2

196000-6-T

COMPUTER SIMULATION OF ANIMAL NAVIGATION

Annual Technical Report to
University of Wisconsin
Period: July 1986 - August 1987
Contract No. 208G-762

Kristina Van Voorhis
Dr. Robert F. Franklin

July 1988

Research Sponsored by:

The University of Wisconsin and the
Defense Advanced Research Projects Agency
DARPA Order No. ARPA-5575
Through Contract with US Department of Army
DAAE07-86-C-R013

Table of Contents

1 INTRODUCTION 1
2 RESEARCH CONDUCTED 2
  2.1 MODELING FOOTHOLD SELECTION 2
    2.1.1 Foothold Selection in a Natural System 2
    2.1.2 Computer Simulation of Foothold Selection 3
  2.2 TERRAIN MODULE DEVELOPMENT 7
  2.3 GRAPHICS DEVELOPMENT 7
3 SUMMARY 8
4 FUTURE WORK 10

List of Figures

igure 1. Cattle Guard Configuration of Experimental Rough Terrain Runway 11

Figure 2. Constraining Search Space for Potential Footholds 12

Figure 3. *Blackboard Planning System* 13

Preface

The work described in this report represents our effort to integrate the areas of mobility research and autonomous navigation in support of the Adaptive Suspension Vehicle (ASV). This undertaking was made possible through Subcontract with the University of Wisconsin. The University of Wisconsin mission to provide research on autonomous land traversing capabilities for the ASV has been supported by the Defense Advanced Research Projects Agency (DARPA) through contract with the Department of the Army[1]. The findings and conclusions presented in this report do not necessarily represent the views of the above agencies.

---

[1] Reference: DARPA Order No. ARPA-5575 and Department of the Army Contract No. DAAE07-86-C-R013.

1 INTRODUCTION

The robotics research community is striving to endow a wide variety of vehicles with the capability of autonomous mobility. Related research is being undertaken in two intrinsically different test vehicles. The ASV (Adaptive Suspension Vehicle), which uses legs as a means of propulsion, is being utilized to address problems of mobility. Mobility research is concerned with the problem of traveling over terrains of high spatial complexity. Machine autonomy can be defined as the ability of a machine to perform tasks in an arbitrarily complex and dynamic environment without external assistance during operation. Autonomy is a subject of research in the wheeled ALV (Autonomous Land Vehicle) program. By endowing the ASV with a decision system for autonomous navigation over rough terrain, both efforts can be concentrated in one test-bed. In support of the University of Wisconsin's research to provide the ASV with an autonomous land traversing capability, ERIM has undertaken a corollary effort to develop concepts for machine mobility which can be implemented in that project.

The goal of the research program described in this report is to further the understanding of autonomous performance on rough terrain through the investigation of the following areas:

- How does a legged animal select a foothold from among a suite of potential footholds? What sources of information, both internal to the animal (system) and sensed from the environment, are relevant to this problem?
- How does a system (natural or machine) blaze a trail through rough terrain? What constitutes a necessary and sufficient affordance in the environment to be considered a trail and what information is retained by the system to make future use of the trail?
- Given that aspects of a trail are learned, how are they used to renegotiate a trail when the system is facing it for the second (or Nth) time?

Three specific tasks were undertaken during this first year for the purpose of beginning an investigation of the above questions through animal experiments and computer simulation:

- Performing experiments with Nubian goats, maintained at ERIM facilities, to determine their strategies for foothold selection.
- Development of a terrain module to simulate a complex and dynamic environment with both tactile and visual properties.
- Development of a graphics display module to provide views of the simulated terrain and a vehicle.

2 RESEARCH CONDUCTED

2.1 MODELING FOOTHOLD SELECTION

Research on foothold selection during terrain traversal was conducted using two approaches. Experiments were undertaken with Nubian goats on simulated rough terrain in order to explore the ways in which natural systems select footholds during terrain traversal. A computer simulation of rough terrain traversal was developed in parallel with the animal studies. Pertinent results from the animal experiments were integrated into the computer simulation.

2.1.1 Foothold Selection in a Natural System

Previous work performed by ERIM in support of the ASV[2] involved studying the locomotion of Nubian goats, as a model species, in confined, experimental situations. These studies showed that analysis of kinematics alone was not sufficient to account for the ways in which quadrupeds use their limbs for crossing rough terrain. The research indicated that the emphasis in experiments needed to be placed on the logical level of control as opposed to simply examining the gaits employed by animals. The preliminary model of information processing mechanisms used by goats in solving terrain problems which resulted[3] served as a basis for developing experiments specifically designed to address foothold selection strategies in Nubian goats.

An experimental protocol was established for exploring the means by which Nubian goats determine the physical characteristics of individual footholds. Results of these experiments were seen to be crucial for understanding movements made and forces applied by a system while evaluating the viability of particular segments of terrain. The basic experimental terrain structure used in our studies of goat locomotion was a runway composed of wooden blocks. The blocks could be arranged into a variety of configurations, for instance a long, narrow path or a cattle guard pattern (Figure 1). Though the configuration of the terrain was changeable, each block was stationary during experimentation. Goat traversal of the terrain was videotaped for subsequent computer analysis.

A variant of this terrain structure was created for the purpose of investigating the role of terrain compliance in the selection of footholds. A prototype, spring-loaded "soft" block was constructed and tested. This new type of block was visually identical to the other stationary terrain blocks but would compress when a force was applied to its surface. This compliance characteristic was added to the terrain by building several "soft" blocks, according to the design of the prototype. These compliant blocks were placed into one of the basic rough terrain patterns, specifically a long narrow path configuration.

---

[2] This research was performed under DARPA Contract No. DAAE01-84-K-R001 through subcontract with Ohio State University (contract number RF452622).

[3] R. F. Franklin. 1986. Summary of Quadruped Locomotion Research - First Year. Environmental Research Institute of Michigan. Report to Ohio State University on Contract Number RF452622.

Since the compliant blocks were indistinguishable from the stationary blocks when viewed from above, the animals could not predict the degree of compliance visually. They were forced to test each foothold individually, using tactile measures, to determine its support characteristics. Preliminary results show that unacceptable footholds based on compliance characteristics were avoided by the goats on subsequent runs across the terrain. It is proposed that the goats memorize the locations of the unsuitable terrain blocks. In addition, distinct changes were seen in the gaits used by goats before and after encountering the compliant terrain. Results obtained from these experiments were integrated into a computer simulation decision system for selecting footholds.

2.1.2 Computer Simulation of Foothold Selection

Legged Vehicle Simulation. To further address the issue of foothold selection in legged systems, a computer model of the processing required to find footholds was developed. It was built on the following sub-systems: a vehicle/sensor simulation, a terrain evaluation system, and an existing planning system[4].

A simulation of a legged vehicle operating in a complex environment was implemented on a Symbolics computer in Zetalisp. The system comprised two layers of control: utility level and trafficability level. The utility level provides planning on a global scale, while the trafficability level planning is performed on a local scale. The complex terrain environment was represented by a fractal array, in which each element value represents elevation.

The utility level of the simulation was built upon an autonomous navigation simulation shell originally developed under contract for the ALV[5]. In this layer, the sum total of the vehicle's knowledge of its terrain environment is converted into a set of utility indices. The utility index of a piece of terrain is a measure of the "desirability" of that piece of terrain, in the context of the vehicle's current mission. Utility is a mission- or task-dependent interpretation of terrain features and is represented as a cost map derived from the elevation fractal. If a mission goal were identified by some higher level mission planner, this sub-system would be able to chart a route to that goal using what knowledge it had of the terrain. The system assumes that some means will be available to interpret the terrain information to yield the utility index taking into consideration factors such as vehicle capabilities, urgency of the mission, and the need for concealment.

In the utility level, the vehicle represents its terrain environment, centered about itself, in a hierarchical stack of maps. At the top-most level of this stack, the information is the coarsest. Each subsequent map in this stack is a higher resolution representation of the center of its predecessor in the stack. All maps in the stack have the same number of elements. The terrain dimension represented by an element changes from map to map. The highest resolution map, hence, also encompasses the smallest area in real space. As the vehicle navigates through the terrain, the highest resolution map is updated with sensor information. New information is propagated through the stack by way of data compression and a procedure of "spatial scrolling". Spatial scrolling is the process of maintaining egocentricity of the vehicle throughout the stack of maps. Using this paradigm of data representation, a route is obtained from the vehicle's

---

[4] "A decision system for autonomous robot navigation over rough terrain", Quek, F.K.H., Franklin, R., Pont, W.F., September 1985. Proc. SPIE Conf. on Intelligent Robots and Computer Vision, V. 579 #59-50, pp. 377-388. Boston.

[5] This research was performed under DARPA contract number DACA76-4-C-0005 through subcontract with Martin Marietta (contract number GH4-116861).

current location to an intended goal by the operation of a routing engine. The routing engine makes use of wave propagation and trace-back mechanisms to identify a maximal utility route.

The trafficability layer, as currently implemented, operates primarily with elevation information. At this level of planning the vehicle determines what terrain to traverse based on the utility route and through the foothold selection process. A multimodal approach to successive foothold candidate generation and elimination was implemented. This strategy was based upon our experimental studies of foothold selection by Nubian goats. The three levels to this approach which have been implemented and which are illustrated in Figure 2 are:

- candidate elimination/selection by reachability constraints
- candidate elimination/selection by visual sensing
- candidate elimination/selection by tentative footing.

From the operating domain of all possible terrain, only a subset needs to be considered for the purpose of finding immediate footholds. All terrain beyond that which intersects the volumetric envelope reachable by the limb for which a foothold is required can be excluded from subsequent processing. This strategy efficiently marshals the resources available to a system by permitting a succession of coarse to fine processes to be performed on progressively decreasing quantities of data. Such an approach to foothold selection therefore addresses the real time problem.

Once the terrain reachable by the limb under consideration has been identified, another level of processing of the remotely sensed data may be used to further prune the amount of terrain to be evaluated. In such processing, the texture, slope and other aspects of the terrain available from non-contact sensing come into play. The resolution at which the terrain needs to be examined for visual and tactile evaluation has to be higher than that at which reachability is computed. In the simulation, higher resolution data were obtained by "fractal-expansion", a process of growing a fractal within the original fractal. The region thus expanded is deterministically derived from the existing terrain so as to maintain continuity at region boundaries. Since the simulation addresses the logical control and not the terrain interpretation problem, an arbitrary process was assigned to determine if the terrain was acceptable by visual sensing. Currently, the terrain is checked for smoothness.

After the candidate terrain for footholds has been pruned by the visual sensing process, the remaining terrain is ranked in terms of "desirability". The desirability of a terrain location as a foothold is a measure of the degree to which it affords traversal of the vehicle in the planned direction of travel. The most desirable of these is then tested for compliance in a tentative footing mode.

The use of terrain compliance as a test in the foothold selection process is supported by the experiments in which the goats traversed terrain containing "soft blocks". Since these blocks have an appearance identical to other blocks in the terrain, differing only in their compliance from the others, the animals tested each foothold individually to determine its support characteristics.

In the simulation, it is assumed that compliance is a property that is independent from the visual properties of the terrain. As for the visual test, the compliance test is simulated by an arbitrary process on the original fractal. In this case the terrain is checked for spikes. If the foothold is acceptable according to the compliance test, it will be taken. If not. the next most desirable foothold is tested. The testing of foothold candidates is repeated until a foothold is found or all the candidates have been exhausted.

To support the trafficability control scheme, a high resolution, short range map was included in the simulation. Such short term, highly detailed spatial memory exists in humans. Furthermore, it was determined in the experiments with goats that they can operate in a mode in which they are unable to see their feet. Thus, the terrain immediately in front of them has to be memorized to a resolution necessary for foothold selection. In the simulation, data which scroll off this high resolution map are lost.

In order to incorporate real data into the simulation, a map of actual terrain replaced the fractal terrain. A US Army Engineering Topographic Laboratory (ETL) map of the Denver-Martin/Marietta site was integrated at both the utility and trafficability levels. After running the simulation with the different maps, it became evident that the fractal terrain was the more difficult one for the vehicle to traverse.

Distributed Architectures. As a first step towards distributing the simulation across multiple machines, a single component of the simulation was selected that is highly suitable for a general purpose computer when written in a language like "C". The sensor model was selected for two reasons. First, a more extensive and realistic model already existed that was written in C for a VAX/VMS system. This model is a ray trace program that simulates the ERIM 3D range sensor. For the project reported on here, a version of the program was written to run on an IBM PC-AT. Second, this model provided the system with the interesting and very real problem of occlusion in sensor views. That is, obstacles obstruct the view of what is behind them. Software communications tools were written which utilized *TCP/IP* to invoke this sensor simulation from a Symbolics.

Since the PC-AT was not powerful enough to handle the amount of sensing required by the simulation on the Symbolics, a version of the sensor simulation was written in C for a SUN computer. The graphics display in the simulation includes a portion of the map to be scanned, plan view (X-Y plane) of the scanned region, and an angle-angle-range image of the scanned region. A color look-up-table (LUT) was written for effective display of the above elements. Network communications tools similar to those above were written for a SUN and integrated with the 3-D simulation on the SUN in order to invoke it from a Symbolics computer.

Currently, data transfer between the Symbolics and SUN is not fast enough for effective use of the distributed sensor simulation in either the legged vehicle simulation or the blackboard planning system described below. It will be necessary to test the hardware and software extensively in order to determine the source of poor network performance.

Blackboard Planning System. The legged vehicle simulation described above operates in a rigid sense-plan-act cycle. In order to make the simulation more versatile and sensitive to changes in processing requirements and the order of processing, we determined that implementing the legged vehicle simulation in a blackboard architecture (BBA) would prove useful. As a first step, we began to develop a planning system in such an architecture, with a simple sliding vehicle model. The modularity of the system permits the substitution of a legged vehicle model with few modifications.

The following is a brief description of a blackboard architecture. A BBA has three components: 1) knowledge sources 2) blackboard 3) control structure.[6] Knowledge sources (KSs) are independent programs which generate, combine, and evaluate possible solution elements (hypotheses) to the given problem; each has a condition-action format. The blackboard is a structured, global database that records hypotheses generated by KSs. Blackboard and KS interactions are regulated by a control structure that cycles through the following three steps: 1)

---

[6] Franklin, R. and Finsel, N. November 1986. Advanced Concepts for Autonomous Vehicle Planning. ERIM. Draft.

Compare KS conditions against data on blackboard. 2) Mark KSs whose conditions are satisfied and choose one of these KSs to invoke. 3) Invoke the KS to generate or modify data on the blackboard.

The 2-level planning system has been implemented in two blackboards and distributed across a Symbolics 3640 and 3670. The two levels are utility (global, mission-based planning) and trafficability (local planning) which considers terrain and vehicle characteristics in the selection of a path. The diagram in Figure 3 is an overview of this blackboard planning system. As in the original system, the utility level of planning involves two major tasks: mission-based route generation and cost-map maintenance.

A group of knowledge sources has been developed for each of these tasks. The trafficability level consists of the following tasks, each of which is performed by a set of knowledge sources: terrain evaluation, local memory maintenance, path planning, and path to motion conversion.

In the original simulation, the only interaction between the two planning levels was via routes generated at the utility level and transferred to the trafficability level. There was no means of recovery if no footholds were found in the trafficability layer. Since no mechanism was implemented to update the utility level maps with foothold data, the utility level planner was unable to generate paths different from those that failed (it remained the best according to the data available at the utility level). In the new system, we have closed the loop by transforming and transferring local terrain information having navigational value at the trafficability level to cost information at the utility level.

Other components of the system which were not part of the BBA were a vehicle model and a sensor model. Both of these models as well as the blackboard supporting the tasks of maintaining elevation data in local memory and early stages of terrain evaluation (sensor view processing) were implemented on the Symbolics 3670. The Symbolics 3640 supported the blackboard that manages tasks at the utility level of planning, final stages of terrain evaluation, maintenance of navigational information in local memory, path planning, path to motion conversion, as well as data transfer between the trafficability and utility levels of planning.

Communication services were developed using TCP/IP to transfer data between the two machines in support of this distributed system. Two of these services transfer processed sensor images from the Symbolics 3670 to the Symbolics 3640. Another service transfered motion commands back to the Symbolics 3670 that supported the vehicle model.

In the original legged vehicle simulation, high resolution terrain data were generated when required by the vehicle's path planning module. Excessive time was required to perform this process and therefore we have developed a more time- and space-efficient method to maintain high resolution terrain data in the blackboard planning system. Two pre-generated terrain maps, consisting of the underlying topology and high frequency surface characteristics, are maintained on the Symbolics 3670. At the time of scanning, data from these two maps are combined in the region covered by the sensor view to form 16-bit elevation data. These data are evaluated according to slope and roughness and the resulting 4-bit data are sent to the second Symbolics using TCP/IP. Although retrieval time of high resolution data is influenced by network performance, it is less than the execution time of the method currently implemented in the legged vehicle simulation, that of frequent terrain generation.

The blackboard planning system described above is currently unfinished. Concurrency and complexity in this system became a very real problem, as evidenced by knowledge sources causing undesirable and excessive activity of other knowledge sources. In order to remedy this problem in the blackboard supporting the utility level of control, a new flag structure was built; the state of one or more flags may be used to determine whether or not a knowledge source may be invoked. Also, a subset of the relevant knowledge sources was rewritten to comply with this new structure. Similar changes must also be made in the blackboard supporting sensor view processing. An incident that will still be able to occur after the above changes are implemented is that of two or more knowledge sources trying to alter the same flag at the same time. The results of such actions cannot be predicted and yet they must be avoided. In order to produce a completely reliable system, a robust protocol for dealing with problems of concurrency must be developed. Appropriate changes must then be made to the system in order to realize this protocol in the blackboard planning system.

2.2 TERRAIN MODULE DEVELOPMENT

In support of the computer simulations described above, two programs were developed to generate simulated terrain. The first program generates fractal terrains using a randomized mid-point migration strategy. An attempt was made to write this program in C on a PC-AT. It was decided that the PC-AT was too slow and the addressable memory too limited for the purpose and an improved version was written to run on the Symbolics. This version of the fractal generation program was completed and used to generate synthetic terrains for the simulations described in the previous sections.

The second program is a terrain editor which gives an experimenter the ability to create complex, synthetic terrains having relief and elevation characteristics. The program has an interactive interpreter front-end. The body of the editor is a set of subroutines which facilitate the addition of terrain features (e.g. roads, landmarks, barriers such as rivers etc.). The terrain editor was built with expansion and the capability of adding new terrain objects in mind. In order for others to make use of the terrain editor software effectively, extensive documentation was written for this system. A draft of this document has been completed which includes the level of detail necessary for others to expand the system.

2.3 GRAPHICS DEVELOPMENT

ERIM began to develop the graphics module for the computer simulation of a legged vehicle, in order to provide perspective views of the terrain and the vehicle. However, in working with the University of Wisconsin, it became evident that software had already been developed to provide views of the vehicle. Therefore, ERIM's work concentrated on perspective views of the terrain alone.

It was decided that the graphics module would be written for a PC-AT. The resolution required for adequate representation was studied and it was decided that the EGA (Extended Graphics Adaptor) then on the PC-AT was not suitable. The PGA (Professional Graphics Adaptor), a vector graphics board, was chosen and installed in the PC-AT. Software was written which uses this board to display the terrain generated, both as pixel-wise scatter plots and facet displays.

As part of the new high resolution terrain maintenance routines implemented on a Symbolics for the blackboard planning system, we developed two other displays. One consists of the world map of low resolution elevation data. The other is a display of the high resolution elevation information in the vehicle's local memory, obtained through sensing.

3 SUMMARY

Research on foothold selection during terrain traversal was conducted through studies of natural systems and computer simulation. Experiments were performed with Nubian goats on simulated rough terrain in order to explore the ways in which natural systems select footholds. A computer simulation of rough terrain traversal was developed in parallel with the animal studies. Pertinent results from the animal experiments were integrated into the computer simulation. A terrain module was developed for building complex, simulated terrains. Graphics display capabilities were also built to provide views of the generated terrain.

During the course of this research, results were periodically passed from ERIM to the University of Wisconsin. The transfer of information was both through presentations to University of Wisconsin and DARPA personnel and in the form of computer code and documentation. A list of the major items delivered to the University of Wisconsin follows:

- **Routing engine source code and fractal world on Symbolics carry tape.**

  This code was provided to the University of Wisconsin early in the project for use during their development of a routing engine[7]. A routing engine is a software tool used to generate a path between two given terrain points from a utility representation of the terrain.

- **Legged vehicle / foothold selection computer simulation source code provided on Symbolics carry tape.**

  This is the primary simulation of the project which illustrates a planning/decision system for the selection of footholds in complex terrain. Updates of this code were provided periodically as advances were made in the simulation.

- **Sensor simulation for PC-AT with EGA, including associated graphics display code and instructions for use.**

  This sensor model written in C for an PC-AT. It is a ray trace program that simulates the ERIM 3D range sensor. This model provides a system with the problem of occlusion in sensor views.

- **Terrain editor, including source for PC-AT and a user's manual.**

  The terrain editor facilitates the generation of simulated, complex terrain having relief and elevation characteristics.

---

[7] This routing engine was developed under DARPA contract number DACA76-4-C-0005 through subcontract with Martin Marietta (contract number GH4-116861).

Videotape summary of Nubian goat studies.

This summary was produced as the final report for quadruped studies done under contract with Ohio State University[8]. The videotape includes segments showing the experiments with compliant blocks done under contract with the University of Wisconsin as described in this technical report.

---

[8] This research was performed under DARPA contract number DAAE01-84-K-R001 through subcontract with Ohio State University (contract number RF452622).

4 FUTURE WORK

A Letter Proposal submitted to the University of Wisconsin in April 1988 addressing the continuation of funding for the work described in this report included the following tasks in a Statement of Work:

1. This Annual Report was to be completed describing the research effort which has taken place to date.
2. Further technical efforts are expected to use existing simulation environments to examine measures of everall terrain roughness as input to vehicle controllers. The nature of this task will be refined through discussion with University of Wisconsin technical personnel so as to best coordinate our efforts.
3. A Final Report covering the entire duration of the program will be prepared in a format meeting University of Wisconsin and DARPA requirements.
4. The possibility of collaboration on a technical publication with University of Wisconsin personnel is being investigated.

The emphasis to be placed on each of the above tasks is being determined through additional discussion with University of Wisconsin technical personnel. At present the goal is to put major emphasis on the development of technical publications and to limit additional simulation work to the refinement of demonstration materials.

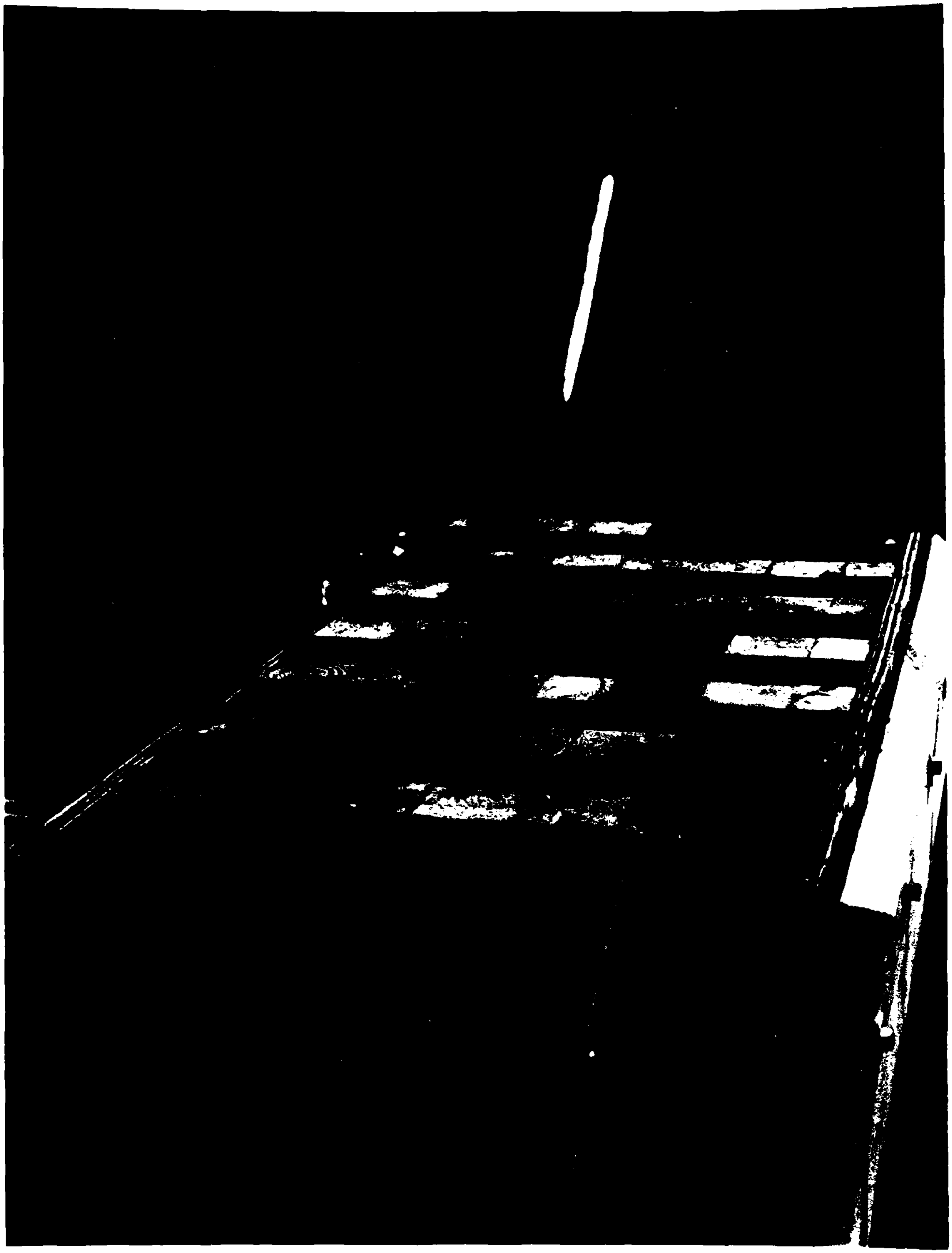
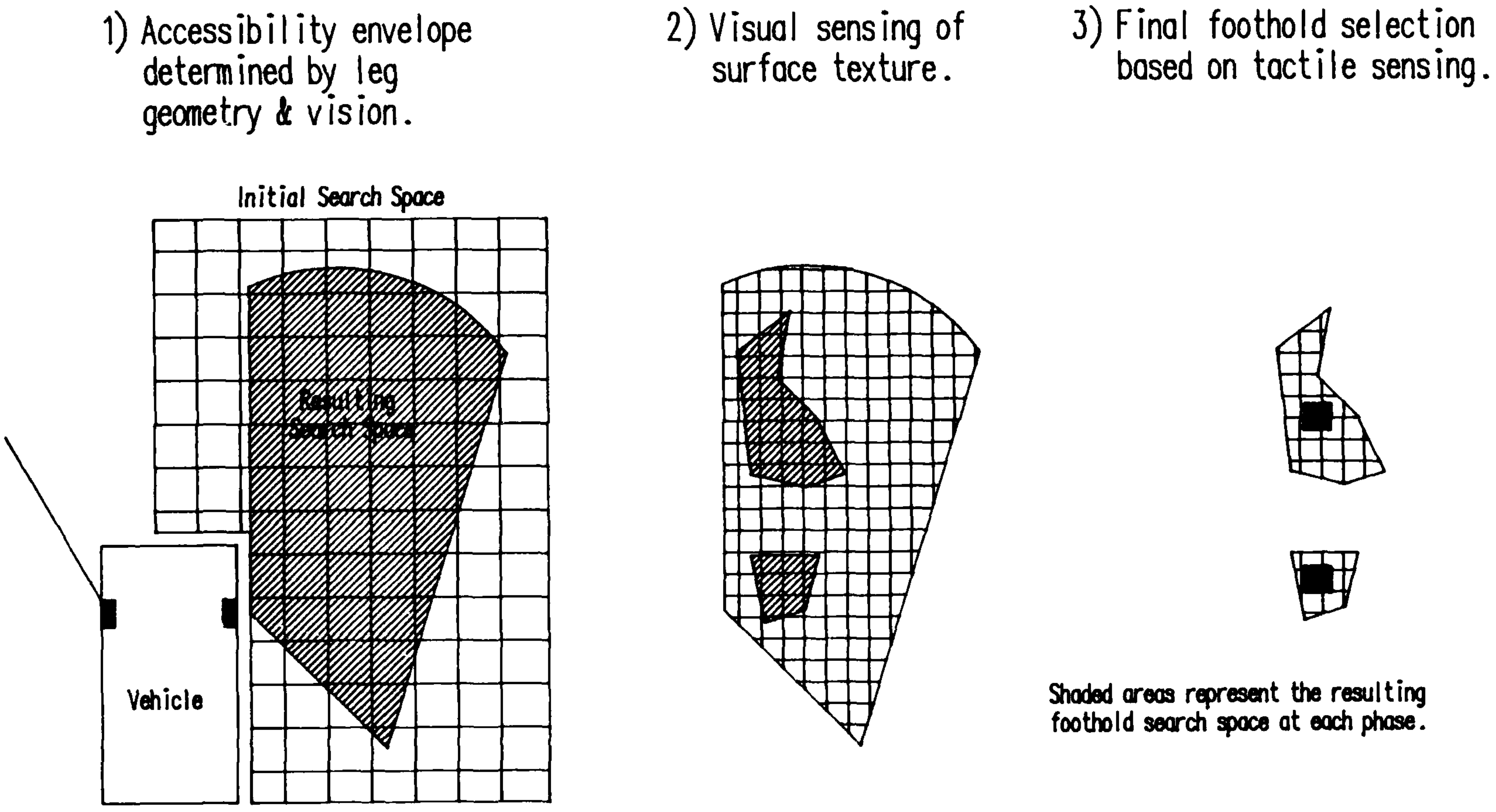


Figure 1. Cattle Guard Configuration of Experimental Rough Terrain Runway



1) Accessibility envelope determined by leg geometry & vision.

2) Visual sensing of surface texture.

3) Final foothold selection based on tactile sensing.

Shaded areas represent the resulting foothold search space at each phase.

Constraining Search Space for Potential Footholds

Figure 2

BLACKBOARD PLANNING SYSTEM

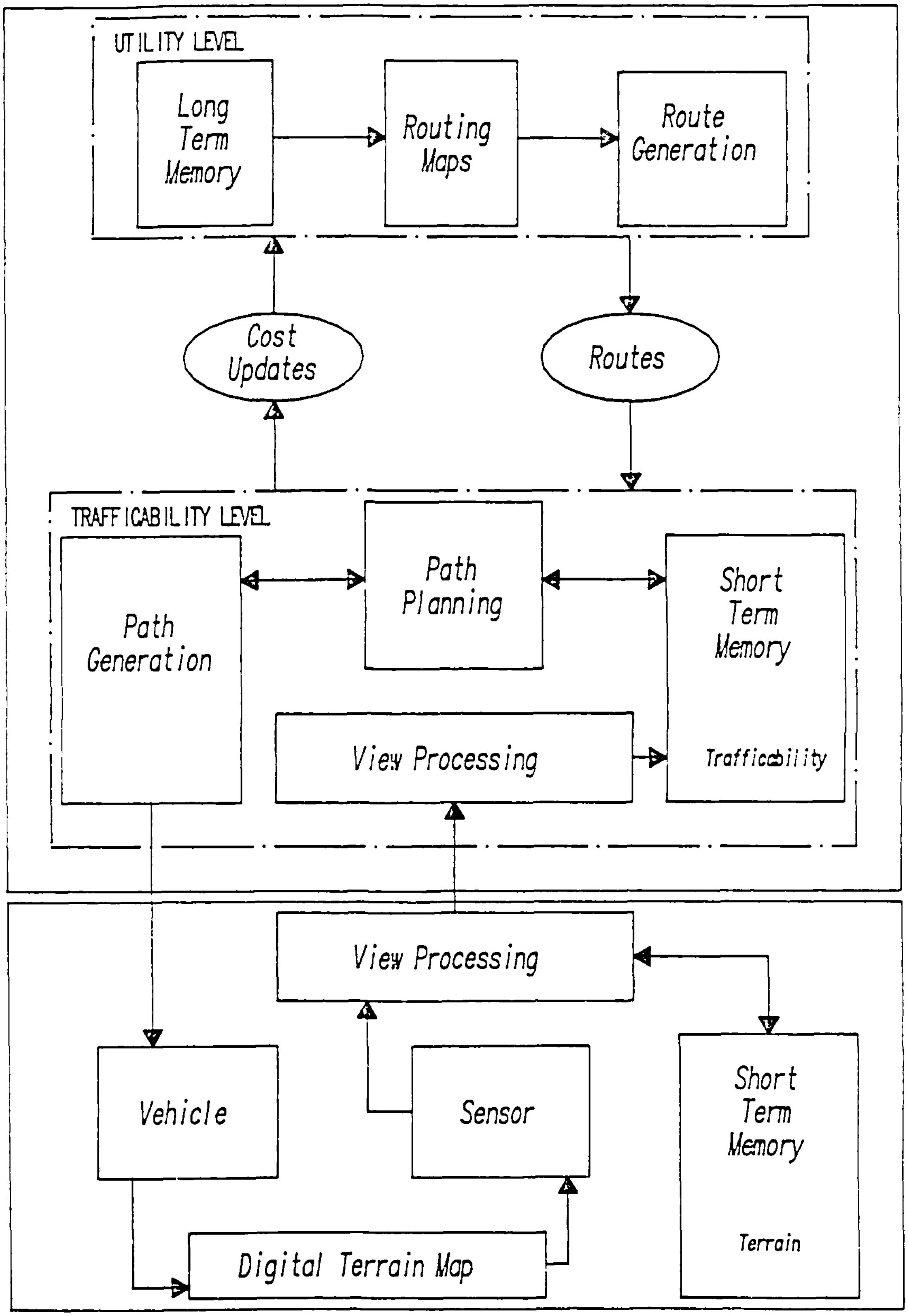
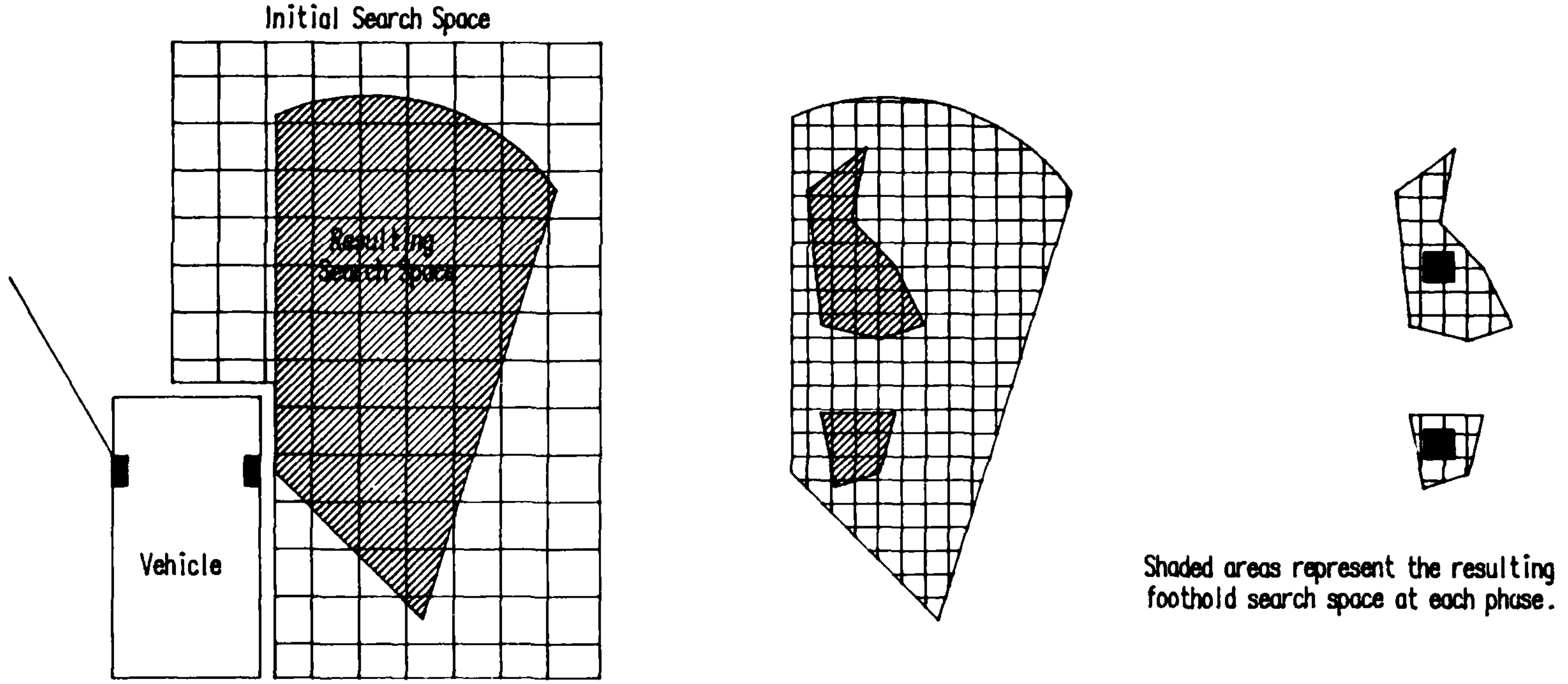


Figure 3

1) Accessibility envelope determined by leg geometry & vision.

2) Visual sensing of surface texture.

3) Final foothold selection based on tactile sensing.



Shaded areas represent the resulting foothold search space at each phase.

Constraining Search Space for Potential Footholds

Figure 2

BLACKBOARD PLANNING SYSTEM

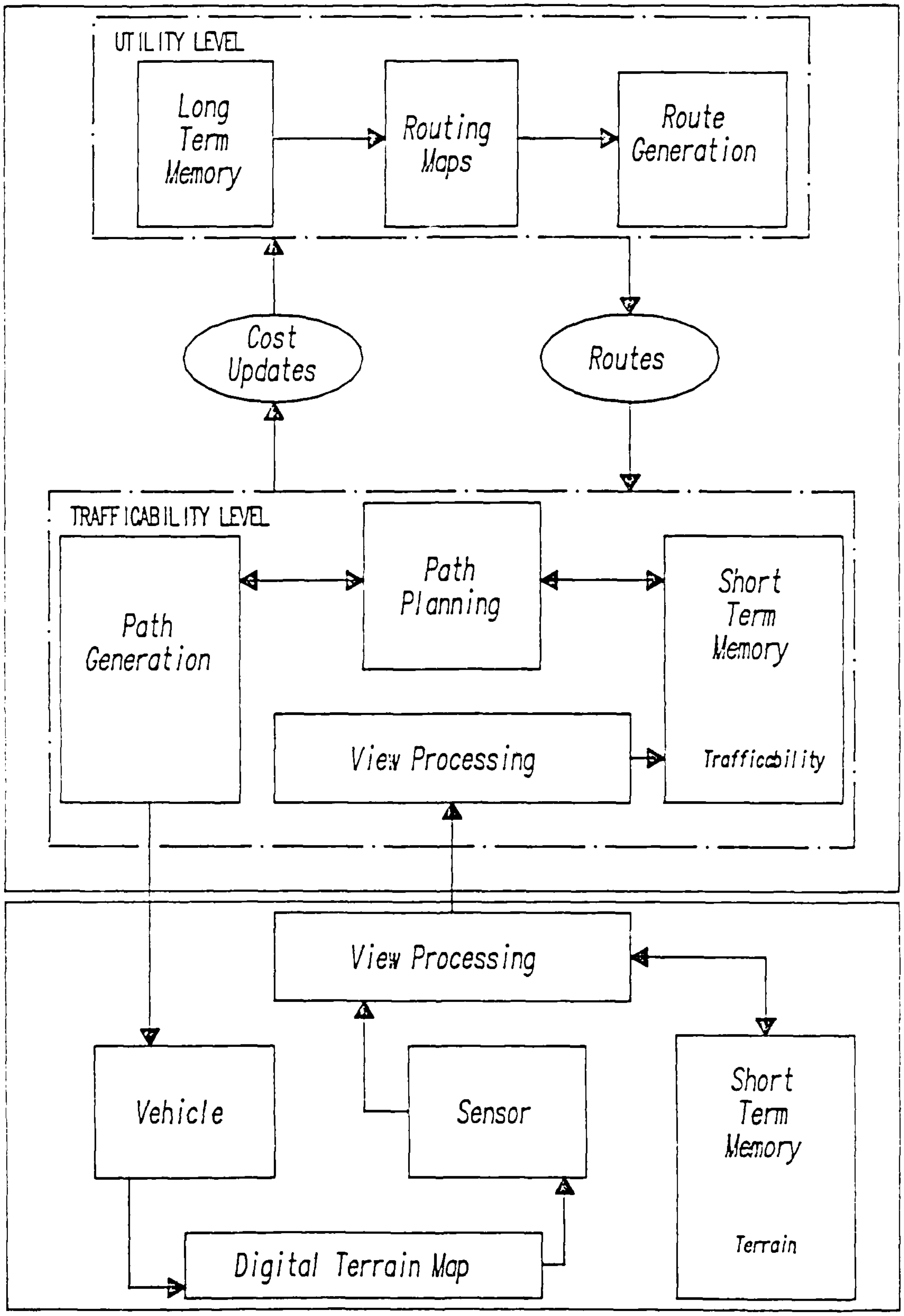


Figure 3