

EXPERIMENTAL STUDY OF INFORMATION LOAD ON OPERATORS OF SEMI-AUTONOMOUS SYSTEMS

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Abstract

A set of experimental results studying the relationship between Human in the Loop performance and user workload in the RoboFlag test environment is presented, with accompanying analysis and conclusions. RoboFlag is an experimental hardware/software test-bed with two teams of 2-6 semi-autonomous vehicles each with Human in the Loop oversight (one or more human operators per team) designed to play games structured around the rules of "Capture the Flag". RoboFlag utilizes small robots based on Cornell University's award winning RoboCup hardware. The objective of RoboFlag is to locate and capture a "flag" by venturing into enemy territory and return the flag to home base without having robots "tagged". Human operators have varying degrees of control over the robots ranging from direct "joystick" control to complete reliance on automation. Operators played a series of games to evaluate performance as a function of information load (speed and number of vehicles). Results showed a positive relationship between game speed and total score. In addition operators reported using more automation as number of robots increased but trusting automation less as game speed increased.

Introduction

Systems of multiple semi-autonomous vehicles have many current and potential applications, including farming (tractors), air traffic control (commercial aircraft), transportation (automobiles on highways), medicinal (environmental and food safety), and defense (troops, tanks, and uninhabited aerial vehicles).^{1,2,3,4,5,6,17} In many cases it is desirable or even necessary to have a human operator with control of certain functions of the system as a whole, or vehicles individually. As a result, the research area of human interaction with automated systems is expanding with focus on more complex and dangerous systems.¹⁶ In order to do so, an interdisciplinary approach involving the fields of cognitive science, psychology and computer

science in addition to more traditional engineering fields is required.

A particularly interesting and challenging application of systems of multiple semi-autonomous vehicles involves the use of Uninhabited Aerial Vehicles (UAV's) in battlefield scenarios for reconnaissance and/or prosecution of high profile/high risk or mobile targets.¹⁶ A good example of cutting edge research in this area is DARPA's *Mixed Initiative Control of Automata-Teams* (MICA) program whose objective is to investigate the problem of designing and controlling semi-autonomous systems of N human operators controlling M UAV's where $M \gg N$.⁶ Unlike the large teams of operators currently required to operate and monitor vehicles such as today's *Predator* or *Global Hawk*, battlefield scenarios of the future will involve single operators operating many UAV's in real time. Such applications make the need for efficient interfaces, a detailed understanding of the limits of human cognitive ability and good overall system integration apparent.

Most current cognitive engineering work related to semi-autonomous systems (such as air traffic control) has focused on narrowed scope problems. For instance, understanding the effects of situation awareness, training and graphical user interface command design on these types of systems requires the problem to be sufficiently focused in order to model the effect and/or gain insight.^{7,8,9} These models can be quite good, but integrating many of these models into a cognitive model of the human operator is far from an end result.¹⁰ As an example, it intuitively makes sense that situation awareness and performance in air traffic control is worse for small numbers and large numbers of vehicles; but the interdependence and modeling of these effects is quite difficult.

The objective of this work is to use a simplified test-bed for semi-autonomous systems in order to evaluate the effects of information load on operators. RoboFlag is an experimental hardware/software test-bed with two teams of 2-6 semi-autonomous vehicles with Human in the Loop oversight (one or more human operators per team) designed to play games with rules similar to "Capture the Flag".^{11,12} Human operators have varying

degrees of control over the robots on their team ranging from direct “joystick” control to total reliance on automation.

Operators played a series of games to evaluate several performance measures as a function of information load (speed and number of vehicles). Data were taken based on single and dual operators. Specific questions to be answered by this work are:

1. *What insight can be gained with regard to the relationship between cognitive workload and Human in the Loop performance in the RoboFlag game?*
2. *How do performance and the use of automation change as the number of vehicles increases?*
3. *What are the effects, if any, on performance and strategy of two operators versus one?*

The answer to each of these will be approached in a somewhat qualitative way by drawing conclusions from the experimental results. Obviously, this method can be limiting; but it provides a good first step to achieving simplified generic information for operator based semi-autonomous systems and insight into experimental refinement.

The outline of the paper is as follows. First, a full description of the RoboFlag game is given. Second a description of the experiment, consisting of two phases. Finally, the paper concludes with experimental results and a discussion of future work.

RoboFlag Description

The RoboFlag test-bed has an interdisciplinary team of researchers investigating solutions to the MICA series of challenge problems. The test-bed allows for the investigation of human interaction with multiple autonomous vehicles in a real-time, hardware-integrated, strategic environment (see Figure 1). RoboFlag’s hardware is similar to that used by RoboCup, Cornell’s championship winning, fully-autonomous robotic soccer game.

The game consists of two teams: Red and Blue (Team 1, Team 2). Each team has the same goal: infiltrate the other team’s territory, capture that team’s flag and successfully return it to the infiltrator’s home zone while protecting their own flag from the adversary. Robots in the opposing team’s territory may be “tagged,” or temporarily sent back to their home zone if they come in contact with an opponent robot. Each team earns points for certain activities. A team’s score is the primary metric for measuring that team’s performance. An autonomous “Arbiter” handles score keeping.¹⁵

Each team is controlled by one (or more) human operator(s) through a graphical user interface (GUI, see Figure 2). Although robots on each team can operate completely autonomously, the human operator has the ability to choose strategy, specific automations and even execute “joystick” (mouse) control of individual robots. The current version of RoboFlag has automated obstacle avoidance (including automatic avoidance of a friendly Defense Zone, defined below). In addition the user has the choice of invoking the following automations/settings at any time:

Stream: Determines type of obstacle avoidance - standard, stream, or motion (heavier fuel use).

Stop: Stops motion/current automation.

Chaser: Chases adversary robot.

Circle Def: Defends home Defense Zone, prevents enemy robots from entering.

Circle Of: Reconnoiters and enters enemy Defense Zone, captures and returns flag.

Init Deploy: Deploys robots to an initial strategic position.

Rush & Stay: Robots rush enemy Defense Zone and stay inside, awaiting further command.

Patrol Border: Robots patrol a line along the border, block or tag enemies.

Tease: Tease and distract enemy robots.

At all times the user can gain control over any robot simply by selecting that robot with the mouse and then assigning a new automation or destination. If a robot running an automation is temporarily directed elsewhere by the user, it will, after reaching its new destination, revert to its activity previous to the Human in the Loop input. A user may also select and command multiple robots at a time by dragging a box over them using the cursor.

The RoboFlag playing field (Figures 1 and 3) consists of a physical 4.0 x 6.0 meter carpeted area. The field is divided in half with one half assigned to each team. Each half consists of three zones: the quarter circular Home Zone, the circular Defense Zone and the remaining Attack Zone. There is an (x,y) coordinate system associated with the playing field with (0,0) at the center. The coordinate system is not absolute, but relative to each team.

Each robot can occupy one of four states: Active (normal operating state), Flagged (in possession of opponents flag), Tagged (robot has performed an illegal move and must be temporarily returned to the Home Zone), and Inactive (robot has entered its own Defense Zone, made contact with an obstacle or run out of fuel). Flagged robots become Active when they successfully return a flag to the Home Zone. Tagged robots are seized by the Arbiter and driven back to the Home Zone

at 0.1 m/s whereupon they become Active. Inactive robots become stationary for the remainder of the game.

Capturing an opponent's flag earns five points, successfully bringing that flag home earns an additional 25 points and tagging an enemy robot earns one point. Points are also awarded if an enemy robot becomes Inactive or is Tagged by Arbiter (runs into a Tagged robot).

A software simulator has been developed (including a physics simulator) and is useful for testing, design and experimentation in situations requiring large numbers of games. Accordingly most games in this experiment were conducted on the simulator. A small set of games with two and four robot scenarios were played on the hardware and compared with results from analogous games on the software simulator.

Finally a logger program was written to log position, orientation, fuel, and operating status for each robot as well as score history at a rate of 30 frames per second. In addition operator inputs through the GUI (mouse and button clicks and selected automation) are recorded as they occur.



Figure 1: Photo of the actual RoboFlag test-bed.



Figure 2: A screen shot of the RoboFlag GUI.



Figure 3: Four screen shots of the RoboFlag game.

Experimental Motivation and Setup

As part of the MICA initiative, a series of RoboFlag games using a GUI designed by students at Cornell University and the California Institute of Technology was played over the summer of 2002. The students also designed a set of automated strategies (described above) that were integrated with the GUI.¹⁴ In September of 2002, a subset of these automations, along with an improved GUI and technologies such as a streamline obstacle avoidance algorithm, were used in the first round of DARPA MICA RoboFlag competitions.^{13,20} Participants included two end users from the Iowa Air National Guard. Games played included two, four and six robots per a team with one and two human operators (sharing a GUI). During the games operator interface interaction was explored by interviewing players to determine their use of automations, trust of those automations, situation awareness, frustration and general interaction with the system.

Several interesting trends were noticed during these games. First, for games with six on six robots, users reported using significantly different strategies than when they played games with two on two robots. There were also differences in strategy observed during games with two versus two human operators rather than one versus one. With these observations as a motivator, a set of experiments was designed to investigate the relationship between user workload/situation awareness and overall level of performance for RoboFlag type systems (i.e. semi-autonomous control of multiple vehicles). Offloading of tasks to increasing levels of automation was also to be investigated. The

experiment was designed in two progressive phases with related goals.

The goal of Phase I was to investigate the relationship between number of vehicles and game speed with regard to certain performance measures such as total score and the operator's situation awareness. The data collected was then to be analyzed 1) for any apparent trends between performance and workload, 2) to provide valuable insight for further refinement of experimental parameters and technique, and 3) to gain useful user feedback for further design and improvement of the RoboFlag test-bed.

The goal of Phase II was to focus on a narrowed set of parameters (number of robots) as it related to total score and use of automation. In addition the relationship between one and two human operators per a team (on both hardware and software) was to be studied.

Phase I

Phase I of the experiment consisted of ten sets of games. Each set contained 12 games of 400 game seconds (approximately 10 minutes) each. Nine of the ten games sets varied two parameters with one versus one human operator (See Figure 4).

	2 Robots	4 Robots	6 Robots
0.25 m/s	Set 1	Set 2	Set 3
0.50 m/s	Set 4	Set 5	Set 6
0.75 m/s	Set 7	Set 8	Set 9
	Each set contains 12 games		

	6 Robots (2v2 Operator)
0.50 m/s	Set 10
	Set 10 contained 8 games

Figure 4: Phase I Experimental Parameters.

Game Parameters:

Game speed and number of robots per a team were varied. Game speed was chosen so as to be correlated with increasing levels of user workload. Game speed was varied between three values: 0.25, 0.50 and 0.75 m/s.

Number of robots per team was chosen as a second parameter correlated with an increase in cognitive workload. Number of robots was varied between three values: two, four, and six per side.

Performance Measures:

Game performance, user workload and situation awareness were assessed using both quantitative and qualitative methods. Surveys were used (TLX and SART) to qualitatively measure user's situation awareness, frustration level and cognitive workload.^{18,19} Users were also given an opened-ended questionnaire section for comments that allowed them to describe in their own words their experience after each game set.

Timeline and Procedure:

Each game set contained 12 individual ten-minute games, with three occurring in parallel, or 40 total minutes of game play. Two game sets were run per testing day. This required six total days of data collection. The logger recorded data from each game. A total of 116 log files were generated. Participants played a game set and completed a TLX and SART survey at the end of each game set. After taking a 15-minute break they played the next game set. Phase I data collection was completed by December 16th, 2002.

Phase I - Results:

Quantitative Results:

Logger data was first examined for trends in total score. The table below (Figure 5) shows mean and standard deviation for total score for each game set.

Total Score Mean and Stdev by game:					
		2 Robots	4 Robots	6 Robots	6 Robot*
0.25 m/s	Mn	341	214	238	
	Std	71	115	88	
0.5 m/s	Mn	532	434	469	643
	Std	238	169	242	128
0.75 m/s	Mn	796	862	763	
	Std	266	376	388	

* Two on two operators

Figure 5: Final scores by game set.

Score data was plotted in several ways: to examine score versus speed for two, four and six robots (Figure 6) score versus speed for six on six robots (one and two players per team, Figure 7) and average total score versus time for six on six robots with one versus two players per team (Figure 8).

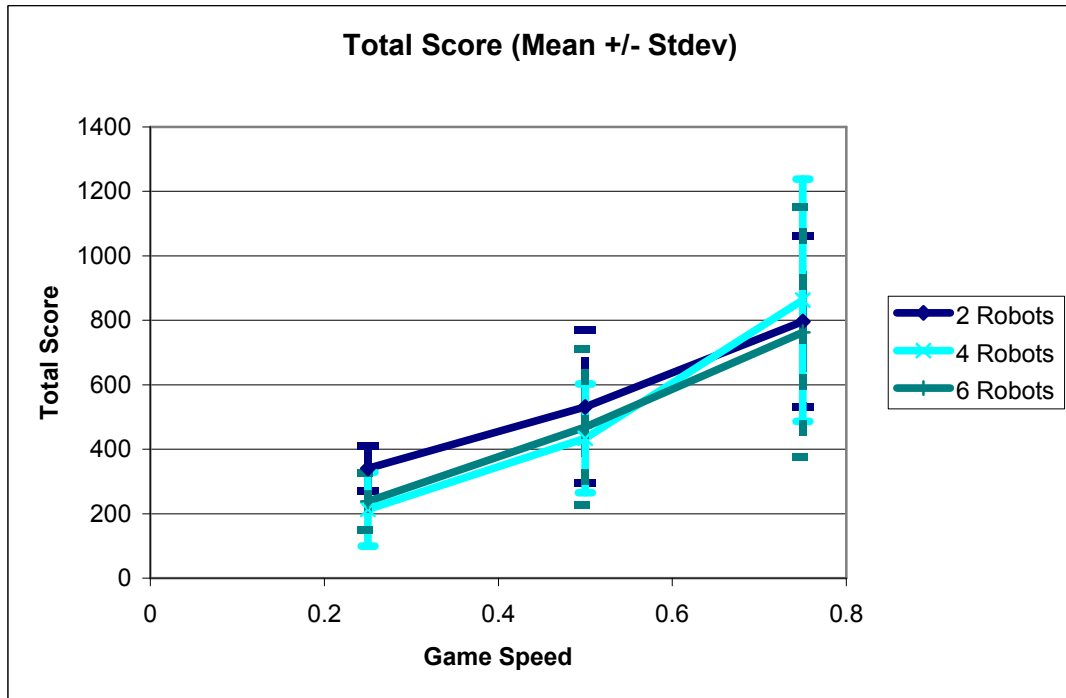


Figure 6: Total Score as a function of game speed and number of robots.

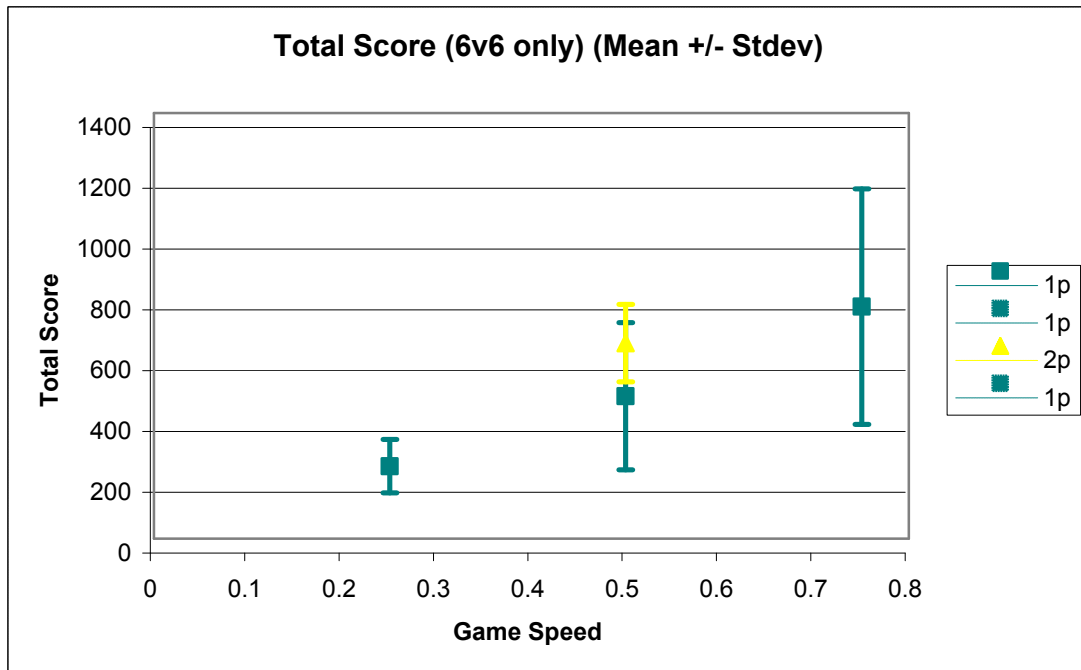


Figure 7: Total score as a function of game speed and number of operators.

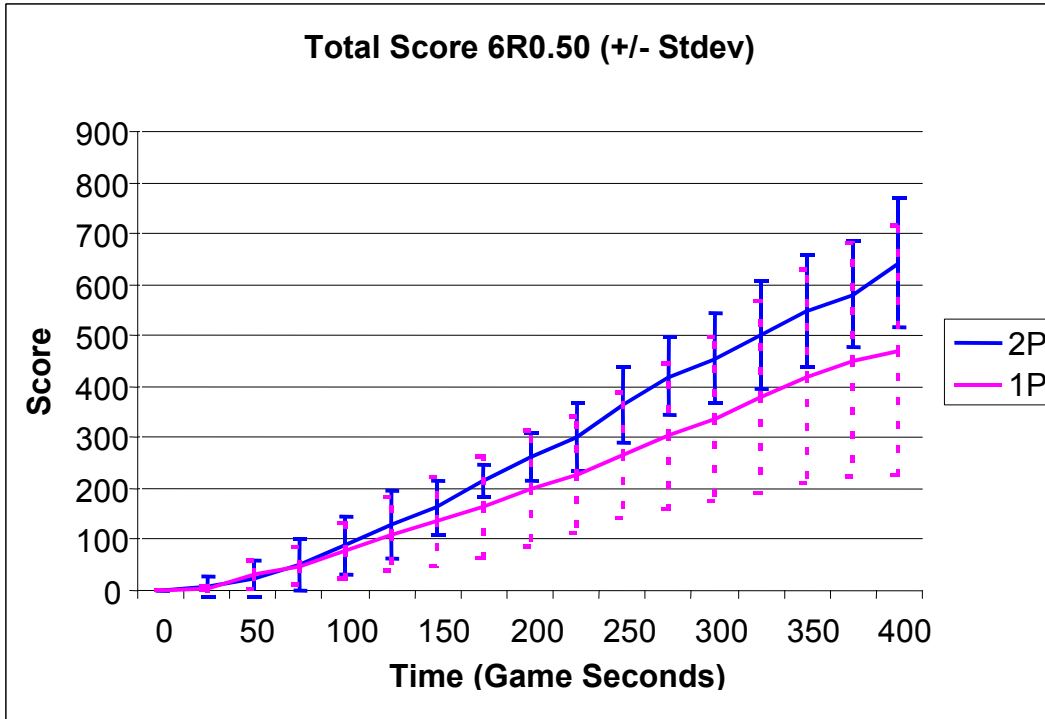


Figure 8: Total score vs. time for one and two players per team (6 robots, 0.50 m/s).

Survey Results:

After each game set operators were given both a NASA TLX and a SART survey. The TLX consists of six fields, Mental Demand, Performance, Physical Demand, Effort, Temporal Demand and Frustration that operators are asked to rate themselves on from a scale of zero to 100. Results from the TLX survey were averaged into a single composite score (with Performance omitted due to confusion on the part of participants). Each value was given equal weighting with results representing a qualitative measure of overall cognitive workload (Figure 9).

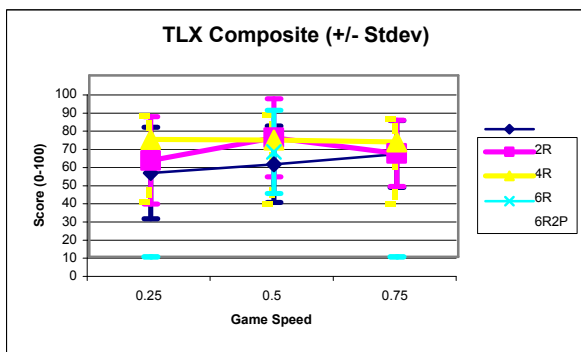


Figure 9: TLX Composite Score as a function of game speed and number of robots.

The SART survey, which consisted of four fields (Demands on Attentional Resources, Supply of Attentional Resources, Understanding of the Situation and Overall Situation Awareness) was used as a qualitative measure of operators Situation Awareness during the game. Users were asked to rate themselves on a scale of one to seven in each respective field after a game set. Figure 10, below, shows the average Overall Situation Awareness during each game set.

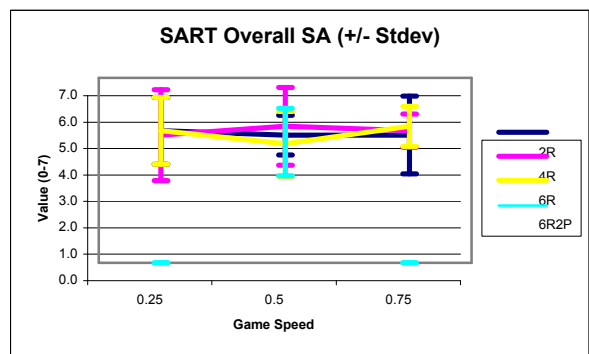


Figure 10: Overall Situation Awareness as a function of game speed and number of robots.

In addition to the survey results, there were several interesting trends in the comments that users made regarding the various game sets:

1. In general users reported “micro-managing” robots in 2v2 games much more than in 6v6. Most users attributed this difference to the relatively higher “value” that each robot commands in 2v2 scenarios. (Loosing a robot is relatively a much larger penalty, thus users spend more time ensuring robots are not tagged or do not become Inactive).
2. As game speed increased operators complained of more lag, uncertainty, and poorer performance by the built in obstacle avoidance. As a result they reported using relatively less automation than in slower equivalent scenarios.
3. Operators reported a significant “learning curve” effect with the various automations. Many users seemed to have a difficult time learning the exact behavior of the automations and reported more uncertainty as game speed increased.

Phase II

Phase II involved playing a new series of games and included an updated version of the RoboFlag software with several new levels of automation in addition to those used in Phase I (see Figure 11).

	2 Robots	4 Robots	6 Robots
1 Player	Set 1	Set 2	Set 3
2 Player	Set 4	Set 5	Set 6
2 Player H/W	Set 7	Set 8	
Notes:	Game speed fixed at 0.50 m/s Individual game length: 10 min		

Figure 11: Phase II Experiment Parameters.

Game Parameters:

Unlike Phase I, game speed was held constant at 0.50 m/s. For games played on the simulator number of robots per team was varied between two, four and six and number of players per side was varied from one to two. For games played on the hardware number of robots was varied from two to four and number of players per side was held constant at two.

Performance Measures:

Performance measures were identical to those in phase I with the noted exception that the SART and TLX surveys were omitted. In addition because of the capabilities of the new logger automation employed as a function of game time was measured. Also user

participation as measured through total mouse clicks inputted into the GUI during a game was examined.

Timeline and Procedure:

The procedure remained similar to that of Phase I. However Phase II consisted of two groups of players with two persons per group. The subjects were drawn from the participants in the initial set of games, thus mitigating any learning curve affects on strategy or performance. Data collection was completed by May 30th, 2003.

Several problems encountered in the first game set were addressed. A game length timer was built into the software so that game length could be consistently enforced (Phase I game length was manually enforced). An improved logger was used to make data acquisition, manipulation and analysis faster, simpler and more transparent. Better planning and experimental design were utilized and identical CPU’s were used to eliminate variation due to processor speed.

Phase II - Results:

Quantitative Results - One vs. One Human Players:

Logger data was first examined for trends in total score and these numbers were compared to results from respective scenarios in Phase I. The table below (Figure 12) shows mean and standard deviation for total score for each game set (300 game seconds in length).

		Comparison of Total Score at 0.50 m/s		
		2 Robots	4 Robots	6 Robots
Game II	Mean	483	381	386
	Stdev	154	110	76
Game I	Mean	399	325	351
	Stdev	178	126	181

Figure 12: Comparison of Total Score

As can be seen from the table above scores were higher in the second set of games for the same respective conditions when compared to the first set of games (Figure 12). This trend continued when the number of robots was varied as illustrated in Figure 13 below.

The average number of GUI clicks increased as number of robots increased (Figure 14), with an average increase of 12.6% per an increase of two robots suggesting that although increased robots required more user oversight users relied heavily on the use of more automation.

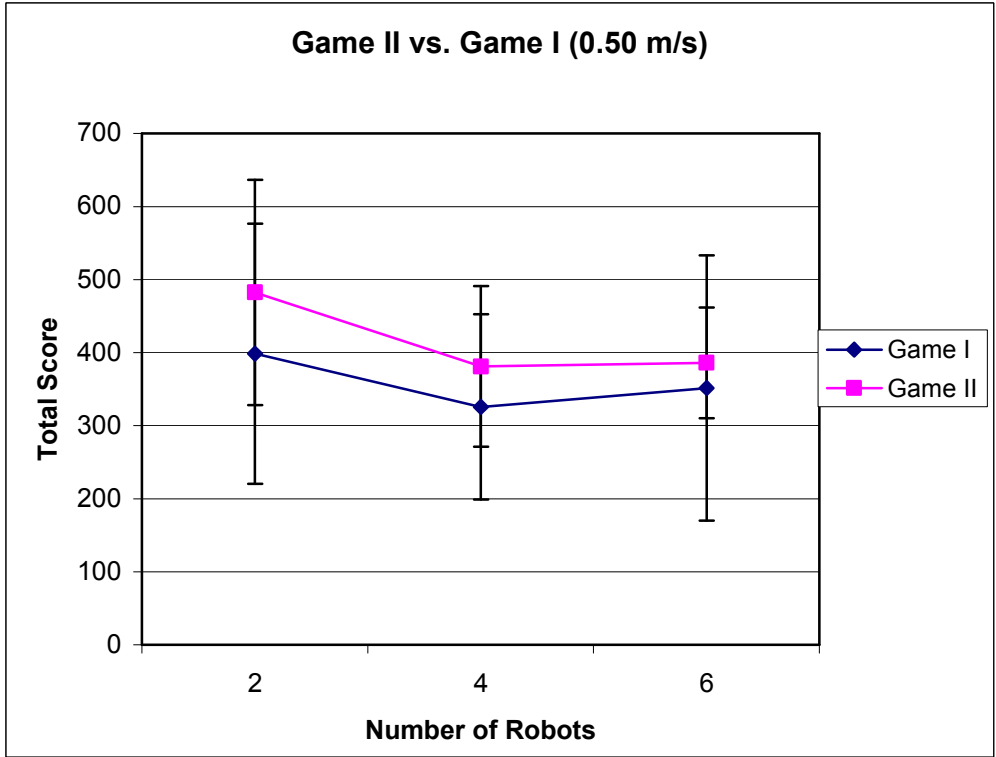


Figure 13: Total score in Phase II Vs. Phase I as a function of number of robots.

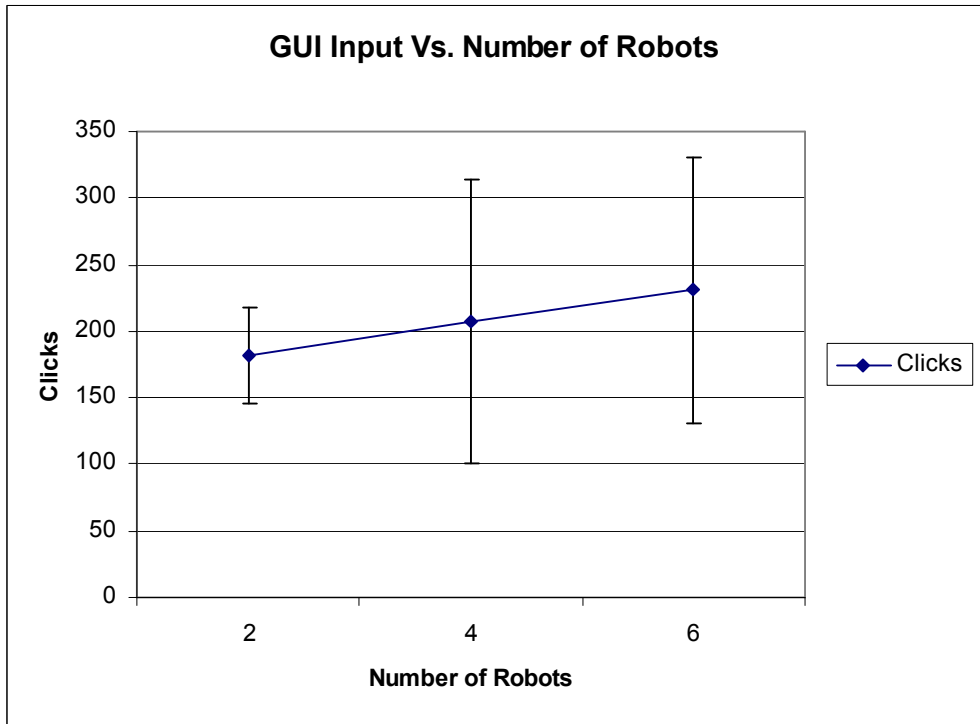


Figure 14: GUI input and number of robots.

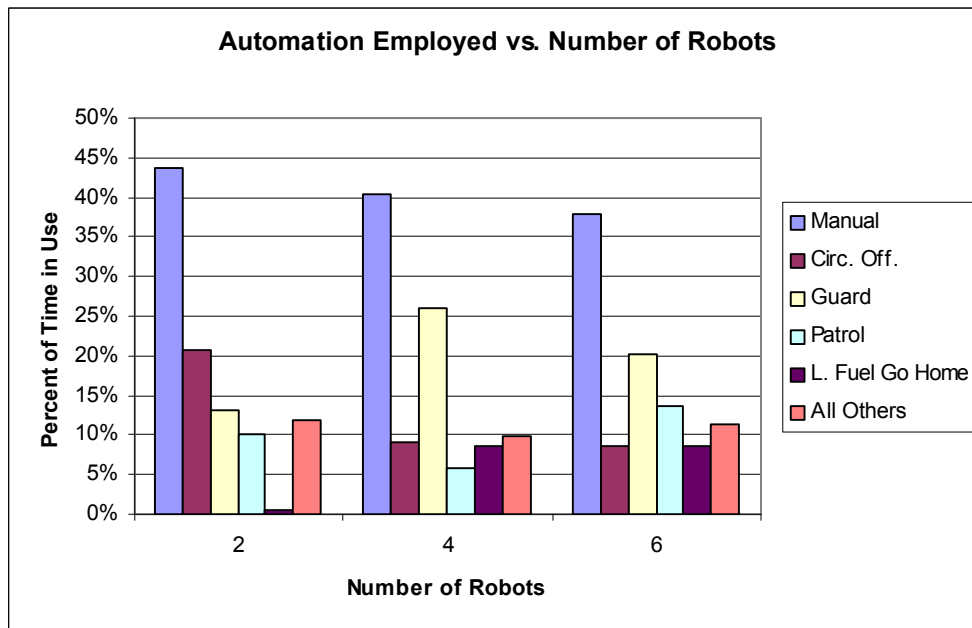


Figure 15: Automation employed versus number of robots at 0.50 m/s for one on one operator games.

Finally, utilizing the abilities of the new logger, data was analyzed to examine which automations were employed as a percentage of game time for each of the games. Results are summarized in Figure 15, above. As can be seen, as number of robots increased manual control decreased, defensive plays were utilized more often and sending robots home automatically when fuel was low occurred more frequently.

Overall a number of trends were noticed in the second set of games. Phase II games saw an increased in total average score of 16% over those in Phase I. As number of robots increased manual control decreased and more defensive plays were used. However, users reported continued problems with obstacle avoidance. In addition, users stated that the ability to tweak parameters, customize and script plays would be very desirable.

Quantitative Results - Two vs. Two Human Players:

Logger data was examined for trends in total score. Figure 16 shows mean and standard deviation for total score for each game set played on the simulator (300 game seconds in length). Data from the two vs. two six-robot game at 0.50 m/s from the first set of games is included for comparison.

In addition to data collected on software two and four robot scenarios at 0.50 m/s a second with two vs. two human operators were investigated on the

hardware (the six robot scenario was omitted due to mechanical difficulties with the system). The tendency for score to decrease as number of robots increases can be observed in both the hardware and software scenarios. However it is important to note that in the case of hardware, total score is significantly less in both cases (Figure 17). This is attributed to technical difficulties encountered during the hardware sessions such as overhead vision drop out and stuck robots (due to mechanical problems) that made robots unusable for certain portions of the game.

User input as measured by clicks in the GUI was also analyzed for both software and hardware games (Figure 18). Results are comparable to those from the one on one scenario above, again values for hardware being less than those for software. This is attributed to increased down time (and thus less required input) due to technical problems mentioned previously.

Finally, for the software case, automation employed as a percentage of game time was also examined. (It should be noted that this was not possible in the hardware case because of certain constraints in the design of the logger software). As with the one on one case, as number of robots increased, manual control decreased. However, the only automation to see a significant increase in use was Guard Position (Figure 19).

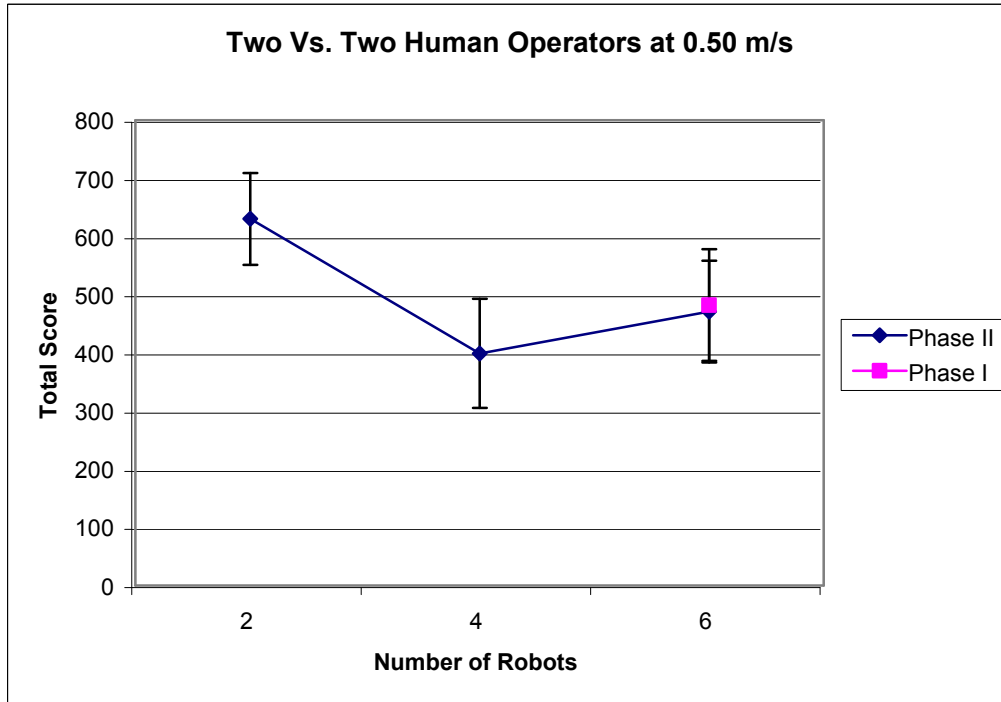


Figure 16: Two player total score as a function of the number of robots for Phase I and Phase II.

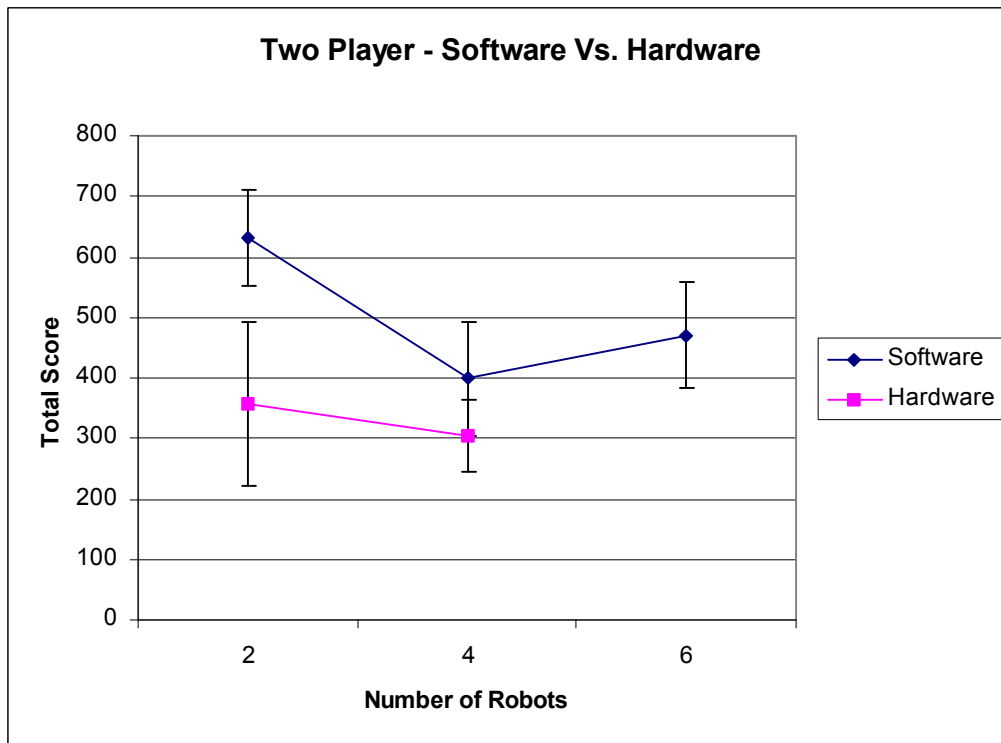


Figure 17: Total Score for two vs. two players as a function of software and hardware implementation.

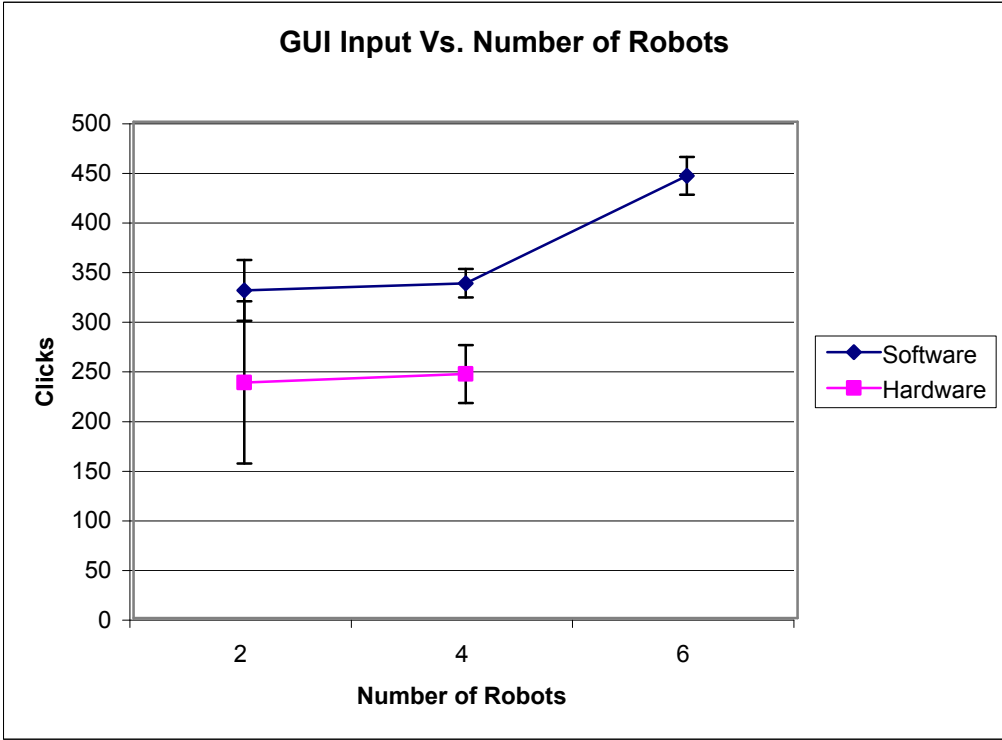


Figure 18: GUI input for two vs. two players as a function of software and hardware implementation.

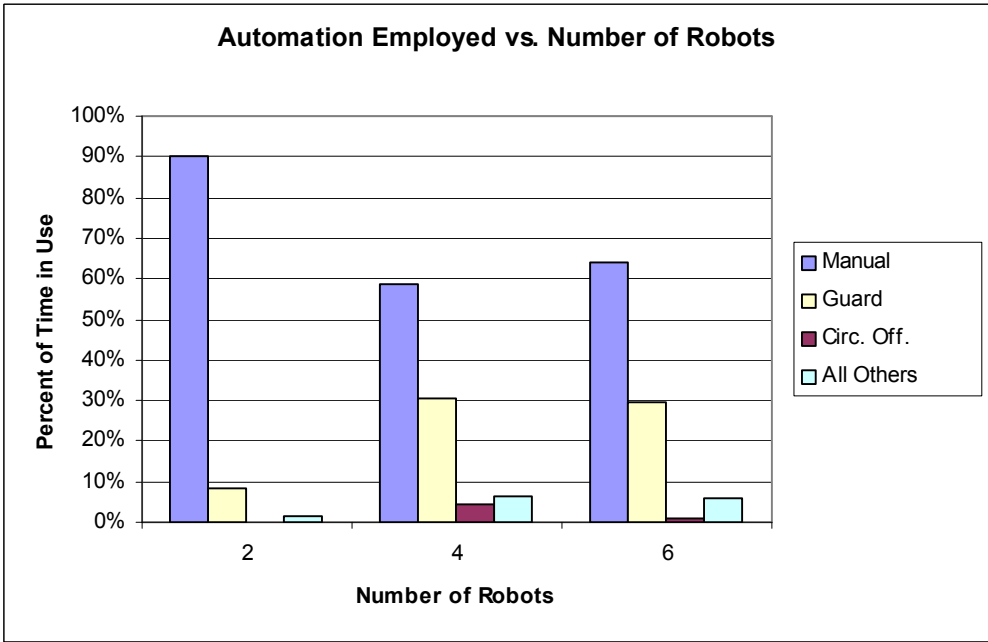


Figure 19: Automation employed as a function of the number of robots for two vs. two players.

Summary:

This study sheds light on the answers to the questions posed previously in the introduction. Based on the results from Phase I and II the following summary has been made:

- Operators “micro-managed” robots more heavily when controlling a smaller number; they relied more on automation as number of robots increased.
- Increasing number of robots was not correlated with a higher score but rather a focus on defensive strategies.
- Increased GUI clicks were correlated with an increase in robots, but only to a modest extent.
- Increased game speed was correlated with an increase in score despite operators complaining of more distrust in the automations and a tendency to use relatively more manual control when possible.
- Cognitive workload remained relatively level as game speed increased, but rose slightly as number of robots increased.
- When automation was improved (Phase II) operators were able to score higher holding other conditions constant.
- Adding an additional human player always increased total score and allowed for less reliance on automation.
- Hardware implementation generated similar results after consideration of poorer performance due to technical problems.

Conclusions:

Accordingly the following conclusions can be drawn regarding the design of similar systems of semi-autonomous vehicles and their application to the DARPA MICA challenge problem.

- As the number of vehicles controlled by an operator increases offloading tasks to automation becomes highly important. However, poor automation design can and will lead to little or no increase in operator performance. Additionally defensive strategies become more important suggesting that automation of this aspect is a priority.

- Because GUI input and subjective cognitive workload increase only slightly as number of robots increase, it appears users try to maximize their participation with the system at all times. This suggests issues relating to insufficient situation awareness due to lack of stimulus are minor.
- Improved automation did result in higher end performance underscoring the importance of this aspect of system design.
- Adding operators always improved team performance thus suggesting a method for increasing general system performance independent of automation.
- Results from hardware implementation serve as a reminder of the importance of testing on physical systems in order to capture all aspects of system integration.

Developing efficient methods of human oversight and control of systems of multiple autonomous vehicles is particularly important in high risk, information intensive areas such as battlefield reconnaissance and target prosecution. A full understanding of human cognitive limits and useful interface design is necessary for developing complete, hardware integrated systems. RoboFlag offers an excellent platform to study these issues by providing a real-time, Human in the Loop environment with actual hardware integration and easy scenario generation with a flexible rule structure.

Future Work:

Future work on interface design and constraints on human cognition as it relates to the MICA initiative will involve developing more detailed test data that can be used to form guidelines for efficient, scalable interface design to attack the more general case of $M \gg N$ UAVs in a real world scenario. Interface and automation design can be improved in order to increase performance metrics in simulated games. In addition, work based on concepts developed earlier by Kirlick in modeling optimal decision making and strategy formulation using Markov Decision Processes will be investigated using MATLABTM⁹. This will facilitate the construction of more efficient automations resulting in greater task offloading by the end user thus freeing

cognitive and attentional resources for the management of a greater number of vehicles.

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