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Flocking for Heterogeneous Robot Swarms: A Military Convoy Scenario

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***Abstract*— In this paper we apply a popular flocking control algorithm to a heterogeneous swarm of robots. The flocking controller contains separation, cohesion and velocity matching terms and has been shown to converge properly in the case of homogeneous swarms. The swarm models a military convoy unit with supply vehicles, defenders, and attackers. Each class of vehicle possesses different maneuvering capabilities and different objectives. In each case we modify the controller accordingly and analyze the emergent behavior of the swarm.**

I. Introduction

Swarm control is a rapidly growing field in robotics. The premise of swarm robotics is that there are numerous advantages of using a group of relatively simple robots to accomplish a task over using a single highly complex robot. In swarm robotics, control is decentralized by assigning to each swarm member a simple control method that, when integrated into the full swarm, will result in higher-level swarm performance that appears to be based on a highly-sophisticated control system. The performance of the swarm that results from linking the swarm robots together is known as emergent behavior.

In swarm control, there are two major fields into which swarms can be categorized, heterogeneous and homogeneous. Homogeneous swarms are those made up of robots that are completely identical, both physically and with respect to their control laws. To date, there has been a great deal of work done with homogeneous swarms and their control methods (see [1], [2], [3], [4], and [5] and the references within for detailed literature review), but there has been considerably less attention devoted to the field of heterogeneous swarms. Heterogeneous swarms combine different kinds of robots that each have their own particular strengths. When these robots work together, the swarm displays the sum of its individual units' strengths (see [6] and [7]).

The motivation for this control design project is military in nature, but the concepts developed could be used in a myriad of applications, both military and civilian. Currently, military convoy operation is extremely hazardous due to the extensive use of Improvised Explosive Devices (IED's). The thrust of the control design project was to lay the ground work for an autonomous convoy that can transport supplies to needed areas without putting human lives at risk. The convoy should be able to drive itself to a given destination while avoiding obstacles, avoiding collisions with other convoy units, maintaining convoy consolidation, and responding to enemy ambushes. In addition the convoy needs to be able to operate in areas far from centralized command stations, where teleoperation becomes unfeasible due to communication constraints. Furthermore, due to the hostile nature of military operational environments, the convoy needs to be able to overcome the loss of individual members and as a result, must not rely on a single "brain" robot to coordinate the swarm. To increase the convoy's performance, the swarm will be heterogeneous; employing two types of robots, a supply unit and a defender unit. The goal of this paper is to build upon past research into successful homogenous swarm techniques and apply them to a homogeneous setting and investigate the resulting emergent behaviors.

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II. Swarm Model

Let $x_i = [x_i, y_i]^T$ and $v_i = [v_{xi}, v_{yi}]^T$ denote the position and velocity of robot $i = 1,\dots,N$. The dynamics of the robots are given by the second order system:

$$\begin{bmatrix} \dot{x}_i \\ \dot{y}_i \\ \dot{v}_{xi} \\ \dot{v}_{yi} \end{bmatrix} = \begin{bmatrix} v_{xi} \\ v_{yi} \\ u_{xi} \\ u_{yi} \end{bmatrix}$$

where $u_i = [u_{xi}, u_{yi}]^T \in U$ is a bounded force input vector for each robot.

The basic control strategy is fashioned after the work on homogeneous swarms in [1]. The control inputs applied to the members of the swarm will be based on two basic parts,

$$u_i = a_i + \alpha_i$$

one from an artificial potential field specific to the type of robot encoding a variety of position-based objectives, $a_i = \sum \nabla \phi$; and one universal velocity matching term $\alpha_i = 1/N \sum_{i=1}^{N} v_i$, that contributes to swarm cohesion and alignment. A visual representation of the inputs taken from [1] illustrates the result of the sum of two control inputs on a single robot in Figure 1.

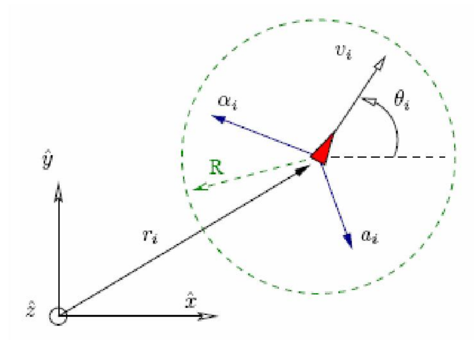

Fig. 1 *Control inputs applied to agent i. [1]*

The first type of robot in the swarm is the *supply unit*. In a military sense, the supply unit's only job is to get supplies from point A to point B, but from a control standpoint, the supply unit is the backbone of the swarm. The second kind of robot is the *defender*. The defender does not seek to drive to the endpoint, but instead maintain a defensive perimeter around the supply units. Lastly, an autonomous *attacker* unit was added to the simulation. In real life, however, the attackers will likely be either humans or human controlled vehicles. The control laws for all of these units are based upon the requirements set out in Table (1).

Table 1: Unit Control Law Design Parameters

Supply Unit	1. Move to goal (defined convoy goal) 2. Avoid collision with other supply units 3. Avoid collisions with obstacles 4. Avoid attacking units 5. Match average velocity of all supply units in sensor range
Defender Unit	1. Move to changing goal (position between supply units and attackers) 2. Avoid collision with other defender units 3. Avoid collision with supply units 4. Avoid collisions with obstacles 5. Intercept attackers that get too close to the supply units 6. Match average velocity of all supply units in sensor range
Attacker Unit	**Used for simulation purposes only (not autonomous in real life)* 1. Move to goal (centroid of supply units) 2. Avoid collisions with obstacles 3. Match average velocity of all supply units in sensor range

III. Control Strategy

Based on the potential function developed by Tanner *et al* [1], a controller for collision avoidance is used. It is a function of the i^{th} robot's distance from any other robot (j) in the swarm (r_{ij}), where r_{min} is the desired position, and R is the point at which the robots no longer affect each other (equations below followed by graph in figure 2).

$$\phi_{ij} = \begin{cases} -a_1\|r_{ij}\| + \dfrac{a_2}{\|r_{ij}\|^2} + \log(\|r_{ij}\|) & \|r_{ij}\| < R \\ -a_1 R + \log(R) + \dfrac{a^2}{R} & \|r_{ij}\| \geq R \end{cases}$$

$$a_1 = \frac{1}{r_{min} + R} \qquad a_2 = \frac{R \cdot r_{min}}{r_{min} + R}$$

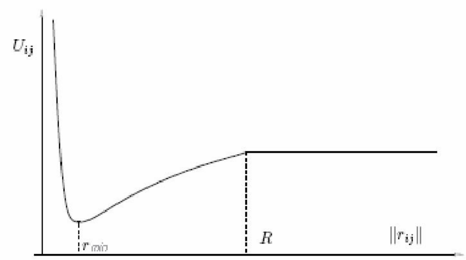

Fig. 2 *A nonsmooth inter-agent potential function [1]*

This function is used in the potential fields of both supply and defender units for collision avoidance, simply with different r_{min} and R values based upon vehicle dynamics, sensor ranges, and the desired mission-dependent performance. As a robot approaches zero distance from another robot, the potential value approaches infinity creating a very strong repulsive force. If the robot is farther away than the r_{min} value, it is pulled towards the r_{min} value providing it is not farther than the R function cutoff distance.

The potential function for the convoy goal is a standard parabolic attractor function. In this equation (seen below, followed by a graph in Figure 3) point (a,b) is the Cartesian coordinate of the goal position and (x,y) is the current position of the robot being evaluated. As can be seen below, there is a negative gradient towards the goal at every position on the graph except for the goal position itself. This continuously drives all robots to the goal.

$$\phi_{goal}(x, y) = (x - a)^2 + (y - b)^2$$

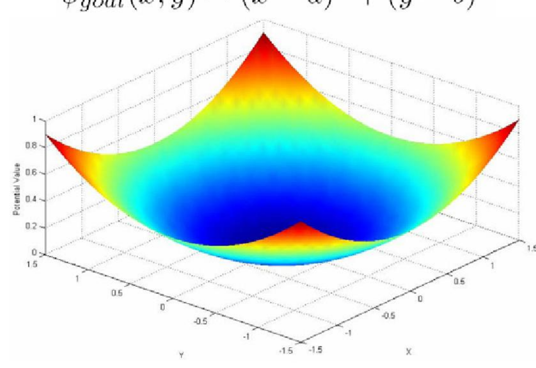

Fig. 3 *A parabaloid with the goal at the minimum*

The obstacle avoidance function is a function defined by Latombe [8, page 300] (seen below) where d(x, y) is the distance from the robot to the nearest edge of the obstacle, D_0 is the cutoff distance where the obstacle avoidance function stops contributing to the potential field, and K_{obst} is a scaling factor.
This function, like the collision avoidance function, grows to infinity as d(x,y) approaches zero to push robots away from the obstacle.

$$\phi_{obst}(d(x,y)) = \begin{cases} K_{obst}\left(\frac{1}{d(x,y)} - \frac{1}{D_0}\right)^2 & d(x,y) \leq D_0 \\ 0 & d(x,y) > D_0 \end{cases}$$

In addition to these control law components, a function is used in each type of robot's control law that will push the robot to match the velocity (speed and heading) of the total swarm where N is the number of units in the convoy and v_i is the velocity of the i^{th} unit.

$$\alpha_i = 1/N\sum_{i=1}^{N} v_i$$

Another control law treats enemy units as large obstacles for supply robots and localized goals for defender robots. This will give the swarm a reactive capability to the introduction of an enemy unit in the known workspace. The enemy units will be driven by a simple control law that guides them to intercept the convoy unit closest to the center of the swarm.

The combination of all of these simple control components results in what appears to be a highly-sophisticated intelligent swarm. The full control laws for the supply, defender, and attacker units can be seen listed below, where N_s is the number of supply units, N_d is the number of defender units, N_a is the number of attacker units, and N_o is the number of obstacles.

Supply:

$$U_i^S = \underbrace{\phi_{goal}(x_i,y_i)\big|_{(a,b)}}_{\text{goal potential}} + \underbrace{\sum_{j=2}^{N_s}\nabla\phi_{i,j}}_{\substack{\text{collision}\\\text{avoidance:}\\\text{supply units}\\\text{(excluding self)}}} + \underbrace{\sum_{k=1}^{Na}\nabla\phi_{i,k}}_{\substack{\text{attacker}\\\text{avoidance}}} + \underbrace{\sum_{m=1}^{N_o}\nabla\phi_{obst_{i,m}}}_{\substack{\text{obstacle}\\\text{avoidance}}} + \underbrace{\left(\frac{1}{N_s}\right)\sum_{n=1}^{N_s} v_n}_{\substack{\text{supply unit}\\\text{velocity matching}}}$$

where:

(a,b)= Cartesian goal position

Defender:

$$U_i^D = \underbrace{\phi_{goal}(x_i,y_i)\big|_{(a,b)}}_{\text{goal potential}} + \underbrace{\sum_{j=1}^{N_s}\nabla\phi_{i,j}}_{\substack{\text{collision}\\\text{avoidance:}\\\text{supply units}}} + \underbrace{\sum_{k=2}^{Nd}\nabla\phi_{i,k}}_{\substack{\text{collision}\\\text{avoidance:}\\\text{defender units}\\\text{(excluding self)}}} + \underbrace{\sum_{m=1}^{N_o}\nabla\phi_{obst_{i,m}}}_{\substack{\text{obstacle}\\\text{avoidance}}} - \underbrace{\sum_{n=1}^{Na}\nabla\phi_{i,n}}_{\substack{\text{attacker}\\\text{intercept}}} + \underbrace{\left(\frac{1}{N_s}\right)\sum_{p=1}^{N_s} v_p}_{\substack{\text{supply unit}\\\text{velocity matching}}}$$

where:

$$(a,b) = \left\| \left(\frac{1}{N_s}\right)\sum_{j=1}^{N_s}(x_j,y_j) - \left(\frac{1}{N_a}\right)\sum_{m=1}^{N_a}(x_m,y_m) \right\|$$

Attacker:

$$U_i^A = \underbrace{\phi_{goal}(x_i,y_i)\big|_{(a,b)}}_{\text{goal potential}} + \underbrace{\sum_{j=1}^{N_o}\nabla\phi_{obst_{i,j}}}_{\substack{\text{obstacle}\\\text{avoidance}}} + \underbrace{\left(\frac{1}{N_s}\right)\sum_{k=1}^{N_s} v_k}_{\substack{\text{supply unit}\\\text{velocity matching}}}$$

where:

$$(a,b) = \left(\frac{1}{N_s}\right)\sum_{j=1}^{N_s}(x_j,y_j)$$

IV. Simulation Results

Figure 4 is a graph displaying the path of ten simulated supply robots exhibiting goal pursuit, collision avoidance, cohesion, and obstacle avoidance.

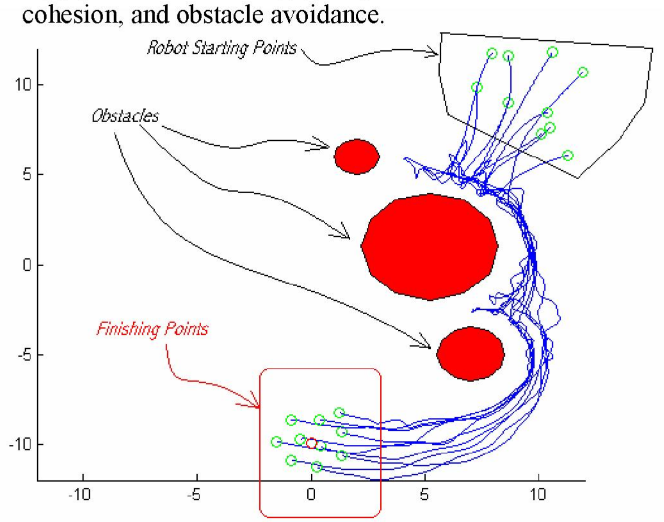

Fig. 4 *Simulation of 10-'Supply Robot' Swarm*

It is easier to understand the behavior of the swarm by looking at a visual representation of the artificial potential field that is created by summing the different potential functions. Figure 5 shows the initial positions of all units for one simulation, and Figure 6 shows the artificial potential field, as seen by a supply unit.

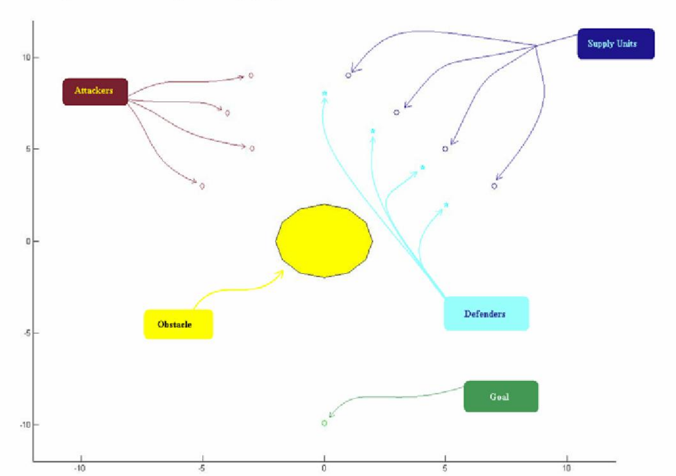

Fig. 5 *Example of an Initial Simulation Configuration*

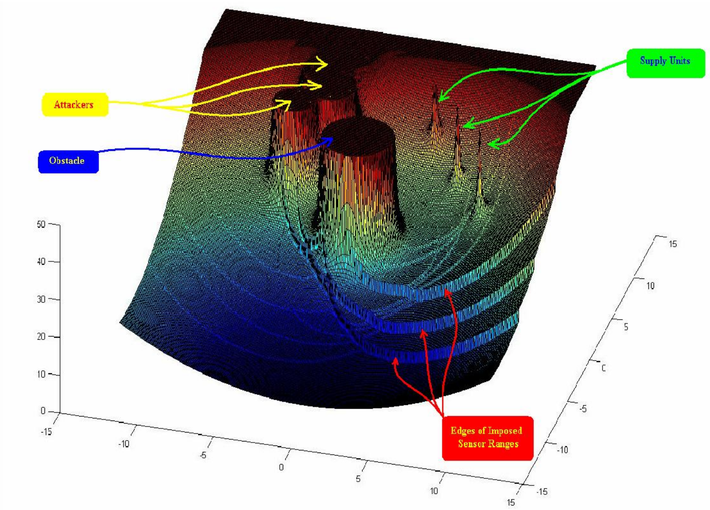

Fig. 6 *Potential Field for Supply Unit from Figure 5*

As seen in Figure 6, an obstacle creates a high potential for the space it occupies in the physical realm, as well as a small buffer distance. Attacker units, however, create a high potential for a large area around the space they physically occupy to ensure that supply units do not move within that area. Other supply units create a high potential for only a minimal area around that which they occupy in physical space. This allows supply units to get fairly close to each other, but still avoid collisions. Also, distinct 'edges' can be seen in the potential field. This is the edge of a sensor range that limits the distance at which a unit can feel the influence of another unit. Finally, the defender units have no influence on this potential field since the supply units are trying to get to the goal as fast as possible, thus it is left to the defender units to avoid collision with the supply units.

For a better look at the defender behavior, a different configuration, as seen in Figure 7, has a potential field that better illustrates the characteristics of the defender control, as seen in Figure 8.

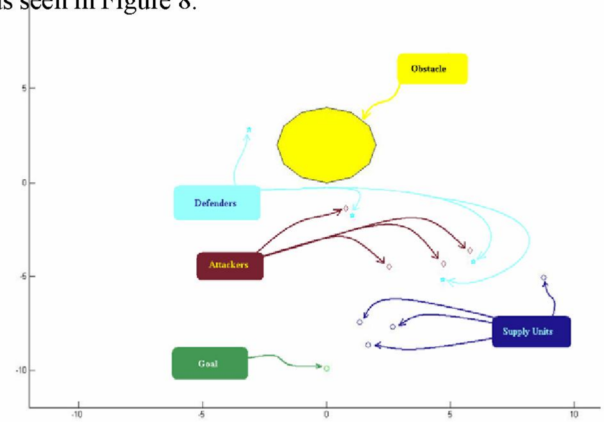

Fig. 7 *Configuration Mid-Way Through a Simulation*

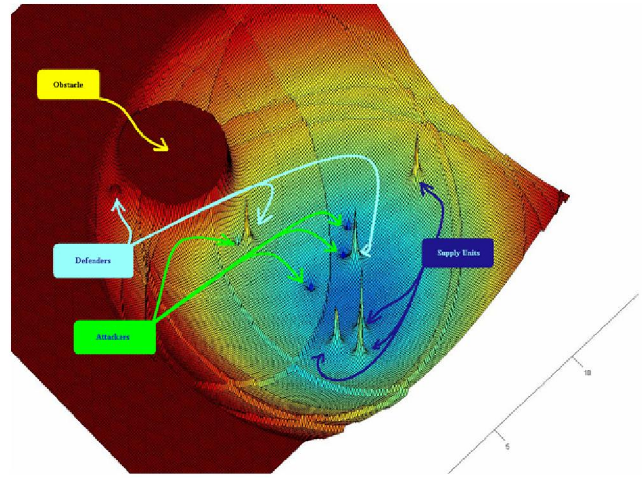

Fig. 8 P*otential Field for Defender Unit from Figure 7*

Figure 8 shows, as in Figure 6, that the obstacle creates the exact same potential as with the supply unit, as do the supply units. In addition to these, however, there are high potentials for defender unit positions identical to those of the supply units, as well as negative peaks for the attacker units. Unless the attackers are near a defender, the defender's goal (lowest potential) is the area between the center of the supply swarm and the attacker swam. If the attacker gets too close to a defender, however, the negative peak becomes the new low potential, pulling the defender towrads it at a rapid rate. This is how the defenders 'intercept' attackers that get too close to the supply units.

The sum of these potential fields, with velocity matching results in the desired convoy performance. Figures 9, 10, 11, 12, and 13 show the progress of the convoy as it moves through the simulation. As in all the previous graphs, the supply units are modeled as circles, the defenders are stars, the attackers are diamonds, and the goal is also a circle.

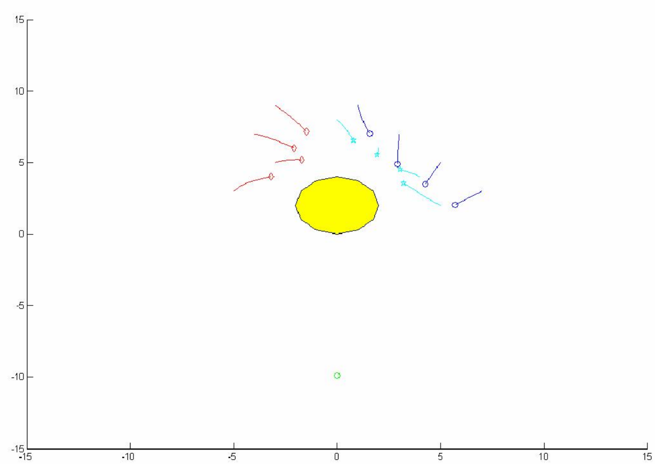

Fig. 9 *Convoy Simulation, 1st Frame*

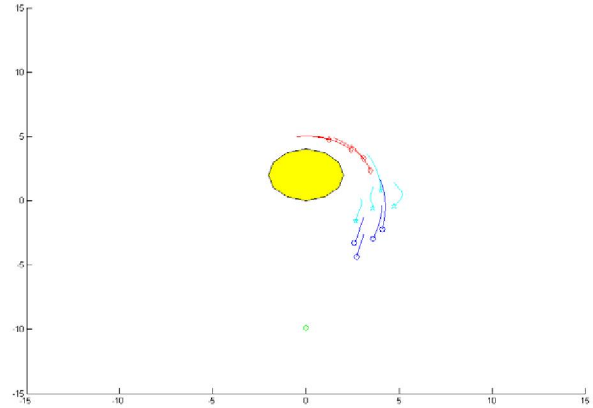

Fig. 10 *Convoy Simulation, 2nd Frame*

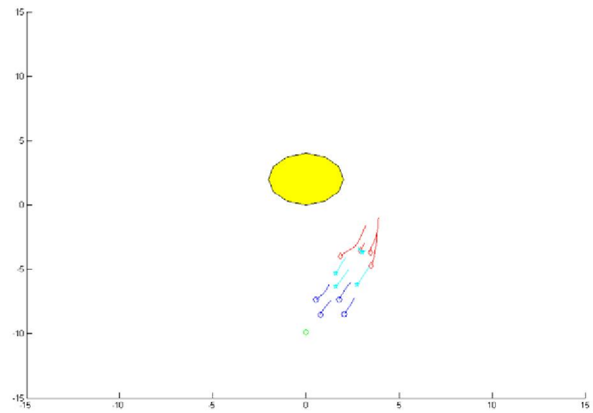

Fig. 11 *Convoy Simulation, 3rd Frame*

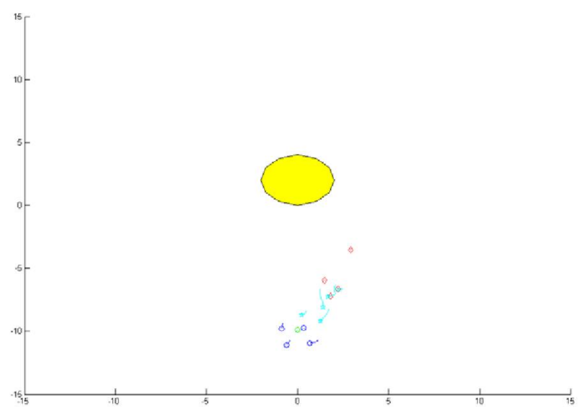

Fig. 12 *Convoy Simulation, 4th Frame*

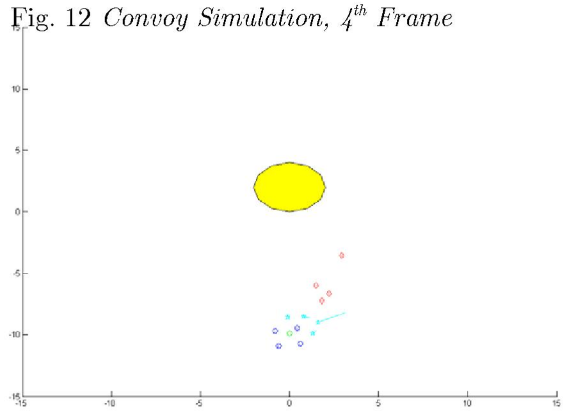

Fig. 13 *Convoy Simulation, 5th Frame*

As the frames progress, the supply units group together and head towards the goal while the defender units group and position themselves between the attackers and the supply units. All the attackers are doing is avoiding the obstacle as they speed toward to middle of the supply units. Once the attacker units begin to get close to the defenders, the defenders begin to break away from their escort formation to intercept the attackers. Built into the simulation was 'kill' criteria that immobilized any attacker that was intercepted by a defender. As a result, by the 4th frame, all attackers have been immobilized. With the attackers no longer pushing the convoy away from its goal, they begin to form an even distribution around the goal position, and the defenders return to their escort positions. The final positions of the units can be seen below in Figure 14.

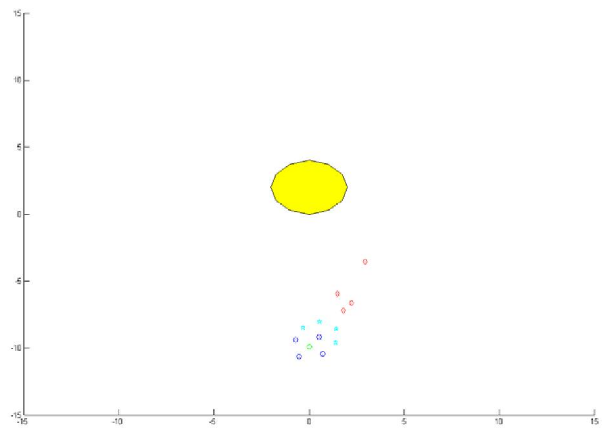

Fig. 14 *Convoy Simulation, Final Positions*

V. Future Work

First, the plans for the autonomous convoy include UAV's flying above the convoy. With their speed and expansive sensor range, UAV's could provide advanced notification of enemies, determine more efficient travel routes, and help control the convoy. UAV's should therefore be integrated into the convoy. They should work together to keep the maximum number of convoy units in their collective sensor range and pass other important data to the convoy.

Second, at the moment, the convoy operates with near-omniscience of the workspace. While each unit is limited by an imposed sensor range limitation, many other factors can, in real life, disrupt the flow of information. Experimentation could be done to determine the point at which the convoy cannot gather enough information to function. One way to make the convoy more robust is to develop a method for units to share information about the known workspace. With this technique, the convoy units could also get information from the UAV's and could construct a greater image of what may lie ahead.

VI. Conclusion

This project was successful in constructing a functional heterogeneous swarm that satisfied the initial requirements set forth. The convoy maintained separation and cohesion while avoiding collisions with other units and obstacles. The convoy was able to protect the supply units by moving away from attackers, yet intercepting them if they came too close. As predicted, the emergent behavior of the swarm did in fact exhibit qualities that appeared to derive from a highly-sophisticated controller, but was actually constructed of low-level behaviors. The project shows that the use of heterogeneous swarms is both feasible and desirable for military convoy applications, and has the potential for a multitude of other applications.

Fig. 15 *Artistic Concept of Real-Life Autonomous Convoy Operation*

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