ground Sensor, PTZ Camera Architecture for Perimeter Protection Demonstration

B. Perimeter Protection Demonstration

Multiple test scenarios were created by varying the number of intruders, direction of intruder approach, and intruder tactics. The goal of each scenario was for the system to effectively prosecute the intruders by detecting and then tracking them for a period of time long enough to consider them neutralized.

The soccer fields in Laurel Point, West Virginia were used as the testing grounds. Figure 12 depicts the demonstration set-up in the form of an aerial photograph of the testing grounds, in which the various assets used in the tests have been shown. A single layer of ground sensors runs along two sides of the Area of Interest (AOI), which is approximately a rectangle with dimensions of 80 meters by 150 meters.

The ATR function was partially simulated in this demonstration. Each intruder is equipped with a GPS tracking unit, which transmits the location of the intruder at any time to the PTZ cameras, but not to the collaborative control software. Intruders can either be detected by a legitimate trip of a ground sensor or by a PTZ camera when the GPS coordinates overlap with the current view of one of the PTZ cameras. A *Sensor Request* message was sent by a ground sensor or PTZ camera when an intruder was detected. Once the swarming algorithm directs a PTZ camera to begin tracking an intruder, the camera uses the GPS coordinates to actually track the intruder through its pan range. An intruder is considered neutralized either when a guard dispatched to prosecute the intruder comes within a prescribed short distance of the intruder or the intruder has been tracked continuously for a prescribed period of time.

It is possible for a camera to lose the target being tracked when the target leaves the operational range or field of view of the camera. In such cases the swarming algorithm causes another camera to pick up the target and resume tracking it to the completion of the target's prosecution. This phenomenon was observed in some of the demonstration tests.

The Search or Uncertainty Φ_{Θ} pheromone deposits were altered for this scenario. Since intruders can only enter the protected area from outside the perimeter, Uncertainty pheromone deposits were made only at the perimeter and propagated into the protected area at a speed roughly equal to the speed of an intruder on foot. As a sweep was made of an area, the Uncertainty pheromone was cleared out from the field of view of the sensor. However, new Uncertainty pheromone would immediately begin to propagate back into that area from the adjacent regions representing possible intruders just beyond the range of the sensor moving into the previously surveyed area. Thus the Uncertainty pheromone maintained an accurate representation of where potential intruders could still be hiding based on the history of sensor sweeps in the area.

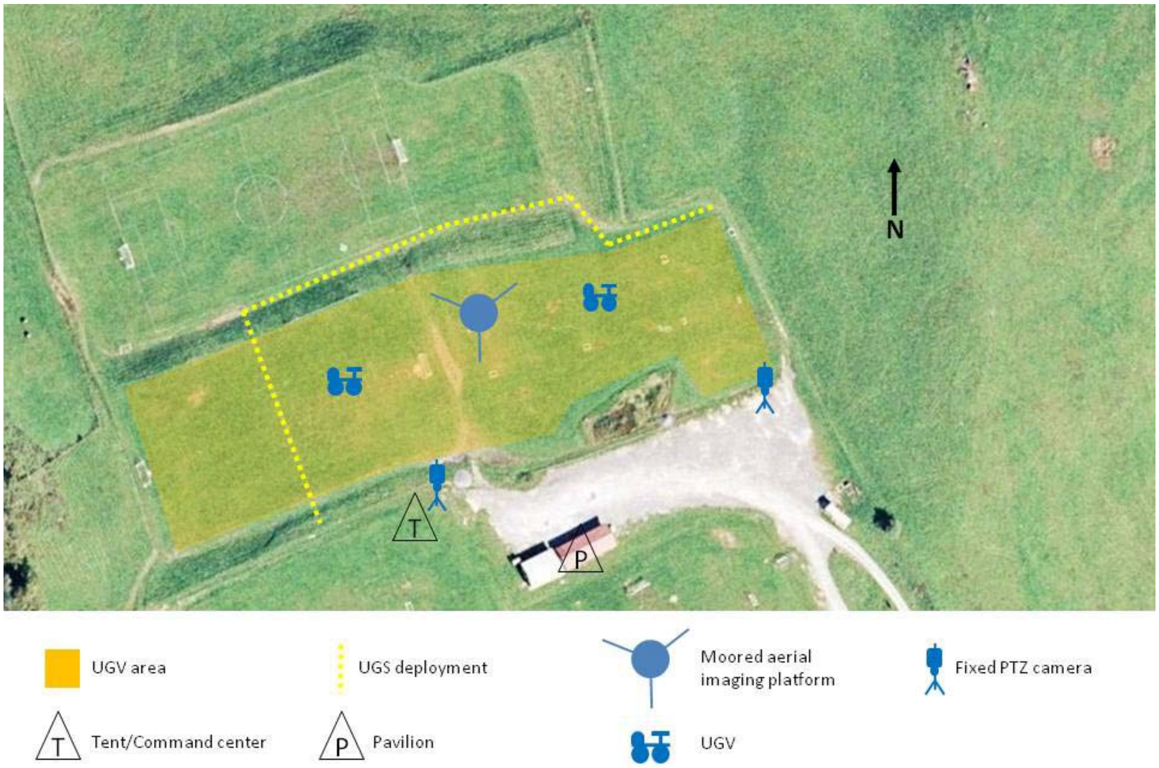

Figure 12. Overhead view of soccer field and placement of sensors

Since energy conservation is critical in persistent surveillance and patrol applications all the nodes in the network were designed to minimize energy usage. Ground sensors were designed to operate with only the acoustic sensors powered on. When the acoustic sensor tripped, the seismic sensor was activated to further classify the intrusion and eliminate acoustic false alarms. For the UGVs energy usage was minimized by adjusting the parameters of Eqn (3) to keep the UGV stationary until it was needed elsewhere such as supporting the tracking of multiple intruders in an area.

Eighteen separate tests were performed. Each test involved between one and five intruders, entering from different angles or employing different strategies to try to confuse or thwart the swarming algorithm.

Figure 13 shows one of the tests that included five intruders entering the perimeter from multiple angles one of them bypassing the UGS field entirely. In this scenario all five intruders were detected, tracked and neutralized within one minute of the first intruder detection event by one of the UGS. A summary of each test result is presented in Table 1. Three neutralization methods were used. The first required the camera to track the intruder until a guard arrived. The other two only required the camera to track the intruder for either 30 seconds (T30) or 15 seconds (T15) before the intruder was considered neutralized. The total time from when the first intruder was detected entering the perimeter until the last intruder was neutralized is listed in the table. DT.001 and DT.003 were similar except that the UGVs were not present in DT.001. Other identical runs are marked as “a” and “b”. Those marked with an “*” included at least one intruder that entered the field from the East, bypassing the UGS’s entirely. That intruder was only detected by the normal surveillance activities of one of the four cameras. The number of intruders tracked and neutralized by each UGV or PTZ camera is also listed in the table. An “n+” indicates the number of intruders that the sensor successfully tracked until neutralized and an “n-“ indicates the number of intruders that the sensor started to track but lost.

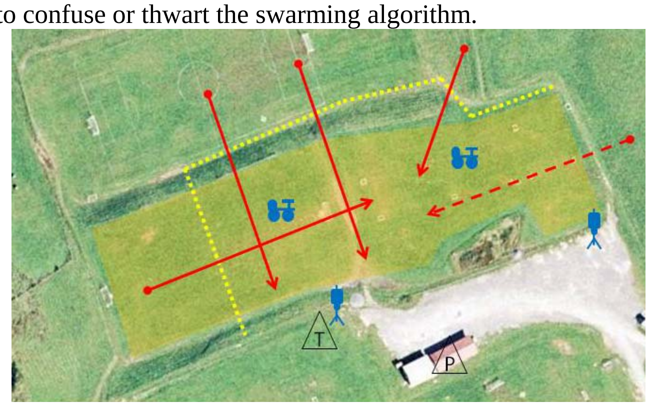

Figure 13. DT.013b with four cameras, five intruders and one avoiding the UGS field

Table 1. Summary of Test Results

Test	Num Intruders	Neutralize	Time (mm:ss)	UGV-17	UGV-18	PTZ-51	PTZ-52
DT.001	1	Guard	1:42	<na>	<na>	1+	
DT.002a	1	T30	0:45		1+		
DT.002b	1	T15	0:27	1+			
DT.003	1	T15	0:21				1+
DT.005	1	T15	0:31		1+		
DT.006	1	T15	0:29	1+			1-
DT.007	2	T15	0:58	1+	1+		
DT.008	2	T15	0:58				2+
DT.009	2	T15	0:45	1+	1+		
DT.010	3	T15	1:03	1+	1+		1+
DT.011*	3	T15	0:53		1+		2+
DT.012*	4	T15	0:59	2+		1+	1+
DT.013a*	5	T15	1:58	1-, 1+	1-, 1+	1+	1-, 2+
DT.013b*	5	T15	1:02		1+	2+	2+
DT.015a	2	T15	0:42				2+
DT.015b	2	T15	0:50	1-	2+		1-
DT.017	2	T15	0:58			1-	2+
DT.018*	2	T15	0:56	1+		1+	

* These runs include at least 1 intruder entering the perimeter while bypassing the UGS field

Overall, the system performed well during operational testing: all intruders were detected, tracked, and neutralized within two minutes with a minimum of human intervention. In the tests in which there was one more intruder than available tracking cameras, the swarming algorithm successfully multiplexed the tasks among the available cameras to detect and track all five targets until prosecution. The swarming algorithm demonstrated its effectiveness in coordinating the sensors under its control to ensure that all intrusion attempts were thwarted.

VIII. Conclusion

Previous work demonstrated the versatility and adaptability of the swarming algorithms for controlling multiple air and ground vehicles. This research demonstrated the capabilities of this software in controlling a wider range of sensor platforms in more advanced scenarios. The ability to control PTZ cameras and merge data collected from ground sensors was demonstrated. Additionally the ability to seamlessly accommodate and cooperate with any number of human patrols was demonstrated in the facility protection scenario. The algorithms demonstrated an ability to easily handle the addition or removal of entire nodes as well as accommodate the errors in communications and noise common in sensors while still effectively accomplishing their overall mission. The OSI demonstrated how one person could monitor, visualize and help manage multiple diverse swarming sensors building a common operating picture over a large area. In summary the onboard digital pheromone swarming algorithms successfully coordinated the behaviors of multiple air and ground sensors in a realistic surveillance and security applications.

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