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ADVANCED NAVIGATION FOR PLANETARY VEHICLES APPLYING AN APPROXIMATE
MAPPING TECHNIQUE

by

Timothy R. McJunkin

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Electrical Engineering

Approved:

Dr. Robert W. Gunderson
Major Professor

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Committee Member

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Committee Member

Dr. James P. Shaver
Dean of Graduate Studies

UTAH STATE UNIVERSITY
Logan, Utah

1994

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I especially thank Dr. Robert Gunderson for his never ending support and mentorship. As a teacher, advisor, and friend, Dr. Gunderson has facilitated my personal and academic growth. I only wish I could run as far and as fast as he can.

I would also thank George Powell for keeping me in trouble and teaching me an appreciation for sushi. Without George's encouragement, I would have never had the courage to take on a project such as this.

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I thank my family whose emotional and financial support allowed me to continue my education for such a long duration. Thanks for not calling me a "professional student" too many times. Thanks for the love and encouragement.

I would also like to thank my peers and teachers throughout my education. The constant challenge continually caused me to improve. I only hope I gave you some of the same in return.

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ABSTRACT

Advanced Navigation for Planetary Vehicles Applying Approximate Mapping Technique

by

Timothy R. McJunkin, Master of Science

Utah State University, 1994

Major Professor: Dr. Robert W. Gunderson
Department: Electrical Engineering

This thesis provides a method for compressing the information provided by JPL Mars rover obstacle sensors by creating an approximate map of the terrain around the vehicle. This thesis demonstrates that this method provides adequate information for a human operator to negotiate complex obstacles fields.

By dividing the area around the vehicle into regions and classifying each region as to how dangerous (impassable), the sensor data can be accumulated with minimal overhead. The terrain in each region has a number between zero and one, with zero meaning completely passable and one meaning completely impassable. A continuum of possible values between the extremes classify in the sense of fuzzy set theory. This process allows obstacles to be represented in the map as an abstraction of the data instead of being arduously tracked individually, requiring much memory and complex processing. The map concept is also valuable in the respect that via translation of the vehicle information is passed to regions without direct sensor inputs. This allows the system to track obstacles to the side and to some extent behind the vehicle. The system, therefore, could potentially deal with complex situations where this information would be valuable such as a situation where it needs to recognize and back out of a trap.

This thesis includes the development of the approximate mapping algorithm, explanation of the integration with a test bed vehicle, demonstration of the algorithm using the test bed vehicle, and

ground work for the development of an automatic decision making scheme, which will constitute the continuing research effort.

(149 pages)

CHAPTER I

INTRODUCTION

Consider if you will, your thought process as you maneuver your car through a parking lot. You do your best to avoid numerous varieties of obstacles: other automobiles, concrete curbs, lighting poles, and shopping carts. These items are strewn haphazardly throughout. Even on a good day, obstacle avoidance can be challenging even with your very good eyesight and highly tuned response to the behavior of your favorite '79 jalopy.

Now imagine that your sensory input is reduced to a bare minimum. These sensors are in fixed positions with respect to the direction the vehicle is facing and will be able to tell if an object is protruding above ground at certain points in the forward direction. Given these indications and your brain's memory and finely trained inference ability you would probably still fair pretty well.

However, a computer algorithm, responsible for processing the sensor inputs of an autonomous vehicle with such a sensor system, has a much larger problem with the task. Any computer has several billion fewer neurons and much less experience in the art of survival in hostile parking lots.

A successful autonomous planetary vehicle must have a sophisticated inference process implemented in a extraordinarily compact way in order to meet the economic and practical constraints placed on a space mission (i.e. relatively slow flight approved processors and limited volume, mass and power). Such a system gives up precision and completeness in measurements of the surroundings, but compensates by using innovative "intelligent" approaches to the problem.

A. *Pathfinder and Related Research Goals*

Currently, the United States has one funded mission which has the goal of placing a mobile ground vehicle on the surface of an alien world. Pathfinder will deploy a microrover, 9.5 (kg with

a height of 28 cm) on the surface of Mars from a landing vehicle in 1997. Upon deployment, the vehicle will explore the area around the landing craft.

The first task of the rover will be to move out from the lander, turn around, and retrieve images of the deployment of the landing craft itself. A primary mission objective is to critically examine the rover's technical abilities to determine feasibility and improvements for possible future endeavors. The rover will then explore the area around the lander to a maximum distance of ten meters. The rover will roam this area on commanded way points, desired destinations, given from Earth control station. The way points will be chosen after careful examination of panoramic images returned by the lander. This will ensure that the vehicle does not wander into inescapable traps. After being given a way point the rover navigates autonomously using an optical sensor package and behavioral algorithms. If the way point is chosen judiciously the vehicle should have little trouble arriving at the way point.

The vehicle moves at a slow pace, taking optical sensor data after each movement of about 10 centimeters. Even at a slow pace the ten meter radius will be explored in a few short months. Because it primarily relies on solar radiation, the power system of the rover is not energy limited to the life span of on board batteries. The life span of the rover is estimated at one year. A secondary mission is therefore a possibility. During an extended mission the rover may be turned loose outside the "eye sight" of the lander. The rover team on Earth would not have the benefit of lander images for determining way points. The vehicle would then benefit greatly from a system which processes image data farther ahead and tracks obstacles in an efficient way and bases movement decision on a localized map generated by sensor data.

B. *Problem Statement*

All sensor systems are imperfect. Accuracy and completeness in obtaining sensor information come at great expense in volume, mass and computational power. To find a balance point in this

trade off, Jet Propulsion Laboratory (JPL) has developed an elegant obstacle detection sensor suite that uses striping lasers and Charge Coupled Device (CCD) Cameras. These sensors give accurate information about the terrain in front of the vehicle. However, the lasers diverge in a fan-like projection. Sensor information becomes sparser the farther in front of the vehicle the lasers go. Therefore, relying only on the current sensor data to make a decision about how to proceed is sketchy. This is one reason JPL only processes sensors up to one vehicle length ahead of the rover.

The benefits of looking farther ahead are debatable. The more global the information the rover has about the environment ahead of the more efficiently the system could navigate; the vehicle can recognize dead ends sooner than with only shorter range information. The benefit is a matter of reducing path length. The debate is over how much path length reduction outweighs the extra processing required to plan a path at a greater distance ahead of the vehicle. For the purpose of this thesis the assumption is made that attempting to peer ahead a greater distance provides a significant advantage to the system and is thus worthy of implementation if the processing needed for this extension is reasonable within the scope of the system. A brief argument for the extension of the vision of the vehicle sensors is given in the body of this thesis.

The most important aspect of this thesis is the development of a system which can accurately represent the terrain around the rover using sensor data provided by the current hardware included on the JPL micro-rover. This system will provide significant benefits over current behavioral algorithms.

C. *Sensor-based Navigation Systems*

Several other schemes have been developed for the purpose of sensor-based obstacle avoidance. Among these is JPL's behavioral approach. Others have developed various schemes for other land roaming vehicles using non-traditional, "intelligent", approaches for systems with various sensor packages.

The JPL obstacle avoidance system is based on a "behavioral" model of insects [1]. A series of

if-then-else statements provide the decision for movement. Rules are fashioned somewhat like the following:

- If an obstacle is detected directly in front then backup and turn right.
- If a wheel trap is detected in front of the right wheel then go to the left.

A limitation of the JPL scheme is the restriction of exploration to the “eyesight” of the landing craft. Images from the landing craft’s stereo cameras are used for general guidance from the Earth for defining way points to the rover. The range of the mission is a ten meter radius from the lander, which is the range of the stereo cameras of the landing craft. The need for this restriction is that without a planned path communicated from Earth, based on photos of the area, the rover could wander into a situation that could leave it hopelessly stuck. The current scheme might enter such a situation, such as a ring of rocks and not recognize it.

Also, the algorithms base decisions on current sensor data [2]. Since the sensors only cover the area in front of the rover included between the most outside lasers, obstacles which pass through the sensor’s field of view to the side are forgotten. This information would be valuable when a complex situation arises in which the vehicle now passing an obstacle on its left finds a large obstruction directly in front of it. A system which remembered the previous obstacle would have the opportunity to consider turning right to go around the frontal obstacle thus avoiding a maneuver which causes it to veer back towards the previous obstacle potentially causing oscillatory behavior.

Current algorithms only look ahead one vehicle length. This is like walking around always looking at the ground directly in front of you. A trip wire or hole will never trap you, but you could end up on a outcropping with cliffs on three sides, terrified to even try to turn around by the time the situation is recognized.

Many schemes have been developed that attempt to avoid the pitfalls of sensor based navigation. A robot using laser range sensors making navigation decisions based on a Kohonen [3] neural network

is described in [4]. This system is a goal-oriented system and works well given regular obstacles of a minimum height, the height of the ranging laser. The sensor setup is not useful for the needs of the JPL type rover but portions of the navigation concept are interesting.

Another system utilizes fuzzy logic in a behavioral structure. The control is based on fuzzy rule bases which interpret sensor information from speedometers and ultra-sonic sensors. This research has developed a custom VLSI chip to perform the fuzzy inference process at high rates [5]. This work is created for a continuously moving vehicle with variable velocity.

The Russian Marsokhod will rely on tele-presence for navigation [6]. The rover will send full images back and a safe path will be planned out. The rover is then sent on its way. When it reaches the end of that path, it sends more images and repeats the process. This method will be very arduous. With a minimum of 20 minutes of transmission time each way, it could take months to move a significant distance.

D. *Approximate Mapping Solution*

The system developed and reported in this thesis provides another alternative for organizing and presenting sensor data in an easily interpreted manner requiring only minor storage and processing on the part of the system. This system condenses sensor information into a form which balances the need for adequate information and the need for reducing the amount of data to be processed. This scheme has been specifically designed to fit the JPL Rocky Rover, although the concept could potentially find use in other vehicle systems with modifications.

The approximate map or fuzzy map takes on this problem by describing the environment in imprecise terms. Instead of tracking every sensor point in order to track every detected obstacle in the local vicinity of the vehicle, the fuzzy map describes the terrain around the vehicle by classifying various regions. This corresponds to human information processing. A human does not generally describe a set of stairs by its exact dimensions when trying to walk towards them. Instead, the

directions would be, “the stairs are a little bit to the left in front of me.” With the map the rover avionics system describes the linguistic description of “a rock near to the right front” by giving the near right front region a membership in the set of impassable regions dependent on the size of the rock. The mapping method described in detail in this thesis accumulates and translates sensor information, in a sense forming the system’s visual memory.

E. Towards a Fuzzy/Neural Based Decision System

The map is a basis for the formation of an autonomous system. The map is the puzzle piece between the sensors themselves and a decision making system. It performs the abstraction process by limiting the information presented to the decision system. At this point the decision system is a featureless block on the system level diagram. Many possibilities exist for the formation of this system ranging from a behavioral scheme to fuzzy or neural network schemes to hybrids of behavioral, fuzzy and neural based algorithms. The map was originally designed with a artificial neural network in mind. Continuation of research at Utah State University (USU) is already underway to close the loop and arrive at an autonomous vehicle.

F. USU Test Bed Vehicle

To test, develop and demonstrate the fuzzy map and continuing developments, it was decided, in November of 1993, that a vehicle be constructed. This vehicle was to emulate the JPL vehicle in the optical sensor suite only. True rover mobility was an unaffordable luxury for a project on a “shoe string”.

The design and construction of a working, useful vehicle was accomplished only with the team work of a small group of determined people. The author emphasizes the fact that none of this research would have been possible without the resourcefulness and vision of George Powell, then at Space Dynamics Laboratory, and Dr. Robert Gunderson, Utah State University, Electrical Engineering

Department, and the quality personnel they recruited to be a part of this project.

CHAPTER II

PROJECT GENESIS

This chapter will describe the background behind Utah State University's involvement with JPL in rover research. The development of a plan for planetary vehicle research and origination of the concept of the approximate map is discussed briefly.

A. *Precursors*

In March of 1993, a meeting was held on the USU campus to discuss the final development of the speedometer for the Mars 1996 balloon guiderope system [7]. At that time, I became involved with Mars related research when I was graciously awarded a fellowship by the Rocky Mountain NASA Space Grant Consortium in their effort to provide support for such endeavors. At that time, financial concerns of failing support from the French space agency CNES brought Bruce Murray, Vice President of the Planetary Society, to suggest that the personnel involved in the Mars guiderope speedometer at USU turn their attention to other projects, such as rovers, if the speedometer project fell through. Soon after that meeting the CNES did pull the plug on the speedometer due to required system mass cuts. This of course left those involved with the speedometer free to pursue other things, whether they liked it or not.

After a few months of muddling, the opportunity to start working on planetary vehicles arose. George Powell made contact with Brian Wilcox, Technical Group Supervisor of the Robotics Vehicle Group at JPL. A trap made up of a ring of rocks was determined to be a problem which currently had no adequate solution and became the beginning of this research. A circle of rocks which has an entrance just wide enough for the rover to enter is a potential "show stopper". If the rover happens to find the entry, it seems quite possible that it may never line up with the gap in the rocks ever

again. The rover could potentially be trapped by its own obstacle avoidance system.

Working with this information and basic knowledge about the JPL rover sensor operation, George Powell and I began to brainstorm the problem, looking for an innovation. Using USU's rich background in the use of neural networks, our first approach was to apply the sensor information to a neural network and allow the network to learn from the response of a human to the sensor information. It soon became apparent that an automatic system would need some way of remembering the sensor information from past iterations, since the human would definitely use remembrances of past sensor data in making the next decision.

Our first idea for creating a memory for the system was to provide a grid map in the local area around the vehicle. Each area would be specified as either clear or impassable. The processor would track each area. This map would be presented to a neural network as well as current sensor information. The idea was that larger blocks made up of many of these smaller map blocks would keep a global history of the terrain the rover had seen. The local part of this map could detect a trap when a contiguous ring of map blocks had been created as the rover explored. This would hopefully help lead the rover back to the entry.

B. *Naiveté of Plan is Revealed*

In November of 1993, George Powell and I visited Mr. Wilcox in Pasadena, California where I was able to see the JPL vehicle for the first time. In the discussions with Mr. Wilcox, we brought up our ideas. Although still supportive of our involvement, he quickly pointed out some basic flaws in our mapping idea. In the first place, dead reckoning is used for determining the rover's approximate position. Within very few moves, the error in the position information would make our mapping process virtually useless. Secondly, to keep track of past terrain, the map would have to become larger and larger. Brian Wilcox gave us some possible suggestions including: looking further ahead to give a neural network a chance at a richer set of data. We were very positive about our discussion

Table I. Initial USU Rover team members and responsibilities.

Personnel	Responsibility
Dr. Robert Gunderson	Faculty advisor.
George Powell	Project director, Cost manager
Tim McJunkin	Approximate mapping algorithms, software development, hardware integration
Kurt Olsen	Windows user interface development
Collin Lewis	Mechanical hardware design and development
Jessie Floyd	Mechanical hardware development and machinist
Gordon Olsen	Electronics hardware design and development
Frank Walker	Logistical assistance
Larry Denys	Software serial communications
Monte Frandsen	Electronics hardware consultant

with Mr. Wilcox even though our initial ideas were shot down.

C. *Plan for a USU Test Bed*

During the same Pasadena trip, parts were obtained for the building of a vehicle for use at USU. George Powell and Dr. Robert Gunderson had decided that for demonstration and testing purposes a vehicle emulating the JPL vehicle should be constructed. We purchased a radio control (RC) car chassis and radio transmitter and receiver.

In three months the rover was built with the efforts of a team that was beginning to form. The team should be noted for pushing ahead of schedule to have the vehicle running for a demonstration for State of Utah officials in mid-February, a full month ahead of the original schedule. The original team members are list in Table I.

D. *Revised Mapping Plan*

Through November and December, the new and improved ideas that have become the basis for this thesis were developed. The idea stuck that an exact map, or description of the terrain in front of the rover was not critical. In giving someone directions about backing up a truck, you do not

tell them that “there is a concrete barricade three feet-two inches from the left rear bumper” but that “there is a wall close to the left end of the truck”. Following this, I came up with the idea of dividing up the local terrain around the vehicle up into overlapping regions. Each region would have a designation as to how dangerous it would be to attempt roving into it. This idea presented itself after many weeks of reading Lotfi Zadeh’s work [8] and his growing group of follower’s literature [9, 10, 11] about fuzzy logic applications and fuzzy set theory.

Fuzzy set theory allowed each region to be classified, in varying degrees, into the set of impassable regions. For use in an algorithm, each region has a value in the range $[0, 1]$ associated with it. A zero designates a completely passable region, thus a low membership in the set of impassable regions. The set of passable regions is the inverse of the impassable set, so the membership value would be the negation of that for the impassable set. For a region \mathcal{R} , the membership in the set of impassable regions is formalized as $m_{\mathcal{I}}(\mathcal{R})$. So region \mathcal{R} ’s membership in the set of passable regions, $m_{\mathcal{P}}(\mathcal{R})$, is given in Equation (1) as its logical inverse.

$$m_{\mathcal{P}}(\mathcal{R}) = 1 - m_{\mathcal{I}}(\mathcal{R}) \quad (1)$$

The initial sketch of the fuzzy map is shown in Figure 1. The fifteen regions in front of the rover are chosen as regions because they each have a sensor input associated with them. The rest of the regions were chosen because of assumed interest in knowing what is in that region. These non-active sensor regions must obtain their information in another way. The idea of passing information back to these regions with translation of the rover was a key to making this map truly useful. The detailed process of how the map works is given in Chapter IV. The structure of the map has not been change very much from the time of its conception.

The fuzzy map’s achievement is the reduction of data from the sensors to a small size so that little memory is required and processing of the information from a decision making point of view

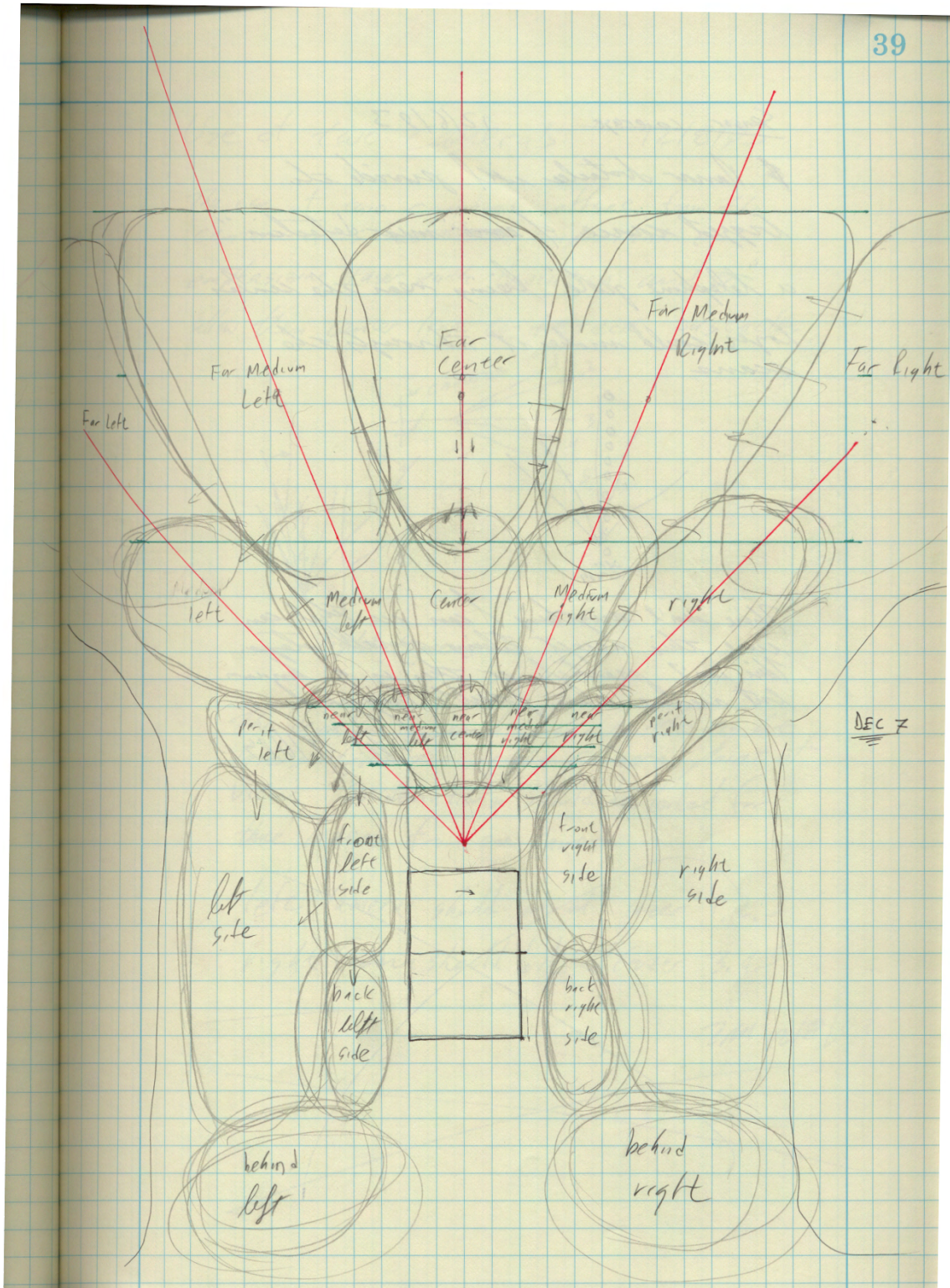


Figure 1. Concept drawing of fuzzy map.

can be minimized. Initially the map was designed with the goal of using it as input to an artificial neural network. Reducing the number of inputs to a neural network greatly reduces the size and complexity required.

E. *Verification of the Map*

Testability is another major benefit of the map. The map can be shown to a human operator using a color coded display of the map. Each of the regions is colored according to its membership value in the set of impassable regions. Low membership values are colored green, and high membership values are colored red, with in-between values passing through yellow completing the stop light analogy. In the corresponding grayscale map used in this thesis, black represents zero and white represent unity. The map shown in Figure 2 solicits a response of turn right to avoid the nearby obstacles to the front-left of the vehicle to pursue the possible path indicated to the left. By testing with a human operator, allowing the rover to be guided only by the map information, the usefulness of the map can be demonstrated.

An even stronger conclusion can be drawn. If a human can drive the rover successfully with only the minimal information in the map, then an autonomous system can be contrived, in principle, that can do the same. This is a strong statement, but I have reasonable cause for being bold, since it is a simple process of defining a rule base, based on an expert human rover driver's experience.

The results of the verification of the map using the USU test bed vehicle are shown and described in Chapter VI.

F. *The Idea Catches On*

During the next several months, the concept was presented and demonstrated to several groups. The Idaho National Engineering Laboratory (INEL) contracted USU to build a duplicate of the test bed vehicle for their own testing purposes for potential use in hazardous waste management. JPL

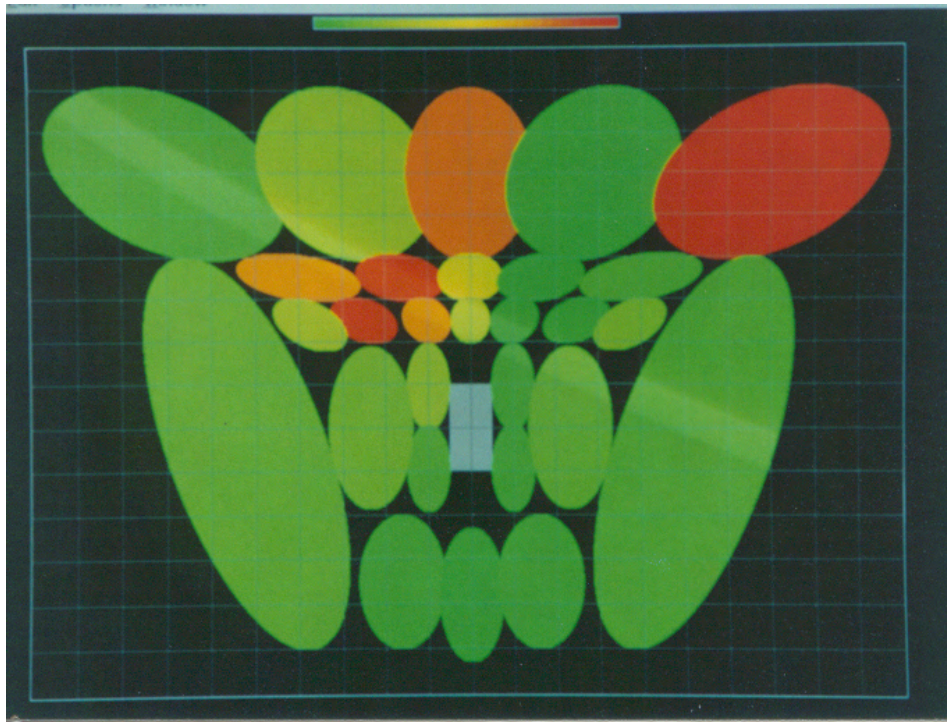


Figure 2. Display of fuzzy map indicating that a right turn is the correct move.

has expressed continuing interest in the fuzzy map algorithms. In a follow-up meeting with JPL, the concept of the approximate map where as a mature idea that is worthy of continued research as a tool for rover navigation in fields with dense obstacle distributions.

The research concept and initial results were published at a conference in Moscow, Russia [12] and several other groups including the Center for Persons with Disabilities at USU [13].

CHAPTER III

ROCKY ROVER OBSTACLE SENSORS AND CHASSIS

This chapter provides a general description of the JPL planetary micro rover, Rocky 4, and its autonomous navigation system. The micro rover will accompany a lander to Mars on the 1996 Pathfinder mission

A. *Rocky Rover*

The JPL Rocky 4 rover has been chosen as the vehicle for the Mars 1996 Pathfinder mission. The Rocky micro-rover design was chosen as the only practical vehicle of several planetary vehicles considered. The rover has six wheels attached to a set of bogie levers. The front and rear set of wheels can be steered using Ackerman steering, front wheel steering like all automobiles. The rover is capable of climbing obstacles larger than the diameter of the wheel [1]. The rover moves in short increments of about a quarter wheel rotation at a time.

Communication between the rover and lander uses UHF modem links with a range of approximately one kilometer. The on-board processor is based on an Intel 80C85. The processor reads the rover's cameras, sending them back to the lander for transmission to Earth, and interprets images for the obstacle avoidance and navigation [1]. All navigation algorithms are also computed by the on-board processor.

The primary obstacle avoidance sensors used on the JPL Rocky Rover are an active illumination optical system. The rest of this chapter provides a description for how the sensor package works and how JPL utilizes the sensor information.

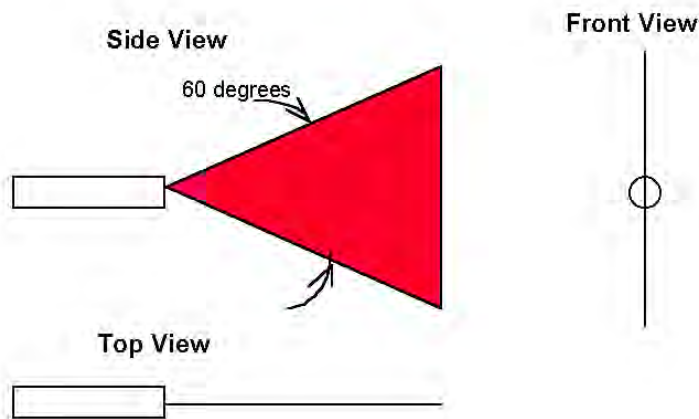


Figure 3. Light from lasers is diverges into a narrow width plane at an angle of approximately sixty degrees.

B. *Sensor System Overview*

The optical sensors on JPL's vehicle rest on a sensor bar which is mounted to the front of the rover approximately 25 centimeters above the ground. The optical sensor system consists of five striping lasers and two Charge Coupled Device (CCD) cameras. The striping lasers are semi-conductor lasers with a lens causing the light to diverge into a narrow plane emanating to fill a full angle of sixty degrees, as shown in Figure 3.

The plane of light causes a line to be painted where it reflects from a surface. On a level surface, a straight line is cast by a striping laser which is oriented vertically. The orientation of the five lasers is shown in Figure 4. The top view of Figure 4 shows the fan of light projected on the ground and the relative location of the cameras, represented as ovals. The side view of Figure 4 shows the position of the camera relative to the ground and the angles which are described in following sections. If a laser strikes an obstacle protruding from the ground the stripe follows up over the obstacle. From

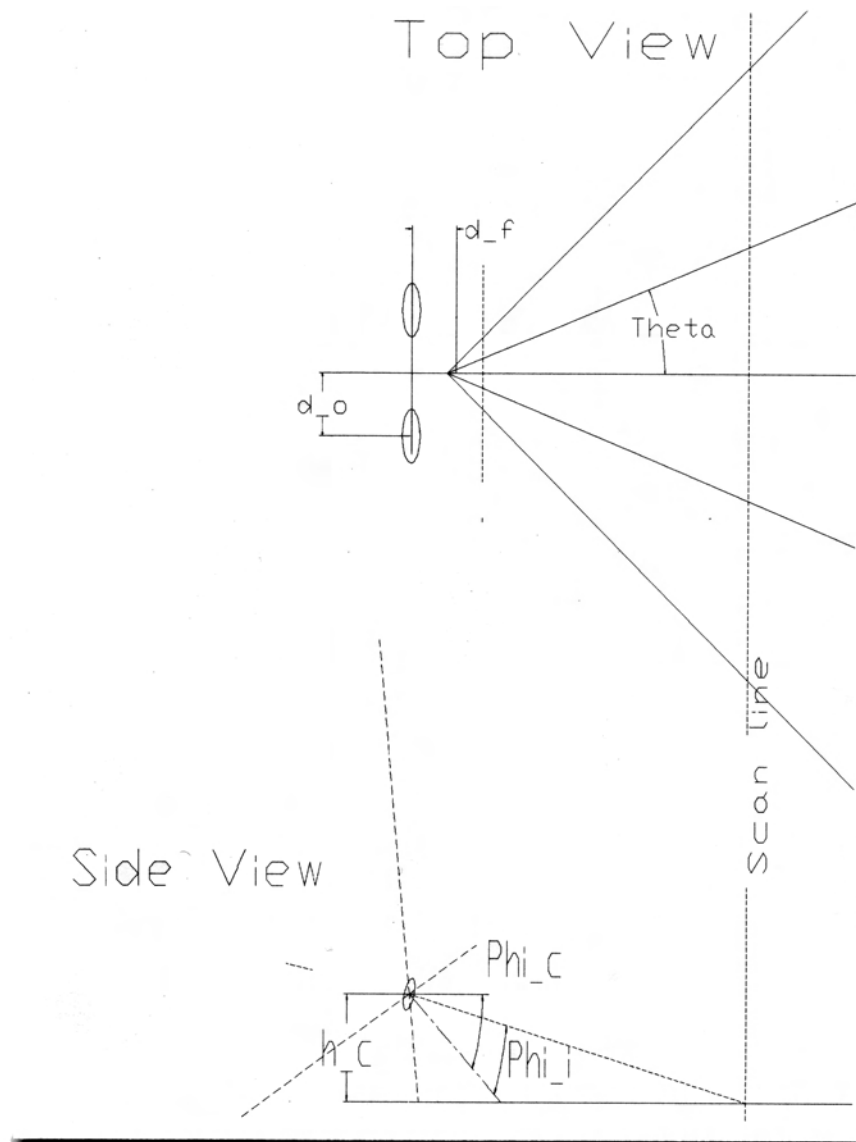


Figure 4. Drawing of striping laser geometry.

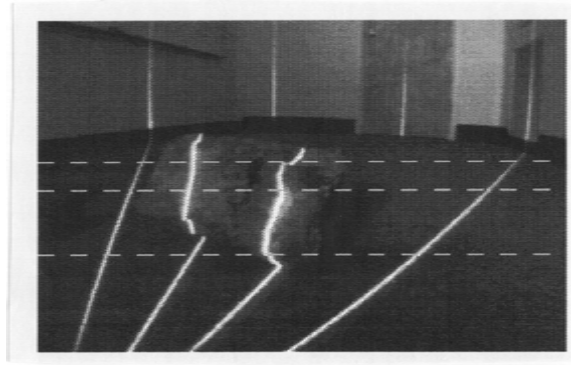


Figure 5. Image from rover camera showing disruption of laser path

the point of view of the cameras this looks like the line bends away from the expected path, as seen in Figure 5. This is the basis of the entire sensor system. For an obstacle to be detected it must be in the path of the laser plane and in the field of view of the camera. To reduce the processing of the image even more, JPL uses only a few horizontal rows of pixels for obstacle detection. These rows, called scan lines, are selected such that the projected line would be at a particular distance on a level surface. An obstacle can only be detected if it intersects with a laser and the projection of the scan line to the camera and, of course, neither the laser or the view of the camera are obstructed by another object.

1) *Lasers:* The semi-conductor lasers used for laboratory testing at JPL are 8mW lasers (flight lasers will be more powerful since there are no human eyes to damage). The lasers are powered by a 5V source with a current of about 100mA. The lens in front of the laser distributes the light into a planar beam. The five lasers are distributed on a support bar with brackets holding each in place. The center laser is adjusted so that a line is cast along the extension of the center line of the rover. The other lasers are adjusted so that the lines are projected at given angles which intersect at a common point in front of the rover. Each of the laser planes is also adjusted to be vertical to the ground surface. The center of each beam is adjusted such that it strikes the level plane at the

farthest distance the system is interested in inspecting, since reflections from nearer points will be more intense due to proximity. This setup provides coverage of the area in front of the rover with dense collection of laser stripes near the rover, but sparse coverage of longer range terrain.

2) *Cameras:* The two cameras are monochrome CCD matrices with a collecting lens. The cameras are placed one on each side of the lasers. It is necessary to have the cameras offset from the center of the vehicle in order to sense a deflection in the projected stripe from the center laser. The cameras are angled downward so the center of focus is near the center of interest of the obstacle detection scheme. Each pixel of the focal plane can be sampled by the processor. As mentioned above only selected scan lines are used in the process of obstacle detection, although the whole image can be collected for transmission back to Earth.

For obstacle detection in this thesis, the right camera will be used for the two right lasers and the center laser and the left camera for the two left lasers and the center laser also. This gives two opportunities to detect obstacles on the center laser which tends to be the least sensitive and also the most important. It is least sensitive because the angle that the unobstructed line makes in the focal plane is the most acute of the three used for each camera.

3) *Inclinometers:* JPL uses inclinometers to measure the pitch and roll of the sensor suite. This input is used to interpret optical sensor information when the rover is not set on level terrain. For the purpose of this initial research the rover will be assumed to be on flat terrain. Examples of the disruption an inclined sensor gives to the system developed for this thesis is given in the results chapter.

C. *Obstacle Detection*

Using the five lasers and two cameras, the system can detect deviations in the landscape at points in view of the camera and in the path of one of the lasers. Given the plane created by a

laser and a vector associated with a ray reflecting from an obstacle then striking a particular photon sensitive element of the camera, it is a simple matter of trigonometry to determine the location of a particular laser spot with respect to the vehicle. Equations (1) – (3) describe the location of a laser spot (x_r, y_r, z_r) , which illuminates a pixel with coordinates (x_p, y_p) . A trigonometry derivation of these equations is contained in Appendix A.

$$y_r(x_p, y_p, n) = \frac{D_n}{a_n - x_p g_{yp} b_n \sqrt{1 + \tan^2 [\phi_c - \tan^{-1}(y_p g_{yp})]}} \quad (1)$$

$$x_r(y_r, n) = \frac{a_n y_r - D_n}{b_n} \pm d_o \quad (2)$$

$$z_r(y_r, y_p) = h_c - y_r \tan[\phi_c - \tan^{-1}(y_p g_{yp})] \quad (3)$$

where (4) – (8)

$$a_n = \sin \theta_{l_n} \quad (4)$$

$$b_n = \cos \theta_{l_n} \quad (5)$$

$$D_n = d_f a_n \mp d_o b_n \quad (6)$$

$$g_{xp} = \frac{2 \tan \frac{\Phi_{FOV_x}}{2}}{N_x} \quad (7)$$

$$g_{yp} = \frac{2 \tan \frac{\Phi_{FOV_y}}{2}}{N_y} \quad (8)$$

where h_c is the height of the camera; ϕ_c is the declination from horizontal of the camera; θ_{l_n} is the angle of the n^{th} laser from the rover's centerline; d_f is the distance forward from the position of the cameras to the point where the lasers intersect; d_o is the distance the cameras are offset from the center of the vehicle (for the \pm the top sign is used for the right camera and the bottom for the left); N_x and N_y are the number of pixels in the horizontal and vertical dimensions of the CCD

array. Using (1),(2), and (3); knowing the pixel location (x_p, y_p) for the laser l_n that is responsible; the coordinates (x_r, y_r, z_r) of the terrain illuminated can be found.

For use in this thesis the number of scan lines are limited to three, numbered from 0 to 2 where $m = 0$ is the far scan line. The lasers are numbered, depending on the active camera, 0 through 4 with $n = 0$ being the far left laser for the left camera and the far right laser for the right camera.

The vertical pixel location, y_p , is fixed by the scan line choice. Giving each scan line an integer designation m , (1) – (3) become functions of x_p and m .

Finally the coordinate transfer equations are written with the scan lines included as:

$$y_r(x_{p_{m,n}}, m, n) = \frac{D_n}{a_n - x_{p_{m,n}} g_{xp} b_n e_m} \quad (9)$$

$$z_r(y_r, m) = h_c - y_r c_m \quad (10)$$

and

$$x_r(y_r, n) = \frac{y_r a_n - D_n}{b_n} \pm d_o \quad (11)$$

with constants for the m^{th} scan line defined as

$$c_m = \tan(\phi_c - \phi_m) \quad (12)$$

$$e_m = \sqrt{1 + c_m^2} \quad (13)$$

where ϕ_m is the vertical angle of the scan line with normal vector (pointing direction) of the camera. $x_{p_{m,n}}$ denotes the pixel location for the n^{th} laser for the m^{th} scan line.

The above equations show that geometrically the laser striping system is functional for finding location of obstacles and are useful for use simulations, the equations do not accurately describe the system using with real cameras. Due to lens curvature the ray entering the lens will change direction

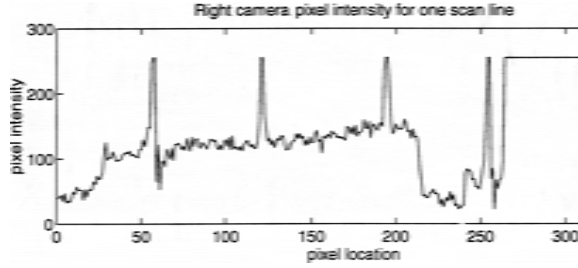


Figure 6. One scan line of pixel intensities showing peaks at laser locations.

and strike the focal plane in a different spot than expected. This deviation is a function of the angle in which the ray enters the lens and the shape of the lens. Fortunately neither JPL or this thesis require the exact coordinates of an obstacle. The sensor information can be calibrated using known obstacles.

D. *Locating the Lasers on a Scan Line*

A horizontal row of an image is represented as a series of N pixel intensities, $p_i(x)$ with x in the range $[0, N - 1]$. To provide symmetry between left and right cameras, $x = 0$ is the left most pixel for the left camera and the right most pixel for the right camera. The brightest objects in the field of view should be the lasers. An example of intensities of one row of pixels is shown in Figure 6. The location of the laser appears as a variable width pulse stepping out of the background intensity level. The high level towards pixel 300 is a light surface with an ambient light source reflecting brightly. This is not a differenced scan line. The width of a laser is dependent on the proximity of the object reflecting the light. A matched filter of sorts is used to find pixel locations. The filter is simply a spike at the center surrounded with zeroes to a width supporting the widest laser occurrence anticipated then negative spikes to average out the background. Equations (14) and (15)

describe the correlation of the filter with the row of the image.

$$F(x) = \sum_{j=-M}^M p(x-j)f(j) \text{ for } M < x < N - M \quad (14)$$

$$f(j) = \begin{cases} -a & -M \leq j < -W \\ 0 & -W \leq j < 0 \\ b & j = 0 \\ 0 & 0 < j \leq W \\ -a & W < j \leq M \end{cases} \quad (15)$$

The constant, W , is one half the widest laser pattern expected and, M , is one half the width of the filter. Also for convenience the filter should sum up to zero such that a uniform intensity region gives a zero result. as expressed in (16).

$$\sum_{j=-M}^M f(j) = 0 \quad (16)$$

An equivalent expression for (16) substituting values a and b from (15) is

$$2a(M - W) = b. \quad (17)$$

A filter threshold is set such that it detects lasers and ignores background noise. With a scene that has a great deal of high spatial frequencies and at greater distances, detecting the lasers can be a challenge. To deal with this challenge an image differencing technique is used. Images are recorded with the lasers on and with the lasers off. As long as the images register with each other correctly virtually the only things left in the image are the lasers. Once the location of the lasers can be detected the remaining work is an interpretation problem.

E. *Expected Pixel Location and Pixel Deviation*

If the surface in front of the rover is level the lasers stripe out lines in particular places on the ground with respect to the rover. This means that each laser is expected at a certain position along a row of pixels. The expected pixel location for the n^{th} laser on the m^{th} scan line is denoted as $E_{m,n}$. The expected pixel location for each scan line/laser pair can be found experimentally by placing the system on a level surface and finding the pixel locations.

The pixel deviation is simply the measure of the distance between actual location of the laser pixel on a scan line and the expected pixel location. Since the laser is a vertical plain, a protruding obstacle bends the lasers up towards the top of the image causing a positive (as defined above) pixel deviation on the near side (same side as camera) and center lasers. Denoting the pixel location as $P_{m,n}$, the pixel deviation is given in (18).

$$\Delta P_{m,n} = P_{m,n} - E_{m,n} \quad (18)$$

Placing known sized obstacles at specific location allows for the accumulation of calibration data. JPL forms a matrix based on the pixel deviation and inclinometer data to interpret sensor information. The rover is inclined at various pitches and rolls and pixel deviations noted for incorporation into the obstacle detection scheme. Since the USU test vehicle is not equipped with inclinometers and for simplification of this initial work, the assumption of locally level terrain, requires only use of the pixel deviation for the algorithms.

F. *JPL Use of Sensor Information*

JPL uses scan lines within one vehicle length of the front of the rover. The sensors are therefore collecting very close range, tightly sampled terrain data. The system looks for several particular types of hazards, such as: large obstacles or holes which would be traps one of the vehicles wheels.

JPL interprets the sensor data to determine the location of any traps and then uses the behavioral algorithm, as described in the introductory chapter, to proceed. If the path is clear, the rover moves towards its intended goal. If a hazard is detected at a certain location the rover makes its next move to avoid it. The decision tree is based only on sensor information and a ring buffer which holds the locations of most recent large obstacles which pass to the sides of the rover. The sole purpose of doing this is to check to see if any appendages, scientific sensors, are going to collide with them during a turning motion. Inside of one vehicle length, the JPL scheme will most likely not miss a dangerous hazard since the lasers are very close together at short distances in front of the rover.

CHAPTER IV

APPROXIMATE MAPPING ALGORITHM

The approximate mapping algorithm developed here serves the purpose of compressing and conditioning sensor information so that it may be more readily utilized by a automatic navigation decision scheme. The source code for the algorithm is contained in Appendix B. The map divides the terrain around the vehicle into regions with each region quantified with a number between 0 and 1. The number indicates the danger in proceeding towards that region. A number near 0 represents a region with no severe hazards, and a number near 1 dictates an impassable obstacle in the region. A cliff or boulder are both considered impassable hazards.

Figure 7 shows a typical display with a photograph of corresponding terrain below it. The map is formed using two main processes. The first is processing the sensor information and accumulating that information in the fifteen regions in front of the vehicle which have active sensor inputs, that is, a scan line and laser intersection associated with the region. The second process is a translation process. The map information is passed into adjacent regions with the motion of the vehicle. This provides for a certain amount of visual memory which will be necessary for a system to make adequate decisions. The bright yellow spot in the region in front of the rover is merely a sensor glitch. Glitches, as in most real world systems, do occur here also. These glitches are usually due to lighting conditions or anomalies in image capturing process.

A. Necessity for Providing Visual Memory and Extending Sensor Range

There are two main areas in which a state type representation of sensor data has advantages over the sensor data alone. First the map will remember objects that move out of the field of view of the sensors. Since the sensors only scan a limited region in front of the vehicle, a maneuver away

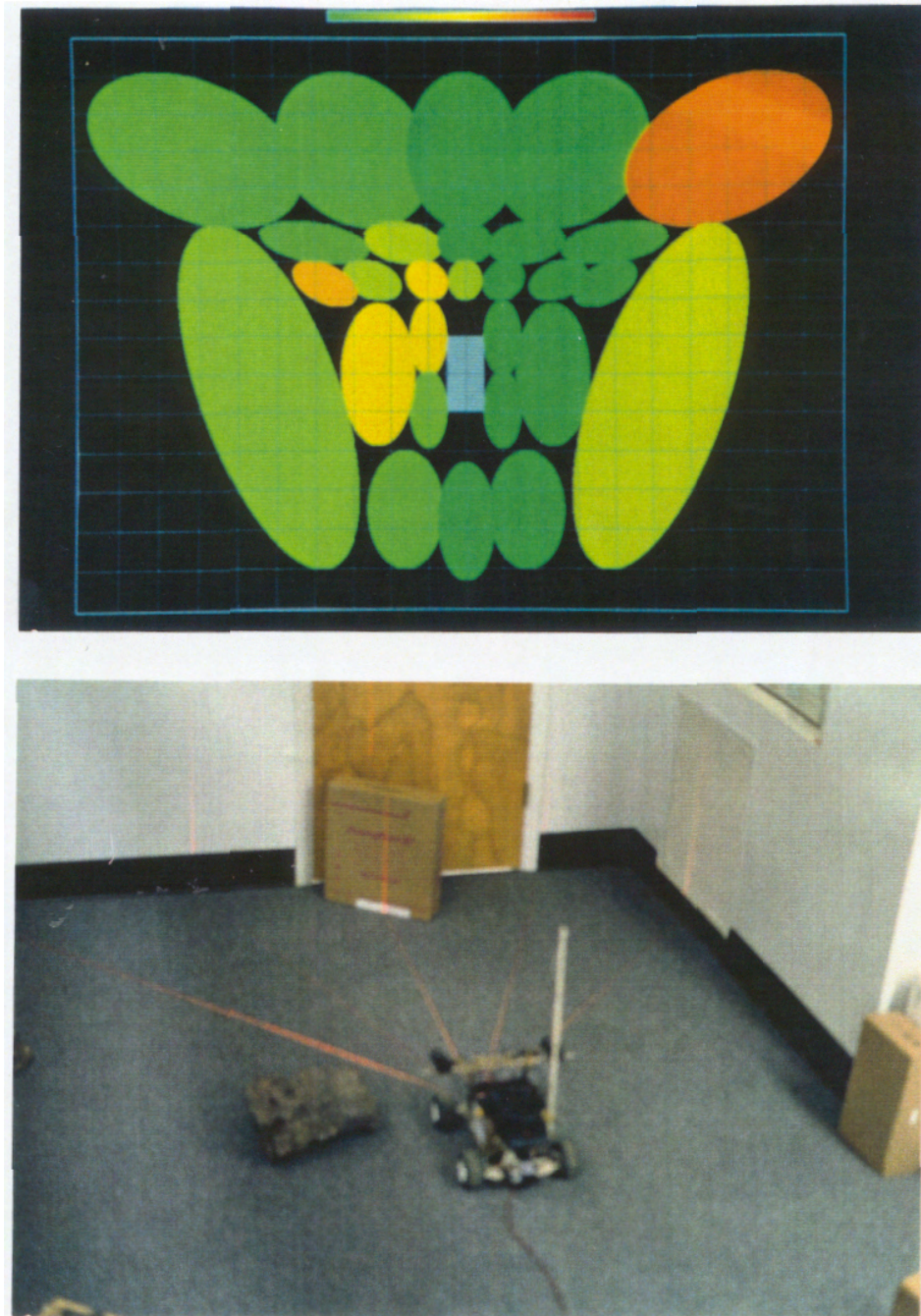


Figure 7. Fuzzy map example with overhead picture of terrain that generated the map.

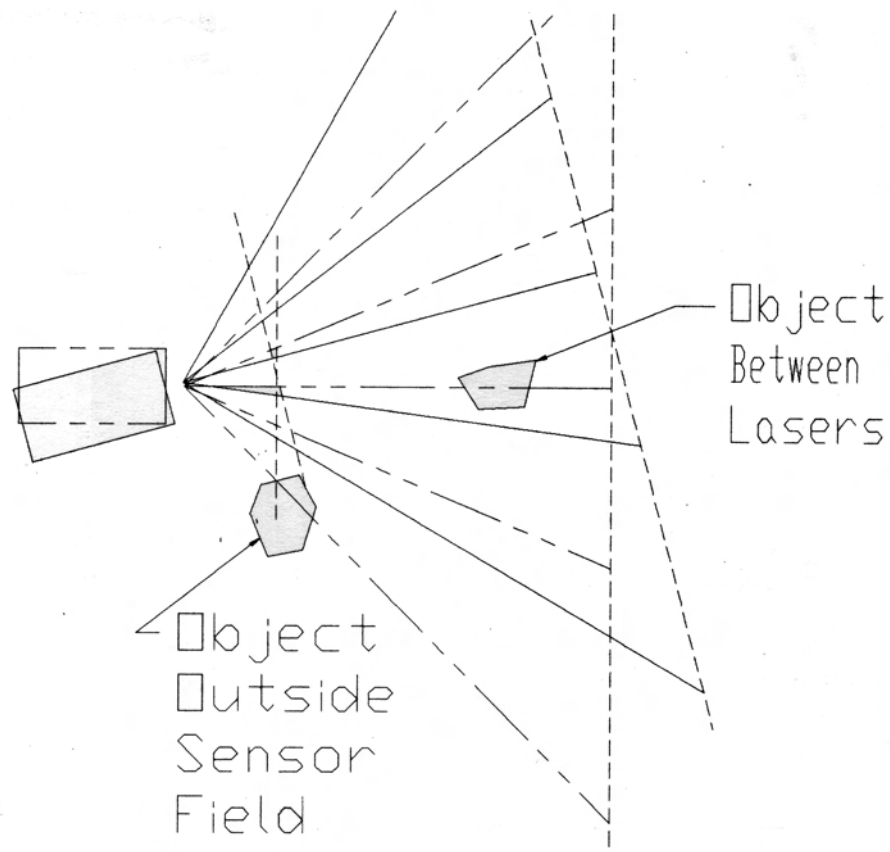


Figure 8. Scenario showing to examples of the importance of visual memory.

from an obstacle towards the boundary of the sensed region will put it out of the sensor's view. As represented in the Figure 8, if at this point the overall goal is to move the direction towards that obstacle, the system will decide to move back towards that obstacle, possibly now approaching from an angle that would cause a collision without sensors picking the obstacle again. Of course this problem could be solved if the system required that the vehicle move a certain distance forward before allowing for course correction. This would be a state representation of the system in which it would be in a mode that limits its possible motions based on previous sensor inputs. This would dictate a hierarchy that requires the system to compound complexity because of the possibility of

recursion. A subset of this problem occurs primarily at distances greater than JPL's farthest scan line. Obstacles that have been detected can slip in between laser stripes and no longer be detected by the sensor suite. In these cases the approximate map retains information about these obstacles in a finite amount of physical memory. The decision in the scenario previously mentioned can be made based on the regions of the map next to the rover. So the obstacle now shows up in the region to the side of the rover and the system will not turn back that way until the danger in that region has decayed away.

The second area that gives the approximate mapping scheme value is that it takes data for greater distances ahead. For medium range path planning ,greater sensor range can be shown to add significant benefit. Given obstacle information for even three vehicle lengths ahead, the vehicle could prevent itself from making a longer trip than necessary. Figure 9 shows a scenario that a system that looks even slightly farther ahead than is currently being considered by JPL will improve efficiency of getting to the target destination. Here, the vehicle comes to a rocky area blocking direct travel to the goal. Since the longer range sensors pick up the general shape of the peninsula sloping to the left of the rover, it deviates in that direction. The shorter range vehicle continues forward and happens to find a small section of the blockade sloping to the right from the desired direction. It therefore follows the line to the right and takes the long road home. There are obviously counter examples that might force the system to make a similarly poor choice. In general, a system can detect larger structures and trends with longer range sensor information and, therefore, is better off with extension of its vision.

B. *Justification of Map Regions*

For this thesis the location of map regions has been primarily based on intuition. The front active regions are each located with a laser and scan line intersection associated with it.

1) *Active Region Locations:* The active regions are highlighted in Figure 10. Since the sensor

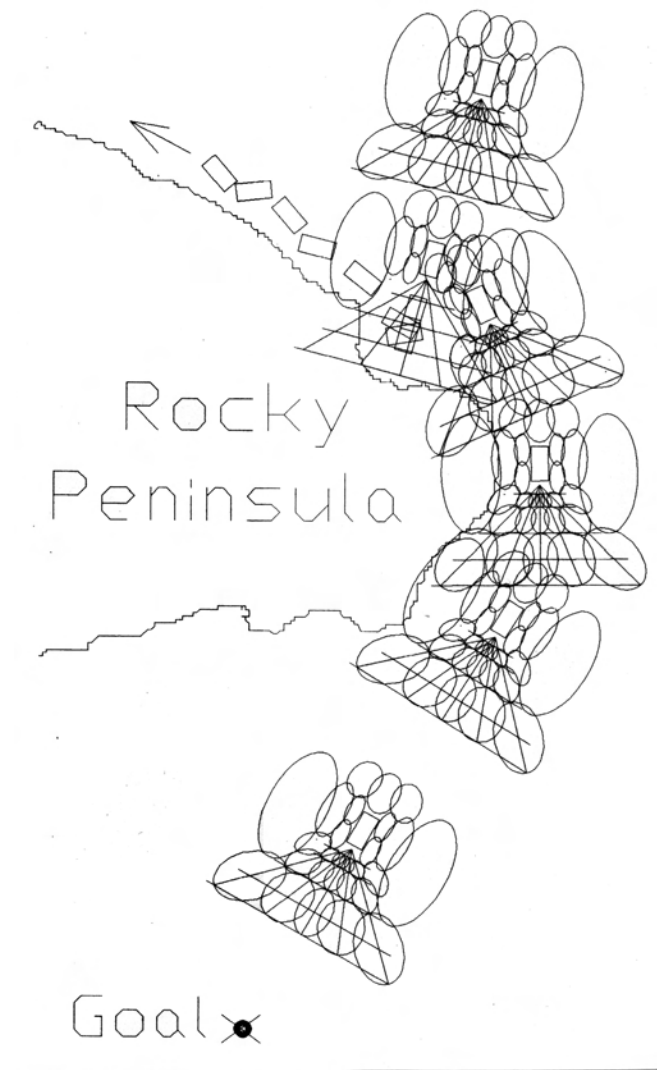


Figure 9. Example giving support to scanning for obstacles at a longer range.

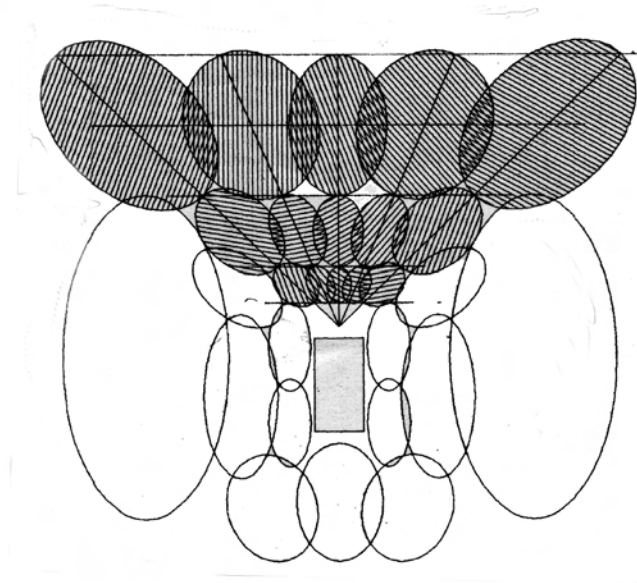


Figure 10. The fuzzy map active regions.

does not pick up an obstacle until it is closer to the vehicle than the scan line, the active region's far point is set on the intersection point and overlaps with the surrounding regions. The regions overlap to represent the somewhat ambiguous representation of obstacles. Hazards are not necessarily contained in only one region. Note that the computer user interface map shows the regions as ellipses even though this is only an approximation. The author's image of the map is closer to the concept sketch shown in Figure 1.

2) *The fuzzy map "virtual" regions:* The regions not highlighted in Figure 10 are chosen based on locations with information that is generally used by a human driving a car. The two small regions immediately to the left and right of the closest row of active regions to the vehicle are peripheral areas. The peripheral regions are areas which a driver would check before turning. The four regions immediately to the side of the rover affect a decision to turn also especially if the vehicle is given slip steering abilities. The front two regions in this set must be checked before making a forward Ackerman turn. The back two regions should be considered before attempting a reverse maneuver. The rest of the regions give more general local information and should not have an immediate effect on the rover's decision but do indicate trends in the terrain which are useful in optimizing the path taken when there are few hazards indicated by the map.

3) *Naming of Regions:* For convenience and linguistic description purposes each region has a name and an abbreviation. Figure 11 shows the name for each region and its abbreviation.

C. *Sensory Data and the Active Regions*

As indicated in the previous chapter, the presence of an obstacle is indicated by a deviation in the location of a particular laser on a scan line. A small pixel deviation indicates either a small obstacle or an obstacle just inside the scan line. A large pixel deviation indicates a large obstacle which is closer to the rover. At a certain pixel deviation, the obstacle would be considered large and

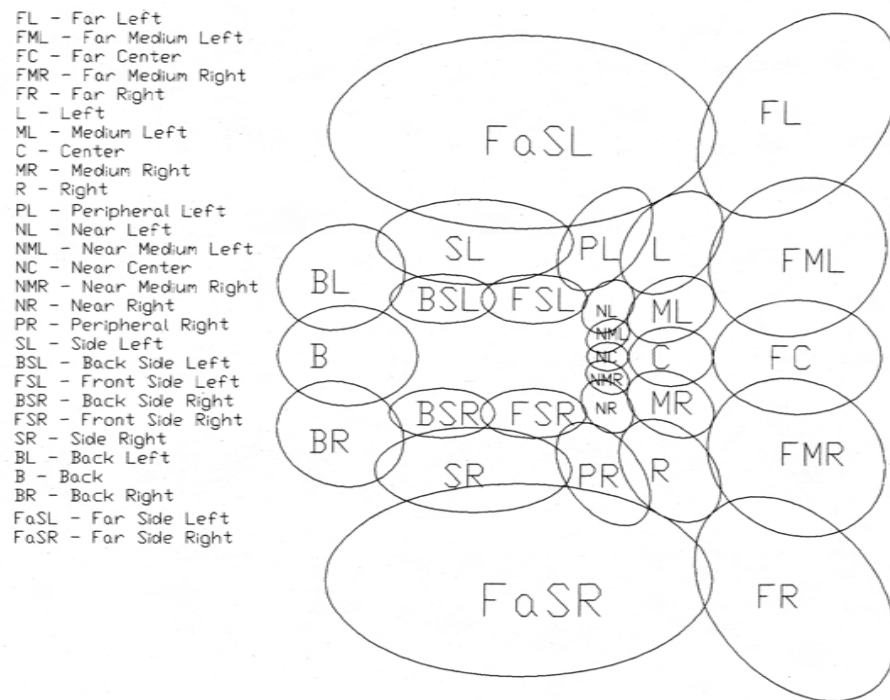


Figure 11. Names and locations of fuzzy regions.

close enough to the front end of the associated region that it is impossible for the vehicle to enter that region (i.e. the membership value should be 1). A larger pixel deviation indicates that the object is closer to the rover; therefore, the obstacle is actually in the next closest region and will be picked up by the next closest scan line. Since it is assumed that there are no obstacles behind this tall obstacle, the membership value for the farther region should begin to decrease. At the point where the near region has full membership the far region should have a zero membership value.

To justify the above assumption since the sensor system is not omniscient, so the system has no idea what is behind the large obstacle described. The above assumption is justified because the sensor system is not omniscient, a large object will block its view of anything behind it. Thus, the contents of the region behind is unknown. If the rover moves past the obstacle the sensors will again land on the regions behind and will then find out how passable the region is. However, if it is already considered impassable the system will avoid that region completely and possibly bypass a viable path.

1) *Fuzzy Membership Function:* To map the pixel deviation into the fuzzy map, a function of pixel deviation, $\Delta P_{m,n}^c$, to a membership value in the set of impassable regions, $\mu_{m,n}^c$, (note the superscript c indicates the camera which is active; it is dropped for clarity in the following equations) is defined by a piece-wise linear function such as equation (1).

$$\mu_{m,n}(\Delta P_{m,n}) = \begin{cases} 1 & \Delta P_{m,n} \leq a \\ \frac{\Delta P_{m,n} - b}{a - b} & a < \Delta P_{m,n} \leq b \\ 0 & b < \Delta P_{m,n} \leq c \\ \frac{\Delta P_{m,n} - c}{d - c} & c < \Delta P_{m,n} \leq d \\ 1 & d < \Delta P_{m,n} \leq e \\ \frac{\Delta P_{m,n} - f}{e - f} & e < \Delta P_{m,n} \leq f \\ 0 & \Delta P_{m,n} > f \end{cases} \quad (1)$$

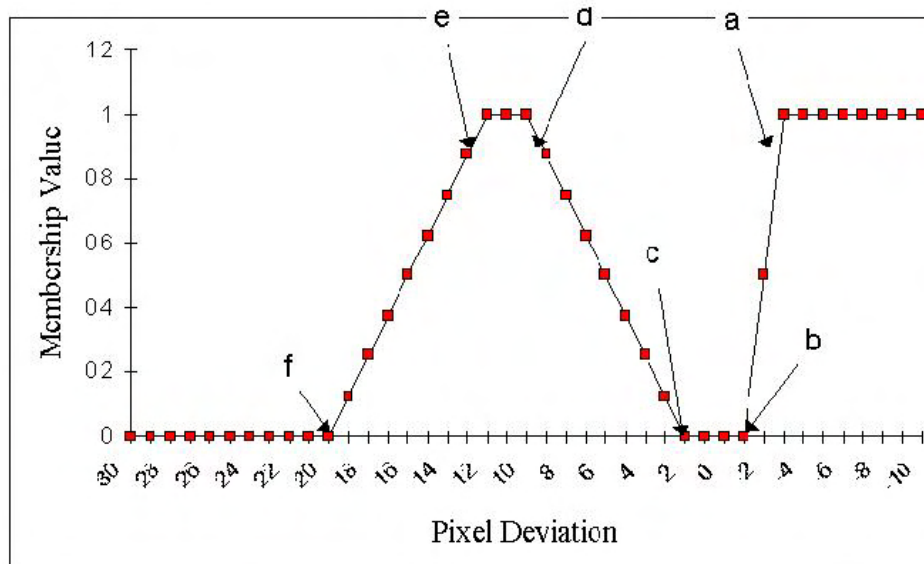


Figure 12. Fuzzy membership function mapping pixel deviation to membership value.

Figure 12 shows the fuzzy membership function. A negative pixel deviation means that a hole has been detected. Since a hole can be more dangerous to the mission than a boulder, the membership function rises quickly and remains high for fairly small laser deflections. Point *a* on the membership function is the deviation at which a depression in the terrain is considered impassable and the membership value should be at the maximum. Point *b* represents the pixel deviation where a hole begins to be significant. Between points *b* and *c* there is a question as to whether an obstacle exists. Due to lighting conditions or slight variations in the terrain, the expected pixel location can vary a few pixels so the region $[b, c]$ is left at 0 to neglect noise. At point *d*, an obstacle is considered to completely block the region from entry. A pixel deviation equal to point *e* indicates that a tall obstacle is now near the boundary between the region and the next nearer region. For pixel deviations between *e* and *f* the obstacle is between regions becoming more in the near region towards *f* and the responsibility of the near scan line. For the scan line nearest the rover, there is

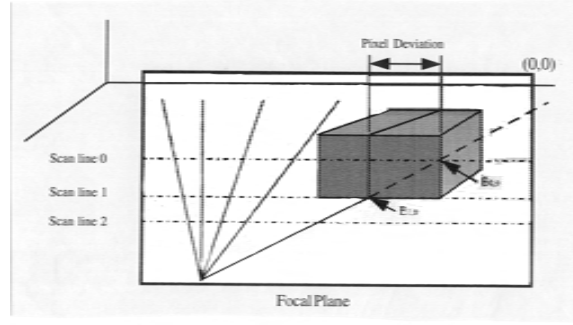


Figure 13. Drawing showing the pixel deviation for a vertical obstacle just entering the region of the next closest scan line.

no nearer scan line; therefore, points e and f are placed at infinity and the membership function does not come back down to 0.

Guidelines for setting these points are based partly on the fact that the laser planes are vertical to level ground. Because of this a vertical obstacle intersecting the plane will show up at approximately the same horizontal pixel location for each row of pixels. Thus, as shown in Figure 13, the pixel deviation, $\Delta P_{m,n}$, for a vertical obstacle just crossing the next closest scan line is equal to the expected pixel location for the next closest scan line, $E_{m+1,n}$ minus the expected pixel location of the scan line, $E_{m,n}$. Table II summarizes the guidelines to choosing the membership function break point locations. Following Table II the functions should be defined starting with the closest scan line. The c parameters for each sensor's membership function is a free variable and is set based on desired sensitivity.

The map is designed to accumulate information. Therefore, the membership value of the region previous to sensor input should be added to the sensor membership value determined by (1). The accumulated membership value, $\aleph_{m,n}$, is bounded to the range $[0, 1]$. The expression for this

Table II. Guidelines for choosing break points for fuzzy membership functions.

point	location range	comment
$a_{m,n}$	$a_{m,n} < b_{m,n}$	The closer a is to b the more sensitive the function is to depressions.
$b_{m,n}$	$b_{m,n} < 0$	b chooses allowance for noise.
$c_{m,n}$	$c_{m,n} > 0$	c chooses positive noise allowance.
$d_{m,n}$	$c_{m,n} < d_{m,n} < e_{m,n}$	The closer d is to c the more sensitive the function is to protruding obstacles.
$e_{m,n}$	$E_{m+1,n} + c_{m+1,n} - E_{m,n}$	This begins to decrease $\mu_{m,n}$ when $\mu_{m+1,n}$ begins to climb, for a vertical obstacle.
$f_{m,n}$	$E_{m+1,n} + d_{m+1,n} - E_{m,n}$	This makes $\mu_{m,n}$ zero when $\mu_{m+1,n}$ is one.

accumulation is given in (2).

$$\aleph_{m,n}[k] = \max \{1, \aleph_{m,n}[k-1] + \mu_{m,n}[k]\} \quad (2)$$

For the center laser, $m = 2$, both cameras take a reading. For this reason the center region membership values are determined by (3).

$$\aleph_{m,2}[k] = \max \{1, \aleph_{m,2}[k-1] + h (\mu_{m,2}^L[k] + \mu_{m,2}^R[k])\} \quad (3)$$

where h is a constant chosen in the range $[0.5, 1)$. This allows the center laser to have two opportunities to find the obstacle but not have a small reading from each camera indicate a menacing obstacle. Table III translates the m and n values to the region abbreviations.

D. Translation of Fuzzy Membership Values

The map is relative to the vehicle; thus, it moves with the vehicle. Obstacles detected at one location move with respect to the rover and the map. This means information in a region of the map should be passed to adjacent regions which move into the area previously occupied by the original

Table III. Reference m and n values to region abbreviations.

	Left Camera			Right Camera	
m/n	0	1	2	1	0
0	FL	FML	FC	FMR	FR
1	L	ML	C	MR	R
2	NL	NML	NC	NMR	MR

region. Figures 14 and 15 show the original position of the map with respect to the maps position after an incremental movement. In effect, the fuzzy membership value of a region decays with movement and flows into appropriate adjacent regions. Figure 14 shows a forward movement of the vehicle and the map. The regions adjacent to the back of other regions move into area previously occupied by the forward region. In Figure 15, an Ackerman turning maneuver is shown for the vehicle and the map. Note that the regions outside of the turning arc move further than the inside regions.

The method for translating values must be simple, else the purpose of the map is defeated. The simplest method is to have the region value decay by a set percentage per move and to transferred the percentage decayed to the adjacent regions.

1) *Decay of membership value due to translation of vehicle:* The decay factor is based on the number of moves necessary to translate the current location of the region completely out of its original location. For the active regions this distance is the length of the path, l_c , from the center of the region to the outside edge in the direction of travel. The center is chosen because an obstacle causing full membership occurs at approximately the center. Equation (4) expresses the decay of a membership value by a constant $a_{\mathcal{R}}^d$, where d denotes a direction of travel and \mathcal{R} denotes the region.

$$\aleph_{\mathcal{R}}[k+1] = a_{\mathcal{R}}^d \aleph_{\mathcal{R}}[k] \quad (4)$$

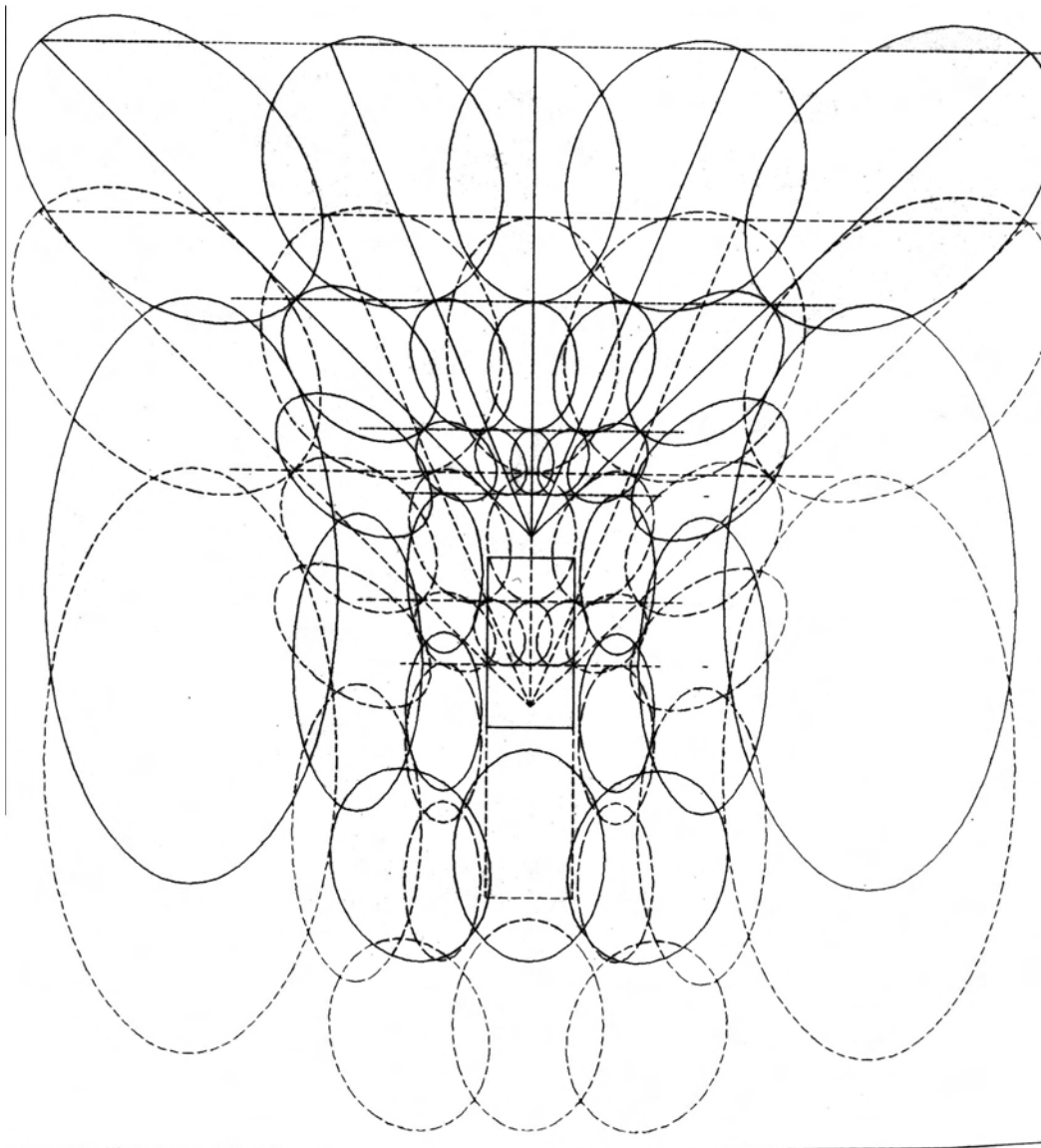


Figure 14. Forward translation of rover moves areas that were in forward regions to regions behind them.

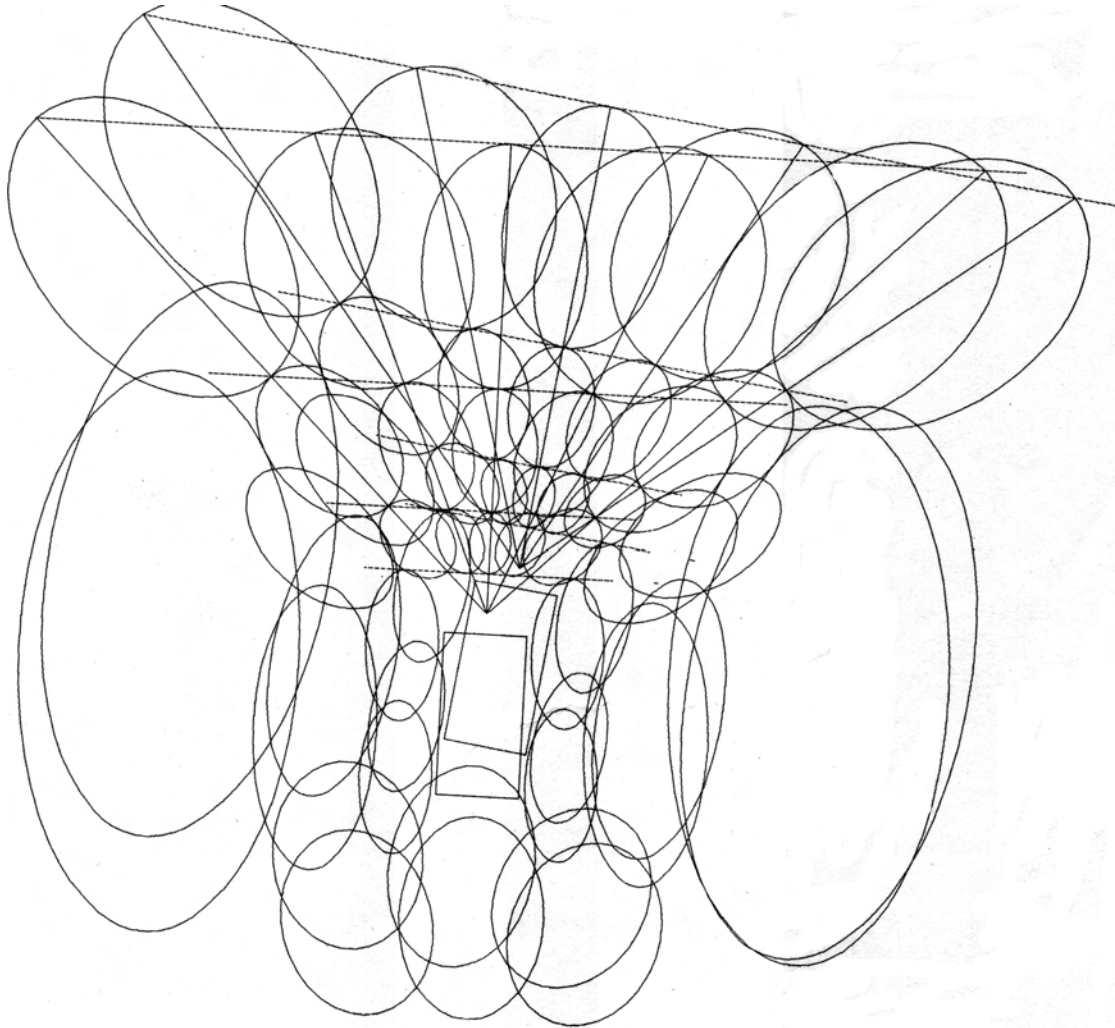


Figure 15. Ackerman turning translation translates and rotates the map through old map regions.

The constant a can be chosen by determining the number of moves that should be required to clear a region with full membership. Finding the distance l_c for the region and knowing the incremental distance for each move, Δd , the number of moves required is the ratio $l_c/\Delta d$. The membership value is required to decay from 0.9 to 0.1 in $l_c/\Delta d$ moves. Equation (5) expresses this requirement.

$$0.1 = 0.9 (a_{\mathcal{R}}^d)^k \text{ where } k = l_c/\Delta d \quad (5)$$

From this a can be found with (6).

$$a_{\mathcal{R}}^d = \sqrt[k]{1/9} \text{ where } k = l_c/\Delta d \quad (6)$$

The variable k is not limited to the set of integers in (5) and (6).

For the “virtual” regions the decay constant is based on the full cross-sectional distance across the region. This is reasonable because a hazard must move from the front of the region through the entire region. The expression for the decay constant for the virtual region is the same as in (5) and (6), except l_c is now the entire length of the region.

2) *Transfer of membership value:* The portion of the membership value that decays is passed back to regions opposite the direction of translation. So regions which share an overlapped area will pass information between each other. The constant for the amount translated is denoted as $b_{\mathcal{R},\mathcal{R}_i}^d$ where \mathcal{R}_i is the adjacent region passing information into \mathcal{R} . The full expression for updating membership values is given in (7).

$$\aleph_{\mathcal{R}}[k+1] = a_{\mathcal{R}}^d \aleph_{\mathcal{R}}[k] + \sum_{\text{all adjacent } \mathcal{R}_i} b_{\mathcal{R},\mathcal{R}_i}^d \aleph_{\mathcal{R}_i}[k] \quad (7)$$

Choosing appropriate b 's has been accomplished heuristically based on a couple of reasonable guidelines. First, the sum of the b 's for passing information out of a region is approximately equal to $1 - a$ for that region as in (8).

$$\sum_{\text{all adjacent } \mathcal{R}_j} b_{\mathcal{R}_j, \mathcal{R}}^d = 1 - a_{\mathcal{R}}^d - c_{\mathcal{R}}^d \quad (8)$$

The constant $c_{\mathcal{R}}^d$ is introduced as a forgetting factor so some of the information is lost as past sensor information becomes vague. The choice of how much each b gets is dependent on the percentage of its shared border area in the direction normal to the movement of the vehicle. If two regions border a region to the rear, such as Left (L) and Medium Left (ML) border Far Medium Left (FML), see Figure 11, the constant, $b_{FML,L}^{\text{forward}}$ controlling the amount going to region L will be somewhat larger than $b_{FML,ML}^{\text{forward}}$ for ML .

One other consideration is made. When adjacent regions have much different overall areas the b 's between them must be adjusted. The approximate adjustment is to multiply the b found using (8) by the ratio of the total areas of the two regions. Therefore, a large region being passed information from a smaller region will have a smaller b . This causes that area's membership function to grow at a slower rate.

E. *Algorithm Summary*

A description of the approximate mapping algorithm is given here. Figure 16 gives a flow diagram of the process. The source code for the approximate mapping algorithm is included in Appendix B. The windows interface handles all user inputs and gives over control to the mapping algorithms when operator gives a movement command.

Initially the all map region values are set to 0. This was the obvious first choice as initial values for the map assuming a clear map until sensor information is available. A more cautious approach would be to set all regions except the active regions to full membership to make sure the rover does

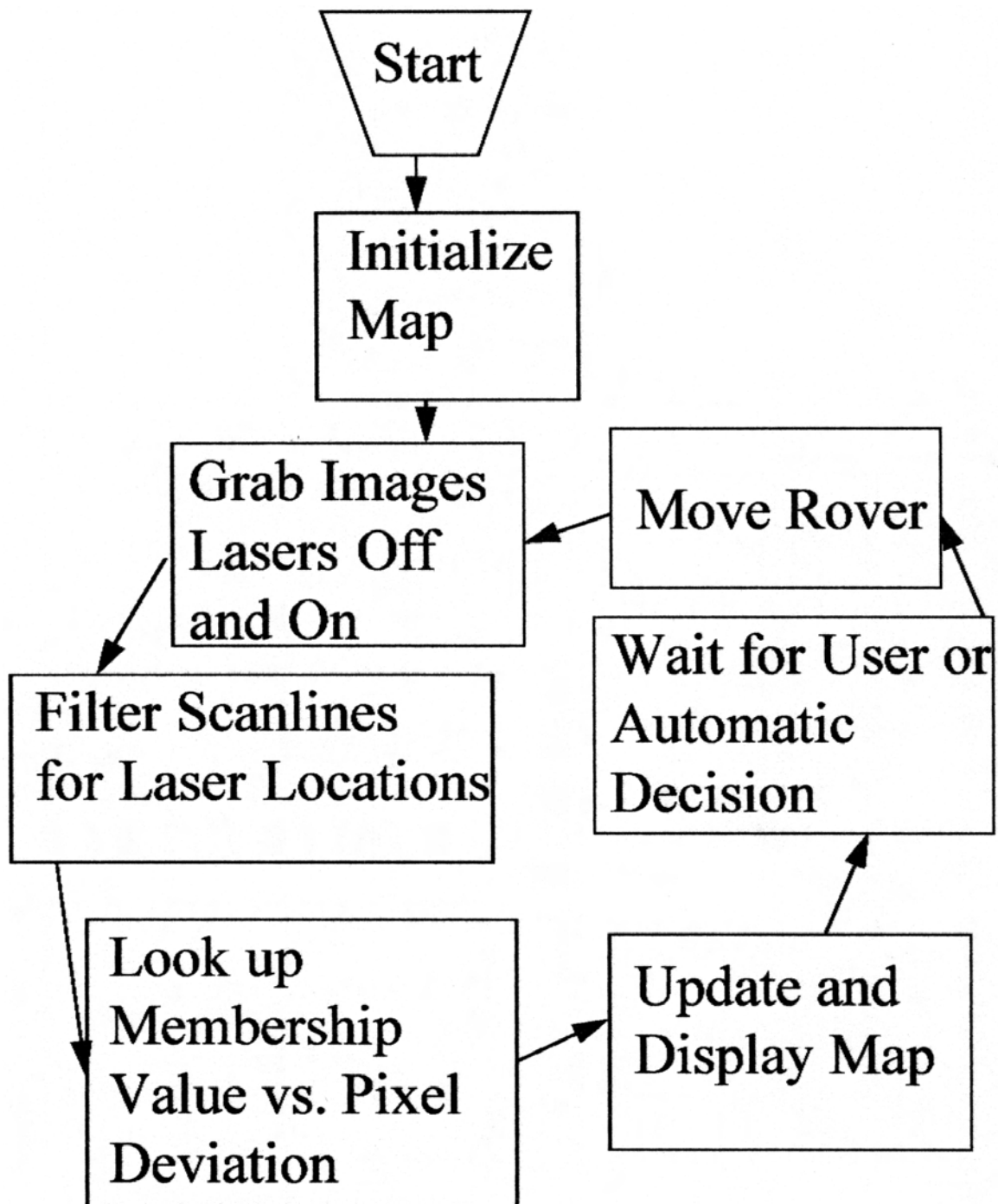


Figure 16. Flow diagram of approximate mapping algorithm.

not turn or back into obstacles in the first couple of moves.

1) *Grab Images:* The first task is to get image information from the camera. An image is grabbed by the frame grabber card and stored as 512 by 512 8 bit grayscale images in memory of the PC. Images from each camera are taken both with the lasers on and off, for the purpose of image differencing. The image differencing works well as long as the lasers do not add significantly to the overall ambient light condition in which case the intensity levels are shifted by the frame grabber card and image subtraction does not give desirable results. If the images to be differenced do not exactly register, due to video signal disturbance, the differencing causes anomalies which will cause errors in laser detection.

2) *Find Laser Pixel Location:* The filtering process described in Chapter III, explains how to find the bright spots corresponding to a laser on one row of the image. Each scan line is processed from the outside or the active side to the inside with the left camera searching left to right and the right camera searching right to left. The algorithm begins with a default threshold for the filter value. The algorithm looks for a local maximum on the scanline above the minimum threshold. After finding a local maximum, the algorithm logs the pixel location of the laser and goes on to find the next minimum.

If the algorithm does not find enough lasers, local maximums above the threshold, it tries again with a lower threshold. If the threshold becomes too low spurious laser locations are found, so a minimum threshold is set as a stopping point. This method allows the system to adapt to different lighting conditions.

Another check is performed to make sure the pixel location found for a particular laser is actually that laser. If the pixel deviation is out of a range, it is assumed that it is not a correct value. If it is too low, the pixel value next to it is checked. If it is in the correct range the pixel value is shifted over. If it is too high, it is assumed that the laser was missed either due to being too dim or being

physically blocked by an obstacle. For far scan lines it is highly probable that a low signal to noise ratio (SNR) is the cause and no obstacle is assumed. For the closest scan line, a missing laser is considered critical. Either a large obstacle is blocking the camera or even worse a large cliff caused the missing lasers. In either case the interpretation is made that a menacing obstacle lurks nearby and the region is given full membership.

Since the system used here turns either all lasers on or all lasers off, there is some chance of confusion of which laser caused a particular bright spot on a scan line. In the case of the far scan line a tall obstacle fairly close to the vehicle can show up in the range of the nearest neighboring laser. This is not critical however because this does not occur at the near scan line unless a huge obstacle is immediately in front of the rover and the algorithm tends to make the map “red” anyway. Mistakes due to this system glitch at far scan lines are a nuisance but do not subtract from the abilities of the map. The difficulties can be solved by incorporating additional system hardware which allows one laser at a time to be activated, as the actual Rocky rover does.

3) *Membership Value and Map Update:* After the pixel locations are found the membership values are looked up and added to the map appropriately as described above. The new map values are then displayed to the human driver via the user interface or to an automatic system for a navigation decision. The system also keeps track of dead reckoning position and angular heading and displays this also. The source code for the dead reckoning system is given in Appendix B.

4) *Move Rover and Repeat:* When the user gives a command, the rover is controlled via a digital to analog board in the PC to the RC transmitter. The vehicle is moved a predetermined distance with either right, neutral, or left turning signal on the front wheel steering servo. When the rover completes its move the process begins again with the imaging process.

CHAPTER V

INTELLIGENT DECISION ALGORITHMS

This chapter sets up several possibilities for using the approximate map as input to an automatic decision scheme.

A. *The Benefits of Using the Approximate Map for an Automatic System*

The map provides several features of the map which are conducive to developing a tractable autonomous navigation system. As mentioned previously, the map provides a minimal memory and processing scheme for tracking sensor information. The whole point of creating an approximate representation of the terrain around the vehicle is to create a tractable image to present to an autonomous system.

The map creates a representation of the world that can be presented to a human operator. If a human operator can negotiate obstacles referring only to the approximate map, it is highly probable that a reasonable system can be designed to perform a similar process. Since the map compresses the information about the environment, the size and complexity of the decision system can be made computationally tractable. This is extremely important if the attempt to mimic human behavior is taken on by a neural network or fuzzy rule base, since the complexity of the structure increases greatly with the addition of more inputs. So the reduction from a full image (given a 320 by 200 image) to the map (28 regions) is extremely valuable.

The visual memory is also in a form which can be analyzed. The regions to the side and behind the vehicle can be visually inspected with the position of obstacles around the test vehicle to assure that the system is remembering in an accurate and valuable manner. Finally, the structure of the map allows it to easily link to several intelligent decision making schemes, such as a neural network,

traditional logic, or fuzzy logic inference systems. These possibilities are the topic of the following sections of this paper.

B. *Autonomy Via Artificial Intelligent Schemes*

The ultimate goal of this research is to provide an autonomous decision making process for the rover that improves upon current algorithms. This could be done in many different ways. In this section, the methods being considered will be covered briefly. The first is the possibility of training a neural network to emulate the human response. The second is the generation of a fuzzy rule base to perform the decision process. The third is a hybrid of the first two in which a fuzzy rule base is generated via a neural network structure and trained to fine tune the system. And a fourth, which is not autonomous but possibly useful anyway, is the use of the fuzzy map for tele-operation of the vehicle.

C. *Preliminaries*

There are several things which must be decided on before approaching the problem of creating an intelligent controller. The first is what type of input will be given to the system. This spot is obviously filled with the ordinal membership values of every region defined on the fuzzy map. It could also be filled with only the direct sensor data and some other way of remembering obstacles, probably at much greater memory and processing expense.

The second consideration is the type of output from the system. This question must be answered taking into account the physical abilities of the vehicle. It is possible that the steering control be completely proportional requiring a continuous range of outputs. The speed and distance the rover travels between each sample of the terrain is another consideration. The speed itself could be variable. The steering of the vehicle can also be Ackerman or slip. For the purpose of this research into obstacle avoidance algorithms, due primarily to the fact that USU test bed has only front wheel

Ackerman steering, only five possible choices are allowed: go forward, back up, turn right (forward drive), turn left (forward drive), or call for help. The system will have to make the decision between these alternatives based on the obstacle information in the fuzzy map and a heading error vector.

D. *Neural Networks*

A neural network solution to the decision system design requires a complex structure of simple building blocks simulating those of neurons in animal brains. Many common methods for training use supervised training, such as back propagation of error. In this method a large set of input/output data is collected from the real system. In this case the input to the system is the fuzzy map and the desired output is the “expert” human response to the map. The input is fed through the network. If the actual output is different from the desired output, the error is translated back and the system parameters are changed to reduce the error. This technique has been used successfully for system identification and control systems.

E. *Fuzzy Rule Base*

Even though neural networks have had numerous successes, even at USU [14] [15] and [16], and many exciting possibilities exist for them, there are some drawbacks to using such a “learned” system. The primary disadvantage is that analysis of signals at inter-nodes in the structure is just as impossible as analysis of what one neuron in your brain is contributing to your ability to walk down the street. In a fuzzy-rule base, an expert uses a spoken or written form of language to describe criteria used for a particular process. This linguistic description, for the purpose of fuzzy inference, needs to be formed as if-then statements. If she is tall, then she must duck a little to get under the door; Or, if she is really tall, then she must duck a lot. This description is imprecise in terms of what tall and ducking a lot mean. This is where the fuzzy inference method differs from the behavioral methods. Numerous rules may be described for a certain control process and all those rules are fired

for each decision; but, each rule is fired only to the degree in which the antecedent is “true”. The statement “the 5 feet 6 inch woman is tall” is true to a certain degree depending on how the expert forms a membership function. In this fashion rules can be developed to make decisions based on the fuzzy map and desired direction inputs. The advantage over neural networks is that each rule can be analyzed for each fuzzy map “image”.

F. *Fuzzy-Neural Technique*

There may be a compromise between the previous two methods. Examples of this are shown in [17] and [18]. A network structure could be developed that took the place of the rules. In such a system a node (neuron) would fire to the extent that the rules antecedent was true. Nodes could be predefined for rules that are obvious. But, for more subtle aspects that even an expert would have trouble explaining verbally, the system could be trained via back propagation to randomly initialized nodes. After training, these nodes could be analyzed as rules since the structure is not as amorphous as a multi-layered initially random network.

G. *Tele-operation*

One of the major drawbacks to tele-operation is that, normally, complete images must be transmitted back in intervals that allow the object being controlled remotely to avoid hazards and allow it to perform its functions adequately. This is a huge amount of information to transmit, especially over planetary distances. The twenty minute time span between Earth and Mars would cause at least an hour delay between image retrieval and up-link of commands. With the fuzzy map it is possible to send back only 28 characters to represent the maps membership values. The time delay for signals is not helped but the duration of the image sent is dramatically reduced.

CHAPTER VI

UTAH STATE UNIVERSITY TEST BED VEHICLE DEVELOPMENT

For the purpose of testing the mapping algorithms with the same sensor set up as used by JPL's rover, a test bed vehicle was constructed. The cost of the vehicle was minimized by using commercially available parts as much as possible and by doing all processing off board using a personal computer. The test bed is necessary for the purpose of convincing JPL and others that USU has a serious interest in contributing to the world of autonomous vehicles. As a demonstration tool the test bed gives a realistic setup for testing the algorithms developed. Having the rover realized in hardware also limited the amount of software development which had to be completed to test the system. A software simulator of the sensors in a virtual world would have taken excessive development time. This chapter gives a brief functional description of each system component.

The main blocks of the test bed system are tied together by electronics on a printed circuit board in the test bed vehicle and the personal computer.

A. *Test Bed Chassis*

After much consideration, the basis for the test bed chassis was made from a ten to one scale (RC10) radio control car chassis. Figure 17 shows the rover chassis in development. Figure 18 shows the completed test bed in a Mars like setting. The suspension was made rigid and other minor modifications made to allow the vehicle to support the telemetry and sensor systems, and batteries. The motor driving the rear wheels of the vehicle was chosen to be a small 12 volt DC motor geared down to a very low speed (approximately 50 rpm) corresponding to a linear forward (or backward) speed of approximately 5 cm/s. The slow speed is similar to that of the actual rover. The rover moves in 10 cm increments so speed is a low priority. The front wheel turning angle is controlled



Figure 17. Photograph of RC10 car chassis with modifications to suspension.

with a servo.

The four wheel system with on the back wheels is obviously not built for mobility. In fact, the vehicle bogs down in a on a few centimeters of sand and is completely stopped by even a small rock. The vehicle is only intended for use on flat surfaces. This is just as well because the sensor package does not include inclinometers such that data can be interpreted properly when the optical sensors are at a pitch of a significant amount.

B. *Optical Sensor System*

As mentioned previously the optical sensor system is made up of five diode lasers and two CCD cameras. The output signal of the CCD cameras is a standard video signal. The video telemetry system has only one channel. Therefore, the two cameras are multiplexed. The printed circuit board has a video switch integrated circuit and a video buffer. The video switch is activated by one of the channels on the forward control system described later. The lasers are also controlled. To conserve power and prevent electronics from over heating, the lasers are switched off and on. Switching the lasers also allows image differencing to be done to increase sensors signal to noise ratio.

The diode laser (Power Technology Inc.) are the same laser used by JPL for laboratory testing. The output of the lasers 7.0 mW at a wavelength of 670 nm.

C. *Video Telemetry System*

The video telemetry system transmits the selected CCD camera signal to the personal computer allowing the rover to maneuver without a tether. The system is made up of a commercial device for transmitting television signals a short distance. The transmit station sits on the rover and the receive station near the computer. The signal from the receive station is recovered using a video cassette recorder, which pulls out the video and audio channels from the radio frequency (RF) signal transmitted in the 900 Mhz band allocated for wireless in home applications. The video signal feeds

into an image digitizing, frame grabber card, in the computer. The image is then available for use by the sensor algorithms previously described.

Two different frame grabbers were used throughout this project. The first was a low cost monochrome frame grabber which divided each horizontal row into 320 elements. The first series of results shown in this thesis used this frame grabber card. The second card used gave better resolution, 512 elements per row, and faster display speed. It is also capable of doing processing on the card itself. The higher capabilities of the card were not utilized in this project but are available for future advancements.

Two different sets of CCD cameras were also used. The first pair were the least expensive model available. These cameras were small surveillance cameras with a highly curved, fisheye type lens used to get a wide field of view. The mounting of the cameras was a flat bracket. The cameras were secured using a strong two way tape. This made adjustment difficult. The new cameras were made with a standard camera mount. They have higher resolution and have a detachable lens with adjustable aperture and focus.

The audio channel of the television transmitters is used for the telemetry of heading information provided by an eight point digital compass. Each of the eight compass headings is translated into a signal of a different frequency in the audio range. It is decoded into a voltage using a frequency to voltage converter. The voltage is then read into the analog to digital board and interpreted by the software.

An eight point compass is not very useful for accurate heading information but can be used to correct the dead reckoning heading at transitions of the digital compass. If the dead reckoning heading error becomes large enough to disagree with the coarse compass an adjustment can be made. The heading is not necessary for the approximate mapping algorithm but is used as input to the vehicle operator as an error in heading to weigh against obstacle information.

D. *Forward Communication Control*

The system is linked to a personal computer. Control signals from the computer are sent via commercial radio control transmitter and receiver. The transmitter has been altered by tapping into the potentiometer's sweep so the voltage can be controlled with a digital to analog board in the computer. Two channels control the motion, motor drive and turning servo mechanisms. For the purpose of these experiments only four possible movements are allowed: forward, backward, full right with forward driver, and full left with forward drive. Full proportional Ackerman steering and full velocity control are possible in future implementations.

Two digital channels are also utilized for the control of lasers and camera switch. This was designed such that the 5 volt logic signals would change the sweep voltage to the extremes of the range. The signal on the receiver side is a pulse width modulated (PWM) signal which has a fifty percent duty cycle for neutral position of sweep voltage with higher duty cycles for higher voltages and corresponding lower duty cycles for lower voltages. A circuit which compares duty cycles to the neutral signal is used as the switching logic. The PWM switching circuit was designed by Gordon Olsen. The switches turn the lasers off and on and switch from left to right camera signals.

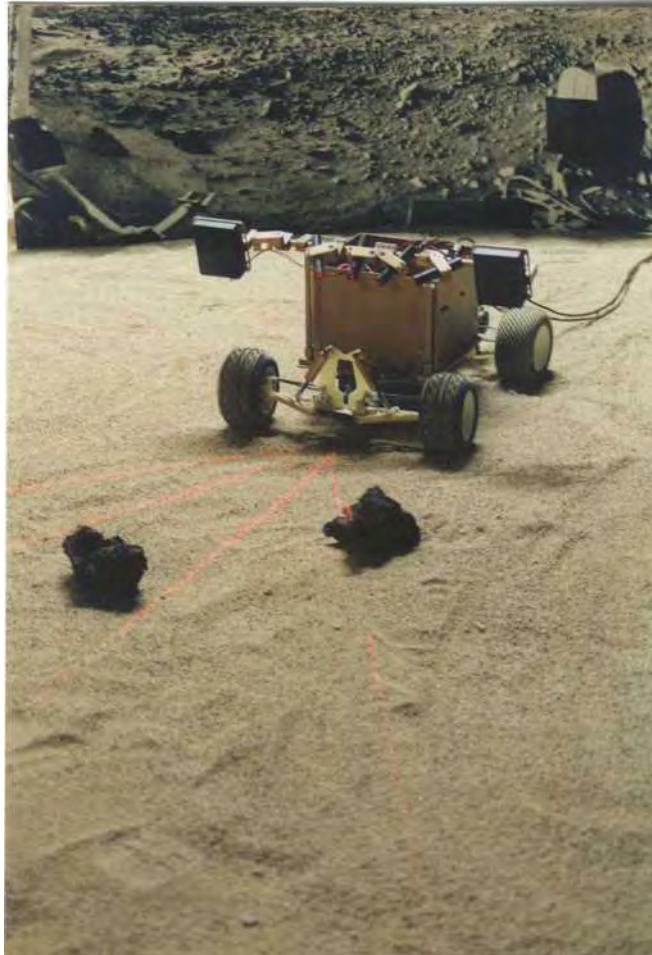


Figure 18. Photograph of completed chassis with lasers activated.

CHAPTER VII

RESULTS

This chapter describes the results of the approximate mapping algorithm as integrated into the USU test bed vehicle system. The majority of the results are pictorial, showing portions actual runs of the vehicle through obstacles fields set up in a laboratory setting. Two additional runs are included in Appendix C. Finally, some of the limitations of the current system are demonstrated to stimulate interest in continuation of this research effort.

A. *Approximate Mapping Runs*

The following examples are runs demonstrating the map process. The images for each iteration are also shown with the map. The highlighted arrow and the bottom of each set of images is the direction the rover proceeded on the next move. The left side compass shows dead reckoning heading of the rover. The compass on the right is the desired heading used to guide the driver to a fixed destination. The driver of the rover is instructed to primarily avoid obstacles but proceed towards a goal if possible.

All maps are shown in a gray scale with lightest shades meaning no obstacles. The images have the scan line locations faintly superimposed. When drivers were attempting to navigate by the map the images were not visible to them.

The success of the mapping algorithm is measured in two ways. The first test is how well does the map represent the actual terrain around the rover. This is a subjective test. If the map gives enough information to allow a human driver to get through a set of obstacles then the subjective test is validated by the practical test. So the practical test is exactly how well can a human drive the rover from just the map. Two runs are shown here to demonstrate the map. Several more are

included in Appendix C. Obviously, the more experienced drivers generally made it through the course more readily, but all were capable of avoiding obstacles via the map only.

B. *Run One*

The first run shown in Figures 19 and 20 was a straight forward run with one obstacle, not counting the wall. In the first moves, the obstacle appears in the far right regions first with the wall showing up on the right. The obstacle moves forward into the nearer regions and the wall begins to be detected in the far right side region. When the obstacle passes to the side, it begins to appear in the virtual regions to the left side. The regions to the left signify that an obstacle did pass to the left and should prevent the system decision maker from turning left until the region returns to near green (black) shades.

This run demonstrates the maps ability to remember the obstacles, even after they have passed out of the sensors field of view.

C. *Run Two*

This run shows a substantially longer run with a much more complex maze. The desired direction for this run is a heading slightly to the left of the start heading. The desired heading was chosen to put the vehicle into the corner of the room. The driver's experience level was fairly high. Figure 21 shows the start of the run.

The driver initially turned to the left to correct for heading error and encounters the first obstacle. By the fifth and sixth moves, Figure 22, the driver realizes that to avoid the obstacle a maneuver must be made to the right. A more cautious driver might have seen clues that a large obstacle was coming, but still managed to avoid the obstacle. It is difficult to trust the longer range areas, especially, if the driver puts a priority on course correction.

After negotiating the first hazard the driver remained to the right until the obstacle has decayed

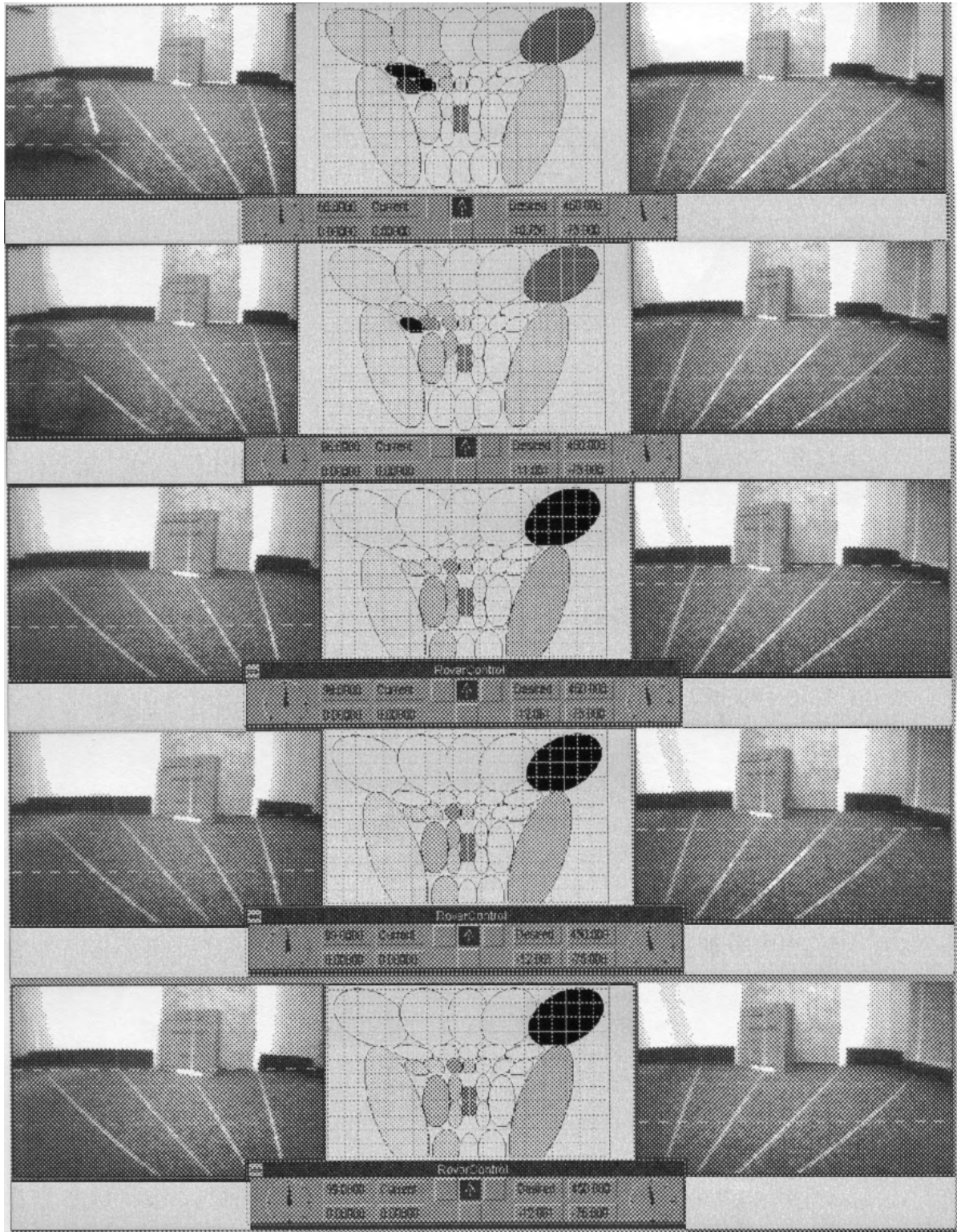


Figure 19. Run 1—all forward moves and only one obstacle.

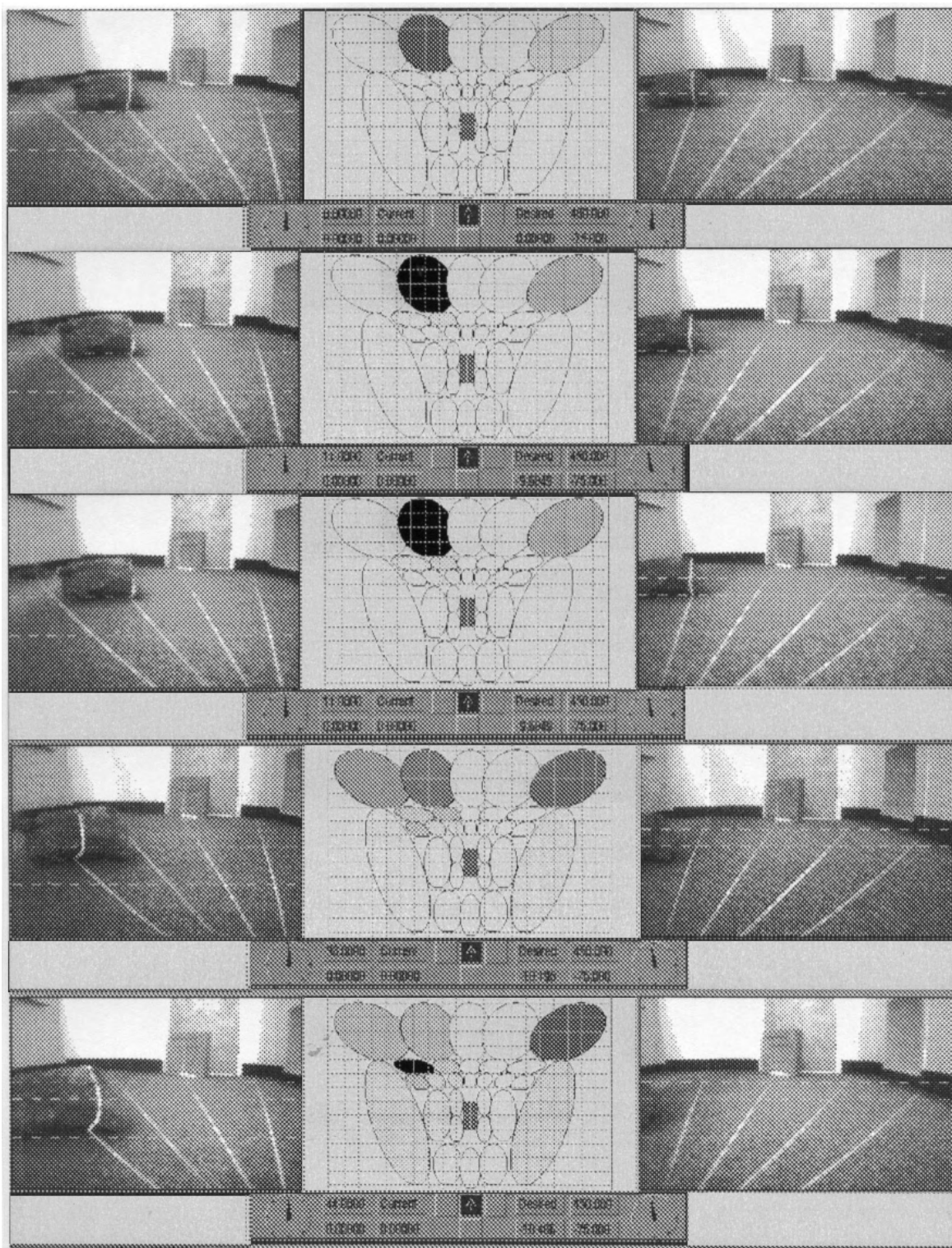


Figure 20. Run 1 continued

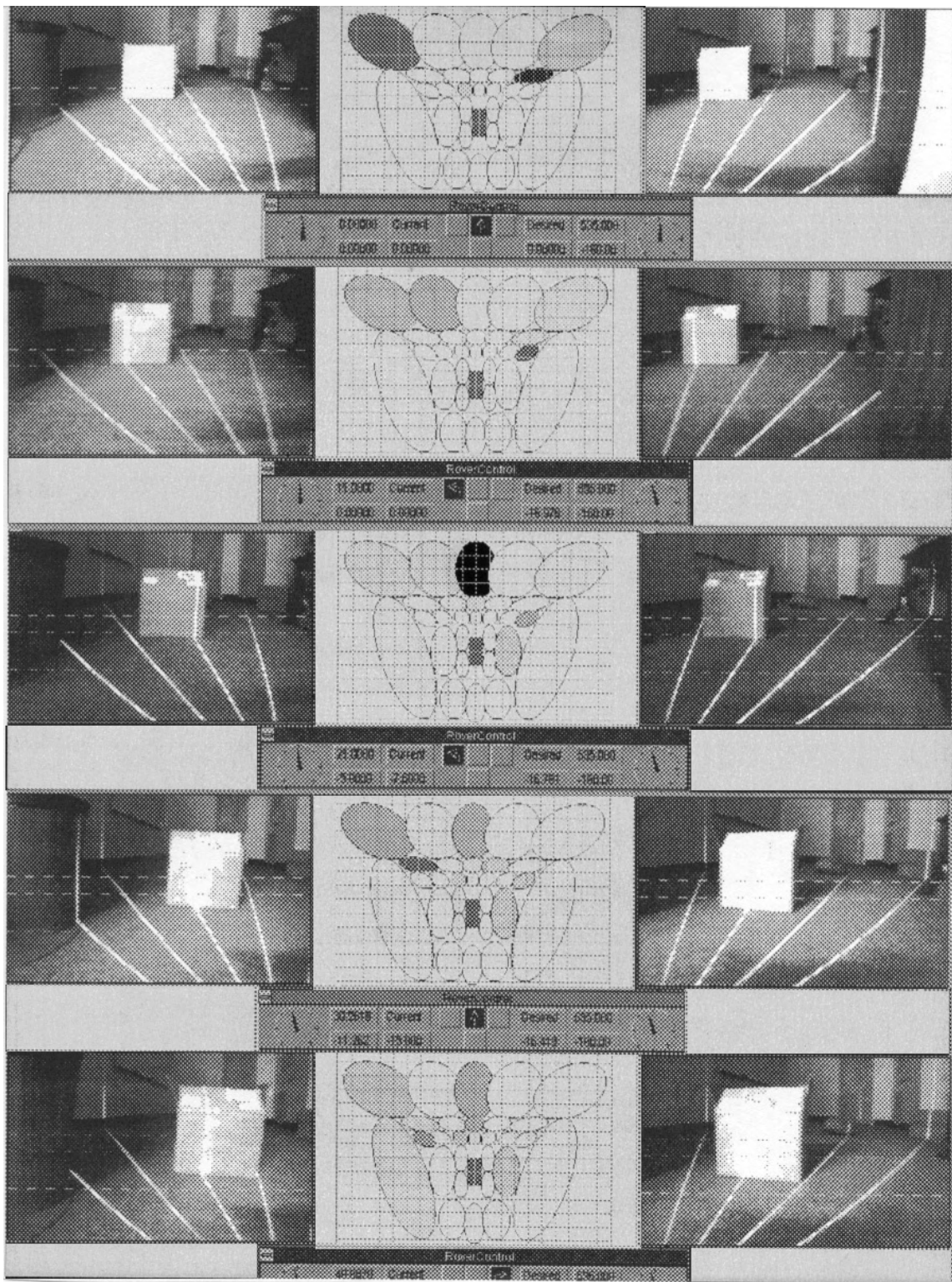


Figure 21. Run 2-Initial moves with complex course.

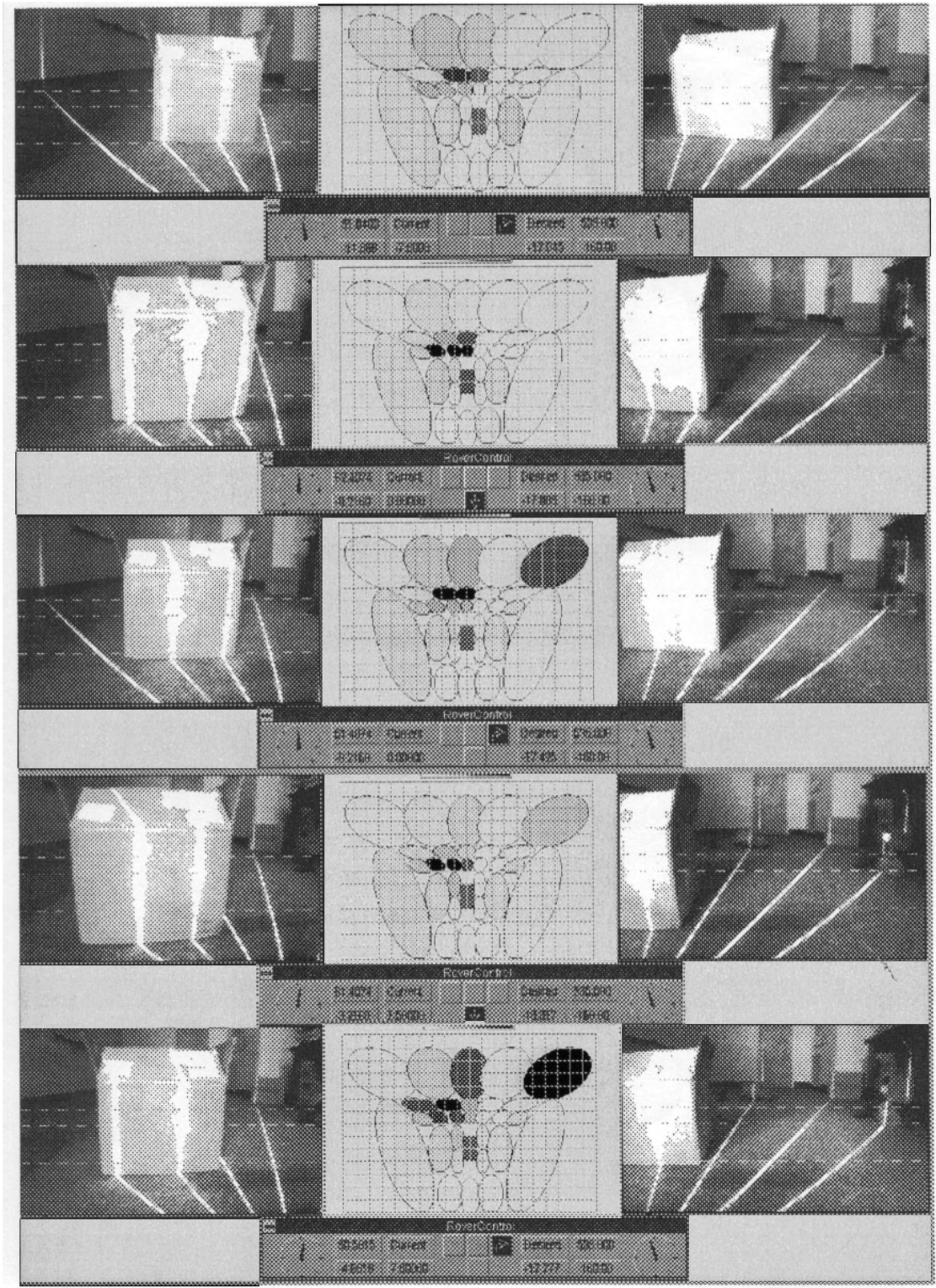


Figure 22. Run 2 continued—Driver forces to go right to avoid obstacle.

from the front left side regions, Figures 23 and 24. The map encourages the appropriate behavior, when the driver realizes that the front side regions are in the path of a turning maneuver. The driver then suppresses the decision to go left because of the high membership value in that region.

After passing the obstacle, driver again makes the decision to correct for course heading but is foiled again by another obstacle, see Figure 25. At this point the driver, avoids the second obstacle and in Figures 26 through 29 makes it to the corner of the room.

This run demonstrates the full ability of the map to represent a complex situation and guide a driver through a course with a very limited amount of data. It is also possible to see that the driver could explain to you in simple terms what caused a particular decision.

D. *Demonstration of Limitations of Current System*

There are situations in the real world in which the current system fails completely. As previously mentioned, unlevel terrain causes the current test bed vehicle to fail. Three situations of uneven terrain are demonstrated here. In Figure 30, the rover is shown on level ground with no obstacles. Here the lasers intersect with the scan lines at the expected pixel locations. The first situation has the rover's front wheels off the ground about one inch. In Figure 31, the results are shown in the images and resulting map. The other two situations, side wheels lifted and back wheels lifted cause similar unacceptable results, as shown in Figures 32 and 33.

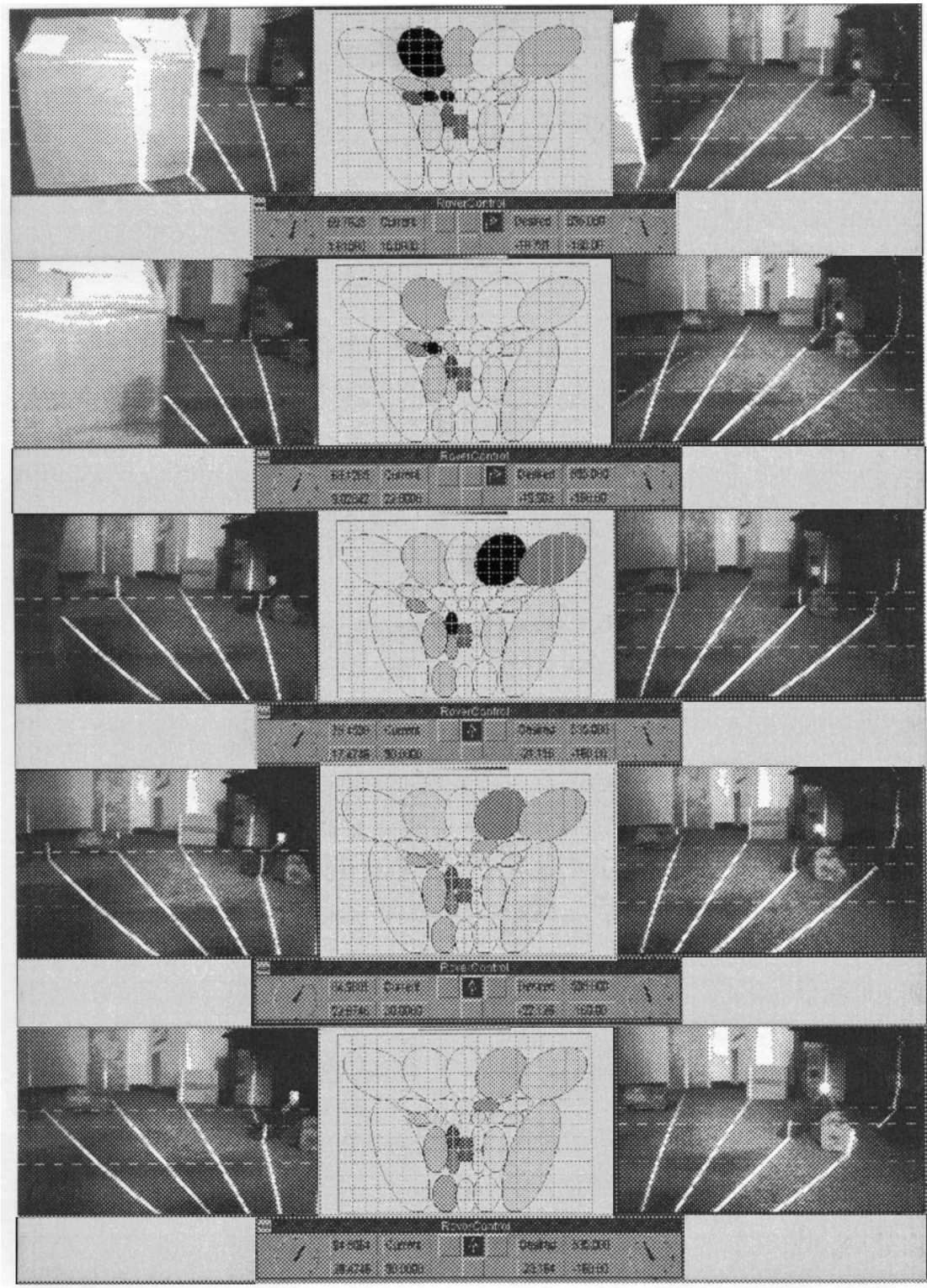


Figure 23. Run 2 continued—Driver stays to the left of the obstacle.

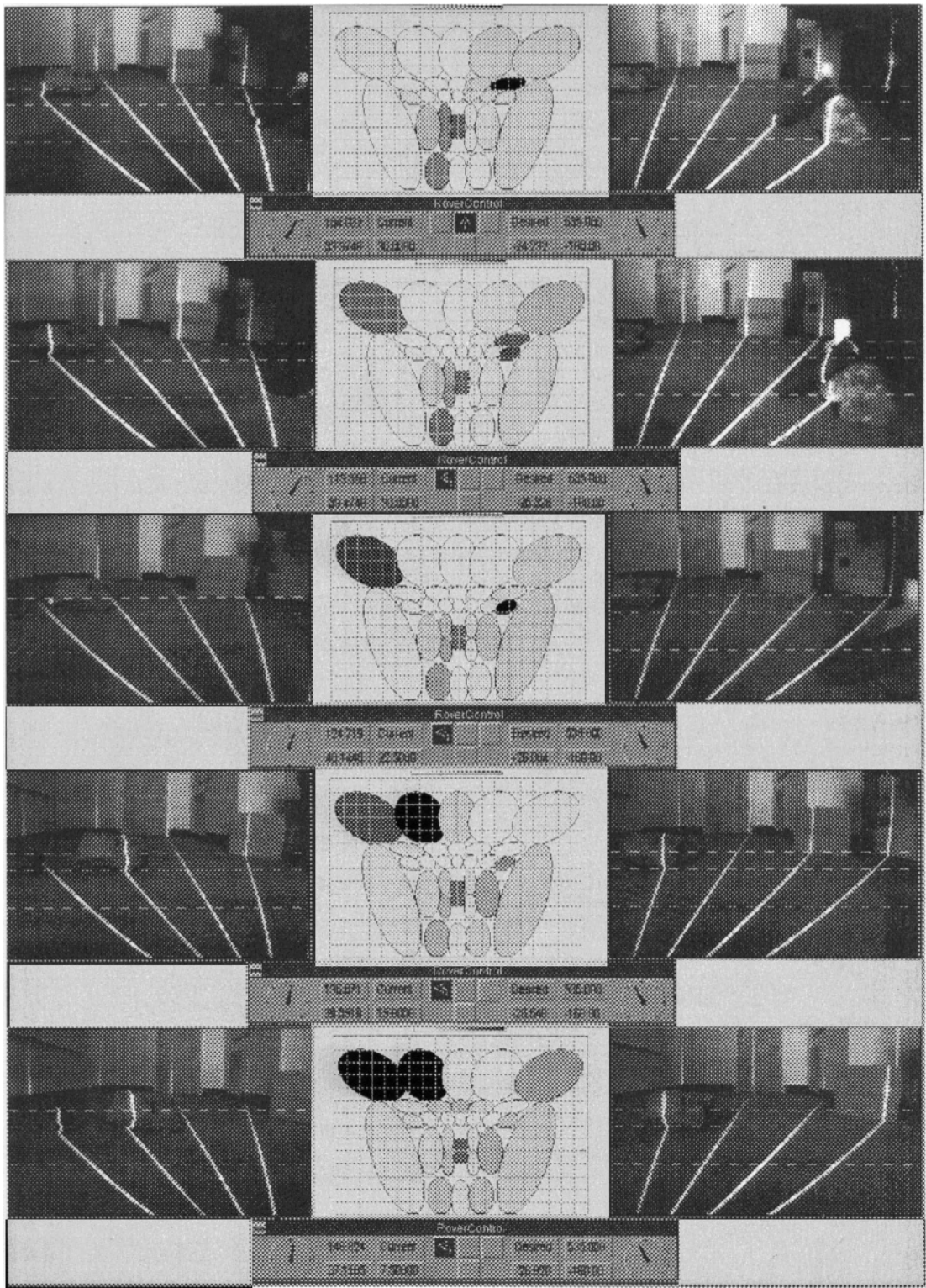


Figure 24. Run 2 continued.

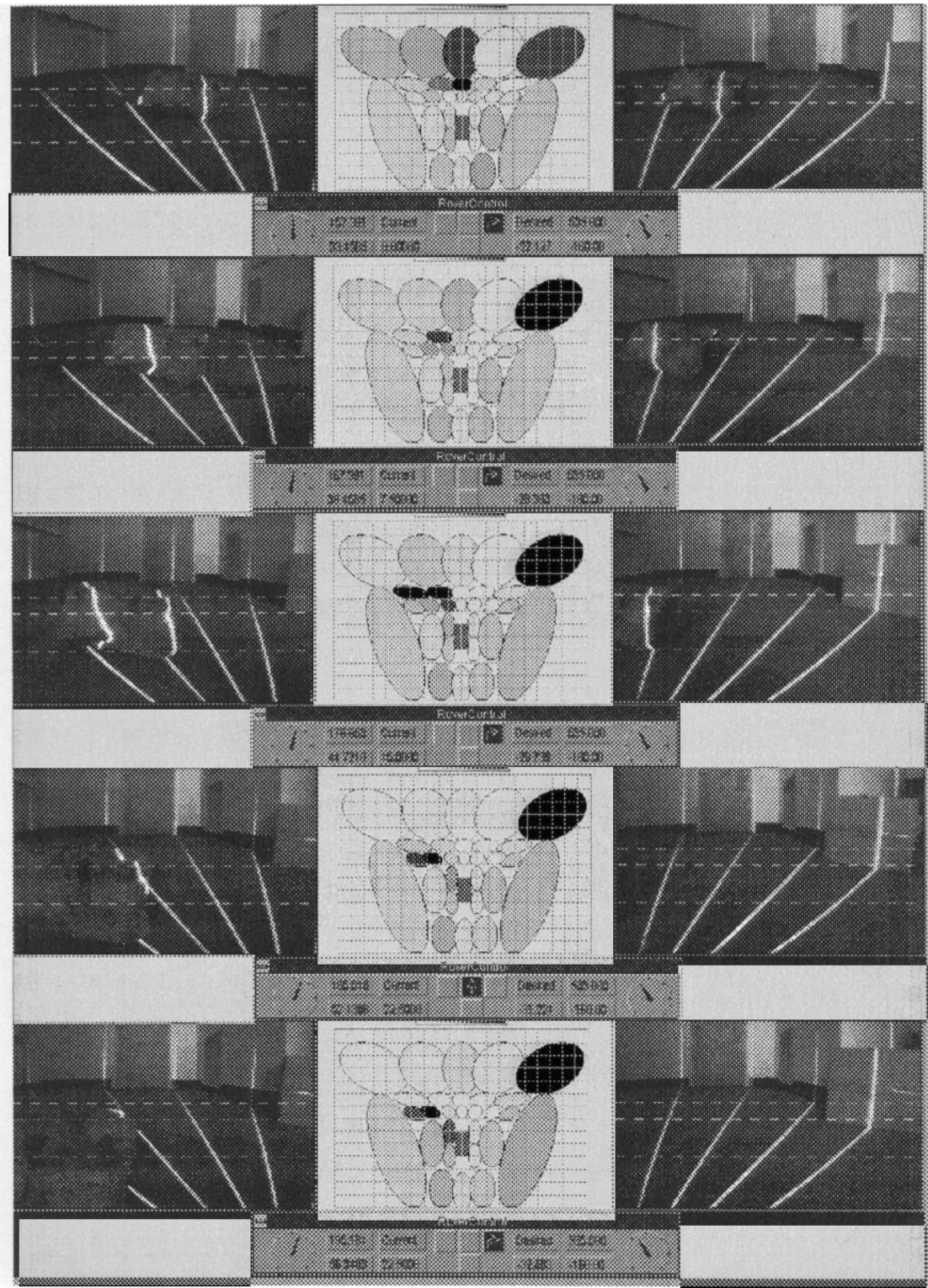


Figure 25. Run 2 continued.

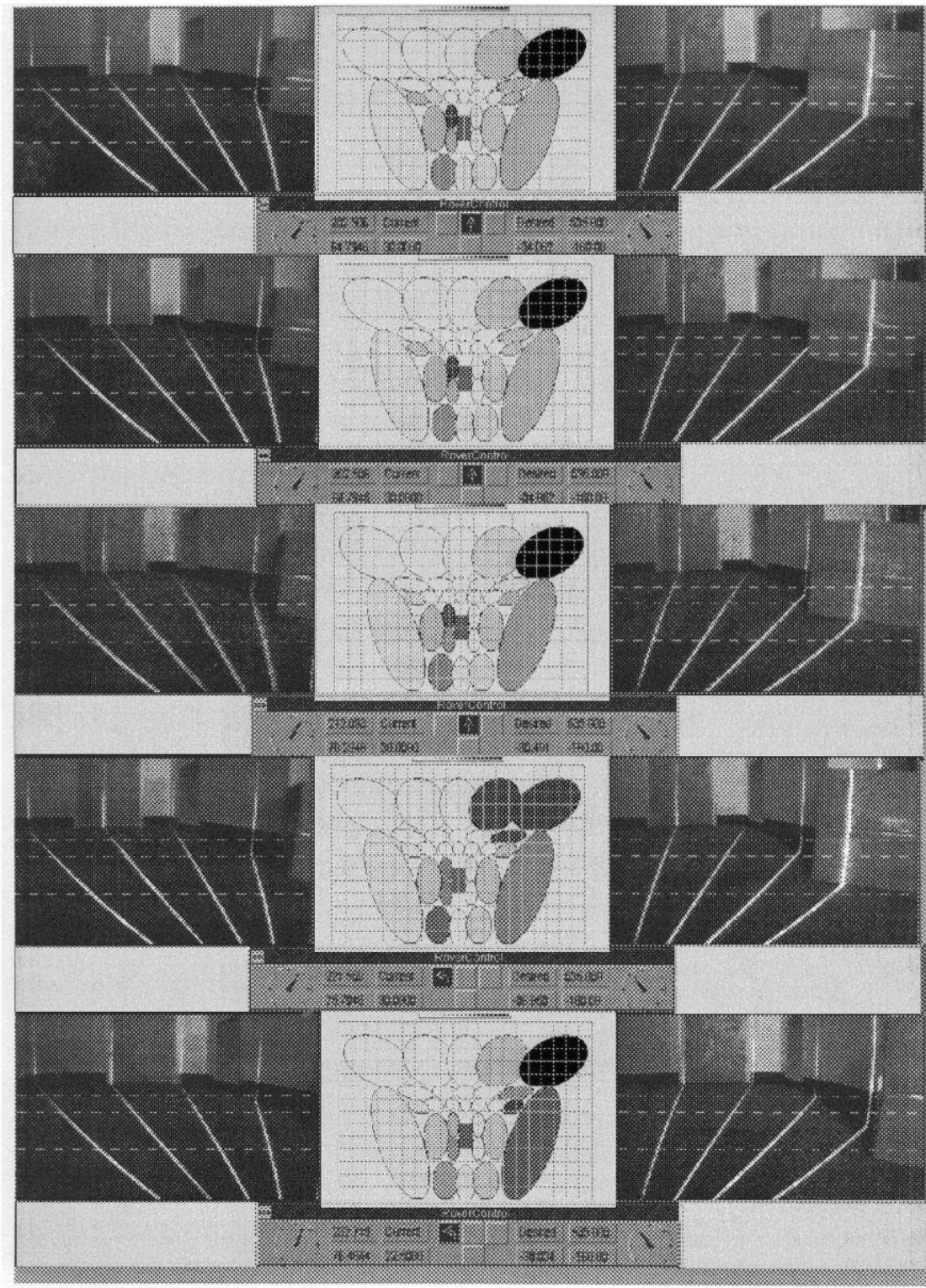


Figure 26. Run 2 continued.

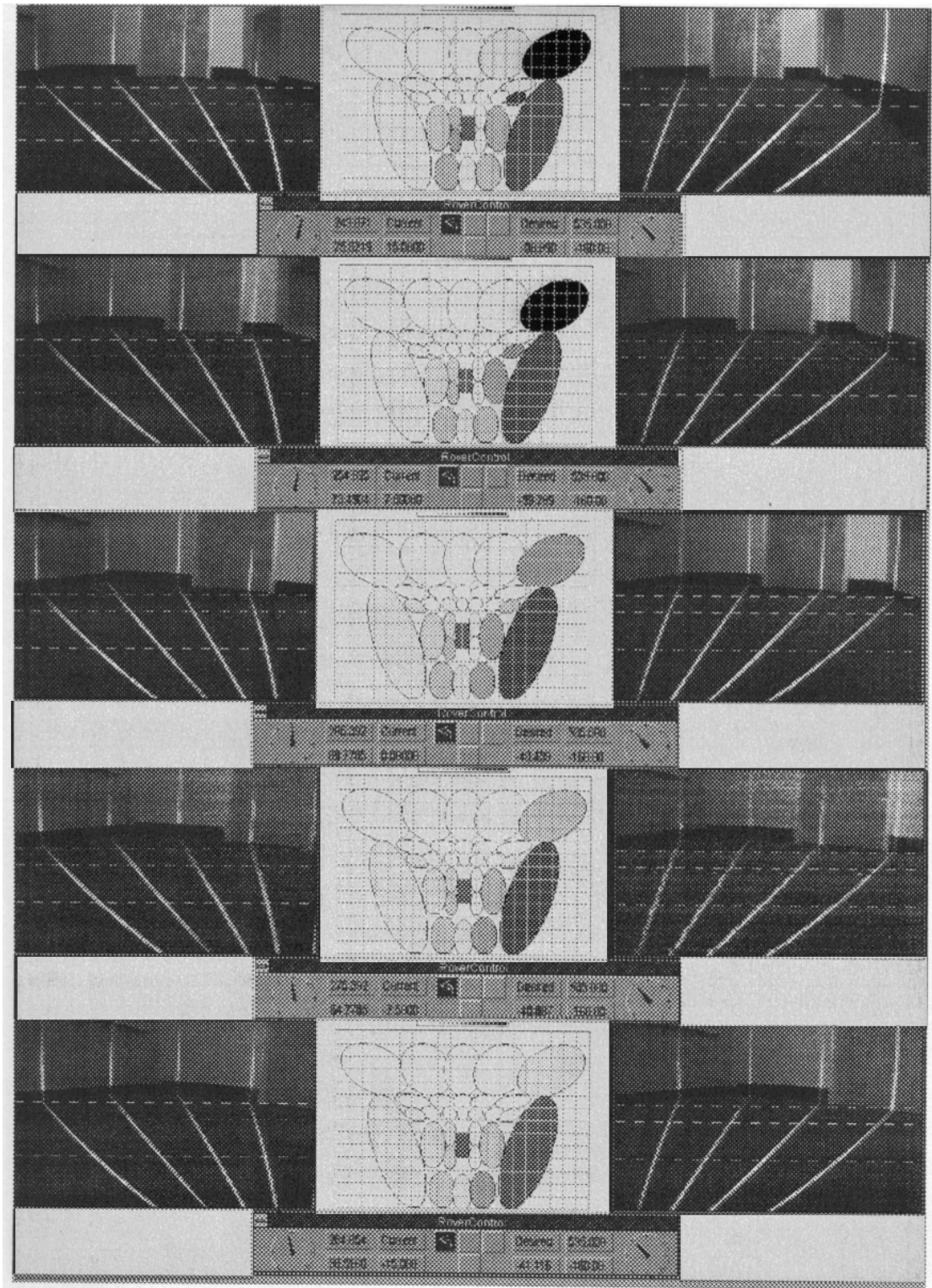


Figure 27. Run 2 continued.

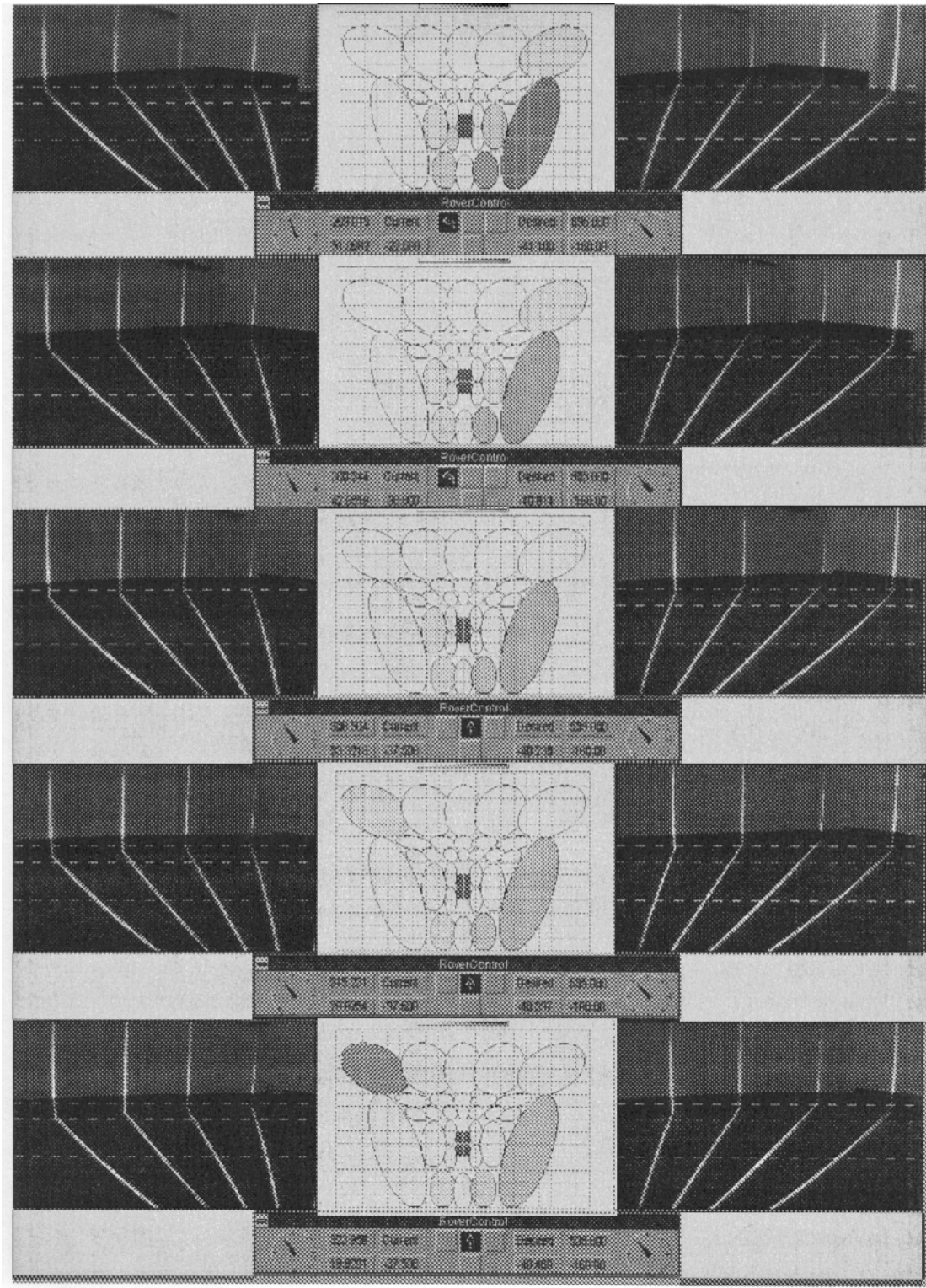


Figure 28. Run 2 continued.

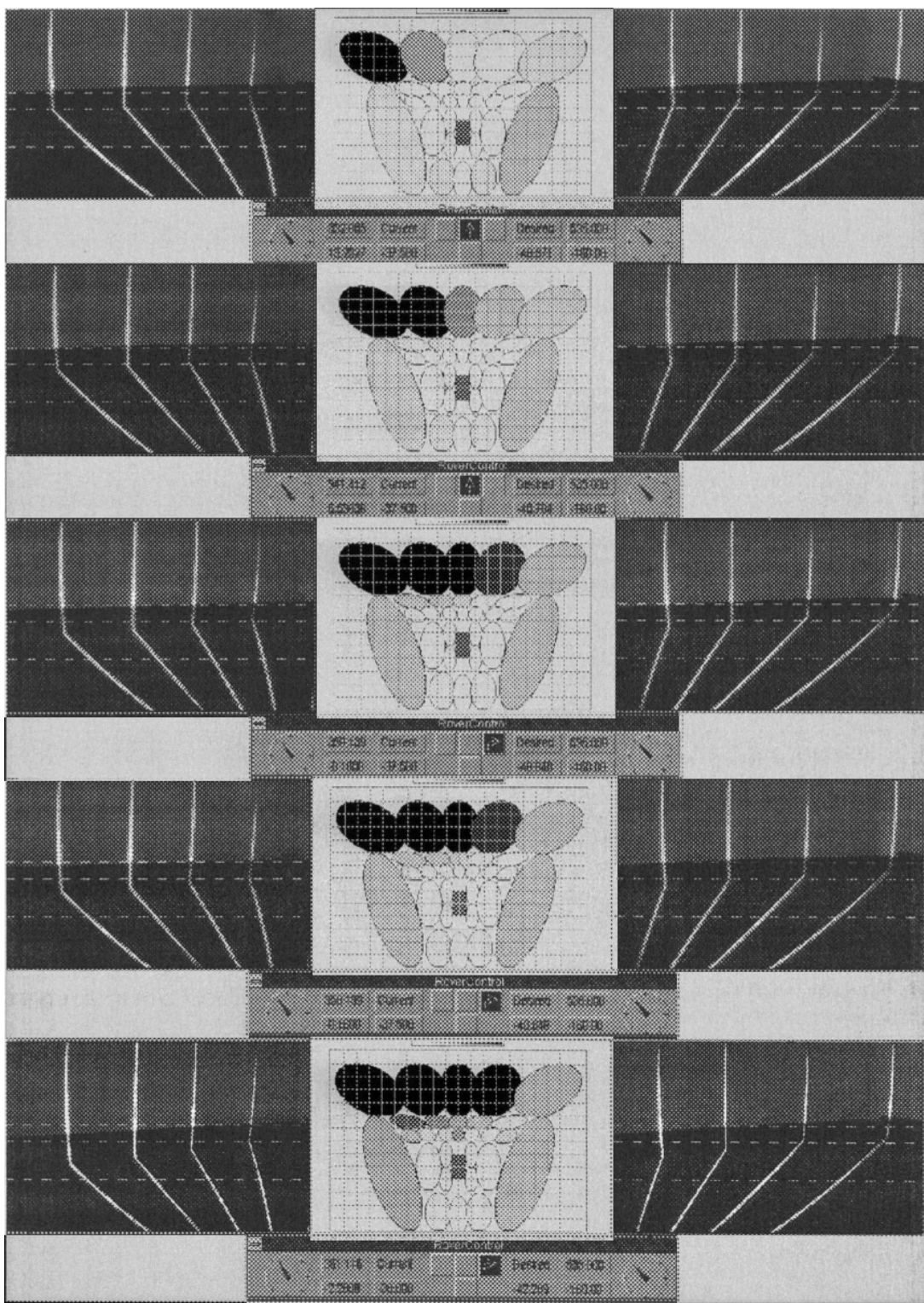


Figure 29. Run 2 continued.

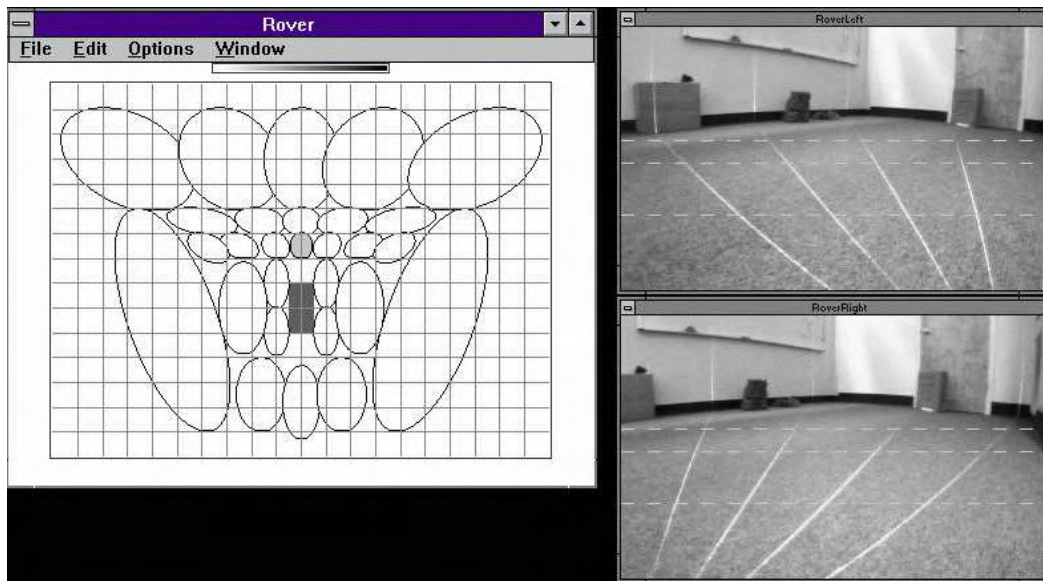


Figure 30. Images and map with vehicle on level terrain.

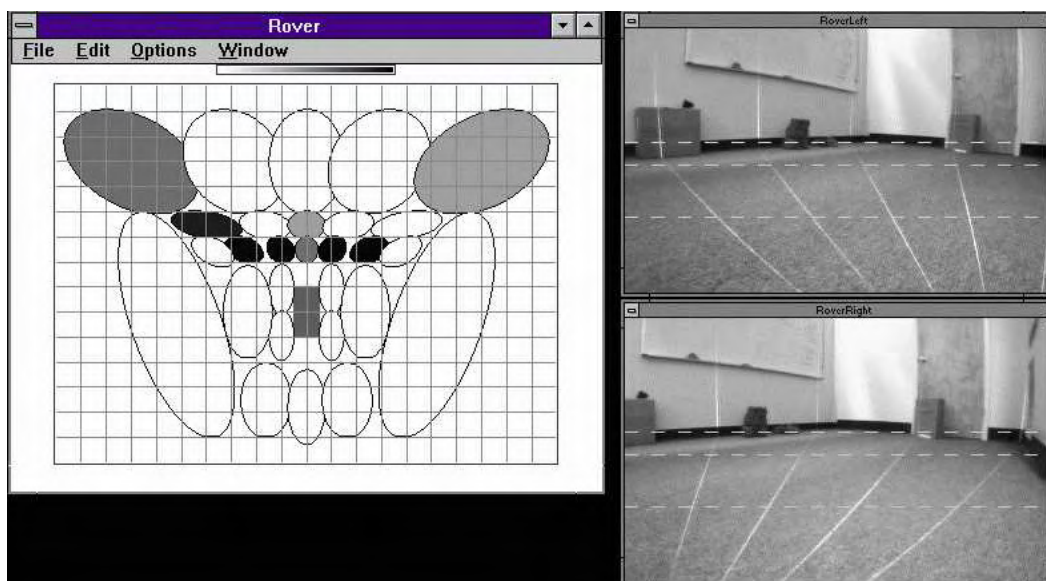


Figure 31. Images and map with front wheels elevated.



Figure 32. Images and map with left wheels elevated.

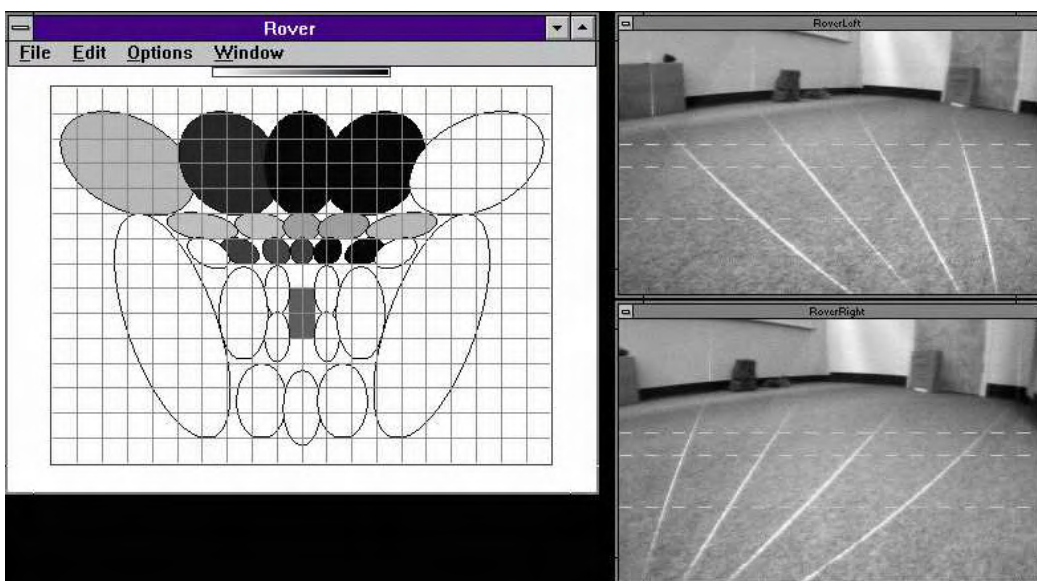


Figure 33. Images and map with back wheels elevated.

CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS

The goal of this work was to develop a system which utilized the JPL Rocky Rover sensor package and could benefit the JPL system. The mapping algorithm which has been developed here adds a visual memory to the system at a low processing and memory cost. The design of the map as a set of values between 0 and 1 lends itself very well to use in a relatively simple and intuitive decision making scheme, as described in Chapter V.

In this work, I conceptualized the idea of approximate mapping utilizing the idea of fuzzy logic for the use in a system with imperfect, incomplete sensor information. The work required the development of algorithms which could implement the mapping idea within the frame work of JPL's rover vehicle.

Although the creation of the fuzzy mapping is the primary concern of this thesis, the complete package required me to develop software to communicate with various hardware components and with commercial routines provided with the frame grabbers and analog to digital boards. I also played a lead role in directing the team towards the creation of a working test station for use on this research and continued work in the area of autonomous vehicle research.

A. *Performance of the Map*

As shown in Chapter VII, the map gives a good compact representation of the obstacles the vehicle senses. Trials have shown that the vehicle can be driven through a complex field of obstacles with only the map as guidance. The translation process based on the decay of membership values works adequately. A better solution to this translation is not apparent at this time.

The conclusion of this thesis is that the map has met the goals for this research. In a very

compact system, the sensor data is transformed into a quality representation of the terrain around the vehicle. The concept of the map has been complimented by JPL. The project needs to advance in several areas, outlined in the remainder of this chapter, in order to be a candidate for use on the flight JPL vehicle.

B. *Recommendations for improving the map*

Issues which need to be addressed to make the map usable outside the laboratory test area are defined here. The first is to take into account inclination of the vehicle. The second is to investigate the ideal placement of the regions. Another is to make the translation of the map values based on the actual distance moved between samples.

1) *Inclination:* To be useful on a mobile vehicle such as Rocky, the map must interpret optical sensor data using information from inclinometers to adjust the expected pixel location for level terrain. It is recommended here that the map is a useful enough idea to pursue taking it to the next stage of adding the ability to use inclinometer data to deal with terrain that is not level.

2) *Placement of Regions and Scan Lines:* The number and placement of regions used for this thesis seems to be adequate. However, the placement of regions most likely can be optimized by changing the regions, subdividing larger regions, or numerous other possibilities. It is recommended that a critical look is taken at the map region locations and experiments made to qualitatively determine better map arrangement.

3) *Generalized Translation of Map:* The movement of the rover can be broken down into rotational and transitional locomotion. It is recommended that this concept be used to make the map translation of membership values based on actual movements of the rover. This could also be useful to applying the mapping technique to other applications which require continuous motion and variable velocities.

C. *Recommendation for Future Test Bed Vehicle*

It is also recommended that for the purpose of demonstration and continued development of this project that a more sophisticated vehicle eventually be acquired or built by USU. A rover which has mobility to crawl in sand and over small rocks for be a great asset to the program and may be necessary to truly test autonomous algorithms in a realistic setting.

D. *Application of Approximate Mapping Algorithm*

In addition to the application of the approximate mapping algorithm to planetary vehicles, a form of the map could be used in numerous Earth-bound applications. Assistance systems for wheel chairs could be based on a continuously operating map based on alternate sensors. Automotive and industrial vehicles could eventually benefit from systems based on this research.

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