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PATH SELECTION SYSTEM SIMULATION AND EVALUATION FOR A MARTIAN ROVING VEHICLE

by

Stephen Lee Boheim
William C. Purdon

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Analysis and Design of a Capsule Landing System and Surface Vehicle Control System for Mars Exploration

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Troy, New York

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CONTENTS

		Page
	LIST OF ILLUSTRATIONS	v
	LIST OF TABLES	vi
	ACKNOWLEDGEMENT	vii
	ABSTRACT	viii
I.	INTRODUCTION	1
II.	COMPUTER SIMULATION STRUCTURE	3
	A. Goals and Considerations	3
	B. Block Diagram Structure	4
	C. Information Flow	7
III.	COMPUTER SIMULATION METHODS	9
	A. Terrain Characterization Block	9
	B. Path Selection System	9
	1. Sensor Simulation Block	10
	a. Types of Sensor Simulators	10
	b. Range Measurement Simulation	15
	2. Terrain Model Construction Block	18
	3. Path Selection Algorithm Block	22
	C. Vehicle Dynamics Block	23
	1. Simulation Capabilities	23
	2. Simulation Methods	24
	D. Display and Evaluation Blocks	31
	1. Terrain Display Block	31
	2. Terrain Model Display Block	33
	3. Systems Evaluation Block	35
	a. Quantitative Evaluation	35
	b. Heuristic Evaluation	37
IV.	PATH SELECTION SYSTEM EVALUATION	38
	A. Path Selection System Description	38
	1. System Similarities	38
	2. System I (single beam sensor; approximate terrain model)	39
	3. System II (single beam sensor; exact terrain model)	40

Page

4. System III (double beam sensor; approximate terrain model) 41

B. Test Situation 42
C. Discussion 44

1. System I (single beam sensor; approximate terrain model) 44
2. System II (single beam sensor; exact terrain model) 49
3. System III (double beam sensor; approximate terrain model) 50

D. Summary 52

V. CONCLUSIONS 56

A. Summary of Progress 56
B. Conclusions and Future Work 57

1. Terrain Characterization 57
2. Sensor Simulation 58
3. Terrain Modeling and Path Selection Algorithms 59
4. Vehicle Dynamics Simulation 59
5. System Evaluation 59

APPENDIX 61

LITERATURE CITED 62

LIST OF ILLUSTRATIONS

		Page
Figure 1	Simulation Structure	5
Figure 2	Comparison of Single and Double Beam Mid-Range Sensors	11
Figure 3	Mid-Range Sensor Scan (Top View)	12
Figure 4	Comparison of Vertical-Fixed and Vehicle-Fixed Sensors	14
Figure 5	Geometry of Beam Impingement Calculation	16
Figure 6	Terrain Modeling Schemes	19
Figure 7	Encoded Terrain Models	21
Figure 8	Vehicle Motion Model	27
Figure 9	Terrain Contour Map - $z=f(x^3,y^2,x)$	32
Figure 10	Terrain Contour Map - $z=f(x^3,y^2,x)$ with Boulders	34
Figure 11	Test Situation	43
Figure 12	Typical Vehicle Path	45
Figure 13	Performance of a "Confused" Path Selection System	53
Figure 14	Design Considerations for Sensor Beam Elevation Angles	55

LIST OF TABLES

		Page
Table I	Path Selection System Characteristics.....	42
Table II	Performance Results for System I (single beam sensor; approximate terrain model).....	46
Table III	Additional Performance Results for System I (single beam sensor; approximate terrain model).	48
Table IV	Performance Results for System II (single beam sensor; exact terrain model).....	49
Table V	Performance Results for System III (double beam sensor; approximate terrain models).....	51
Table VI	Additional Performance Results for System III (double beam sensor; approximate terrain model).	52

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ABSTRACT

The development of a computer package for the simulation and evaluation of proposed path selection systems for an autonomous Martian roving vehicle has been undertaken. The package incorporates a number of realistic features, such as the simulation of random effects due to vehicle bounce and sensor-reading uncertainty, to increase the reliability of the results. To further enhance the usefulness of the package, both qualitative and quantitative evaluation criteria have been established.

The performance of three different path selection systems has been evaluated to determine the effectiveness of the simulation package, and to form some preliminary conclusions regarding the tradeoffs involved in designing a path selection system. Using the results of these preliminary studies, suggestions for future development of the capabilities of the computer simulation package have been presented.

I. INTRODUCTION

The large communications delay time from (nine to twenty-five minutes) between the surface of Mars and a mission control group stationed on Earth makes ground control of an unmanned exploratory vehicle on Mars awkward and potentially inadequate. The development of an autonomous vehicular path selection control system is therefore mandatory for the success of the mission. This system should be able to select a path to a specified destination such that dangerous obstacles are avoided and other mission considerations are met. The fulfillment of these objectives requires the development of a path selection system containing both hardware and software devices capable of effectively analyzing the terrain surrounding the vehicle. It is certainly a stringent requirement that these systems be able to operate with a high degree of reliability, and that they must also be capable of calling for Earth control under appropriate circumstances.

Previous efforts concerning this area of investigation have concentrated upon development of terrain modeling systems, analysis of the effects of sensor error upon the terrain model, and the study of path selection algorithm characteristics. One of the previous investigations did include the integration of terrain modeling and proposed path selection systems for the purpose of algorithm performance evaluation (Ref. 1). However, these works have been mainly applicable to a long-range obstacle detection system (with sensor ranges between 50 and 1500 meters), and have not included quantitative criteria for performance evaluation. In an attempt to evaluate proposed path selection systems and to expand the usefulness of simulation techniques so as to indicate requirements in terrain model, sensor, and path selection design, this study was initiated.

The project has been divided into two main tasks. The first is concerned with the development of a computer package which provides the capability of dynamically simulating a wide variety of sensor, terrain modeling, and path selection combinations under reasonably realistic conditions. The second task involves the establishment of criteria for judging the path selection system's performance, as simulated by the computer package developed in the first task.

It should be emphasized here that these investigations have been directed at mid-range (three to thirty meters) sensor and path selection applications, as distinct from short-range applications using a tactile sensor and the previously studied long-range system. It should also be noted, however, that the simulation package has the potential for extension to, or subsequent inclusion of, the other range applications.

The following section presents a discussion of the overall computer simulation package, including its structure, functions, and information flow. Specific discussion of individual block development studies and implementations is given in Section III. Section IV demonstrates the effectiveness of the computer simulation package by comparing the performances of three different path selection systems. The final section presents a summary of the progress, conclusions, and suggestions for future work in this area.

A user's guide for the computer simulation package is available, and its table of contents is included here as an Appendix.

II. COMPUTER SIMULATION STRUCTURE

A. Goals and Considerations

The computer simulation package is a self-contained unit. Not only does it simulate the functions of a terrain sensor and a modeler, contain a path selection algorithm, and simulate the vehicle's motion dynamics, but it also includes a mathematical description of a terrain and evaluates system performance using criteria established for this purpose (see Section III, D.3). The inclusion of the latter two items into the system reduces error-prone handwork and extends considerably the scope of the simulation's evaluation capabilities.

Three major considerations were taken into account during the computer package design. First, the flexibility and realism of the simulation is of primary importance. The substitution of alternate vehicle configurations, path selection algorithms, terrain models, and sensor schemes, must be conducted with a minimum of effort and a low probability of error. Inputting of terrain data must be flexible enough to represent a wide variety of terrain characteristics and appearances. As more information is gained concerning the true Martian terrain, it will be important to be able to easily construct terrains which reflect this knowledge.

As a second consideration, it must be possible to incorporate non-ideal features which tend to degrade performance. Such additions enhance the realism of the simulation, thereby improving the reliability of the results. Such non-ideal features include: vehicle bounce, vehicle tilt due to terrain slopes, and sensor-reading uncertainty.

The third consideration is that the structure of the computer

simulation should be segmented according to function. All activities pertaining to a single function should be grouped into the same block, if possible. Proper structuring is of considerable importance to the flexibility requirement that substitution of alternate proposed sensor systems and vehicle configurations be easily executed. This subject will be further discussed in the next sub-section.

B. Block Diagram Structure

The computer simulation package has been structured so that each block contains a separate function (see Figure 1). This allows easy substitution of alternate simulation schemes. There is a minimum of interdependence of one block upon the other, and changes in one will not result in changes in another.

The entire system operation can be divided into four major functions. These are: 1) the terrain characterization function, 2) the path selection system function, 3) the vehicle dynamics function, and 4) the system evaluation and simulation display function.

The terrain characterization function is used to mathematically describe and store some arbitrary terrain that will be used in the simulation. It is self-contained in that it is independent of any other function, and it is assigned a separate block in the block diagram structure.

The path selection system function can be further divided into 1) the sensor operation simulation sub-function, 2) the terrain modeling process sub-function, and 3) the path selection algorithm sub-function. These sub-functions are not entirely independent and will often be highly correlated. A change in a particular sensor scheme may force an accompanying change in the terrain model if the new sensing scheme provides a

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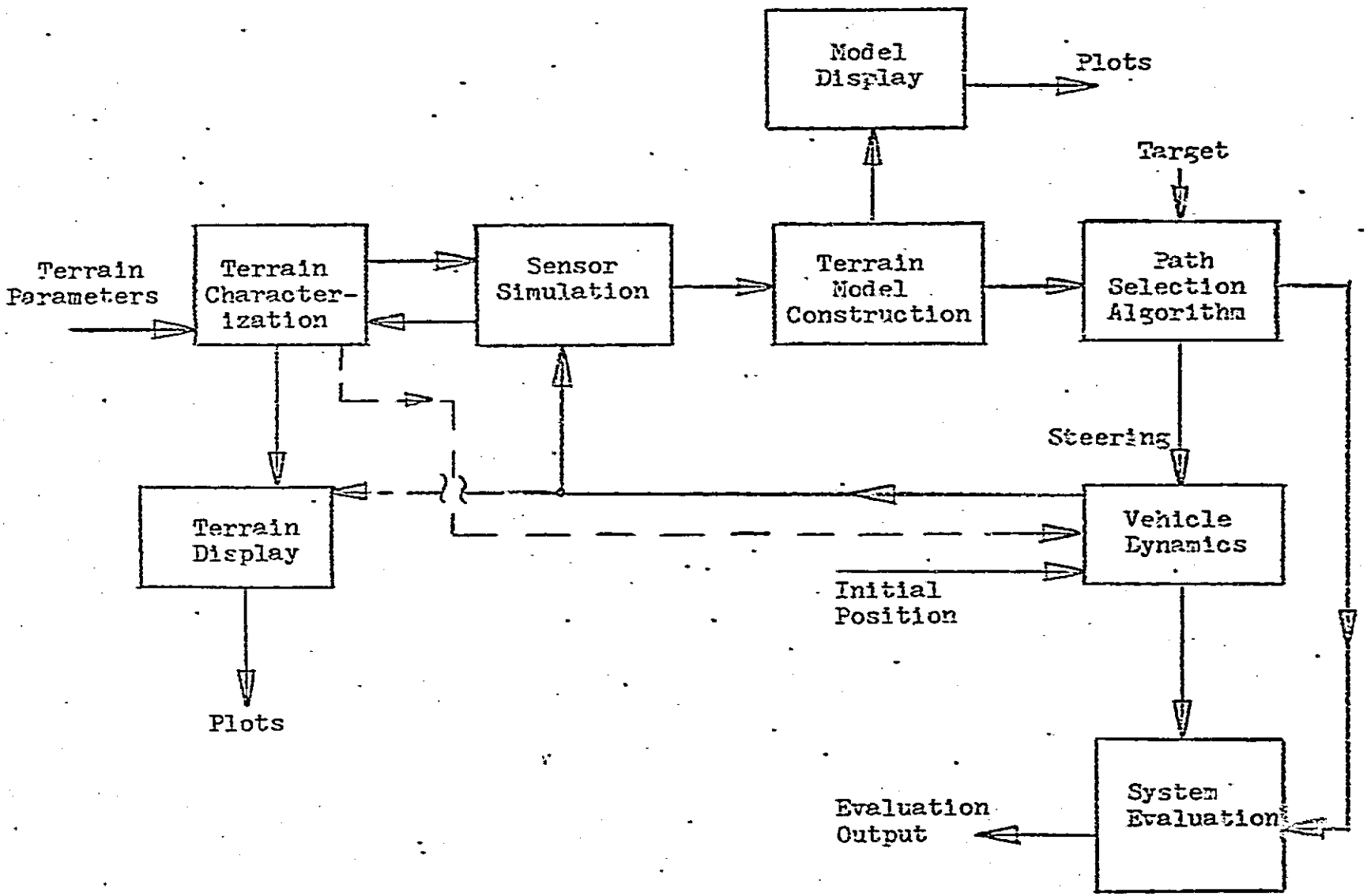


SIMULATION STRUCTURE

Figure 1

different type of information. In a similar fashion, the path selection algorithm will often be dependent upon the sensor and model schemes. These sub-functions have each been assigned a separate block. The resulting three blocks are the only ones in the simulation package which are dependent upon one another.

The third major function of the program is vehicle dynamics simulation. The response of the vehicle to the commands of the path selection system must be simulated, by determining how the moving vehicle is affected by the terrain and how this in turn may affect the path selection system. This function is assigned a single block in the block diagram structure as it is independent of the other functions.

The fourth major function, system evaluation and simulation display, supplies visual information indicating what the vehicle is doing, what the terrain looks like, and how the path selection system as a whole is performing. Because of the nature of the information to be represented, this function is assigned three blocks: 1) the terrain characterization display block, 2) the terrain model display block, and 3) the system evaluation block. Each block is totally independent of the others.

Summarizing, Figure 1 shows the overall structure of the block diagram described above. Excluding the display functions, there are six major blocks. The actual path selection control system is simulated by a closed loop (solid lines) containing the sensor simulation terrain model construction, path selection algorithm, and vehicle dynamics blocks. The terrain characterization block contains a mathematical representation of the surface upon which the simulated vehicle is traveling. Finally, the system evaluation block provides a quantitative measure of the vehicle

and path selection system performance during the simulation.

C. Information Flow

Information flow was one criterion for distinguishing between the various functions described above. The simulation structure was partially dependent upon making the information transferred between blocks (shown as connecting lines in Figure 1) as meaningful as possible to the simulation objectives. An understanding of the type of information exchange is implicit to understanding the operation of the entire simulation process.

The inputs to the terrain characterization block are specified by the user and determine the mathematical terrain description (specified in a cartesian coordinate system) that will be stored in this block. This block will then be able to provide a z coordinate (altitude) for any set of x,y coordinates specified by other blocks in the structure. The sensor simulation block uses the terrain characterization block extensively while simulating the operation of a mid-range sensor.

The outputs of the sensor simulation block are the range measurements made by the mid-range sensor, and these values represent the terrain as the mid-range sensor sees it. The terrain model construction block processes the sensor's measurements, and passes a model of the terrain to the path selection algorithm (and to the terrain model display block for visual representation). The path selection algorithm block uses this terrain model, the present location, and the location of the target, to generate steering commands, i.e., to choose a path. The vehicle dynamics block then moves the vehicle using the steering commands and monitors the performance of the moving vehicle. When the mid-range sensor is to be used again, the location, direction, velocity, etc. of the vehicle are passed

to the sensor simulation block. The cycle repeats itself until the vehicle arrives on target or until the simulation is halted for some other reason. The system evaluation block monitors the performance of both the vehicle and the path selection system and provides a quantitative performance measure at the end of the simulation.

The dashed lines in Figure 1 are used to describe non-essential information flows which may be desirable to enhance the system's flexibility and display capabilities. The longer broken line can be used to supply terrain linked non-ideal behavior such as vehicle attitude and vehicle bounce to the vehicle dynamics block. The shorter dashed line can be used to supply information to the terrain display block concerning the vehicle's location during its motion. Thus, the vehicle's path during a simulation run can be displayed graphically.

III. COMPUTER SIMULATION METHODS

A detailed discussion of each block in Figure 1, including its development, operation, and capabilities, will now be presented.

A. Terrain Characterization Block

The development of the terrain characterization block is discussed at greater length in Reference 2.

This block represents a mathematical description of the Martian terrain (using cartesian coordinates), and allows the user to specify some polynomial representation and build Gaussian distributions upon this base. These descriptions are used to convey low frequency terrain features. In addition, a special-features input is used to specify high frequency and discontinuity components, such as boulders, craters, and crevasses. The user can specify the general characteristics of each of these special features, thereby enhancing simulation flexibility. All of these special features are constructed by the use of singularities in the mathematical description of the surface.

Once the simulation of the path selection process begins, the terrain characterization block provides other blocks in the simulation package with the value of the altitude (z) of the terrain at any point (x,y). Since the block will be used extensively during the simulation, it incorporates many time-saving procedures. For example, partial nesting techniques are used when computing the polynomial features.

B. Path Selection System

Several path selection system schemes were available at the beginning of this work. A simple scheme was chosen initially so that

effective simulation techniques could be developed. It is assumed that as evaluation of these simple path selection schemes is performed, more advanced systems will be developed and evaluated.

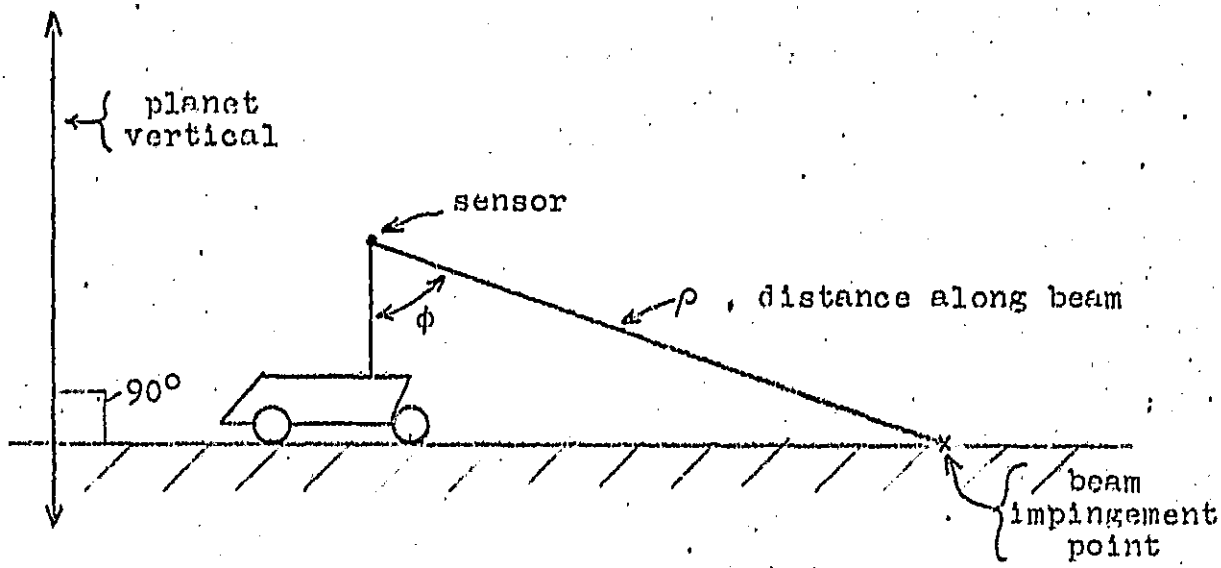
The path selection system has been previously subdivided into the sensor simulation block, the terrain model construction block, and the path selection algorithm block. Each of these blocks will be treated separately.

1. Sensor Simulation Block

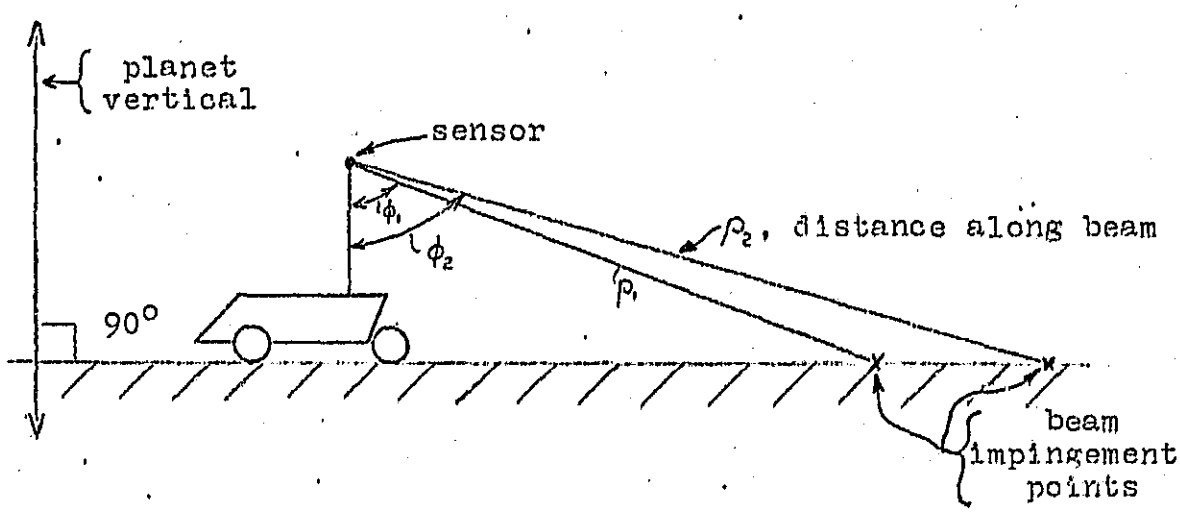
a) Types of Sensor Simulators

The scheme chosen for an initial development of this block involved a laser beam scanner with zero beam-width. The vehicle was assumed to be a point source with the sensor located directly above (with respect to the true planet vertical). The scan was assumed to be instantaneous, and there was a uniform time assumed between scans. A single beam was used and discrete samples were taken during each scan. The beam had a fixed elevation angle (ϕ) measured with respect to the planet's vertical (see Figures 2A and 3).

The scheme provided the terrain modeling block with azimuth, elevation angle, and the length of the beam (ρ) from the sensor to each of the sampled impingement points on the terrain surface. Random uncertainty of error in the measurement process due to vehicle bounce could be introduced to the elevation angles and/or the range measurements at the user's option. The method for this addition of noise



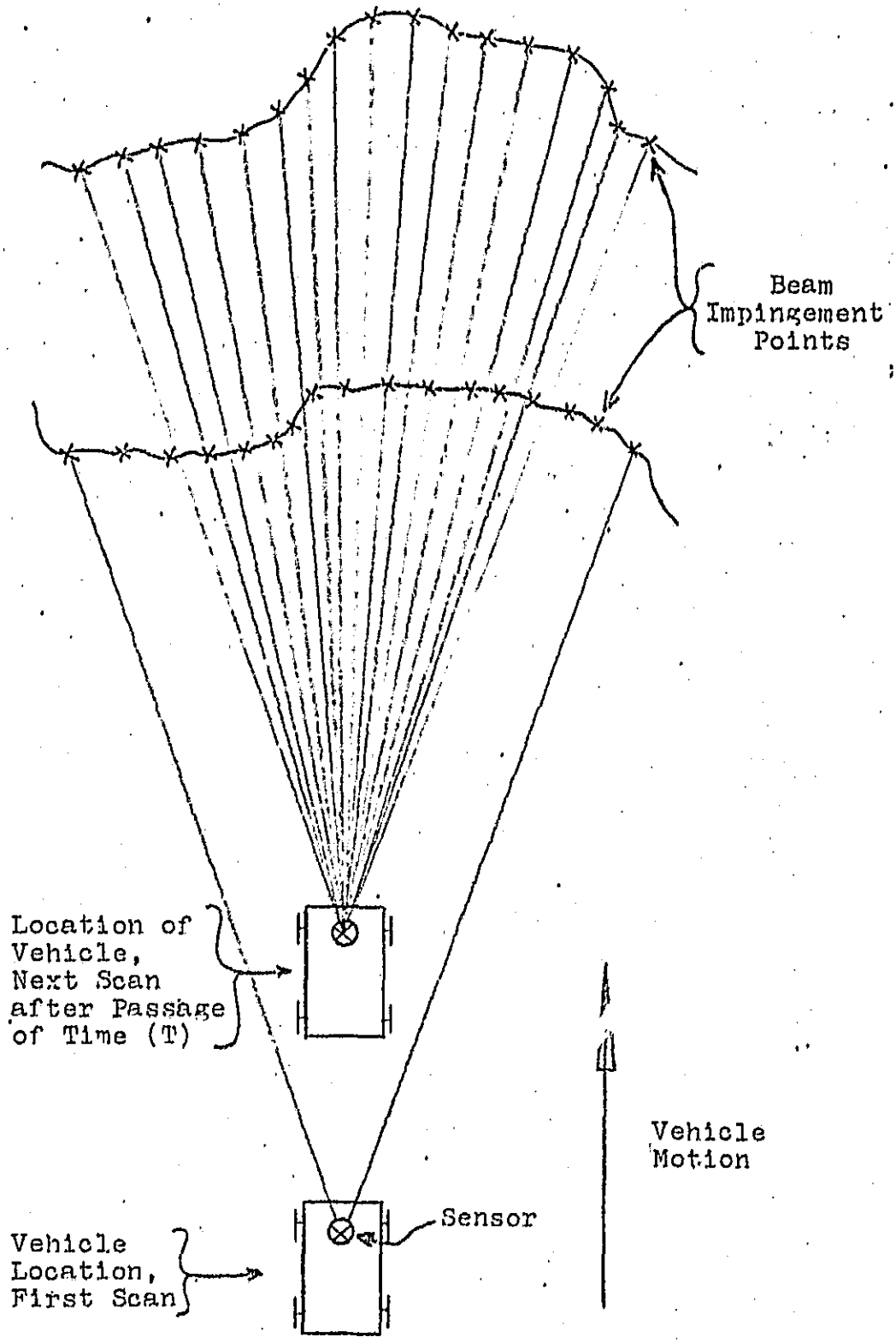
(A) Single Beam Configuration
(side view)



(B) Double Beam Configuration
(side view)

COMPARISON OF SINGLE AND DOUBLE BEAM MID-RANGE SENSORS

Figure 2



MID-RANGE SENSOR SCAN
(Top View)

Figure 3

is described in Section III, C.2.c.

An additional sensor scheme was then implemented. In this scheme, two, three, or four beams simultaneously sweep the surface (see Figure 2B for an illustration of the case with two beams). Each beam has a different fixed elevation angle measured with respect to the planet's vertical. The assumptions of uniform time between sensor scans, discrete samples, and instantaneous sweep were also used for this scheme. Output to the terrain model construction block was adjusted so that sets of range measurements, azimuths, and elevation angles were included. Noise could be added to any of the elevation angles and/or range measurements at the user's option.

It was then decided to simulate a sensor whose orientation with respect to the vehicle was fixed and would be affected by the in-path and cross-path slopes of the terrain beneath the vehicle.* The precise location of the mid-range sensor had to be calculated as the sensor could no longer be assumed to be directly above the vehicle. The mathematical transformations necessary to establish the sensor location and their derivations are given in the program user's guide. The two previously described sensor schemes were then adjusted to incorporate this feature (see Figure 4A), and are hereafter referred to as vertical-fixed sensors.

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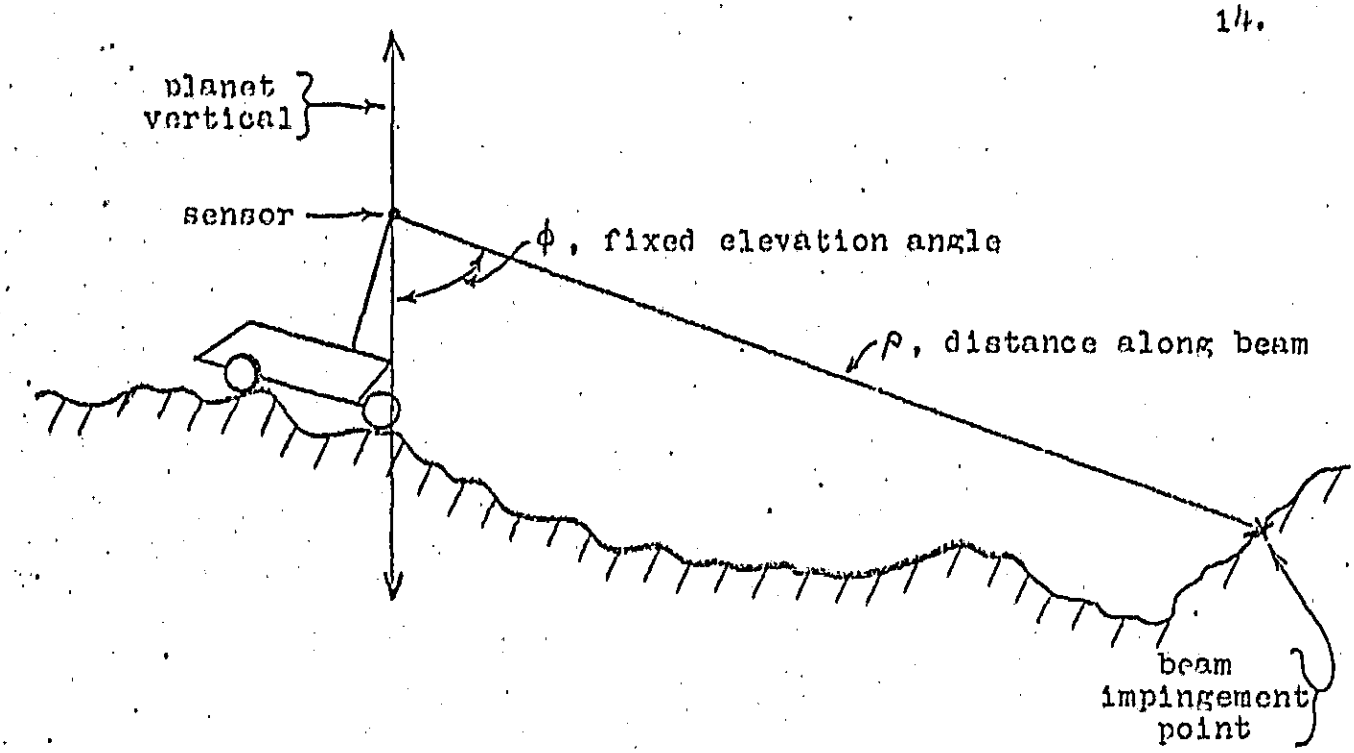
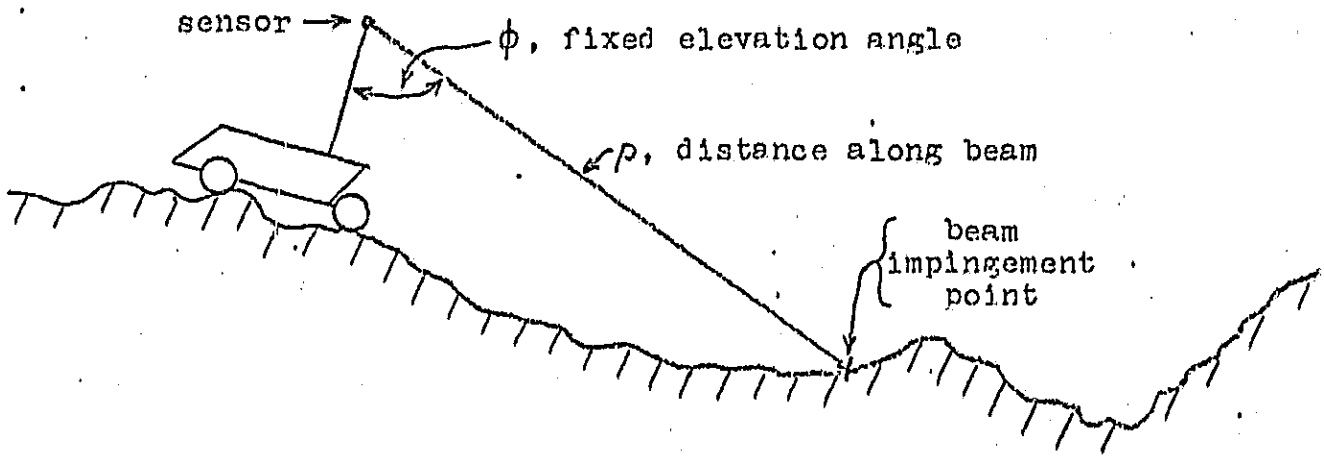
* The in-path slope is defined as the slope of the terrain measured in the direction of the vehicle's motion. The cross-path slope is measured in the direction perpendicular to the vehicle's motion.



(A) Vertical-Fixed Sensor



(B) Vehicle-Fixed Sensor

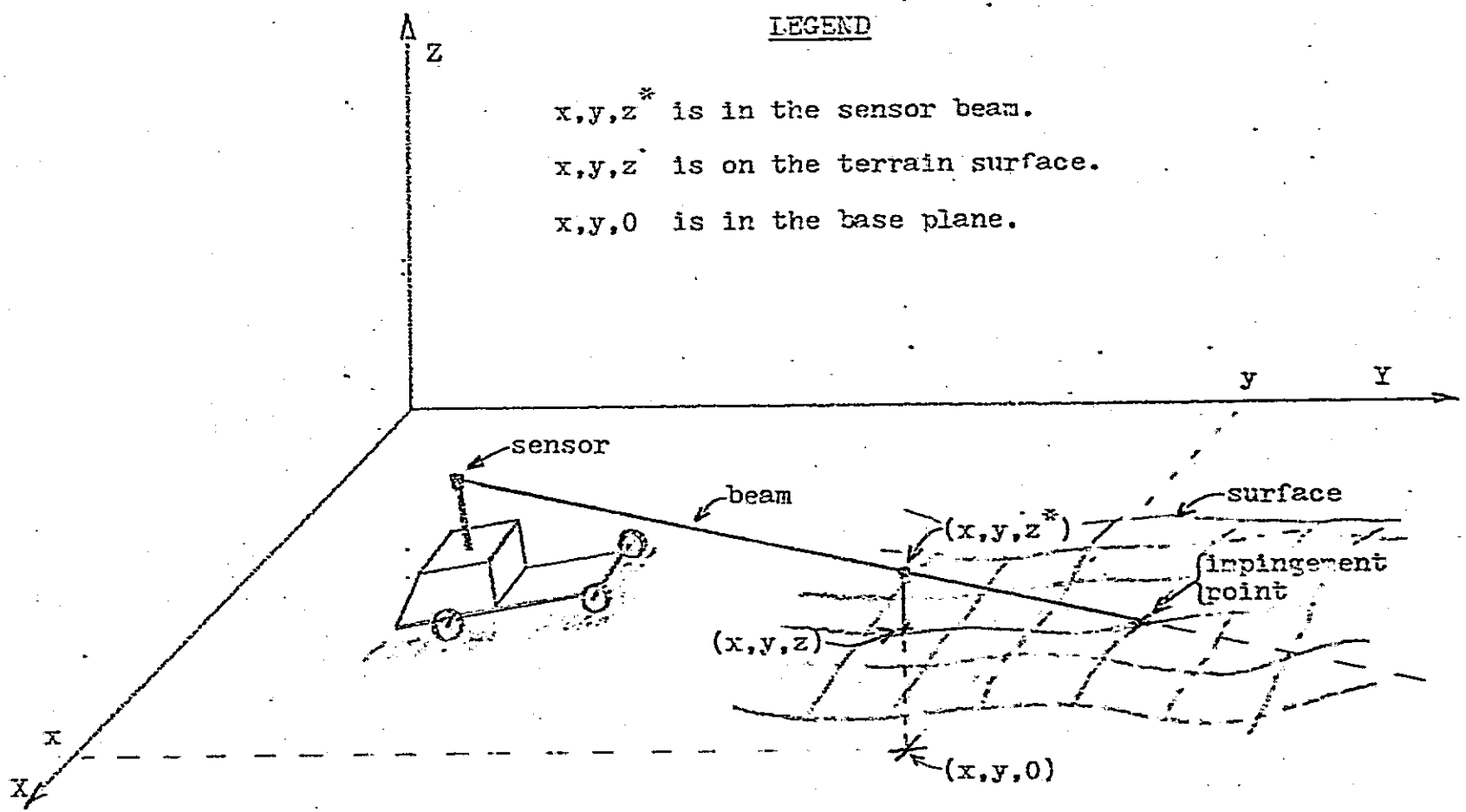
COMPARISON OF VERTICAL-FIXED AND VEHICLE-FIXED SENSORS

Figure 4

The vehicle-fixed sensor scheme is similar to the above schemes in that the scan time is instantaneous, discrete samples are taken, and there is a uniform time (T) between scans. One, two, three, or four simultaneous beams each with a different elevation angle may be used. Output to the terrain model construction block includes sets of azimuths, elevation angles, and range measurements. Noise may be added to any of the elevation angles and/or range measurements at the user's option. Unlike the previous schemes, the elevation angles are measured with respect to the sensor mast, and are held constant with respect to this mast as the beam is swept across the surface (see Figure 4B).

b) Range Measurement Simulation

The sensor simulation block simulates the motion of the laser beam and its impingement upon the terrain's surface. This is done by initially assuming that the length of the beam is zero meters and then increasing the length of the beam by one meter increments. Defining the beam height as z^*, the x,y,z^* coordinates (see Fig. 5) of the beam at each incremented length may be computed. The x,y coordinates are also supplied to the terrain characterization block, which generates the altitude (z) of the terrain at the point x,y. The length of the beam is increased until the beam passes beneath the surface (i.e. $z-z^*$ is negative), or until the range limit of the laser is exceeded.



GEOMETRY OF BEAM IMPINGEMENT CALCULATION

Figure 5

If the beam passes below the surface within the range limit (specified by the user), then an interval halving algorithm is used to obtain the true impingement point between the two points on the beam above and below the surface. By specifying the maximum acceptable altitude difference between beam and terrain, the user can control the accuracy of the simulated range measurement obtained from the interval halving algorithm. An initial guess scheme is used for multiple beam sensors to avoid unnecessary computations. Once a beam range has been calculated, then this range can be used as an initial guess for the length of the other beams for a given azimuth.

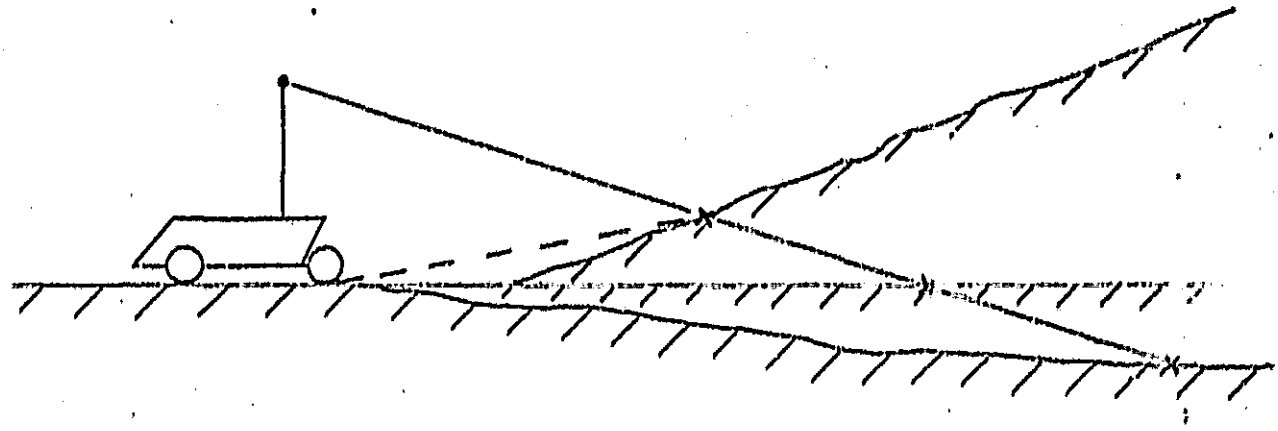
For the sensors whose elevation angles were measured with respect to the planet's vertical, the coordinates (x,y,z^*) along the beam could be readily computed. For the vehicle-fixed sensor, the elevation angles are measured with respect to the sensor mast, making computation of points along the beam more complicated. To simulate this situation, a new cartesian coordinate system with the origin at the sensor is assumed. By calculating the beam points with respect to this new coordinate system, and then multiplying by an appropriate transformation (composed of the directional cosines of the new axes), the beam points can be converted to the coordinate system in which the mathematical model of the terrain is defined. Once this has been achieved, the range measurement techniques described above may be utilized (see the user's guide for

particulars of transformation mathematics).

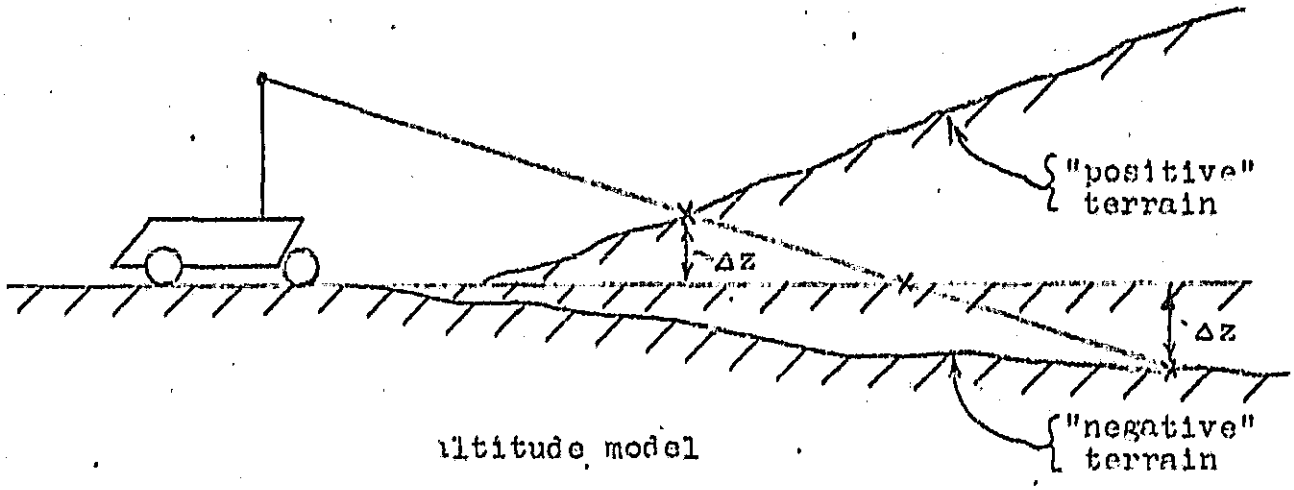
2. Terrain Model Construction Block

Two previous efforts, which have investigated the subject of terrain modeling (Refs. 1 and 3), have developed indices which indicate the major terrain features that are crucial to the safe motion of the vehicle. These works go beyond the level of implementation that is presently available. Consideration at this stage is aimed at general concepts of terrain model types, and at the criteria on which they depend.

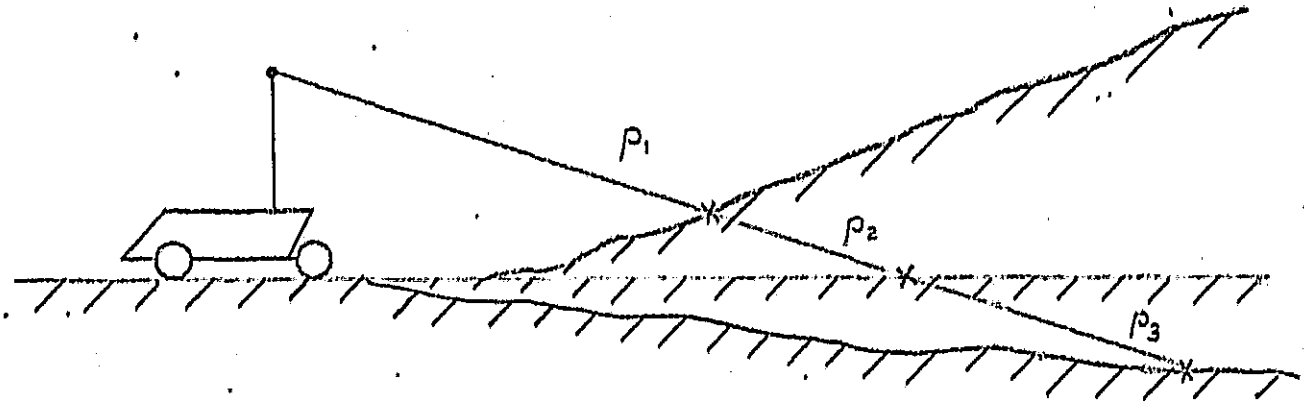
Essentially, five distinct terrain models were proposed in this investigation. The first three of these models depend upon measurements at two different points upon the terrain surface to achieve their significance. These are illustrated graphically in Figure 6, and are referred to as 1) slope, 2) altitude, and 3) range models. Because of the geometry of the situation, any one of these particular models can be obtained from any of the others. However, in terms of algorithm decision criteria, a certain model may be more convenient and meaningful to a particular proposed obstacle-detection path selection system. Models have been implemented which are both slope based and range based. For each discrete azimuth angle, the slope model converts the supplied range information (from the mid-range sensor) into slopes by assuming a linear slope from the vehicle's position to the impingement point of the sensor beam. The range model stores the sensor's range measurements without any processing. The models in both cases then become an array of stored numerical data (for each mid-range sensor scan) which reflect the particular criteria on which the terrain



slope model



altitude model



range model

TERRAIN MODELING SCHEMES

Figure 6

model is based (slopes, ranges).

A fourth concept of the modeling process is to encode the data obtained from the sensor into single-bit representations. Using some predetermined criteria, the model assigns a given value, (1), to sensor data (or combinations of this data) if the data falls within threshold limits and some other value, (0), if the data is outside of these boundaries. In this manner, a set of the values (0's and 1's) is obtained for each sensor sweep, Figure 7A. If several of these sets were stored for presentation to the path selection algorithm at the same time, the model would begin to resemble a code of acceptable and nonacceptable terrain features, Figure 7B. This type of model is certainly more visual than the previous three, and in a sense actually involves some of the decision process itself in that it "decides" whether given points on the terrain are within some limit (presumably acceptable), or outside of it (unacceptable).

The final model proposed was one which constructs a mathematical representation of terrain characteristics. An example of this would be the fitting of an equation to data in order to represent a contour line. Algorithms are available in the literature which determine the minimum order of equations that fit sets of data, and then let the terrain model be the set of resulting equation orders. The basis for such a model would be regression analysis. This model has been left as a topic for future work.

The models discussed above are an attempt at defining some of the basic criteria which can be used in terrain model construction. It is expected that as the path selection system

Any Scan	0	0	0	1	1	1	0	0	0	1	1	1	1	0	0	0	0	1

(A) Single Sweep Model

Model at Time t+2T

Scan 6	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
Scan 5	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	1	1	1
Scan 4	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1
Scan 3	0	0	0	0	0	0	0	1	1	1	1	1	0	1	1	1	1	1

Model at Time t+T

Scan 5	0	0	0	0	0	0	0	1	0	0	0	0	1	1	1	1	1	1
Scan 4	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1	1
Scan 3	0	0	0	0	0	0	1	1	1	1	1	0	1	1	1	1	1	1
Scan 2	0	0	0	0	0	0	1	1	1	1	1	0	0	1	1	1	1	1

Model at Time t

Scan 4	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1	1
Scan 3	0	0	0	0	0	0	1	1	1	1	1	0	1	1	1	1	1	1
Scan 2	0	0	0	0	0	0	1	1	1	1	1	0	0	1	1	1	1	1
Scan 1	0	0	0	0	0	1	1	1	1	1	1	0	0	1	1	1	1	1

(B) Stored Sweep Model

ENCODED TERRAIN MODELS

Figure 7

evaluation tool becomes useful in assessing particular modeling schemes, more complex models will be developed.

3. Path Selection Algorithm Block

The development of the path selection algorithm block assumed that, on the basis of some criteria (e.g., slope acceptability, range threshold, etc.), the path selection algorithm would choose an acceptable path along one of the mid-range sensor's scanning beams (see Figure 3). In one of the path selection algorithms presently implemented, the testing of criteria is accomplished by comparing the terrain models' slopes or ranges with threshold slopes and ranges. If the model-supplied values are acceptable, the algorithm issues appropriate steering commands. If they are unacceptable, the algorithm continues a search of the terrain model for other paths.

Considering a slightly different situation, the encoded terrain model data is already in a go, no-go form (see Figure 7B). Since the traversability criteria has already been applied, the path selection algorithm need only search the data for an acceptable path.

Both types of algorithms have been software implemented, and both search the terrain model data in a specific sequence. The heading angle from the vehicle's present location to its destination (target) is calculated and then compared with all of the sensor beam directions. The direction nearest the heading angle is chosen as a tentative path. If the terrain model data (slope, range, etc.) for this direction is acceptable, the vehicle receives

a steering command to head in this direction. If this path is not acceptable because an obstacle is indicated, the algorithm then searches one path to the right, one path to the left, two paths to the right, and so forth until a traversable path is found. The direction of this path then becomes the new steering command for the vehicle.

An emergency path selection algorithm has also been simulated. This subset of the path selection algorithm is only used when the vehicle encounters some obstacle it cannot negotiate. This situation could occur if the vehicle lands in a steep crater or on a butte, or if the mid-range sensor did not detect some dangerous obstacle which the vehicle has encountered. The emergency path selection algorithm might involve backing the vehicle up or stopping and providing mission control on Earth with a television picture of the situation.

The extension of any of the terrain models to include several sensor scan sets permits the development of more powerful path selection algorithms. In the case of slope, range, or altitude models, a secondary criterion for traversability might be the minimization of energy used for motion. Thus, not just a safe or acceptable path is selected, but rather an optimal one (on the basis of energy considerations).

C. Vehicle Dynamics Block

1. Simulation Capabilities

The purpose of this block is to dynamically simulate the motion of the vehicle and to provide the evaluation block with information for analysis of the vehicle's motion. The vehicle

dynamics block must also provide the sensor simulation block with various vehicle parameters (location, heading, speed, etc.), so that a sensor simulation may be performed.

Much attention has been directed at simulating the vehicle's motion realistically, and many non-ideal situations can be effectively modeled. To date software implementation has been completed in the following areas:

a) Vehicle Response Time - Provisions have been made so that the vehicle can turn only at a specific rate and so that the travel of the vehicle during very slow sensor scans and/or very slow computer calculations can be simulated. The user may assume ideal conditions, if desired.

b) Vehicle Motion - It has been assumed that the vehicle drives itself uphill and coasts downhill. Therefore, two models of vehicle motion (an uphill model and a downhill model) have been determined. These models calculate the power required to traverse a slope and the speed of the vehicle on this slope.

c) Random Disturbances - Noise of two types may be added to components of or measurements made by the path selection system. The addition of noise simulates random effects due to bouncing of the vehicle, steering errors, etc.

d) Short Range Sensor - An ideal mechanical sensor simulator is available. Since a short range mechanical sensor may interfere with science operations, this simulation provision is optional and is controlled by the user.

2. <u>Simulation Methods</u>

a) Vehicle Response Time - The motion of the vehicle has

been divided into three states, the length of each being controlled by the user.

1) Run State 1 - represents the motion of the vehicle from the start of execution of the steering command until the start of use of the mid-range sensor.

2) Run State 2 - represents the motion of the vehicle during the use of the mid-range sensor. The effects of vehicle motion on sensor measurements can be simulated if the sensor takes a finite amount of time (run state 2) to make the range measurements. An instantaneous sensor would eliminate run state two.

3) Run State 3 - represents the motion of the vehicle from the end of use of the mid-range sensor until the start of execution of the next steering command. This state allows analysis of time delay of steering command generation due to a slow onboard computer. The onboard computer must construct a terrain model from the sensor measurements and use a path selection algorithm to generate the new steering command. A very fast onboard computer would eliminate run state 3.

The run states are executed cyclically, starting with run state one, until the vehicle arrives on target or the vehicle gets into trouble (due to dangerous terrain) and must stop. Information concerning the vehicle's velocity, location, and present heading is passed to the sensor simulator and terrain model during run state two. Similar information is passed to the path selection algorithm between run states two and three.

Note that the end of execution of a particular steering command can occur during any of the run states, or during none of them. This enables analysis of a variety of steering rates, this parameter being controlled by the user. By making the steering rate sufficiently small, one can simulate a vehicle which generates steering commands faster than they can be executed. A very large steering rate allows "instantaneous" response to steering commands.

b) Vehicle Motion - The point below the center front edge of the vehicle's wheelbase on the Martian surface (x_a, y_a, z_a) - (see Figure 8), is moved in discrete horizontal steps of fixed length (STEP), the value of which is determined by the user. If the vehicle is on an in-path slope (α), then the length of a discrete path increment becomes STEP/cos (α) = S.

When the vehicle is on a positive slope, a potential energy formula, derived in Reference 1, is used to calculate power requirements and the velocity of the vehicle. Specifically:

$$P.E. = 0.00838(W)(D)\sin(\alpha + \theta)$$

where:

P.E. = potential energy, in watt-minutes,

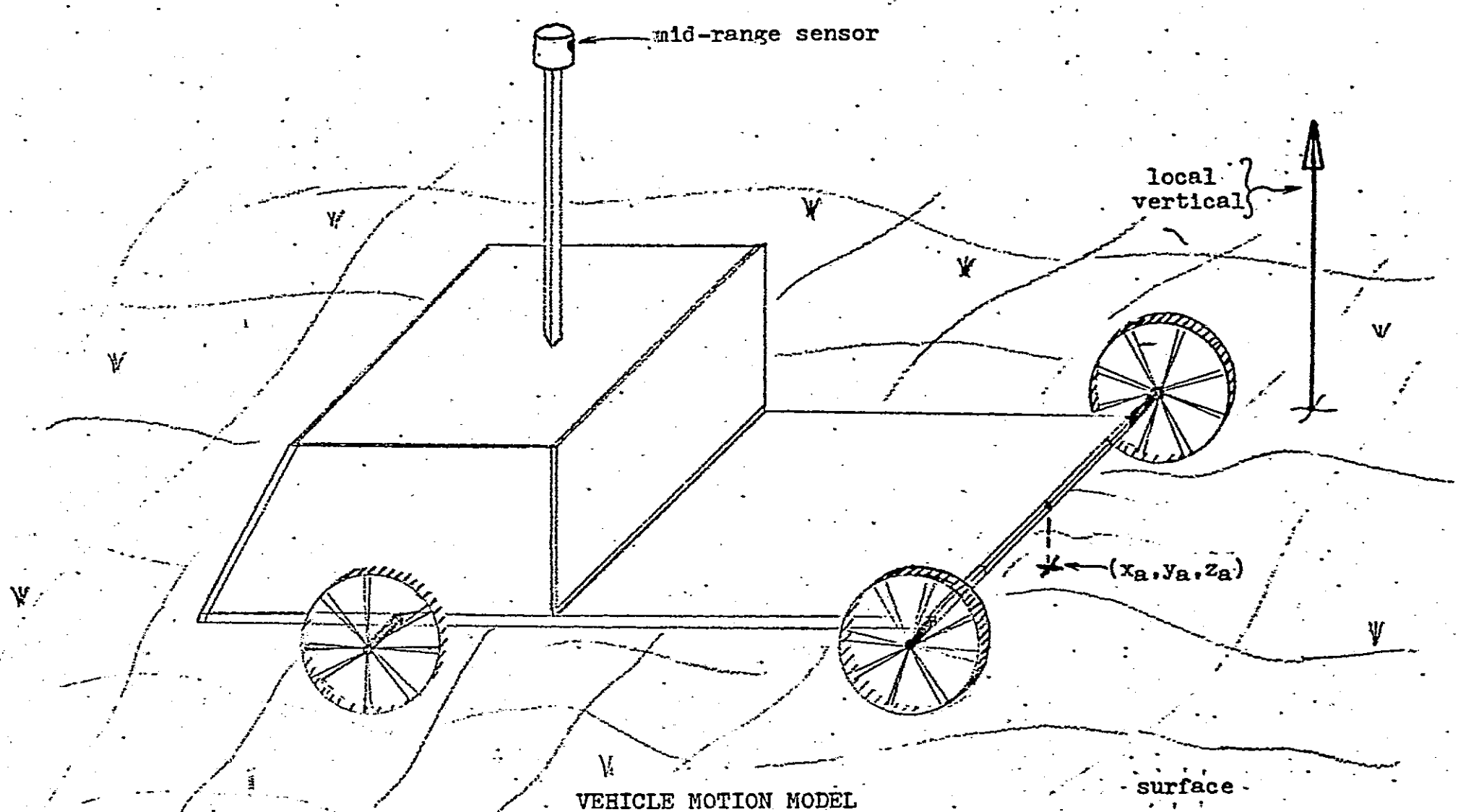
W = weight of the vehicle, in pounds,

D = the distance traveled, in feet,

θ = the drag angle (effects of friction, wheel slippage, etc.),

α = the slope of the terrain.

Since $\text{POWER} = \frac{\text{ENERGY}}{\text{TIME}} = \frac{\text{ENERGY} * \text{VELOCITY}}{\text{DISTANCE}}$, then



VEHICLE MOTION MODEL

Figure 8

it follows that

POWER = 1.65W VELOCITY sin $(\alpha + \theta)$; where POWER is in watts, and VELOCITY is in meters per second.

Using this formula, the velocity and the power required may be calculated. Note that the user specifies available power and the drag angle (θ). Steep slopes that would force the vehicle's velocity to be less than some minimum velocity (determined by the user) would have prevented execution of the vehicle motion models and other action would have been taken.

When the vehicle is on a negative slope, the motors of the vehicle are turned off and the vehicle is allowed to coast down the hill. Therefore, no power is consumed. This situation has been modeled as a block sliding on an inclined plane, and the equations of motion are:

$$(W)\sin\alpha - U_K N = m a$$

$$N = W \cos\alpha$$

thus $$a = g (\sin\alpha - U_K \cos\alpha)$$

where a = acceleration of vehicle, in meters/sec^2

α = in-path slope of terrain

U_K = coefficient of friction (effects of friction, wheel slippage, etc.)

W = weight of vehicle, in pounds

N = normal force on vehicle from surface, in pounds

g = gravity on Mars, 3.62846 meter/sec^2.

If the acceleration is negative, then the vehicle cannot accelerate down the slope. In this case, assume that the vehicle's

motors bring the vehicle up to maximum speed instantaneously using zero watts of power and then shut off. If the acceleration is positive, and since the length of the path increment S on the slope is known, then:

$$S = v_o t + 0.5at^2$$

$$v_f - v_o = at$$

and

$$v_f = (v_o^2 + 2.0aS)^{0.5}$$

where:

v_f = final velocity of the vehicle at bottom of slope, in meters/second

v_o = initial velocity of the vehicle at top of slope, in meters/second

S = length of slope, in meters

t = time to traverse slope of length S, in seconds.

If regenerative breaking is being employed by the vehicle, then the final velocity and the slope length must be adjusted so that the vehicle never exceeds its maximum attainable speed. If the vehicle is already moving at this velocity when a downhill slope is encountered, then the vehicle maintains this velocity and uses no power.

c) Random Disturbances - Noise may be added to any component or measurement of the path selection system. Consider the fact that displacing a vehicle wheel by some amount x will cause some displacement y of some component in the path selection system. If the vehicle employs some sort of shock damping system, then the relation between y and x can be modeled approximately by a second order differential equation:

$$\ddot{y}(t) + \zeta\dot{y}(t) + \omega_n^2 y(t) = x(t)$$

where ζ = damping of system (specified by user)

ω_n = natural frequency of system (specified by user)

The easiest way to simulate the above differential equation on a computer is by use of the difference equation:

$$Y(k) = -CY(k-1) - DY(k-2) + AX(k-1) + BX(k-2)$$

where the sampling rate T is implicit in the equation and zero initial conditions are assumed. Development of the coefficients A,B,C,D and the sampling rate T is presented in the user's guide. If white noise is applied to the difference equation in the form of X(k), then the output Y(k) will be second-order low-pass filtered white noise. If this quantity is applied directly to the path selection system component in question, then the results of random disturbances to that component may be analyzed.

If one wishes to simulate a linear relation between bouncing vehicle wheels and some component, then the white noise should be applied directly to that component.

It should be noted that judicious scaling of the white noise is important and is controlled by the user. A subroutine generates random numbers between zero and one. The user specifies the mean and the maximum deviation of the mean and these random numbers are then scaled accordingly and used as inputs to the difference equation.

The entire random noise scheme has been set up so that the user can apply different types of random noise (filtered or unfiltered) to as many variables of interest as desired.

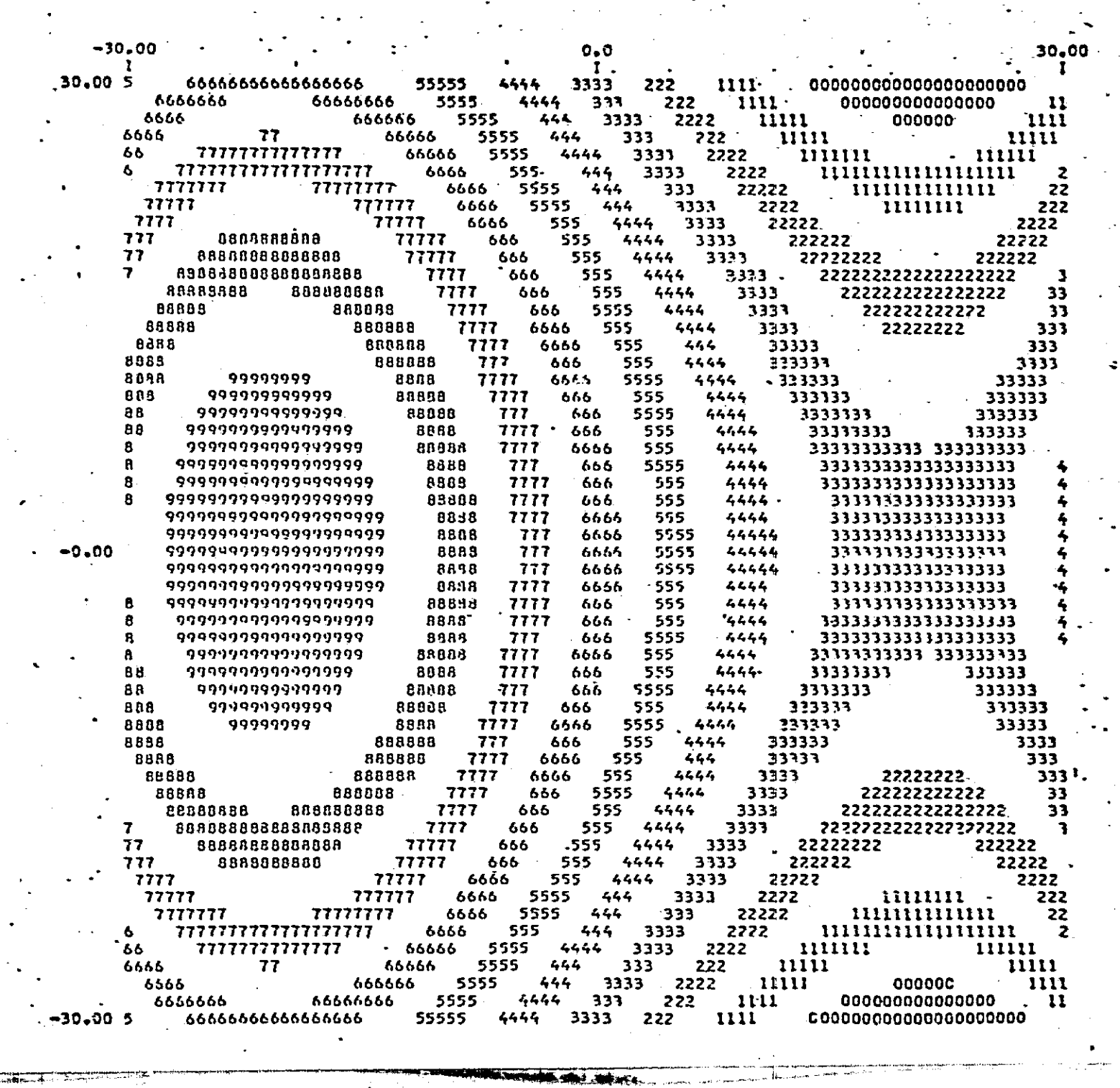
d) Short Range Sensor - An ideal mechanical sensor can be simulated at the user's option. The height of the surface at a distance of

STEP meters (defined in Section III, C.2.b) in front of the vehicle is calculated and the slope is computed with respect to the point on the surface below the front of the vehicle (x_a, y_a, z_a) - (see Figure 8). If the slope is not within acceptable limits (specified by the user), then the emergency mode of the path selection algorithm is executed.

D. Display and Evaluation Blocks

1. Terrain Display Block

The initial development of this block was performed by Mr. Michael Martin, and subsequent completion and refinements were carried out by the authors. Since visual representations of the terrain surface were considered highly desirable, several methods of graphical output were evaluated. A decision was made, mainly due to the ease of implementation and small cost, to use a line printer to construct a contour map of the terrain modeled in the terrain characterization block. The software implementation of this block utilizes the symbols 0-9 and blanks to represent 19 bands, or ranges, for contour display. All values of the terrain surface altitude within a given band range are represented by that band symbol. An example of the output from this block can be seen in Figure 9. Several versions of this program were written, but the most useful one automatically searches the entire terrain area to be displayed and determines the individual band ranges (which are all equal). The size of the area to be displayed is also automatically determined and scaled by the program by taking the maximum difference between the target location and initial vehicle location x and y



TERRAIN CONTOUR MAP

$z = f(x^3, y^2, x)$

Figure 9

coordinates and establishing slightly larger square boundaries. The terrain display block can also represent special features such as boulders (see Figure 10).

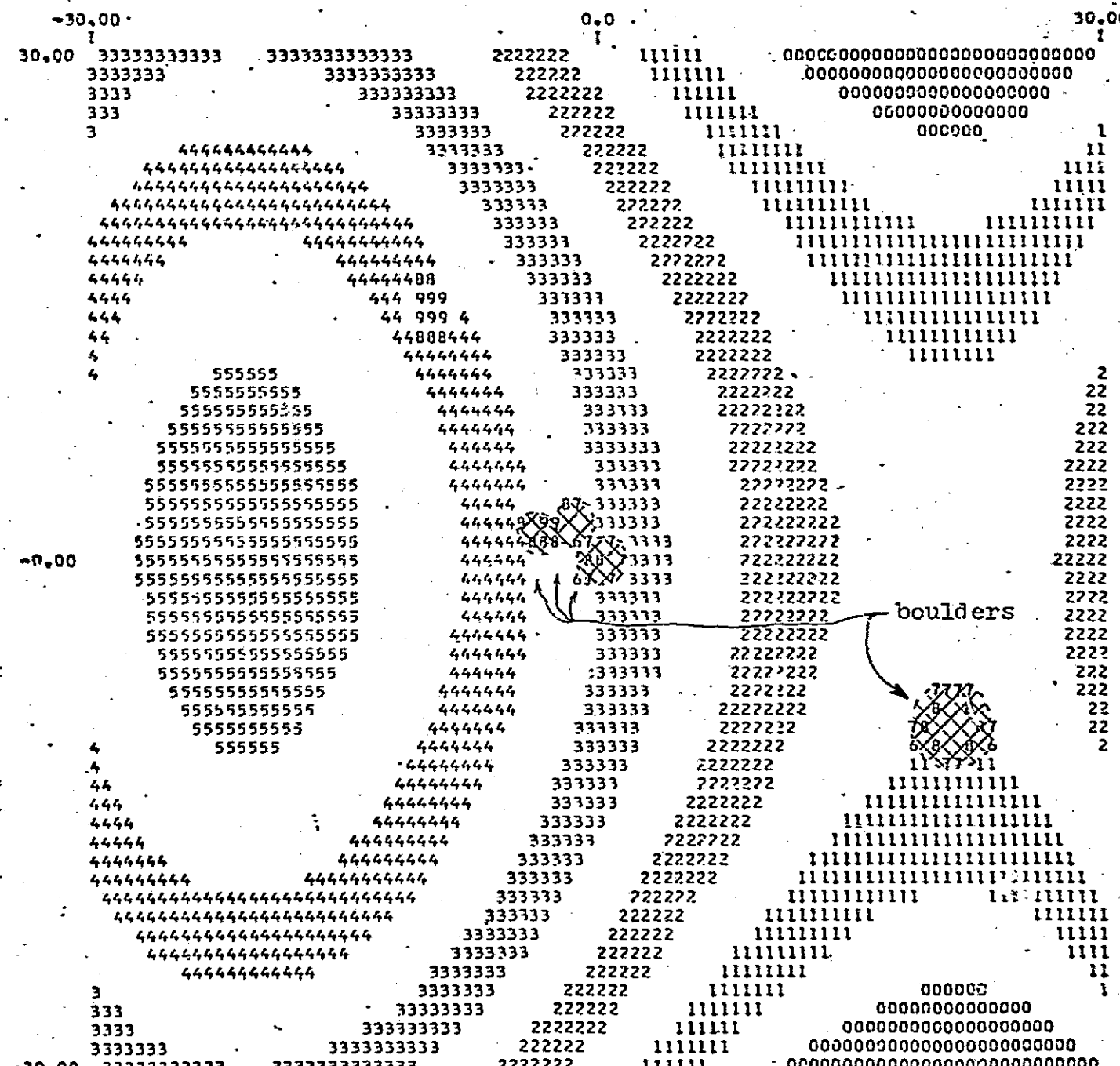
After expanding the area displayed by the terrain contour map, two other types of maps were developed. The first map is the vehicle path map, as shown in Figure 13, Section IV. The path of the vehicle, initial vehicle location, and the target location are shown graphically. An appropriate symbol is also used to indicate when the mid-range sensor is being used along the vehicle's path. If the vehicle moves off of the area shown, no graphic record of its progress outside the map's limits is presented.

The second map is an overlay of the vehicle path map onto the terrain contour map. The grid marks have been deleted from the overlay (see Figure 12, Section IV).

It should be noted that because of the amount of calculations required (10,140 separate altitude calculations), there is a definite time penalty (depending on terrain complexity) when searching a terrain for its maximum and minimum points to enable automatic vertical scanning. There is also a memory penalty (about 40K bytes), but it was felt that the convenience of a completely automatic contour map outweighed these disadvantages. Both penalties may be easily circumvented by allowing the user to specify the maximum and minimum altitude values of the terrain to be displayed. This assumes that the user knows exactly how his terrain behaves, an assumption which may be unwarranted for complex terrains.

2. Terrain Model Display Block

The form of the terrain model display block is highly dependent



PRINT CHARACTER	ALTITUDE LOWER LIMIT
0	-2.62
	-2.74
1	-1.87
	-1.50
2	-1.12
	-0.75
3	-0.38
	-0.00
4	0.37
	0.75
5	1.12
	1.49
6	1.87
	2.24
7	2.61
	2.99
8	3.36
	3.74
9	4.11
	4.48

TERRAIN CONTOUR MAP

$z = f(x^3, y^2, x)$
(with boulders)

Figure 10

upon the nature of the terrain model used in a simulation. The development of this block has therefore been left as a subject for future work.

3. Systems Evaluation Block

To develop an effective means for evaluating the performance of the vehicle for various path selection systems, both quantitative and heuristic methods have been implemented in the systems evaluation block.

a) Quantitative Evaluation

It is desired to describe mathematically as many important features of the performance of the path selection system as possible so as to minimize the need for subjective evaluations. The following formula has been postulated so that important characteristics of a system and their relative importance can be stated analytically:

$$M = \sum_{i=1}^{3} W_i F_i$$

where:

M = the figure of merit of the system,

F_i = indices that represent the important characteristics, or features, of the system,

W_i = the weights of the corresponding indices.

The figure of merit, indices, and weights are defined so that their numerical values will vary between zero (worst case), and unity (best case). In other words, the importance and/or the desirability of a variable increases as its value increases.

If the weights and indices are appropriately chosen, then the system which generates the highest value of M, when the above formula

is applied, would be the most desirable system. Assuming that the indices chosen adequately describe the system's performance, there still remains the selection of the values of the weights. At this point in time, the weights have been selected so that all performance indices are assumed to be equally important. Adjustment of these weights for performance indices not equally important has been left for future work.

The actual mechanics of each index must now be considered. Tentatively, it has been decided that three indices sufficiently describe vehicle performance, and, if certain conditions are met, the number of indices may be reduced to two. The three indices are:

(i) Path Length - If D_m is the distance between the starting point and the target, and $D_e + D_m$ is the length of the path chosen by the vehicle, then the index defined by

$$F_1 = \frac{D_m}{D_e + D_m}$$

provides a measure of the selected path length.

(ii) Battery Time - If the total time taken by the vehicle to reach its target is called $T_e + T_m$, and the time that the vehicle uses its batteries is called T_b, then the index defined by

$$F_2 = \frac{T_e + T_m - T_b}{T_e + T_m}$$

provides a measure of the battery usage time.

(iii) Traverse Time - If D_m is the distance between the vehicle and the target, and the maximum

velocity of the vehicle is V_m, then the minimum time required to reach the target is $T_m = D_m/V_m$, and the index defined by

$$F_3 = \frac{T_m}{T_e + T_m}$$

provides a measure of the total travel time.

The first index penalizes long and/or wandering paths while the second penalizes the selection of paths that contain steep slopes, thereby forcing the vehicle to rely on its batteries as well as its radioactive thermal generators (RTGs). If the vehicle must slow down for other reasons besides steep slopes (e.g., tactile sensor contact), then the system will be penalized for this loss of time through the third index.

b) Heuristic Evaluation

Some important characteristics of a system are not easily described in quantitative form, and yet these characteristics certainly seem to require consideration. The following two features fit into this category:

(i) Safety of Path Selected - Although the safety of the vehicle is of primary importance, it is difficult to analytically describe the inherent danger to the vehicle present in a selected path. What is hoped to be an indication of safety has been implemented by counting the number of times the tactile sensor indicates the vehicle is about to encounter an obstacle.

(ii) Correct Performance - Situations may arise where the vehicle is called upon to "not succeed". For example, if the target is surrounded by an untraversable crevasse, then it would be better for the vehicle to get "close", rather than attempt to reach the exact target. This feature is a purely heuristic characteristic, and any evaluation in this area would be performed by humans.

IV. PATH SELECTION SYSTEM EVALUATION

In order to demonstrate the effectiveness of the techniques presented in Section III, the performance of the three path selection systems described below has been evaluated.

A. Path Selection System Description

1) System Similarities

We shall consider a laser sensor mounted on a mast such that the base of the mast is directly above the point (x_a, y_a, z_a) shown in Figure 8, Section III. The laser beam is used every three seconds to instantaneously measure the ranges to the impingement points in 17 directions in front of the vehicle (as shown in Figure 3, Section III), each direction being separated by 2.5 degrees. These ranges are processed by a terrain modeler, which generates a model of the surface and a heading (from North) for each of the 17 areas scanned. Heading calculation errors will result if the terrain model neglects the effects of in-path and cross-path slopes (in-path slope alone has no effect). If the sensor's beam does not impinge upon the surface within some specified distance r (where r is the greatest measurable distance from the sensor to the impingement point - a sensor design limitation), then the terrain modeler will assume that no obstacle exists in that particular direction. A path selection algorithm will search the terrain model for a traversable path and generate the appropriate steering command, this command being one of the terrain model's 17 calculated headings. All three path selection systems will use the same path selection algorithm, as described in Section III, B.3. It is assumed that the onboard computer will perform

the necessary computations instantaneously. It will also be assumed that the vehicle instantaneously responds to steering commands generated by the path selection algorithm.

In addition to its mid-range sensor, the vehicle is assumed to have a short-range tactile sensor. If this sensor indicates trouble, or the normal path selection algorithm cannot find a traversable path, an emergency path selection algorithm will be used. Specifically, the vehicle will stop, instantaneously* rotate thirty degrees clockwise using no power, and then use its normal path selection system to find a new route.

The differences between the three path selection systems will now be discussed. Note that the beam elevation angle and the sensor height specified in the following system descriptions are measured with respect to the true planet vertical when the vehicle is on a horizontal plane.

2) <u>System I</u> (single beam sensor; approximate terrain model)

Path Selection System I uses an instantaneous single beam sensor (as shown in Figure 2A, Section III) with a beam elevation angle from the mast of 82.4 degrees. The sensor is mounted two meters above the surface, and the laser beam impinges the surface 15 meters in front of the sensor.

The terrain modeler assumes that the point two meters directly below the sensor (using the planet vertical) will always be on the Martian surface. The terrain from each of the 17 impingement points

* This is a simplifying assumption, not intended to be realistic. If the emergency mode was used in a real situation, the vehicle would probably communicate with Earth, thus incurring a time penalty.

to this hypothetical surface point is assumed to be linear. The slopes of these "linear" terrain segments can then be calculated and stored, along with the corresponding headings, as the terrain model. To calculate the true headings of each of the laser beams, the model assumes that the deflection angles measured by the sensor are measured in the true horizontal plane, i.e., the effects of in-path and cross-path slopes are ignored.

The path selection algorithm uses the maximum and minimum traversable slopes of the vehicle as thresholds, and uses the terrain model information to generate a go, no-go map (similar to Figure 7A, Section III) which is then searched for a traversable path.

3) <u>System II</u> (single beam sensor; exact terrain model)

Path Selection System II is similar to System I in that a single beam sensor of height two meters is again used, but the elevation angle of the sensor beam has been adjusted to 79.4 degrees so that the beam strikes the surface 11 meters from the sensor if the vehicle is on a horizontal plane (see Figure 2A, Section III).

The terrain modeler assumes that the terrain is linear from the point directly below the center front edge of the vehicle's wheelbase (x_a, y_a, z_a) - see Figure 8, Section III) to the 17 beam impingement points. The modeler takes into account the effects of in-path and cross-path slopes when calculating the true location of the beam impingement points. The slopes of the "linear" terrain segments and the true headings of these slopes are found

from the geometry of the situation, as developed in the user's guide.*

The path selection algorithm is the same as that used in System I.

4) System III (double beam sensor; approximate terrain model)

Path Selection System III uses an instantaneous double beam sensor (as shown in Figure 2B, Section III) with beam elevation angles from the mast of 66.8 and 70.85 degrees. The sensor is mounted three meters above the surface. If the vehicle is on a horizontal plane as shown in Figure 2B, Section III, then the lower laser beam impinges the surface 7 meters in front of the sensor.

The double beam sensor makes a set of measurements in 17 directions of interest. The terrain modeler processes each set of the range measurements by subtracting the lower beam length from that of the upper beam and converting the length difference to a time interval. This time interval is then compared to predetermined thresholds, and a go, no-go map, similar to the map in Figure 7A, Section III, is generated. This modeling scheme was originally proposed in Reference 4. The headings of the 17 lower beams are computed by assuming that the deflection angles measured by the sensor are measured in the true horizontal plane, i.e., the effects of in-path and cross-path slopes are ignored. This modeler is the same as that used in System I. The upper beam is assumed to

* Unlike the other two path selection systems, this system's terrain modeler does not assume that the mid-range sensor measures impingement point directions in the true horizontal plane.

have the same headings as the lower beam at corresponding measurement points.

The path selection algorithm for this system searches the terrain model map, as explained in Section III, B.3, to find a traversable path.

The main characteristics of these three systems are listed in Table I, below.

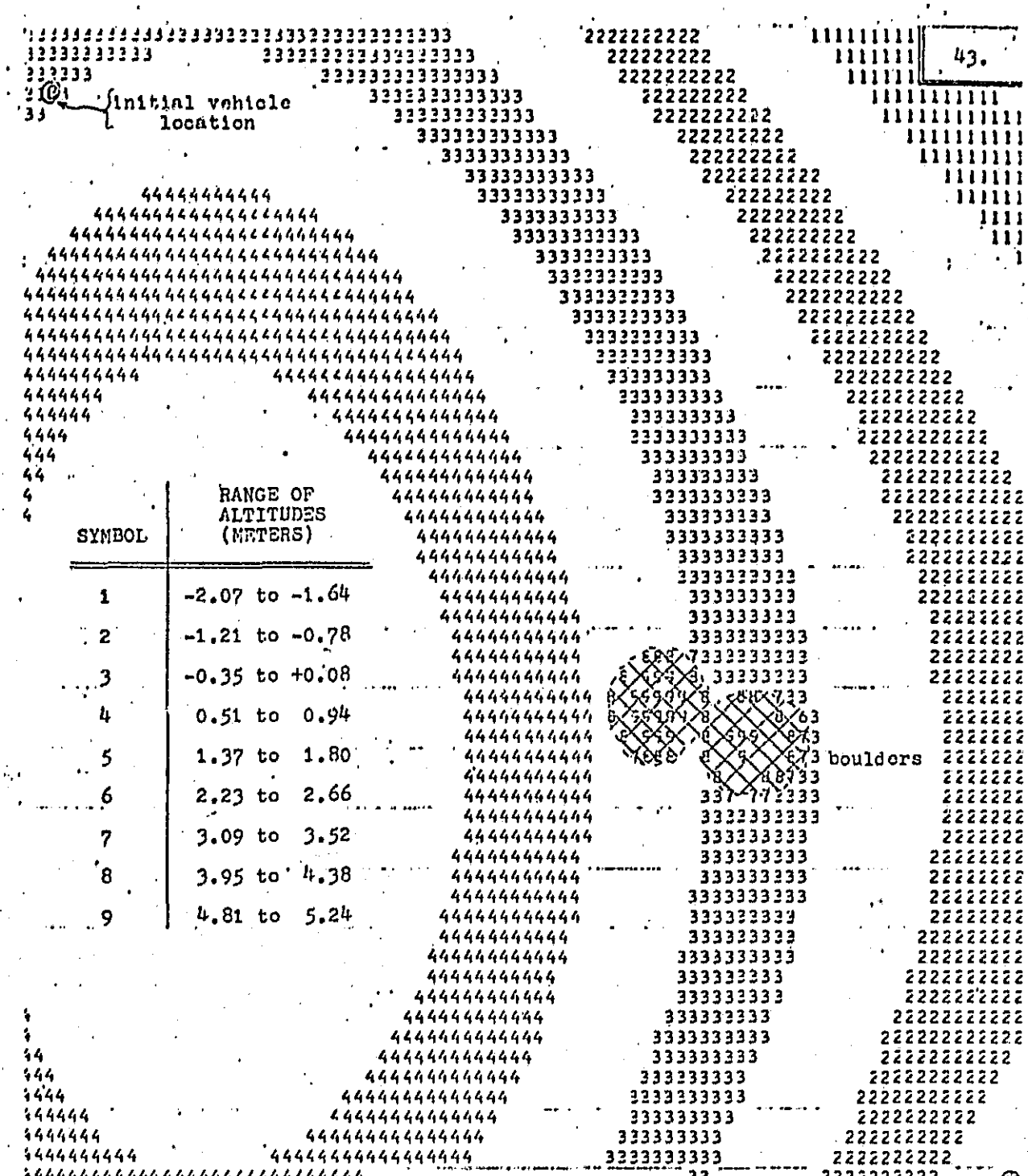
TABLE I

PATH SELECTION SYSTEM CHARACTERISTICS

Item	System I	System II	System III
Number of Sensor Beams	1	1	2
Beam Elevation Angle (degrees)	82.4	79.4	66.8 70.85
Sensor Height (meters) above ground	2	2	3
Terrain Model Type	slope model-approximate calculation	slope model-exact calculation	time interval go, no-go map
In-Path, Cross-Path Slope Compensation	no	yes	no

B. Test Situation

The vehicle and a target are placed on the surface shown in Figure 11, with the vehicle headed directly for the target. For each path selection system, four test situations have been prepared. Each system has been simulated using both vehicle-fixed and vertical-fixed mid-range



SYMBOL	RANGE OF ALTITUDES (METERS)
1	-2.07 to -1.64
2	-1.21 to -0.78
3	-0.35 to +0.08
4	0.51 to 0.94
5	1.37 to 1.80
6	2.23 to 2.66
7	3.09 to 3.52
8	3.95 to 4.38
9	4.81 to 5.24

TEST SITUATION

Figure 11

sensors, and both sensors are operated under "ideal", i.e., deterministic, and "noisy" conditions. The "noise" consists of adding uniformly distributed random variations of zero mean and a maximum deviation of 15 degrees to the actual in-path and cross-path slopes of the terrain beneath the vehicle. Since the vehicle dimensions are set at 3.3 x 2.6 meters (10x8 feet), the addition of this noise can be thought of as representing the effects of traversing terrain irregularities having maximum heights or depths of 0.9 meters.

C. Discussion

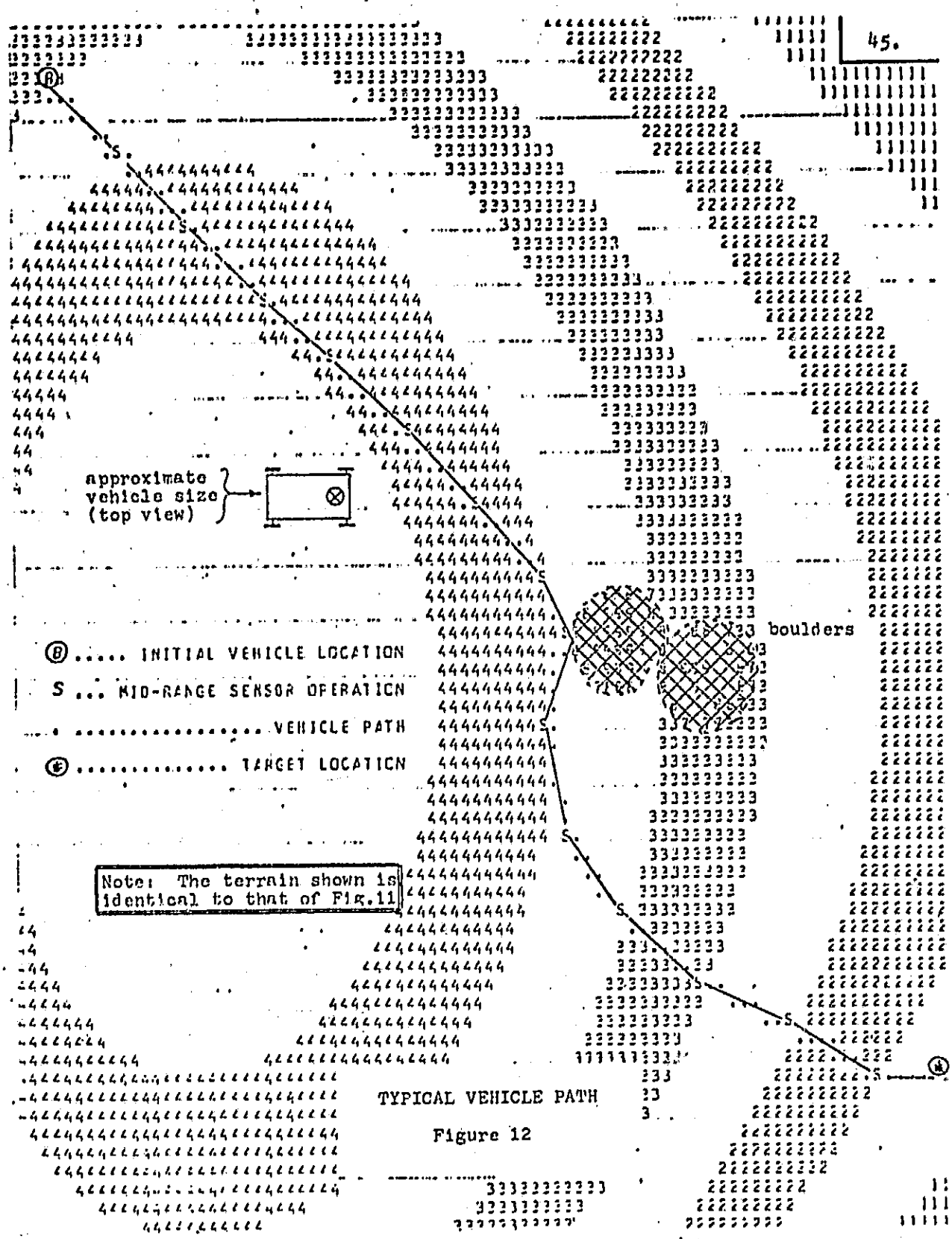
The performances of the three path selection systems in several tests are summarized in Tables 2 through 6 in terms of the following criteria:

(i) Selected path length,
(ii) Battery usage time,
(iii) Total travel time,
(iv) Figure of merit (M),
(v) Number of times that the emergency mode of the path selection algorithm is used (N).

In this analysis, no distinction is made between using the emergency mode because of obstacle contact, or using the mode because of a request from the normal path selection algorithm due to the fact that the algorithm cannot find a traversable path.

1) System I (single beam sensor; approximate terrain model)

The performance results for Systems I are shown in Table II, and a typical path chosen by the vehicle is shown in Figure 12. For all test situations, the vehicle reached its target. However, the vehicle always bumped into the boulders. From the terrain model output, it was determined that the vehicle was unable to get close enough to the boulder to determine that an obstacle existed



TYPICAL VEHICLE PATH

Figure 12

without then contacting the boulder. Once contact occurred, the vehicle always tried to "just miss" the boulder, and as a result, usually hit the obstacle again. The terrain modeler detected the obstacle at a safe distance (a definite slope change was evident), but the go, no-go thresholds that the path selection algorithm was using were too large to indicate a dangerous situation. Therefore, it was concluded that for slope models, the go, no-go thresholds should not be as large as the vehicle's maximum traversable slope.

TABLE II

PERFORMANCE RESULTS for SYSTEM I
(single beam sensor; approximate terrain model)

Item	Vertical-Fixed Sensor		Vehicle-Fixed Sensor	
	No Noise	Noise	No Noise	Noise
Test Number	1	2	3	4
Selected Path Length (meters)	78.5	80.5	77.0	79.0
Battery Usage Time (seconds)	1.34	1.34	1.34	1.34
Total Travel Time (seconds)	52.33	53.67	51.33	52.67
M	0.97	0.96	0.98	0.96
N	2	4	1	3

The vehicle-fixed sensor produced a terrain model where a five degree difference in measured slopes from those obtained with the vertical-fixed sensor was common. Thus, this sensor seemed to produce models inferior to those produced by the vertical-fixed sensor.

This was especially noticeable when the vehicle was close to an obstacle, as the vehicle-fixed sensor tended to "lose" edges of the obstacle. The reason for this is the approximations made by the terrain modeler. The steering commands are generated using directions in which the laser beams, due to in-path and cross-path slopes, are not pointing. The importance of this error is magnified when the range measurements are very short, such as when the vehicle is close to an obstacle. Note, that the vehicle-fixed sensors fared better against the obstacle according to the results in Table II. In losing edges of the obstacle, the vehicle tended to wander and luckily wandered away from the obstacle, whereas the vehicle, guided by the vertical-fixed sensor, hit the obstacle more squarely, and took longer to negotiate it.

When adding "noise" to the vehicle's in-path and cross-path slopes, drastic range measurement differences occurred. Slope deviations of 7 to 10 degrees from those slopes calculated under no-noise conditions were common. Again, the vertical-fixed sensor produced better results than did the vehicle-fixed sensor, for the same reason cited above.

Two additional test situations (numbers 5 and 6 in Table III) were run in an attempt to improve System I's performance. In test 5, the same situation exists as in test 1, but the mid-range sensor was used twice as often (i.e., every 1.5 seconds). The vehicle detected the obstacle and was able to turn so that only one boulder contact occurred, rather than the two contacts made in test 1. Again, the slope thresholds used by the path selection algorithm were too large to allow for efficient obstacle avoidance.

TABLE III

ADDITIONAL PERFORMANCE RESULTS for SYSTEM I
(single beam sensor; approximate terrain model)

Item	Vertical-Fixed Sensor		Vehicle-Fixed Sensor	
	No Noise	No Noise	Noise	Noise
Test Numer	1	5	4	6
Elapsed Time Between Sensor Scans (seconds)	3.0	1.5	3.0	3.0
Beam Separation Angle (degrees)	2.5	2.5	2.5	5.0
Selected Path Length (meters)	78.5	77.0	79.0	78.0
Battery Usage Time (seconds)	1.34	1.34	1.34	1.34
Total Travel Time (seconds)	52.33	51.33	52.67	52.00
M	0.97	0.98	0.96	0.97
N	2	1	3	2

A different method was then used to obtain better performance, as shown in test 6, Table III. Here, the radial increment between sensor beams was increased from 2.5 to 5.0 degrees. All other parameters were the same as for test 4. Since the path selection algorithm chooses a path from one of the beam directions, then the vehicle can effectively turn twice as fast, as it is now scanning an area twice as large as before. Since the boulder was relatively large, this increase in space between the beams has no penalizing effect on performance. The usual problem of slope thresholds still

caused obstacle contact.

2) System II (single beam sensor; exact terrain model)

Although this path selection system also always reached the target (see Table IV), contact was always made with the boulder at least once, indicating the same slope threshold problem as associated with System I.

TABLE IV

PERFORMANCE RESULTS FOR SYSTEM II
(single beam sensor; exact terrain model)

Item	Vertical-Fixed Sensor		Vehicle-Fixed Sensor	
	No Noise	Noise	No Noise	Noise
Test Number	7	8	9	10
Selected Path Length (meters)	80.0	80.5	80.0	81.5
Battery Usage Time (seconds)	1.34	1.34	1.34	1.34
Total Travel Time (seconds)	53.33	53.67	53.33	54.33
M	0.96	0.95	0.96	0.95
N	2	1	3	1

Note however, that System II operates much better under noisy conditions than does System I (refer to Table II for comparison), as it compensates for the effects of the disturbed in-path and cross-path slopes. Tests 8 and 10 yielded better results than tests 7 and 9 because, for this particular terrain situation, the vehicle approached the boulders from a different angle, thus allowing easy avoidance of the

obstacle. The angle of approach is different because the terrain modeler, in compensating for the in-path and cross-path slopes when calculating beam headings, provides the path selection algorithm with true beam headings. Thus, the available steering commands are affected by the amount of "noise" present, allowing some directional drifting between sensor scans. The figures of merit penalize this extra path length, but do not account for the fact that boulder contact has been reduced (by luck more than by design) since the normal and emergency path selection algorithms both require no time for execution.

3) System III (double beam sensor; approximate terrain model)

This is the only system where some tests never used the emergency mode, and it is the only system where, in some tests, the vehicle failed to reach its target (see Table V). In terms of obstacle response, the system performed better than did Systems I and/or II. As soon as the two beams struck the boulder, it was identified as an obstacle. This is more desirable than the results obtained earlier, where increases in slopes were measured but the critical thresholds were not surpassed. The vehicle-fixed sensor yields better results than the vertical-fixed sensor because the terrain model is set up to reflect changes in slopes with respect to the vehicle, rather than trying to measure actual slopes.

However, System III proved to be extremely sensitive to the noise, as variations in slope caused unacceptably large variations in the range measurements. In test 14, the large variations in range due to noisy in-path and cross-path slopes oriented the

TABLE V

PERFORMANCE RESULTS for SYSTEM III
(double beam sensor; approximate terrain model)

Item	Vertical-Fixed Sensor		Vehicle-Fixed Sensor	
	No Noise	Noise	No Noise	Noise
Test Number	11	12	13	14
Selected Path Length (meters)	76.5	77.5	76.5	18.0
Battery Usage Time (seconds)	1.34	1.34	1.34	1.34
Total Travel Time (seconds)	51.00	51.67	51.00	12.00
M	0.99	0.98	0.99	failed
N	0	2	0	11

vehicle such that its terrain modeler indicated obstacles surrounded the vehicle after the vehicle had moved about 18 meters towards the target. System III was successful with a vertical-fixed sensor subjected to noise (test 12), but only because the terrain model generated a "go" condition when no range measurement was possible (due to sensor design limitations affecting the greatest measurable distance).

Test 15 (see Table VI) indicated that the system has difficulty negotiating gently sloping terrain. In this test, the boulders were moved slightly so that the vehicle would head for a wedge, or cave, between the two boulders. Since the emergency path selection algorithm only allows clockwise rotation, the vehicle was expected to wander around for a while before it re-oriented itself. However,

TABLE VI

ADDITIONAL PERFORMANCE RESULTS for SYSTEM III
(double beam sensor; approximate terrain model)

Item	Vertical-Fixed Sensor	
	No Noise	No Noise
Test Number	11	15*
Selected Path Length	76.5	123.5
Battery Usage Time (seconds)	1.34	15.68
Total Travel Time (seconds)	51.00	82.34
M	0.99	failed
N	0	9

*In test 15, the obstacle was moved slightly so that the vehicle would make contact at a point resembling a cave.

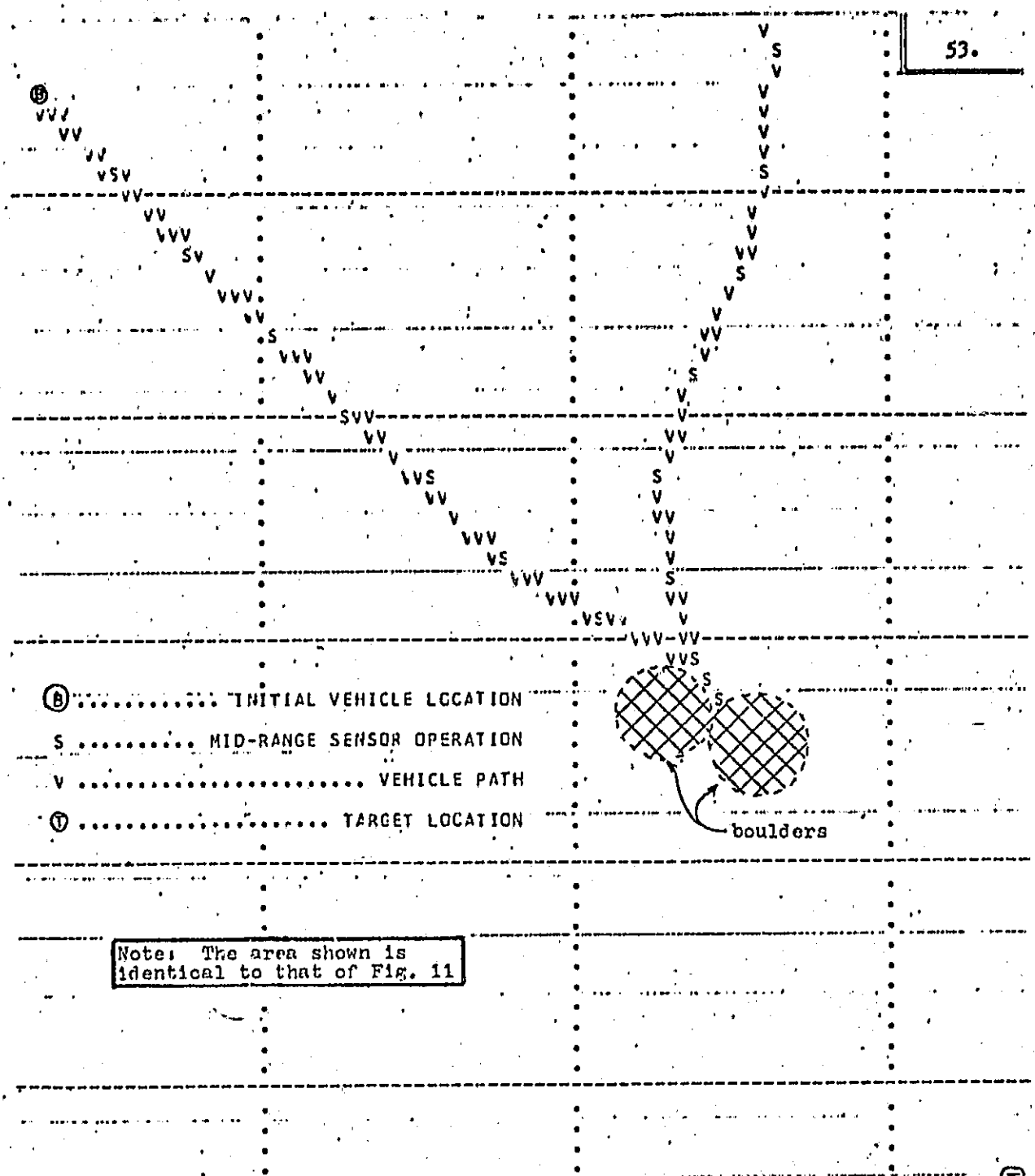
the vehicle became lost (see Figure 13) as the terrain model indicated a solid barrier where only smooth slopes existed. The simulation was terminated when it became evident that the vehicle would take an excessive amount of time to reach the target.

D. Summary

Summarizing the above results, the following statements, many of which are intuitively obvious, can be made:

(i) When using slope type terrain models, the obstacle thresholds should not be as large as the vehicle's maximum traversable slope.

(ii) For slope type terrain models, increased use of the sensor allows better obstacle resolution, but may not be necessary if item (i) is satisfied.



Note: The area shown is identical to that of Fig. 11

PERFORMANCE OF A 'CONFUSED' PATH SELECTION SYSTEM

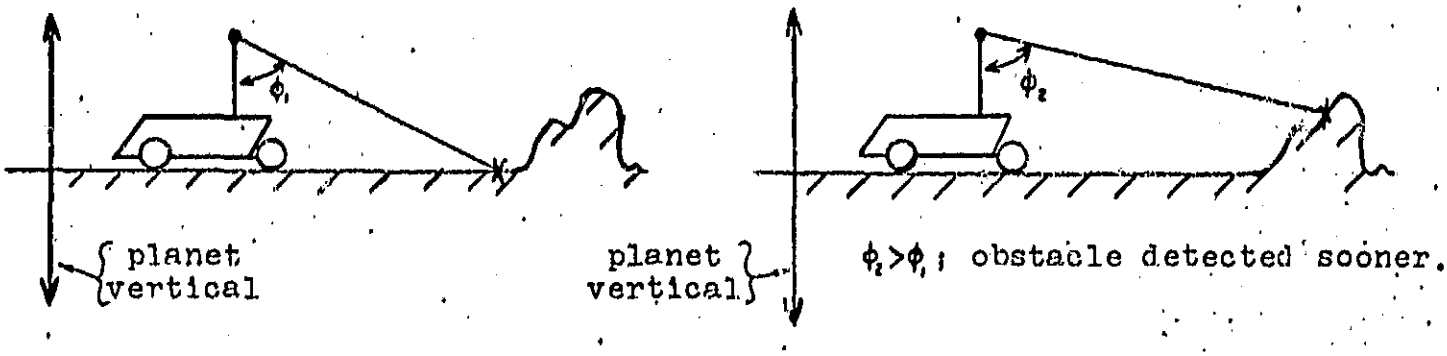
Figure 13

(iii) Increasing the terrain sector scanned by the mid-range sensor allows the steering commands to become more effective when the vehicle is meaneuvering around an obstacle, but then some terrain is overlooked. This increase may not be necessary if item (i) is satisfied.

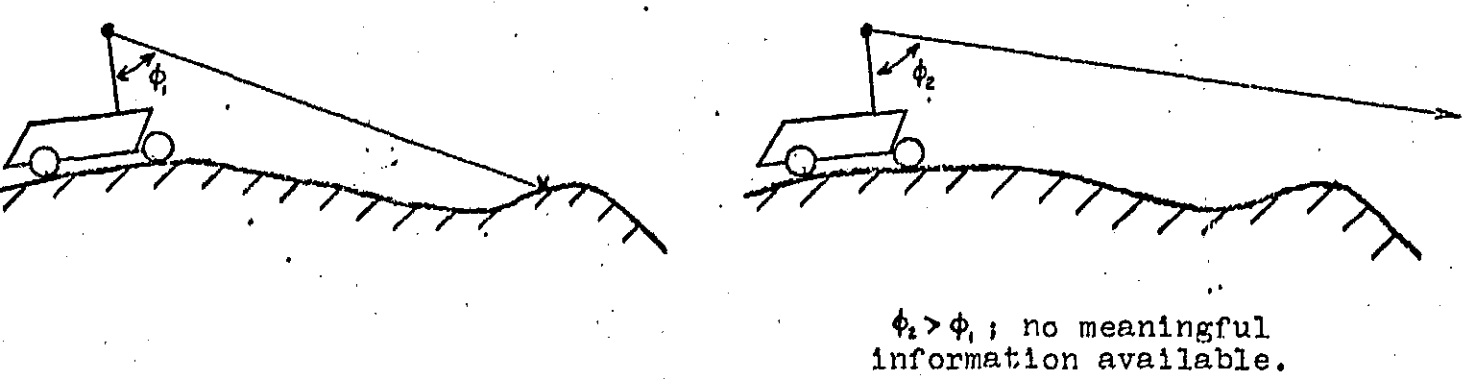
(iv) The slope type terrain model's sensitivity to in-path and cross-path slopes is decreased as the accuracy of the assumptions made in constructing the terrain model is increased.

(v) Increasing the elevation angle of the sensor beam for slope type terrain models improves performance when in-path and cross-path effects are negligible. If these effects are not small, then the performance of the vehicle will be adversely affected. All of these situations are illustrated in Figure 14.

(vi) The differencing method of terrain modeling (as developed in Reference 4), is highly sensitive to in-path and cross-path slopes, and is more effective when used in conjunction with a vehicle-fixed sensor than with a vertical-fixed sensor.



(A) Negligible In-Path and Cross-Path Slopes



(B) Significant In-Path and Cross-Path Slopes

DESIGN CONSIDERATIONS FOR SENSOR BEAM ELEVATION ANGLES

Figure 14

V. CONCLUSIONS

A. Summary of Progress

During the past 15 months, a roving-vehicle path selection evaluation system has been developed. The system can realistically simulate and uniformly evaluate the performance of path selection systems under consideration for a Martian roving vehicle. Work has progressed through the complete specification of the evaluation system's structure, and to various levels of software implementation of the individual structural components.

The terrain characterization block employs polynomial, gaussian, and special feature models to mathematically simulate Martian terrains.

Sensor characteristics and terrain modeling concepts have been investigated. The operation of both vertical-fixed and vehicle-fixed sensors has been simulated. Several terrain modeling and path selection algorithm schemes have been software implemented.

The vehicle dynamics block has been software implemented to fulfill the present simulation requirements. Its capabilities include non-ideal behavior characteristics which add to the realism of the simulation.

The display and evaluation blocks have reached a preliminary stage of development. The terrain characterization display block allows a visual representation of the terrain upon a standard line printer. The selected path of the vehicle may also be displayed separately, and/or be superimposed upon the terrain contour map. The evaluation block provides information useful in comparing and evaluating the relative merits of different path selection systems.

Finally, three path selection systems have been evaluated to

demonstrate the capabilities of the simulation package and to form some preliminary conclusions regarding the tradeoffs involved in designing a path selection system.

B. Conclusions and Future Work

This computer simulation system appears to be the first attempt at establishing a uniform means for path selection system performance evaluation. Preliminary results indicate that the system can successfully simulate and evaluate the performance of path selection systems. Further development is necessary, however, to increase the effectiveness of the simulation, especially in the area of evaluation criteria. The following areas of work are suggested to increase the scope and usefulness of the simulation package:

1) Terrain Characterization

Although considerable flexibility is available when constructing models of Martian terrains, terrain specification is tedious as one must specify each and every terrain feature. If polynomial terrain descriptions are being used, it is difficult to select coefficients to give some desired terrain. To avoid these problems, a polynomial fit to given data points or a regression analysis might be more direct and less time-consuming. Another approach to this problem might involve allowing the simulation program to randomly add boulders, craters, etc., to some base terrain specified by the user. It also might be possible to allow the user to sketch a desired terrain on a cathode ray tube device, and then have the computer generate the appropriate descriptive equations.

As terrain complexity increases, calculation time to obtain

an elevation at a particular point on the surface also increases. Since the altitude acquisition section of the terrain characterization block is used many thousands of times during a typical simulation, speed in calculation is essential. It is suggested that this section of the block be rewritten in ASSEMBLER language to further decrease calculation time.

2) Sensor Simulation

If the accuracy of the range measurement simulation is critically important, then the following situation will introduce undesirable error. If the angle of incidence of the sensor beam with the terrain surface is small, then any point along the one meter segment of the beam that passes through the surface may be within the required vertical difference tolerance specified by the user.* Since the interval halving algorithm starts at a point midway between the two end points of the beam segment that intersects the surface, the simulated range error can be as high as 0.5 meters. Since most practical laser sensors will also give unpredictable results in this situation, this simulation error might be acceptable. If simulation accuracy is essential, however, the simulation scheme might have to be modified to account for this situation.

As demonstrated in the user's guide, errors in approximating the in-path and cross-path slopes adversely affect the true orientation of the mid-range sensor. If this error is judged to be undesirable, the vehicle model used for the sensor simulation block will have to be

* This tolerance was set at 0.01 meters for all simulations in Section IV.

refined.

3) Terrain Modeling and Path Selection Algorithms

To illustrate the capabilities of the simulation package, several simple terrain models and path selection algorithms have been software implemented and analyzed in Section IV. More advanced schemes should now be analyzed. Initial efforts in this area might involve a) implementation of schemes available in the literature, and b) modification of the simple schemes already available.

4) Vehicle Dynamics Simulation

Although the sensor simulators consider the vehicle's dimensions, the vehicle dynamics block treats the vehicle as a point source. For purposes of motion simulation, this assumption is valid. However, since the vehicle has non-zero dimensions, it cannot move through keyholes, so to speak. Improvements in this block should involve detection of obstacles* that would prevent vehicle motion, such as discontinuous terrain slopes.

5) System Evaluation

Most of the discussion in Section IV was based upon analysis of data which was not graphically presented. Factors such as how quickly a path selection system "sees" and responds to an obstacle have been determined by inspection of the changes in the terrain model as the vehicle approaches an obstacle. Also, the figures of merit did not seem to give good correlation between desirable path selection systems and safety of the chosen path. Rather as particularly noted in System II, safer paths were penalized because of

* The block must determine if it is possible to traverse the terrain that the path selection system has chosen. This obstacle detection should not be confused with that of the path selection system, which is subject to error.

their slightly greater lengths. It is imperative that more representative evaluation criteria be formulated. Initial efforts in this area might be a) addition of new indices to account for path safety and speed of vehicle response to obstacles, and b) adjustment of the index weights to provide higher correlation between the figures of merit and desirable path selection systems.

APPENDIX

Table of Contents of User's Guide

SECTION A.....INPUT DATA SETUP AND APPROPRIATE JOB CONTROL CARDS

General Notes
Simulation Setup Card
Terrain Feature Cards
Mid-Range Sensor Cards
Vehicle Dynamics Cards
Noise Cards
Initial Condition Card
Job Control Card Setup for IBM 360/50, using HASP II.

SECTION B.....PATH SELECTION SYSTEM BLOCKS

General Notes
Existing Sensor Simulators
Addition of Other Mid-Range Sensor Simulators
Existing Terrain Models
Addition of Other Terrain Models
Existing Path Selection Algorithms
Addition of Other Path Selection Algorithms

SECTION C.....ADDITION OF RANDOM DISTURBANCES

The Present System
Addition of New Noise-Corruptible Quantities

SECTION D.....CONTROL FLOW

SECTION E.....VEHICLE DYNAMICS BLOCK

Simulation Assumptions
Uphill-Motion Modeling
Downhill-Motion Modeling

SECTION F.....TERRAIN CHARACTERIZATION METHODS

SECTION G.....INTERMEDIATE OUTPUT AND AVAILABLE MAPS

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