NAVIGATION OF A HIGH VELOCITY TELE-OPERATED GROUND VEHICLE THROUGH AN OBSTACLE RICH ENVIRONMENT

by

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S.B. Electrical Engineering,
Massachusetts Institute of Technology, 1997

SUBMITTED TO THE DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS IN
PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE IN AERONAUTICS AND ASTRONAUTICS

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 1999

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Signature of Author_____

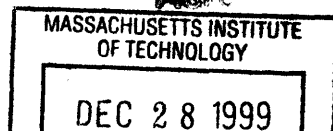Department of Aeronautics and Astronautics
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Abstract

An experiment was designed and conducted to investigate the use of *a priori* overhead images in navigating an unmanned tele-operated ground vehicle through an obstacle rich environment. The obstacle courses contained many of the same types of elements that would exist in an urban setting. The corresponding *a priori* images depicted these obstacle courses but included some drawbacks that could be expected in an overhead image of an urban environment. For instance there were objects on the course that were not depicted on the overhead image and vice versa.

The overhead images were prepared in low, medium, and high resolutions. These resolutions, one meter, half meter, and centimeter scale, were selected to be representative of what might be available in real situations. Subjects controlled the vehicle using a joystick, with reference to the *a priori* image and a real-time video image from the vehicle. The subjects' times to navigate the courses and their paths were recorded during the experiment. From this information, post analysis showed what types of decision errors they made on each course.

Statistical analysis showed that there was no significant performance difference between the three different obstacle courses. Subjects took the longest time to navigate the courses using the low resolution overhead images, and took the shortest time with the high resolution images. There was a statistically significant difference between the average course completion time with the medium resolution map and the high resolution map. Medium and high resolution lead subjects to rely less on the video image from the vehicle. This caused them to occasionally make incorrect navigation choices. With low resolution subjects tended to use clearly discernable paths and avoid shortcuts which could have saved time. This nuance in the behavior with different resolutions underscores the importance of experimentation and suggests that further study is necessary.

ACKNOWLEDGMENT

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1   INTRODUCTION

1.1   BACKGROUND

Advances in miniaturization of both electrical and mechanical systems have opened up new possibilities for the use of unmanned ground vehicles. For example, the Charles Stark Draper Laboratory's Unmanned Vehicle Lab, UVL, developed a pair of small, unmanned, vehicles for explosive ordinance disposal missions [1]. Currently small teams of highly trained military personnel are the only means of disposing of unexploded ordinance. This work is time consuming, tedious, and extremely dangerous. The two vehicles, EOD-1 and EOD-2, illustrate a concept in which humans are taken out of danger and are replaced with expendable ground vehicles. Similarly, Carnegie Mellon University has done research on legged ground vehicles. One Carnegie Mellon robot, named Dante II, rappelled into the crater of an active Alaskan volcano in 1994 [2]. This is another example of an unmanned ground vehicle which can be used to keep humans out of peril. Unmanned ground vehicles are especially useful in space applications where it is often difficult, if not impossible, to send a human to the location of interest. Recently the Mars Pathfinder mission demonstrated how a small, simple, unmanned vehicle may obtain large amounts of scientific data [3]. The advances of technology not only make unmanned ground vehicles useful for space or dangerous applications, but allow them to be used in more mundane and repetitive services. For example, for six days a ground vehicle was used to engage people and provide interactive guided tours at the Deutsches Museum Bonn. During these six days, the ground vehicle interacted with over 2,000 visitors [4].

Despite these examples, there are still several fundamental issues which the technology advances have yet to overcome. For example, small unmanned ground vehicles are often battery powered and thus suffer from limited range and operation time. A larger problem is that of navigation in environments that are not completely known, characterized, and modeled before the ground vehicle encounters them. Many unmanned ground vehicles, especially fully autonomous ones, must be custom designed for specific environments and packed with sensors and processors to try to identify features in that environment. This often has taken the form of camera vision

systems with image processing software. However, due mainly to limitations in software and hardware complexity, these ground vehicles operate best in low obstacle density locations, and at low speed.

Achieving sustained high speed, greater then 0.5 m/s, has proven difficult for unmanned systems. The issue is not of propulsion, but of the related reduction in avoidance time. The faster a vehicle travels, the faster it must identify obstacles and react in order to avoid collisions. Only in environments where obstacles are few and far between have fully autonomous ground vehicles been able to operate at high speeds without risking collisions.

Many of the useful applications of unmanned vehicles involve their use in human environments, which are rich in obstacles and other dangers. These include both indoor and outdoor applications. While rich in obstacles, indoor settings are easier for unmanned ground vehicles to navigate due to the regularity and uniformity afforded by buildings. While all buildings vary, some factors are common to most structures. For example, the ground is often level, and the walls and hallways are straight. Hallway intersections are almost always perpendicular and doorways are often many times larger then the vehicle. Smart designers and programmers can take advantage of this uniformity to give an unmanned ground vehicle the ability to use its limited sensor and processing capabilities to successfully navigate in indoor environments.

Outdoor environments generally do not afford such uniformity or regularity. Thus operating autonomously outdoors can be a much more challenging problem, especially in an urban environment. Not only can obstacle avoidance be more difficult, but navigation may prove more difficult as there is more likely to be unexpected or unforeseen objects in outdoor settings. At present, computer hardware and software does not allow a fully autonomous ground vehicle to operate at high speed and identify the various objects in such an environment. Consider for example, the nontrivial task for computer hardware and software to look at one tree at two different angles and not only identify both images as those of trees, but of the same tree. Coupled with moving at 2 m/s, the problem is currently out of the reach of hardware that would fit on a small unmanned ground vehicle.

Tele-operation is one way to overcome the shortcomings of fully autonomous ground vehicles. For tele-operation a human driver controls the vehicle from a remote location. To accomplish this the vehicle must have at least some communications with the operator, much more than an autonomous vehicle would need. However, humans are better than computers at certain tasks, so a tele-operated vehicle can have greater capabilities than an autonomous vehicle.

For example, a human can look at two pictures of the same tree and not only identify them as trees, but also recognize them as the same tree. The human can do this instantly and send course corrections to the vehicle as necessary.

For successful tele-operation, several issues must be addressed. One issue, mentioned earlier, is that of communications between the operator and the vehicle. Ideally the operator would have continuous contact with the rover, receiving sensor information and sending commands in real-time. Provisions must be made for the situation where this communications link is lost.

Sensor configuration is another area of concern. Sensors necessary for successful tele-operation are often very different than those needed for autonomous operation. Thus the vehicle must be designed with tele-operation in mind and careful study must be made as to which sensors are necessary to enable human control, with the goal of minimizing both weight and power.

In addition to information provided by the vehicle, a human operator may have access to other sources of information regarding the environment the vehicle will operate in. A street map of the area may be available giving the street locations and other man-made landmarks. Alternatively, a topography map could prove more useful as it would give more information on the actual terrain. Knowing limited observational information, such as the relative location of some feature, may allow an operator to successfully navigate an environment about which they know nothing else about. On the other extreme, precise overhead images giving all landmarks and features may be available from an aerial fly-over or from an imaging satellite. Any additional *a priori* information and its usefulness will vary greatly depending on each situation and the vehicle's purpose.

Closely related to the issue of what information is available is how to design the human-vehicle interface. All the information needs to be presented to the operator in a logical and useful format that maximizes the operator's understanding of the vehicle's current situation and environment.

Once issues like these are resolved, tele-operation allows an unmanned vehicle to operate at high velocity through an obstacle rich environment. To better understand the issues related to tele-operation of a high velocity ground vehicle, it is necessary to create experiments that approximate real world situations where certain factors can be held constant while varying others. To do so, however, means concentrating on only a few issues at a time while leaving the others to be dealt with later, or by others.

An experiment was devised to investigate the issue of *a priori* information, in the form of an overhead image, and its usefulness to an operator in navigating an obstacle rich course. As will be explained, of the various issues related to tele-operation, *a priori* environment information is one which is not platform dependent and which can be most easily generalized to almost any unmanned ground vehicle.

1.2   APPROACH

1.2.1   Environment

Currently there are private and government initiatives looking at the use of high velocity unmanned vehicles in outdoor urban settings. For example, the Defense Advanced Research Projects Agency, DARPA, has a Tactical Mobile Robotics, TMR, project which is investigating the use of small unmanned robots for various military missions. Many of these missions are specific to urban settings. Given this interest, and the degree of technical challenge, it was decided to concentrate on the factors involved in navigating an urban setting at high speed.

1.2.2   Available Information

Once a vehicle enters a new environment it can provide the operator with a host of information on the environment. However, what information the operator receives from the ground vehicle is wholly dependent on what sensors are put on the ground vehicle. Usually after the ground vehicle is deployed, it is too late to bring it back and change its sensor package to try to better suit the vehicle to the environment. This is just one reason it would be beneficial to have some *a priori* information on the environment the vehicle will operate in. Any *a priori* information can also be an aid when deciding on a strategy for navigation. Once the vehicle has entered the environment, changes can be made based on any new information gathered. Again, a human tele-operator is better suited for evaluating new situations and making course changes than would the on-board processors of a fully autonomous vehicle.

Figure 1-1 features a block diagram of a generic tele-operated ground vehicle in which *a priori* information is available.

In this figure it is clear that the human operator is at the center of the system. Through the operator station they are presented information on the real world environment that the ground vehicle is located in. This information is derived from the *a priori* information and the sensor information located on board the vehicle, which is presumably updated in real time. While both the on board sensors and the *a priori* information convey information about the real world environment, neither of them can give a complete picture. Any *a priori* information, by the fact that it is not updated after being provided, can suffer from inaccuracies which stem from any changes in the environment that take place after the *a priori* information is gathered. In Figure 1-1 this is represented by the dashed line between the Real World Environment and the *A priori* Information. Through experimentation, an understanding can be obtained on the how a human operator is able to use a specific type of *a priori* information, given its inherent qualities and limitations, in conjunction with the vehicle's sensors, to successfully navigate the local environment.

Real World Environment

A priori Information (Overhead Images)

Errors

Operator Station → Human → Ground Vehicle → Sensors
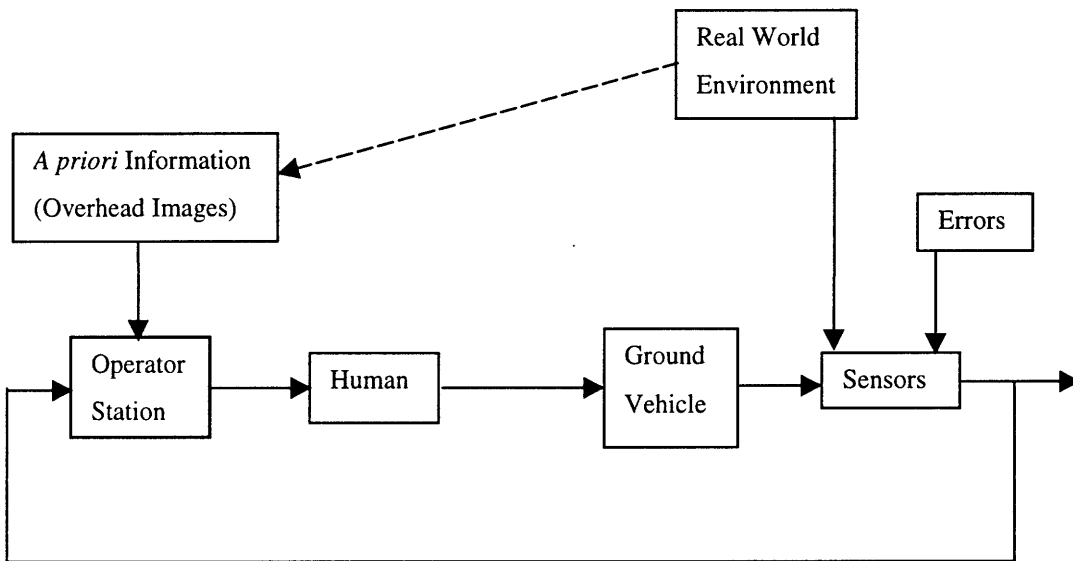
Figure 1-1 Control flow for a tele-operated vehicle for which *a priori* information is available.

One reason that investigation of *a priori* information is of interest is that this information is completely independent of the vehicle specifics. Thus a better understanding of what factors are important in the usefulness of such information can be applied to many different vehicles with different mission profiles.

1.2.3 *A priori* Information

An increasingly important and powerful tool for gathering information on outdoor urban environments are imaging satellites. In the past, various governments have used these "spy" satellites to take detailed images of various strategic targets. However due to changes in technology and in politics, 1 meter accurate images will soon be commercially available. Four separate companies, Aerial Images, Space Imaging, Earth Watch, and Orbimage, have plans to launch 1 meter capable imaging satellites this year [5]. Before satellites, aircraft were widely used to obtain overhead images of sensitive areas. Aerial photography is still a very important source of overhead image information, not just for military purposes, but also for civilian use including agriculture, wilderness management, and urban planning.

Due to the various techniques and companies mentioned above, overhead image information is readily available to a wide assortment of people. For this reason it makes sense to concentrate on the scenario where the *a priori* information would take the form of overhead images of the environment. The images could be obtained in a number of different ways, but the source is not crucial for the experiment.

In an experiment designed to investigate the possible usefulness of an *a priori* overhead image several realities and shortcomings of overhead images must be accounted for. Due to their very nature, overhead images can not give any information as to what might be under other, larger, objects. A highway overpass, or a bridge, blocks information on what lies underneath them. Also there are other significant objects that are just too small from an overhead perspective to be detected. For example, poles or chains blocking a roadway may prevent a ground vehicle from passing, but may be too small to be detected from an overhead image.

The age of the overhead image may also affect its usefulness for navigation purposes. Between the time an image is taken of a location, and the time a ground vehicle tries to travel in this location, much can change. Objects could be added or taken away from the location in this time, altering the optimal course a ground vehicle would take.

The image quality is also of interest. The image resolution will make some objects easier to detect than others. A low image quality can mask the existence of individual features. As mentioned previously, commercially available images are available at the 1 meter accuracy level. However, even higher resolution images may be available from government satellites, or through non-satellite means. Specifically, aerial photography may provide better image resolution from a fly-over than is possible with satellites.

Lastly, for an overhead image to be useful for navigation once the vehicle has entered the pictured location, the operator must have some idea of where the vehicle is. While controlling the vehicle, location knowledge will help the operator make decisions as to which direction to travel. This is especially important when unexpected obstacles are present, or the location otherwise deviates from the expectations derived from the overhead image.

2 SYSTEM IMPLEMENTATION

For the experiment, a ground vehicle was needed to navigate the course. This vehicle had to be reliably controllable through tele-operation and had to also support various sensors. These sensors were used to give the operator information in addition to the overhead image. A schematic system overview is shown in Figure 2-1.
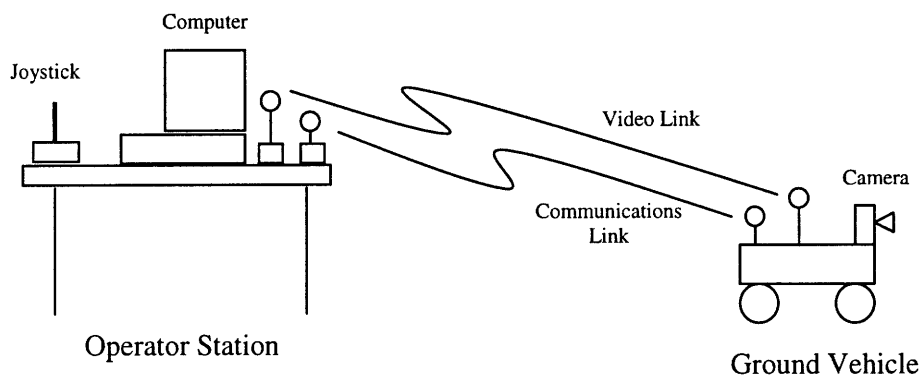
Figure 2-1 System overview.

2.1 GROUND VEHICLE HARDWARE

2.1.1 Platform

The Pioneer AT four wheel rover, pictured in Figure 2-2, made by Real Work Interface, Inc. (RWI) and distributed by ActivMedia Inc. was chosen as a base mobility platform. It was chosen for its sturdy construction, adaptability, and ease of mounting additional hardware. In addition, at a rated top speed of 1.5 m/s, the Pioneer AT was the fastest off-the-shelf microrover available for purchase at the time. Figure 2-3 gives the dimensions of the vehicles and labels the various features and components of the vehicle.
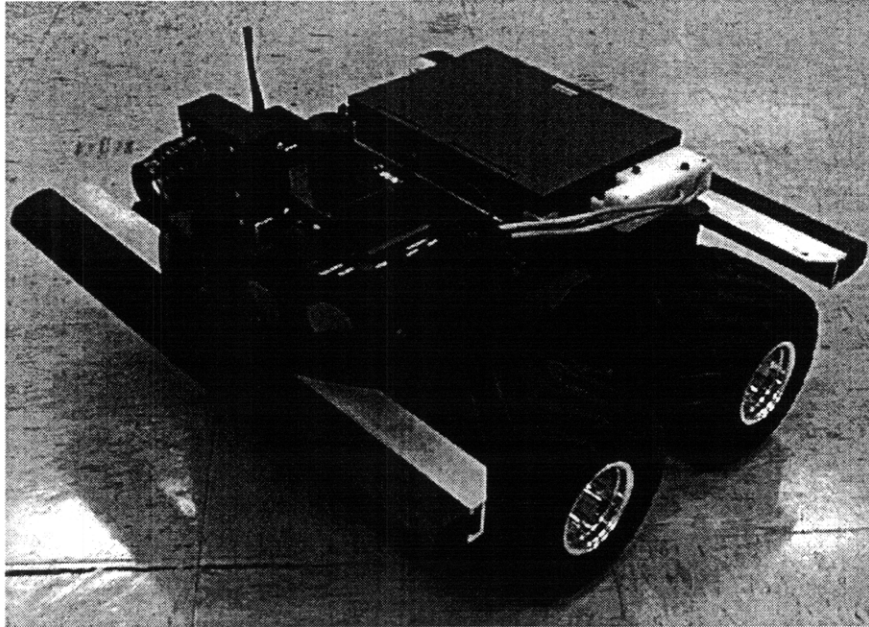
Figure 2-2 Pioneer AT, here equipped with compact laptop and front mounted camera.
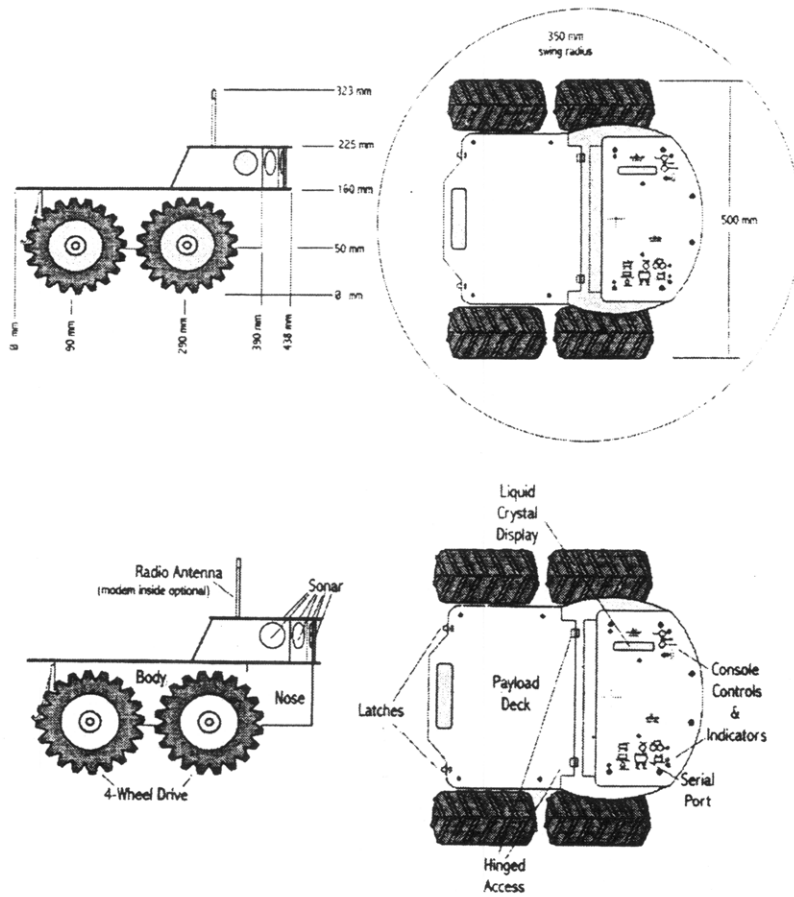
Figure 2-3 Dimensions and Features of the Pioneer AT

2.1.2 Pioneer AT Microcontroller

The Pioneer AT rover comes with a 16MHz Motorola MC68HC11F1 running on a 4 MHz bus. This microcontroller makes commanding the vehicle simple as it controls the following inputs and outputs (I/O):

- Two high-power, reversible motor drivers

- Two position-encoder inputs

- Eight multiplexed sonar outputs

- Eight digital input ports

- Eight digital output ports

- One 8-bit analog-to-digital input port (0-5 VDC at 10 Hz)

- One digital timer output (1 microsecond resolution)

- One digital timer input (1 microsecond resolution)

- One RS232 serial port

2.1.3 Battery

The Pioneer AT was powered by a single 12 Volt DC, 7 A-hr sealed lead-acid battery, providing power for everything within the vehicle except for the video transmitter. As is often the case, in actual use the battery capacity proved to be less then optimal. It was necessary to have several charged batteries ready to swap into the vehicle throughout each run of the experiment.

2.1.4 Motors and Encoders

The Pioneer AT platform is a four wheeled vehicle. Each wheel is driven by a reversible DC motor. The two wheels on each side are synchronized by a toothed belt, thus each wheel spins at the same velocity as the other wheel on the same side. This reduces the possibility of slippage. It also allows differential steering. Differential steering is accomplished by having the wheels on one side of the vehicle spin faster then the wheels on the other side, giving the vehicle a rotational velocity component. If the wheels on each side turn in opposite directions at the same time the vehicle turns in place.

The front motors each have 100 tick per revolution optical shaft encoders. This high resolution allows for an accurate measure of how quickly the wheels are spinning. The MC68HC11 on board microcontroller compares the two readings from the encoders to determine at what speed the vehicle is moving forward, turning, or both.

2.1.5　Sonar

Seven ultrasonic sonar transducers are built into the top console on the Pioneer AT rover. The sonars are controlled by the microcontroller and fire at a rate of 25 Hz, with a range from 10 cm to over 3.5 m. Due to the many errors associated with sonar transducers they often did not return very accurate information which reduces their usefulness for navigation. In actual use they proved useful only to help the operator determine which part of the vehicle had hit a wall or other object.

2.1.6　Bumpers

The Pioneer AT was purchased with optional bumpers. These proved useful in protecting the vehicle during high speed collisions, especially during the testing and debugging period. They covered the entire width of the vehicle, not only protecting the body but also the wheels in the front and back. They also housed switches that allowed the microcontroller, and thus the operator, to know when one of the bumpers had been hit.

2.1.7　Wireless Modem

The communications link between the Pioneer AT ground vehicle and the operator station which allowed tele-operation was implemented with a pair of Proxim 900 MHz, 9600 baud radio modems. One modem was mounted inside the top console of the Pioneer AT and connected to the vehicle's serial port connection to the microcontroller.

2.1.8　Video Camera and Transmitter

To allow the operator to see the immediate environment around the ground vehicle, a camera was mounted on top of the vehicle. The black and white camera had 380 lines of resolution. A pinhole lens was used to allow the operator to have a wide (90 degree) field of view. With the camera mounted on the very back of the vehicle, in conjunction with the pinhole lens, the operator was able to see the front of the vehicle. This proved to be essential for maneuvering

through the course. Being able to see the front of the vehicle relative to the objects on the course the operator could quickly and easily position the rover to go past an obstacle at high speed without colliding with it.

A Plane Talk video transmitter allowed the operator to receive the video signal and see the camera view. This transmitter operated at a 2.4 GHz frequency and gave a very strong signal over a considerable range. To help ensure a strong signal, the video transmitter had an independent power source. By having its own separate batteries, a strong signal strength could be maintained even as the vehicle's 12 VDC lead acid battery drained. The transmitter and its antenna were mounted on the back of the top console not only to allow the antenna to have maximum exposure, but to also be out of view of the forward looking, rear mounted, camera.

2.2 OPERATOR STATION

Successful tele-operation requires an operator station that supplies information in a clear, concise, format that allows the operator to make decisions as to the direction and speed the ground vehicle should travel.

2.2.1 Operator Station Hardware

A pentium class desktop computer was used to run the operator station software. It would be possible to implement the operator station on a laptop for greater mobility, but it was not necessary for this experiment. Connected to the computer was a joystick which functioned as the operator's primary input device.

A Proxim wireless modem was also used to complete the modem pair needed to establish the communications link with the vehicle. A directional plate antenna was used to receive the video signal allowing the operator to see the camera images. The computer had a Hauppauge TV tuner card to allow it to process and display the video signal from the video receiver connected to the plate antenna.

2.2.2   Operator Station Software

Figure 2-4 shows the graphical user interface used during the experiment. This screen capture image was taken when the vehicle was being tested in the Charles Stark Draper Laboratory courtyard.
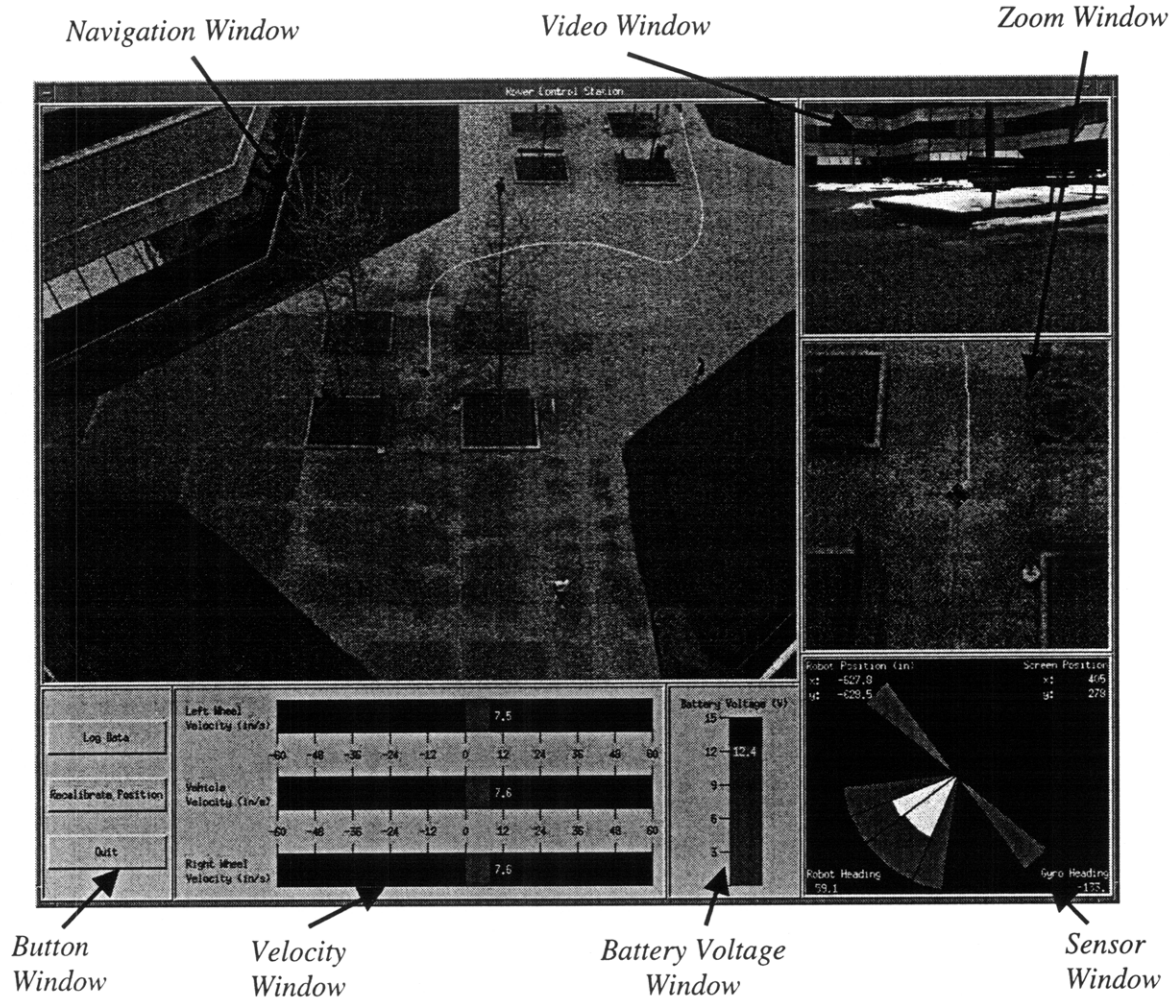
Figure 2-4 Screen shot of the graphical user interface (GUI) used on the operator station during testing in C.S. Draper Laboratory courtyard

This interface uses the entire computer screen and has 16 bit video depth allowing 65536 simultaneous colors. The resolution is set at 1152x864 pixels. This graphical user interface (GUI) refreshes at about 8.4 Hz, except for the video window which refreshes at the higher rate of 60 Hz, due to the Hauppauge tuner card's special hardware that writes directly to the computer's video memory.

Navigation Window

The navigation window is the largest window and is where a previously generated overhead image is displayed. It is 800x600 pixels in size and contains the overhead image, and several computer-generated graphical elements. Each of these are demonstrated in Figure 2-5. The most important graphical element is the rover icon. The icon is scaled in size to match the scale of the overhead image and represents the location and the direction that the rover is currently pointing.
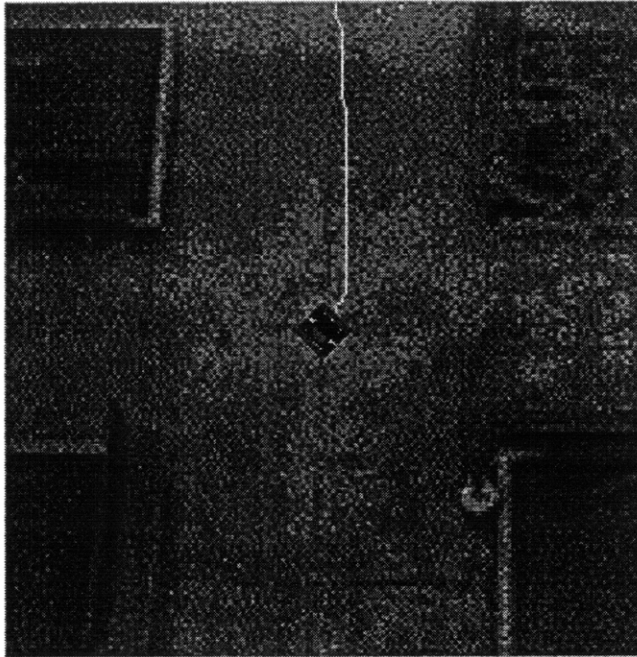
Figure 2-5 Rover icon and trail.

To allow the user to easily tell the direction the rover is pointing, a colored rectangle on the icon represents the raised console on the actual vehicle. This rectangle is gray when the base station is started, but turns red once the rover has established a communications link with the operator station. This allows the operator to easily know when they can start commanding the vehicle to move. The icon also shows the vehicle's bumpers. The icon's bumpers are black unless the vehicle's bumpers are registering contact in which case the icon's bumpers turn red and an audible tone to alerts the operator. As the rover travels, and the icon moves, the station draws a yellow line representing the last 1000 position locations of the rover. These position locations are determined by the vehicle's microprocessor, using dead reckoning with the left and right wheel velocity values. This effectively creates a solid yellow line that shows the path the ground vehicle has recently traveled.

Zoom Window

During the actual experiment the zoom window was not necessary and was blacked out. This window is normally used when the overhead image covers a very large area. When this is the case, the small scale makes it very difficult to see the rover icon and to navigate. With the zoom window, the user is given a view in which each pixel represents one inch no matter what scale the overhead image has. Therefore, the rover icon is a large size and it is easier for the operator to guide the vehicle around nearby obstacles. The zoom window is 320x320 pixels.

Video Window

Video from the vehicle's onboard camera is shown in the GUI's video window. This window is located in the upper right hand corner and is 320x240 pixels. This window is updated at 60 Hz giving a continuous and smooth view from the camera. This is especially important for operation at high speed where there can be little or no delay between what the vehicle sees and what the operator sees. Any delay would make tele-operations difficult, and nearly impossible at high speed.

Sensor Window

The sensor window is located in the lower right hand corner of the GUI. It is 320x245 pixels and presents the operator with information from the vehicle's sonars and bumpers. Sonar output is presented as sensing cones, one per sonar. When there is no echo reported from that sonar, its cone is gray. If the sonar receives an echo its cone is colored yellow an amount corresponding to the distance of the echo. If the echo indicates something is far away the cone is mostly yellow, as the object is closer the cone gets shorter and shorter. If the sonar echo is within 30 cm the entire cone is colored red to alert the operator. The seven cones rotate to match the vehicle's heading, which helps the operator keep track of the vehicle orientation.

If the front bumper is compressed, a section of the sensor window turns red. An audible tone is also used to alert the operator that the vehicle is pushing against a stationary object. If the rear bumper is compressed a different section of sensor window turns red and the same tone is heard.

Battery Voltage Window

The Pioneer AT is a battery operated vehicle. In addition to powering the motors, the battery also powers the onboard microcontroller, video camera, sonars, and wireless modem. As

the battery starts to run down, the large current draw of the motors would cause the voltage to spike low for small amounts of time. However this would be enough to disrupt the electrical components. During the experiment it was important to ensure that such disruptions did not occur. To help, the battery window was created to make it easy for the operator to see the voltage level. The window has a simple display that shows a bar of varying height corresponding to the battery voltage. When the voltage is at a safe level, above 12 volts, the battery voltage bar is green; as the voltage goes below 12 volts, the bar turns read. This is an important feature as the color change makes it easy for the operator to notice when the voltage spikes to low levels, even when the spike is too short for the operator to be able to read the temporary voltage level. Just by seeing the color change it is clear that the voltage level is spiking low, and that there is a risk that various components of the electrical system may reset.

Velocity Window

Three colored horizontal bars show the vehicle's speed in a 516x215 pixel velocity window. The bars show the velocity of the left wheels, the translational velocity, and the velocity of the right wheels. Forward velocity is shown with green bars and rear velocity with red bars. By showing these three velocities separately the operator has confirmation of the vehicle's direction of travel. If the right and left wheels travel at different velocities then the vehicle is executing a turn through differential steering. If the left and right wheels are traveling in opposite directions, then the vehicle is turning in place, as described earlier.

Button Window

For purposes of the experiment all program functions were prepared before each subject started, and thus the buttons in the button window were disabled

3   EXPERIMENTAL DESIGN

3.1   SETUP

With a ground vehicle and an operator station built and tested, an experiment was designed to investigate the effects of *a priori* overhead image resolution on the navigation performance of an unmanned ground vehicle. In the experiment each subject was asked to navigate through an obstacle course as quickly as possible. Each subject navigated three obstacle courses with either a high, medium, or low resolution overhead map. The obstacle courses were presented to the subjects in the same order, but the order in which they saw the different resolutions was counterbalanced. The images and courses were designed to have the same types of issues that real overhead images and outdoor urban environments would present to an operator. These issues are described in greater depth later in this chapter. The obstacle course was constructed indoors. Conducting the experiment indoors simplified the setup and increased the repeatability of the experiment for each subject.

3.2   PROCEDURE

Each subject was brought into the room where the experiment was conducted, though there was a large paper shield to prevent them from seeing the obstacle course. They were first asked to fill out the biographical section of a questionnaire which asked their age, gender, and previous experience with remote controlled vehicles and arcade games. To mitigate any learning curve effect associated with acquiring some familiarity with the rover and its driving characteristics, each subject was given time to practice driving the vehicle. As part of the training process, they were specifically instructed to practice turning the vehicle in place. During this practice time, they drove the vehicle while watching the vehicle only, then while watching the vehicle and looking at the operator station, and lastly while only looking at the operator station. The operator station provided them with an overhead image of the obstacle course and a real time video image

from the vehicle. During the practice time each subject was exposed to the different types of obstacles and features they would encounter within the obstacle course. They also got to see how the various obstacles were depicted on the overhead images.

Figure 3-1 has an actual high resolution overhead image the operator was given with the various obstacles labeled. They were instructed to try to complete each obstacle course as quickly as possible without colliding with the walls or any other part of the course except for the goal, a large red traffic cone. Once they touched the traffic cone they were done with the course and gave no further commands to the ground vehicle. For each course the operator was given as much time as they wanted to study the overhead image. Once they were ready they pressed the space bar to start the data logger and then proceeded to navigate the course. After completing each course they then filled out another section of the questionnaire with regard to their experience with that course and waited in another room while the next obstacle course was set up.
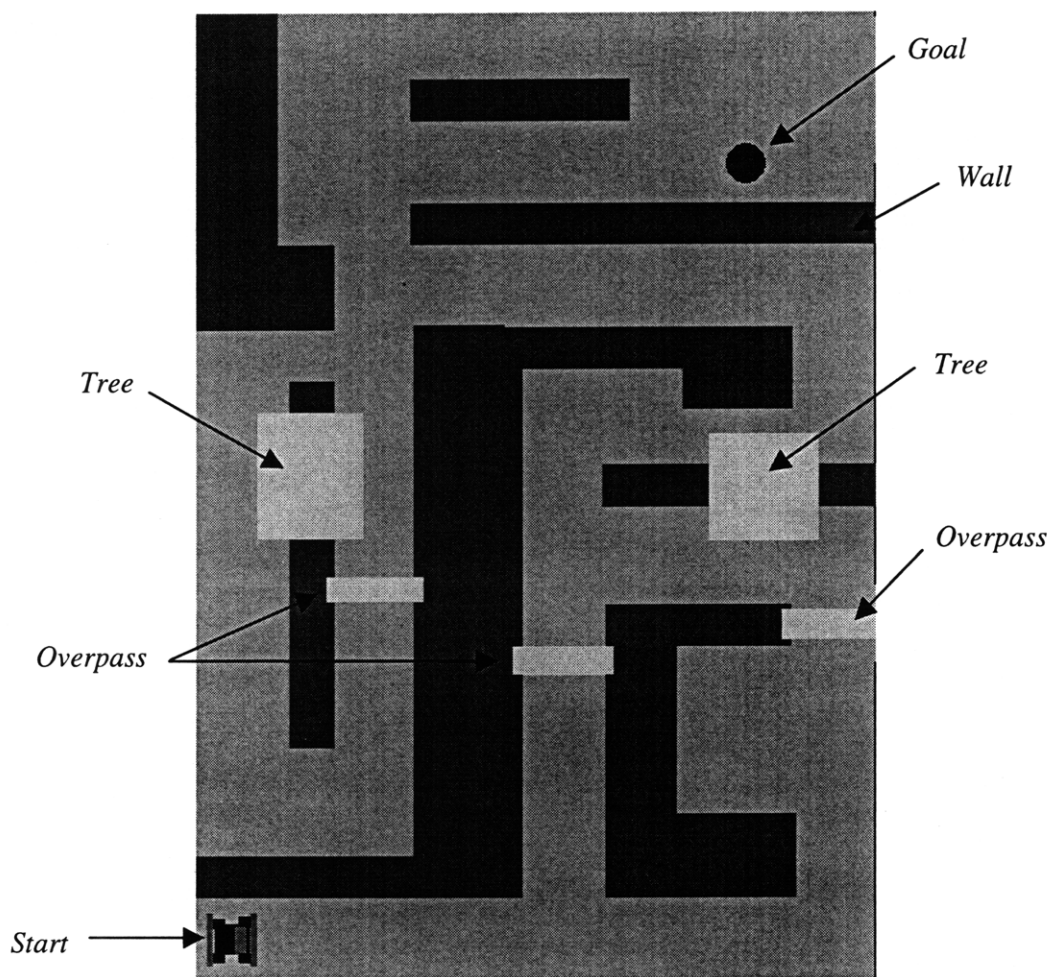
Figure 3-1 High resolution overhead image as presented to operator with obstacles and other features labeled.
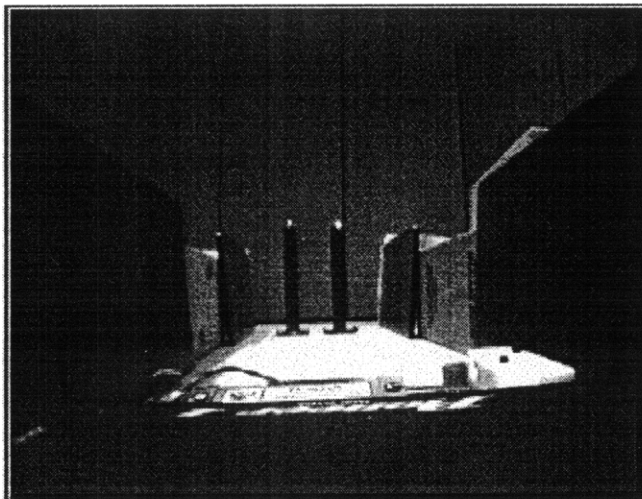
3.3   OBSTACLE COURSES

3.3.1   Course Features

Each of the three courses were primarily composed of various walls. In addition to walls there were other features corresponding to real world obstacles that a ground vehicle may encounter. As discussed earlier, one of the issues being investigated is how well the operator is able to use the overhead image when the image has various inaccuracies. The course was designed to demonstrate the different urban environment features and corresponding overhead image inaccuracies to the operator.

Poles

On the actual obstacle course there were poles that blocked some routes. These poles were never depicted on the overhead image, thus the operator never knew when or where to expect them. The poles were examples of obstacles that may not appear on an overhead image due to their small overhead profile, but which nonetheless proved to be major hurdles. This was the case because they blocked what would ordinarily appear to be viable paths for the vehicle. Each maze contained at least one set of poles. Figure 3-2 shows how poles appeared to the subject through the video camera

Figure 3-2 Two poles as they looked to the operator in the video window.

Trees

Another feature of the obstacle course were objects that approximated trees. These objects appeared to be very large from the overhead view, however they did allow space for a ground vehicle to pass underneath them. Like trees, they did block out a significant amount of light underneath, and also adversely affected the wireless communications link due to a shield effect caused by their large area. These are all properties that a tree might have in a real-world outdoor environment. The trees were constructed out of flat cardboard boxes supported on their sides by walls, creating the tree effect. The operator knew that if they chose to, they could always pass under a tree. Trees were always depicted on the overhead image as a light gray square so the operator also always knew where they were located. Figure 3-3 shows a tree.
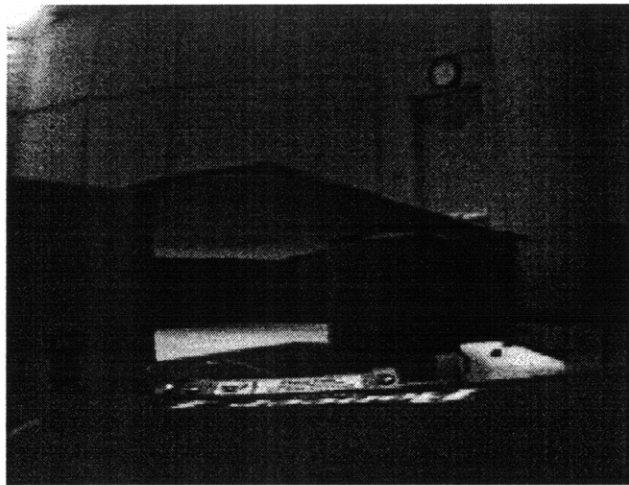
Figure 3-3 Tree.

Overpasses

Overpasses are another limitation of overhead images that was investigated. There were two types of overpasses, blocked and unblocked. An unblocked overpass allowed the ground vehicle to pass underneath it unimpeded, whereas a blocked overpass did not allow the vehicle to pass. They appeared identical on the overhead image and were always depicted as light gray rectangles. Thus the operator, when studying the map, could see where overpasses were located, but could not tell from the map alone if they were blocked or not. This could only be known by looking underneath the overpass with the vehicle's camera. These obstacles represent the very real limitation of using overhead images, namely the uncertainty of what may actually be located underneath other objects such as overpasses. They were made out of boxes that were laid on walls across passageways as shown in Figure 3-4. Since they were small, they did not block

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much light or interfere with the video signal. For the blocked overpasses, poles were placed on their sides underneath them, effectively blocking the vehicle from passing.
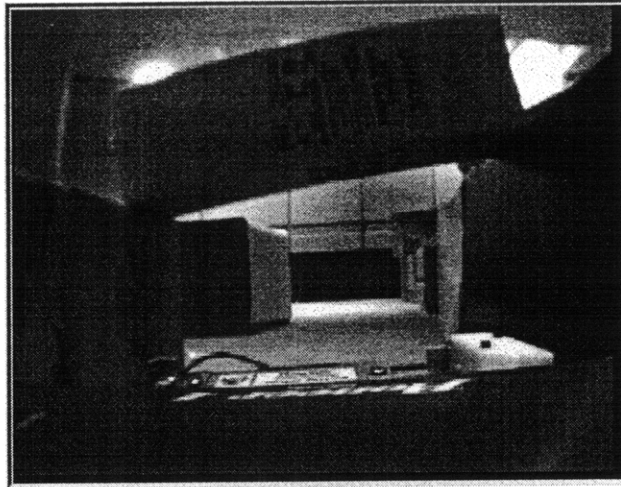
Figure 3-4 Overpass.

Wall Holes

Another inaccuracy in the overhead image was that some walls shown as being solid, in fact had holes in them that were large enough to allow a ground vehicle to pass through them, as pictured in Figure 3-5. This approximates the situation where the overhead image may be out of date so that it does not show the current reality of the environment that the vehicle traverses. This is the opposite of poles which block viable routes. With wall holes the user was not expecting them, but they provide viable routes. The operator had to decide to take advantage of them or not. Wall holes are different from overpasses because the operator never knew *a priori* where a wall hole was located.
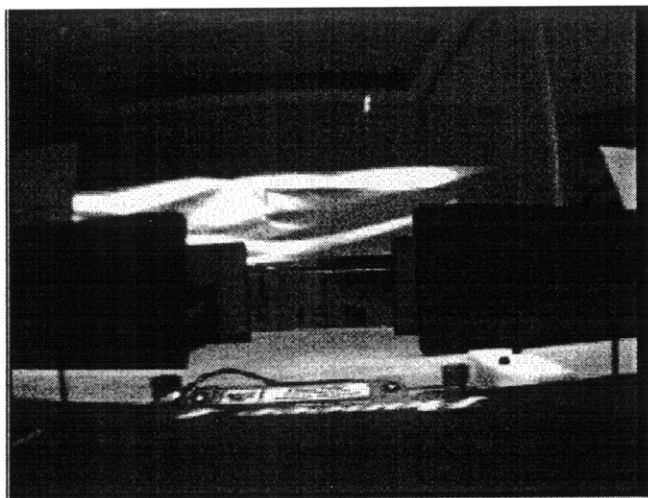
Figure 3-5 Wall hole.

3.3.2   Course Layout

Each of the three courses was carefully designed. First, all of the viable travel paths for the vehicle were made 3 feet wide to allow ample space for the vehicle to travel. During testing it was found that if the paths were perceived as too narrow, operators were reluctant to send the rover down them at full speed for fear of hitting one of the walls.

The courses were also designed so that they shared a common framework, constructed out of tables, but had enough different features, constructed of boxes, such that each course was unique, and so that knowledge of one course did not help the subjects navigate another. This effect was aided by changing the starting and ending points, relative to the common framework, for each course.

The courses were designed such that it would be clear when the operator did not see one of the course features mentioned above. However, the most important feature of the course layouts was that no matter which path the operator chose to take, they were presented with the same types of obstacles. Thus in each course the operator would see a tree, poles, a hole in the wall, and overpasses, no matter which route was chosen. This is illustrated in Figure 3-6 which gives a detailed map of the actual obstacle course, in contrast to Figure 3-1 which is the high resolution overhead image as the operator saw it.

As shown on the figure the ground vehicle starts (depicted here as a white triangle) in the lower left hand corner. The dashed white lines show possible paths for the ground vehicle. After proceeding for a short distance the operator is presented with an unexpected hole in the wall at point A. At this point they can pass through the hole in the wall or continue straight. If they go through the hole they reach point B where they should be able to see that the overpass is blocked. If they proceed straight to point C it is clear that they have not looked at the video screen to see the blockage under the overpass. To proceed from point B they should head towards point D, at which time they can decide to go under the tree to save some time or to proceed to point E where they will need to stop and turn in place, which takes more time. Either way they will get to point F where they can turn to reach the goal. If they go down the path towards point G it is clear that they have not used the video window to notice the poles blocking this path. Again, the poles are not shown on the overhead image given on the operator station. To reach the goal they have to proceed to point H and down the second path. So by choosing to go through the hole at point A the subject has seen a hole in the wall, an overpass, a tree, and poles.

Figure 3-6 Actual Course Two with possible paths shown with dotted white lines and decision points labeled with letters.

Back at point A, if they had proceeded straight to point I they would be presented with the same dilemma as at point B, where if they use their video window they should see the blocked overpass and not waste time heading down this path to point J. From point I they either have to go back to point A, or proceed to point K. Here they can then go under the overpass to point L where they are given the opportunity to go under the tree, again saving time, or proceed around. In any case they will arrive back at point F. Note that they have to travel some distance to get to point F, which is why it is shorter to go through the hole in the wall at point A. If they do go down this route they again have seen a hole in the wall, an overpass, a tree, and poles.

3.3.3   Basic Course Construction

The courses were constructed out of conference tables put on their side and cardboard boxes. The boxes were used because they give a solid presence when viewed with the vehicle's video camera, yet are light enough to be easily moved. This is important as it allowed one basic framework constructed out of the heavy tables, to be adapted and changed to be completely different and form three separate obstacle courses. Figure 3-7 has a picture of one of the courses.


Figure 3-7 Course Three.

3.4   OVERHEAD IMAGE RESOLUTION

Three distinct resolutions were used for the overhead images presented to the operator at the base stations. The high resolution image used all the pixels available from the operator station monitor. This corresponded to an exact, or perfect overhead image where each pixel represented 0.018 meters. The medium resolution gave 0.5 meter accuracy. Thus each distinct pixel was 0.5 meters on each side. This caused some distortion, but each feature was still easily distinguishable. Low resolution in this experiment had 1.0 meter pixels. This corresponds to image qualities available through commercial satellite imaging services, but it should be noted that the course was on a smaller scale than a real urban environment. These maps showed significant degradation in image quality and at this resolution features become very difficult to distinguish. The medium and low resolution maps were generated with computer software that divided the high resolution map with grids whose boxes were medium and low resolution pixel

size. The software then colored each block according to the average color of all the pixels in that box, creating new larger pixels. Figure 3-8 shows the high, medium, and low resolution overhead images, as seen by the operator, for course two. All the images for courses one and three are given in appendix A along with maps showing the location of wall holes and poles.
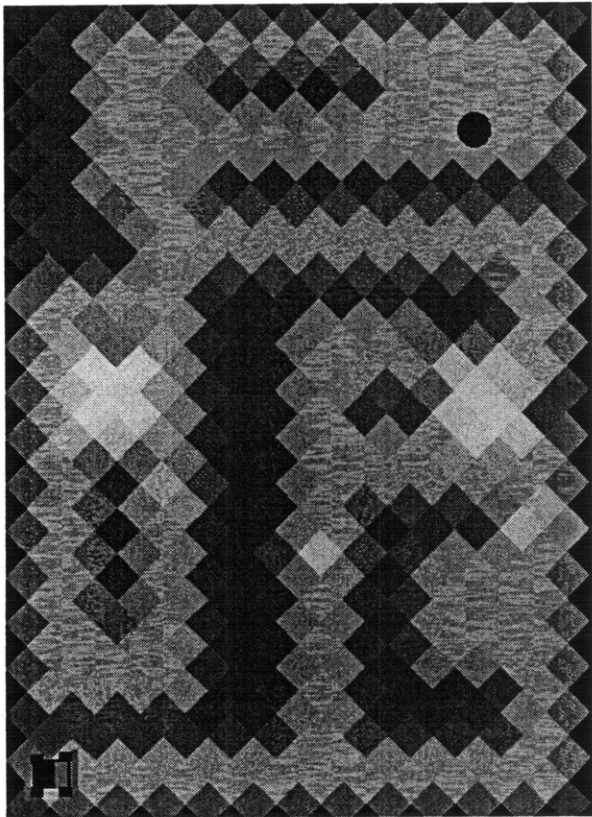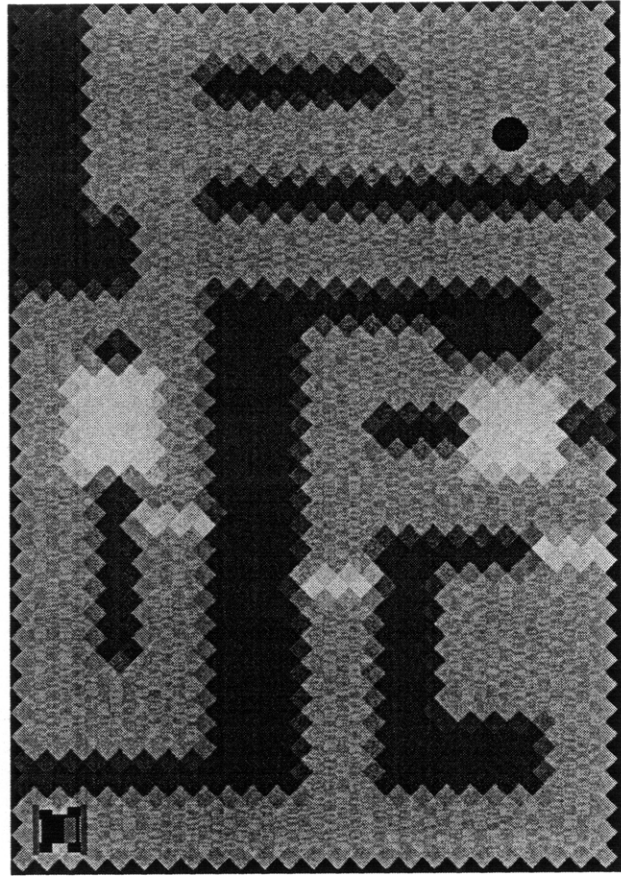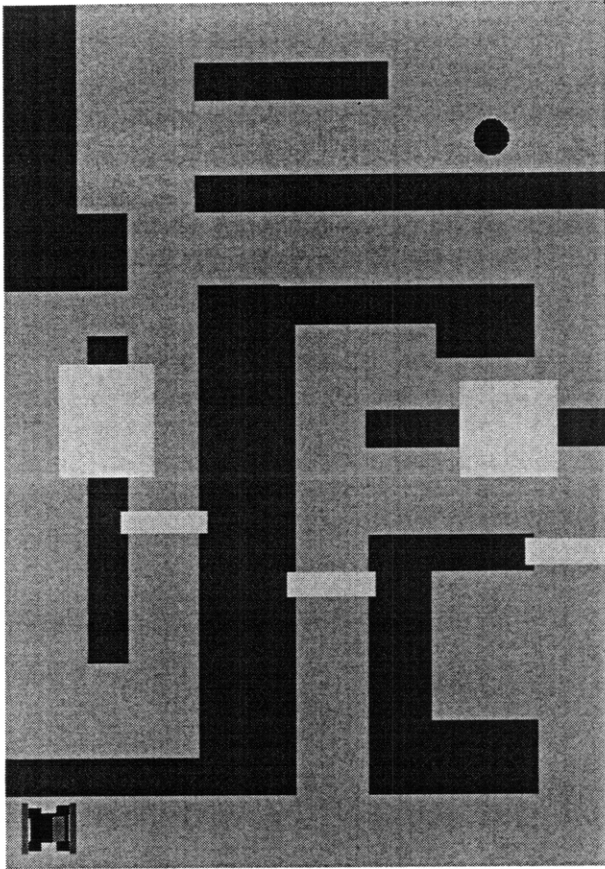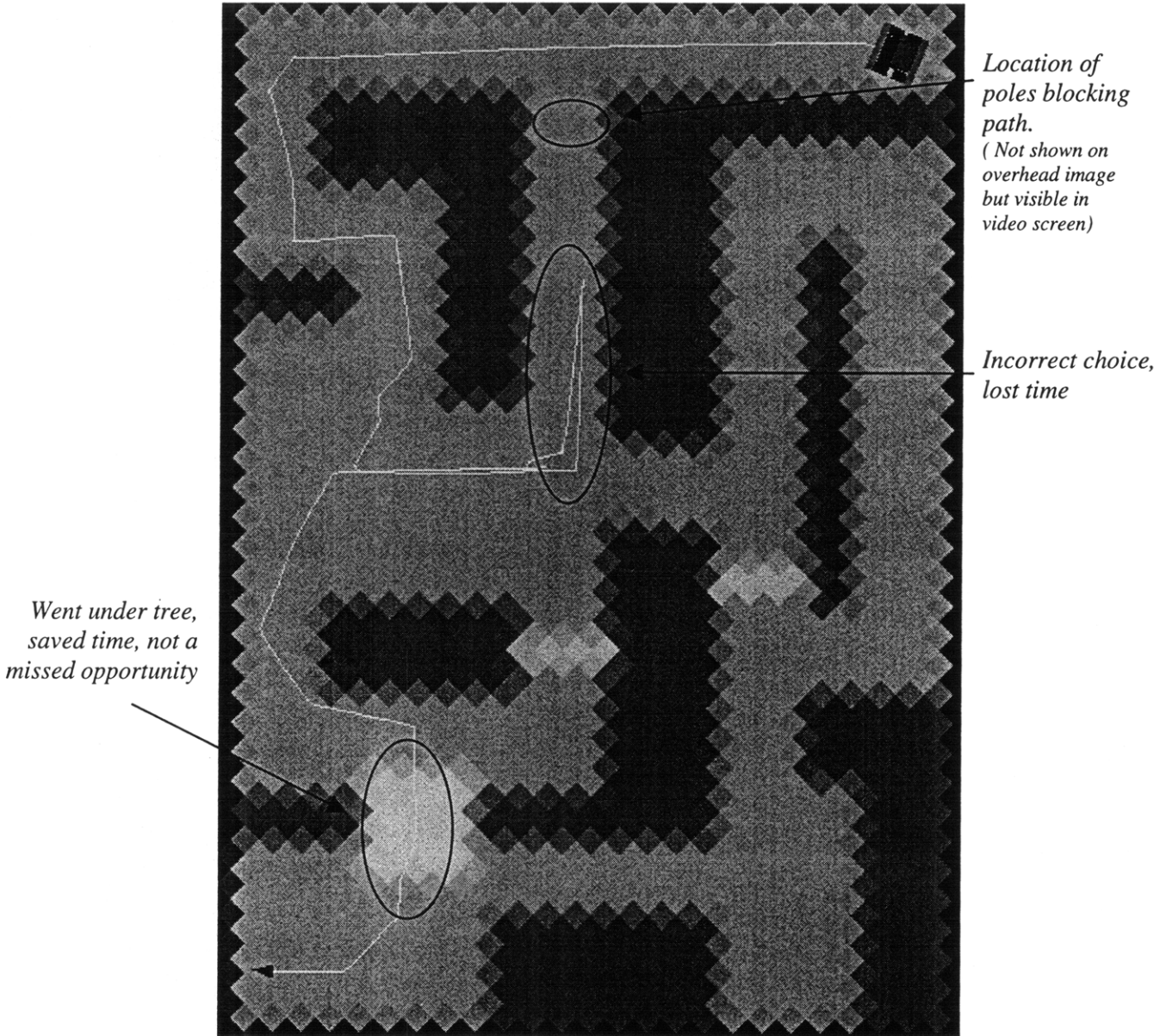
Figure 3-8 Map Two in High Resolution (Top
Left), Medium Resolution (Top), and Low
Resolution (Left)

4 RESULTS

Each time the operator navigated through a course, the operator station recorded the time, x position, y position, heading, left wheels' velocity, right wheels' velocity, and the commanded velocity and heading. With this information the operator's time to navigate through the course and their chosen path is very clear. With the heading data it is also easy to tell when the operator rotated the ground vehicle in place to look with the camera, even if the ground vehicle did not change positions.

By looking at the vehicle's path and the heading during each course, the number of incorrect path choices and missed opportunities the operator had can be determined. Figure 4-1 shows a screen capture after one subject navigated a course. It is clear that the operator did not use the video screen to notice the poles indicated in the figure. Since poles were never shown on overhead images, the only way to detect them was by seeing them through the vehicle's on-board camera. By concentrating on the overhead image and neglecting the video window, the subject proceeded down a blocked pathway until the vehicle was much closer to the poles. This would be categorized as an incorrect choice and cost time as the subject then had to back-track. They did go under the tree at the beginning of the course, saving time. Had they not done so, this would be categorized as a missed opportunity. For each time an operator navigated through an obstacle course, the time to complete the course and the number of incorrect choices and missed opportunities are of interest.

Six subjects completed the experiment. The subjects were graduate students with an average age of twenty. Each subject navigated through the three different courses in the same order, however the resolution of the corresponding overhead image they had was counterbalanced as shown in Table 1. This table also gives the amount of time it took, in seconds, for each subject to navigate each course.

Location of
poles blocking
path.
(Not shown on
overhead image
but visible in
video screen)

Incorrect choice,
lost time

Went under tree,
saved time, not a
missed opportunity

**Figure 4-1 Sample run showing incorrect choice caused by under
utilization of video window.**

	Course One	Course Two	Course Three
Subject A	High 69	Medium 69	Low 73
Subject B	High 77	Low 340	Medium 111
Subject C	Medium 113	High 82	Low 143
Subject D	Medium 220	Low 279	High 96
Subject E	Low 86	High 108	Medium 145
Subject F	Low 143	Medium 104	High 131

**Table 1 Image resolution and time to navigate
course, rounded to the second, for each subject.**

4.1   COURSE COMPARISON

The different courses were designed to be of roughly the same difficulty. To verify this, the time data given above was analyzed to see if there is a significant difference between the time to navigate the three courses. The average time to navigate course one was roughly 118 seconds, 173 seconds for course two, and 117 seconds for course three. A paired T test on the time data was performed to compare course one to course two, course one to course three, and course three to course two, to see if there was any significant difference in the time it took the subjects to navigate the courses. The difference in navigation times between the courses were not statistically significant ($p > 0.05$). This confirms the original goal: to make the courses roughly equivalent in terms of navigation time and difficulty.

4.2 RESOLUTION COMPARISON

4.2.1 Time

The bar graph in Figure 4-2 is based on the same time data as Table 1, and shows the effect of image resolution on completion time. When navigating courses using an overhead image at the lowest resolution, the average time is nearly double the average time for navigating with the high resolution overhead images. Also, the lower the overhead image resolution, the larger the range of completion times. This can be seen best by comparing the standard deviation of the completion times for each of the three resolutions. The standard deviation for the low resolution image completion times is twice that for the medium images and nearly four times as great as those with high resolution.
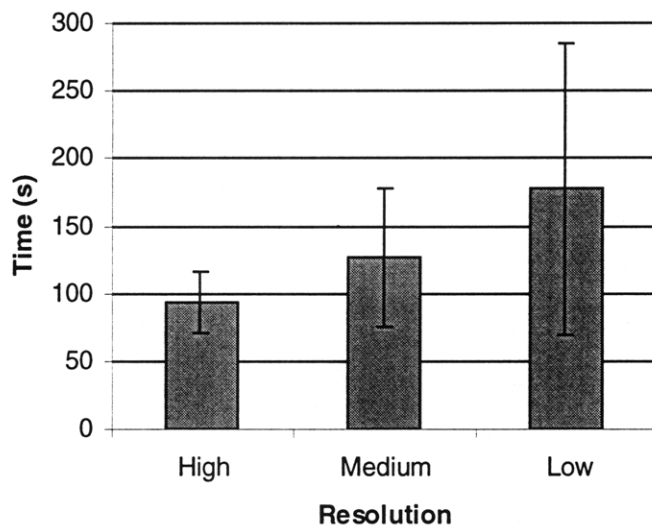

Figure 4-2 Average time to navigate course, in seconds, for each of the different types of image resolution. Standard Deviation bars for each resolution is also given.

A paired T test on the different resolution time shows that there is a statistically significant difference between the completion times for the high resolution images and the medium resolution images ($p < 0.05$). A paired T test between the high resolution times and the low resolution times also show a statistically significant difference between them, but at a lower confidence level ($p < 0.10$). Higher significance between high and low resolution can not be shown due to the large standard deviation of the low resolution times. There was no statistically significant difference between the times with medium resolution and low resolution images.

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4.2.2　　　　Missed Opportunities and Incorrect Decisions

While all operators did fairly well with the high resolution overhead images, they reacted differently to the medium and low resolution images. These differences can be best seen and understood by looking at the actual mistakes which were made.

As explained before, a missed opportunity is when an operator ignored a route or a short cut that would diminish the time to navigate the course. An incorrect decision is when the operator headed down a certain path when it was clear, usually from the video screen, that this path was not a viable route to the goal. Figure 4-3 gives a summary of the number of these errors that occurred for the high, medium, and low resolution overhead images.
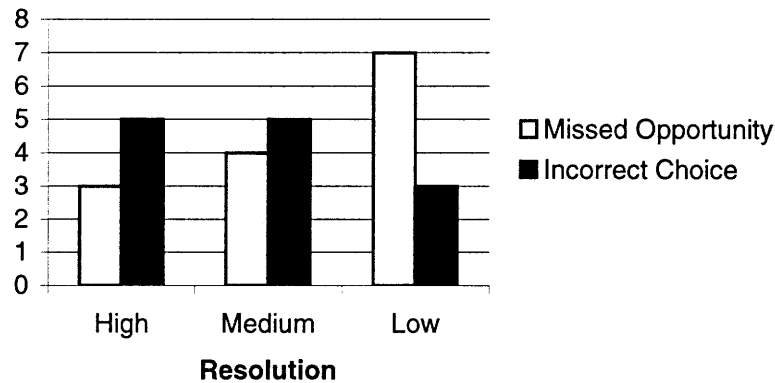
Figure 4-3 Number of Missed Opportunity and Incorrect Choice errors by each subject for the various resolutions.

Figure 4-3 confirms comments made by several of the subjects in the post-experiment questionnaires. With the low resolution overhead images, many subjects relied more heavily on the video screen. This affected how they controlled the ground vehicle, which types of mistakes they made, and how quickly they could navigate obstacle courses. With the low resolution overhead image many subjects found it hard to figure out exactly where they were on the obstacle course. Often they would have to stop and study the course map and compare it to the video screen to determine exactly which features on the map corresponded to which features in the video screen. This was especially true with holes in the wall as they were unexpected and could look like entrances to regular pathways. Many subjects said later that they made the conscious choice to try to stay on pathways which were still discernable on the low resolution map, than to try to take advantage of any features like trees or overpasses. This is the one reason why the low resolution times were longer, and why the low resolution images produced the most missed opportunities.
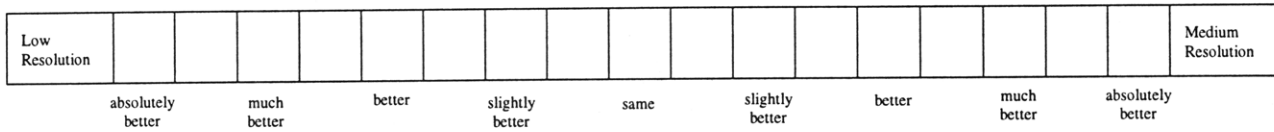
Another point of interest is the lower number of incorrect choices made when using the low resolution overhead image. By relying heavily on the video screen when given a low resolution overhead image, the subjects had the lowest number of incorrect choices. By concentrating on the video screen they were quickly able to see poles or blocked overpasses and were able to compensate.

In contrast, when using the high and medium resolution overhead images the subjects had fewer missed opportunities, but more incorrect choices. This stems from the fact that subjects indicated they were more comfortable and trusting of the overhead images since the resolutions were better and features were easily distinguishable. Thus they spent more time watching the icon on the overhead image than they did examining the video window. Several subjects commented that with the good overhead images they would use the video screen to help navigate turns but would rely on the overhead image for straight segments and making decisions. This led to cases where subjects missed obstacles that were clearly blocking their path because they had already decided to head down that path based on the overhead image. Figure 4-1 shows a good example of a subject doing this.
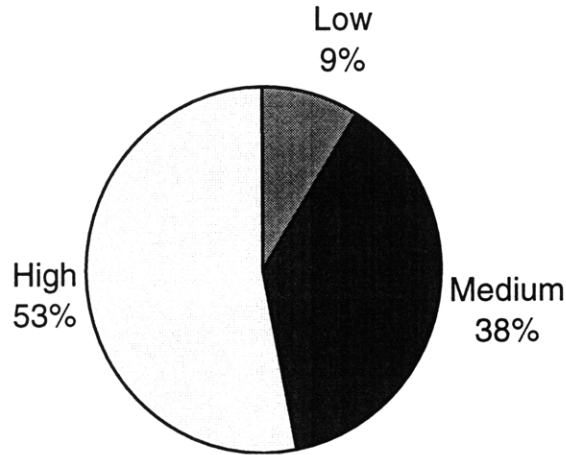
The completion times with the higher resolutions were still better than with the low resolution because even with an incorrect choice, it usually did not take too much time to reverse and go in another direction. Missed opportunities cost more time, and these were more likely with the low resolution images.

4.2.3   Operator Preference

After completing the experiment, subjects where asked to compare the different resolutions as part of an analytic hierarchy process [6]. This is done by asking them to place a mark on a scale where being equally useful is in the center, and one being more useful on the left side of the scale and another being more useful is on the right. An example of this scale is shown in Figure 4-4. The results of the analytic hierarchy process are given in Figure 4-5.

Low Resolution															Medium Resolution
	absolutely better		much better		better		slightly better		same		slightly better		better	much better	absolutely better

Figure 4-4 Selection Scale for Low Resolution versus Medium Resolution.

Low
9%

High
53%

Medium
38%

Figure 4-5 Pie Chart showing relative operator preference for overhead image resolution.

The high resolution image is the most preferred, however it is of interest to note that the high and medium resolutions are close in value, especially compared to the low image resolution. This corresponds to the fact that a similar number of errors were made by subjects with both types of resolutions.

5 CONCLUSION

The results give valuable insight into the use of *a priori* information for navigation of a high velocity tele-operated unmanned ground vehicle. Given an *a priori* overhead image, subjects were able to navigate an obstacle rich environment. The resolution of the overhead images had an important impact on not only how quickly the course was navigated, but also on what types of mistakes were made.

The data shows that the lower the resolution, the longer it took to navigate the course. This was due to an increase in missed opportunity mistakes and also to a decrease in confidence in knowledge of the immediate environment and how it corresponded to the *a priori* information. On a fundamental level, the decrease in resolution caused operators to use and trust it less than the higher resolution images. They shifted to rely more on the video screen which changed the nature of how they operated the vehicle and their strategies for navigating the obstacle courses.

The medium and high resolution images were seen by many operators as being equivalent in their usefulness. This is demonstrated by the fact that similar types, and number of, mistakes were made with both resolution types. Operators were able to navigate the course faster with the high resolution image. This may partly be due to the increased confidence that several subjects claimed to have when using the high resolution image. However this confidence did lead to certain missed opportunity mistakes. These mistakes could have been avoided by more attention being paid to the video screen showing the actual environment in front of the ground vehicle.

Thus, it is not always the case that higher resolution is better. In a real world environment an *a priori* overhead image that is of high resolution, but out of date so that it is not very accurate, could lull the operator into a false sense of trust in the overhead image. In cases where the *a priori* overhead image is known to be dated, it may be better to degrade its resolution to reinforce to the operator that it can not be completely trusted.

While this work has shown that *a priori* information can be useful, it has also shown that there are nuances in its use and its effect on the operator. Further study would prove useful in obtaining a better understanding of these subtleties. An experiment with more subjects may show if the time to navigate with low resolution is indeed statistically significantly higher than the time with medium or high resolution images. It is also important to actually conduct real world trials
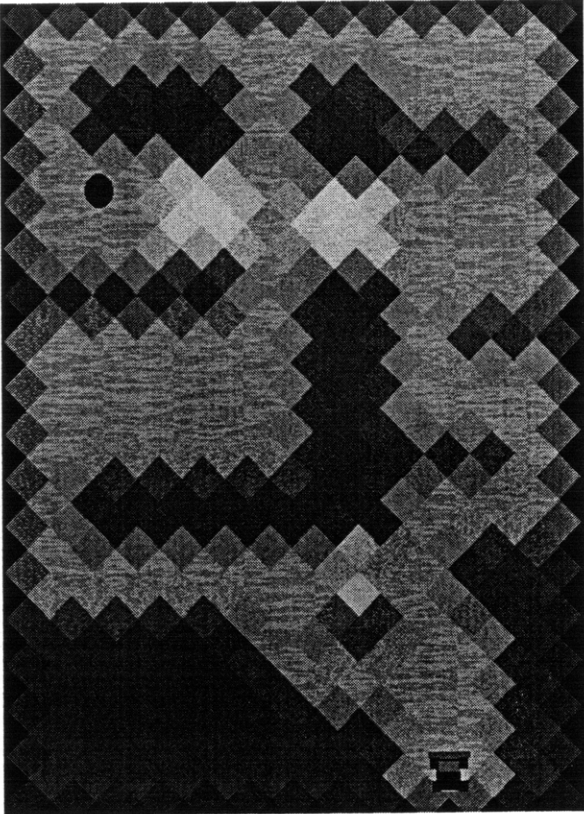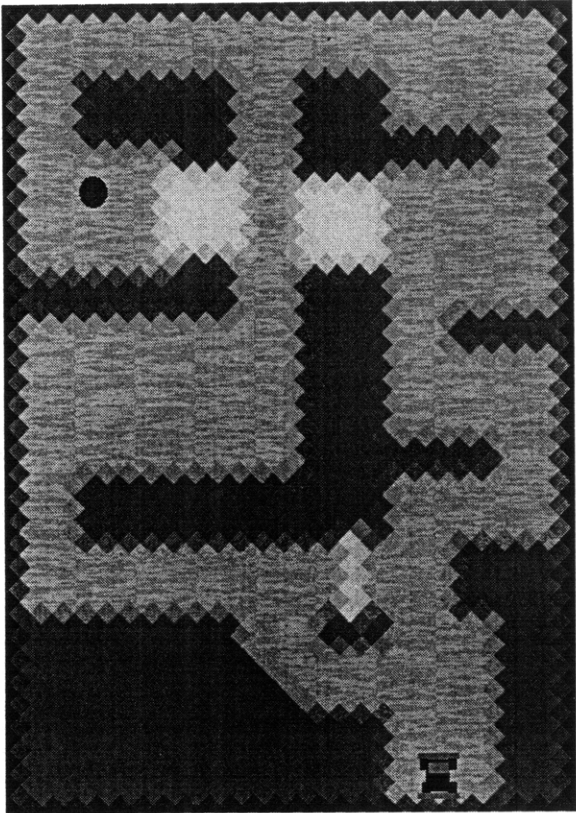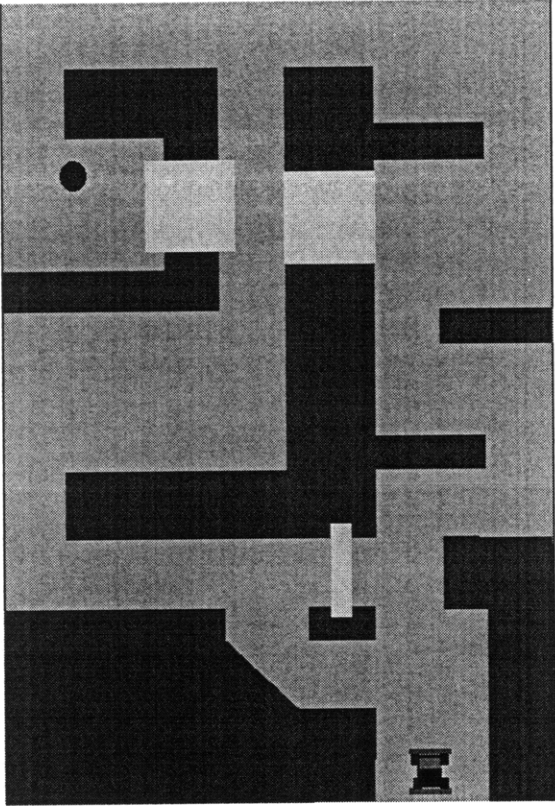
of any proposed tele-operated high velocity systems outdoors. For experimental purposes it was expedient to conduct trials indoor to ensure repeatability. For precisely this reason, the unpredictability of the outdoor environment, real world trials and experiments are necessary.
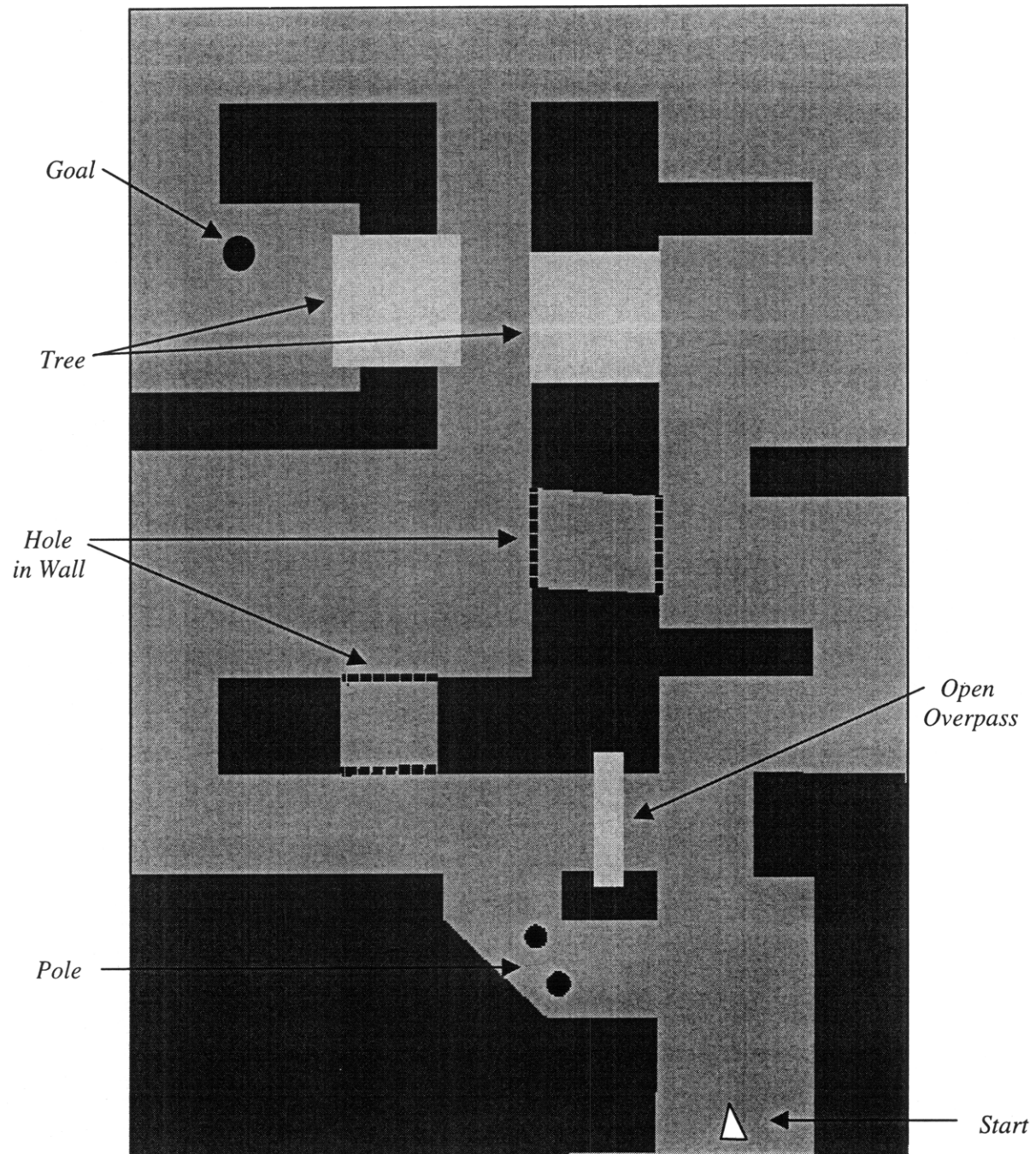
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Appendix A

Course One in High Resolution (Right), Medium
Resolution (Bottom), and Low Resolution
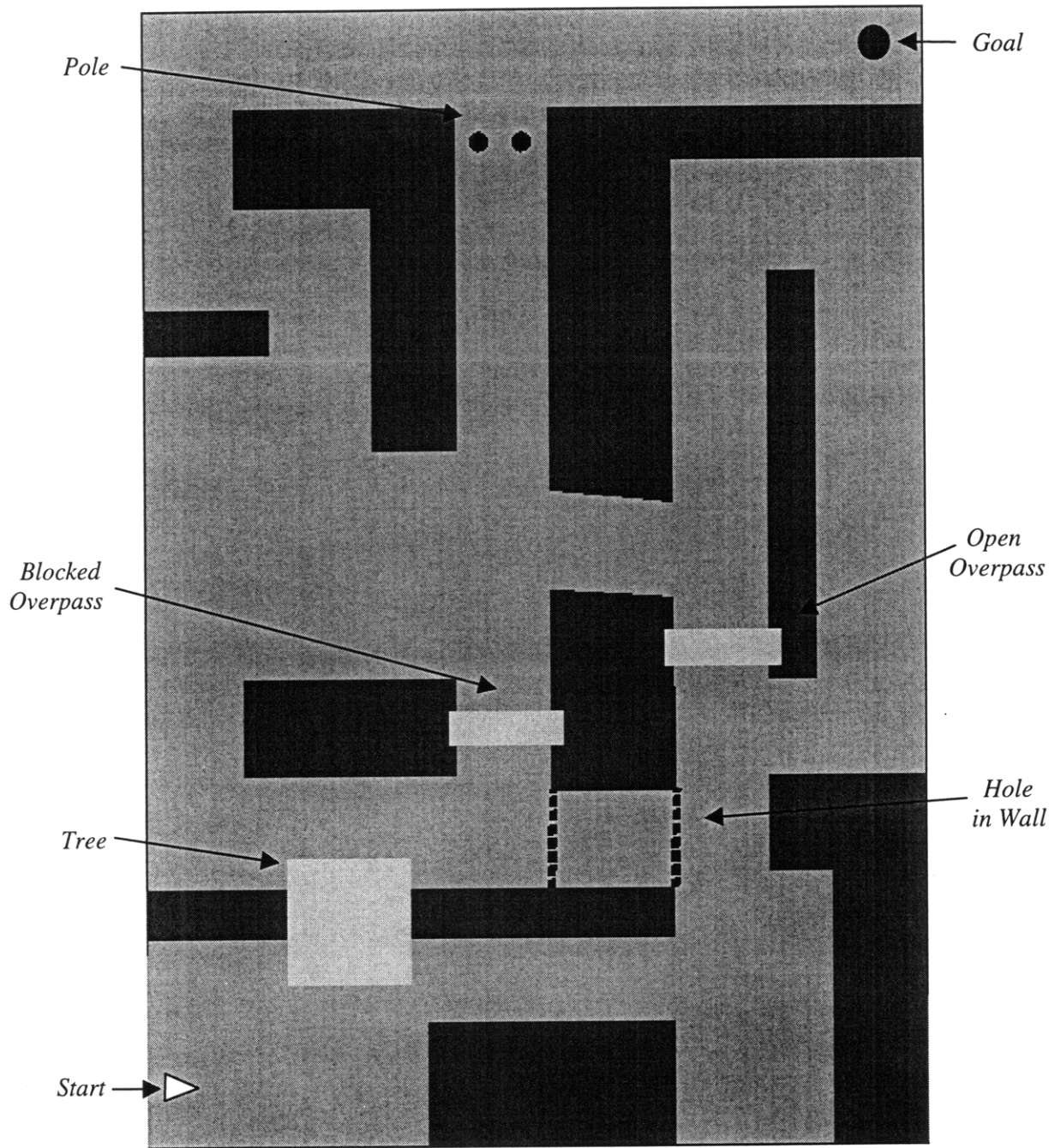(Bottom Right)

Master Map of Course One showing hidden features.

Course Three in High Resolution (Right), Medium Resolution (Bottom), and Low Resolution (Bottom Right)

Master Map of Course Three showing hidden features.