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Effective Robot Team Control Methodologies for Battlefield Applications

MaryAnne Fields, Ellen Haas, Susan Hill, Christopher Stachowiak, and Laura Barnes, member IEEE

Abstract— **In this paper, we present algorithms and display concepts that allow Soldiers to efficiently interact with a robotic swarm that is participating in a representative convoy mission. A critical aspect of swarm control, especially in disrupted or degraded conditions, is Soldier-swarm interaction- the Soldier must be kept cognizant of swarm operations through an interface that allows him or her to monitor status and/or institute corrective actions. We provide a control method for the swarm that adapts easily to changing battlefield conditions, metrics and supervisory algorithms that enable swarm members to economically monitor changes in swarm status as they execute the mission, and display concepts that can efficiently and effectively communicate swarm status to Soldiers in challenging battlefield environments.**

I. INTRODUCTION

Large teams or swarms of robots can provide an efficient way to perform battlefield tasks such as minefield clearance, reconnaissance, surveillance, and security. For most realistic applications, the swarm will simultaneously address more than one task, while the supervisor, either a Soldier or an algorithm, will interact with the swarm, monitoring its performance and modifying its tasks. We seek to design a control strategy and set of metrics that will enable a Soldier to effectively control a large robotic team as it conducts relevant tasks.

Our control strategy is a dynamic potential field method in which the controlling field is a non-linear sum of simpler fields, each of which provides control for a specific behavior or task. The potential field approach provides a natural way to adjust the overall behavior of the swarm by changing the weighting parameters for the associated field. Human operators can express the control adjustments in terms of distances, time periods, and the relative importance of each of the tasks.

The vector field approach compensates for changes in swarm strength as well as for some navigational errors because each robot computes its direction vector using a small set of field parameters and its current perceived position. In general, robots do not need to communicate with each other to perform their mission. However, there is a supervisor that must periodically collect information from all the robots to monitor the swarm's status.

Numerous methods have been proposed for control of multirobot systems. This work shares characteristics with potential field and leader follower methods. In the potential field approach introduced in [1], the desired formation patterns are represented in terms of queues and formation vertices. Each robot is assigned to an artificial potential trench representing a node of a desired formation. This method greatly improves on node to robot formation structures; it still requires a method to redistribute the robots among the nodes of the formation as battlefield conditions change, so the computational complexity would grow with large swarms. Other examples of potential field approaches are discussed in the work of Balch, Gazi and others [2-11].

Leader-follower strategies have also been proposed for control of multi-robot systems [12-15]. In these approaches, a designated group of leaders provides trajectory information to the rest of the robots. In [14], the leader-follower approach is extended by adding a control graph that defines the relative position of each robot in the formation. By maintaining a relative distance and orientation with respect to the reference robot, the team of robots can follow several different formations.

The main contribution of our work is the introduction of a control strategy that allows the swarm to address multiple tasks in a dynamic battlefield. We also introduce a set of metrics that allows a human supervisor to monitor and adjust the overall behavior of the swarm. By adjusting the control parameters for the vector field, the shape, cohesiveness, and dispersion of the swarm can be controlled. Unlike with approaches where nodes or vertices must be calculated for differing formations and swarm members, this approach uses a single differentiable surface which attracts all swarm members. This factor makes large swarm sizes a practical reality.

The proposed method is demonstrated with simulations of forty robots. In addition, we present results from operator studies designed to determine the information that operators require to remain aware of the swarm's status. Other results,

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MaryAnne. Fields is with the U. S. Army Research Laboratory, Aberdeen, MD 21005 USA (phone: 410-278-6675; fax: 410-278-6675; e-mail: maryanne.fields@us.army.mil).

Ellen Haas is with the U. S. Army Research Laboratory, Aberdeen, MD 21005 USA (e-mail: ellen.haas@ us.army.mil).

Susan Hill is with the U. S. Army Research Laboratory, Aberdeen, MD 21005 USA (e-mail: susan.hill@ us.army.mil).

Christopher Stachowiak is with the U. S. Army Research Laboratory, Aberdeen, MD 21005 USA (e-mail christopher.stachowiak@ us.army.mil).

Laura Barnes is with the Automation and Robotics Institute at the University of Texas at Arlington, Fort Worth, TX 76118 USA (e-mail lbarnes@arri.uta.edu).

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utilizing a team of four custom-built robots, are presented in [16].

The rest of the paper is organized into 4 sections. Section II describes the control procedure used to direct the activities of the swarm. Section III describes the metrics that the supervisor or the human operator can use to monitor the behavior of the swarm. Section IV describes the simulation studies we conducted to support this research. Section IV describes some concepts for a Soldier Machine Interface. In section V, we discuss some experimental results that we have obtained. Finally, in section VI, we give conclusions and comment on future direction for our project.

II. SWARM CONTROL ALGORITHM

A. Example Scenario

As an example scenario, consider a convoy of ground vehicles accompanied by a large team of robots. The robots have two tasks: to provide perimeter security around the convoy as it performs its mission and to provide reconnaissance of areas of interest as they are identified by an operator. We assume that the robots are equipped with a range sensor for obstacle avoidance. Team members communicate with at least 1 vehicle of the convoy, which provides information about the extent, position and orientation of the convoy. In environments where line-of-sight between each robot and the convoy is not guaranteed, the robots may be required to communicate with each other to relay information from the convoy. In our simulations, we use a team of notional air vehicles, but the control methodology works for ground vehicles as well.

In this paper we construct our dynamic potential field from 3 fields: one for convoy security, one for exploring areas of interest, which we refer to as Hot Spots, and one for obstacle avoidance. The resulting field is defined as

$$V\begin{pmatrix}x\\y\end{pmatrix} = m_C C\begin{pmatrix}x\\y\end{pmatrix} + m_H H\begin{pmatrix}x\\y\end{pmatrix} + m_O O\begin{pmatrix}x\\y\end{pmatrix}. \tag{1}$$

Here m_C, m_H and m_O are scalar functions of time and position that determine the relative importance of each field.

B. Providing a Perimeter for the Convoy

Consider a convoy that at time t, has geometric center ($x_c(t)$, $y_c(t)$) and heading, $\theta(t)$. The convoy vehicles can be enclosed within a series of concentric ellipses with the ratio of the ellipses' axes, $\gamma(t)$. We will view these ellipses as the contours of a bi-variate normal distribution that can be used to construct a vector field to control the movement of the swarm. The bi-variate normal is

$$f(x(\theta), y(\theta), t) = e^{\alpha((x(\theta)-x_c(t))^2+\gamma(t)(y(\theta)-y_c(t))^2)} \tag{2}$$

where α controls the spread of the function. To simplify the discussion, we will drop the time variable, t, and the heading, θ, from the remaining equations. G(x,y) is the associated gradient vector:

$$G(x,y) = \begin{pmatrix}g_x\\g_y\end{pmatrix} = 2f(x,y)\begin{pmatrix}x - x_c\\ \gamma(y - y_c)\end{pmatrix} \tag{3}$$

With no modifications, the vector field G(x,y) attracts the swarm members to the center of the ellipse. However, by using a nonlinear weighting function, we can attract the swarm to a specified elliptical ring around the convoy.

Defining a weighted distance function as

$$d(x,y) = \sqrt{(x - x_c)^2 + \gamma^2 (y - y_c).^2} \tag{4}$$

we can define an elliptical ring as the set of points, (x,y), satisfying\

$$R - \Delta R \le d(x,y) \le R + \Delta R, \tag{5}$$

for some $R > 0$ and $\Delta R > 0$. For a small positive number, ε, we can define the following two weighting functions

$$W_{in} = \frac{1}{1 + e^{-\alpha_{in}(d-R)}}, \quad \text{with } \alpha_{in} = \frac{-1}{\Delta R}\ln\left(\frac{1-\varepsilon}{\varepsilon}\right).$$

$$W_{out} = \frac{e^{-\alpha_{out}(d-R)}}{1 + e^{-\alpha_{out}(d-R)}}, \text{with } \alpha_{out} = \frac{1}{\Delta R}\ln\left(\frac{1-\varepsilon}{\varepsilon}\right).$$

The vector field

$$C^*\begin{pmatrix}x\\y\end{pmatrix} = \frac{(W_{in} - W_{out})}{d(x,y)}\begin{pmatrix}x - x_c\\ \gamma(y - y_c)\end{pmatrix} \tag{6}$$

attracts robots to the elliptical ring described in equation 5. Figure 1 illustrates this vector field. Note that over most of the domain, the length of the field vectors is close to 1. Near the elliptical ring, the vectors shorten, and within the ring the vectors die off. Within the elliptical ring, we will allow the robots to orbit the center. The resulting vector field is

$$C\begin{pmatrix}x\\y\end{pmatrix} = C^*\begin{pmatrix}x\\y\end{pmatrix} + \frac{e^{-\alpha_{\perp}(d-R)^2}}{d(x,y)}\begin{pmatrix}-\gamma(y - y_c)\\ x - x_c\end{pmatrix} \quad . \tag{7}$$

Although we have presented the vector field centered at the origin with no rotation, it is straightforward to change these parameters as the convoy moves around its environment.

C. Reconnoitering Hot Spots

In addition to providing a perimeter for the convoy, the robots may need to explore areas of interest, or Hot Spots, which are specified by the operator. Hot spots may be persistent or temporary and the level of interest in a specific Hot Spot may vary over time. Let (x_h,y_h) be a Hot Spot and let the vector field associated with this Hot Spot be:

$$H\begin{pmatrix}x\\y\end{pmatrix} = W_H(x,y)\begin{pmatrix}x - x_H\\ y - y_H\end{pmatrix} \tag{8}$$

In this discussion, Hot Spots are temporary, and interest in a particular Hot Spot depends on the proximity of the convoy. Define $d_H(x,y)$ as the distance between any point (x,y) and the Hot Spot:

$$d_H(x,y) = (x - x_H)^2 + (y - y_H)^2 .$$

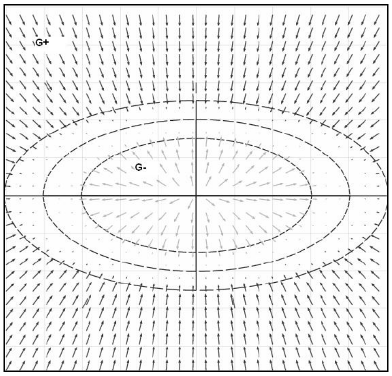

Fig. 1. A vector field to attract swarm members to an elliptical ring.

The following weighting function:

$$W_H(x,y) = \mathcal{S}(n)e^{-\alpha_H(d_H(x,y))}e^{-\alpha_C(d_H(x_c,y_c))} \tag{9}$$

attracts nearby robots *provided* that the convoy is close enough to the Hot Spot. The parameters $\alpha_H > 0$ and $\alpha_C > 0$ control the size of the region of attraction around the Hot Spot. The function, $\mathcal{S}(n) > 0$, is a saturation function that controls the number of robots that are attracted to the Hot Spot.

D. Obstacle Avoidance

The last component of the field in (1), O, is obstacle avoidance. In this field, the robot uses its range sensor information to determine a viable direction of travel. If no obstacles are present, this vector is zero. Note that if obstacles, including other robots, are present, this vector will dominate the vector sum given in equation (1).

III. MEASURES OF PERFORMANCE

In our work, we want provide operators with methods to monitor the state of the robot team as it performs the tasks discussed in the example scenario. This information could be consumed by either a human or an algorithmic supervisor and used to control the behavior of the robot team. Information that could be important to the supervisor includes the size of the team, the reliability of communications, and geographic information.

The size of the team is simply the number of robots in the team that can be controlled by the supervisor. We assume that any robot that can communicate with the supervisor can be controlled. Attrition, reinforcement, and communication problems affect the size of the team.

Communication data such as quality of service for each of the links alerts the supervisor to swarm members that are temporarily or permanently uncontrollable.

Geographic information for the robot team includes global information, such as the parameters for a bounding box enclosing the team (location of a corner, length, width and height) and the number of distinct subgroups in the swarm. Local information such as bounding box parameters for each of the subgroups may also be useful. We will use inter-robot distance to find the subgroups in the swarm. Consider two robots r_i, located at (x_i,y_i),and r_j, located at (x,y_j), and define L_{ij} as:

$$Lij = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \text{ .}$$

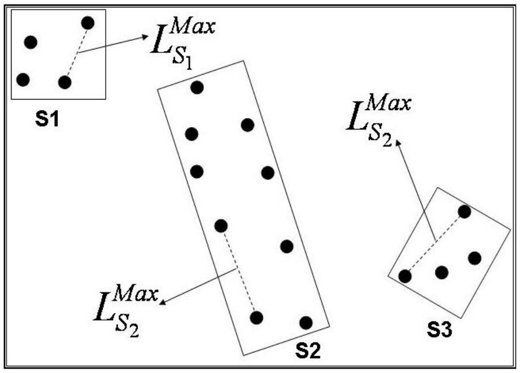

Fig. 2. An illustration of the geographic information collected from the robotic team.

IV. SIMULATION STUDIES

In this work, we utilized the Unreal Tournament game engine to simulate a convoy of 4 trucks accompanied by a swarm of 40 robots. We have created several classes in the Unreal Script language to support our work. Each type of vehicle is described by a class. Swarm vehicles are modeled as ducted fans. Each swarm member is equipped with a planar range sensor to sense obstacles and other swarm members, and it has perfect knowledge of its position. The convoy trucks are modeled in a separate class. A swarm unit and a convoy unit are also created to manage unit level tasks (mostly information gathering). In these studies, our algorithmic supervisor was a method in the swarm unit class. A super class, called *AugmentedConvoy*, expedites the communication between the convoy of trucks and the swarm of robots.

In our scenario, the convoy drives along a set of waypoints. Convoy vehicles have small random variations in their speeds so that inter-vehicle spacing is not constant. We have created two classes of waypoints to support our work: *WayPoints*, which are simply positions on a map, and *PausePoints*, which cause the convoy to temporarily stop. In addition, we have created a HotSpot class to enable the experimenter or the operator to specify an area of interest.

At each timestep, the convoy computes its geometric center, orientation, and the length of the axis for an enclosing ellipse. Each swarm vehicle uses this information to calculate its own direction vector.

We performed several types of simulations. In the first set of experimental trials, there were no *HotSpots*. The swarm was able to maintain an elliptical perimeter around the convoy as it moved. The ellipse changed shape to adjust to the movement of the convoy. In particular, as the convoy executed a turn, the ellipse became circular.

In the second set of trials, we added *HotSpots*. In this case, some swarm members responded to the *HotSpots*, while the majority of robots maintained the perimeter around the convoy. In these trials, we used 1, 2 or 3 *HotSpots*.

Figures 3 and 4 show 2 snapshots from a simulated trial. The yellow spheres indicate the location of the *HotSpots*; the red spheres are the waypoints that the convoy uses to control its path. In Figure 3, there are 3 distinct groups within the swarm. The largest group surrounds the convoy in an elliptical pattern. Each of the *HotSpots* also has a subgroup of the swarm robots. Later in the simulation, as shown in Figure 4, the swarm regroups. As the convoy turns the corner, the swarm formation compresses into a circle.

Based of the original HotSpot trials, we adjusted the weighting function defined in Equation (9) to improve the performance of the swarm. The most predictable control was obtained by splitting the swarm into two groups: sentries and explorers. The sentries responded only to the convoy information; the explorers also responded to the HotSpots. Explorers could switch groups if the number of sentries fell below a critical level.

We used the simulated swarm to provide for a series of studies on human swarm interaction that we describe later in this paper.

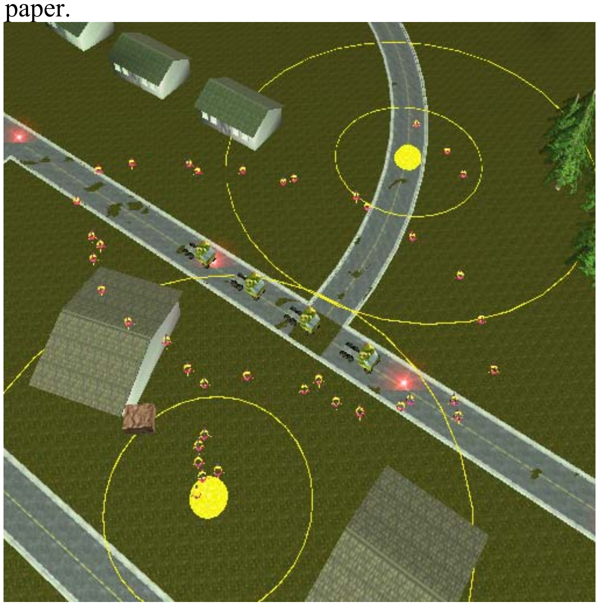

Fig. 3. The robotic swarm separated into three subgroups as it simultaneously addresses 2 *HotSpots* and perimeter security for the convoy.

V. Interface Concepts

After consulting with military subject matter experts and testing out swarm behaviors, we determined that the swarm would provide the Soldier with four types of information. The resulting notional display is shown in Figure 3. A map and text boxes provide the geographic information collected from the swarm. Colored buttons and additional text boxes provide other types of information, such as swarm health, swarm communication and convoy status. We added display information in different modalities (spatial audio and tactile cues) because previous research suggested that audio and tactile cues can increase awareness of surroundings and cue visual attention, especially when the user experiences a high visual load [15]. We hypothesized that visual swarm displays supplemented by audio and/or tactile information (visual + audio, visual + tactile, and visual + audio + tactile displays), would communicate swarm activities to the Soldier more quickly and accurately than the swarm display with visual information only.

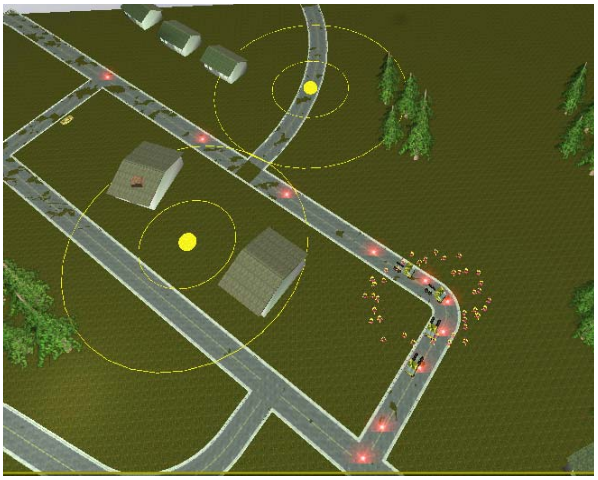

Fig. 4. The robotic swarm adapting formation to follow the truck convoy through a turn.

Press FIRE to start!

Press [Fire] to join the match!

Swarm Commo: Swarm Reformed

Alpha: 7

Bravo: 0

Charlie: 30000

Fig. 5. The notional swarm display used in our operator studies.

VI. Operator Studies

A laboratory study was conducted to evaluate the swarm display interface. A total of 16 male Marines with a mean age of 19 years from the Marine Detachment at Aberdeen Proving Ground acted as volunteer participants. All had normal hearing and normal color vision.

We evaluated the swarm interface in a dual task paradigm to emulate the multitasking environment found in military missions. The marines needed to simultaneously monitor the swarm display and perform mission planning control tasks on the modified simulation laboratory (MSIL). The MSIL is custom software developed by Stachowiak (2008) to resemble the Robotics CTA (RCTA) Simulation Laboratory (SIL) crew station. The four MSIL tasks used in this study were click and hold, drag and drop, point to point, and text selection tasks.

Audio cues were played over Sony headphones at 75 dBA. Tactile cues were experienced from one of three EAI tactors mounted in a belt worn on the participant's torso. During all experimental conditions, pre-recorded M1A2 engine noise was played at 65 dBA over Sennheiser headphones to simulate vehicle noise encountered by Soldiers.

The independent variables in this study were swarm display information and swarm display type. Swarm display information was swarm health, swarm communication, and convoy communication. Swarm display types were visual display only (V); visual display supplemented with audio cues (VA); visual display supplemented with tactile cues (VT); and visual display supplemented with audio and tactile cues (VAT). The dependent variable included participant time to complete tasks on both the swarm display and on a secondary task. Qualitative measures included the NASA Task Load Index (TLX) rating scale to evaluate workload [17] and the Modified Cooper-Harper Evaluation Tool for Unmanned Vehicle Displays (MCH-UVD) [18] to obtain ratings of the Swarm display qualities. A final questionnaire allowed each participant to compare display types and to provide additional comments on the quality and quantity of information provided by the Soldier interface.

For each experimental condition, one Marine was seated in front of two computer monitors and simultaneously performed the swarm display and the MSIL tasks, using the swarm display modality assigned to that condition. Each Marine was instructed to do his best at the MSIL task but to respond as quickly and accurately as he could when a message was presented on the swarm display interface. Each Marine performed one 13-minute experimental condition for each display type, in which approximately 4 swarm health, 8 swarm communication, and 4 convoy status warnings were presented as they occurred in the swarm scenario on the swarm display. Swarm scenarios were varied slightly between trials. After the swarm scenario was completed, the Marine completed the questionnaires. At the end of the fourth and final condition, they filled out the Final Questionnaire.

Swarm display experiment accuracy data indicated that 99.9% of all signals were correctly detected and recognized.

An analysis of variance (performed on the swarm display response time data indicated the display type (F = 57.086, p = 0.000), information type (F = 7.704, p = 0.000), and map number (F = 7.910, p = 0.000) had significant effects on the response times for the exercise.

Display type resulted in the most variability in response time. A statistical analysis (Bonferroni *post-hoc* test) on the display type data indicated that Marines using multimodal cues (visual supplemented by audio, tactile or both audio and tactile) had a significantly shorter response time for multimodal cues (VA, VAT, VT) than for visual cues alone. The response time for combination VAT cues was significantly shorter than for VA and VT cues. There was no significant difference in mean detection time between VA and VT cues.

Figure 6 shows mean response time as a function as display type. The largest mean difference in response times (between V and VAT displays) was 1.5 seconds, which may make a practical difference in U.S. Army operations in which seconds count. A statistical analysis on the information type indicated that Swarm Communication had a significantly shorter mean response time (1.73 s) than Swarm Health (2.06 s) and Convoy Communication (1.90 s). However, the range of the response time, approximately 0.33 s, may be too small to make a practical difference in U.S. Army mobile operations.

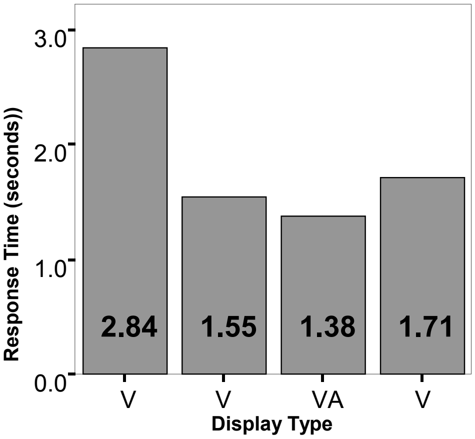

Fig. 6. Mean response time for the primary, swarm-related, task as a function of display type.

An analysis of variance on mean task response times for the Click and Hold, Drag and Drop, Point to Point, and Text Selection activities in the secondary tasks indicated the display type had a significant affect on the secondary task response time. For the Click and Hold task, Marines had significantly shorter response times for VAT and VA displays (8.99 and 9.03 sec, respectively) than for V displays (9.15 sec). For the Text Selection task, Marines also had significantly shorter response times for the VAT and VA displays (8.53 and 8.59 seconds, respectively) than for the V displays (8.79 sec). For both text selection and click and hold tasks, there were no significant differences between the V and VT cues. The range of response times, less than 0.5 sec, may be too small to make a practical difference in U.S. Army mobile operations. Furthermore, *post-hoc* test results showed that there were no significant differences between display types for the Drag and Drop and Point to Point tasks.

An analysis of variance performed on the NASA TLX workload ratings indicated that the type of display type had an effect on the workload rating (F = 19.223, p = .000). Statistical analysis on the workload data indicated that Marines using V cues only reported significantly higher levels of workload than with VA, VT and VAT cues. There were no significant differences between the VA, VT and

VAT displays. The workload with V-only cues was rated as more than twice as great than with the other display types.

Interviews with the Marines indicated that their display type preferences were consistent with the performance and workload scores: 73% preferred the VAT display over other display types, 20% preferred the VA display, and 7% preferred the VT display. The V display was least preferred by 73% of the Marines. All the Marines stated that they liked the level and type of information content of the displays.

A more detailed discussion of the operator studies is found in [19]

VII. CONCLUSIONS AND FUTURE WORK

In this paper we have described a potential field method to control a swarm of robots, allowing the swarm to simultaneously address more than one task. We have also presented a set of metrics that the swarm or its human supervisor could use to monitor and modify its behavior.

In our current research, we are examining additional metrics and algorithms that the swarm can use to describe its state. In future operator studies, we will allow the Soldiers to adjust the behavior of the swarm.

From interviews with our study participants, we received valuable suggestions regarding the use of swarms in future military operations, particularly on the use of swarms in gathering information about potential improvised explosive devices (IEDs**).** Future research could also explore the manner and type of presentation of IED-related information in swarm displays.

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REFERENCES

[1] S. S. Ge and C. H. Fua, "Queues and Artificial Potential Trenches for Multirobot Formations," IEEE Transactions on Robotics and Automation, vol. 21, pp. 646-656, 2005.

[2] T. Balch and M. Hybinette, "Social potentials for scalable multi-robot formations," in Proceedings IEEE International Conference on Robotics and Automation 2000, pp. 73-80.

[3] G. H. Elkaim and R. J. Kelbley, "A lightweight formation control methodology for a swarm of non-holonomic vehicles," in IEEE Aerospace Conference, 2006.

[4] V. Gazi, "Swarm aggregations using artificial potentials and sliding-mode control," IEEE Transactions on Robotics and Automation, vol. 21, pp. 1208-1214, 2005.

[5] V. Gazi, B. Fidan, Y. S. Hanay, and M. İ. Köksal, "Aggregation, foraging, and formation control of swarms with non-holonomic agents using potential functions and sliding mode techniques," Turkish Journal of Electrical Engineering and Computer Sciences, July 2007.

[6] S. S. Ge, C.-H. Fua, and W.-M. Liew, "Swarm formations using the general formation potential function," in IEEE Conference on Robotics, Automation and Mechatronics, 2004, pp. 655-660.

[7] D. H. Kim, H. O. Wang, Y. Guohua, and S. Seiichi, "Decentralized control of autonomous swarm systems using artificial potential functions: analytical design guidelines," in 43rd IEEE Conference on Decision and Control, 2004, pp. 159-164.

[8] R. Olfati-Saber and R. M. Murray, "Distributed Cooperative Control of Multiple Vehicle Formations using Structural Potential Functions," in 15th IFAC World Congress, July 2002.

[9] J. Yao, R. Ordonez, and V. Gazi, "Swarm Tracking Using Artificial Potentials and Sliding Mode Control," in 45th IEEE Conference on Decision and Control, 2006, pp. 4670-4675.

[10] L. Chaimowicz, N. Michael, and V. Kumar, "Controlling Swarms of Robots Using Interpolated Implicit Functions," in Proceedings of the IEEE International Conference on Robotics and Automation, 2005, pp. 2487-2492.

[11] N. E. Leonard and E. Fiorelli, "Virtual leaders, artificial potentials and coordinated control of groups," in Proceedings of the IEEE Conference on Decision and Control, 2001, pp. 2968-2973.

[12] G. L. Mariottini, F. Morbidi, D. Prattichizzo, G. J. Pappas, and K. Daniilidis, "Leader-Follower Formations: Uncalibrated Vision-Based Localization and Control," in IEEE International Conference on Robotics and Automation, 2007, pp. 2403-2408.

[13] J. Shao, G. Xie, and L. Wang, "Leader-following formation control of multiple mobile vehicles," IET Control Theory & Applications, vol. 1, pp. 545-552, 2007.

[14] J. P. Desai, J. P. Ostrowski, and V. Kumar, "Modeling and control of formations of nonholonomic mobile robots," IEEE Transactions on Robotics and Automation, vol. 17, pp. 905-908, 2001.

[15] J. Fredslund and M. J. Mataric, "A general algorithm for robot formations using local sensing and minimal communication," IEEE Transactions onRobotics and Automation, vol. 18, pp. 837-846, 2002.

[16] L. Barnes, M. A. Fields, and K. Valavanis, "Swarm Formation Control Utilizing Elliptical Surfaces and Limiting Functions," to appear in IEEE Transactions on Systems, Man, and Cybernetics--Part B, vol. 39, 2009.

[17] S. Hart, & Staveland, L. (1988). "Development of NASA TLX (Task Load Index): Results of empirical and theoretical research,” in P. Hancock and N. Meshkati, Eds. Human Mental Workload, Elsevier Science Publishers.

[18] M. L. Cummings, Meyers, K. & Scott, S. D. (2006). "Modified Cooper-Harper Evaluation Tool for Unmanned Vehicle Displays", Fourth Annual Conference of UVS Canada, Montebello, Quebec.

[19] E. Haas, S. Hill, C. Stachowiak and M. Fields (2009).” Designing and Evaluating a Multimodal Interface for Soldier-Swarm Interaction”, 53rd Annual Meeting of the Human Factors and Ergonomics Society, San Antonio, TX.