TESTING AND IMPROVEMENT OF A COMPLEX SYSTEM

Autonomous Planetary Rover Simulation and Experimentation

Design Proposal

16.621

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Executive Summary

The Aerospace community uses many complex systems, such as airplanes, satellites, and planetary rovers. This project will test a proposed hybrid developmental approach for these systems. The project is based on the need for new and better ways to accurately predict and improve the performance of complex systems, such as a planetary rover. The hybrid approach combines experimental and Monte Carlo simulation approaches into an iterative combination, and it is hypothesized that the hybrid design will show greater performance improvement over the baseline rover than the experimentally derived design alone.

The rover that will be tested is a small car operated by a handyboard. It will be completing the mission of finding a path to a randomly placed IR beacon from a random starting location while navigating past obstacles. Three versions of the rover will be tested on the final, unknown test field: the baseline rover, the experimentally derived rover, and the hybrid design rover. Observations will be made during the development of the rover towards discovering and describing the individual contributions made towards improvement by experimentation and simulation. The project is planned to be completed within a 15 week time period and has a real world budget of $399.00, but will cost MIT and the 16.62x class $0.00.

1.0 Introduction

1.1 Background

The use of complex systems is constantly expanding in both aerospace engineering and numerous other fields, and with the spread of these systems, their complexity increases as well. Due to this complexity, the systems and any dependents often suffer from unreliable behavior, which may result in unsafe operating conditions or a mission failure.

Although testing of systems used to be done experimentally, many fields are now using an analytical approach. An example is wing design in which numerous wind tunnel tests were performed in the past, but now the airfoils are developed on computers and then tested in a wind tunnel for confirmation.

1.2 Previous Work

Although there is much interest in the development of complex systems, little experimentation has been done in this field, as evidenced by a relative lack of publications on the topic. The hybrid developmental approach proposed for this project is one way of attempting to improve a system, not totally unlike many others that are currently in use. This approach combines experimentation with Monte Carlo (MC) simulation. A Monte Carlo simulation involves the use of stochastic numbers and thousands of trials of which statistics are taken to describe the behavior of the system that is being modeled. Monte Carlo simulations are already used for analysis and modeling in many fields, including aerospace technology development, molecular chemistry, economics, nuclear physics, radiotherapy, and transportation engineering.

1.3 Value of Project

A hybrid developmental approach will integrate the two current kinds of testing and development, experimentation and simulation, into one. Experimentation will be used in conjunction with computer-aided analysis to provide superior development capabilities. This will be done by using experimentation to refine a model of the rover and vice versa. The results from the MC simulation will then be used to change the rover with the intent of improving its performance on a given task. It is proposed that this hybrid approach will offer the most benefit to high levels of complex systems. This project will use the hybrid developmental approach with an autonomous planetary rover, and will also discover and describe the individual contributions made towards improvement by experimentation and simulation.

2.0 Objective

2.1 Hypothesis

A hybrid developmental approach for an autonomous rover operating on an unknown test field will yield greater improvement than a solely experimentally developed design, and the individual contributions made towards improvement from both the experimental and the simulation portions of the hybrid approach can be discovered and described.

2.2 Objectives

1 - Successfully collect performance data on an unknown test bed for multiple configurations of an autonomous rover in order to measure and compare performance in task completion time.

2 - Observe behavior of rover and the modifications suggested by experimentation and simulation during the hybrid development process in order to describe the contributions made towards performance improvement of the rover by the two approaches.

2.3 Success Criteria

1 - Collection of data that clearly supports or does not support the hypothesis that task improvement increases when the hybrid developmental approach is used.

2 - Observations are made during the development processes that pinpoint the contributions that simulation and experimentation make to the overall system improvement.

3.0 Literature Review

Although there is a plethora of information available about complex systems in general, Monte Carlo simulations, and other ways to model systems, there does not seem to be any previous research that describes particular contributions towards improvement. The information that has been found contains some background into the growing complexity of systems and the industrial and academic reactions to this growth, addresses other novel types of experimentation with complex systems, contains information on complex systems in general, and discusses Monte Carlo simulations.

A rapid increase in complexity of systems and industry's expanding use of these systems have left many engineers without necessary skills for the workplace.[1] It is with this difficulty in mind that this project was formed. Academic institutions, such as MIT, have changed their curriculum to reflect the new challenges that face the engineering community. Some programs offer graduate students the opportunity to study both engineering and management to prepare for the changing workplace. One particular class at MIT is Aerospace Product Design (APD), which focuses on preparing students to understand "systems behavior via highly integrative multi -disciplinary processes." The course instructor goes further in defining a system in this context as "A collection of interrelated elements with functionality greater than the sum of the independent element functionalities."[1] This new emphasis in curriculum evidences the importance of complex systems and the necessity of investigation into their development and behavior.

Many techniques already exist to assist in the design of complex systems. Quite often these techniques involve modeling of various kinds. As systems have grown more complex, the use of high-powered computers to analyze and model the systems has also grown. Two such types of modeling seemed most relevant to the proposed project: metamodeling and simulations of simulations. The metamodel idea uses a Gaussian Process (GP) model to predict the outcome of another model based on past data sets and a new input. It uses a Gaussian probabilistic distribution as the prediction of the new input's output and also gives an estimate of the confidence in its own result. This technique is one of many metamodeling techniques, including Response Surface Equations and Neural Networks. The benefits of accurate metamodeling are listed as: "1. Integration across different teams and organizations. 2. Reduction in design cycle effort and quick tradeoff for evaluation. 3. Visibility and transparency. 4. Enabling of the day-to-day use of probability methods. 5. Allowing for parametric design definitions."[2]

Metamodeling seems to be quite similar to simulations of simulations. This second technique was developed as a response to increasing use of simulations to model systems before they are completed or when unavailable. With increased use, the models progressively become more complex themselves, and at some points more complex than the systems they are made to model. The use of distributed simulation to simulate another simulation allows the developer of the original simulation to find errors or bottlenecks within the model before use. This technique was developed mainly with the idea of reducing the costs of complex simulations.[3]

Complex systems come with given uncertainties, and particular attention has been given to accurately modeling the uncertainties to predict their effect on the system. DeLaurentis and Mavris suggest a way to classify and to model uncertainties.[4] One of the main concerns of this 16.62x project will be internal uncertainties of the rover and external uncertainties from the environment. The DeLaurentis and Mavris paper will be a useful resource as the simulation of the rover is made. The paper by Rehman, Lock, and Nguyen will also be useful as this project progresses as it describes a process by which particular system design factors can be isolated and optimized.[5] Since this project is predicting improvement in particular performance parameters, the process given in the Rehman, Lock, and Nguyen paper will be examined in more detail and consulted for use in the project at hand.

There is, as stated earlier, a large amount of research and information available on Monte Carlo (MC) simulations. Marczyk is a strong supporter of the MC simulation as the strongest stochastic tool due to its integration of complexity, robustness, and uncertainty.[6] He believes that too much emphasis is put on optimization with other simulation tools, and not on robustness. He calls the result of a MC simulation a "good enough" solution.

The final paper examined, by Toshikazu and Yoshikazu, discusses how to identify influential parameters on a MC simulation. A MC simulation allows many simulations to be run with random combinations of uncertainties. The occurrence of a 'failed' trial will allow the designer to identify the combination of uncertainties that lead to the failure. This identification will then allow for changes to the design, resulting in more predictable outcomes from the real system. Since most complex systems have many uncertainties to consider, it can be difficult to pinpoint the particular parameters that contributed to the failure. Toshikazu and Yoshikazu propose a method to isolate the important influential uncertainties which could be useful for the proposed project of hybrid testing and development of complex systems. Their approach will help describe the contributions made toward improvement by experimentation and simulation. Their proposed method was successfully tested with an autonomous flight system.[7]

This 16.62x project seems to fall under the category of yet another way to develop and test a complex system, but the discovery part of the project, describing the contributions towards improvement that both experimentation and simulation offer, is expected to add insight to complex system development.

4.0 Technical Approach

4.1 Experiment Overview

This project will use a hybrid developmental approach in the development of an autonomous rover to be tested on an unknown test field. The rover will undergo experimental testing and will also be simulated by a MC simulation. Two designs will be suggested by the two forms of testing. The rover will be tested in three configurations on the final test bed: the baseline state, the experimental results state, and the final hybrid design state. The final hybrid design will be a combination of suggestions from the experimental and simulation stages, while the experimental design will be based solely on the experimental results. The quantity measured will be the necessary time to complete the task of making a path from a starting location to a randomly placed IR beacon.

4.2 Apparatus

The test field will be a 6' by 6' section of the gridded floor of the hanger. It will be littered with boulders and will be set up randomly by a faculty member for the final test, making it unknown and unpredictable. The software that is available from Professor Boppe and will be used for this experiment is called Requirements Driven Development - 100 (RDD-100), which uses a Monte Carlo simulation. It has the ability to simulate the various functions of complex systems and provides statistical analysis on the simulated performance of the modeled system.

4.3 Test Articles

The rover that will be used is a car that carries a handyboard that was built for the Spring 2002 class of 16.070. The handyboard has an IR sensor and commands the motors for the car's four wheels. For a more detailed description, see section 5.2.

4.4 Measured Quantities

The measured quantity will be the time needed to reach the IR beacon from a given starting location. The car and beacon will start within five and eight feet of each other to normalize time results.

5.0 Experiment Design

5.1 Design for Apparatus

The boulders for the playing field will be rocks that are collected from campus construction sites or Professor Boppe's house. A small wall will be built around the test bed to stop the rover from exiting the playing field during a run.

The simulation will be built during the first few weeks of 16.622 and will be based on baseline and additional experimental testing. The RDD – 100 is capable of isolating specific functions within the overall system during simulation and provides statistical analysis of the modeled system.[8] The simulation will vary many factors such as the starting location of the rover, the location of the IR beacon or goal, the number of obstacles, the placement of obstacles, and the amount of power available to the rover. Professor Boppe will assist in the construction of the simulation of the rover and the operation of the software as it is well known to him. Figure 3 is a state transition diagram example of logic for both the simulation and the rover. It was developed by Professor Boppe. Figure 4 is a schematic that shows planning for the simulation. It highlights the three primary processes within the simulation: rover mechanics, rover logic, and the environment. It was also provided by Professor Boppe.

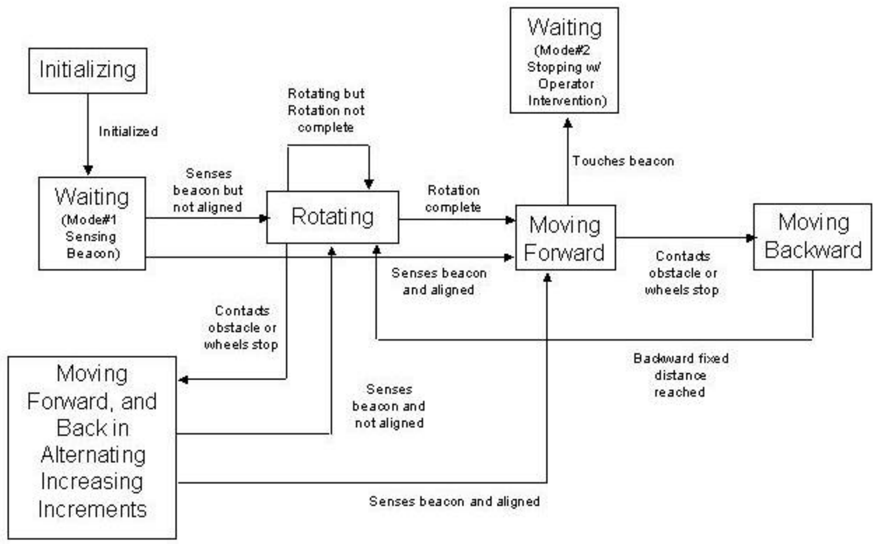

Figure 1: State Space Diagram for simulation and rover logic

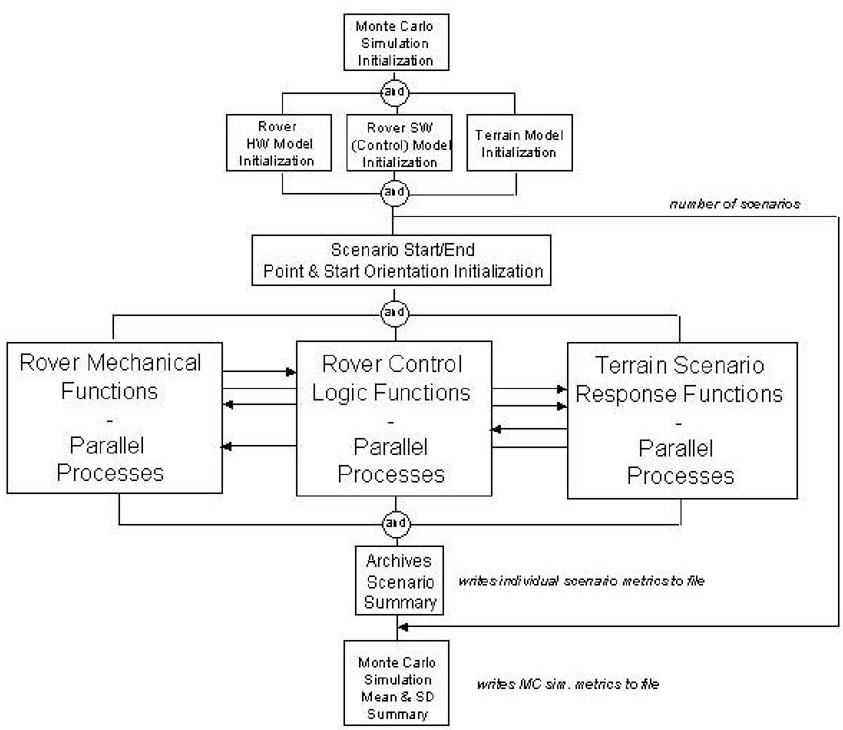

Figure 2: Simulation planning – 3 primary processes

5.2 Design for Test Articles

The rover that will be used is a car that measures 12 inches by 6 inches, has four wheels, two front touch sensors, and carries a handyboard. The handyboard (see Figures 3 and 4) has an IR receiver and controls the motor of the car. The handyboard runs on C code that is loaded by the compiler Interactive C, which has already been obtained. The rover was used in the last year for a 16.070 project, and that code still exists. While this project is more complicated, the existing code will be used as a starting point for coding the new mission.

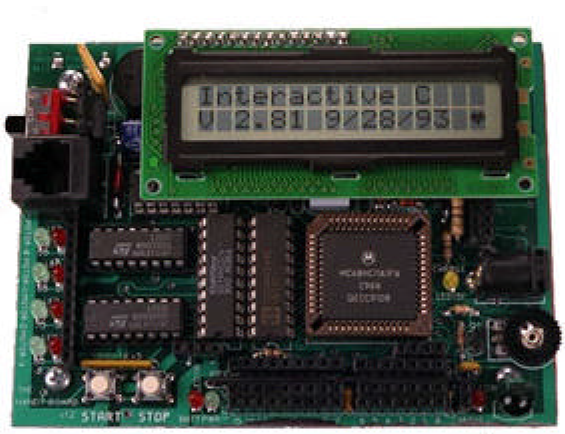

Figure 3: Handyboard[9]

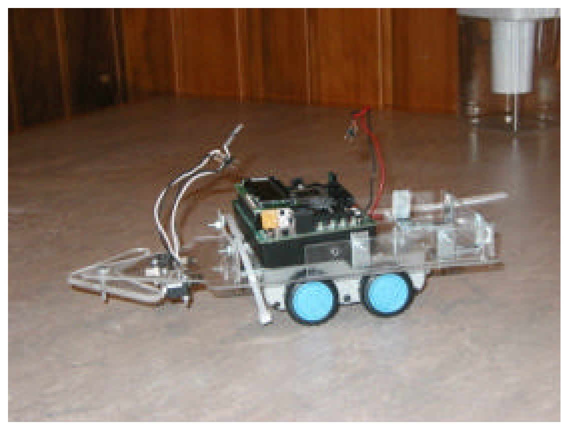

Figure 4: Car with handyboard in place

The following mission has been chosen for the rover: the rover will move from its starting point to locate and move to an IR beacon. The beacon will always be able to be seen above the rock obstacles. A search for an algorithm to support this mission is underway. The following pseudocode, written by Malena, is an example of the logic that could be used for this mission.

Constant Signal algorithm:

Randomly choose rover start location and IR beacon location.

Choose such that there is a distance of 5-8 feet between the two locations.

Rover turns on.

Rover pivots until signal is found.

Rover moves towards beacon.

If the rover loses the signal:

Rover pivots until it finds it again.

If the rover detects an obstacle:

Rover backs up

Rover pivots a certain number of degrees,

Rover moves towards beacon.

If the rover hits the beacon:

Rover shuts off motors.

5.3 Experimental Procedures

The following is a general outline of the procedures that will be followed to complete this experiment. During the development and testing stages, detailed records will be kept to facilitate the discovery and description of contributing factors from experimentation and simulation towards improvement in performance of the rover.

1 Collect boulders for test field.

2 Refine existing code for the rover to accomplish its new mission.

3 Run baseline tests to examine rover performance, sensor performance, environment/rover interaction, and battery and motor performance.

4 Make modifications to rover based on intuition and experience gained from the baseline tests to create a new baseline rover.

5 Perform experimental tests, record information, and record suggestions for improvement to rover.

6 Develop a simulation based on the baseline tests and the experimental tests and run it numerous times to generate statistics about its operation and to observe its performance in various situations.

7 Record observations from the simulation and record suggestions for improvement to rover.

8 Test baseline, experimental, and simulation rover designs and compare the performance of the rover in time needed to reach the goal from the designated starting locations.

5.4 Measurement Systems

A stopwatch will be used to measure the time from the beginning to the end of the path of the rover. A tape measure will be used to place the rover, its goal, and also the boulders on the grid. The grid is already marked with one foot squares, but additional tape may be laid down to aid in measurements.

5.5 Errors

Human error in time and distance measurements will be the most significant error in the data for this project. These errors are not expected to effect the data greatly, however, as they will account for less than a percentage point of the expected effected quantities (0.1 second error or 0.5 inch error out of 200 seconds of time or 72 inches of measurement). Variability in the rover could cause error in measurements. The main concern with the rover is the durability of the motor after repeated trial runs. The level of battery power available will be measured at regular intervals during testing, and breaks will be taken to recharge the batteries to full power.

5.6 Test Matrices

Each rover configuration will be tested ~10 times with different starting locations for the rover and its goal at each run. After speaking with Professor Kuchar, it has been demonstrated that the number of needed tests will not become clear until after some initial testing is done. The variation in times of the tests will determine how many tests will need to be performed to get statistically significant data. The same pairs of locations will be used with each configuration to encourage statistically significant data collection. During experimental runs, simulation, and the final testing runs, the rover and its behavior will be studied in an attempt to describe and qualify the contributions of both experimentation and simulation towards improved performance of the rover. The test matrix can be found in Table 1. A star indicates that the selected rover design and testing will occur.

Table 1: Test Matrix

rover design	**test 1 … test 2 … test 3 … test n-1 … test n**		
	unknown test field	**contributions from experimentation**	**contributions from simulation**
baseline design	☆		
experimentally derived design	☆	☆	
hybrid developmental approach design	☆		☆

5.7 Variables

The primary independent variable for the testing will be the configuration or status of the rover. The starting location of the rover and the location of the IR beacon will change with each test. The starting locations will be constant between the various rover configurations. The starting locations are another independent variable that will be determined at the beginning of the final testing. The battery power at the beginning of each test is a parameter that will need to be measured. The dependent variables being measured during this experiment are the time needed to complete a path from the given starting location to the location of the IR beacon and whether or not the task was completed.

5.8 Origin of Materials

The rover being used is a car that was built for the 2002 16.070 class. Its operating system will be an onboard handyboard. These cars already exist within the department and will not need to be purchased. The 'boulders' on the test field will be rocks collected from campus construction sites or Professor Boppe's home. The gridded floor of the hanger will be used as the test field. A last possible purchase is that of any new sensors, but it is not anticipated that they will be needed. As there were many cars built for 16.070, a lack of backup parts is not a concern.

5.9 Safety Concerns

There are no major safety concerns associated with this project.

6.0 Data Analysis

Data analysis will begin as soon as the rover is functional. Two major analyses will need to be done, that of performance on the final test bed and the discovery of contributions from the two approaches within the hybrid approach. When considering performance improvement, this project will be searching for a trend of improvement for the ~10 tests run in each rover configuration. For example, to confirm the hypothesis, the overall performance of the hybrid rover would be better than that of the experimental rover or baseline rover. A better performance implies shorter test field task completion times. Much of the analysis will be graphical, which will illustrate trends well. The same pairs of locations will be used for each of the rover configurations to keep results as comparable as possible.

Errors are likely in the final testing stage due to the small number of runs. It will be determined during testing how many runs are required to result in statistically significant data. The decision will be based on the variation of times of runs. The smaller the standard deviation of times, the smaller number of runs will need to be made in order to collect statistically significant data.

The discovery and description analysis of contributing factors towards improvement will be qualitative and not quantitative. Constant records will be kept during the development and testing stages and these will be analyzed to describe the contributions from experimentation and simulation.

The hypothesis will be proven or disproved by the presence or absence of statistically significant shorter task completion times for the hybrid design rover than the baseline or experimentally derived rover. It is also necessary that the project is able to describe individual contributions towards improvement in order for the hypothesis to be proven true.

7.0 Project Planning

7.1 Budget

The car and handyboard have already been acquired from the 2002 16.070 class final project at no cost to the project. Rocks will be collected from campus construction sites or Professor Boppe's house, which will accrue no cost to the project. It is not anticipated that a purchase of more sensors will be required, as many exist on other 16.070 cars and are available at no cost. A detailed version of the budget is available in Table 2.

Table 2: Budget

Required Item	**Source**	**Number**	**Price/Unit**	**Real World Price (dollars)**	**16.62x Cost (dollars)**
Car Body	MIT	1	~ 100.00	100.00	0.00
Handyboard	MIT	1	299.00	299.00	0.00
RDD – 100	Boppe	1	NA	NA	0.00
Rocks	Construction sites / Boppe	~25	0.00	0.00	0.00
Additional Sensors	MIT	NA	NA	NA	0.00
Total				**399.00**	**0.00**

7.2 Schedule

The rover has already been obtained, and building will commence at the start of term for both the rover logic and the simulation. The majority of the time during the project will be spent testing and suggesting changes to the rover. Two weeks have been allowed for final testing, but no more than six hours of actual final testing time should be needed. A large time requirement in this project will be the time needed to make changes to the rover's hardware and software. This time is included under the development stages for experimentation, simulation, and hybrid. The last seven weeks of the term are being left for data analysis and presentation and report work. A detailed schedule is available in Table 3.

7.3 Support

The testing will occur on the gridded floor of the hanger. Testing time will be coordinated with another 16.622 group using the floor. No machine shop time is anticipated. The RDD - 100 is being supplied by Professor Boppe and the car(s) are being supplied by the technical support staff.

Table 3: Schedule

Task	Start Date	End Date	Week:														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Experiment Setup	2/4	3/9															
Build Simulation	2/4	3/9															
Build Test Bed	2/4	2/9															
Build Rover	2/4	2/23															
Rover Development	2/17	4/18															
System Testing	2/17	3/9															
Experimental Approach	2/24	3/9															
Simulation Runs	3/10	4/6															
Hybrid Approach	3/17	4/6															
Final Testing	4/7	4/18															
Analysis and Presentation	3/3	5/13															
Data Analysis	3/31	5/4															
Oral Progress Report	3/3	3/6															
Final Presentation	4/7	5/1															
Final Report	4/7	5/13															

8.0 Conclusion

This project will develop and test a rover that follows the signal from an IR beacon to make a path from a starting to end location. A hybrid developmental approach composed of both experimental and simulation components will be used to suggest modifications to the rover to improve its time performance in completing the task at hand. It is expected that the design suggested by the hybrid approach will have superior performance to the baseline rover and the design suggested by solely experimentation. During experimentation and development, this project will discover and describe the contributions from experimentation and simulation made towards improvement in performance.

9.0 Acknowledgements

We would like to acknowledge our project advisor Professor Charlie Boppe for initiating the project and helping us understand it, Professor Murman for helping us get out the kinks, Professor Greitzer for challenging us to make the project better, and Dick Perdichizzi for finding a rover. Thanks also to Paul Elliott, Professor Dubowski (Course 2), and Jamie Anderson (Draper Labs) for possible rover leads.

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## Appendix A	Detailed Drawings of Apparatus

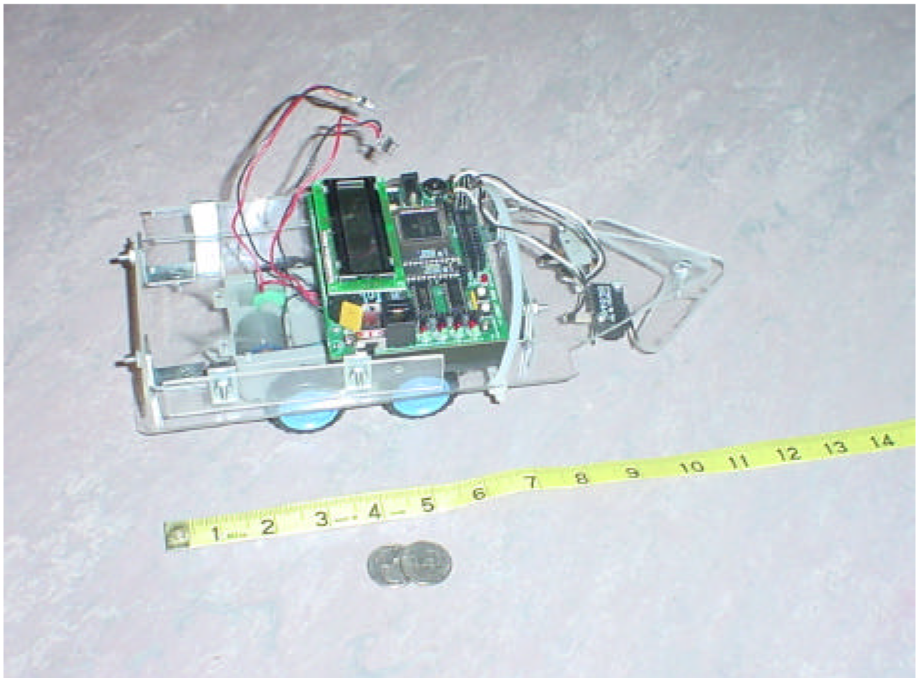

Figure 3: Side view of car with scale

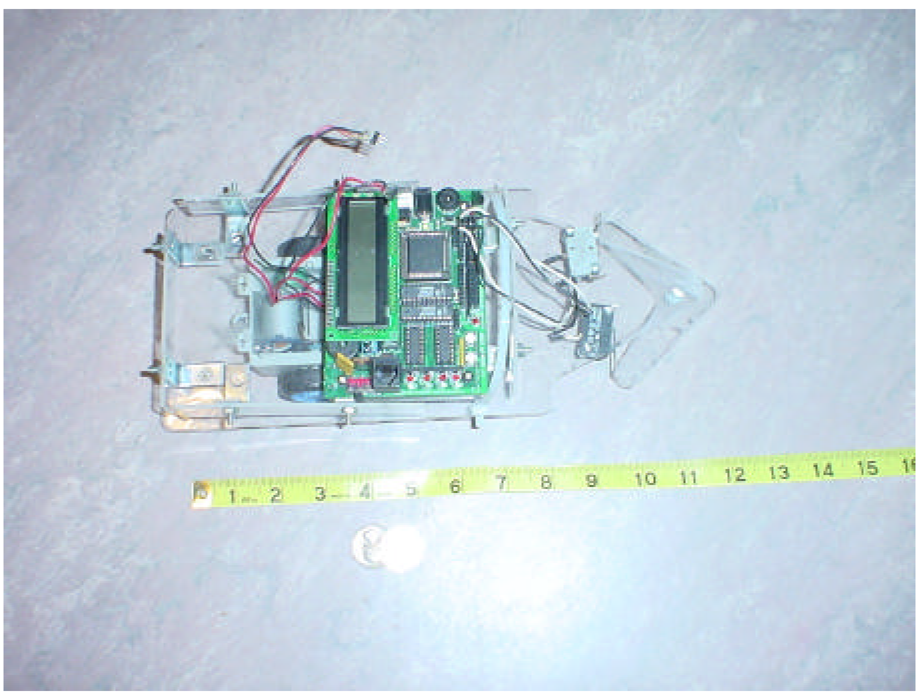

Figure 4: Top view of car with scale

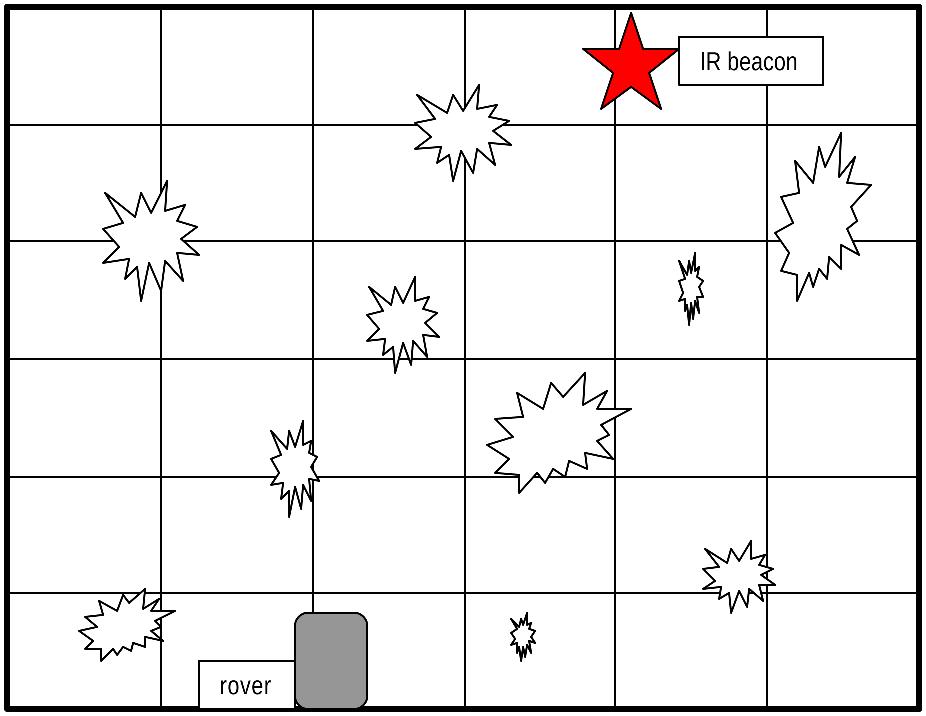

Figure 7: Example of test bed

Appendix B Detailed Parts List

Apparatus

- rover (12" X 6" X 3")
- RDD – 100 software
- Interactive C software
- IR beacon
- 2 handyboards
- handyboard serial cables
- 9V batteries

Test Equipment

- tape measure
- stopwatch
- battery power measuring device

Materials

- rocks
- wood (2" X 4") for barrier

Facilities

- gridded floor of the hanger