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Supervisory Autonomous Control of Homogeneous Teams of Unmanned Ground Vehicles, with Application to the Multi-Autonomous Ground-Robotic International Challenge

Katrina L. Corley

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**SUPERVISORY AUTONOMOUS CONTROL OF HOMOGENEOUS TEAMS
OF UNMANNED GROUND VEHICLES, WITH APPLICATION TO THE
MULTI-AUTONOMOUS GROUND-ROBOTIC INTERNATIONAL CHALLENGE**

Katrina L. Corley

**A Thesis Submitted to the
Graduate Studies Office
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Mechanical Engineering**

April 26, 2011

Embry-Riddle Aeronautical University

Daytona Beach, FL

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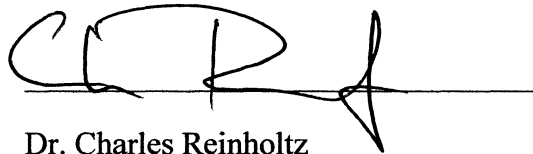
SUPERVISORY AUTONOMOUS CONTROL OF HOMOGENEOUS TEAMS
OF UNMANNED GROUND VEHICLES, WITH APPLICATION TO THE
MULTI-AUTONOMOUS GROUND-ROBOTIC INTERNATIONAL CHALLENGE

by

Katrina L. Corley

This thesis was prepared under the direction of the candidate's thesis committee chairman, Dr. Charles Reinholtz, Department of Mechanical Engineering, and has been approved by the members of her thesis committee. It was submitted to the Mechanical Engineering Department and was accepted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering.

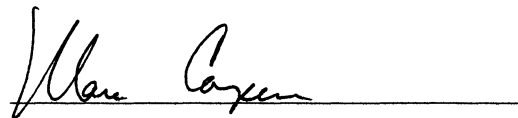
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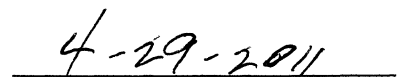
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ABSTRACT

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There are many different proposed methods for Supervisory Control of semi-autonomous robots. There have also been numerous software simulations to determine how many robots can be successfully supervised by a single operator, a problem known as fan-out, but only a few studies have been conducted using actual robots. As evidenced by the MAGIC 2010 competition, there is increasing interest in amplifying human capacity by allowing one or a few operators to supervise a team of robotic agents. This interest provides motivation to perform a more in-depth evaluation of many autonomous/semi-autonomous robots an operator can successfully supervise. The MAGIC competition allowed two human operators to supervise a team of robots in a complex search-and-mapping operation. The MAGIC competition provided the best opportunity to date to study through practice the actual fan-out with multiple semi-autonomous robots.

The current research provides a step forward in determining fan-out by offering an initial framework for testing multi-robot teams under supervisory control. One conclusion of this research is that the proposed framework is not complex or complete enough to provide conclusive data for determining fan-out. Initial testing using operators with limited training suggests that there is no obvious pattern to the operator interaction time with robots based on the number of robots and the complexity of the tasks. The initial hypothesis that, for a given task and robot there exists an optimal robot-to-operator efficiency ratio, could not be confirmed. Rather, the data suggests that the ability of the

operator is a dominant factor in studies involving operators with limited training supervising small teams of robots. It is possible that, with more extensive training, operator times would become more closely related to the number of agents and the complexity of the tasks. The work described in this thesis proves an experimental framework and a preliminary data set for other researchers to critique and build upon. As the demand increases for agent-to-operator ratios greater than one, the need to expand upon research in this area will continue to grow.

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CHAPTER 1: INTRODUCTION

This work presents an experimental framework for testing multi-robot teams. In the experiment, small robots are operated by a single operator and data is collected in an effort to measure operator-robot interaction time and overall success in performing a mission. Each robot utilizes tank steering, line sensors and bump sensors in coordination with C-based code for lower-level autonomy. These robots interface with an Operator Control Unit (OCU) running LabView to implement the supervisory control portion of the experiment. Operators are tasked with supervising a team of small robots starting with one robot and increasing to a total of three robots. Each testing session is five minutes in duration. During the first test session, the operator is required to count the number of laps the robots have completed and avoid obstacles by taking control of the robot prior to collision. During the second test session, the operator is required to count the number of laps the robots have completed and avoid obstacles given feedback. During the final test session, the operator is required to count the number of laps the robots have completed, avoid obstacles using visual feedback, and visually identify combatants and noncombatants.

Applications

In many current applications multiple users are required to operate a single robot. One such example is the Predator UAV currently being used by US military forces overseas. Two operators are required to operate each Predator. Because this is typical of most robotic systems that are currently implemented, the number of people operating the systems far exceeds the number of robots. While the robots are accomplishing the important goal of removing humans from a hostile environment, they generally do not increase efficiency or productivity. It is clearly desirable to have a single human operating multiple robots with autonomous capabilities and intervening only when the robots require assistance. These multi-robot teams would, for example, be able to search and map an area faster and more efficiently than a human while achieving one of the goals of robotics, removing humans from tasks that are dull, dirty, or dangerous. In addition,

automated identification of objects of interest (OOI) allows a robot to contact the operator for support while the robot maintains surveillance of the OOI.

Prior Work

Crandall and Cummings [2007]

Based on the desire for a single operator to control multiple robots, many new questions have arisen. From Crandall and Cummings, some of these questions are:

How many robots should there be in the team? What human–robot interaction methodologies are appropriate for the given human– robot team, mission, and circumstances? What autonomy levels should the robots in the team employ, and when should changes in these autonomy levels be made? What aspects of a system should be modified to increase the team’s overall effectiveness? (Crandall and Cummings)

In order to answer these questions they believe that a set of metric classes must be developed. Metric classes must contain key performance parameters, identify the limits of the team members, and have predictive power. A key performance parameter is a measureable quantity the gives a sense of the team’s overall effectiveness. To test the developed predictive metrics single human to multiple simulated robot testing was conducted. During an eight minute period, users were tasked with moving the simulated robots through a maze and collecting objects. At the end of the eight minutes, any robots left on the field were considered to have been destroyed in an explosion. Operators were asked to maximize their score based on the formula: $\text{Score} = \text{Objects Collected} - \text{Robots Lost}$. A two-screen user interface was used with a map of the maze and known objects on the left and a city map on the right. Only one robot could be controlled at a time. Once a robot was selected, the operator designated a goal location by dragging the robot’s goal icon. The robot then generated a path and the operator had the opportunity to modify its course. Four kinds of indicators were used to assist the operator in controlling the robots: the assign task indicator, the visual task indicator, the time warning indicator, and the deliver object indicator. Dijkstra’s shortest-path algorithm was used to navigate the robots through the maze. Each operator completed six eight minute long sessions. During the first four sessions, either two, four, six, or eight robots were randomly selected. The selected pattern was repeated for the other four sessions. A

total of 12 participants were used for this study with three women and nine men. A professor, ten students, and one community member were used. The authors felt it was important to note that simulated robots often behave differently than real robots and thus metrics used with real robot systems will be different than those used for simulated robots. The observed number of robots successfully controlled was between four and six.

Olsen, Wood, & Turner [2009]

Like Crandall and Cummings, Olsen, Wood and Turner worked to develop metrics for humans driving multiple robots. They first tested their metrics using simulated mazes where the operator had direction and distance based robot control of three types of robots: simple robots, bounce robots, and planning robots. The simple robots moved directly toward the goal until they either reached it or hit an obstacle. The bounce robots bounced off obstacles and tried to get closer to the goal even if they could not find a direct path. In addition, bounce robots could not back up and were programmed to stop when a local move that would take the robot closer to the goal could not be found. Planning robots had a sensor radius and utilized a shortest path algorithm to find the point closest to the goal within its sensor radius. The planning robots stopped when they were at the point closest to their goal within their sensor radius and also had the capability to avoid dead ends that are not larger than their sensor radius. During testing, eight participants were used in eight races with a total of 18 robots and 10 targets to find. Two races were conducted with simple robots, three races with bounce robots, and three races with the planning robots. This pattern was then repeated with fewer obstacles and then again with the same complexity but with a lower user interface resolution. Olsen, et al. also continued their testing one step further and performed real robot testing. For this testing four robots were placed in a maze. The operators needed to send each robot to its specified target location. Two types of control schemes were used: direction-only control where the user monitored the robot to avoid collisions, and short-range-goal control, where cameras guided the robots toward the goal, but did not avoid collisions. For this testing 18 users with both types of control were used. It was determined that, for the robots with direction-only control, the operator could effectively control only one robot. With the short range camera control, two robots could be effectively controlled.

Velagapudi, et al. [2008]

Velagapudi, et al. used USARSim to investigate the effect of the number of robots on an Urban Search and Rescue (USAR) task. Four to twelve simulated unmanned ground vehicles performing USAR tasks were tested in the 2006 RoboCup Rescue Virtual Robots competition arena. Search tasks were performed using 4, 8, and then 12 robots. A total of fifteen participants each did three 15 minute sessions. Based on this testing the authors concluded that 8 to 13 robots were optimal for performing USAR tasks.

Adams [2009]

Adams developed a multiple agent supervisory control (MASC) system where robots performed indoor material transport tasks. Four heterogeneous ground vehicles were used for this testing. The bases used for two of the robots were TRC Labmate mobile bases. A SensorBot with 16 ultrasonic sonar and infrared sensor pairs as well as a structured-light source and camera and a stereo camera pair was used as one of the robots. A VisionBot with a stereo camera pair and a camera that was mounted on a turntable were used as another of the robots. The other two robots were a PumaBot and the ZebraBot and were used to transport objects from one location to another. This study was one of the first multiple robot user evaluations that used real robots rather than simulated ones. The NASA Task Load Index was used to evaluate the hypothesis that the number of robots a human supervises does not affect the perceived workload level. The hypothesis that perceived workload levels are not affected by increased experience with the system was evaluated as well. The final hypothesis evaluated was that the number of robots does affect task performance. Each of the robots had differing levels of autonomy as well as different tasks. Operators performed a single robot task, a two robot task and then a four robot task. Task completion times, successful task completions, the number of operator errors, etc. were measured during these tests. The focus of this experiment was the analysis of the experimental data rather than developing a framework that could be expanded or reused. Failures encountered during the testing included communication failures, low batteries, and bumper activation. All trials with system problems were completed with the robots that were still functioning. The author discovered that while

there was little difference in the time required to complete the tasks with one or two robots the required time became significantly longer when supervising four robots and that the number of tasks completed successfully decreased as the number of robots increased.

Azarnasab and Hu [2007]

A collaborative system with many real and simulated robots was designed for this project. For testing, examples of a real four robot team scenario and a two real robot and six simulated robot scenario are used. The real robots utilized a combination of real and simulated sensors to move in a real environment. Users had the ability to change system parameters such as speed and also had control of vision, localization and navigation for the robots via graphical user interface. Overhead images of the real field were used to localize the robots on the playing field. The real robots used for this experiment are Khepra robots with 8 proximity sensors. The focus was on the design and implementation of a system of multiple robots rather than the testing of multiple robots to determine the optimal number to operate. While this approach does offer the option of including or focusing directly on real robots, because these robots are interacting with a virtual environment and sensors, they may not respond in the same way as robots in a real world environment.

Dixon, Dolan, et al. [1999]

RAVE (Real And Virtual Environment) is a software framework that allows the operation of multiple heterogeneous mobile-robots. The operation of multiple-robot systems requires an extensive base of capabilities such as communications, user interfaces, and support for simulation. RAVE allows the development and testing of multiple types of robots in simulation that can then be transferred to real world robots. RAVE also allows any robot program to be run on either a real or simulated platform. One of the largest benefits of this approach is the ability to determine whether or not an additional sensor would be useful before purchasing it. In addition, it can allow the testing of simulated robots along with actual robots. Three graphical user interfaces (GUI) are available in RAVE. The observer GUI only has the capability to view the overall system state. The commander GUI has the ability to actually control the robots.

The super-user GUI has the most control over the system and was the only GUI allowed to control the execution of a system run. In addition these GUIs operate over the internet allowing operators to be located in a wide variety of areas. RAVE's main components are libraries for robot programs, information servers, and a set of user interfaces. While these libraries allow for testing of real sensors that have been simulated it also allows for the creation of virtual sensors that have no real world counterpart such as indoor GPS sensors. Virtual sensors have the ability to have noise included in their output as well to replicate to some degree the variation that is seen in real world sensors. RAVE has been used for the Millibot project where a team of small robots is used to carry out surveillance tasks. RAVE has also been used on several other platforms, including two outdoor all-terrain vehicles and three model tank robots. This software framework was designed to allow the implementation of combinations of real and virtual robots.

RoboFlag and RoboCup [2001]

RoboFlag was developed at Cornell as an advancement of RoboCup. It is a robot based game of capture the flag where there are two teams of five simulated robots competing. The RoboCup environment was designed to allow for easy testing of software algorithms to determine their effectiveness. The RoboCup competition involved fully autonomous robots that work as a team to play soccer. Both of the competitions utilize fully autonomous robots. While proving to be an excellent test bed for algorithms, these competitions lacks the key component of user supervisory control for multi-robot teams.

Parasuraman [2003]

Participants in this research program controlled a team of simulated robots within the RoboFlag environment. These participants completed a total of 45 trials. There were nine different combinations of the opponent "posture" (offensive, defensive, or mixed) and environmental uncertainty (visual range of the robots: low, medium, or high). Participants performed five mission trials with each of the possible combinations. The NASA Task Load Index (TLX) and 3-D Situation Awareness Rating Technique (SART) questionnaires were used to evaluate participant load for the tasks. It was determined that the RoboFlag arena is viable for evaluating operator strategies for controlling multiple robots.

Trouvain and Wolf [2002]

Trouvain and Wolf conducted an experiment that evaluated their multi-robot control interface. The experiment allowed them to gather data and feedback that would allow them to improve their interface. A line-of-sight goal point navigation algorithm was used to guide the robots through the simulation. The robots had a 360° two dimensional scanning device that was range limited. For this setup the scanning device is error free. The control interface was composed of two map displays. One displayed the environment and other objects such as robots or obstacles. The second displayed a small section of the area with the maximum detail level. Operators were given a group of homogeneous robots in an environment where inspection points appear randomly. Operators were tasked with navigating a robot to an inspection point where the robots could inspect the area with their sensors while monitoring all robots to avoid inspection delays. Operators used two, four, and eight robots in two different environments. Operators received written instructions at least one day prior to testing and also received 30 minutes of training. Trouvain and Wolf noted that increasing the autonomy of the robots improved the control aspect, but did not improve the operator's ability to monitor them. They also noted the common problem of an operator interacting with the wrong robot. Their operators also requested the capability to control multiple robots at the same time.

Olsen and Wood [2004]

Olsen and Wood performed fan-out experiments where operators performed a maze-searching task. The operator controlled the robots by dragging their goal to a different location. As with the previously discussed work by Olsen, Wood, and Turner there were three types of simulated robots: simple, bounce, and plan. Eight participants were used for the first race. Each ran eight races with 18 robots available and 10 targets to find and an obstacle density of 35%. Two races were run with simple robots and three each were run with the bounce and plan robots for a total of 64 trial runs. Fan-out for the simple robots was 1.46, for the bounce robots it was 2.94, and for the plan robots it was 5.11. The experiment was then repeated with an obstacle density of 22%. For this obstacle

density the fan-out for the simple robots was 1.84, for the bounce robots it was 3.36, and for the plan robots it was 9.09. For the third test the fan-out was 1.12 for the simple robots, 2.47 for the bounce robots, and 3.97 for the plan robots. The test was then repeated again, but with the robots having varying speeds. Based on this test it was possible to see that the faster the robot moved the lower the fan-out. The authors concluded from this research that their model for fan-out based on activity time over interaction time did model many of the effects seen in human interaction with multiple robots. They also concluded that fan-out was more complex than the equation would indicate.

Balakirsky, et al. [2007]

The RoboCup Rescue competition was first held in 2006. It was based in the USARSim framework. Robots were simulated with their sensors and actuators allowing for seamless transportation from real-world counterparts to simulated robots. The maximum team size for 2006 was 12 virtual robots. Teams of heterogeneous robots were used for this competition. The simulator did provide accurate ground truth data for capabilities such as localization and avoidance of bumping. Tasks for the competition included locating victims and providing information about them as well as developing a comprehensive map of the environment. In this competition one operator was able to coordinate up to seven robots at a time.

Humphrey, et al. [2006]

Humphrey, et al. used a modified version of the USARSim package called the UTFARSim (Unreal Tournament with Flash and Actionscript Robotic Simulator for their research. The goal of their experiment was to evaluate their user interface and measure changed in workload and situational awareness in a robot increase from six robots to nine. Robots were able to explore forward, spin 360°, look at a specific robot, go to a robot's location, or defuse a bomb. Twenty volunteers were used. These volunteers had to at a minimum have a high school education, be comfortable with computers, have experience with first-person-shooter video games, and have no experience or prior exposure to the maps or interface used for the testing. Three types of robots: scout,

bombardier, and bomb were used for the experiment. Operators acted as bomb squads and searched the given area for static brown robots that represented bombs. For the six robot tasks operators controlled four scouts and two bombardiers while locating and disarming two bombs. For the nine robot task operators controlled six scouts and three bombardiers and were tasked with locating and disarming three bombs. Operators had ten minutes to complete the task of disarming all the bombs. Operators completed two trials of each the six robot and nine robot tasks after completing a training task with six robots and a single bomb. The NASA-Task Load Index questionnaire and a three dimensional Situation Awareness Rating Technique questionnaire were used for the experiment. All of the bombs were successfully neutralized for 16 of the six robot trails and for nine of the nine robots tasks. Also the mean time required to neutralize all of the bombs for the six robot task is seven minutes and six seconds and for the nine robot task is eight minutes and twenty-nine minutes.

Crandall et al. [2003]

Crandall et al. identified two concepts that play a part in determining the usefulness of a system. The first was the robot's level of autonomy and the second was how well the robot interacts with the human. To test these predictions the simulated 3-robot teams were evaluated for two interaction schemes. For the first scheme, operators used a point-to-point control scheme where robots received instructions at each intersection and continued moving forward until they received a new command. For the second scheme (region-of-interest), operators placed a goal marker on the map and the robot moved toward the goal while mapping the environment. Operators could interact with a robot as long as they chose until they decided to neglect it. Once the robot had been neglected, the operator was required to either control a second robot or perform two-digit arithmetic problems before being allowed to interact with the first robot again. Thirteen operators were used for the experiment. Operators were trained in controlling the robots and then performed six five-minute sessions each in a different world. A second study was completed with a three robot team as well. Three goals were present at any time and any robot was allowed to collect a goal. Once one goal was collected another appeared until nine goals had been gathered. Operators were permitted to interact with any robot at any

time. This experiment consisted of 23 users who each performed six sessions. Crandall et al. found that the more region-of-interest robots in the system the faster the team was able to complete a mission.

Trouvain, Schlick, and Mevert [2003]

Trouvain, et al. presented a study of a unique multi-robot user interface. A simulated semi-autonomous system composed of three different user interfaces that could control one, two, or four robots was tested. The three different user interfaces were camera only, map only, and camera and map combined. The zero score of performance is set by an autonomous robot without a priori knowledge or operator intervention that explored to find paths to the goal points. If the user did nothing the score was zero, and if the user interventions were counterproductive then the score was allowed to go negative. The maximum limit of the score is determined by an autonomous robot driving optimum paths it was given a priori and represented by a 1. The operator may intervene by issuing single waypoint type commands. Eleven male operators participated in this experiment. All operators were scientists or engineers who were experienced computer users. A three dimensional terrain was used for the small failsafe vehicles in this experiment. This meant that the robots were not allowed to fall into negative obstacles, such as trenches, that could not be detected by the sensors. Small unmanned ground vehicles with a diameter of 50 centimeters with a maximum velocity of 1 m/s and maximum climb angle of 20 degrees were used for the base robots. A single horizontally stabilized beam type optical range finder was mounted 50 centimeters above ground to aid in obstacle avoidance and navigation. A shortest path algorithm using the most recent map was utilized by the autopilot. A camera was also mounted at a one meter height above the ground. Operators were given a total of one hour of training with an example of two robot trials with all three interfaces and a briefing of the experiment goals on the day before the experiment. A written instruction manual was given to the operators on the day of the trial. The cognitive demands of the two and four robot tasks were too high to override the autopilot and operators tended toward reactive rather than proactive patterns. Performance levels for two and four robots were similar, but the mental demand for four robots was considerably higher.

Table 1: Compiled List of Previous Research

Researchers	Year	Type of Robots	Number of Robots
Trouvain & Wolf	2002	Simulated	2, 4, & 8
Trouvain, Schlick, & Mevert	2003	Simulated	1, 2, 4
Crandall et al.	2003	Simulated	3
Olsen & Wood	2004	Simulated	18
Humphrey et al	2006	Simulated	6, 9
Balakirsky et al.	2007	Simulated	12
Crandall & Cummings	2007	Simulated	2, 4, 6, 8
Olsen, Wood, & Turner	2009	Simulated	18
		Real	4
Velagapudi, et al.	2008	Simulated	12
Adams	2009	Real	4
Azarnasab & Hu	2007	Real	2 and 4
		Simulated	6
Dixon, Dolan, et al.	1999	Real and Simulated	Hardware dependent
RoboFlag	2001	Simulated	5
Parasuraman	2003	Simulated	5

Ongoing Work

CANINE (Collaborative Autonomous Navigation In a Networked Environment)

CANINE is an ongoing research project where teams will design unmanned and autonomous ground robots. The robots will be shown an axisymmetric object between 5 cm³ and 25 cm³ in maximum dimension. The object will be thrown 10m away and then the robot will go find and retrieve the object. This will be completed over six phases where there will be objects of similar shape, but different color as well as moving humans on the course. The goals for this competition are to complete the tasks in a reasonable amount of time with minimal operator supervision.

MAGIC 2010

The Multi Autonomous Ground-robotic International Challenge (MAGIC 2010) was a challenge designed to draw cutting-edge proposals for fully autonomous ground vehicles. These ground vehicles were required to be deployed quickly and effectively during both a military operation and a civilian emergency such as a hurricane. MAGIC 2010 opened

the door for a new group of autonomous ground vehicles that are able to operate in a more intelligent manner to provide the necessary support required by human colleagues. This challenge was open to industry and academia, but not government organizations. The Defence Science & Technology Organisation (DSTO) in Australia and the Research Development & Engineering Command (RDECOM) in the United States took the lead in organizing MAGIC 2010. MAGIC 2010 ended in November 2010. It has been included in the ongoing work area as a result of feedback from event sponsors who were already discussing the next steps for a second MAGIC completion at the conclusion of MAGIC 2010.

The Challenge Arena

The Challenge was held at the Royal Adelaide Showgrounds in Adelaide, South Australia. The larger central area of the track was used to host a ground control station and command center as well as three service zones. A mix of temporary and permanent boundaries were used to contain the UGVs to the desired challenge area. The aerial photograph in Figure 1 shows these features.

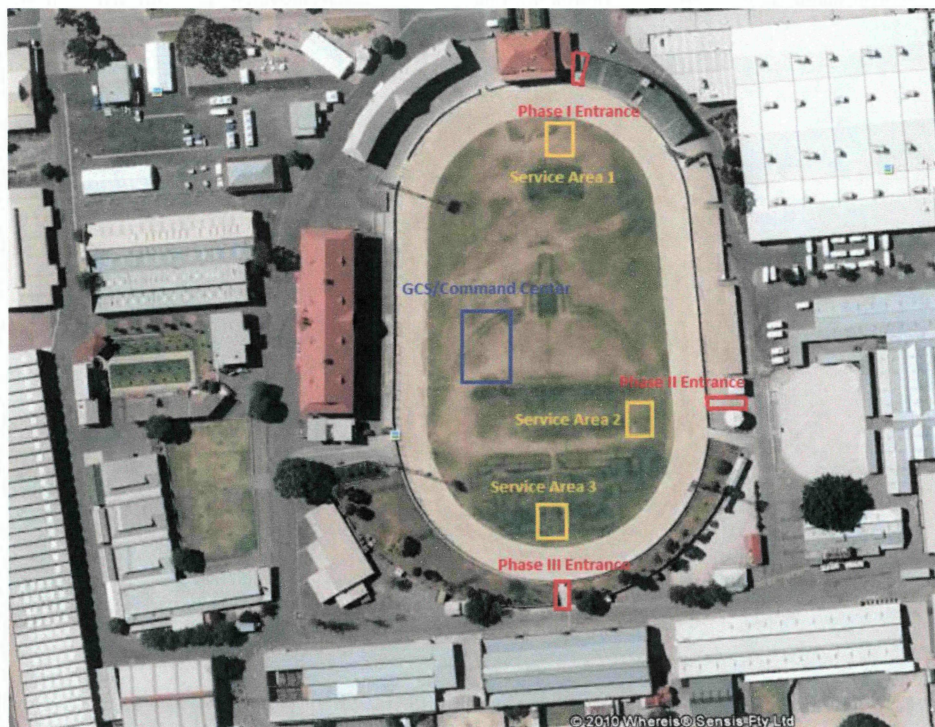


Figure 1: Royal Adelaide Showgrounds

The Challenge

The first portion of the challenge involved the submission of a proposal that detailed the proposed methods of intelligence, surveillance, and reconnaissance that would be required for multi-vehicle teams operating in an ever-changing urban environment. Ten teams from the United States, Australia, Canada, Japan, and Turkey were shortlisted to receive funding to move forward with a demonstration of their proposed technologies. These teams were Magician and Strategic Engineering from Australia, Northern Hunters from Canada, Chiba from Japan, Cappadocia from Turkey, RASR, Cornell, Michigan, Virginia Tech, and University of Pennsylvania from the United States. Teams Numinance and University of New South Wales were also selected to continue to the next phase, but did not receive funding.

The second portion of the challenge involved a site visit to each of the shortlisted teams during which a judging panel reviewed the performance of prototype ground vehicles that could adapt to many of the necessary tasks required for MAGIC 2010 such as being able to coordinate autonomously and dynamically as well as planning and carrying out tasks while coping with a series of changing priorities. Following the site visits, five teams were then short listed to receive funding to build and develop prototypes for the challenge. These teams are the University of Pennsylvania, Michigan, and RASR from the United States, Team Magician from Australia, and Team Cappadocia from Turkey.

The final portion of the challenge was the actual competition held in Australia in November of 2010. Each team was allowed a combined time of three and a half hours to complete each of the three phases. The phases all increased in complexity over time. A mock urban environment approximately 500m x 500m was used for the challenge. This environment contained obstacles and features that would be encountered in the real world, including but not limited to buildings, grass, sand, holes, curbs, fences, and humans. The operators were not in line of sight view of the UGVs. While GPS was available outdoors, it was not available indoors and was also subject to the normal interruptions encountered when using GPS. Some a priori knowledge was provided to teams, such as the location, number, and area of buildings. During the competition,

objects of interest (OOI) were required to be located, identified, and neutralized. The OOI were both static and mobile and were located randomly in the challenge area. OOIs included humans who may be hostile combatants or non-combatants as well as static objects such as trash cans. In addition, a real-time data feed was used to simulate the information that would typically be relayed by an Unmanned Aerial System (UAS).

Teams were required to have a minimum of three robots and a maximum of two operators during the challenge. For each disruptor UGV that has the ability to neutralize static OOI, the challenge required two sensor UGVs that were able to explore and map the area as well as identifying OOI. In order to complete the challenge, teams had to completely explore and accurately map the challenge area and accurately identify, classify, and neutralize all of the hostile OOI within a three and a half hour period.

The Phases of MAGIC 2010

During Phase I of the competition, the UGVs were required to enter the competition field through a designated entry point. During this portion of the competition the UGVs did not have a UAV feed and did not encounter mobile OOI. The UGVs were required to map the area in its entirety and neutralize all static OOI. While completing this phase the UGVs encountered a maze made of felt covered boards, barrels used as position markers in assorted colors, parked cars, as well as corridors of chain link fence covered with a black fabric. One of the challenges of the maze involved the use of a laser range finder (LRF) for obstacle detection. Different materials reflect the laser beams differently. For example, darker objects may absorb more of the laser radiation, and, in the case of fabrics, the laser beams may travel all the way through the fabric and not give an accurate representation of where a fabric boundary is located.

The Phase II environment that the UGVs encounter was more complex than the one they faced in the Phase I area. During Phase II the UGVs encountered mobile OOI (both combatants and non-combatants) as well as similar obstacles to those encountered in Phase I. In addition, the robots also encounter a large sand pit which they could travel through or circumvent. A UAV feed provided additional information on where the

mobile OOI were located. Mobile OOI moved in set patterns during the entire phase II operation.

Phase III further increased the complexity of the challenge. During this phase, all of the complexities of previous challenges were. In addition, that phase included a sniper capable of disabling robots and a portion where mobile OOI (both non-combatants and combatants) may share a portion of the same path. This requires timing and precision as the combatant could only be neutralized when alone. The number of mobile OOI encountered in Phase III was also greatly increased compared to Phases I and II.

The Teams

Team Michigan

Team Michigan was composed of the APRIL Laboratory at the University of Michigan and Soar Technology. The APRIL Laboratory is led by Assistant Professor Edwin Olson and focuses on the study of autonomy, perception, robotics, interfaces, and learning. They approached MAGIC 2010 by solving the three problems they realized were associated with fielding a team of robots. These three problems are: 1) having the human operator be able to efficiently interact with the robots and command them in manner they understand, 2) developing a system that can sort the orders so that individual robots can be given tasks, and finally 3) giving the robots perceptual capability to function for extended periods of time without needing to contact the operator for assistance.

Michigan chose to break their high-level planning down into two different planners to achieve the goals of exploring the area efficiently and knowing when to send the disruptor robots out. These planners are the exploration planner and the neutralization planner. The exploration planner is used to create a map of the world using LIDAR data and designates areas as explored and unexplored. Areas that are in between explored and unexplored areas are designated as frontier. Factors such as distance to the goal and the change of robots paths overlapping are used to ensure that goals are allocated to the robots evenly. The operator does have the ability to direct a robot to a specific area and

once the planner has notified the operator that an area has been completely mapped, the operator may then assign the robot to a new region. The neutralization planner is tasked with directing the disruptors to the OOI that need to be neutralized. The goal is to spread the disruptors evenly around the area to be explored and then guide one to an OOI before notifying the operator. The operator may then give the command to neutralize the OOI.

Michigan's ground control station (GCS) had an interface that allowed the operator to control the robots at various levels so that they could modify the behavior of the entire team or choose to command an individual robot or alter even a subcomponent. The robot-operator interface was designed to only present the operator with options that were relevant to the given situation. To update situational awareness for the operator the system provides notification of significant events such as OOI detection or low batteries. After selecting a robot the operator is able to see its telemetry and position on the map as well as other relevant information about the robot's status.

As part of the challenge it was necessary to combine maps from multiple robots. Michigan chose to use Simultaneous Localization and Mapping (SLAM) algorithms to compute the relative positions of the robots. Two mechanisms were used to align the robots internal maps: map-to-map alignments and tag observations between robots. Custom fiducial markers were placed on each robot that allowed the vision system on one robot to determine the full three-dimensional position of another robot. This provided the relative position of one robot to the other.

The software for Team Michigan is composed of self-contained modules that communicate over the Light-weight Communications and Marshalling (LCM) system. LCM provides a high-bandwidth multi-cast message passage system designed specifically for use in robotics. There are three modules used on each robot: the navigation module, the mapping and estimation module and the perception module. The navigation module controls the robot's individual path planning within a radius of approximately 20m and ensures obstacle avoidance while traveling along its path. This planner builds a terrain map from LIDAR data and assigns a cost to each cell. The higher

the cost of a cell the more difficult it is to traverse. This allows the shortest path to be computed using a wavefront approach. An iterative algorithm is then used to smooth the path the robot travels. The mapping and estimation model utilizes a SLAM solution to estimate the robot's position. The perception module is tasked with identifying hostile objects as well as tracking them. Color and shape data from the camera and LIDAR are fed into this module and then a bounding rectangle is used to extract the object's dimensions.

Team Michigan fielded 15 specially designed robots for MAGIC 2010. These robots are shown in Figure 2. The robots are laser-cut from wood and then glued together to form a chassis. The robots also contain a laptop computer, two microcontrollers, and a variety of other sensors. Each robot is powered by a 24V LiFePO4 battery that is run through DC-DC converters to provide any additional voltages. The robot chassis is made of 9mm Baltic Birch plywood that was laser-cut. This method provided a low cost method that allowed multiple iterations before settling on a final design. The robots use a skid-steer drive system with four wheels. A custom torsion bar shock isolation system was used to minimize vibrations that would interfere with the sensor readings.

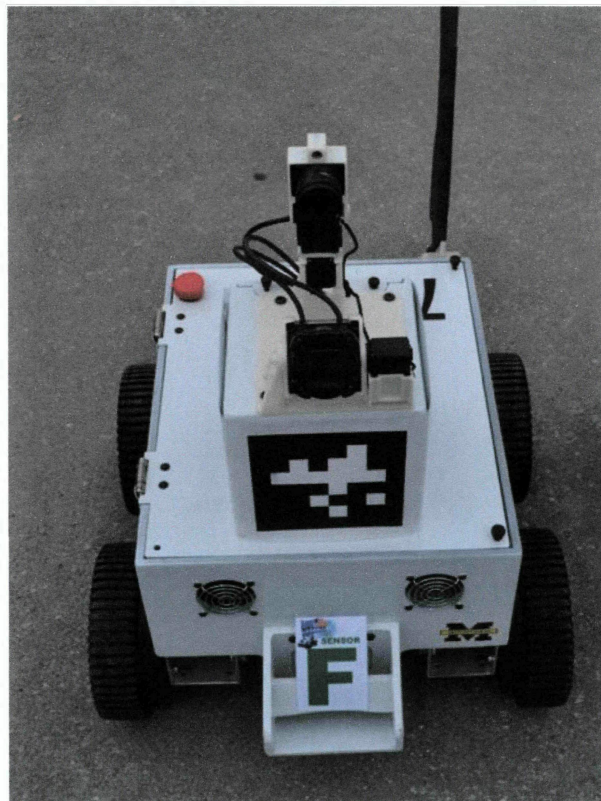


Figure 2: Team Michigan Robot

The main sensor on the Team Michigan robots is the Hokuyo UTM 30LX laser range-finder (LRF). Michigan's innovative approach uses a Dynamixel AX-12 servo to move the LRF which allows the sensor to produce a 3D point-cloud. Two additional Dynamixel servos were used to pan a PointGray FireflyMV USB camera fitted with a 2.8mm focal length lens which produces a 90° field of view relative to the robot. The LRF and camera are mounted on an ABS mount printed on a uPrint 3D printer, which allows precise of the relative positioning of the sensors. The rear wheels on the robot are fitted with encoders to measure the angular rotation. Additionally, a custom IMU with 6 degrees of freedom is used to ascertain the motion of the robots. A standard 2.54 GHz Lenovo Arrandale laptop containing 4GB of RAM and a solid-state drive is carried onboard to control the robots. The laptops operate in Ubuntu 10.4 and run software that was written in Java. The robots use a 900 MHz radio to transmit command and control data to and from the ground control station that is able to provide a bandwidth of 115.2 Kbps. When located near each other, the robots are able to transmit data at higher bitrates over the 802.11 mesh network.

Team Penn

The University of Pennsylvania team is led by Associate Professor Daniel Lee and is based out of the General Robotics, Automation, Sensing and Perception (GRASP) Laboratory. They saw the challenges for MAGIC 2010 as combining indoor and outdoor sensing, mapping, navigation, and planning and effectively using a limited set of inputs from a human operator.

Team Penn chose to leverage software intelligence in combination with hardware that is inexpensive, but robust. They use a hierarchical decomposition of the perceptual planning and control algorithms. To ensure rapid interaction between the robots and the humans it is necessary for the robots to be clear about probabilistic uncertainty. The higher level is a global map with the exploration plans generated at the ground control station and lower level plans generated on the robots. A 2.5D representation of the world is created using the LIDAR. The hierarchical mapping is based on the IMU, odometry data, and LIDAR information. GPS is only used for registration. For this challenge, Team Penn decided that operating without GPS would be simpler than operating with

potentially incorrect GPS typical in environments such as those selected for MAGIC 2010. There were two operator consoles: the planning operator console and the vision operator console. The vision operator console only deals with visual objects that have been identified. These are shown to the human to confirm identification. The graphical user interfaces were design to make the operators jobs as simple as possible. All code for the Team Penn robots was written in MATLAB.

The Team Penn robots, an example of which is shown in Figure 3, are based on a skid steer platform. Seven of these robots were used during MAGIC 2010. Each robot uses two Hokuyo UTM 30 laser range finders utilized on these vehicles. One is stationary while the other is panned back and forth along with one camera. Team Penn used an innovative approach to obtain a 360° video image. They used a silver Christmas ornament sliced in half as a spherical mirror and pointed a camera up at it. By taking the image from the camera and undistorting it, they were able to see the full 360° image reflected on the sphere. A standard Mac Mini computer was used to provide the computing power onboard the Penn robots. In addition an onboard GPS and IMU were used for navigation of the robots. The Penn robots use RS485, USB, and wireless communications. The wireless communications are in the 2.4 GHz and 915 MHz bands to include as much redundancy as possible.



Figure 3: Team Penn Robot

Team RASR

Team RASR (Reconnaissance and Autonomy for Small Robots) is led by Robotic Research, LLC and also includes QinetiQ North America, General Dynamics Robotics System, Cedar Creek Defense, Del Services, LLC, and Embry-Riddle Aeronautical University. The Team RASR approach was to develop a system capable of providing long term value to the war-fighter. To develop such a system, Team RASR created design constraints for creating a near future military usable technology. These constraints were to use a relevant (deployed) platform, make use of low-cost and reliable sensors, create a modular control system that is expandable and operates by using innovative software algorithms to reduce the computing footprint required, to reduce communications bandwidth, to be able to cope with communications loss, and to maximize battery life and mission runtime by reducing additional power requirements.

Team RASR chose to use a hierarchical system that utilizes a distributed coordination layer and a set of specialized planners to solve mapping and neutralization problems. Elements at the top of the hierarchy have slower planning cycles and elements at the bottom have faster cycles and higher resolution. The coordination layer plans the motions of the unmanned ground vehicle (UGV) group which involves allocating tasks. Modules are composed of a Coordination Planner that interacts with the Global Autonomous mobility Model. Each robot has an Autonomous Mobility Layer composed of a local map and exposure database, the Local Autonomous mobility Model and the Local Mission Model. This planner is responsible for navigating a single vehicle and coordinating locally if neutralization is required.

There are three representations used for Team RASR: the Autonomous Mobility World Model, the Mission Specific World Model, and the Situational Awareness World Model. The Autonomous Mobility world Model provides information on the terrain traversability and is used to determine the cost of the plans from a mobility standpoint. The Mission Specific World Model contains information about objects of interest and predicts what their paths may be. A probability density function is used to represent an object of interest's presence at a location at a given time. Also, a record of object of interest exposure is maintained on this map and the probability of their detonation based on

neutralization status. The Situation Awareness World Model was designed to ensure that the operator understands the environment and allows them to intervene if necessary. The coordination layer exists on each UGV as well as on each OCU allowing it to benefit from the larger computational capacity.

Team RASR utilizes a new algorithm called K-means Line of Sight (KML) to compute the smallest number of points from which all areas in the search space can be viewed. The autonomous mobility layer is based on the High Maneuverability Planner that has been previously utilized by the US Army for various programs. This module is responsible for generating the path for each UGV. Detection of static features is achieved by fusing data about shapes with data from the camera about color and texture. The Mission Model maintains information about humans and is also responsible for predicting human actions. The Terrain Aware Coordination Tool for Intelligent Control (TACTIC) is used to dynamically predict objects of interest as well as provide directions during the neutralization process. A Kalman filter with inputs from the six degree of freedom IMU, wheel encoders, differential GPS, visual odometry and the LRF is used to allow the robot to navigate in GPS-denied areas. An After Action Review toolkit allows the operator to view camera footage from the mission after the fact and pan, tilt, and zoom the images while viewing the navigation solution and a 2D or 3D LRF map display.

The Team RASR UGVs are the Talon platform made by QinetiQ-North America and modified for this competition. Figure 4 shows the RASR modified Talon platforms. A team of eight platforms was fielded for MAGIC 2010 with a total of seven running at competition. A single commercial off the shelf (COTS) Hokuyo LADAR was used to aid in navigation. It features a unique spinning mechanism coupled with a mirror that provided 360° of coverage. A custom navigation system was developed to be used for the competition that was tailored to the mission constraints. A single Mac Mini was used as the computing platform for the UGVs. Rather than choosing an expensive radio, Team RASR opted for an 802.11 radio in the same price range as those on currently fielded systems and focused on dealing with communications losses which happen regardless of the price of the radio. In addition Robotic Research also used a system of three COTS cameras to provide a 360° field of view for the video as well. The cameras are positioned

at equidistant points on the head. Each of the three video feeds are combined to enable to operator to have a 360° view around the robot allowing the unique feature of driving the robots backwards. A custom E-stop radio and power distribution/E-stop board with battery hot swap capability were also developed for the competition as well. A COTS wireless game controller was used for teleoperating the robots.

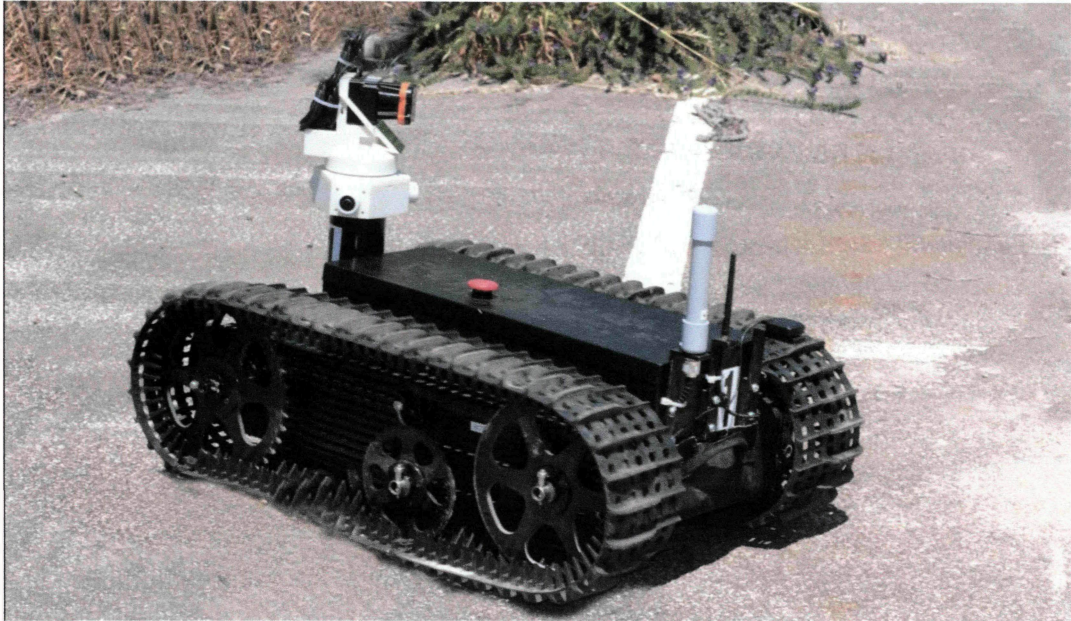


Figure 4: Team RASR Robot

Team MAGICian

Team MAGICian was composed of The University of Western Australia, Flinders University, Edith Cowan University, Illiarc, and Thales Australia. Their approach focused on the team's skills: Artificial Intelligence, Robotics, Computer Vision, Signal Processing, Autonomous Agents and Multi-Agent Systems, Human Computer Interfaces and Systems Engineering.

For MAGIC Team MAGICian elected to use a Service Oriented Architecture that used the Data Distributions Service standard currently being used as part of the US Navy Open Architecture Computing Environment. Their software addressed what they saw as the five key tasks of the challenge: team planning and coordination, searching (both exploration and patrolling), tracking, mapping, navigation, and interfacing with the operators. The robots used search patterns to determine where there were areas to map

and explore or patrol. A potential object of interest triggered the robots to start tracking and identification behavior. Once an object of interest had been located the robot would communicate with its team mates to neutralize the object. Two maps were utilized (a physical map and an influence map). The influence map contained information such as the location of objects of interest, which areas have been explored, etc.

System components included a vehicle controller, OOI, LIDAR, vehicle management, path planner, goal planner, video management, collision avoidance, landmark detection, and map generation. The vehicle controller received a plan from the path planner and then created/executed a plan of movement. The OOI interfaced the LIDAR and camera to broadcast both the id and position of an object of interest. The LIDAR provided an interface for all the LIDAR equipment and was responsible for broadcasting distances. Vehicle management received all position and heading information and interacted with the Inertial Navigation Unit to maintain the robot's position. The path planner received the desired goal and determined the best path for the robot to traverse. The goal planner received the global map, the local map, and the robots current state and determines what the robots goal should be. Video management received the map and video and returned a point cloud as well as the robots position and velocity. Collision avoidance received a point cloud of objects and generated a distance map for the robot. Landmark detection received video, local maps and distances to land marks which it then used to create a new map for the robot. Map generation provided an interface with SLAM and generated a new local map.

Exploration of new areas used a Multi-Robot Frontier-Based Exploration approach. A combination of groups and pattern matching algorithms were utilized on the WAMbots. Objects of interest were tracked based on color and template based tracking from regions of interest identified by the LIDAR and cameras. As objects of interest were confirmed the system tended to favor false positives to reduce the chance of missing an object of interest. Their navigation approach used cameras to determine which areas it was possible to drive through and then the information was combined with data from the LIDAR to modify the robots paths. Coordination was based on a Market-Oriented-Programming approach by which the optimal distribution of robots could be found.

The base platform fielded by Team MAGICian at MAGIC was the Pioneer AT3 by Mobile Robots in Figure 5. This platform was designed to be a research platform and was readily available. The WAMbot included built in 100 tick encoders and came with a base software set that was extended. In addition it used a Vector 2X digital compass as part of its integrated navigation system. A MEMsense IMU/Gyro was also onboard the vehicle. Three laser range finders were used on WAMbot: a SICK LMS 111, a Hokuyo URG-04LX-UG01 (angled toward the ground for collision avoidance), and an Ibeo LUX. A COTS pan/tilt/zoom was also used as well as a Qstarz 818X Bluetooth GPS receiver.

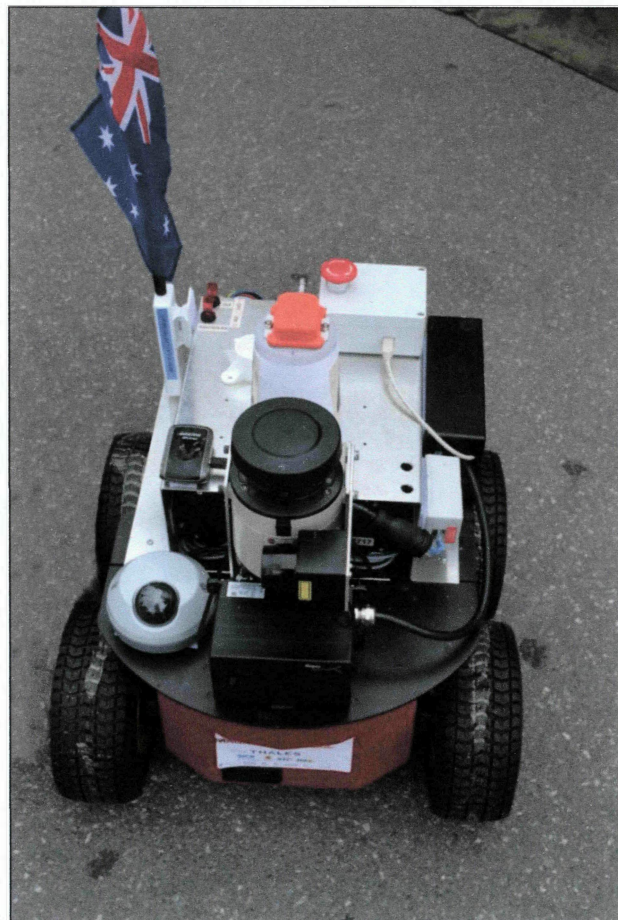


Figure 5: Team MAGICian Robot

Team Cappadocia

Team Cappadocia was composed of ASELSAN Inc., The Ohio State University, The Middle East Technical University, The Bilkent University, and the Bogazici University. Their approach featured standardized UGV components with JAUS compliant modules,

automated object of interest detection and tracking, intelligent localization that used decision making, an innovative technique that allowed automated UAV image processing, advanced mission planning with optimized route planning that was automated, reliable communications, automated mission implementation, configurable human-machine interface displays.

A module driven architecture was used to control Team Cappadocia's robots. These modules were the Low Level Controller, the Automatic Target Tracking module, the Vehicle System Management module, Sensor Fusion module, Multi Robot Data Fusion module, High Level Planning and Control module, Dynamic Mission Planner module, and the World Model Knowledge Store module. The Low Level Controller module used sensor data to direct the vehicle. The Automatic Target Tracking module was responsible for detecting and tracking objects of interest. The Vehicle System Management module was responsible for the JAUS interface on the vehicle. The Sensor Fusion Modules were responsible for creating the local map from the most accurate data and localizing any objects of interest. This map was then shared with the Multi Robot Data Fusion module at the ground control station. The Multi Robot Data Fusion module was responsible for fusing the data from the robots together. The Dynamic Mission Planner generated high level commands for the system. The High Level Planning and Control module navigated the robot based on the commands it received from the Dynamic Mission Planner. The operation map was stored in the World Model Knowledge Store module.

Team Cappadocia purchased COTS vehicle bases and then outfitted them with subsystems that were readily available with ASELSAN. This platform can be seen below in Figure 6. The platform was a four-wheeled skid steer base with motors that had encoders. There were two different power systems featured on these robots: a Ni-MH pack that powered only the drive system and a set of Li-Ion batteries that were used with a DC to DC power converter. A COTS computer with a PC-104 data acquisition module was used to control servos, acquire sensor data, and monitor the system health. Several internal state sensors were incorporated onto the robots: wheel encoders, an inertial measurement unit (IMU), and a yaw rate gyroscope. A Real-Time Kinematic Differential GPS was used in the ground control station to transmit correction to robots. A SICK

LADAR with a 360° field of view was used for object detection. A color Pan-Tilt-Zoom camera was used to send a video to the operators as well as to detect and track the OOI. Wimax wireless network units that operate in the 5.8 GHz frequency band and use Multiple Input Multiple Output (MIMO) antennas were used for the majority of the communications to and from the robots. Additionally a 900 MHz radio modem was used for the E-stop communications.



Figure 6: Team Cappadocia Robot

MAGIC 2010 Results

The results for MAGIC 2010 were announced at the 2010 Land Warfare Conference held in Brisbane, Australia. Team Michigan took home the first place trophy for MAGIC 2010 and a \$750,000 prize. Team Penn took home the second place trophy and a \$250,000 prize. Team RASR took third place for MAGIC 2010 and a \$100,000 prize.

MAGIC 2010 Conclusions

Like many of the autonomous vehicle competitions sponsored each year MAGIC 2010 was designed to push the boundaries of the tasks that current autonomous vehicles are capable of performing. As a result of this competition we have systems that are capable of multi-agent searches and could be of use in theater. However, more development on these vehicles is still necessary before they could go into the hands of any warfighter. The majority of the currently fielded robots used in combat situations utilize tracked platforms not wheeled platforms. In general these vehicles are required to travel over rough terrain where wheeled vehicles could get high-centered. Four of the finalists in this competition chose to utilize small wheeled platforms that most likely would not be suitable in a real combat situation, unlike the already field proven Talon platforms used by Team RASR. In addition, many of the sensors used are not combat certified to withstand the conditions encountered in theater. Also while this was only a simulated representation of the tasks it would be necessary to perform in theater none of the finalists were able to successfully complete all of the phase areas. These simplified tasks are a representation of the tasks, but in no way convey the difficulty of actually identifying a combatant. A combatant will look the same as the noncombatant standing next to him in real life and will only be able to be distinguished based on a behavior that would be considered out of the ordinary. Many of the teams competing in MAGIC 2010 also feel that while this is a large step forward in multi vehicle autonomy many of the challenges encountered in MAGIC 2010 still need more improvement before used in the field. In conclusion, I feel that great strides forward have been made in multi-vehicle autonomy, but there are still other areas that need to be improved before these vehicles are suitable for use in theater.

CHAPTER 2: DEVELOPMENT OF A FAN-OUT EXPERIMENT

There is no current widely accepted standard for fan-out. There are several proposed methods such as Crandall and Cummings and Olsen, Wood and Turner. While both of these groups tested the effectiveness of their methods, the approaches were very different. The proposed systems utilize either simulated robots or a combination of both simulated and real robots. These approaches do offer the added bonus of testing robots in simulation before working with actual hardware, but do not accurately represent tasks that would commonly be required of autonomous robots. Current tasks such as remotely identifying erratic behavior of surface vehicles, identifying and defusing bombs with a ground vehicle, or distinguishing civilians from combatants require very different tasks than those used to evaluate fan-out metrics. MAGIC raised the issue of developing a standard test bed for evaluating these multiple vehicle systems. A standard test bed with specified tasks would allow testing to determine fan-out for the given task. This standard test bed would also allow testing of algorithms on a common platform to determine which was more effective. This standardization would ensure that consistency between test results and allow for a more accurate characterization of both fan-out and algorithm effectiveness. This experiment was designed to create a framework for performing this testing and collecting some preliminary data. This initial framework provides a starting point that can be extended and critiqued by other researchers.

Robots

The robots designed for this research utilized cost efficient commercial off the shelf components that were readily available to the researcher. The base of the robot was constructed from metal hardware from a Vex robotics kit. This hardware was used to form a square base that would support the remaining system components. Vex continuous rotation servo motors and tank tread were used to provide mobility for the robot. Line following sensors from the Vex robotics kit were mounted to the front of the robot to allow the robot to follow black line courses on the floor and provide a level of autonomy. A Vex limit switch was used to provide obstacle notification to the user through the operator control unit. The standard Vex 7.2V 2000mAh Ni-Cd batteries were

used to power the robot and its onboard electronics. A standard commercial off the shelf IP camera was used to provide video to the operator control unit so that the operator had a first person view when driving the robot as well as when observing it to avoid obstacles. Arduino Pro Mini 3.3V boards were used to provide onboard control and interface the communications between the robot and the operator control unit. Xbee Pro 60mW modules with wire antennas were used to provide a communications link between the operator control unit and the robot. Two switching voltage regulators were used onboard to regulate the voltage sent to the components. The camera required 5V and the Xbee modules required 3.3V. Four robots were built for this research with three being used for testing and one remaining as a backup unit in the event of any difficulties. Figure 7 below displays photos of the completed robots used for testing in their final version. A complete parts list can be found in Appendix A.

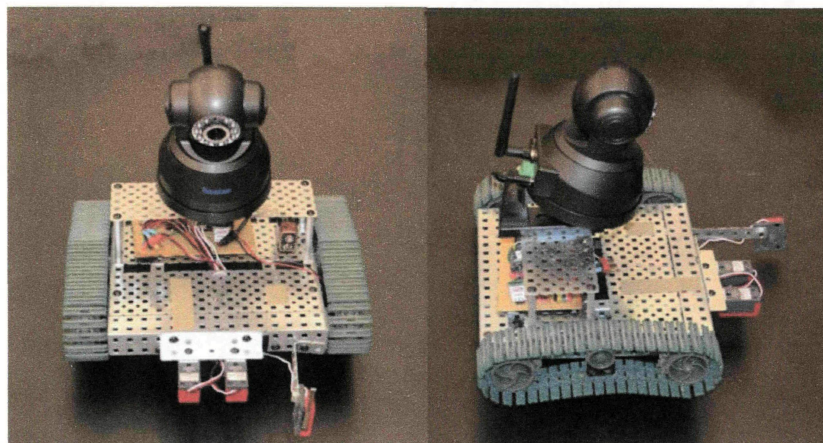


Figure 7: Research Robots

Software

Robot Software

The onboard Arduino was used to control robot level interactions. Arduinos use a modified C library to interface with sensors and other hardware. The software controls serial communications over the Xbee at a baud rate of 57,600. The code checked to see if a command for the robot is being sent over serial and if it is then follows the commands in the message. If no serial commands were being received the robot continued to

operate in autonomous mode. Autonomous mode was defined by several different cases. The first case was called if the limit switch was not closed and the line sensors were over white space. The robot continued moving forward for this case. The second case was called if one of the line sensors was over a line. This meant that the robot was instructed to turn in order to continue following the line. The third case was called if the limit switch was closed indicating that the robot had encountered an obstacle. If the limit switch was closed the robot will stop pending operator intervention. The final case was that both line sensors were over a line. For this case, the robot stops pending operator interaction.

Operator Control Unit

The operator control unit was run on a HP Pavilion DV7-2185dx Quad Core laptop for testing with a secondary monitor connected to allow viewing of all the necessary information. The secondary screen to the left was used to display the video feeds from the robots so that the operator is able to monitor and control the robots. This screen can be seen below in Figure 8. There were then different user interfaces for each phase of testing. The simplest user interface allowed the user to control the robot, but had no indication of whether the robot had hit an obstacle. This interface had several buttons that the operator needed use to submit data as well as to control the robot. Figure 9 below displays an image of this user interface. One button sent serial and allowed the user to drive the robot. Another allowed the operator to specify that the robot had completed another lap. Additionally there was an indicator that updated to let the operator know how much time they had spent actually in control of the robot. The last button encountered on this interface was the Stop Everything button which stopped the code and told it to write all the collected data to a text file. The next user interface utilized the same buttons but also had a led that indicated whether or not the robot had encountered an obstacle. Figure 10 below displays an image of the second user interface. The final user interface was the most complex, with all of the previous buttons as well as buttons that were clicked when the operator viewed an object of interest. Figure 11 below displays an image of the final operator interface for all three robots.

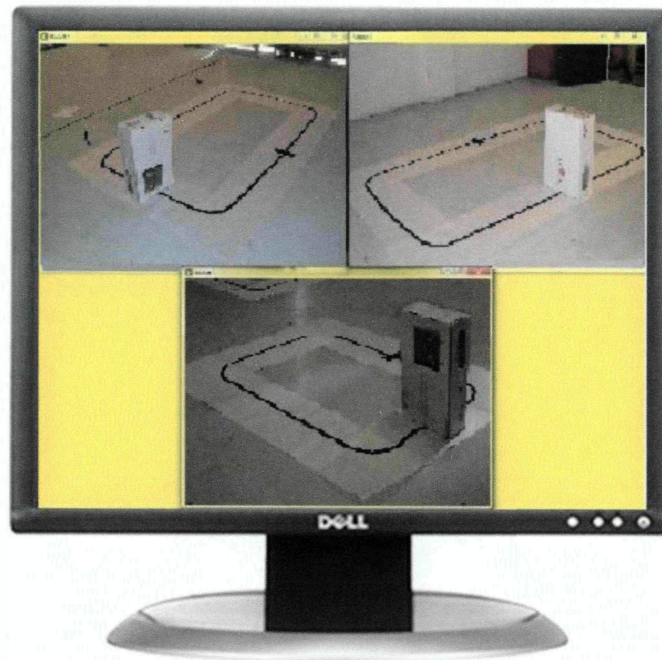


Figure 8: Video Windows for Robots

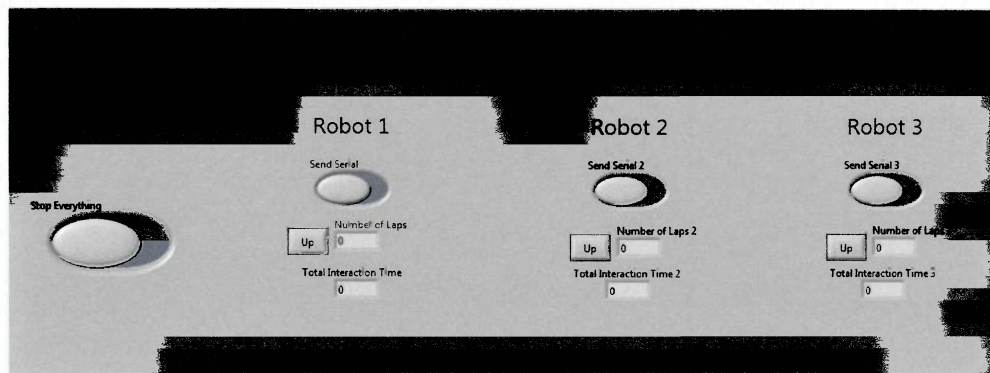


Figure 9: Operator Interface for First Round of Testing

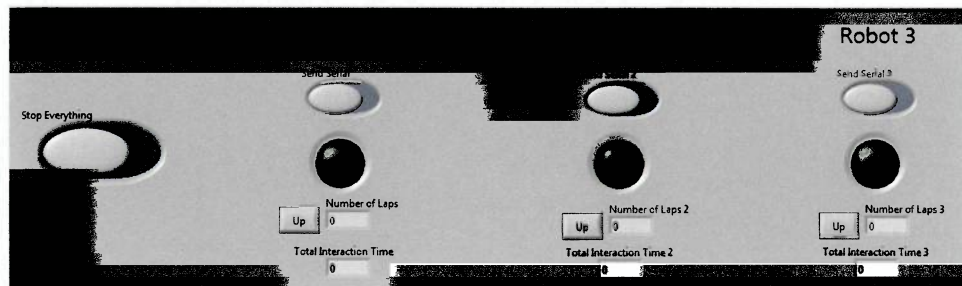


Figure 10: Operator Interface for Second Round of Testing

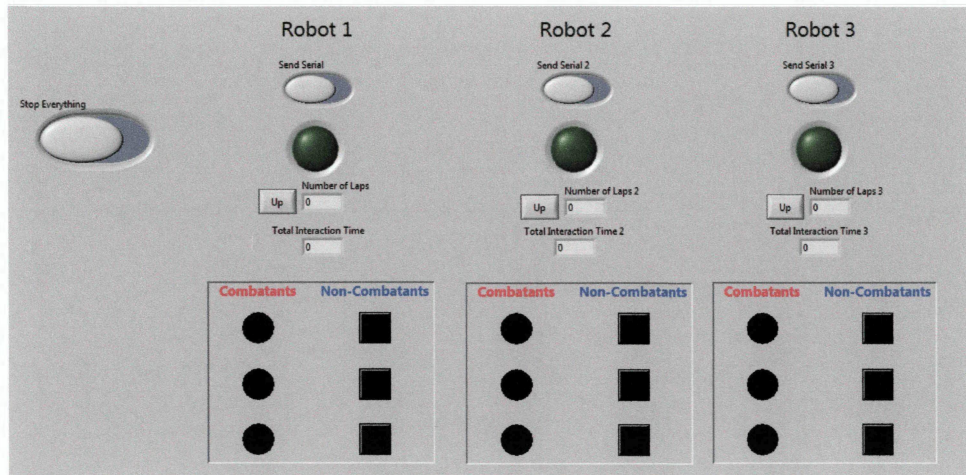


Figure 11: Operator Interface for Third Round of Testing

Experimental Process

Participants were first brought in and asked to read and sign the consent form found in APPENDIX B: CONSENT FORM and read the experiment directions. The score was defined in the directions as total time = interaction time + penalties. The penalties are two minutes for incorrectly identifying a combatant and four minutes for identifying a non-combatant as a combatant. They then had the opportunity to ask any relevant questions or have instructions clarified. A five minute period then began where the participant had the opportunity to drive the robot, let it follow lines, and in general familiarize themselves with the operation and response of the robot and its video. The first phase of testing then began. For phase I there were three five minute sections where the operator interacted with a single robot. Each of these sections was performed with the same robot on the course seen in Figure 12: Single Robot Course below. Circles represent objects of interest the same color as the circle and green boxes represent obstacles. Additionally the horizontal line represents the lap starting point where robots stopped at the end of each lap if running autonomously. During the first section the operator only had feedback from the camera to operate the robot and had to count laps. The second section provided the operator with additional obstacle feedback in the form of a led that lit up when the robot hit an obstacle or was sitting on a line. The third section provided an additional level of complexity by requiring the operator to indicate when an object of interest was seen by clicking buttons on the operator interface. Objects of

interest can be seen in Appendix APPENDIX F: OBJECTS OF INTEREST. Sample operator views from the cameras on the robots can be found in Appendix APPENDIX J: OPERATOR CAMERA VIEWS. The first sequence of images shows the robot approaching a 12V lead acid battery starting from approximately four feet away from the battery. The second sequence of images shows the robot approaching two of the OOIs from approximately four feet away. This process was then repeated for both two robots and three robots. The courses for the two robot portion can be seen in Figure 13 below. Figure 14 below displays the layout for the three robot portion. It is important to note that on the track on the left there is a portion labeled simulated obstacle. The angle of the course at this location caused the robot to stop each time it reached this point as if it had hit an obstacle. Objects of interest and obstacles were located in the same location for each test to ensure the accuracy of the results. It is also important to note that if a robot became in-operational and could not be reset the time period continued. All robots were then reset for the next testing phase. The obstacles for the two robot portion were placed so that once the second robot was started the first one had already reached the obstacle and then so on so that the operator was constantly interacting with the robots. Based on some initial testing it was possible to see that operators would not be able to operate all three robots with obstacles on the course as well.



Figure 12: Single Robot Course

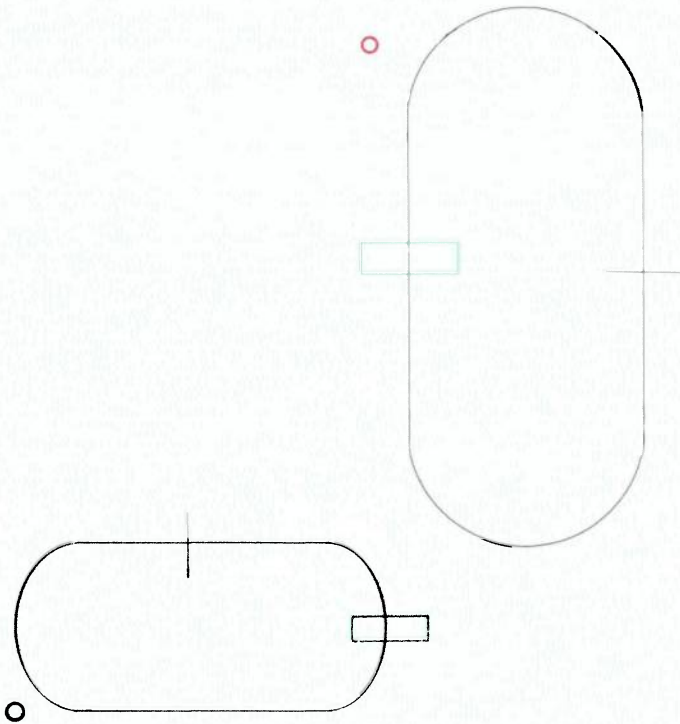


Figure 13: Two Robot Courses

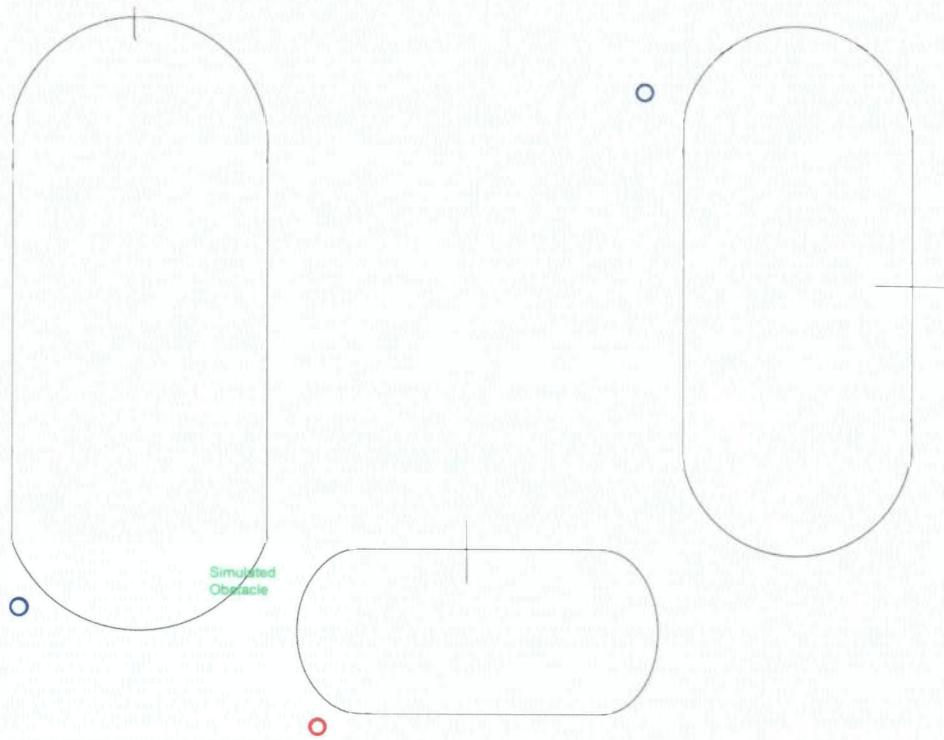


Figure 14: Three Robot Courses

CHAPTER 3: RESULTS AND ANALYSIS

Eight participants were used for this research. Two participants were female and six were male. Of these participants there were five college students, one high school student, one faculty member, and one outside professional with an average age of 25. Participants were asked to complete a survey after testing and answer some general questions about themselves as well as the difficulty of their tasks. This survey can be seen in APPENDIX C: SURVEY. Full results for the testing can be found in Figure 15 below displays the participants experience with both robots and video games. Participants were asked if they felt driving more robots is too difficult. Six of the participants felt that it was too difficult and two felt that it was not. In addition they were also asked at what number of robots controlling them became too difficult. Participants were evenly split, half of them said two robots and half of them said three robots. Half of the participants had errors in counting the objects of interest which caused some heavy penalties to their interaction times. Those operators who had little or no experience with robots tended to feel a sense of disorientation and have trouble determining which direction the robots should be driving in on the track if the robot wandered off. Interaction times tended to vary highly between robots. Additionally there does not appear to be any pattern for whether interaction times increase or decrease as difficulty increases. The total scores seen in Table 2: Total Interaction Times below indicate a large variance from the best interaction time to the worst. The time difference between the best score and the worst score is 23.2 minutes. This is a very large difference and indicates that while the person with the best score might be good at operating more than three robots, the person with the highest score probably would not be able to operate more. One reason for this large difference was penalties from OOI identification errors. In the test data in APPENDIX D: COMPLETE RESULTS, one of the operators received a total of 16 minutes in penalties for incorrectly identifying non-combatants. I initially hypothesized that for a given task and robot there exists an optimal robot-to-operator efficiency ratio. Based on this data I now believe that rather than an optimal robot-to-operator ratio there is actually an optimal operator. Given that all operators received the

same amount of training and interaction with the robots, the only difference is the actual operator. Figure 16, Figure 17, and Figure 18 below show the experimental data, the average interactions times and the standard deviation for the one robot, two robot, and three robot cases. The average interaction time for the single robot case was 7.63 minutes and the standard deviation was 3.26 minutes. For the two robot case the average interaction time was 11.35 minutes and the standard deviation was 2.84 minutes. The three robot case had an average interaction time of 10.01 minutes and a standard deviation of 7.43 minutes. For the three robot case it is important to note that one operator had a total of 16 minutes of penalties, which affected the standard deviation and the average interaction time.

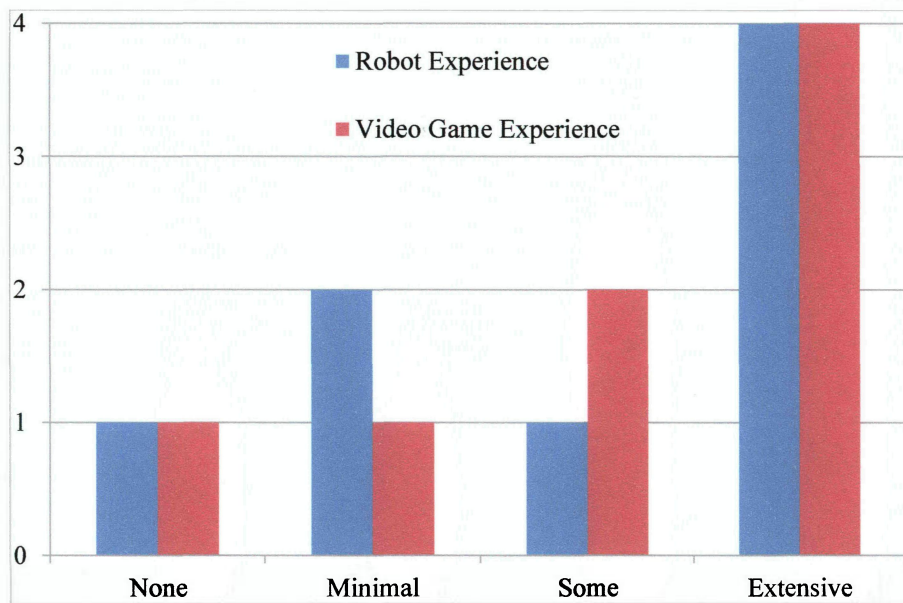


Figure 15: Operator Robot and Video Game Experience

Table 2: Total Interaction Times

Operator	Single Robot (min)	Two Robots (min)	Three Robots (min)	Total Time (min)
1	12.9	14.7	8.7	36.3
2	2.6	8.8	27.2	38.6
3	9.8	15.1	12.4	37.3
4	8.3	13.3	5.6	27.2
5	6.0	10.3	7.6	23.9
6	9.2	9.4	5.7	24.3
7	7.9	11.8	9.1	28.8
8	4.3	7.4	3.8	15.4

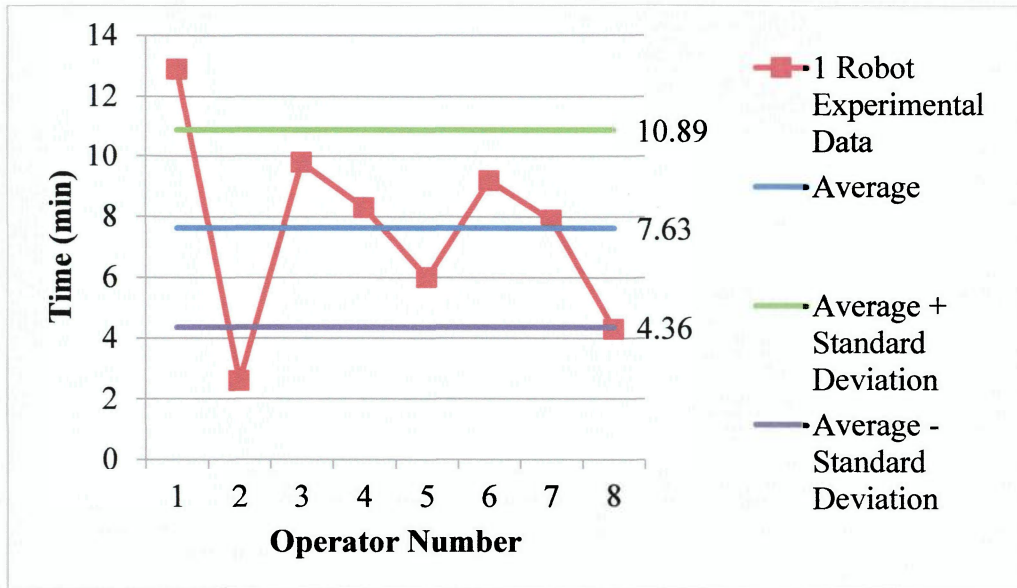


Figure 16: Single Robot Experimental Data, Average, and Standard Deviations

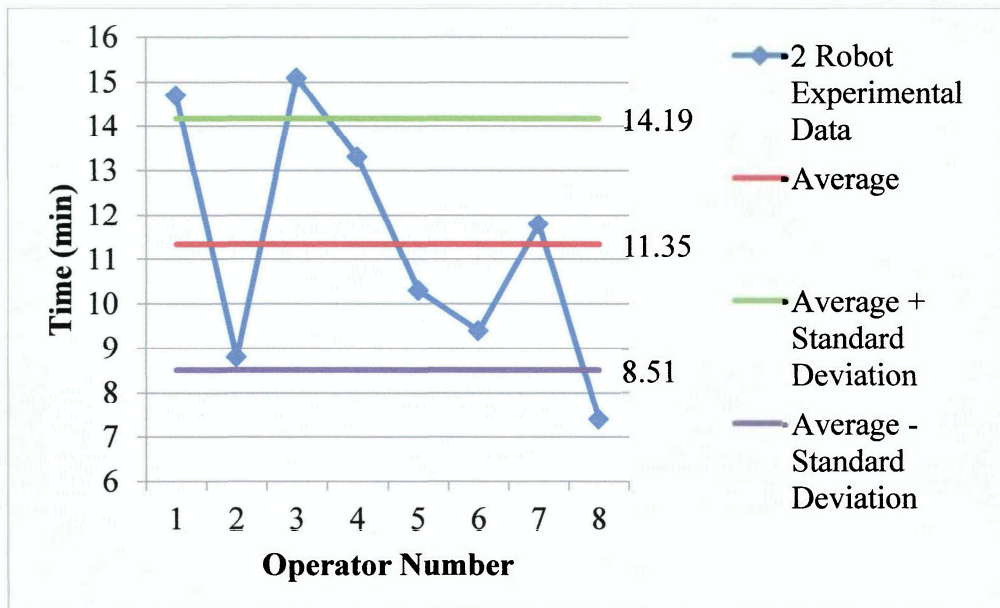


Figure 17: Two Robot Experimental Data, Average, and Standard Deviations

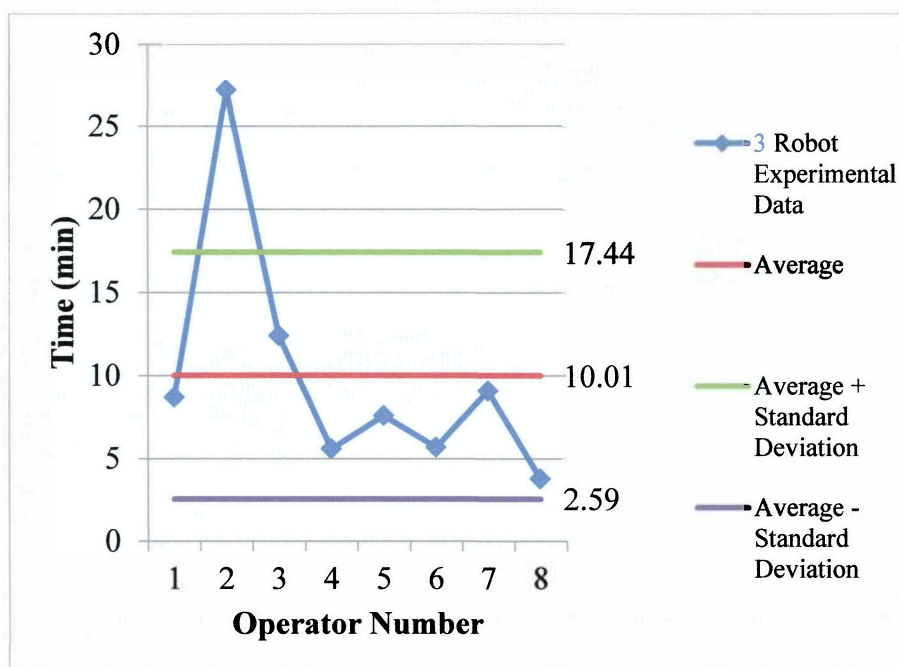


Figure 18: Three Robot Experimental Data, Average, and Standard Deviations

One interesting note to make based on observing participants is that those with the most experience with either robots or video games were not necessarily the ones with the best operating times. While interacting with the robots it was noted that the vast majority of participants tended to go around obstacles on the outside rather than turning the vehicle slightly and allowing the robot to continue autonomously. Also some of the participants seemed to prefer to drive the robots off the line and then back onto the line course rather than attempting to let the robot do so autonomously. Some participants also tended to overdrive the robots. By the term overdriving the robots, I imply that rather than discovering the best method to control the robots during the testing they continued to try to drive the robots for long periods encouraging larger control delays. Another interesting note discovered during testing was the lack of a pause button. Only one participant discovered a way around this. Faced with this lack and several robots going off course at once, this participant chose to allow one robot to run into an obstacle making it stop. While other participants noted the lack of this button, no one else noted this feature and used it when the robots ran off the track. One participant chose to only drive a single robot at a time. Another opted to take control of the robot and stop it every time there was an object of interest.

The most significant challenges of this research were maintaining multiple robots under frequent use, monitoring battery life, and being able to charge enough batteries to run for multiple iterations. Other problems encountered during the research involved the COM ports used to communicate with the robots. Xbee USB Explorer boards were used to interface the robots with a PC running Windows 7. As with most other USB devices the computer occasionally decides to eject the COM ports at random. This problem was resolved by modifying the code to continue to try to reopen the COM ports until it is able to do so if it encounters an error. As always when operating in a Wi-Fi rich environment communications can also experience interference or swamping if more powerful signals are present in the area. The two different versions of Wi-Fi camera were used on the robots. The original version did not go through a boot-up motion sequence, but the newer version did. The boot-up sequence on the newer cameras could not be turned and while they initially booted quickly while running on batteries after several weeks they began to be temperamental when trying to boot off the batteries while the first version never had any problems. The floor of the testing environment was another challenge to be faced. Upon initial testing before experimentation it was discovered that the floor caused false positive readings with the Vex Robotics Line Sensors and could cause the robots to stop or malfunction at any time. A simple and inexpensive solution to this problem was to place the track on the white paper side of Reynold's freezer paper. By running the course on paper the majority of the false positive readings from the course were eliminated. Some of the Vex motors also had problems with overheating after running for five to ten minutes. If given approximately ten minutes to cool down the motors could then be run again. During testing one motor did burn up and had to be replaced, but the replacement motor was also found to heat up in the same manner even though it was new.

CHAPTER 3: RECOMMENDATIONS

Understanding the problem of testing multiple robots is much more complex than initially expected. For this research robots that were made of lower level parts were used. If this research were to continue the first step would be to purchase reliable platforms that would eliminate some of the lower level hardware problems such as motor failure and communications problems. Lower level sensors such as the line following sensors and limit switches are also not sufficient for guiding the robots. In order to have this line of research more accurately represent some of the real world scenarios encountered and develop some conclusive results as to fan-out a more intelligent robot that is capable of supporting higher level sensors such as higher resolution cameras, compasses, and laser range finders would be necessary. One platform that could possibly be considered is the Pioneer platform from Mobile Robots. This platform is designed for research and has capabilities that include the ability to run with sonar, cameras, and many other sensors. These robots can be programmed in either C or C++. As these are standard programming languages new algorithms and control structures could be tested as research advanced to verify which ones allow the robot to operate at peak efficiency. The Pioneer robots have been developed for repeatability and repeated testing and should prove to be a more reliable research platform. Another improvement would be to use better batteries that offered a longer runtime. The batteries used for this experiment had been previously used and tended to lose some of their capacity. The Pioneer robots offer the ability to have one, two, or three hot-swappable batteries which would allow for continuous running of the experiment without having to restart the entire robot and allowing for longer runtimes. With more effective robots that have broader capabilities I believe it will be possible to gain a better understanding of fan-out for homogenous robots. Once this understanding is gained, I believe that it would be possible to expand the homogenous testing to include other ground robots of various sizes as well as unmanned air systems (both indoor and outdoor), autonomous surface vehicles, and autonomous submarines. As a continued push is made to move forward with having a single operator running multiple robots this field of research will continue to grow and become more important. Training the operators and giving them multiple opportunities to perform the

tasks could also improve the interactions times. Current operators for unmanned systems are typically required to complete training in order to operate the systems. With a group of trained operators it may be possible to see similar times among all operators. This then raises the question in my mind: “Do only those operators who have are gifted at controlling the robots continue through the entire training process?”.

CHAPTER 4: CONCLUSIONS

This research provides a step forward in determining fan-out. While an advancement in the testing of fan-out has been made, this initial framework is not complex enough to be used to provide conclusive data for determining fan-out. Through testing it was determined that there is no obvious pattern to the operator interaction time with robots. The initial hypothesis, that for a given task and robot there exists an optimal robot-to-operator efficiency ratio appears not to be true. Based on the data I now believe that rather than an optimal robot-to-operator ratio there is actually an optimal operator. Given that all operators received the same amount of training and interaction with the robots, the only difference is the actual operator. It is possible that with more extensive training or opportunities to interact with the robots that operator times would become more closely grouped together. As the push for single operator to multiple robot systems grows larger with the advent of competitions such as MAGIC 2010, the demand for more data on this problem will continue to grow. With this growth the importance of having accurate test beds for determining optimal interaction ratios as well as testing algorithms will become even more important. This research provides a good starting point to expand upon and continue to develop such a framework that can continue to be developed as technology and commercial demands increase.

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APPENDIX A: PARTS LIST

	Part Description	Quantity
1	Wireless IP Camera	1
2	Arduino Pro Mini 3.3V	1
3	Xbee Pro 60mW Wire Antenna	2
4	Xbee Breakout Board	1
5	Xbee USB Explorer	1
6	3.3V 1A Switching voltage regulator	1
7	5V 1A Switching voltage regulator	1
8	Vex Line Tracker	2
9	Vex Limit Switch	1
10	Vex Robotics 3-Wire Motor	2
11	Vex Robotics 7.2V Robot Battery	2
12	Vex Robotics Tank Tread Kit	1
13	Metal frame components and screws from Vex Starter Kit	

APPENDIX B: CONSENT FORM

CONSENT FORM

Embry-Riddle Aeronautical University

I consent to participating in the research project entitled:

Supervisory Control of Homogeneous Teams of UGVs as related to MAGIC 2010

The principle investigator of the study is:

Charles Reinholtz (reinholtc@erau.edu)

Additional investigators:

Katrina Corley (corleyk@my.erau.edu)

Additional information:

Please contact Katrina Corley at the above email for more information on this research project.

Background:

Currently, a multi-person team is required to operate a single robot. The Army and other defense forces want a single person to operate multiple robots. As this is a new field, no frameworks exist for testing multi-robot teams. Multi-robot teams could more effectively search and map an area while removing humans from tasks that are dull, dirty, and dangerous

The experiment:

Subjects will drive a team of small (about 1 pound) robots starting with one robot and increasing to a total of four robots. Each testing section will take 15 minutes. During the first portion, the operator will be required to count the number of laps the robots have completed and avoid obstacles without notification of obstacles. During the second portion, the operator will be required to count the number of laps the robots have completed and avoid obstacles given feedback. During the final portion, the operator will be required to count the number of laps the robots have completed, avoid obstacles using feedback, and visually identify combatants and noncombatants (represented by 5 in. tall army men) and choose to whether or not to issue a neutralization command. Please see the attached image of the user interface. Sessions will be 5 minutes each with breaks in

between. A standard joystick and computer mouse will be used to drive the robots. The only discomfort that may be involved is a feeling of being overtasked.

Time:

Between 4 to 5 hours will be required of each participant. There will be breaks in between each set of runs allowing the operator time to get up and leave the area before coming back.

Rewards:

A reward system is used rather than paying the participants. The operator with the lowest total interaction time with the robots will receive a gift card. The score and penalties will be computed as described below.

Score:

- Total time = interaction time + penalties

Penalties:

- 2 min penalty for incorrectly identifying combatant
- 4 min penalty for neutralizing non-combatant

Data Collection:

Confidential- names and data can be matched, but only members of the research team will have access to that information. Publication of the data will not include names.

Participation in this test will be anonymous and the only data made public on the participant will be the operator's gender, major, and college classification (senior, freshman, graduate student, professor, etc.).

Right to refuse participation:

Participants have the right to refuse participation at any time without any penalties. Participants who do drop out will be ineligible to receive the reward and will receive no other compensation.

The individual above, or their research assistants, have explained the purpose of the study, the procedures to be followed, and the expected duration of my participation. Possible benefits of the study have been described, as have alternative procedures, if such procedures are applicable and available.

I acknowledge that I have had the opportunity to obtain additional information regarding the study and that any questions I have raised have been answered to my full satisfaction. Furthermore, I understand that I am free to withdraw consent at any time and to discontinue participation in the study without prejudice to me.

Finally, I acknowledge that I have read and fully understand the consent form. I sign it freely and voluntarily. A copy has been given to me.

Date: _____

Name (*please print*): _____

(Participant)

Signed: _____

(Participant)

Signed: _____

(Researcher/Assistant)

APPENDIX C: SURVEY

Supervisory Control of Homogeneous Teams of UGVs as related to MAGIC 2010 Survey

Name: _____

Age: _____

College Classification: _____

Gender: _____

1) How much experience do you have driving/working with robots?

_____ Extensive

_____ Some

_____ Minimal

_____ None

2) How much experience do you have playing video games?

_____ Extensive

_____ Some

_____ Minimal

_____ None

3) Did you feel that operating more robots is too difficult?

_____ Yes

_____ No

If yes: At what number of robots did it become too difficult?

_____ 1

_____ 2

_____ 3

APPENDIX D: COMPLETE RESULTS

Phase I Results

	Test 1A	Test 1B	Test 1C	Test 1C Penalties	Total Time for 1 Robot (sec)	Total Time (min)
1	253.5	227.6	172.1	120	773.1	12.9
2	53.1	42.3	58.5	0	153.8	2.6
3	175.5	211.7	199.6	0	586.8	9.8
4	215.3	148.2	136.6	0	500.1	8.3
5	123.2	158.5	78.4	0	360.1	6.0
6	114.2	100.0	97.0	240	551.3	9.2
7	121.2	172.0	180.9	0	474.2	7.9
8	94.9	79.6	82.4	0	256.9	4.3

Phase II Results Part 1

	Robot 1	Robot 2	Test 2A Total	Robot 1	Robot 2	Test 2B Total
1	149.3	141.8	291.2	69.1	99.6	168.7
2	81.4	63.8	145.3	73.4	86.4	159.8
3	150.5	142.2	292.7	121.7	120.2	241.9
4	127.7	159.2	286.9	88.2	179.3	267.5
5	100.0	109.0	209.0	78.0	129.3	207.4
6	68.7	126.8	195.5	94.1	103.7	197.8
7	141.5	108.5	250.0	130.6	128.7	259.3
8	67.9	85.2	153.1	76.0	81.7	157.7

Phase II Results Part 2

	Robot 1	Robot 2	Robot 1 Penalties	Robot 2 Penalties	Test 2C Total	Total Time for Two Robots	Total Time (min)
1	227.7	196.8	0	0	424.4	884.3	14.7
2	111.8	112.4	0	0	224.1	529.2	8.8
3	161.5	212.7	0	0	374.2	908.8	15.1
4	85.5	155.8	0	0	241.3	795.7	13.3
5	84.1	116.4	0	0	200.6	616.9	10.3
6	67.7	105.8	0	0	173.4	566.7	9.4
7	80.4	116.5	0	0	196.9	706.2	11.8
8	65.8	65.5	0	0	131.3	442.1	7.4

Phase III Results Part 1

	Robot 1	Robot 2	Robot 3	Test 3A Total	Robot 1	Robot 2	Robot 3	Test 3B Total
1	98.7	71.4	69.7	239.8	29.7	25.1	143.1	197.9
2	16.0	20.7	32.5	69.1	16.6	14.3	20.3	51.3
3	55.5	28.5	81.9	166.0	35.8	39.1	34.4	109.4
4	25.5	40.2	92.4	158.1	26.5	24.1	46.9	97.5
5	32.9	72.8	55.8	161.5	41.1	18.4	28.6	88.2
6	42.7	38.0	50.9	131.6	47.7	37.8	35.6	121.2
7	66.3	17.0	66.3	149.5	27.2	20.5	77.5	125.2
8	31.4	13.6	20.0	65.1	17.3	33.0	43.7	94.0

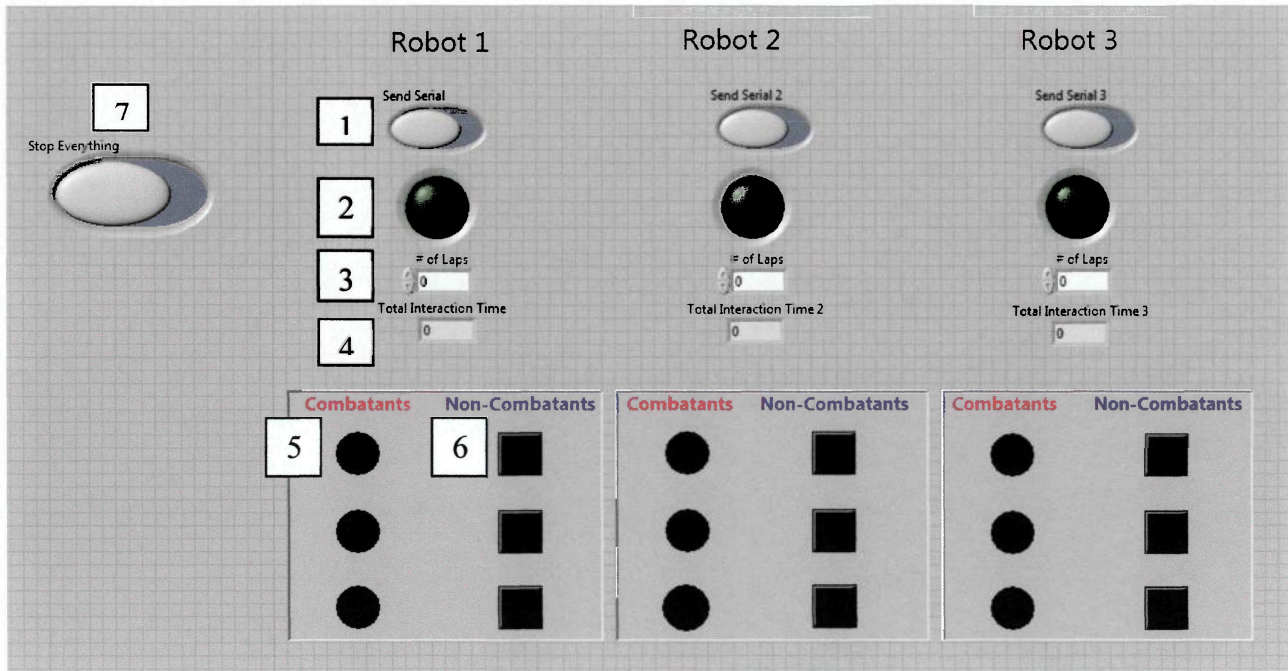
Phase III Results Part 2

	Robot 1	Robot 2	Robot 3	Robot 1 Penalties	Robot 2 Penalties	Robot 3 Penalties	Test 3C Total	Total Time for Three Robots	Total Time (min)
1	54.7	15.8	13.9	0	0	0	84.4	522.1	8.7
2	7.9	15.3	48.0	0	480	960	1511.2	1631.6	27.2
3	122.8	35.9	70.1	0	240	0	468.8	744.2	12.4
4	21.9	25.9	33.9	0	0	0	81.8	337.4	5.6
5	48.3	128.7	30.8	0	0	0	207.8	457.5	7.6
6	53.2	27.2	6.4	0	0	0	86.8	339.5	5.7
7	93.6	147.4	31.1	0	0	0	272.1	546.9	9.1
8	13.4	33.1	22.3	0	0	0	68.8	227.9	3.8

Overall Results

	Total Time (sec)	Total Time (min)
1	2179.5	36.3
2	2314.6	38.6
3	2239.9	37.3
4	1633.1	27.2
5	1434.5	23.9
6	1457.5	24.3
7	1727.2	28.8
8	926.9	15.4

APPENDIX E: DIRECTIONS



The image above is the control panel for the robots being used in this test. To control Robot 1, use the controls under the Robot 1 heading. To control Robot 2, use the controls under the Robot 2 heading, etc.

Information labels 1 through 7 in the figure above indicate the following:

- 1 Click this button to be able to drive the robot and then click it again to have the robot go back to autonomous mode.
- 2 This is a led that will light when feedback from the robot indicates it has encountered an obstacle. When it lights up and stays solid the robot has hit an obstacle and is stopped and waiting for you to drive it around the obstacle.
- 3 This is the number of laps the robot has completed. Click the up arrow every time the robot completes a lap. During the final part of this experiment you will need to identify combatants and noncombatants. Every time you click to say a lap has been completed, the values for the number of encountered combatants and noncombatants will be written into a file. Check to make sure these values are correct before clicking this button.

- 4 This is your total interaction time with each robot. It will update when you click the “Send Serial” button the second time to let the robot resume its task.
- 5 Click these buttons when you see red army men around the track. The top button is the red army man closest to the start line.
- 6 Click these buttons when you see blue army men around the track. The top button is the blue army man closest to the start line.
- 7 Button 7 is used when you are told that the phase is completed. You must immediately click the stop button and are no longer allowed to make changes to the type, status, or number of laps for a robot.

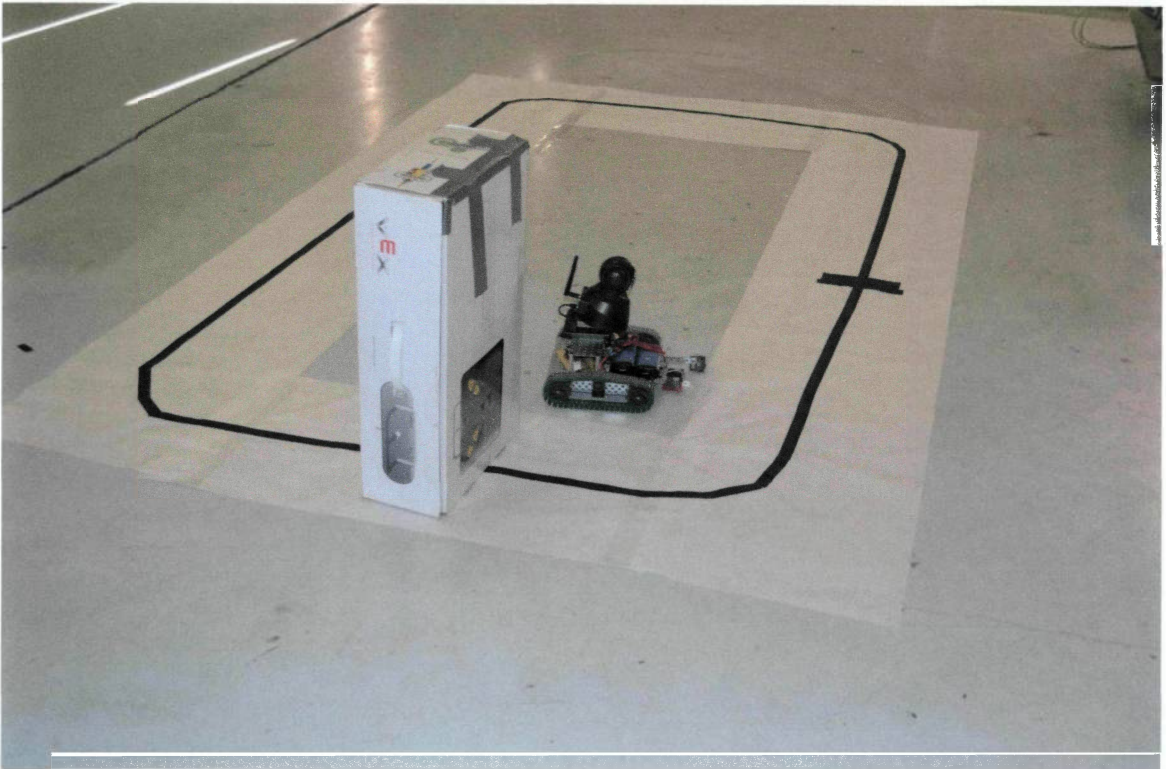
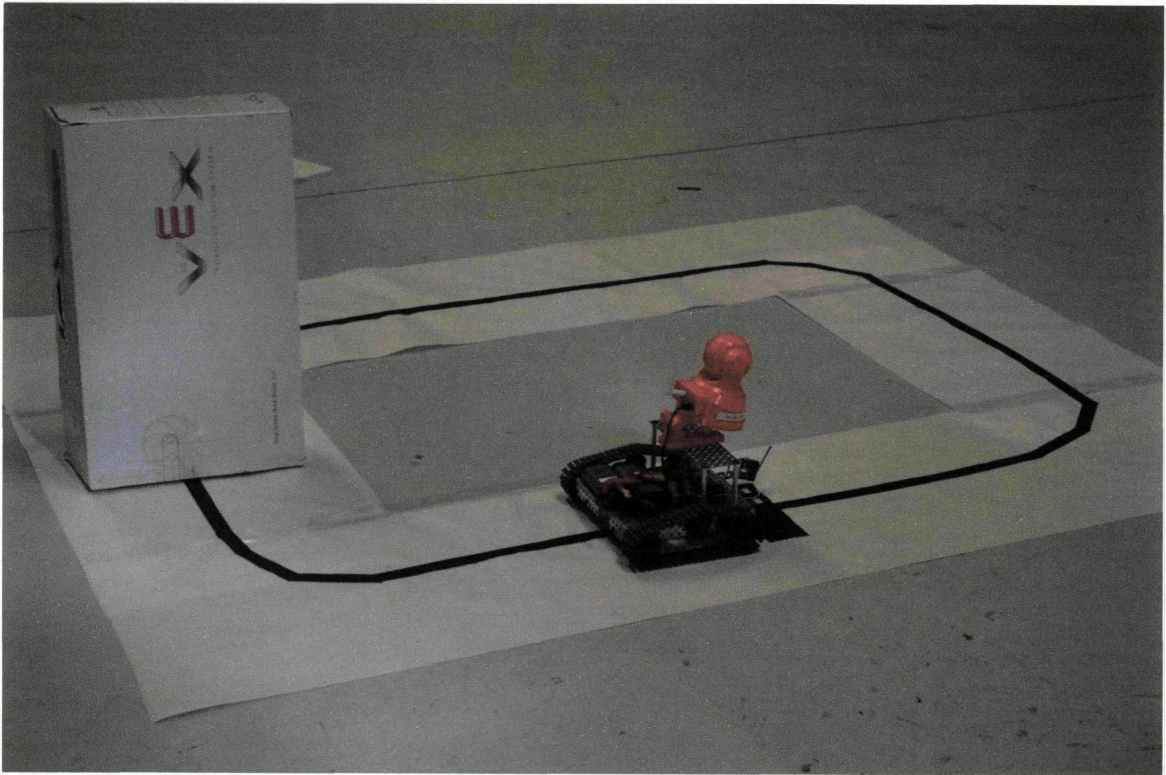


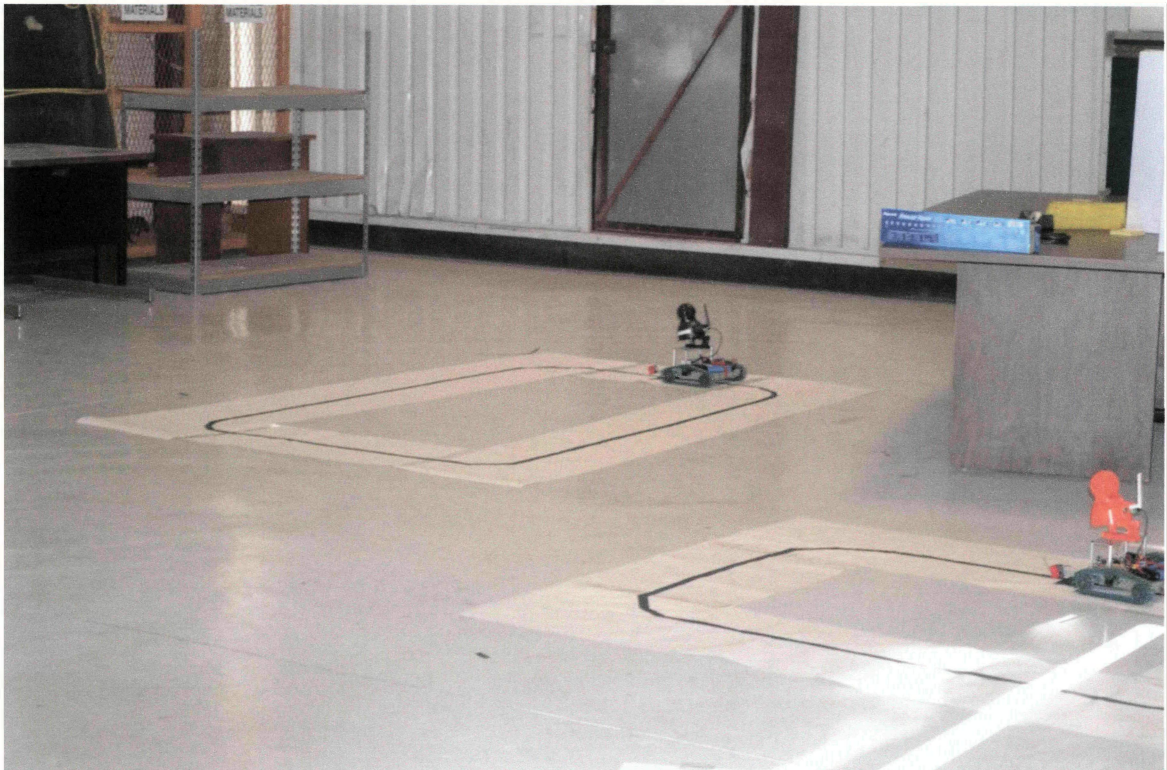
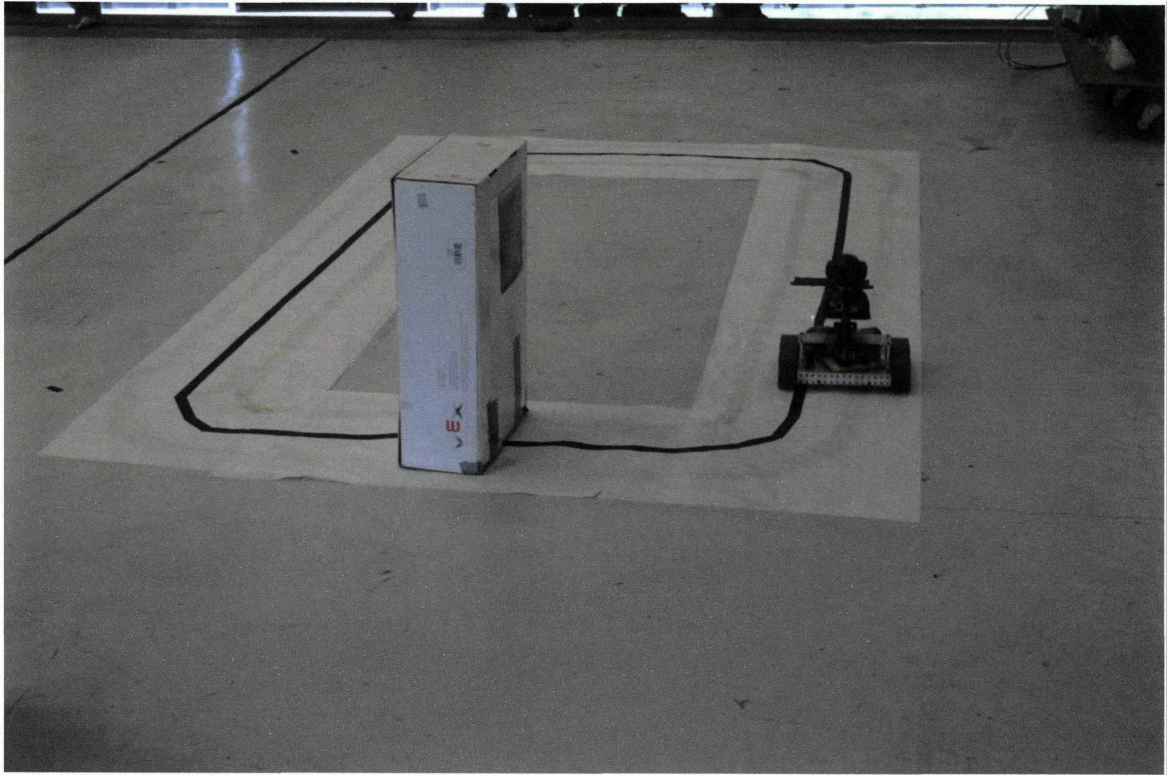
This joystick is used to drive the robots. Forward is forward, backwards is reverse, and left and right control left and right on the robots.

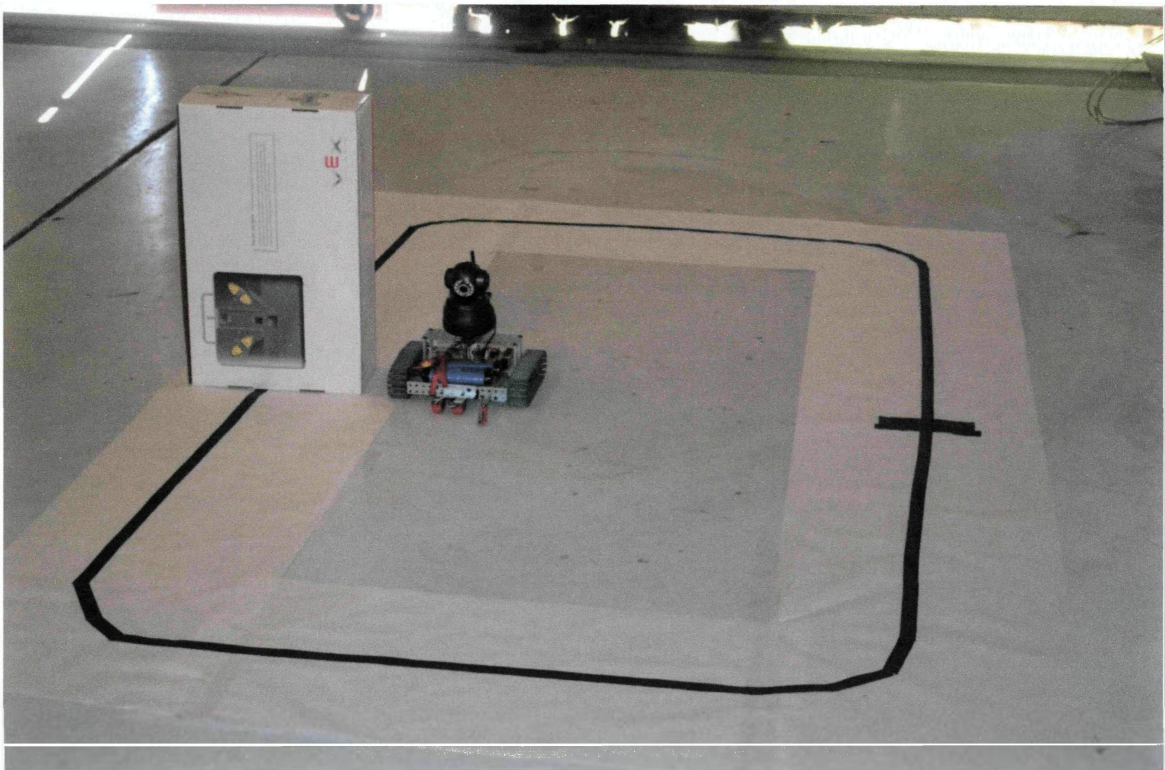
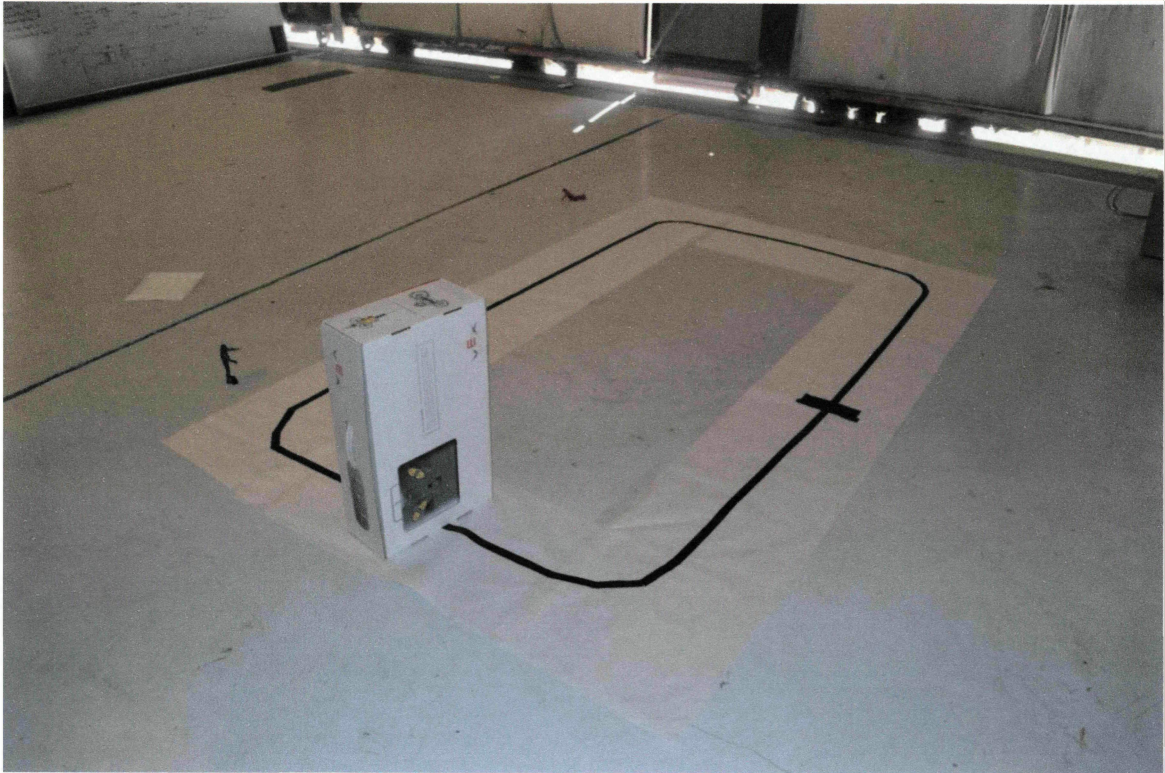
APPENDIX F: OBJECTS OF INTEREST



APPENDIX G: PHOTOS FROM EXPERIMENT







APPENDIX H: IRB APPROVAL

Embry-Riddle Aeronautical University

Application for IRB Approval

Cover Sheet

11-107

Principle Investigator: Charles Reinholtz,

Katrina Corley, Graduate Student.

Project Title: **“Supervisory Control of Heterogeneous Teams of UGVs as related to MAGIC 2010”**

Submission Date: January 18, 2011

Determination Date: January 28, 2011

Review Board Use Only

Initial Reviewer: Teri Vigneau/Bert Boquet

Exempt: ☒ Yes ☐ No

Approved: ☒ Yes ☐ No

Comments: Although this experiment poses ‘no harm’ to participants, it may require an ‘expedited’ review. [Teri Vigneau 1-24-11] This experiment is “exempt” pending modification of the informed consent. [Bert Boquet 1-24-11]

APPENDIX I: ARDUINO CODE

```
#include <Servo.h>

int bump = 0;
int switch_value;
int left_sensor = 3;
int left_sensor_value = 0;
int right_sensor = 1;
int right_sensor_value = 0;
Servo left_motor;
int left_motor_speed = 0;
Servo right_motor;
int right_motor_speed = 0;
int led = 13;
int test;
int left = 90;
int right = 90;
byte byte_read1 = 0;
byte byte_read2 = 0;

void setup()
{
  Serial.begin(57600);
  //Serial.println("Robot 2 Starting");
  pinMode(bump, INPUT);
  pinMode(left_sensor, INPUT);
  pinMode(right_sensor, INPUT);
  pinMode(led, OUTPUT);

  left_motor.attach(10);
  right_motor.attach(9);

  digitalWrite(led, HIGH);
  delay(500);
  digitalWrite(led, LOW);
  delay(5000);
}

void loop()
{
  if (Serial.available() > 0)
  {
    byte_read1 = Serial.read();
```

```
//Serial.println(byte_read1, DEC);
byte_read2 = Serial.read();
//Serial.println(byte_read2, DEC);

if (byte_read1 == 2)
{

    //Serial.println("Command for Robot 1");

switch (byte_read2)
{

    case 1:
    //Right
    left = 0;
    right = 0;
    //Serial.println("Case 1");
    break;

    case 2:
    //Left
    left = 180;
    right = 180;
    //Serial.println("Case 2");
    break;

    case 3:
    //Stop
    left = 90;
    right = 90;
    //Serial.println("Case 3");
    break;

    case 4:
    //Forward
    left = 0;
    right = 180;
    //Serial.println("Case 4");
    break;

    case 5:
    //Reverse
    left = 180;
    right = 0;
    //Serial.println("Case 5");
    break;
```



```

    }

    left_motor.write(left);
    right_motor.write(right);
    delay(50);

    }
}

else
{
    //Serial.println("Running on Sensor Values");

    left_sensor_value = analogRead(left_sensor);
    right_sensor_value = analogRead(right_sensor);
    switch_value = analogRead(bump);

    if (left_sensor_value > 1000)
    {
        if (right_sensor_value > 1000)
        {
            if (switch_value < 1)
            {

                test = 3;
            }
            else
            {
                test = 3;
            }
        }
        else
        {
            if (switch_value < 1)
            {
                test = 3;
            }
            else
            {
                test = 1;
            }
        }
    }
    else if (right_sensor_value > 1000)

```

```

    {
        if (switch_value < 1)
    {
        test = 3;
    }
    else
    {
        test = 2;
    }
    }
    else
    {
        if (switch_value < 1)
            {test = 3;}
        else
            {test = 4;}
    }
}

/* Serial.print("test = ");
   Serial.print(test);
   Serial.println("");
*/

```

```

switch (test) {

    case 1:
        //Left
        left = 180;
        right = 180;
        Serial.println("0");
        break;

    case 2:
        //Right
        left = 0;
        right = 0;
        Serial.println("0");
        break;

    case 3:
        //Stop
        Serial.println("1");
        left = 90;
        right = 90;
        break;
}

```

```

    case 4:
    //Forward
    left = 0;
    right = 180;
    Serial.println("0");
    break;

    case 5:
    //Reverse
    left = 180;
    right = 0;
    break;

}
}

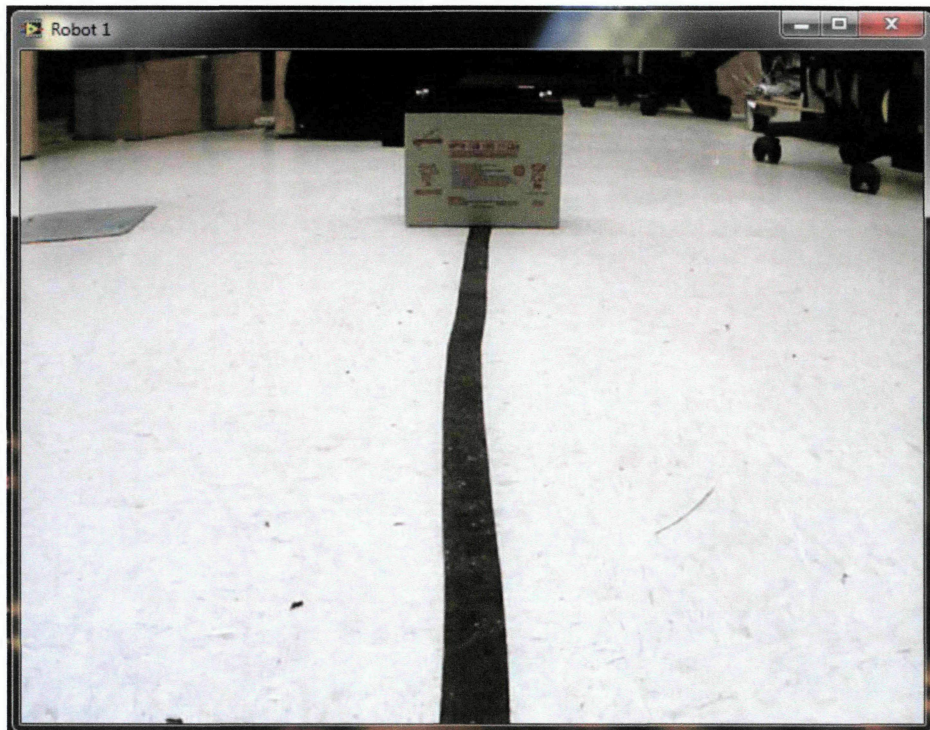
/*Serial.print("bump = ");
Serial.print(switch_value);
Serial.println(" ");
Serial.print("left = ");
Serial.print(left);
Serial.print(" ");
Serial.print("right = ");
Serial.print(right);
Serial.println("");
Serial.print("left sensor = ");
Serial.print(left_sensor_value);
Serial.print(" ");
Serial.print("right sensor = ");
Serial.print(right_sensor_value);
Serial.println("");
*/

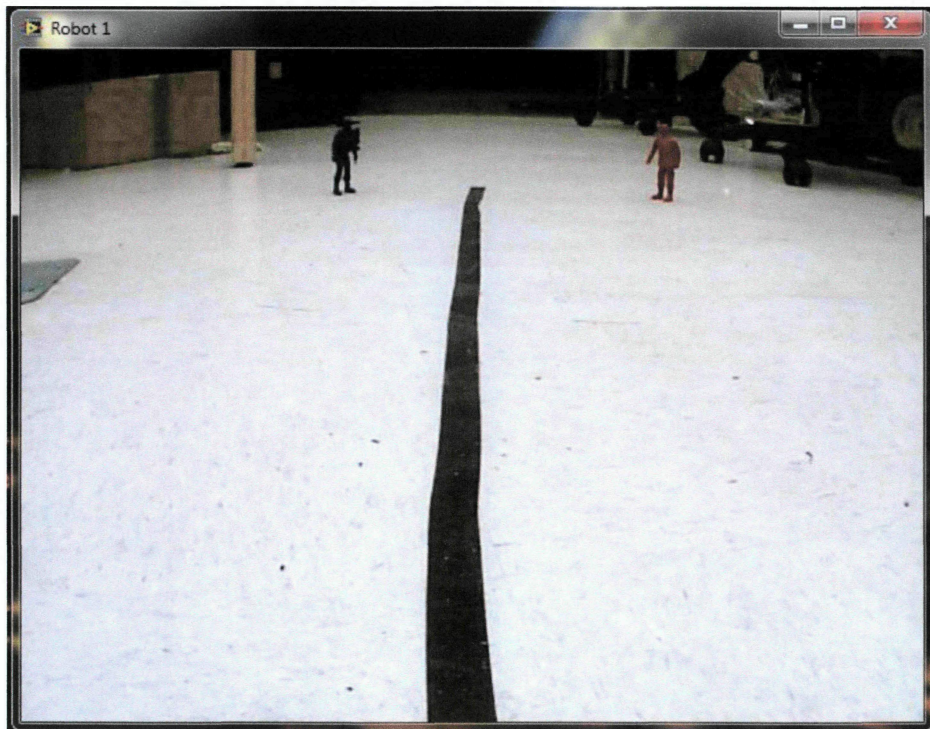
//Serial.println("");
left_motor.write(left);
right_motor.write(right);
delay(10);

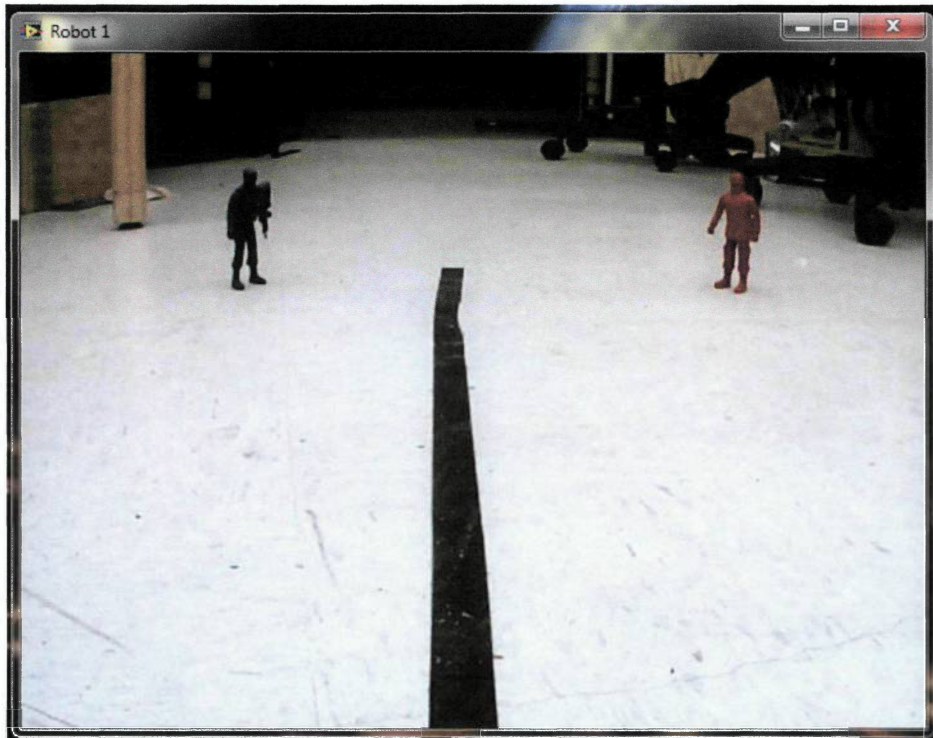
}

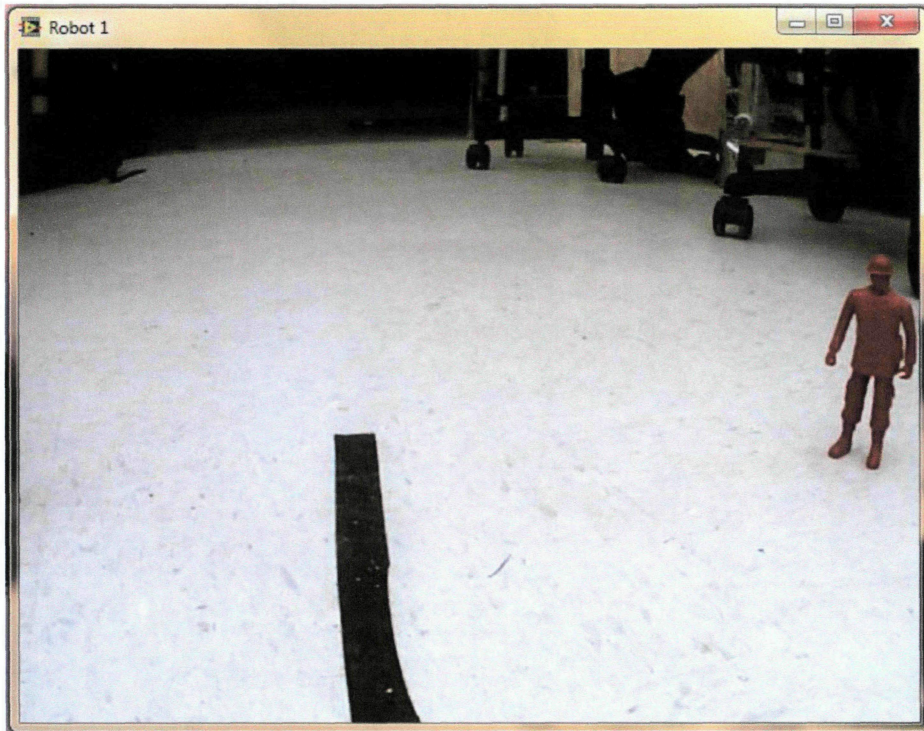
```


APPENDIX J: OPERATOR CAMERA VIEWS









VITA

Katrina Lynn Corley is a native of Thomaston, GA. She received her Bachelor of Science from Georgia Institute of Technology in Atlanta, Georgia in 2009. During her undergraduate years, she interned at NASA Kennedy Space Center during the summers of 2007 and 2008 and then completed a NASA Internship at the Carnegie Mellon Biorobotics Lab in 2009 through Carnegie Mellon University's Go Research! Program. The following summer she was employed as a graduate intern by Robotic Research, LLC and had the opportunity to participate in Team RASR for MAGIC 2010 and travel to Australia for the competition. In May 2011 she graduated from Embry-Riddle Aeronautical University with a Master of Science in Mechanical Engineering with a focus in Autonomous Vehicle Systems.