ARMY RESEARCH LABORATORY

Extreme Scalability: Designing Interfaces and Algorithms for Soldier-Robotic Swarm Interaction, Year 2

by Ellen C. Haas, MaryAnne Fields, Christopher Stachowiak, Susan Hill, and Krishna Pillalamarri

ARL-TR-5222 **June 2010**

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Army Research Laboratory
Aberdeen Proving Ground, MD 21005

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Ellen C. Haas, Christopher Stachowiak, Susan Hill, and Krishna Pillalamarri
Human Research and Engineering Directorate, ARL

and

MaryAnne Fields
Vehicle Technology Directorate, ARL

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14. ABSTRACT

In theory, autonomous robotic swarm can be used for critical Army tasks (i.e., accompanying convoys); however, the Soldier controlling the swarm must be able to monitor swarm status and correct actions, especially in disrupted or degraded conditions. For the concluding year of this two-tear Director's Research Initiative (DRI), we designed multimodal (speech and touch) Soldier-swarm control concepts to allow Soldiers to efficiently control a robotic swarm participating in a representative convoy mission. We used a potential field approach for swarm control because it scales easily to large heterogeneous swarms and allows users to dynamically alter swarm behavior by adjusting field parameters. We tested the effectiveness of the swarm controls in a laboratory study using 12 male Marines (volunteers) with a mean age of 19 years. The metacognition results showed that the swarm (which consisted of members fulfilling sentry and explorer functions) could maintain adequate coverage most of the time. Interface results showed that most participants, 58%, used speech commands first almost exclusively, while the remaining used touch commands first. Results can be applied to future swarm and command and control systems.

15. SUBJECT TERMS

Swarm, swarm interface, potential field approach, multimodal controls, speech controls, touch screen controls

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1. Objective

Robotic swarms consist of a large number (potentially thousands) of small, relatively simple robots capable of autonomous travel and operation as a unit on land, sea, and air. Swarms can implement simplistic rules to accomplish a desired collective behavior that involves interaction between individual members as well as the behavior of the entire swarm (*1*). These behaviors can be combined to enable swarm members to perform critical Army tasks such as accompanying convoys, mapping battlefields, and clearing minefields.

One potential problem with robotic swarms is that they may become unstable when members are disturbed by unexpected changes in weather or terrain, degradation, attrition, or enemy actions, which may negatively impact or terminate the swarm's mission. Soldier-swarm interaction is a critical aspect of swarm control, especially in disrupted or degraded conditions: 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. The growing body of human-robot interaction (HRI) research still has little to say about the design of Soldier-swarm interface displays and controls.

The objective of the first year of this two-year effort was to design algorithms and devices that allow Soldiers to efficiently interact with a robotic swarm participating in a representative convoy mission. In Year 1 (FY08), this objective was successfully fulfilled by (1) providing metacognition algorithms that enable swarm members to efficiently monitor changes in swarm status as they execute their mission (accompanying a manned convoy and searching for improvised explosive devices) and (2) providing display concepts that can efficiently and effectively communicate swarm status to Soldiers in challenging battlefield environments. The objectives of the Year 2 (FY09) research were to (1) extend the metacognition algorithms, successfully developed in Year 1, to enable swarm members to efficiently monitor changes in swarm status in novel, more complex mission scenarios; (2) develop novel multimodal (speech and touch) control interfaces that would allow the Soldier to control or modify the swarm's mission; and (3) develop control measurement methodologies for the swarm control interface, taking into account increased Year 2 swarm complexity.

2. Approach

In Year 2, we expanded our focus to more complex swarm and mission characteristics, designed and developed Soldier control interfaces, and evaluated the expanded swarm capabilities and the Soldier-swarm control interface. We achieved these efforts in a cross-Directorate cooperative effort, exploiting U.S. Army Research Laboratory (ARL) expertise in the key areas of modeling, simulation, and human factors engineering to attempt to solve a future Army problem.

2.1 Swarm and Mission Characteristics

In Year 2, we again used a simulated swarm because it best allowed an analysis of swarm size (number of members) and type (ground, air, or micro systems) required for the mission, as well as the examination of different Soldier-swarm interface technologies. We continued to focus on convoy missions, but we increased the complexity of both the swarm and the mission scenarios. In Year 2, the swarm was split into heterogeneous "sentry" team and "explorer" team members to achieve better control. The sentry team was required to remain with the convoy, while the explorer team accompanied the convoy but was also allowed to leave the convoy to explore nearby "hot spots" (terrain features of interest). The hot spots were made more realistic by introducing a detectable improvised explosive device (IED). Swarm members searched for IEDs using a notional detector. If an IED was found, a swarm member could sacrifice itself to destroy it. To improve the realism of the scenario, we introduced an attrition model in which swarm members were destroyed, with attrition events controlled by a Poisson random variable. Task priorities and metrics were established to express overall swarm status by defining how information from individual swarm members was prioritized and combined at the swarm level.

To support the overall Year 2 goals, we used a potential field approach (also used in Year 1) in which the controlling field is a nonlinear sum of simpler fields, each of which provides control for a specific behavior or task. The fields for the sentry and explorer teams used the same set of simpler fields weighted according to the priorities of each team. This approach was chosen because it scales easily to large heterogeneous swarms and allows a Soldier/user to dynamically alter swarm behavior to meet mission needs by adjusting field parameters.

We introduced metacognition into the swarm system by developing a set of swarm performance measures related to the convoy mission. The first measure evaluated swarm coverage of the convoy. The swarm control algorithm attracts swarm members to an elliptical ring surrounding the convoy. Convoy coverage was considered adequate if there were no large gaps in the ring. Two methods were used to measure coverage. The first, most precise measure computed the maximum neighbor-to-neighbor arc length around the ellipse. Although computing trigonometric functions for each robot in the ellipse was somewhat demanding, this method made it possible to find and track the size of the gap as a function of time. A second, computationally simple method used minimal bounding boxes for both the swarm and the convoy. The convoy was considered "covered" if its bounding box was fully contained within the bounding box for the swarm. Two additional measures used in this study were the number of swarm explorers and sentries. These counts were used to measure the viability of the teams.

As the swarm conducted its mission, it used the above performance measures to modify the behavior of the swarm members. We designated convoy coverage as the most important task. The simplest corrective measure the swarm could implement was to alter the speed of some of its members. This action ensured that explorers returning from exploration tasks would rejoin the convoy quickly and also enabled the swarm to control the neighbor-to-neighbor arc length for members around the convoy. Since we allowed attrition (loss of members) in the Year 2 scenarios, altering the speed did not ensure coverage for the convoy. Thus, another corrective action the swarm could employ was to change the team designation for individual members. In our scenarios, the swarm monitored the number of sentry robots. If the number fell below a critical value (an arbitrary value of 10), the swarm recruited new sentries from the explorer team. It was also possible to convert sentries into explorers, using the number of hot spots to determine the critical number of explorers.

2.2 Soldier Interface Characteristics

Our Year 2 goal was to design an efficient Soldier-swarm map control interface with which the Soldier could use combined multimodal commands to emplace different types of objects (i.e., targets, waypoints, and/or hot spots) at different locations on an interactive map display to allow Soldier control of swarm movement. Figure 1 shows the interactive map used in the Soldier interface. Roads are shown in black, buildings in green, and the swarm is shown as a red circle in the upper right hand corner of the map. We used multimodal (speech and touch) controls because research suggested that when used together in a sequence (combined), speech and touch input may be particularly effective for an interactive map control interface (*2*–*5*).

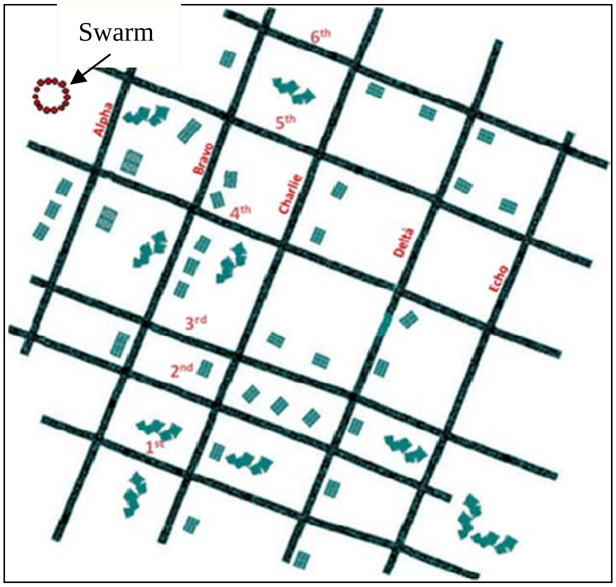

Figure 1. Soldier interface map. The roads are black and the buildings are green.

In designing and evaluating the Soldier interface, we explored several issues. These included the need for measurement of time between multimodal control actions, relevant touch screen targets, and relevant speech commands. These issues are described below.

The first issue is the measurement of time between multimodal control actions. The time between the onset of a first control action (e.g., a speech command) relative to the onset of a second, dependent control action (e.g., a consequent touch command) can be defined operationally as temporal binding. Knowledge of temporal binding is important because it can support a smoother fusion of commands to the system and reduce system error. Although Oviatt (*4*) suggested that identifying time between control actions is important, neither she nor any other researcher actually measured inter-command temporal binding.

The second issue is the need to define input difficulty. In considering motor actions with touch screen displays, neither Oviatt (*2–4*) nor any other researcher explored human performance controlling map objects with different levels of difficulty, such as static (nonmoving) versus dynamic (moving) touch screen targets (also referred to as map objects). In Oviatt's research, all map objects were static and none were differentiated by size. In addition, emphasis on participant response time and accuracy can have an effect on input time and accuracy. If response accuracy was held constant (i.e., by emphasizing accurate responses), the time taken to touch a relatively small target (e.g., an intersection) should be longer than that involved in touching a relatively larger target (e.g., anywhere on a road) (*6*). Similarly, the time taken to touch a moving target should be longer than that required to touch a static target of the same size. If response time were held relatively constant (i.e., by emphasizing fast response time), accuracy of touch response for moving targets and smaller stationary targets should be less than that for larger stationary targets. Because swarm displays, and military displays in general, can include moving elements (i.e., swarm members, robots, and military vehicles), research should explore the effect of targets of increasing level of difficulty (large static targets, small static targets, and small moving targets) on temporal binding of speech and touch commands, with special care given to emphasis on response time and accuracy.

The third issue is the need for relevant speech commands. There is no multimodal research involving constrained (limited or controlled) speech commands. Military speech recognition command grammars often use a limited vocabulary with short words and phrases, because this approach has been shown to work better with current speech recognition technology (*7*). However, Oviatt's research used unconstrained natural language commands, in which participants could use multi-word and multi-sentence commands of their own choosing. Multimodal control research for military and swarm environments should involve constrained speech commands, controlling for number and type of words. The use of a smaller, limited vocabulary would potentially decrease the length of temporal binding time needed for multimodal commands.

The approach for presenting combined multimodal controls to explore the issues described previously is shown in table 1. Speech commands were used to specify targets to emplace on the map (i.e., hot spots, targets, or waypoints), and touch was used to define the location of the map object (i.e., road, intersection, or leading or lagging swarm edge). Speech commands could also include the spatial word "here" (i.e., "hot spot" or "hot spot here"). Speech and touch commands could be used in any order, but both had to be used to complete the sequential set of commands. We hypothesized that both the type of map object and type of speech command would affect the inter-command time (temporal binding) of speech and touch commands.

Table 1. Examples of map tasks and participant responses.

Message from Headquarters	Participant Response
“Put a hot spot anywhere on 1st.”	In any order, **Say** “hot spot” or “hot spot here” (depending on condition). **Touch** screen anywhere on 1st Street.
“Put a waypoint at the intersection of 2nd and Bravo.”	In any order, **Say** “waypoint” or “waypoint here” (depending on condition). **Touch** screen at the intersection of 2nd and Bravo.
“Put a target anywhere at the lagging edge of the swarm.”	In any order, **Say** “target” or “target here” (depending on condition). **Touch** screen anywhere at the lagging edge of the swarm.

2.3 Swarm Simulation Study

The ARL Vehicle Technology Directorate (VTD) conducted a Year 2 simulation study to investigate the effectiveness of the metacognitive performance measures. In the experimental trials, the convoy of vehicles followed a specified path on the road network accompanied by a swarm of vehicles, consisting of the “sentry” team and the “explorer” team. The independent variables were the number of hot spots and the swarm attrition rate. To control the number of independent variables in the experiment, the locations of the hot spots were specified for each experimental trial.

2.4 Swarm Interface Study

A Year 2 laboratory study was conducted at the Human Research and Engineering Directorate to evaluate the multimodal swarm control interface. The independent variables were type of map object, and command type. Types of map objects were (1) swarm leading or lagging edges (moving objects that needed one bit of spatial information to locate), (2) map intersections (stationary objects that needed two bits of spatial information to locate), and (3) map roads (stationary objects that needed one bit of spatial information to locate). Two types of speech commands were used: (1) a choice command in which one of three different one-word commands (“target,” “hot spot,” or “waypoint”) were spoken and (2) a choice command to which an additional spatial word “here” was added (i.e., “target here,” “hot spot here,” or “waypoint here”). Examples of speech and touch commands are shown in table 1. Participant preference (Preferred Modality) in using touch or speech first when inputting each command was also recorded. Dependent variables included inter-command temporal binding time (the difference in time between the onset of the participant’s first audio or touch command, and the onset of the second command), and the proportion of correct speech and touch commands. Dependent variables also included the length of time between the start of the control message and a simultaneous alerting tone (stimulus), and the resulting speech and touch commands (stimulus to onset of speech, and stimulus to onset of touch command times). As recommended by human factors guidelines, onset of touch command time was defined as being that point in time when the participant removed his finger from the touchscreen (*7*).

A total of 12 male Marines with a mean age of 19 years from the Marine Detachment at Aberdeen Proving Ground, MD, acted as volunteer participants. All had normal hearing and normal color vision. For each experimental condition, one Marine was seated in front of the touch screen and performed the swarm control tasks, using the command type assigned to that condition. Each Marine was instructed to respond as quickly and accurately as he could when the visual control message and simultaneous alerting tone were presented on the swarm display interface. A photograph of a Marine participant with the interactive map display is shown in figure 2. Each Marine performed one 30-min experimental condition for each command type. At the end of the second and final condition, they filled out a final questionnaire asking their opinion of the speech and touch interfaces.

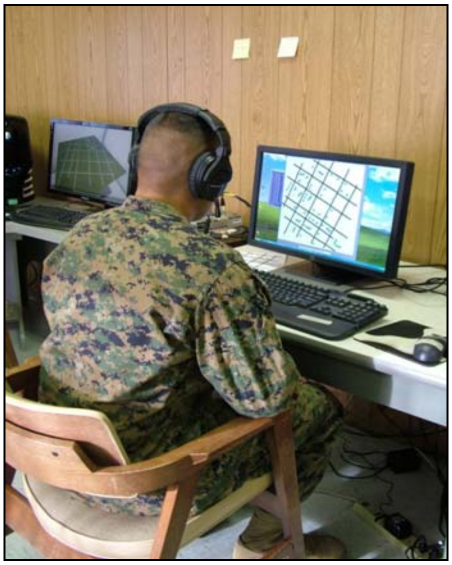

Figure 2. Marine participant with the interactive map display.

3. Results

3.1 Swarm Simulation Study

Results indicated that the swarm could maintain coverage most of the time for the cases studied. In our experimental trials, the swarm responded to 0, 1, or 2 hot spots. In the case of 0 hot spots, coverage problems were the result of attrition. The swarm was able to compensate for loss of members (by speeding up) as long as the total number of swarm member was greater than 10. For the cases of 1 or 2 hot spots, the swarm's coverage problems were the result of geographic dispersion as well as attrition. By changing the team designation for some of the explorers, it was possible to maintain coverage for the convoy. In some experimental trials, we noticed an issue with the team change strategy—our algorithm did not consider geographic location as a parameter for the team change. Consequently, in some cases, explorers near the convoy changed to sentries. To alter the overall convoy coverage, we need to be able to recall explorers from the hot spots. We plan to address this issue in our future work.

3.2 Control Interface Study

Results indicate that less than 2% of the total speech commands were incorrectly uttered (i.e., the participant saying "target" instead of "waypoint"). Results also indicated that participants did not use speech or touch first exclusively when issuing commands. Across participants, 76.7% of commands were speech first, while 23.3% of commands were touch first. Figure 3 shows the number of touch and speech responses for each participant, while figure 4 shows mean temporal binding response times (the difference in time between the onset of the participant's first speech or touch command, and the onset of the second command) for each participant, where positive values denote speech responses before touch, and negative values denote touch responses before speech. The data indicate that 7 participants out of 12 (participants 1, 2, 3, 5, 7, 11, and 12) used speech before touch almost exclusively (using speech first 95% or more of the time, approximately 95 commands out of 100). Two participants (9 and 10) used speech first 88% and 73% of the time, respectively. Two participants (4 and 8) used touch-first commands exclusively, 97% or more of the time, while the remaining participant (6) used touch-first commands 73% of the time. This between- and within-participant variability in the use of command modality should be further explored in future research. Knowledge of command variability should be valuable in the design of future speech/touch systems, to help support a smoother fusion of user commands and to reduce system error.

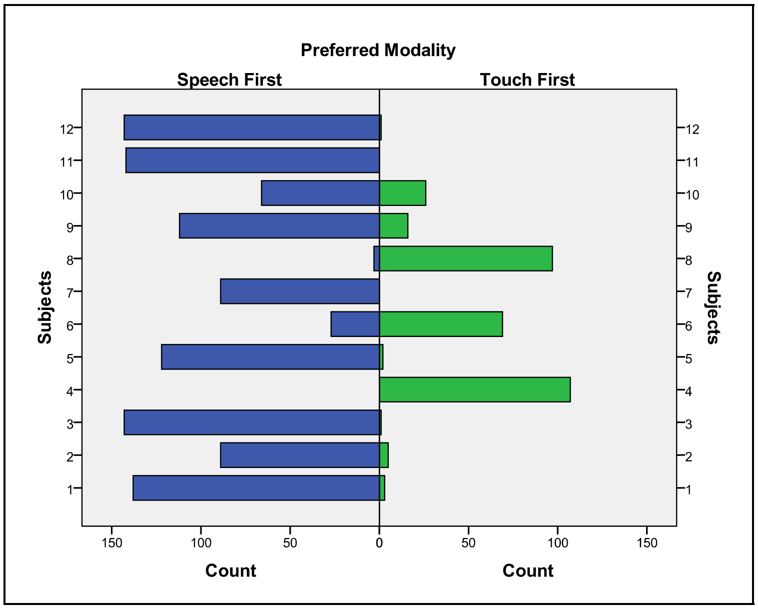

Figure 3. Number of touch and speech responses for each participant.

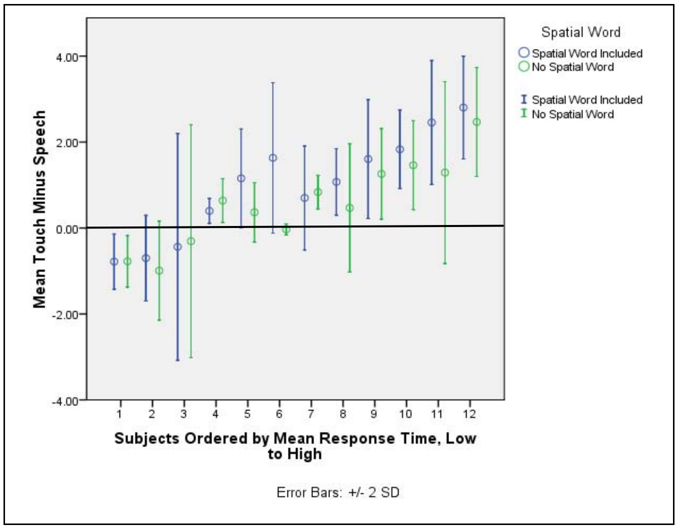

Figure 4. Mean temporal binding times with error bars for individual participants, with participants ordered from low to high mean response times.

For temporal binding (the difference in time between the onset of the participant’s first speech or touch command, and the onset of the second command), a linear mixed model analysis of variance (ANOVA) with a post-hoc Bonferroni analysis indicated significant ($p \le 0.01$) interactions for preferred modality × map object and for preferred modality × command type, and included significant main effects for preferred modality.

Post-hoc results for the preferred modality ×command type interaction (figure 5) indicated that temporal binding time was significantly greater for speech-first commands with spatial words than for touch-first commands with and without spatial words ($p \le 0.001$). Data analysis indicated that longer temporal binding times for speech-first commands occurred because participants who input speech first often waited until their command was completely uttered before touching the screen, while participants who touched first did not always wait until their input was complete before uttering their speech commands. Future research should further investigate the effect speed and accuracy of individual differences in user command preferences on temporal binding time.

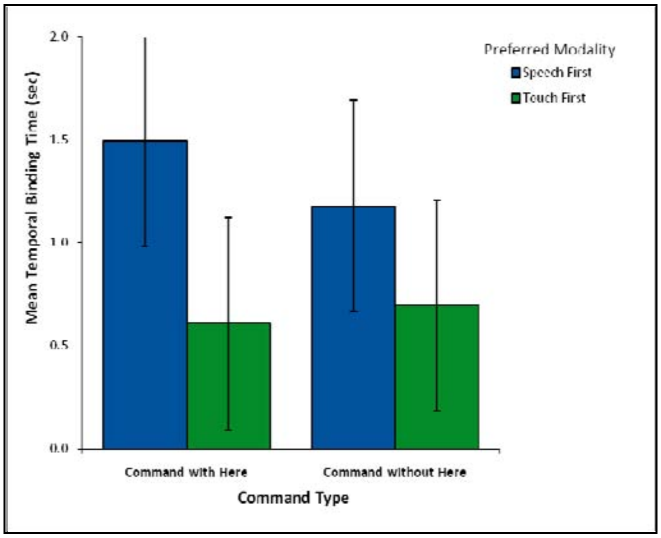

Figure 5. Mean temporal binding times for command type × preferred modality interaction, with 95% conf. intervals.

Results for the preferred modality × map object interaction (figure 6) indicated that temporal binding was significantly greater ($p \leq 0.001$) for speech-first than for touch-first commands, across all map objects. For speech-first commands, temporal binding times for intersections were significantly greater than those for roads or swarm edges, with no significant difference between roads and swarm edges. For touch-first commands, there were no significant temporal binding differences between any map objects.

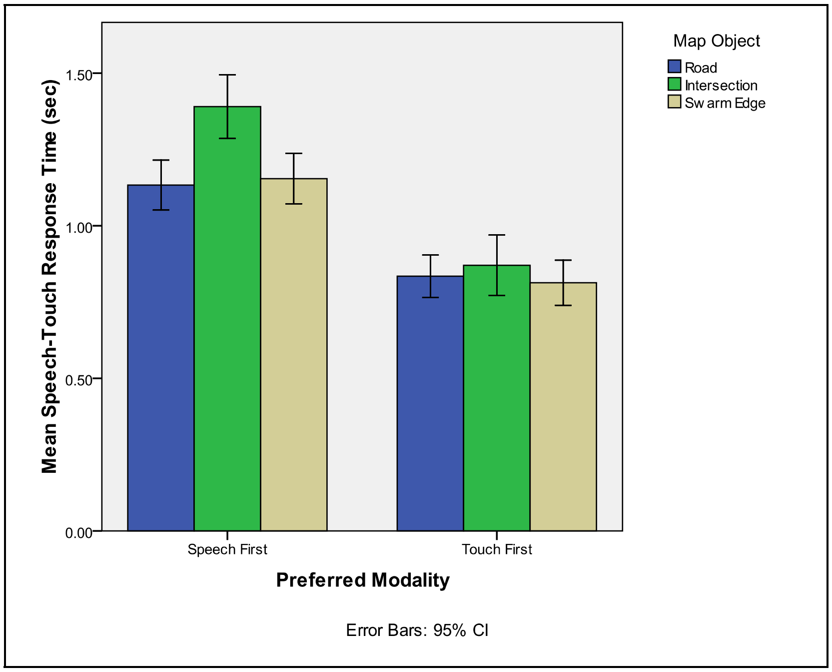

Figure 6. Mean temporal binding times for map object × preferred modality interaction, with 95% conf. intervals.

Results for the preferred modality main effect indicated that the mean temporal binding time was significantly greater ($p \leq 0.001$) for speech-first commands (mean time 1.285 s, s.d. 0.788) than for touch-first commands (mean time 0.839 s, s.d. 0.421). Thus, the difference in temporal binding time between speech-first and touch-first commands was 0.446 s. Again, data analysis showed that this occurred because participants who input speech first often waited until their command was completely uttered before touching the screen, while participants who touched first did not always wait until their input was complete before uttering their speech commands. Future research should examine individual differences in touch and speech command output.

ANOVA and Bonferroni analyses of stimulus to touch and stimulus to speech response times showed significant differences due to map object type. Command inputs using intersections showed significantly greater response times ($p \leq 0.001$) than for roads or swarm edges. There was no significant difference between roads and swarm edges. As can be seen in table 2, intersections had input response times approximately 0.7 s (stimulus to touch) to 0.9 s (stimulus to speech) greater than roads or swarm edges. The results indicated that tasks involving intersections provided greater response times than tasks involving swarm edges and roads. The comparatively short mean response times for moving swarm edges could have been due to the slow (one update/second) screen update rate, which may have resulted in rate of movement of the swarm being slow enough to reduce the level of task difficulty. Further research should involve faster swarm update rates, and an investigation of any potential time/accuracy tradeoff involved in performing this task.

Table 2. Mean response times and standard deviations for map objects and stimulus to speech and stimulus to touch measures.

	Map	**Objects**	**Swarm Edges**
Measure	**Roads**	**Intersections**	
Stimulus to Speech	3.250 (1.423)	3.967 (1.748)	3.264 (1.145)
Stimulus to Touch	3.867 (1.134)	4.852 (1.328)	3.885 (1.300)

On their final questionnaires, Marines commented that the multimodal controls were fast, simple to use, and very helpful. One Marine commented that controls of this type might also extend beyond swarms as a useful display for Squad personal digital assistant (PDA) interfaces for use in providing information regarding IEDs and targets.

4. Conclusions

In Year 1, we successfully defined a 40-member simulated swarm to accompany a 4-member convoy, and successfully developed metacognition algorithms that enabled swarm members to efficiently monitor changes in swarm status as they executed 6 different convoy missions. We also successfully designed a human-swarm display interface that allowed Marines to efficiently interact with a robotic swarm participating in a representative convoy mission.

In Year 2, we successfully extended the metacognition algorithms to enable heterogeneous swarm members to more efficiently monitor changes in swarm status, and developed novel control interfaces that would allowed Marines to control or modify the swarm's mission by placement of targets, hot spots, and waypoints. Research results indicated that for interactions between preferred modality with command type, and preferred modality with map object, temporal binding time was significantly greater for speech-first than for touch-first commands. This indicates that individual differences (in this case, user preference for speech or touch commands first) can have an effect on user performance with a speech and touch display. Future research should further investigate the effect of individual differences in preferences of command input on inter-command speed and accuracy.

Comments by Marines in our Year 1 and Year 2 experiments indicated that multimodal displays and controls permitted them to act as efficient and effective swarm supervisors. Elements of our completed research (i.e., our observations regarding the limitations of our metacognition algorithms and Marine suggestions regarding swarm displays and controls) served as a basis from which to transition our work (see section 6).

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6. Transitions

Our simulation work will be used to support VTD studies of elevation vectors of heterogeneous (ground vehicle and helicopter) swarms currently being conducted by ARL and researchers from the University of Texas in Arlington, TX. In addition, the Micro Autonomous Systems and Technology (MAST) Collaborative Technology Alliance (CTA) has shown interest in the algorithms developed for the simulated swarm, and the Safe Operations of Unmanned Systems for Reconnaissance in Complex Environments (SOURCE) Army Technology Objective (ATO) has shown interest in the control interface. In the first year of this research, papers were published at several international conferences, including the International Conference on Intelligent Robots and Systems (IROS) and the Human Factors and Ergonomics Society (HFES). Second-year research papers are being prepared for these conferences.

In Year 2, we performed additional work beyond that stated within the goals and objectives of the Director's Research Initiative (DRI), by expanding the Year 1 display interface. We replaced the three-dimensional (3-D) view with a more realistic two-dimensional (2-D) map with icons for the swarm members and convoy vehicles. Conditions such as inadequate swarm coverage now cause visual alerts to display messages that identify coverage or team size problems and state the corrective action that the swarm used to mitigate the problem. The expanded interface contains controls that allow the user to adjust the ratio of members in the swarm explorer and sentry teams. Due to time limitations, this interface was not tested. However, the SOURCE ATO has shown interest in performing continuing research using this display interface.

List of Symbols, Abbreviations, and Acronyms

2-D	two-dimensional
3-D	three-dimensional
ANOVA	analysis of variance
ARL	U.S. Army Research Laboratory
ATO	Army Technology Objective
CTA	Collaborative Technology Alliance
DRI	Director’s Research Initiative
FY09	fiscal year 2009
HFES	Human Factors and Ergonomics Society
HRI	human-robot interaction
IED	improvised explosive device
IROS	Intelligent Robots and Systems
MAST	Micro Autonomous Systems and Technology
PDA	personal digital assistant
SOURCE	Safe Operations of Unmanned Systems for Reconnaissance in Complex Environments
VTD	Vehicle Technology Directorate

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