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A Final Report -- June 30, 1977

ANALYSIS AND DESIGN OF A CAPSULE LANDING SYSTEM AND SURFACE VEHICLE CONTROL SYSTEM FOR MARS EXPLORATION

National Aeronautics and Space
Administration

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Submitted by the Special Projects Committee

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ABSTRACT

A number of problems related to unmanned exploration of planets or other extraterrestrial bodies with Mars as a case in point have been investigated. The program has had two principal goals: (a) the design and evaluation of a prototype rover concept with emphasis on mobility, maneuverability, stability, control and propulsion and (b) the development of terrain sensor concepts and associated software for the autonomous control of any planetary rover. The prototype rover studies were intended to serve a double purpose in that the results would be applicable not only to the design of a mission rover but that the vehicle could be used as a test bed for the rigorous evaluation of alternative autonomous control systems.

The prototype rover has been tested extensively and its configuration has been modified to increase its mobility. The concept is now well developed and documented. An alternative toroidal wheel design has been tested and shown to have considerable potential for mission application. The wheel is characterized by a high load carrying capacity, large footprint areas, low footprint pressures and high reliability. The rover can now serve its second, and perhaps more important role as a test bed for the evaluation of alternative autonomous control systems.

An integrated short range (1 to 3 meter) autonomous rover control system employing a one laser/one detector triangulation concept has been simulated by computer and has been implemented and tested on the rover. Included in this effort are the required hardware, telemetry and software. The effectiveness of this short range hazard detection and avoidance system has been assessed through extensive laboratory and field testing. Computer simulation predictions of the performance of this system for autonomous control of the rover have been verified by the experimental measurements. The one laser/one detector system is found to be reliable and effective in avoiding discrete hazards and in planning a safe path to a desired destination provided that general terrain gradients are less than $\pm 10^\circ$. For more severe terrains, the system protects the rover in a fail safe manner by interpreting as impassable terrains which are in fact acceptable. This defect is due to the decision-making algorithm which cannot distinguish between a discrete hazard and a slope on the basis of the limited data provided by the one laser/one detector system.

The feasibility of an elevation scanning system involving multiple laser beams and detectors to reduce the quantization error has been investigated by computer simulation. An eleven laser/sixteen detector system shows considerable promise for supporting a more perceptive and efficient control of a rover. Such a system shows potential for being able to deal with in-path and cross-path slopes as well as compound hazards made up of combinations of terrain features.

The accomplishments of the past decade of research are reviewed along with listings of the technical reports and publications which have accrued. The educational implications of the research programs are also presented.

I. INTRODUCTION

Current national goals in space exploration include a detailed exploration of the planet Mars. In the past, these investigations have employed remote sensing systems carried by fly-by vehicles and more recently orbiting devices. Even more recently, two Viking spacecraft were landed and have performed a number of scientific experiments. On completion of the Viking missions, basic knowledge of biological, chemical and meteorological characteristics of the Mars surface will have been gained. Despite the monumental achievement which the Viking mission represents, the limited zone of exploration as constrained by the ten-foot sampling boom will not fulfill the long-term scientific objectives. Ultimately, a rather more complete exploration of Mars and other suitable planets and extra-terrestrial solar system bodies will be desired.

The major impediment to an unmanned mission of planetary exploration is the long round-trip communication delay. For Mars, this delay varies from a minimum of about nine minutes to a maximum of approximately 45 minutes depending on the distance between Mars and Earth. For other missions, the delays are even longer. Thus, for a mission of any consequence in range and a reasonable duration in time, i.e., several hundred kilometers or more, it is not feasible to rely strictly on earth control to direct a vehicle or equivalent relocatable device from the original landing site to the desired sampling points. It follows that a roving vehicle possessing a high degree of automatism is essential to such missions.

In looking forward towards significant and detailed unmanned planetary exploration, it would appear that developmental activities should be aimed at two basic problems in order to permit either an augmented Viking mission or a sample return mission.

First, the vehicle should be characterized by a high level of mobility in order that reasonable paths be available to reach the desired targets. A vehicle of limited ability to deal with boulders, craters, crevasses, slope and other terrain irregularities may require an inordinate length of time and distance to reach the desired goal. Indeed in some circumstances, such a vehicle may not be able to reach the target. As the vehicle's mobility is increased, it will be able to deal with more difficult terrains. More paths will be available and the opportunity for selecting optimal paths will be increased.

Second, such a roving vehicle should be provided with a guidance and control system of quality comparable to its mobility. The decision as to which path should be followed must be made by a path selection system which is comprised of terrain sensor(s), a terrain modeler and a path selection algorithm. A low level path selection system will have to be biased conservatively to minimize the risk of an unperceived hazard. Thus, many and perhaps all acceptable paths may be excluded, thereby immobilizing the vehicle. The effect of a low-level system is, in fact, to reduce the vehicle's mobility. As a minimum, the path taken towards the desired goal will be lengthier and more time-consuming and the range of exploration will be reduced. On the other hand, a higher level, more sensitive and perceptive system will be able to detect a larger fraction of passable paths and select those most compatible with the mission and the vehicle.

This research program has been addressing these two major problems and other closely related issues with the goal of providing basic knowledge of long-term value to NASA and developing concrete alternatives applicable to future planetary exploration missions.

II. OVERVIEW OF THE PROJECT

During the past few years, emphasis has been directed towards the conception, implementation and evaluation of autonomous roving capability for the Rensselaer rover. The program planned for the period July 1, 1976 to June 30, 1977 is described schematically in Section A of Figure 1. Also shown in Section C of Figure 1 are related activities being conducted under a separate research program funded by NASA Grant NSG 7184. Section B of Figure 1 focussed on a potential hybrid buidance system combining the capabilities of the short-range concepts being studied in this project and of the long-range system being investigated under NSG 7184 is included to suggest an overall guidance which might be superior and which is worthy of future study. This report summarizes progress achieved in vehicular mobility and short-range hazard avoidance systems, namely, Section A of Figure 1; a review of recent progress relating to Section C is provided in Reference 1.

Since July 1 emphasis has been directed towards: improved wheel design, structural modifications to increase turning capabilities in irregular terrain situations, elevation scanning hazard detection systems, higher level short-range hazard detection concepts, computer software and implementation and evaluation of Path Selection System I.

In brief, a very significant improvement in the toroidal wheel design appears to have been made possible by an inversion of the hoop spoke. The new configuration permits a much larger and softer footprint without deformations of the hoops beyond their elastic limits. The inverted hoop spoke also increases the lateral stiffness of the wheel.

The current structural design of the front strut limits the turning radius of the rover in irregular terrain situations where the gradient of the terrain under the front wheels is significantly different from that under the rear wheels. Design concepts minimizing this loss of mobility, have been developed and are to be implemented.

The hazard detection system required by Path Selection System I involves a single laser sweeping at one elevation angle and a single focussed photodetector swept at a different elevation angle. Although this system is effective for a limited class of hazard situations, studies have revealed that a scanning system involving elevation as well as azimuthal sweeping is likely to be necessary. The mechanical design of an elevation sweeping laser transmitter system has been completed.

Higher-level short-range hazard detection concepts employing the laser/photodetector triangulation principle have been under study. The Path Selection System Simulation computer code has been modified to permit the study of a broad range of laser/photodetector combinations and the processing of the sensed data for hazard detection.

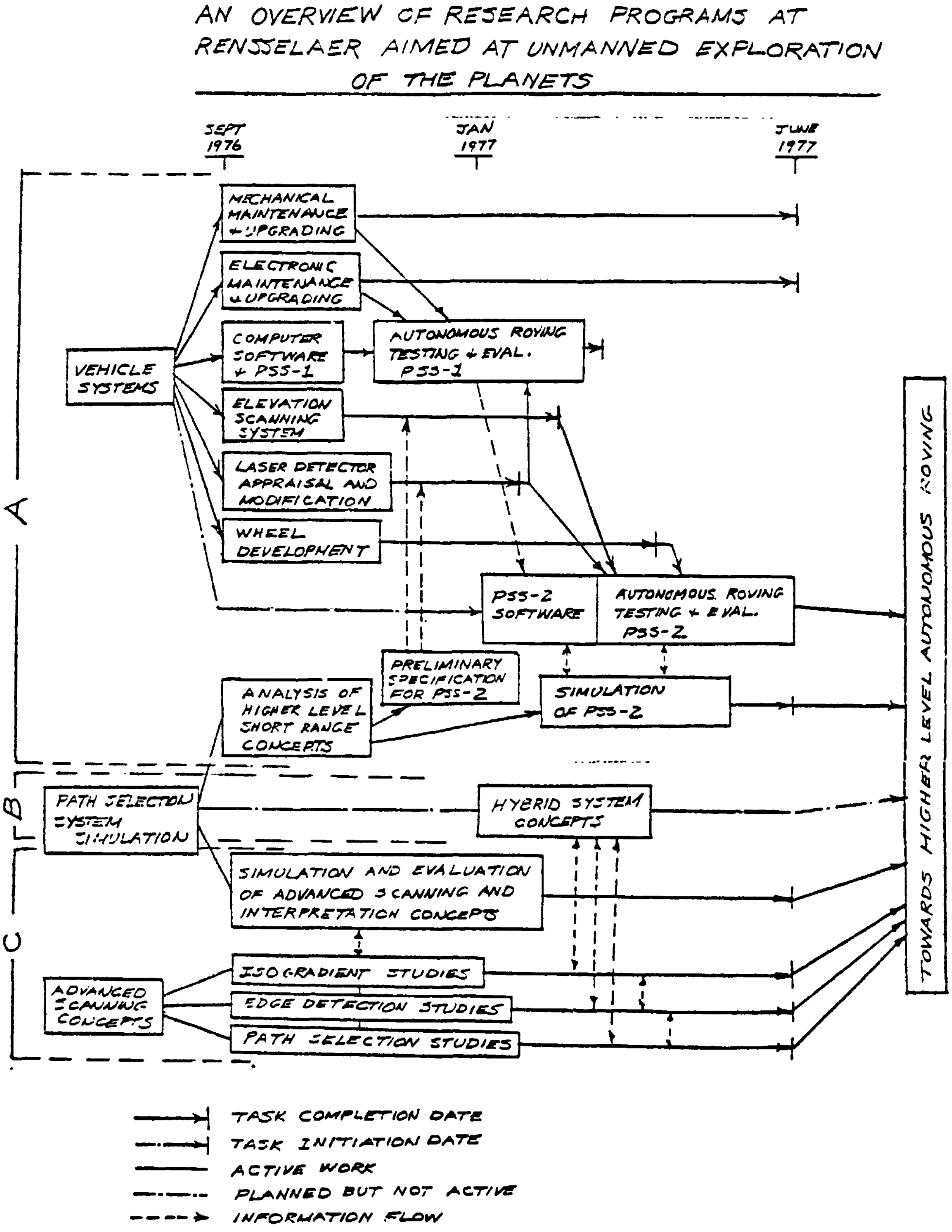

Figure 1 Overview of Research Program at Rensselaer Aimed at Unmanned Exploration of the Planets

Considerable effort has been applied to the completion and validation of computer software for the closed-loop control required by Path Selection System I and to the modification of all of the software required by the new operating system implemented on the IDIIOM-Varian Interactive Graphics Computer System during the summer.

Autonomous roving was achieved in February and a considerable amount of laboratory testing and some field testing was undertaken. The performance of the laser/one-sensor hazard detection system paralleled rather closely the predictions of the Path Selection System Simulation. The need for an effective memory system to guide the vehicle around discrete obstacles was confirmed in the experiments. The inability of the simple system to function in terrains possessing pitch-and-roll gradients in excess of 12-15° was demonstrated in the field. However, when surface gradients were more gentle, the detection system was able to recognize and avoid hazardous paths and to pick directions which were safe.

III. DETAILED SUMMARIES OF PROGRESS

TASK A. Mechanical Systems - J. Koskol, Student Group Leader, D. Jensen, R. Kaltenbach, D. Knaub, K. Schmidt.

Faculty Advisor: Prof. S. Yerazunis

Four major topics relating to the rover's mechanical systems were undertaken. These were:

1. Improvements in the design of the toroidal wheel and the development of a theoretical analysis on which future designs of this concept can be based.
2. Modifications in the vehicle's structural configuration to increase its turning capability in terrain situations involving considerable pitch and roll.
3. Improvement of the current one laser/one detector system to provide for more accurate lens positioning, pointing angle and field of view of the detector.
4. Design, development and implementation of the laser sub-system for a higher level elevation scanning sensor.

Task A.1 Toroidal Wheel Improvements - J. Koskol, D. Knaub, K. Schmidt

The extensive field testing of the rover during the previous year revealed serious defects in the design concept of the original toroidal loop wheel. Efforts to achieve a large footprint/low footprint pressure wheel inevitably resulted in early failure in testing under heavy dynamic loads and in an unacceptable weakness to lateral loading. As a result, an in-depth experimental analysis of the behavior of individual hoops under oblique as well as normal loads and of complete wheels with and without grousers was undertaken during the previous year as reported in Reference 2. Subsequent analysis of the data and photographs suggested that a far superior performance might be obtained if the hoop spoke to which the hoops are attached were to be inverted. In the original hoop spoke configuration, significant deflection of the hoop due to loading leads inevitably to an inflection point at which deformation becomes excessive resulting in early failure. The inverted hoop spoke concept shown in Figure 2 eliminates this inflection point even under extreme loading to the point where the hoop makes contact with the wheel hub. Testing of both wheels reveals that the inverted configuration is far superior to the earlier design which fails very quickly under heavy loads. Another major advantage of the inverted spoke concept is that it is inherently resistant to lateral forces; any lateral displacement automatically produces forces acting against the lateral displacement.

At that particular loading which places the hoop in the static condition shown in Figure 2, several useful geometric relationships along with a complete loading and deflection analysis can be obtained. This information on the behavior of a single hoop can then be employed with appropriate approximations to predict the load/deflection characteristics of a complete wheel. That the approximations made in predicting complete wheel behavior using individual hoop characteristics were appropriate is shown by the comparison in Table 1 of the theoretical and experimental parameters. Many experimental hoops were also tested to veryify the correctness of the theoretical analysis. Experimental findings are compared with theoretical predictions in Table 2.

In order to evaluate further the theoretically based design equations, a life prediction was made for a steel prototype inverted hoop wheel, by using the Goodman S-N diagram technique. The calculated life of the prototype of 40,000 cycles was confirmed by testing to failure on the dynamic wheel testing facility shown in Figure 3 with actual failure occurring at 42,600 cycles. This wheel, which was in fact designed to fail, was a thirty-fold improvement over that of previous designs using the comparable number of hoops and similar materials. Other important characteristics of the wheel include its low footprint pressure (of the order of 0.3 psi), its potentially high payload to wheel weight (capable of exceeding 25 to 1, depending on the materials of construction), and its capability for infinite life when properly designed. The "softness" of the design concept could in conjunction with an appropriate grouser offer exceptional traction characteristics in rough terrain situations.

Full details are provided in Reference 3.

Task A.2 <u>Rover Turning Mobility Improvements</u> - K. Kaltenbach

The current rover front-end design permits a full 90° turn only if the slope of the terrain under the front wheels differs from that under the rear wheels by less than 7°. Otherwise, interference between the front wheels and front strut limits the maximum turning angle for the present vehicle to about 25°. Since this restraint would limit seriously the utility of the rover in evaluation of alternative hazard detection and path selection systems, an analysis of alternative configurations to increase the turning mobility was undertaken.

The geometric analysis produced a family of design curves, shown in Figure 4, which relate the maximum front axle tilt relative to the rear axle in degrees as the ordinate to the included angle in the front strut (see Figure 5) as a function of the increment in height of the front strut beyond the current heights. Also shown is a design curve which would retain the laser/detector mast vertical relative to the vehicle. The effect of the proposed front-end configuration change, which is shown in Figure 5, is to raise the struts and provide clearance for the front wheels. On the basis of this

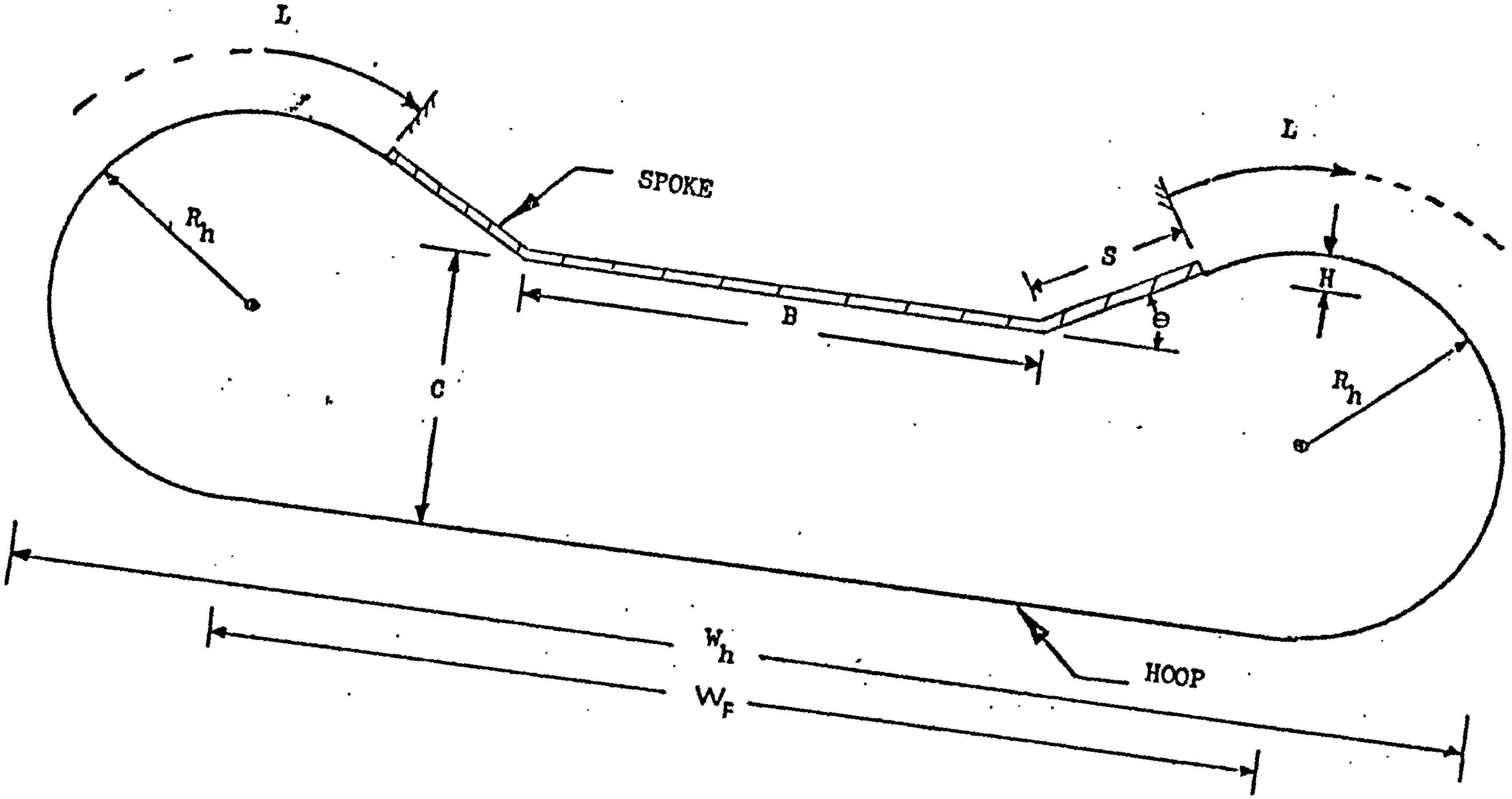

Figure 2 Static Condition for the Inverted Hoop Spoke

Table 1 Theoretical Vs. Experimental Wheel Parameters

	EXPERIMENTAL WHEEL	THEORETICAL WHEEL
$L =$	16.5 in.	16.5 in.
$B =$	2.5 in.	2.5 in.
$S =$	1.0 in.	1.0 in.
$\Theta =$	45.0 deg.	45.0 deg.
$L_w =$	5.70 lbs.	5.75 lbs.
$L_f =$	7.5 in.	7.8 in.
$W_f =$	5.7 in.	5.8 in.
$A_f =$	42.75 in.^{2}	45.20 in.^{2}
$P_a =$	0.133 p.s.i.	0.127 p.s.i.

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Table 2 Theoretical Vs. Experimental Hoops

HOOP NO.	L	B	S	Θ	C_o	C	W_h	H	R_h	W_f	L_h	
43	16	1	1.5	20	3.9	2.9	8.1	0.1	1.6	5.0	4.0	*
					3.7	2.6	8.1	0.2	1.6	4.9	4.2	**
163	18	1	1.0	20	4.6	3.7	8.2	0.1	1.9	3.5	2.3	*
					4.9	3.5	8.2	0.1	1.9	4.2	2.7	**
224	18	3	2.0	40	2.9	1.5	10.1	0.7	1.6	6.0	1.8	*
					2.5	1.6	10.6	0.6	1.4	7.9	5.5	**
293	20	1	1.5	20	5.0	3.8	9.6	0.3	2.1	4.8	2.3	*
					5.1	3.6	9.5	0.3	2.1	5.3	2.3	**
350	20	3	2.0	40	3.5	2.2	11.0	0.9	1.7	7.1	2.4	*
					2.4	1.5	11.2	0.9	1.6	8.1	4.4	**
362	20	4	1.0	10	5.3	4.6	10.5	0.0	2.2	4.5	1.9	*
					5.4	3.8	10.7	0.0	2.0	6.7	2.6	**
438	22	2	1.0	20	5.6	4.5	10.2	0.2	2.3	4.0	1.7	*
					5.0	4.2	10.2	0.2	2.4	5.5	1.8	**
487	22	4	1.0	10	6.0	4.5	11.5	0.1	2.3	6.0	2.4	*
					6.2	4.4	11.4	0.1	2.3	6.8	2.0	**
538	24	1	1.0	20	6.3	4.7	10.6	0.4	2.5	4.7	1.8	*
					7.0	5.0	10.3	0.3	2.8	4.8	1.4	**

* EXPERIMENTAL DATA

** COMPUTER OUTPUT

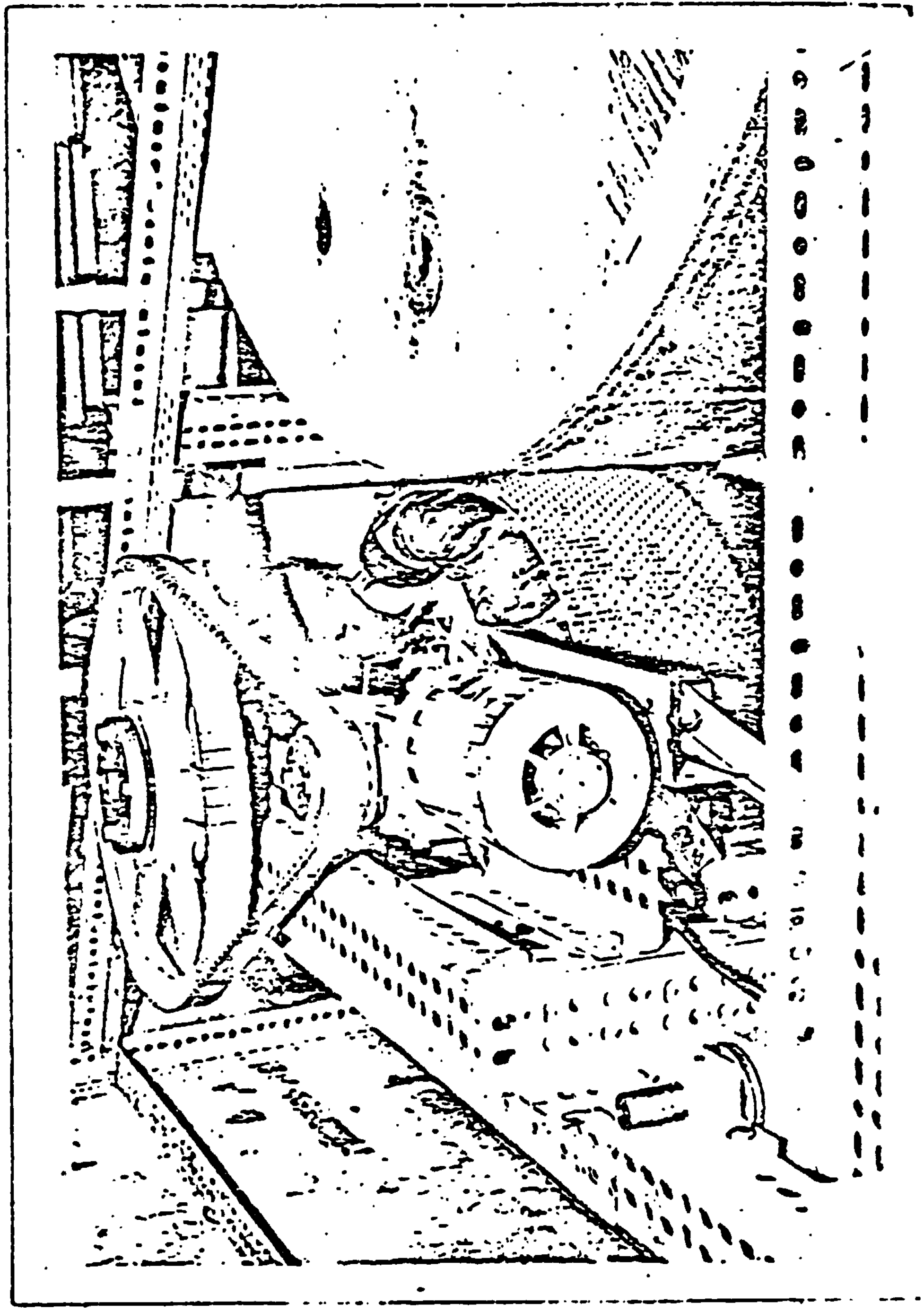

Figure 3 Inverted Hoop Spoke Wheel Undergoing Endurance Testing in the Dynamic Wheel Testing Facility.

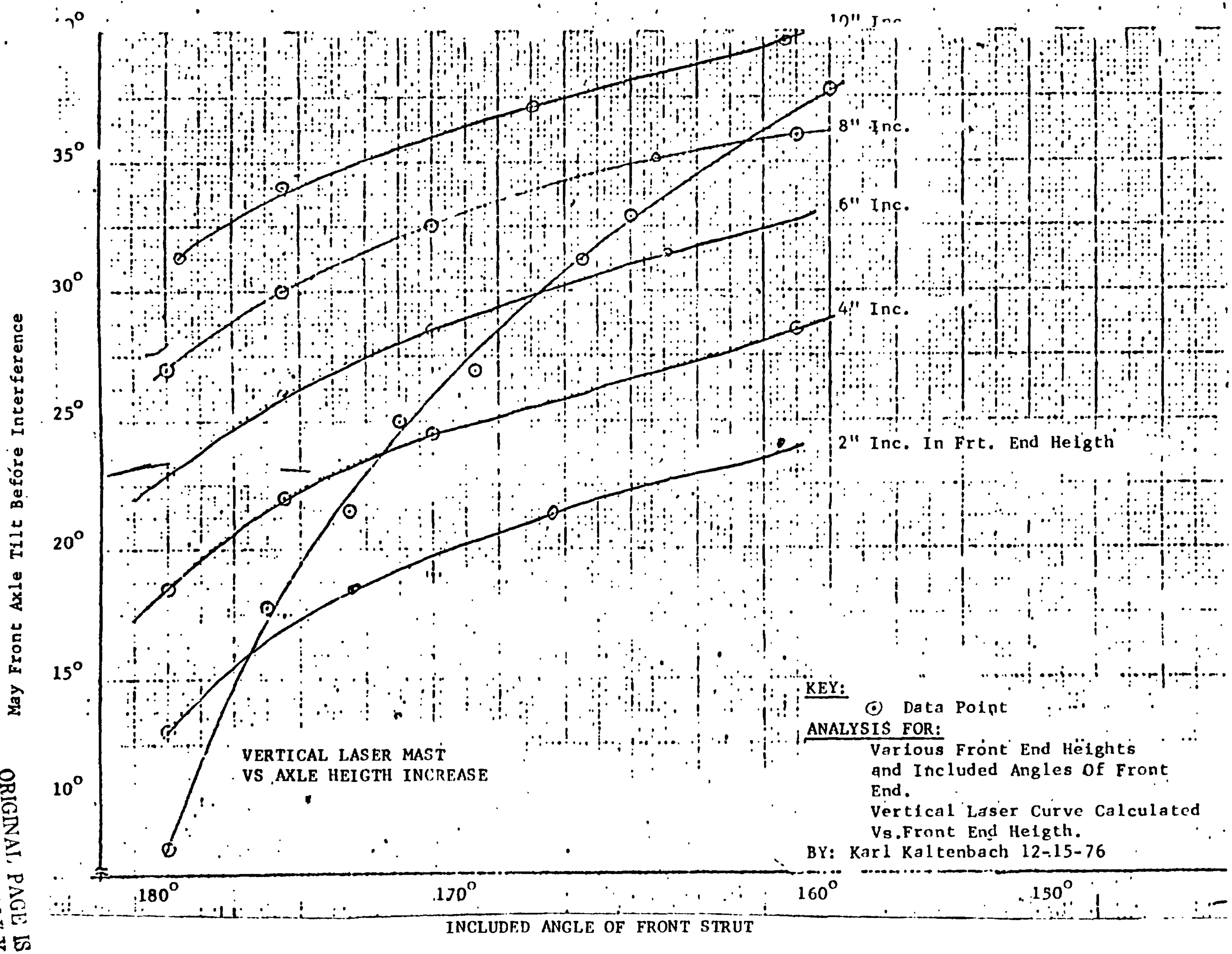

Figure 4 Design Curves Applying to Rensselaer Rover.

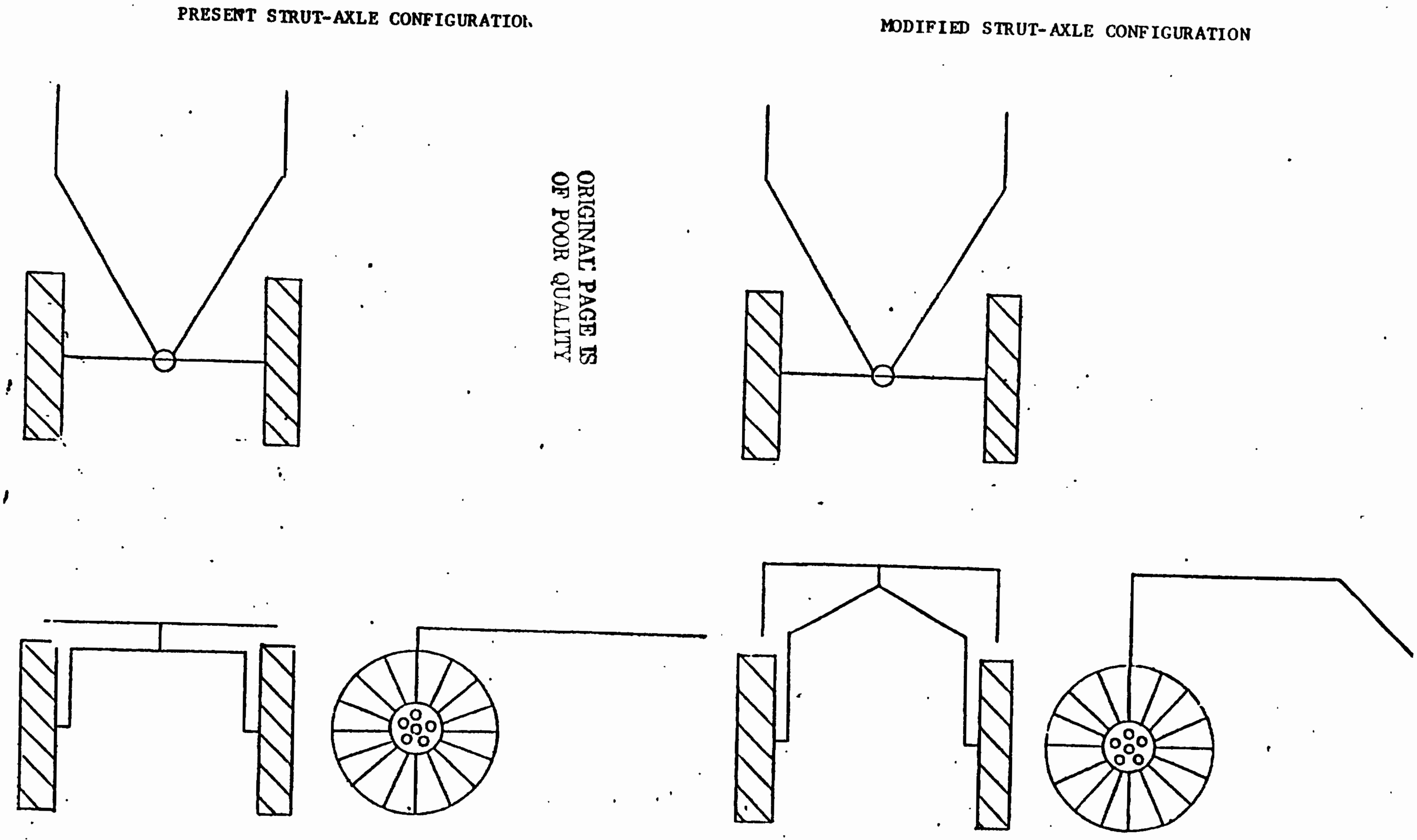

Figure 5 Front Strut-Axle Configurations.

analysis the front strut is being modified to increase the height by 8 inches permitting therefore full 90° turning capability for terrain "tilts" up to some 35°. Since the Rensselaer rover's in-path and cross-path slope capabilities are of the order of 35°, the proposed configuration makes available the vehicle's full turning mobility for autonomous roving experimentation.

Task A.3 Laser/Detector Mechanical Control Systems - J. Koskol

The effectiveness of the one laser/one detector short-range hazard detection system depends critically on the maintenance of specifired geometric factors. Several design modifications intended to improve the current system were implemented. The lens which collimates the laser beam was mounted in a new mechanism involving three adjusting screws as shown in Figure 6. It is now possible to align the lens very precisely so as to achieve the desired collimation and pointing angle, the latter achieved in conjunction with a mirror. For the case of the detector, it was necessary to devise more precise means for "pointing" the detector as well as an improved control. The pointing-angle problem was resolved by a gear train mechanism involving a 2400 to 1 input to output ratio. Accordingly, one input turn results in a 0.15° shift in the detector orientation. Control of the cone of vision of the detector was obtained by the shutter mechanism shown in Figure 7. The device, which is essentially a one-dimensional aperture, can control the cone of vision from 0° to 7° range by 140 revolutions of the screw mechanism. These two design modifications contributed significantly to the autonomous roving experiments.

Task A.4 Elevation Scanning Laser Subsystem - J. Koskol, D. Jensen

Although the one laser/one sensor hazard detection system has application potential as a short range hazard detection system for an autonomous planetary rover, Reference 5 (also see Task D), it has the shortcoming of being too conservative. This is because the go/no decision is set to interpret the lack of signal as a hazard even though the terrain feature causing the lack of signal is not hazardous. Studies have shown that a three-detector system, Reference 7, would be more effective in distinguishing between hazardous and non-hazardous features. Current investigations described under Task D of this report indicate that a multi-laser/multi-sensor system could be very powerful. Proceeding on this assumption, a mechanical system capable of sweeping the laser beam across an elevation angle field was designed and constructed. A rotating mirror capable of rotating up to 7000 RPM is the essential feature. A disk attached rigidly to the mirror shaft serves as a position encoder. A small hole in the disk permits light from a light emitting diode to reach a photodiode, signalling that the mirror is at the reference location. A timing circuit can be actuated on this signal to fire the laser at those subsequent times at which the mirror is in the proper location to produce the desired elevation angle array. The same encoder signal will also serve as input for the feedback control of the mirror rotation. The mechanical system is now complete.

TASK B. Development of a Real-Time Hazard Avoidance Software System - D. Robbins, Student Group Leader, A. Otis, L. Ricci. Faculty Advisor: Prof. S. Yerazunis

Objective: The objective of this task is the implementation of a primitive path selection control system on a minicomputer linked with the Rensselaer rover.

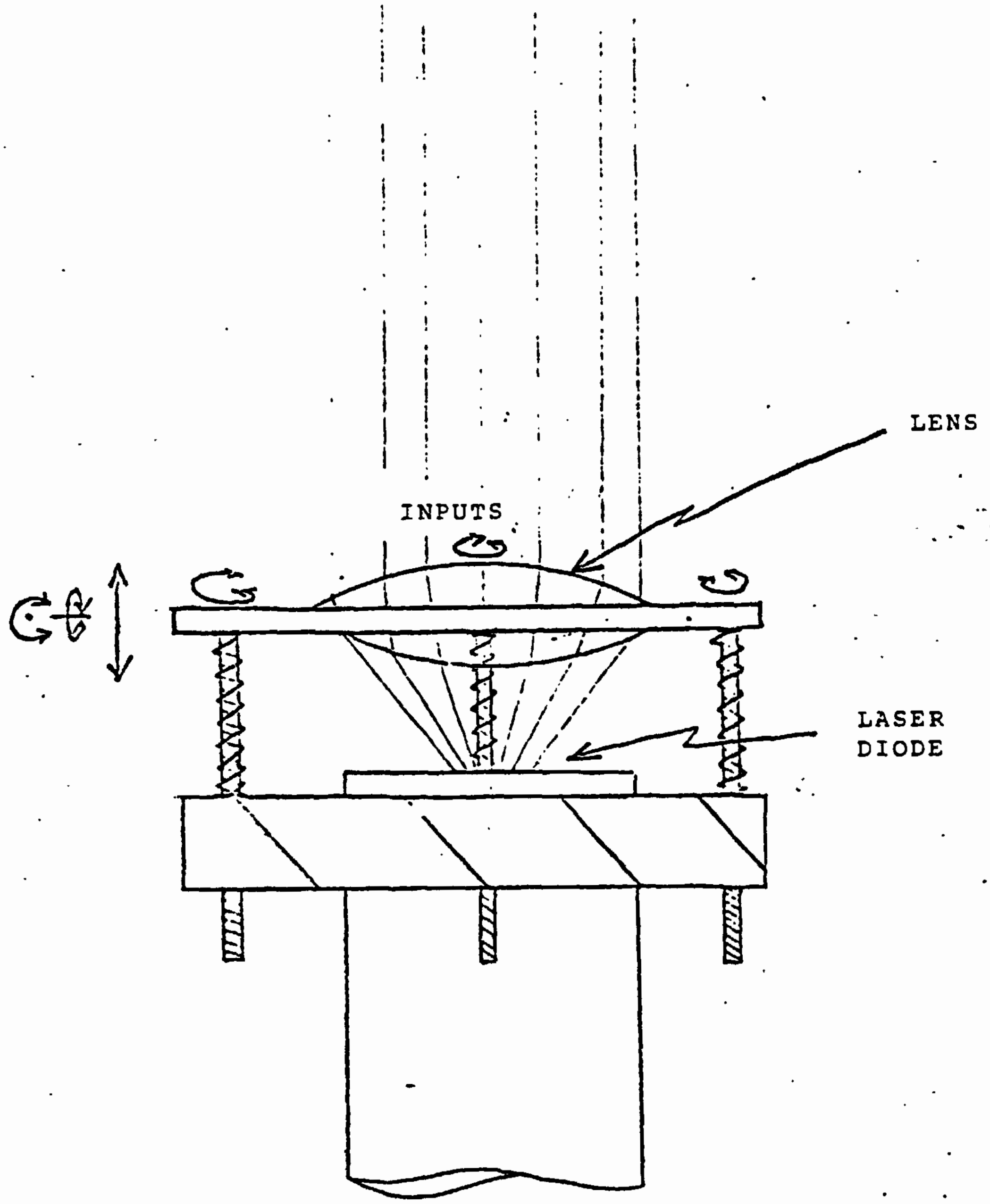

Figure 6 Lens Mechanism

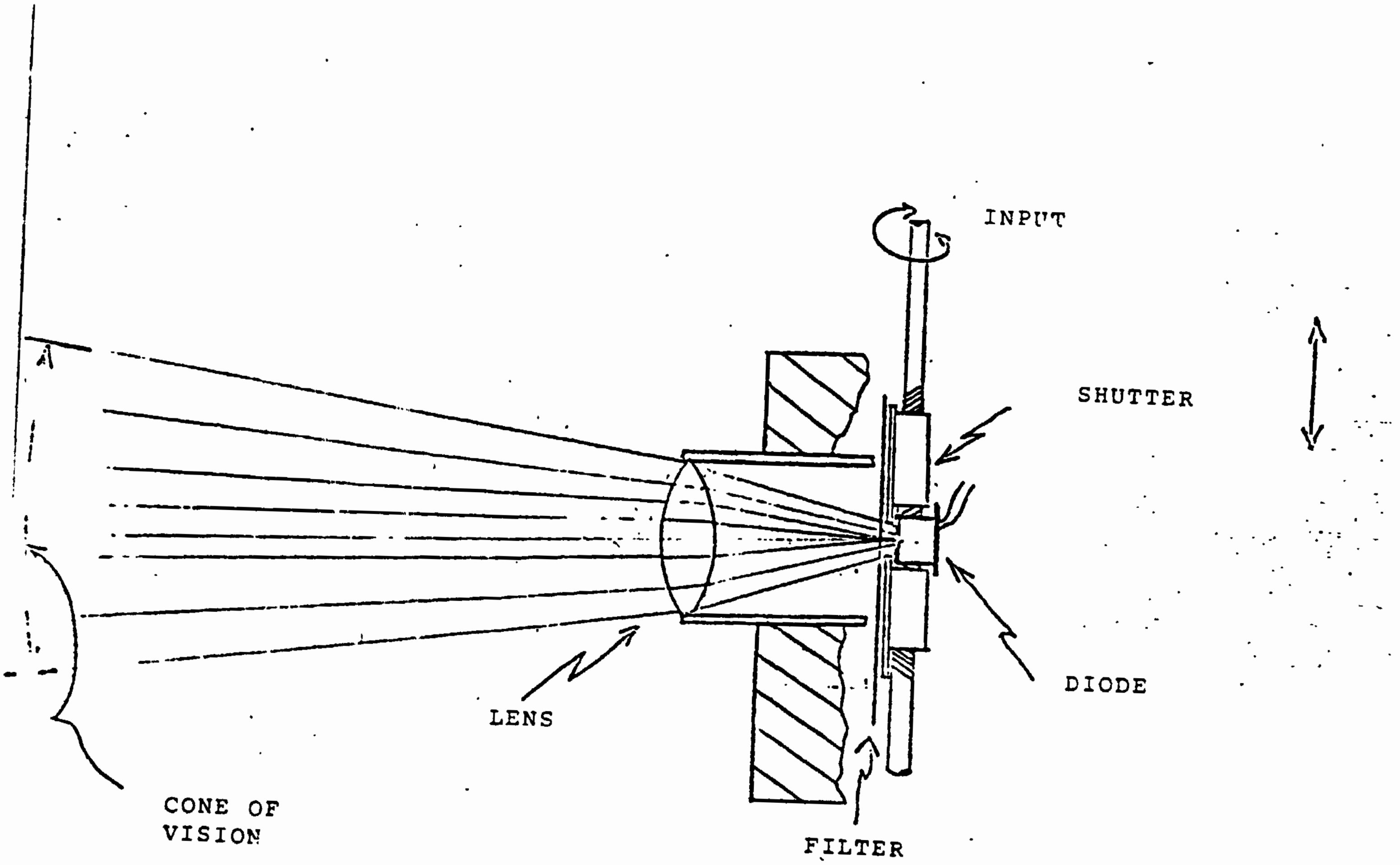

Figure 7 Shutter Mechanism

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This will allow the vehicle to undertake "closed loop" missions under computer control and permit evaluation of the path selection/hazard avoidance system's performance in the field.

Discussion: First, an explanation of the system's operation will be given, followed by a description of the work carried on this year.

The MRV is linked with a 16-bit, 32 K-word minicomputer, the Varian 620-i. There are three communication links, outlined in Figure 8, which handle MRV communication requirements.

The telemetry link transmits vehicle state data and laser terrain-sensing data to the computer interface. The control links are responsible for transmission of commands from the remote control box and the computer to the vehicle.

Communication from the computer interface to the computer itself takes several forms. Direct memory access (DMA) places data words directly into the computer's memory without program intervention. All data from the telemetry link are input into a DMA core region in this manner.

Single-word input transfer requires generation of an interrupt signal and execution of an interrupt handling routine for transfer of a single word from the interface to the computer. Commands from the remote control box are input in this fashion. Single-word output transfer required a special routine to handle transfer of a word from the computer to the interface. Commands from the computer to the vehicle are transferred this way.

Computer interface sense instructions allow the computer to interrogate the interface concerning the interface's state. Sense instructions are employed in the Mars software to differentiate between the two types of interrupts generated by the interface -- end of laser scan interrupts and remote control command input interrupts.

External control (EXC) instructions are available to allow the computer to initiate a specific mode of operation in the interface. In particular, EXC instructions are used to both enable and disable interrupts and DMA as necessary.

Data flow among the software programs is diagrammed in Figures 9 and 10. VEHINT, the interface interrupt handling routine is run whenever the computer interface generates an interrupt. Its purposes are to accept commands input through the remote control link and to buffer laser data words. The OUTPUT routine takes computer-generated commands and remote control box-generated commands and sends them to the interface for transmission over the computer control link.

GYRO decodes the directional and vertical gyroscope data words giving the inertial heading, and pitch and roll angles. It also decodes the front axle roll data. NAVIG1 merely echoes the heading requested by the computer operator. In the final position mode, NAVIG1 calculates the desired heading by calling an arctangent routine.

The teletype routine handles communication between the software and the computer operator. For example, it asks the operator which mode of operation (heading/final position) is desired and the values of the associated parameters.

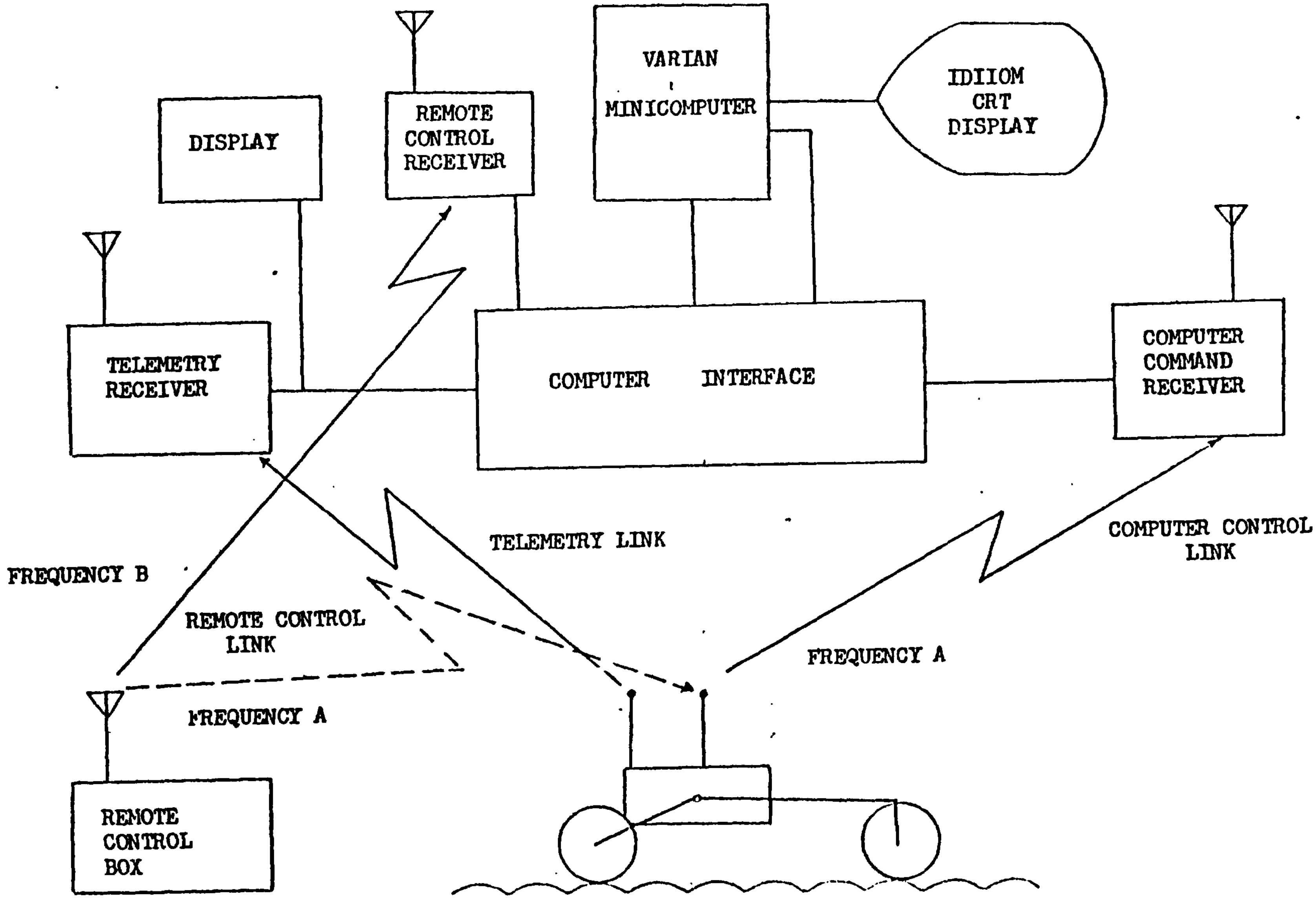

Figure 8 MRV Communication Links

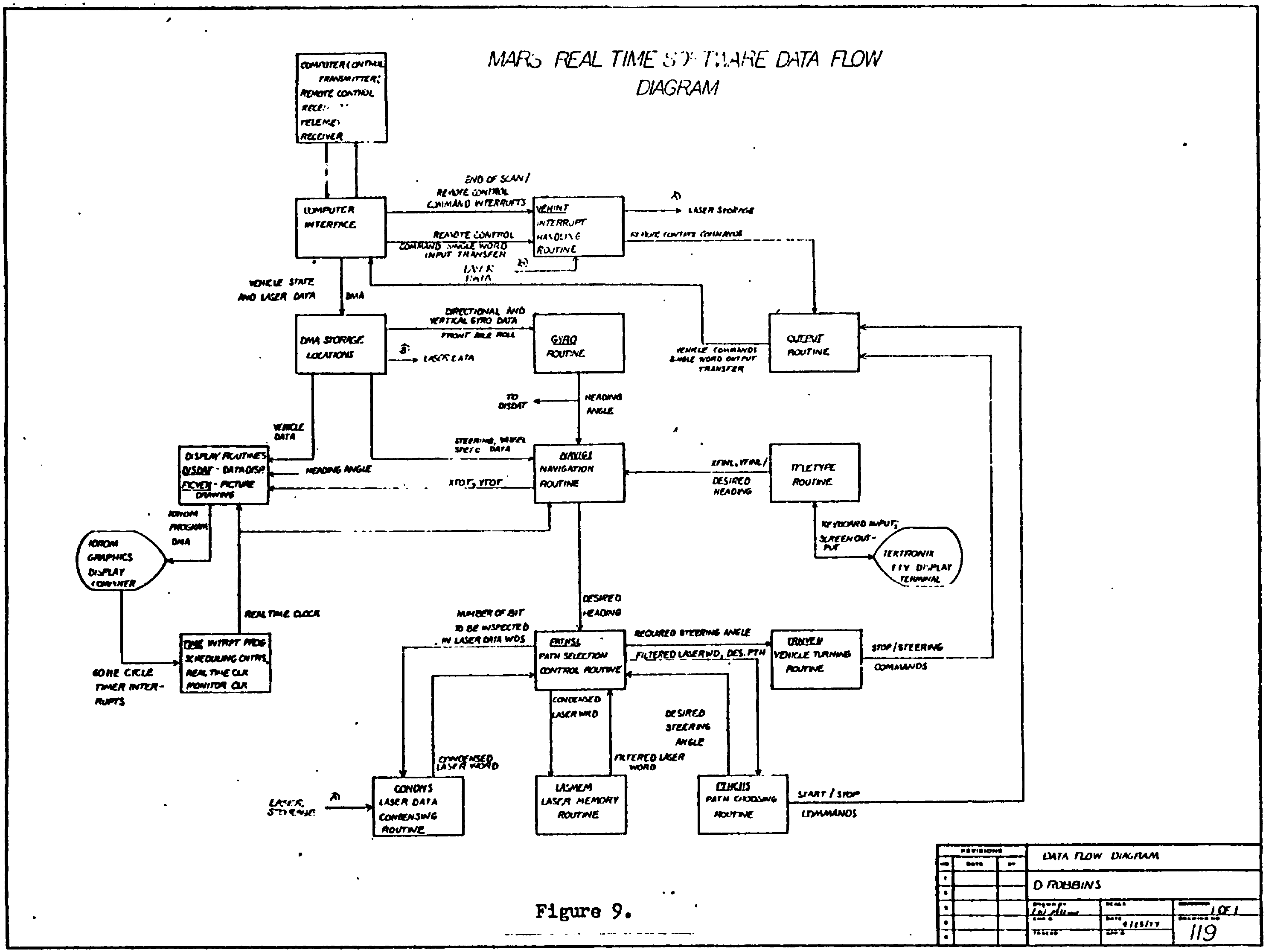
MARS REAL TIME SOFTWARE DATA FLOW DIAGRAM
COMPUTER CONTROL TRANSMITTER; REMOTE CONTROL RECEI... TELEMETRY RECEIVER
COMPUTER INTERFACE
END OF SCAN / REMOTE CONTROL COMMAND INTERRUPTS
REMOTE CONTROL COMMAND SINGLE WORD INPUT TRANSFER
LASER DATA
VEHINT INTERRUPT HANDLING ROUTINE
LASER STORAGE
REMOTE CONTROL COMMANDS
VEHICLE STATE AND LASER DATA
DMA
DMA STORAGE LOCATIONS
DIRECTIONAL AND VERTICAL GYRO DATA
FRONT AXLE ROLL
LASER DATA
GYRO ROUTINE
VEHICLE COMMANDS SINGLE WORD OUTPUT TRANSFER
OUTPUT ROUTINE
TO DISDAT
HEADING ANGLE
VEHICLE DATA
STEERING, WHEEL SPEED DATA
DISPLAY ROUTINES DISDAT - DATA DISP. PICVEH - PICTURE DRAWING
HEADING ANGLE
XTOT, YTOT
NAVIG1 NAVIGATION ROUTINE
XFINL, YFINL / DESIRED HEADING
TTLETYPE ROUTINE
KEYBOARD INPUT; SCREEN OUT-PUT
TEKTRONIX TTY DISPLAY TERMINAL
IMLAC PROGRAM DATA
IMLAC GRAPHICS DISPLAY COMPUTER
REAL TIME CLOCK
60 HZ CYCLE TIMER INTER-RUPTS
TIME INTRPT PROG SCHEDULING CNTRL REAL TIME CLK MONITOR CLK
NUMBER OF BIT TO BE INSPECTED IN LASER DATA WDS
DESIRED HEADING
PATHSL PATH SELECTION CONTROL ROUTINE
REQUIRED STEERING ANGLE
FILTERED LASERWD, DES. PTH
TRNVEH VEHICLE TURNING ROUTINE
STOP / STEERING COMMANDS
CONDENSED LASER WRD
FILTERED LASER WORD
DESIRED STEERING ANGLE
CONDENSED LASER WORD
LASER STORAGE
CONDNS LASER DATA CONDENSING ROUTINE
LASMEM LASER MEMORY ROUTINE
PTHCHS PATH CHOOSING ROUTINE
START / STOP COMMANDS
DATA FLOW DIAGRAM
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Figure 9.

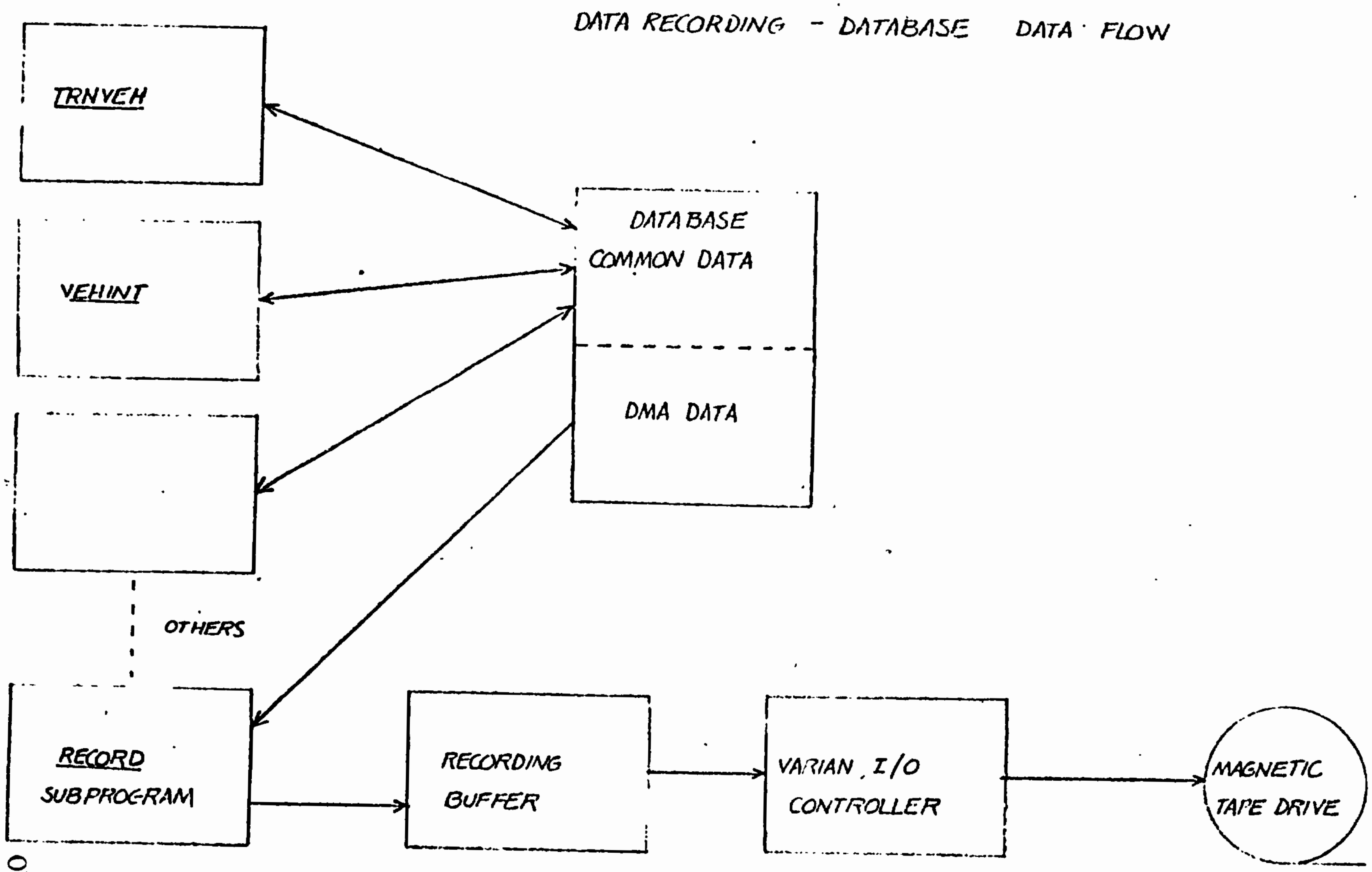

Figure 10.

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Two sets of display routines are available for use. DISDAT and PICVEH display three orthographic views of the vehicle, vehicle state data, x,y coordinates of the vehicle and the real time clock value on the IDIIOM computer CRT screen. A new set of display routines has been written which display the vehicles' position on an x,y grid along with a 1-0 bit stream of the received laser data, and some vehicle state data in decimal format.

Time is the IDIIOM interrupt routine which responds to IDIIOM 60 HZ cycle timer interrupts. Since these interrupts occur at regular intervals, they are used for timing and scheduling purposes.

PATHSL is the path selection control routine. In conjunction with routines CONDNS, LASMEM, and PTHCHS, it selects the path for the vehicle to travel on. To make this selection, it considers both the laser terrain sensing data and the desired heading. TRNVEH generates the vehicle steering commands necessary to guide the vehicle along the path selected by PATHSL.

The data recording subroutine, RECORD, at scheduled intervals, writes DMA data, common data (used to link subroutines) and other important data to a magnetic tape. This tape serves as a detailed mission record and can be analysed off-line on RPI's IBM 360-67 computer. In addition, there is a Varian program, REDUCT, which may be used to perform an off-line octal dump of the tape's contents.

Although Figure 9 suggests that data are passed directly from one subroutine to another, it generally is not. Most data common to two or more programs reside in a common data database to which the individual programs refer.

The executive scheduling routine, EXEL, calls the various subroutines at the appropriate times.

The software described above has been developed over the past 2 years. Work undertaken during the Fall 1976 semester has included upgrading previously developed software as well as designing new software.

Progress has been made in the following areas:

Task B.1 Code Modification

Over the summer of 1976, a new operating system, developed by students at RPI was incorporated in the Varian computer. This operating system, while providing vastly improved performance by the Varian, required a number of changes to existing programs so as to make them compatible with the new system. Among these changes were modification of all absolute format programs to relocatable format and deletion of all implied indirect addressing code present in the MARS software. These changes involved correction of some 1100 lines of assembly language code.

Task B.2 Interrupt/DMA Operation

Interrupt processing is an important part of the communication between vehicle and computer. Problems in the ability of the software to handle properly computer interface-generated interrupts were encountered during the Spring 1976 semester. The efforts outlined below corrected these problems.

Task B.2.1

A new scheduling routine was designed and implemented. This program controls the sequencing and timing of all programs used in the Mars software system, with the exception of interrupt-initiated programs.

Task B.2.2

New interrupt-handling routines were written (TIME and VEHINT). These routines were designed to minimize the time spent by the computer in the interrupt state. They were also, designed to be themselves interruptable, to eliminate problems caused by interrupts occuring at closely spaced intervals.

Task B.2.3

Modifications were made to the Computer Interface hardware. Circuitry was added to permit use of External Control instructions to control the interface. As a result it is now possible for the software to enable or disable interrupts and/or DMA. Circuitry was also added to disable Computer Interface-generated interrupts upon generation of an interrupt by a computer-connected device other than the Mars Computer Interface, (e.g. the IDIIOM display). This permits simplification of the interrupt-handling routines. The two changes outlined yield complete software control over interrupt occurence.

Task B.3 <u>Implementation of Special Purpose Routines</u>

Task B.3.1 <u>Navigation Routine</u>

The navigation routine, NAVIGL, started last semester was finished and evaluated. It was shown that errors introduced by approximations employed in the routine are negligible when compared with inaccuracies in the data presented to the program by sensors on the Mars Vehicle.

Task B.3.2 <u>Output Routine</u>

A routine, OUTPUT, to handle transfer of vehicle commands from the software to the Computer Interface was designed and tested. The routine keeps separate files for computer-generated and Remote Command Box - generated commands. These commands are recorded on to the magnetic tape as they are sent out.

Task B.3.3 <u>Data Base</u>

A data base was created to simplify data transfer between routines and to aid in program initialization prior to start up. The data base contains most data common to two or more programs.

Task B.4 <u>Data Recording and Reduction Programs</u>

Data recording and reduction programs were developed to provide a means of analysing the hazard detection/avoidance system's operation. During a test mission, key program parameters and data words are recorded onto magnetic tape. After test completion, the data on the tape may be examined in detail off-line. Programs which serve these functions are outlined below.

Task B.4.1 Data Recording

The routine, RECORD, records mission data onto magnetic tape. At the beginning of a tape, RECORD writes data format description information which is necessary for IBM 360 interpretation of the tape. RECORD'S features include easy addition of new data words to the list of data recorded during a mission. Also the computer operator may enable or disable the program during a test by throwing a computer sense switch.

Task B.4.2 Data Reduction (Varian 620)

The routine REDUCT was written to allow the computer operator to scan or print out the raw data recorded on magnetic tape. This program does little actual data reduction, but it does provide the operator the opportunity to view mission data without the time and expense required to run an IBM 360 job.

Task B.4.3 Data Reduction (IBM 360-67)

This program was developed to give a detailed, easy to read, description of a Mars Vehicle Mission. Using the magnetic tape written during the mission, the 360 reduction program prints out data as requested by the user. This data can include laser data in the form of a string of 1's and 0's, vehicle commands sent out (in english), steering angles in decimal degrees, etc. A particular effort was made to make the output easily understood. Also, the reduction program will print out a map in x,y coordinates of the vehicle's path during the mission.

Task B.5 Hazard Detection/Avodiance Software

A set of modular programs for hazard detection/avoidance and path selection was developed. These programs should also be suitable for use with future, more advanced path selection systems.

Task B.5.1 PATHSL

The program which controls the modular programs mentioned above is PATHSL. It calculates the necessary steering angle to yield the desired heading angle (determined at the start of a mission), and then calls other routines which put the vehicle on the safe path nearest the desired path (if such a safe path exists). The programs called by PATHSL are discussed below.

Task B.5.2

CONDNS is used to condense the laser data (15 words, only one bit in each of which is used however) into a single word for ease in manipulation. The laser data consists of go/no go information about the 15 paths scanned by the laser. A complete laser scan consists of one shot every 10^o from -70^o to $+70^o$ with respect to the steering angle.

Task B.5.3 LASMEM

The LASMEM routine maintains a laser scan data memory and also creates a buffer zone around the vehicle by path blocking. This scan memory allows the computer to make use of old scan data when attempting to select a safe path. Use of the memory results in the vehicle being less likely to strike obstacles with its rear wheels.

Task B.5.4 PTHCHS

PTHCHS, the path choosing routine has as inputs, the filtered data word from BLOCK and the desired steering angle as determined by PATHSL. It chooses the safe path nearest the desired steering angle. If no good paths are found, a flag is set, and the vehicle is stopped. The vehicle will remain stopped until a path becomes clear. A path could become clear should the vehicle be moved to a different location by a human operator using the Remote Control Box. Clearly, a more sophicated method of dealing with the all-paths hazardous case would be necessary for actual use on Mars, but this system should prove adequate for testing the path selection algorithm.

Task B.5.5 TRNVEH

The vehicle steering routine is TRNVEH. TRNVEH generates the command for steering the vehicle to that discrete steering angle permitted by the real mechanical system which is most nearly equal to the steering angle output from PTHCHS.

Reference 4 summarizes the software development program in detail.

TASK C Experimental Hazard Avoidance Studies - T. Kasura

Faculty Advisor: Prof. S. Yerazunis, Prof. D. Gisser

The rationale underlying the single laser/single detector system hazard is illustrated in Figure 11. So long as a surface capable of back scattering of the laser exists within the zone of perception, a positive signal will be generated by the focused photodetector. If there is no reflective surface situated within the zone, a negative signal will be generated. This rationale is applied to several situations in Figures 12.A, 12.B and 12.C. So long as a reflected signal is detected, Figure 12.A, the terrain is considered safe. Discrete hazards greater than some specified but arbitrary size (determined by the geometry selected by the user) will not produce reflections (or detector signals) as shown in Figure 12.B and 12.C, an event which is to be interpreted as a hazardous terrain.

This concept for assessing the passability of terrain is implemented at 15 azimuth angles covering a field of 140°. Figure 13 illustrates the concept as well as suggesting the condensed laser word, CDNDAT, which is used by the decision-making algorithm. In the first instance, the rover encounters an obstacle on its left side with the leftmost four paths being blocked. Because of the finite width of the rover, four additional azimuth paths are blocked: The decision maker than selects that path most consistant either with the fixed heading or final destination criterion and issues appropriate steering commands.

Experiments were undertaken to evaluate this hazard detection and avoidance system. The heights of the laser and detector were set at 1.68 and 1.0 meters respectively. The pointing angles were selected so that a positive step 12 inches or greater located at a distance of 4 feet from the vehicle would be interpreted as a hazard. A drop of 12 inches at a somewhat greater distance would likewise be considered hazardous. Terrain features falling inside the ±12-inch envelope were considered as safe.

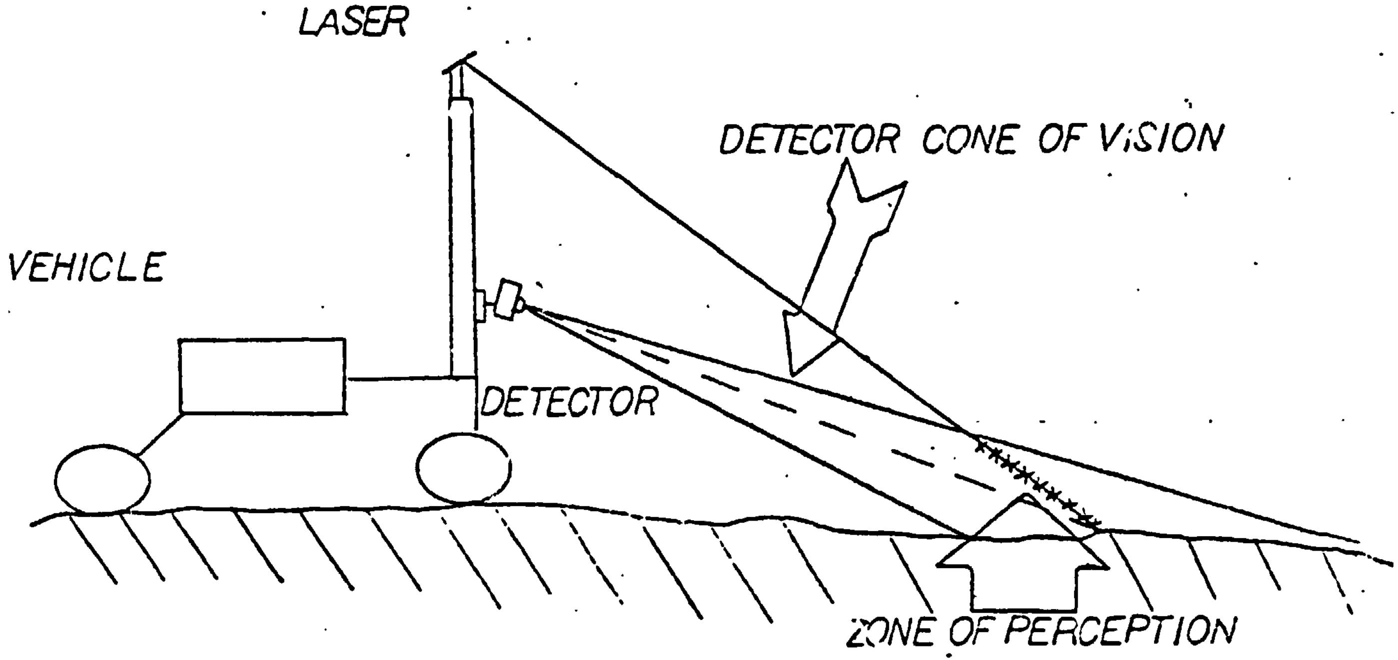


Figure 11 Laser Triangulation Scheme

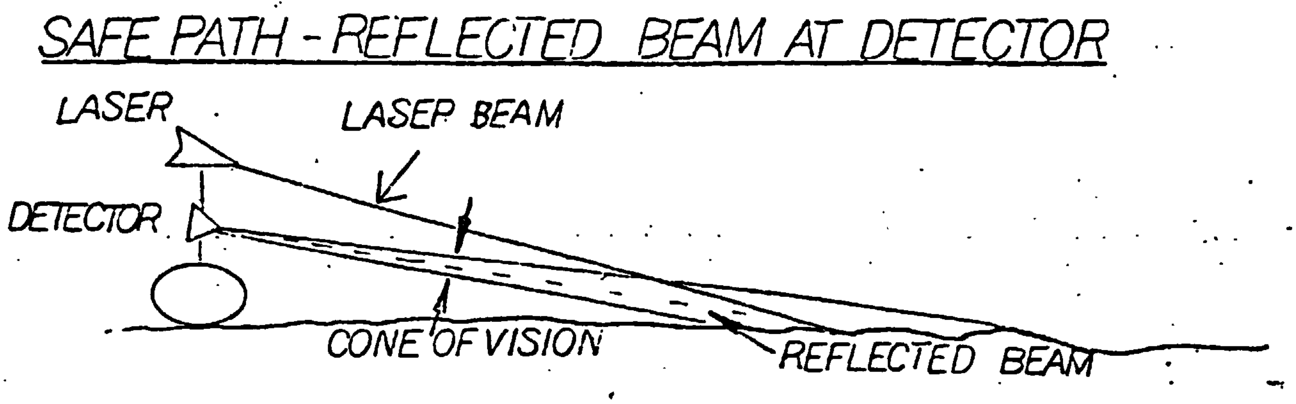

SAFE PATH - REFLECTED BEAM AT DETECTOR

Figure 12.A

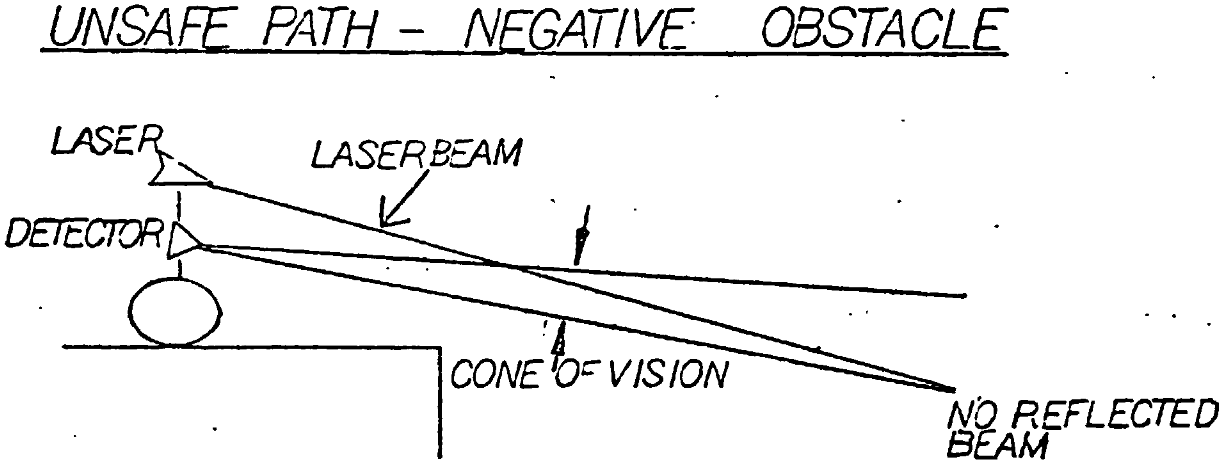

UNSAFE PATH - NEGATIVE OBSTACLE

Figure 12.B

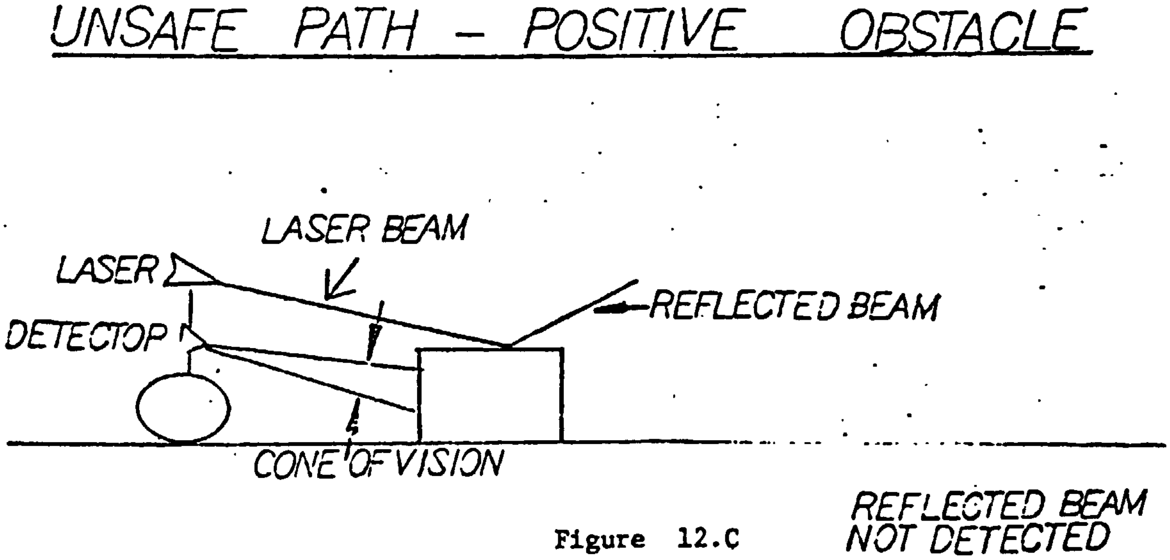

UNSAFE PATH - POSITIVE OBSTACLE

Figure 12.C

Figure 12 Examples of Application of Laser/Detector System.

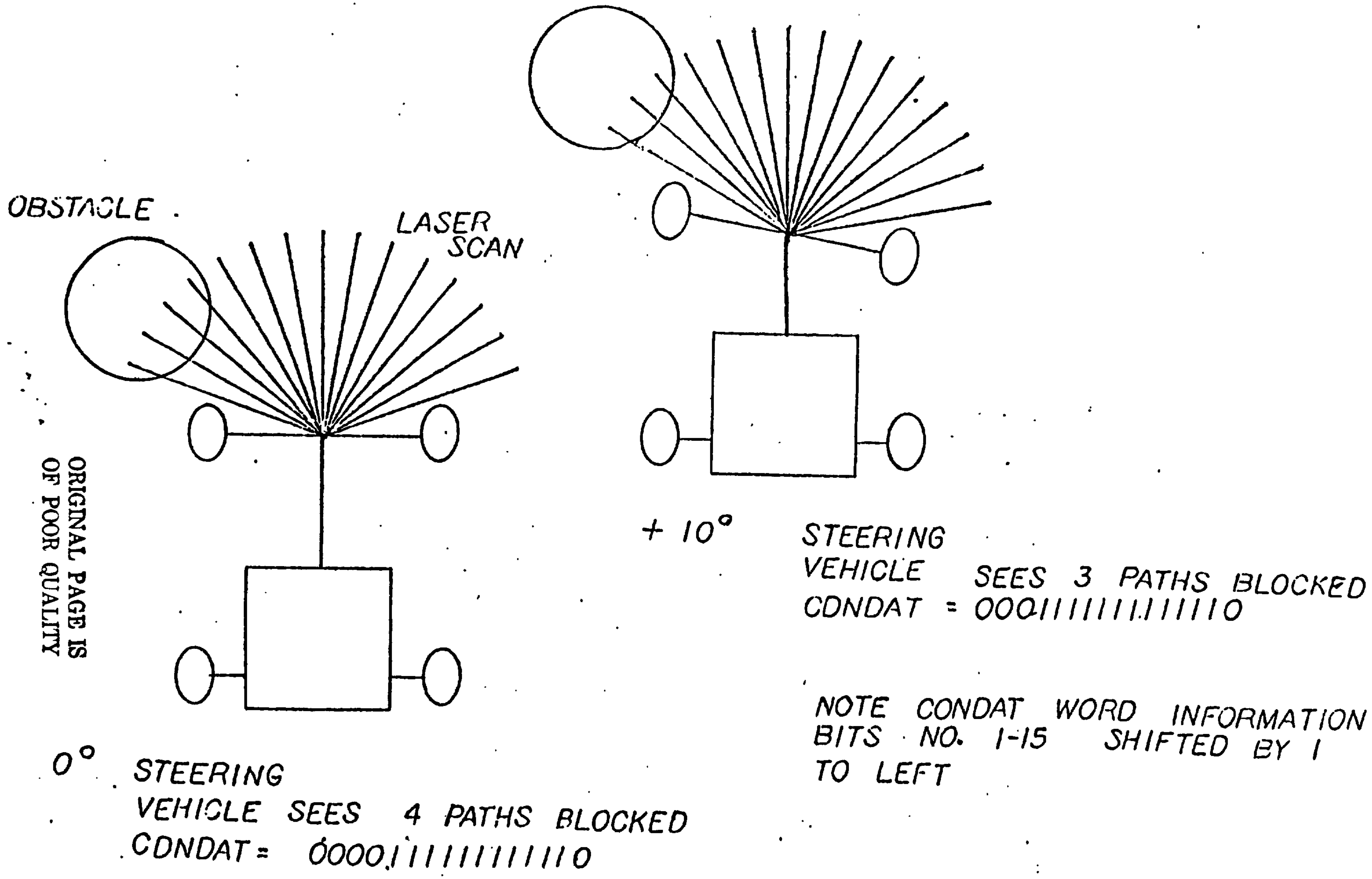


Figure 13 Condensed Laser Word Related To Obstacles

In conducting the experiments, 8 mm motion pictures were obtained for subsequent reference in analysis. The post processor data reduction system referred to under Task B was also employed to provide a hard copy of experimental detail.

A broad range of experiments were conducted in the laboratory including:

1. direct obstacle encounters,
2. long wall hazards,
3. two obstacles forming an opening,
4. staggered hazards, and
5. hazardous and non-hazardous ramps.

Field tests were also undertaken to determine the performance of the system with respect to:

1. a large positive hazard,
2. cliff edges and craters,
3. large boulders in a boulder field, and
4. general pitch/roll situations.

In general, the performance of the hazard avoidance system followed closely the predictions of the Path Selection Systems Simulation Program, Reference 5.

Figure 14 illustrates the reaction of the rover in encountering skewed obstacles. The hazard was sensed and the rover adjusted its path to avoid the obstacle and maintain the desired heading angle. In the case of a long wall, Figure 15, the rover given a desired heading of 45° which would involve an encounter with the wall adjusted its steering to move parallel with the wall. Figure 16 illustrates one of the current defects in the path selection algorithm. The rover was to locate an opening in a long wall situation. Although it was able to locate the opening, it employed too large a steering angle with the result that the rear wheel hit the corner of the wall. As shown in Figure 17, this is due to the dynamics of the rover and requires a higher level algorithm which can retain a knowledge of where the obstacle is located relative to the vehicle. The current system employed in these tests involved only a memory of when the obstacle was last seen and specified a fixed time interval before a maximum steering angle towards the goal could be implemented. In some cases, this system was effective; in others such as the one at hand, it was not adequate. The ability of the rover to locate and pass through a relatively narrow corridor is shown in Figure 18. The vehicle was able to locate and move through a 6 foot corridor (note that the vehicle is 4 feet wide). The ramp tests supported the simulation predictions in that the rover interpreted slopes of 16° as hazards whereas slopes of 11° were considered passable. Likewise, drops (negative features) in excess of 12" were interpreted as hazardous whereas smaller drops were not.

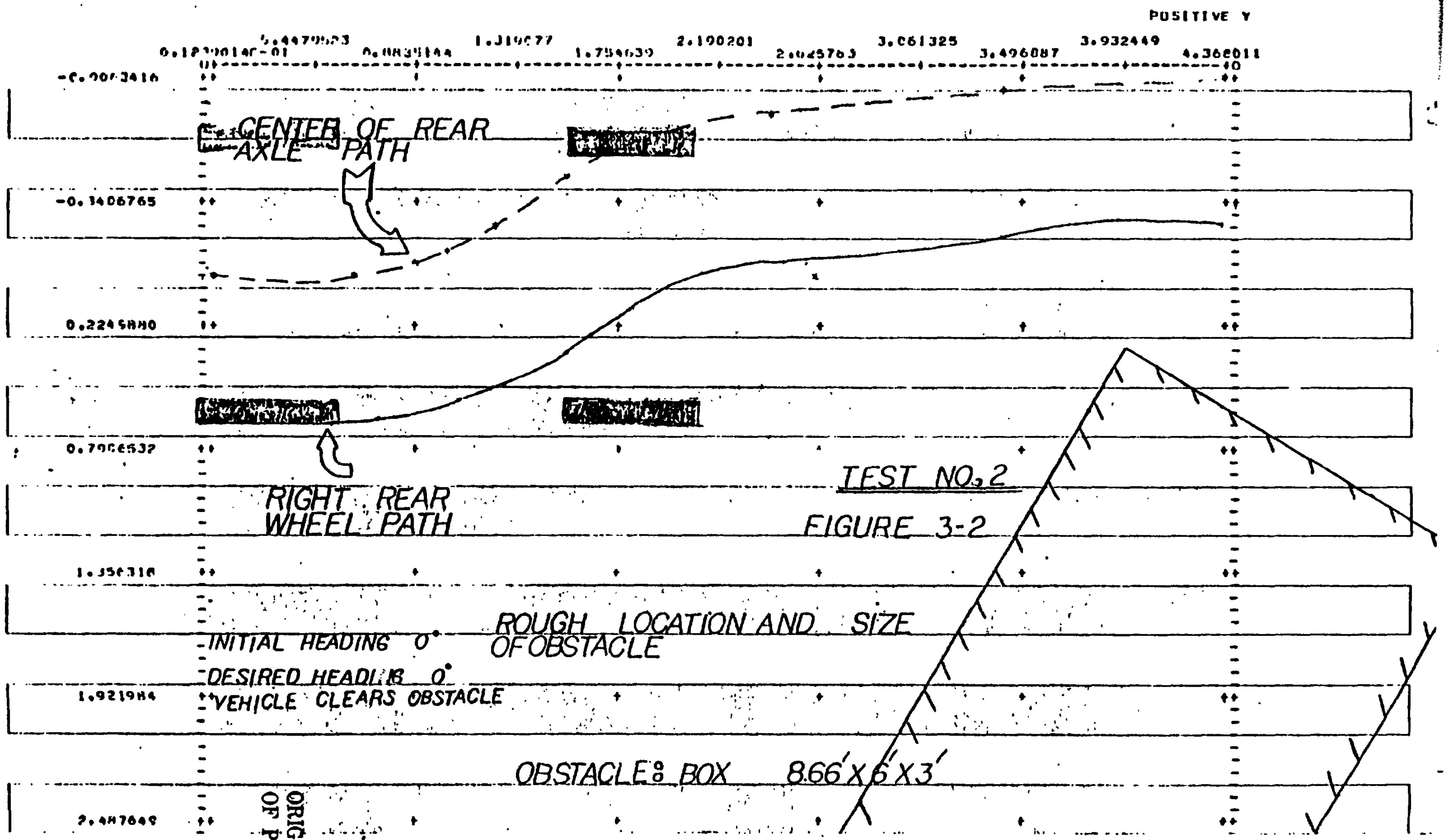


Figure 14 Vehicle and Skewed Obstacle

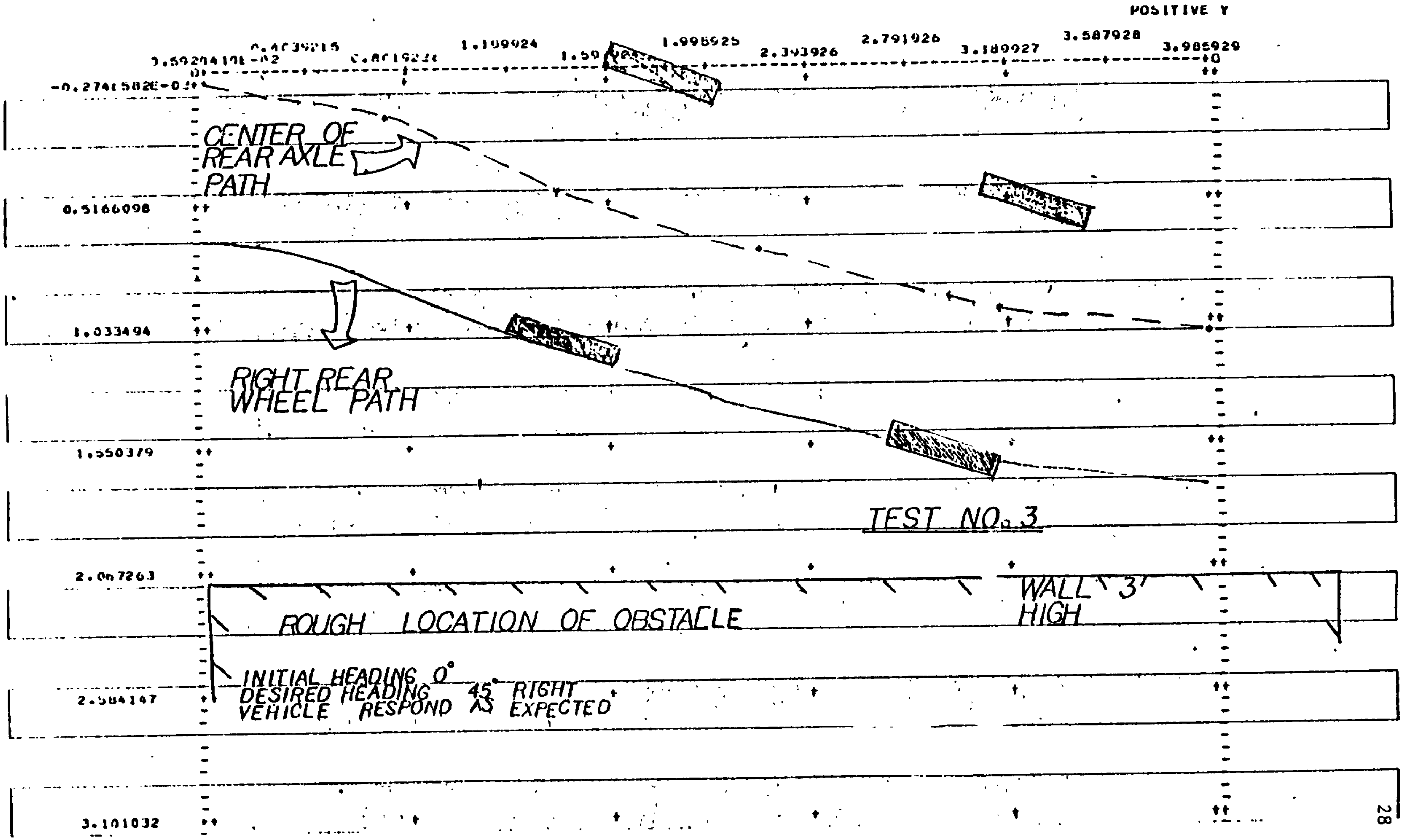


Figure 15 Vehicle and Wall

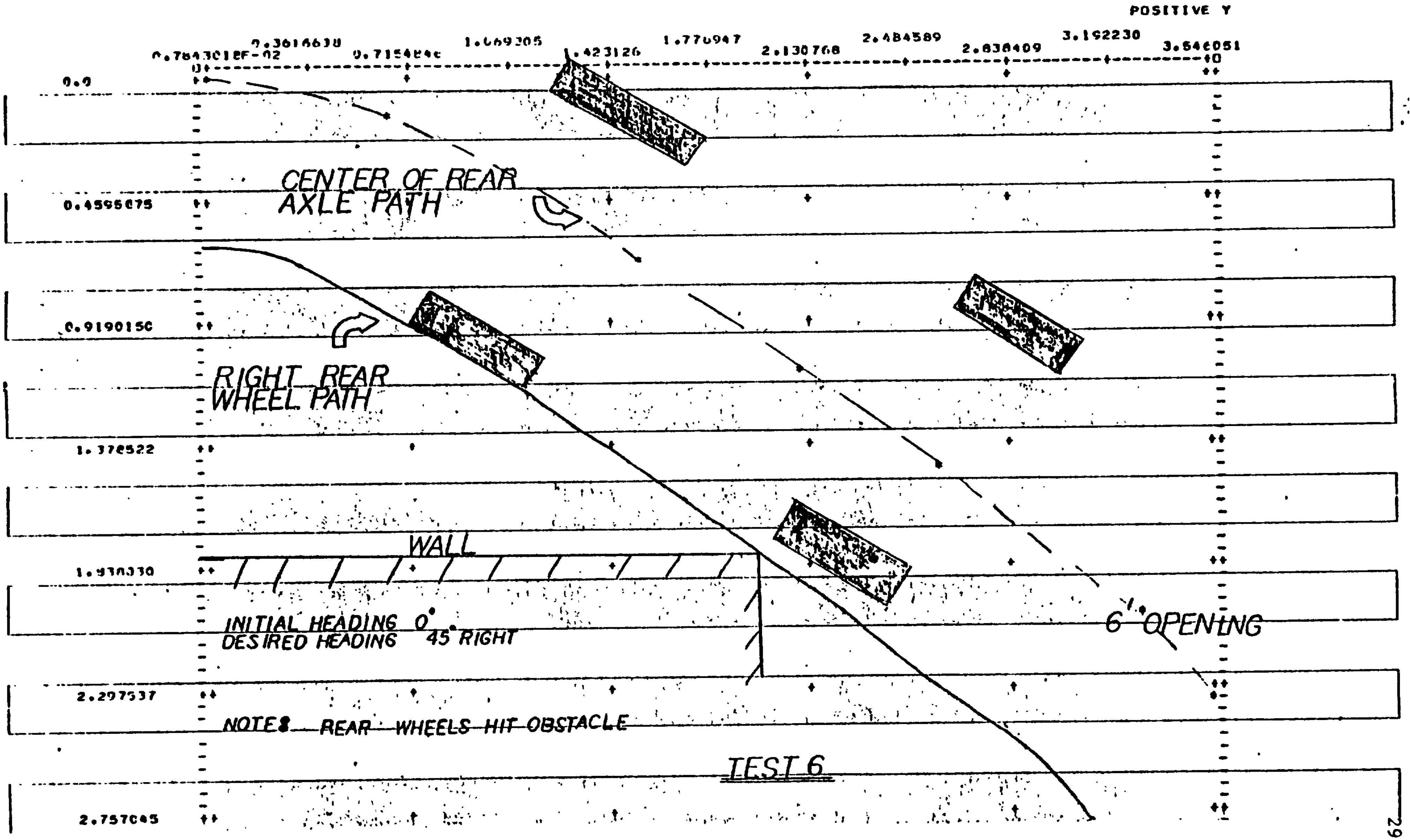


Figure 16 Vehicle And Wall Opening

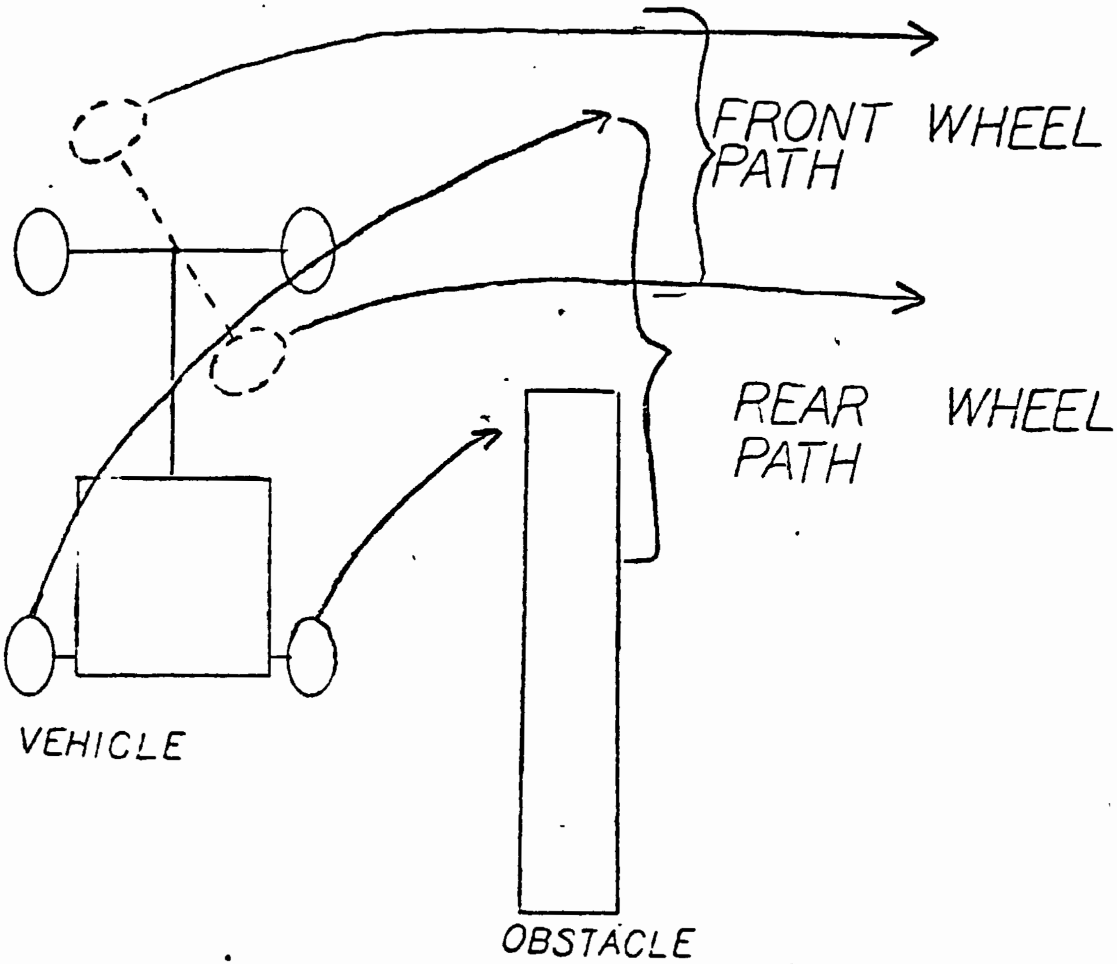


Figure 17 Front And Rear Wheel Paths While Turning

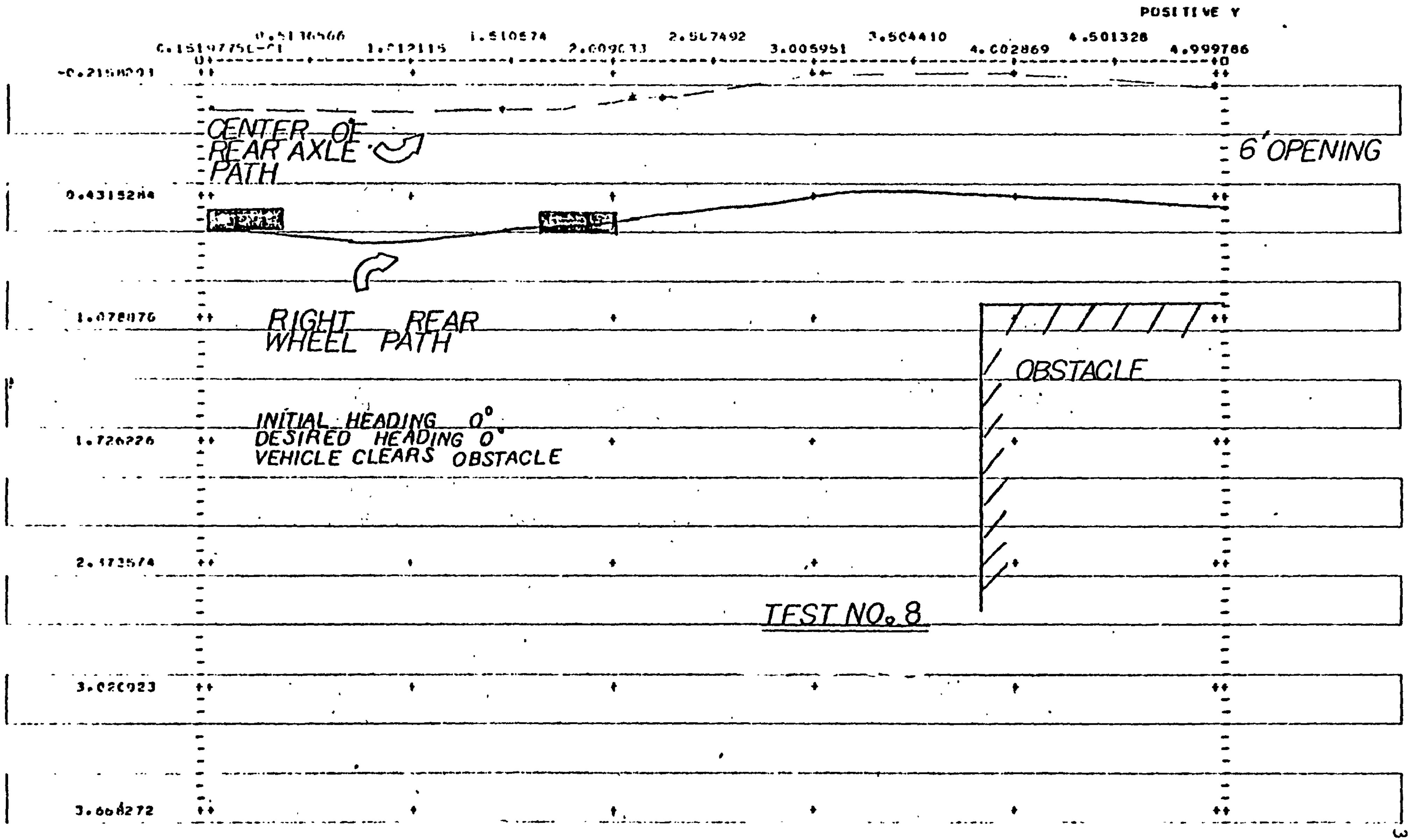


Figure 18 Vehicle And Wall Opening

The performance of the hazard avoidance system in the field also supported earlier predictions. A large positive obstacle was sensed and avoided. Impassable craters and cliffs edges were also sensed and proper control actions were taken. Figure 19 illustrates the reaction of the rover as it was directed to follow a heading which would force it over the cliff edge. The system sensed the hazard and selected a path paralleling the cliff edge, staying therefore as close as possible to the desired heading.

It was noted earlier that a post-processor data reduction system was used not only to provide the graphical output referred to above, but also to obtain a hard copy of the detail data for each experiment for subsequent analysis. Shown in Table 3 are typical laser data and control instructions which were obtained for the cliff experiment described above. The perception of the cliff edge can be noted on the second page of Table 3 where zeros appear on the right hand side of the condensed laser word. (Note that the rightmost digit in the laser word is always zero and is not a factor in the decision making). The post-processor also provides other important data as shown in Table 4 in which the cliff experiment is Test No. 23, File 15. The column headings have the following significance starting from the left: the file number required only as a matter of record, the record number during the test, elapsed time of test in seconds, the x-coordinate of the rover in meters, the y-coordinate in meters, the gyro heading, the steering angle, the difference between the steering angle and the gyro heading, and the vehicle speed. In the cliff test, the cliff was sensed at record 6 and appropriate steering actions were taken.

Between the direct observations made during an experiment, the motion pictures of the test and the post-processor hard copy, a substantial documentation is available for analysis.

These experimental studies lead to the following conclusions regarding the single laser/single detector hazard detection and avoidance concept:

1. Discrete vertical wall hazards are detected and avoidance action is taken. However, depending on the relative orientations of the vehicle and the obstacle, rear wheel collisions may occur. An improved algorithm which remembers the location of the hazard and accounts for the vehicle dynamics is required.

2. The system can locate and guide the rover through openings between obstacles provided that there is sufficient clearance.

3. Drops such as craters, trenches or cliffs are interpreted correctly provided that vehicle roll is modest.

4. The incorrect interpretation of a passable slope and the oblique search pattern as predicted by simulation was confirmed.

5. The implications of severe pitch and roll with respect to incorrect interpretation also predicted by simulation was confirmed by the field tests.

6. An autonomous guidance system using the single laser/single detector concept can be effective provided that the constraints that pitch and roll will not exceed $\pm 10^{\circ}$ are met. However, the system will be extremely conservative and unnecessarily long paths will be selected

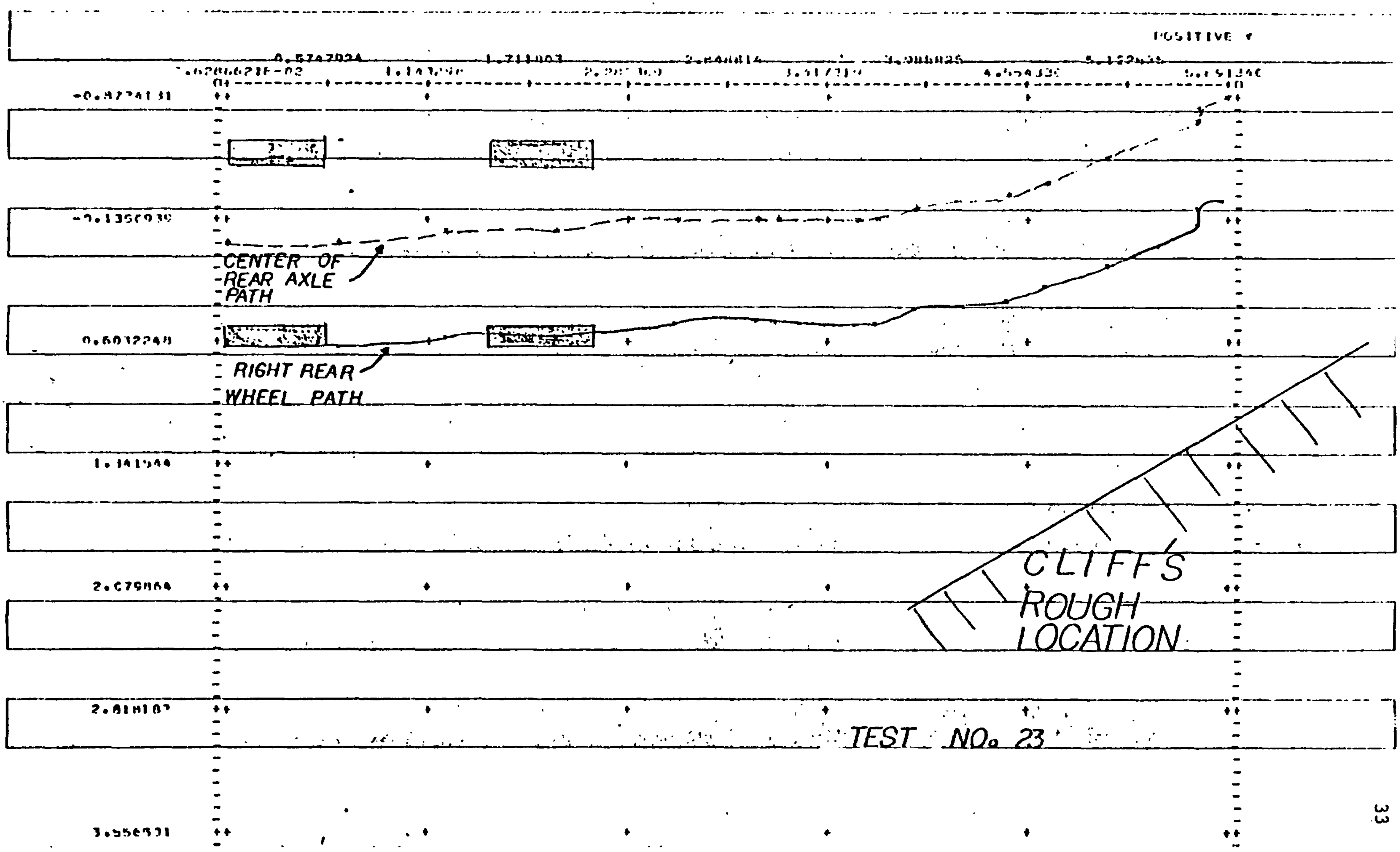


Figure 19 Vehicle Heading Towards Cliff Obliquely

Table 5 Typical Post Processor Output for the Cliff Hazard

```
CONDENSED LASER WORD: 11111011110011110     AT RTC=     74.648
CONDENSED LASER WORD: 11110111110011110     AT RTC=     75.148
CONDENSED LASER WORD: 11110011111001110     AT RTC=     75.648
CONDENSED LASER WORD: 11110111110011110     AT RTC=     76.148
CONDENSED LASER WORD: 11110101111001110     AT RTC=     76.648

FILE= 15     RECORD= 12

CONDENSED LASER WORD: 11100111010001110     AT RTC=     77.148
CONDENSED LASER WORD: 11110111111001110     AT RTC=     77.648
CONDENSED LASER WORD: 11110011110001110     AT RTC=     78.148
CONDENSED LASER WORD: 11100111110011110     AT RTC=     78.647
CONDENSED LASER WORD: 11110111111001110     AT RTC=     79.147
CONDENSED LASER WORD: 11110111110001110     AT RTC=     79.647
CONDENSED LASER WORD: 11110111110001110     AT RTC=     80.147
CONDENSED LASER WORD: 11110111110001110     AT RTC=     80.647
CONDENSED LASER WORD: 11100111110001110     AT RTC=     81.147
CONDENSED LASER WORD: 11110011111001110     AT RTC=     81.647
CONDENSED LASER WORD: 11110111111001110     AT RTC=     82.147
CONDENSED LASER WORD: 11110011111001110     AT RTC=     82.646
CONDENSED LASER WORD: 11110111111001110     AT RTC=     83.146
CONDENSED LASER WORD: 11110111111001110     AT RTC=     83.646

**********END OF FILE 15 **********

FILE= 16     RECORD=  1

OPERATION COMMAND:  MAST UP            DECIMAL VALUE=  119   OCTAL VALUE=000167   AT RTC=     3.582
OPERATOR COMMAND:   MAST STOP          DECIMAL VALUE=  116   OCTAL VALUE=000164   AT RTC=     4.332
CONDENSED LASER WORD: 11111111111111110     AT RTC=     6.665
COMPUTER COMMAND:   FORWARD 1/3        DECIMAL VALUE=  81    OCTAL VALUE=000121   AT RTC=     6.665
COMPUTER COMMAND:   TURN LEFT 00.0     DECIMAL VALUE=  64    OCTAL VALUE=000100   AT RTC=     6.832

FILE= 16     RECORD=  2

CONDENSED LASER WORD: 11111111111111110     AT RTC=     7.165
CONDENSED LASER WORD: 11111111111111110     AT RTC=     7.665
CONDENSED LASER WORD: 11111111111111110     AT RTC=     8.165
CONDENSED LASER WORD: 11111111111111110     AT RTC=     8.665
CONDENSED LASER WORD: 11111111111111110     AT RTC=     9.164
CONDENSED LASER WORD: 11111111111111110     AT RTC=     9.664
CONDENSED LASER WORD: 11111111111111110     AT RTC=    10.164
CONDENSED LASER WORD: 11111111111111110     AT RTC=    10.664
CONDENSED LASER WORD: 11111111111111110     AT RTC=    11.164
CONDENSED LASER WORD: 11111111111111110     AT RTC=    11.664
CONDENSED LASER WORD: 11111111111111110     AT RTC=    12.164
CONDENSED LASER WORD: 11111111111111110     AT RTC=    12.664
CONDENSED LASER WORD: 11111111111111110     AT RTC=    13.163
CONDENSED LASER WORD: 11111111111111110     AT RTC=    13.663

FILE= 16     RECORD=  3

CONDENSED LASER WORD: 11111111111111110     AT RTC=    14.163
CONDENSED LASER WORD: 11111111111111110     AT RTC=    14.663
CONDENSED LASER WORD: 11111111111111110     AT RTC=    15.163
CONDENSED LASER WORD: 11111111111111110     AT RTC=    15.663
CONDENSED LASER WORD: 11111111111111110     AT RTC=    16.163
CONDENSED LASER WORD: 11111111111111110     AT RTC=    16.663
CONDENSED LASER WORD: 11111111111111110     AT RTC=    17.163
CONDENSED LASER WORD: 11111111111111110     AT RTC=    17.662
CONDENSED LASER WORD: 11111111111111110     AT RTC=    18.162
CONDENSED LASER WORD: 11111111111111110     AT RTC=    18.662
CONDENSED LASER WORD: 11111111111111110     AT RTC=    19.162
CONDENSED LASER WORD: 11111111111111110     AT RTC=    19.662
CONDENSED LASER WORD: 11111111111111110     AT RTC=    20.162
CONDENSED LASER WORD: 11111111111111110     AT RTC=    20.662
```

VEHICLE HEADING
TOWARD CLIFF
OBLIQUELY

TEST NO. 23

COMPUTER DATA RESULTS

MEMORY=10

ORIGINAL PAGE I
OF POOR QUALITY

Table 3 (Continued) Typical Post Processor Output for the Cliff Hazard

```
FILE= 16     RECORD=  4

CONDENSED LASER WORD: 1111111111111110        AT RTC=      21.161
CONDENSED LASER WORD: 1111111111111110        AT RTC=      21.661
CONDENSED LASER WORD: 1111111111111111        AT RTC=      22.161
CONDENSED LASER WORD: 1111111111111110        AT RTC=      22.661
CONDENSED LASER WORD: 1111111111111110        AT RTC=      23.161
CONDENSED LASER WORD: 1111111111111110        AT RTC=      23.661
CONDENSED LASER WORD: 1111111111111110        AT RTC=      24.161
CONDENSED LASER WORD: 1111111111111110        AT RTC=      24.661
CONDENSED LASER WORD: 1111111111111110        AT RTC=      25.161
CONDENSED LASER WORD: 1111111111111110        AT RTC=      25.660
CONDENSED LASER WORD: 1111111111111110        AT RTC=      26.160
CONDENSED LASER WORD: 1111111111111110        AT RTC=      26.660
CONDENSED LASER WORD: 1111111111111110        AT RTC=      27.160
CONDENSED LASER WORD: 1111111111111110        AT RTC=      27.660

FILE= 16     RECORD=  5

CONDENSED LASER WORD: 1111111111111110        AT RTC=      28.160
CONDENSED LASER WORD: 1111111111111110        AT RTC=      28.660
CONDENSED LASER WORD: 1111111111111110        AT RTC=      29.160
CONDENSED LASER WORD: 1111111111111110        AT RTC=      29.659
CONDENSED LASER WORD: 1111111111111110        AT RTC=      30.159
CONDENSED LASER WORD: 1111111111111110        AT RTC=      30.659
CONDENSED LASER WORD: 1111111111111110        AT RTC=      31.159
CONDENSED LASER WORD: 1111111111111110        AT RTC=      31.659
CONDENSED LASER WORD: 1111111111111110        AT RTC=      32.159
CONDENSED LASER WORD: 1111111111111110        AT RTC=      32.657
CONDENSED LASER WORD: 1111111111111110        AT RTC=      33.159
CONDENSED LASER WORD: 1111111111111110        AT RTC=      33.658
CONDENSED LASER WORD: 1111111111111110        AT RTC=      34.158
CONDENSED LASER WORD: 1111111111111110        AT RTC=      34.658

FILE= 16     RECORD=  6

CONDENSED LASER WORD: 1111111111111110        AT RTC=      35.158
CONDENSED LASER WORD: 1111111111111110        AT RTC=      35.658
CONDENSED LASER WORD: 1111111111111110        AT RTC=      36.158
CONDENSED LASER WORD: 1111111111111110        AT RTC=      36.658
CONDENSED LASER WORD: 1111111111101110        AT RTC=      37.158
COMPUTER COMMAND:  TURN LEFT 12.9     DECIMAL VALUE=   65   OCTAL VALUE=000101   AT RTC=    37.168
CONDENSED LASER WORD: 1111111111101110        AT RTC=      37.657
CONDENSED LASER WORD: 1111111111000110        AT RTC=      38.157
COMPUTER COMMAND:  FORWARD STOP       DECIMAL VALUE=   80   OCTAL VALUE=000120   AT RTC=    38.157
COMPUTER COMMAND:  TURN LEFT 25.7     DECIMAL VALUE=   66   OCTAL VALUE=000102   AT RTC=    38.324
CONDENSED LASER WORD: 1111111111100110        AT RTC=      38.657
CONDENSED LASER WORD: 1111111111100000        AT RTC=      39.157
CONDENSED LASER WORD: 1111111111100010        AT RTC=      39.657
CONDENSED LASER WORD: 1111111111110000        AT RTC=      40.157
COMPUTER COMMAND:  FORWARD 1/3        DECIMAL VALUE=   81   OCTAL VALUE=000121   AT RTC=    40.157
CONDENSED LASER WORD: 1111111111110000        AT RTC=      40.657
CONDENSED LASER WORD: 0111111111111000        AT RTC=      41.157
CONDENSED LASER WORD: 0111111111111000        AT RTC=      41.656

FILE= 16     RECORD=  7

CONDENSED LASER WORD: 1111111101111000        AT RTC=      42.156
COMPUTER COMMAND:  FORWARD STOP       DECIMAL VALUE=   80   OCTAL VALUE=000120   AT RTC=    42.156
CONDENSED LASER WORD: 1011111111111000        AT RTC=      42.656
CONDENSED LASER WORD: 1111111111111000        AT RTC=      43.156
CONDENSED LASER WORD: 1111111111111000        AT RTC=      43.655
CONDENSED LASER WORD: 1111111111111000        AT RTC=      44.156
CONDENSED LASER WORD: 1111111111111000        AT RTC=      44.655
CONDENSED LASER WORD: 1111111111111000        AT RTC=      45.156
CONDENSED LASER WORD: 1111111111111000        AT RTC=      45.656
CONDENSED LASER WORD: 1111111111111000        AT RTC=      46.155
CONDENSED LASER WORD: 1111111111111000        AT RTC=      46.655
```

Table 4 Typical Post Processor Output for the Cliff Hazard

```
  9     1          8.495     -0.001      0.067    359.169      4.875    359.984      0.001     0.0
  9     2         15.496     -0.002      0.256      0.194     22.774     21.826      0.001     0.0
  9     3         22.495     -0.001      0.266      2.844     23.828     26.172      0.001     0.0
  9     4         29.493      0.019     -0.317    354.125     19.641     13.766      0.001     0.0

 ***********END OF FILE   9 **********

 13     1          6.998     -0.035      0.411    358.969     -0.313    359.756      0.150     0.0
 13     2         13.997     -0.006      1.125      1.922     -0.313      1.776      0.000     0.0
 13     3         20.995      0.018      1.728      4.734     -9.938     -5.203      0.004     0.0
 13     4         27.993      0.033      2.141    358.466    -38.234    319.672      0.002     0.0
 13     5  TEST   34.991      0.007      2.425    351.404    -18.391    333.094      0.004     0.0
 13     6  NO.    41.990     -0.038      2.756    355.422      8.266      3.688      0.104     0.0
 13     7   21    48.988     -0.051      3.438    356.669      8.391      5.006      0.100     0.0
 13     8         55.986     -0.096      4.175      1.781      1.447      2.828      0.030     0.0
 13     9         62.985     -0.098      4.440    358.969     -9.141    358.828      0.001     0.0
 13    10         69.983     -0.099      4.648    358.969    -33.313    323.656      0.001     0.0
 13    11         76.981     -0.105      4.773    357.281    -26.734    330.547      0.008     0.0
 13    12         83.979     -0.124      5.349    357.422    -28.984    328.438      0.002     0.0
 13    13         90.978     -0.165      5.676    340.594     -5.234    341.359      0.001     0.0
 13    14         97.976     -0.201      5.856    351.375     21.047     12.422      0.001     0.0
 13    15        104.974     -0.237      6.077    349.969     22.109     12.078     -0.009     0.0
 13    16        111.973     -0.239      6.086    360.750     13.066      3.766     -0.012     0.0

 ***********END OF FILE  13 **********

 15     1          6.998      0.006      0.417      2.984      1.359      3.844      0.075     0.0
 15     2  TEST   13.997      0.034      0.968      4.875      0.875      5.756      0.078     0.0
 15     3  NO.    20.995      0.089      1.523      7.125      6.344      7.469      0.076     0.0
 15     4         27.993      0.153      2.072      7.766      1.438      9.203      0.005     0.0
 15     5   22    34.991      0.246      2.647     11.281     -9.453      1.828      0.002     0.0
 15     6         41.990      0.376      3.260     12.797     -9.234      3.563      0.000     0.0
 15     7         48.988      0.444      3.666     10.328      8.609     18.938      0.005     0.0
 15     8         55.986      0.448      3.628     11.313     32.047     43.359      0.002     0.0
 15     9         62.985      0.457      3.677     12.438      2.766     15.233      0.002     0.0
 15    10         69.983      0.545      4.076     13.172     -9.211      3.891      0.001     0.0
 15    11         76.981      0.540      4.082     13.031     -9.914      3.047      0.001     0.0
 15    12         83.979      0.547      4.087     13.031     -9.984      3.047      0.001     0.0

 ***********END OF FILE  15 **********

 16     1  TEST    6.998     -0.001      0.006    358.969     -0.094    358.875      0.000     0.0
 16     2  NO.    13.997     -0.030      0.633    356.469      0.094    356.375      0.001     0.0
 16     3   23    20.995     -0.069      1.259    357.984      0.391    358.375      0.092     0.0
 16     4         27.993     -0.094      1.894    358.688      0.344    359.031      0.094     0.0
 16     5         34.991     -0.108      2.500    359.953      0.703      0.656      0.094     0.0
 16     6         41.990     -0.115      2.998    350.672    -23.563    332.710      0.071     0.0
 16     7         48.988     -0.114      3.161    358.266    -25.297    331.969      0.001     0.0
 16     8         55.986     -0.154      3.592    352.991    -29.156    323.734      0.002     0.0
 16     9         62.985     -0.168      3.679    350.672    -18.953    331.719      0.000     0.0
 16    10         69.983     -0.215      3.951    351.063    -34.969    316.094      0.011     0.0
 16    11         76.981     -0.271      4.403    343.641    -26.125    317.516      0.001     0.0
 16    12         83.979     -0.340      4.665    340.891     75.266     56.156     -0.003     0.0
 16    13         90.978     -0.339      4.659    340.688    -41.813    298.875      0.007     0.0
 16    14         97.976     -0.483      5.010    335.453    -27.750    307.733      0.079     0.0
 16    15        104.974     -0.743      5.474    329.297    -24.406    304.891      0.077     0.0
 16    16        111.973     -0.766      5.516    330.953    -48.984    281.969      0.001     0.0
 16    17        118.971     -0.753      5.520    330.281     -1.016    329.266      0.001     0.0
 16    18        125.969     -0.766      5.534    329.969     -1.188    328.781      0.001     0.0
 16    19        132.968     -0.862      5.651    330.344    -43.188    287.156      0.001     0.0
 16    20        139.966     -0.872      5.681     68.578     -1.016     67.563      0.001     0.0
 16    21        146.964     -0.873      5.663    310.484     -1.016    339.469      0.001     0.0

 ***********END OF FILE  16 **********

 17     1          6.998      0.132      0.277     71.250    -18.953     52.297      0.178     0.0
 17     2         13.997      0.146      0.316     47.031     -6.261     20.781     -0.120     0.0
```

because of this bias. In circumstances where the pitch/roll constraints are not satisfied, the system may indicate no satisfactory paths even though the terrain is in fact passable. A higher level system involving multi-lasers and multi-detectors such as is described under Task D is required to provide for more efficient guidance.

These experimental studies are described in detail in Reference 6.

TASK D Development of a Multi-Laser/Multi-Detector Short Range Hazard Detection System - G. Maroon
Faculty Advisors: Profs. D.K. Frederick, S. Yerazunis

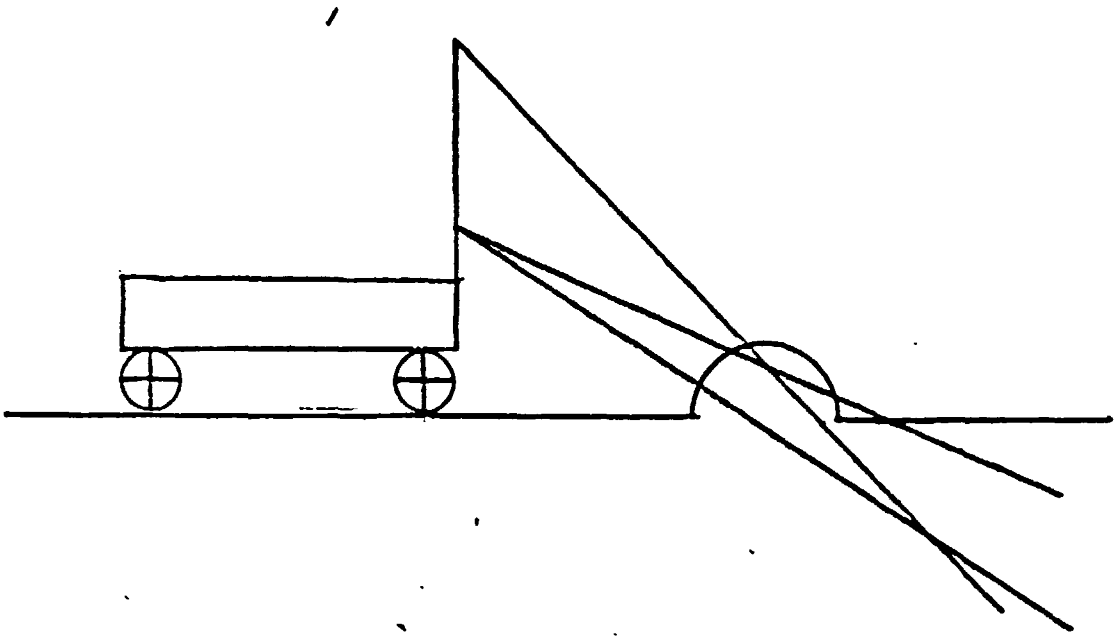
Although the single laser/single detector system can be used as the basis of a hazard avoidance, it suffers from two major limitations. Both of these originate with the fact that the decision regarding the passability of the terrain is based on the issue of whether the terrain lies inside the intersection of a single laser beam and the cone of vision of a single detector. The geometry of the system can be controlled to make this zone of acceptability of arbitrary size. It can, therefore, be set to sense that a boulder or crater of excessive size lies in the rover path. Physically in such a situation as shown in Figure 20 for an unsafe boulder, the laser reflection is outside the field of view of the detector and no signal would be received. A similar result would obtain in the case of too deep a trench or a crater. However, safe terrains could also produce the same result as shown in the case of an incline in Figure 20. This ambiguity indicates that the single laser/single detector system would interpret many safe paths as hazardous and would force the rover to follow unnecessarily tortuous paths. Indeed, under certain circumstances no path would be considered passable.

In addition, the ability of the rover to deal with various terrain features depends on its orientation relative to true vertical. For example, if the rover's slope climbing ability were 30°, it could deal with a 40° slope relative to the rover provided that the rover was inclined downward by at least 10°. Since the single laser/single detector system is capable only of detecting a rise or drop of fixed size, (in the case at hand steps of ±12" which are equivalent to slopes of ±13°), it cannot provide the information required for safe path selection in terrains characterized by significant gradients. Thus, its use in practice would be limited to terrains involving modest gradients of the order of 10° or less.

These limitations were recognized during simulations of the single laser/single detector system. Subsequently, it was shown that a three laser/three detector system could reduce the ambiguity between boulder and slopes, Reference 7. However, this system could not deal with the question of the vehicle orientation, i.e. pitch and roll.

To overcome these serious limitations, a multi-laser/multi-detector concept was investigated. The concept, which is illustrated in Figure 21 for an eleven laser/sixteen detector system, increases both the data density and the data accuracy. In principle, a series of laser pulses at specific elevation angles are fired at a single azimuth angle. Depending on the terrain feature lying within the field of view, particular detectors would signal receipt of a laser reflection indicating the location of terrain. The uncertainty to be associated with the location of a specific bit of terrain would be determined by the geometry, i.e. locations of laser source and detectors, the pointing angles of each and the "cones of vision" of the detectors. In principle, the accuracy of the measurement can be increased by making the "cones of vision" smaller and

Unsafe Boulder



Safe Incline

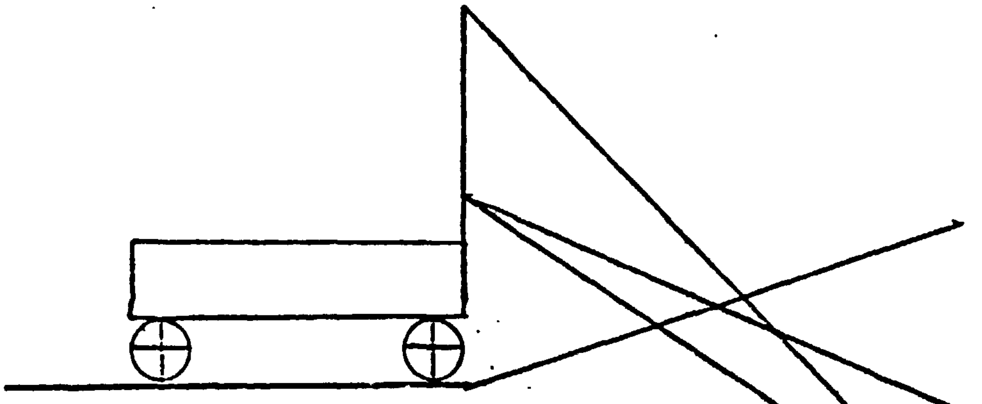


Figure 20 Slope/Boulder Ambiguity

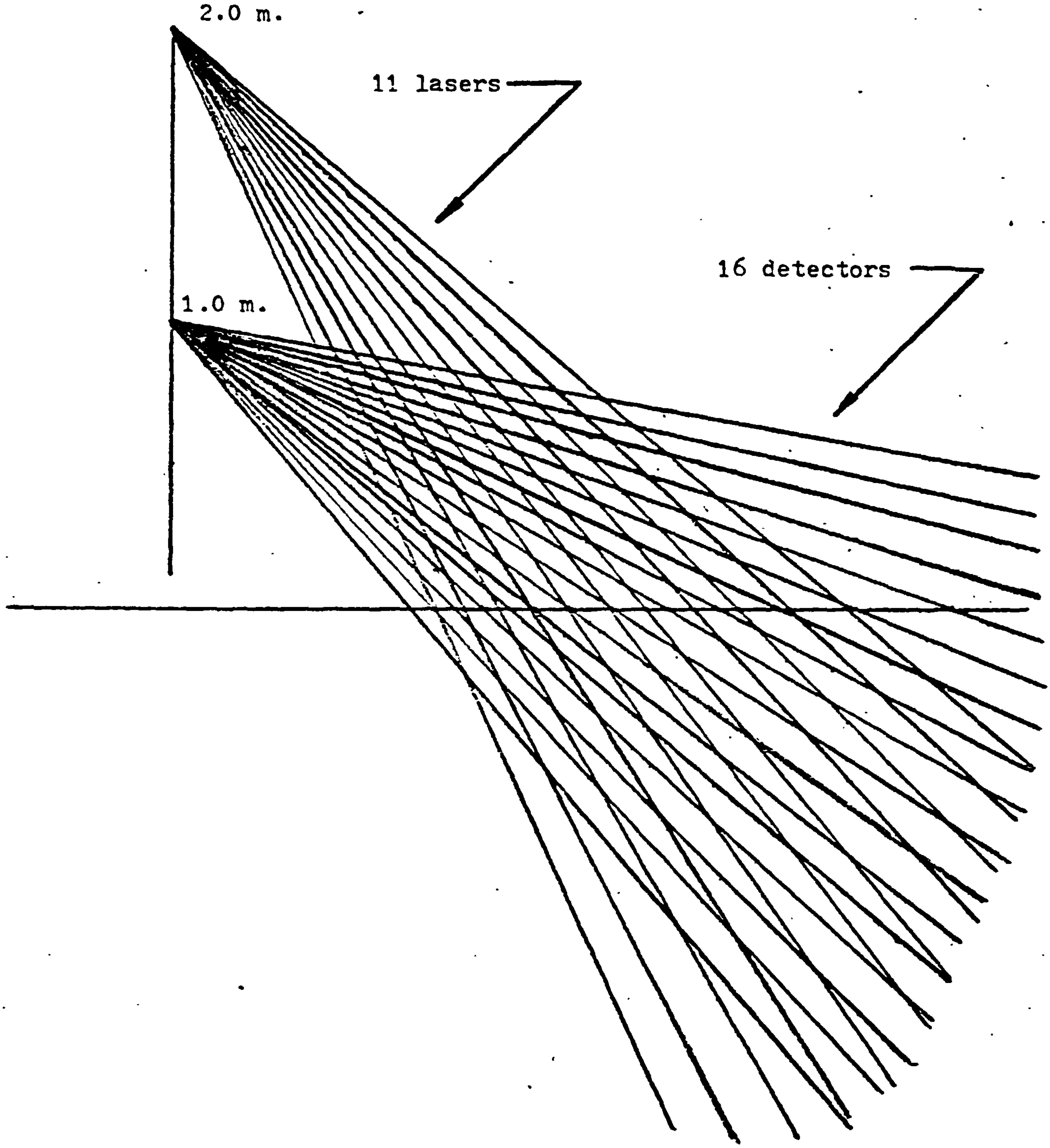


Figure 21 11 Laser, 16 Detector System

smaller and the number of measurements can be increased by a corresponding increase in the number of elevation angles at which the laser is pulsed. In practice, it would be desirable to limit the number of laser pulses to permit higher scanning speeds and in combination with the number of detectors to reduce computational requirements. Therefore, some trade-offs are required between accuracy and implementability.

This multi-laser/multi-detector concept was studied using a portion of Path Selection System Simulator, Reference 5 and 8, as a static simulator. In this case, with the rover located at a specific distance from some terrain feature such as a slope or boulder and with a specified multi-laser/multi-detector system, the simulation generated the signals which could be expected. The rover was then moved a specified distance and the simulation was repeated. By this procedure were obtained a sequence of perceptions depending on the specific sensor concept, i.e. the number of lasers and detectors, pointing angles, etc., the terrain feature and its location relative to the rover.

Two techniques have been found useful in interpreting the information which can be obtained from this concept. The first is a numerical technique which uses the height-distance data associated with each possible combination of laser and detector. The second technique is one of pattern recognition.

The numerical technique is useful in estimating the general inclination of the terrain located within the field of view. It is illustrated in Figure 22 in which are plotted the estimated heights and distances of the terrain surfaces from which the laser light is reflected. The case shown in Figure 22 involves a section of level terrain followed by a slope incline. Shown in Table 5 are the slopes which would be estimated for a set of specified inclinations as a function of the distance from the rover mast to the beginning of the slopes for an 11 laser/16 detector system. It should be noted that this data processor understates the inclination of positive slopes at the larger distances because it includes the reference terrain (i.e. terrain which is parallel to the vehicle horizontal) in the calculation.

An alternate data processor which excludes all but the last reference terrain data appears to have the potential to perceive the inclination at greater distances albeit with increased error, Table 6. It should be noted that both data processors converge to the same result as the vehicle approaches the terrain feature more closely. It should also be observed that the error in estimating the slope depends on the inclination of the terrain and increases with increasing positive slope.

What is not shown in Tables 5 and 6 is that the estimation error is a direct function of the data density (i.e. member of lasers) and the data discreteness (i.e. primarily determined by the cone of vision of detectors). A 22 laser/32 detector system covering the same total field of view produces estimates which are in error by half of that of the 11 x 16 system.

Although these numerical techniques can provide an estimate of the inclination of the terrain, in themselves they cannot distinguish between a planar inclination and another terrain form which would produce the same integral result. For example, a boulder superimposed on a small slope would be indistiguishable from a greater slope.

X -Position of "Yes" Returns

\\ -Area

Slope = $\tan^{-1}\left(\frac{2\ \text{Area}}{\text{Length}^2}\right)$

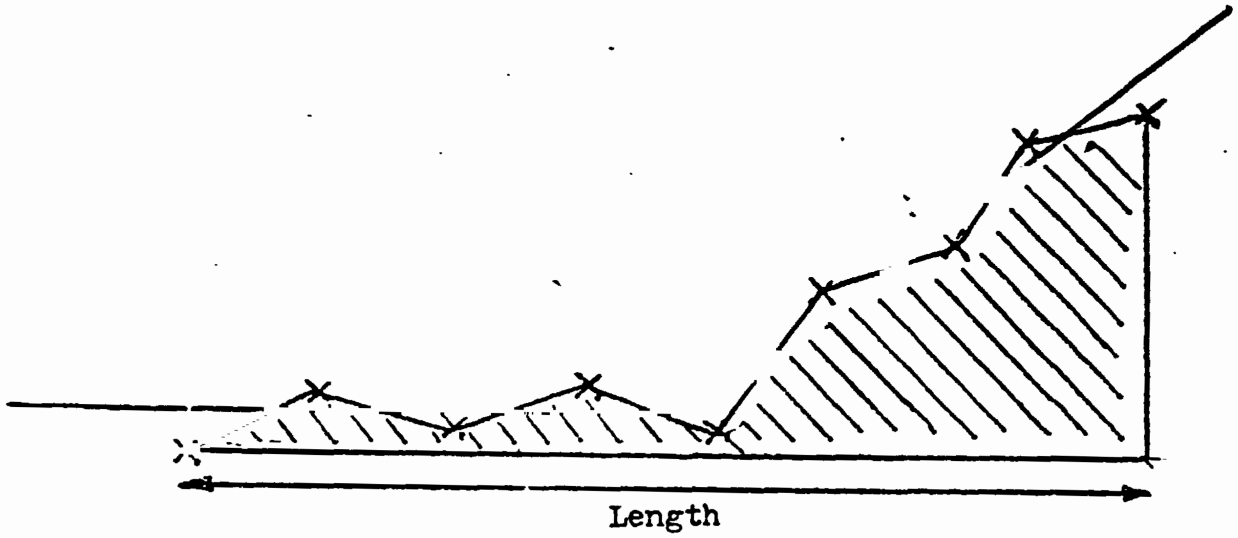


Figure 22 Area Integration Technique

Table 5 Area Integration Results Including Reference Terrain Data for an 11 Laser/16 Detector System.

Expected Slopes
(degrees)

Distance (meters)	Test Slope 35	25	15	0	-15	-25
1.18	15.1	7.0	5.5	-4.6	-14.4	-23.2
1.16	17.5	7.0	5.5	-4.6	-14.4	-23.5
1.14	17.5	8.9	5.5	-4.6	-14.4	-23.5
1.12	17.5	8.9	5.5	-4.6	-14.4	-24.9
1.10	17.5	8.9	5.5	-4.6	-14.4	-24.9
1.08	19.6	8.9	7.9	-5.6	-14.4	-24.9
1.06	19.6	13.3	7.9	-4.6	-14.4	-24.9
1.04	19.6	15.1	7.9	-4.6	-15.4	-25.1
1.02	21.8	15.1	7.9	-4.6	-15.4	-25.1
1.00	21.8	17.5	7.9	-4.6	-16.2	-25.1
.98	25.8	19.8	7.9	-4.6	-17.2	-25.1
.96	28.3	19.8	7.9	-4.6	-17.2	-25.4
.94	30.6	19.8	7.9	-4.6	-17.2	-25.4
.92	30.6	21.8	7.9	-4.6	-17.2	-25.8
.90	30.6	21.8	7.9	-4.6	-18.0	-26.0
.88	30.6	21.8	10.0	-4.6	-18.0	-26.0
.86	36.5	21.8	10.0	-4.6	-18.0	-22.8
.84	36.5	23.7	10.0	-4.6	-18.0	-22.8
.82	36.5	23.7	10.0	-4.6	-18.0	-24.9
.80	36.5	25.5	10.0	-4.6	-18.0	-24.9

Table 6 Area Integration Technique Excluding Reference Terrain for an 11 Laser/16 Detector System.

Expected Slopes
(degrees)

Test Slope

Distance (meters)	25	35	45
1.38	46.2	46.2	65.5
1.36	46.2	46.2	65.5
1.34	46.2	46.2	71.6
1.32	46.2	51.8	54.9
1.30	46.2	39.3	54.9
1.28	35.8	49.5	54.9
1.26	35.8	49.5	60.6
1.24	35.8	49.5	60.6
1.22	35.8	54.9	60.6
1.20	35.8	54.9	45.3
1.18	35.8	39.8	45.3
1.16	35.8	45.3	49.3
1.14	26.8	45.3	53.2
1.12	26.8	45.3	53.2
1.10	26.8	45.3	53.2
1.08	26.8	49.3	61.4
1.06	35.7	49.3	66.6
1.04	39.8	49.3	48.3
1.02	45.3	35.5	50.6
1.00	31.8	35.5	50.6
.98	31.8	38.8	50.6
.96	31.8	41.7	50.6
.94	35.5	41.7	58.0
.92	35.5	48.3	58.0
.90	35.5	48.3	41.2
.88	38.8	48.3	41.2
.86	38.8	37.7	42.2
.84	28.8	37.7	46.3
.82	28.8	37.7	50.3
.80	26.5	37.7	53.7

An alternative approach involves a study of the pattern of the return. Shown in Figure 23 are the laser/detector returns for a 30° inclination. The "1's" correspond to a normal return, i.e. a detector sensed reflection of a laser from a surface; the "3's" correspond to the detector which would have sensed a laser reflection had the terrain been horizontal. That the terrain is upwardly inclined is indicated by the fact that the laser reflection is sensed by detectors with higher pointing angles than would have been the case for horizontal terrain.

A convenient procedure for representing and interpreting these results is to "diagonalize" the data. The diagonalized return is obtained by calculating the number of diagonals by which the actual data are displaced from the diagonal representing horizontal terrain. For the case of Figure 23, the diagonalized return is shown in Figure 24. The pattern of positive parameters is indicative of a terrain feature located above the reference terrain. A downward slope would produce a diagonalized return containing a sequence of negative values. Interpretation of the diagonalized return is also illustrated in Figure 25 for the case of the 11 x 16 system. Note that each diagonal represents roughly a particular elevation. (The curvature is due to the equal spacing of the laser pulses and the equal cones of vision. More nearly horizontal lines can be obtained by modification of the either of these geometrical parameters.) Thus the specific diagonalized return obtained for a feature will reflect directly the elevation of the feature relative to the vehicle horizontal.

Shown in Tables 7, 8, 9 and 10 are the diagonalized returns to be expected from an 11 x 16 system for a set of hemispherical boulders located on horizontal terrain. The distance refers to the location of the center of the boulder relative to the mast on which the sensor system is located. Comparison of these four tables suggests some possible rules which may be useful:

(a) Sequential diagonal increases in successive laser positions occur with increasing frequency with larger boulders. The last 9 scans with the 0.35 boulder and 16 of the last 17 with the 0.5 boulder shows this effect. However, the same effect is observed in 10 of the last 14 for the 0.3 m boulder and in 7 of the last 13 for the 0.25 m hazard. To be sure, analysis of a single scan will not be decisive; however, a rule requiring an event to occur at a specified frequency can reduce the uncertainty. For the requirement the four out of four consecutive scans involve the 0-1-2 pattern in sequential scans can discriminate effectively between 0.25 and 0.35 m boulders. Such a rule would be fail-safe in that its perception for a smaller boulder would result in a no-go decision.

(b) The perception of a 0-1-2 pattern followed by 3 signals is a clear indication of at least a 0.35 boulder.

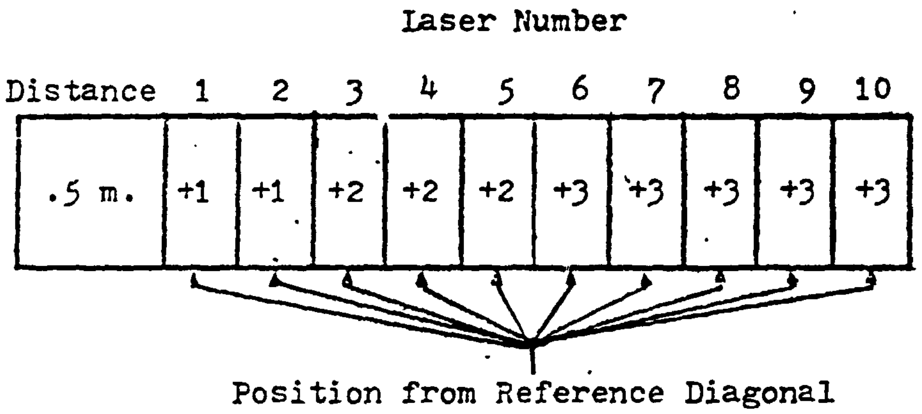
(c) Missing returns due to the masking or shadow effect of the boulder can be an indicator of its size. As in the case the sequential diagonal increase criterion, the frequency of double missing returns must be used to increase the quality of the discrimination.

Similar studies have been made for the cases of craters on horizontal terrains and for craters and boulders superimposed on slopes. Rules for perceiving these features can be deduced along lines similar to those suggested above for boulders.

"1" = Normal Returns
"2" = Returns on Reference Terrain
"3" = Reference Terrain

	LASERS										
SENSOR	1	2	3	4	5	6	7	8	9	10	1
16	0	0	0	0	0	0	0	0	0	0	
15	0	0	0	0	0	0	0	0	0	0	
14	0	0	0	0	0	0	0	0	0	1	
13	0	0	0	0	0	0	0	0	1	0	
12	0	0	0	0	0	0	0	1	0	0	
11	0	0	0	0	0	0	1	0	0	3	
10	0	0	0	0	0	1	0	0	3	0	
9	0	0	0	0	0	0	0	3	0	0	
8	0	0	0	0	1	0	3	0	0	0	
7	0	0	0	1	0	3	0	0	0	0	
6	0	0	1	0	3	0	0	0	0	0	
5	0	0	0	3	0	0	0	0	0	0	
4	0	1	3	0	0	0	0	0	0	0	
3	1	3	0	0	0	0	0	0	0	0	
2	3	0	0	0	0	0	0	0	0	0	
1	0	2	0	0	0	0	0	0	0	0	

Figure 23 Sample Table of Laser-Detector Returns



Laser Number

Distance	1	2	3	4	5	6	7	8	9	10
.5 m.	+1	+1	+2	+2	+2	+3	+3	+3	+3	+3

Position from Reference Diagonal

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Figure 24 Sample Diagonalized Returns

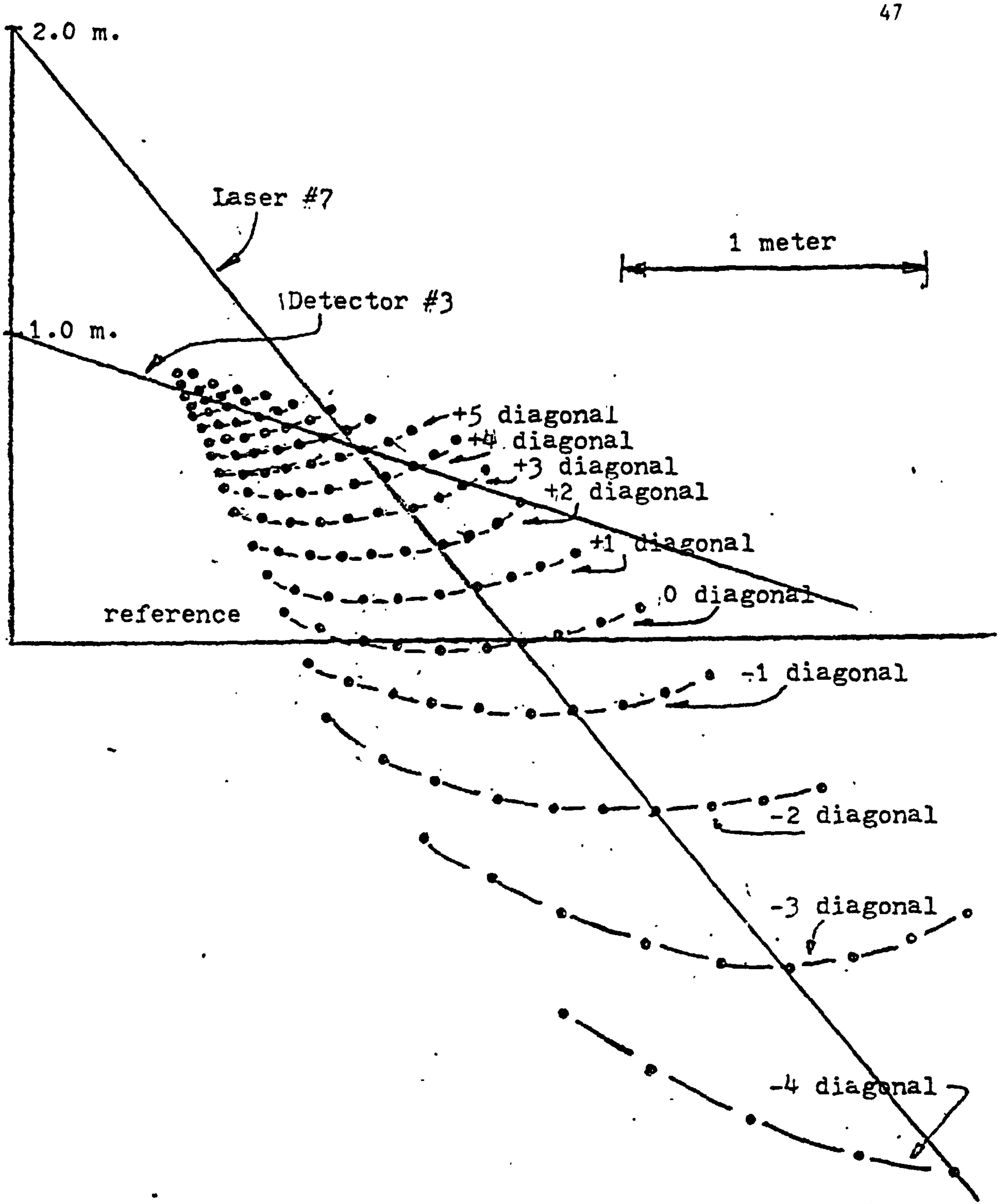

Figure 25 Diagonalized Laser-Detector Field

Distance (meters)	Laser No. 1	2	3	4	5	6	7	8	9	10
1.38	0	0	0	0	0	1	1	1	*	*
1.36	0	0	0	0	1	1	1	1	*	*
1.34	0	0	0	0	1	1	2	1	*	*
1.32	0	0	0	0	1	1	2	1	*	0
1.30	0	0	0	0	1	1	2	1	*	0
1.28	0	0	0	0	1	1	2	1	*	0
1.26	0	0	0	0	1	2	2	1	*	0
1.24	0	0	0	1	1	2	2	*	*	0
1.22	0	0	0	1	1	2	2	*	*	0
1.20	0	0	0	1	1	2	2	*	0	0
1.18	0	0	0	1	1	2	2	*	0	0
1.16	0	0	0	1	2	2	2	*	0	0
1.14	0	0	0	1	2	2	2	*	0	0
1.12	0	0	0	1	2	2	1	*	0	0
1.10	0	0	1	1	2	2	*	*	0	0
1.08	0	0	1	1	2	2	*	*	0	0
1.06	0	0	1	1	2	2	*	0	0	0
1.04	0	0	1	2	2	2	*	0	0	0
1.02	0	0	1	2	2	2	*	0	0	0
1.00	0	0	1	2	2	2	*	0	0	0

Table 7 - Diagonalized Returns for .25 m Boulder.

1.38	0	0	0	0	0	1	2	2	2	*
1.36	0	0	0	0	1	1	2	2	2	*
1.34	0	0	0	0	1	1	2	2	1	*
1.32	0	0	0	0	1	1	2	2	1	*
1.30	0	0	0	0	1	1	2	2	1	*
1.28	0	0	0	0	1	2	2	2	*	*
1.26	0	0	0	0	1	2	2	2	*	*
1.24	0	0	0	1	1	2	2	2	*	*
1.22	0	0	0	1	1	2	2	2	*	*
1.20	0	0	0	1	1	2	2	2	*	*
1.18	0	0	0	1	2	2	2	2	*	*
1.16	0	0	0	1	2	2	2	2	*	0
1.14	0	0	0	1	2	2	2	1	*	0
1.12	0	0	0	1	2	2	2	*	*	0
1.10	0	0	1	1	2	2	2	*	*	0
1.08	0	0	1	1	2	2	2	*	*	0
1.06	0	0	1	2	2	2	2	*	*	0
1.04	0	0	1	2	2	2	2	*	*	0
1.02	0	0	1	2	2	2	2	*	0	0
1.00	0	0	1	2	2	2	2	*	0	0

Table 8 - Diagonalized Returns for .30 m Boulder.

Distance (meters)	Laser No. 1	2	3	4	5	6	7	8	9	10
1.38	0	0	0	0	0	1	2	2	2	1
1.36	0	0	0	0	1	1	2	2	2	1
1.34	0	0	0	0	1	1	2	2	2	1
1.32	0	0	0	0	1	1	2	2	2	*
1.30	0	0	0	0	1	2	2	2	2	*
1.28	0	0	0	0	1	2	2	2	2	*
1.26	0	0	0	0	1	2	2	2	2	*
1.24	0	0	0	1	1	2	2	2	2	*
1.22	0	0	0	1	1	2	2	2	2	*
1.20	0	0	0	1	2	2	2	2	2	*
1.18	0	0	0	1	2	2	2	2	2	*
1.16	0	0	0	1	2	2	2	2	*	*
1.14	0	0	0	1	2	2	2	2	*	*
1.12	0	0	0	1	2	2	2	2	*	*
1.10	0	0	1	1	2	2	2	2	*	*
1.08	0	0	1	2	2	2	2	2	*	*
1.06	0	0	1	2	2	2	2	2	*	*
1.04	0	0	1	2	2	2	2	2	*	*
1.02	0	0	1	2	2	3	2	*	*	*
1.00	0	0	1	2	2	3	2	*	*	*

Table 9 - Diagonalized Returns for .35 m Boulder.

1.38	0	0	0	0	0	1	2	2	2	2
1.36	0	0	0	0	1	1	2	2	2	2
1.34	0	0	0	0	1	1	2	2	2	2
1.32	0	0	0	0	1	2	2	2	3	2
1.30	0	0	0	0	1	2	2	2	3	3
1.28	0	0	0	0	1	2	2	3	3	3
1.26	0	0	0	0	1	2	2	3	3	3
1.24	0	0	0	1	1	2	2	3	3	3
1.22	0	0	0	1	2	2	3	3	3	3
1.20	0	0	0	1	2	2	3	3	3	3
1.18	0	0	0	1	2	2	3	3	3	3
1.16	0	0	0	1	2	2	3	3	3	3
1.14	0	0	0	[illegible]	2	3	3	3	3	3
1.12	0	0	0	1	2	3	3	3	3	3
1.10	0	0	1	2	2	3	3	3	3	3
1.08	0	0	1	2	2	3	3	3	3	3
1.06	0	0	1	2	2	3	3	3	3	3
1.04	0	0	1	2	3	3	3	3	3	3
1.02	0	0	1	2	3	3	3	3	3	3
1.00	0	0	1	2	3	3	3	3	3	3

Table 10 - Diagonalized Returns for .50 m Boulder.

At this point, these rules based on pattern interpretation should be considered as first approximations. Further analysis is required to refine them and to increase the reliability of the interpretation. The advantages to be gained by increasing the data density and reducing the uncertainty to be associated with each signal by using more lasers and detectors must be established. The benefits to be gained by a higher level system must be balanced against the increased scanning time and computation before a firm position can be taken.

The combination of the numerical technique, which provides an estimate of the average inclination of the terrain and the pattern recognition technique, which provides insights as to the local terrain characteristics, may be superior to either approach applied individually.

Finally, all of these studies were aimed at interpreting the terrain along a single azimuth. After success has been achieved in this goal, it will be necessary to obtain an interpretation of cross-path terrain characteristics. Although, it has not yet been demonstrated that the multi-laser/mutli-detector concept can produce the desired level of interpretation, the results obtained to date offer promise for success. Reference 9 describes in detail these investigations.

IV. CONCLUDING REMARKS

Over the ten year period during which this NASA grant supported studies related to the unmanned exploration of Mars, a number of significant problems areas have been studied. During the first half of the period, the investigations addressed important but not coordinated tasks such as:

1. On-line atmospheric parameter updating during landing trajectories.
2. Adaptive trajectory control using variable thrust and/or drag processes in concert with atmospheric parameter updating.
3. Feasibility of autogyro concepts for landing as opposed to retro-rocketry.
4. Roving vehicle configuration design concepts with particular attention to mobility, maneuverability and dynamics.
5. Global navigation concepts for the location of the rover.
6. Development of a three-dimensional path selection system simulation to serve as an aid for assessment of alternative autonomous guidance systems.
7. A non-linear optimization computer program for guidance in the design of an overall unmanned mission.
8. Optimization of gas chromatographic separation systems.

About 1972, it was decided to focus the project effort on a prototype planetary rover and the required sensor systems including software required for an unmanned planetary mission with Mars serving as a case in point. In the interval, the following tasks were pursued:

1. A prototype rover was designed, constructed and tested with respect to configuration, dynamics, propulsion and control. The current version which has gone through several iterations is a device of exceptional mobility and stability. New concepts in torroidal wheel design have been developed and evaluated. The rover provides a test bed which can be use in complex real terrains for rigorous evaluation of terrain sensing and interpretative systems for autonomous control.

2. In-depth studies of the feasibility of using range/pointing angle data such as might be acquired by a laser rangefinder have been pursued. Methods for detecting discrete obstacles and their outlines out to 40 meters have been developed. Techniques for estimating the slopes and gradients of the terrain have been conceived and evaluated. The effects of instrument and system noise on these interpretations have been deduced. The range/pointing angle concept has been shown to be feasible for the mid-range (4-40 meters) guidance of an autonomous rover.

3. The detection and avoidance of hazards in the short range (i.e. 1 to 3 meters) has studied not only in theory and analytically but also by actual experiment using the rover both in laboratory and field environments. This system which is based on the triangulation of a laser and a focused photodetector has a very real feasibility. A single laser/single detector system together with the associated software has confirmed the performance predictions of the Path Selection System Simulation Program.

The investigations made possible by this NASA Grant have led to new support in recent years. The range/pointing angle concept research is now being supported by the Office of Aeronautics and Space Technology through Grant NSG-7184. The short range hazard detection studies are being supported by OAST (NSG-7369) and by the Jet Propulsion Laboratory (Contract 954,880). Thus, this grant has laid the foundation for a sustained program of research in the area of artificial intelligence and robotics. The past work and work now in progress has potential for application outside the more narrow goal of unmanned planetary exploration.

The achievements during the past decade are documented in over 50 technical reports and 44 publications which are listed in Appendix A as well as numerous thesis and project reports.

Beyond these, the impact of the project on the education of students from the junior undergraduate to the doctoral level has been profound. As shown in Figure 26, over the ten year period there were some 262 student-participant years involved in the program. The actual number of students who had the benefit of the experience is more nearly 200 since some participants were on the project for more than one year. Their reaction to the activity particularly after graduation and employment has been uniformly enthusiastic. The project provided an opportunity to deal with real and practical design challenges covering activities ranging advanced theoretical studies to construction, testing and evaluation. The student's perception of modern engineering has been substantially enhanced.

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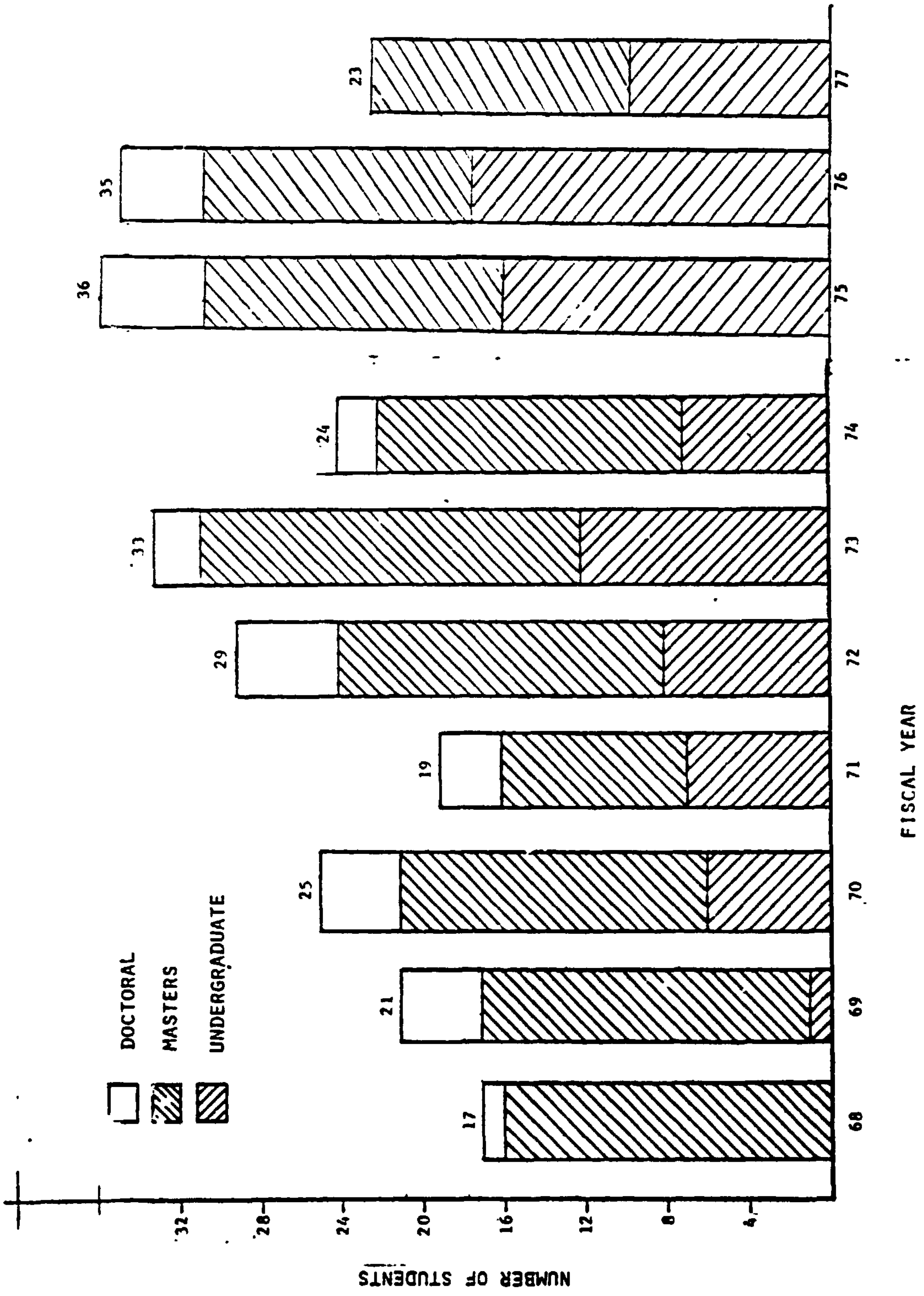

Figure 26 Student Participation in the Project

In closing, it should be observed that NASA's support has contributed to the public interest through the technical knowledge which has been gained and through the superb educational experience gained by a large number of engineering students. NASA's support over this extended period of time is deeply appreciated by Rensselaer.

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Appendix A

Listing of RPI Technical Reports
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