"MINE MAPPING BY A ROBOT WITH ACOUSTIC SENSORS"

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Introduction

The Civil Engineering and Construction Robotics Laboratory at Carnegie-Mellon University (C-MU) proposed the "Demonstration of Robotic Mapping of Mine Spaces" to USBM in August 1984. A physical demonstration was performed in the Bruceton mine on 29 March 1985. This paper contains the following sections:

- Outline of major components of the robot system
- Functional description of model software
- Experimental statement and report of results
- Conclusions and recommendations.

Prior work in CECRL and in the Robotics Institute (RI) provided the basis for the demonstration. In CECRL Whittaker had developed the TERREGATOR, a testbed for autonomous vehicle motion capable of performing in a mine environment. In RI Crowley had developed a system for assembling a local composite model (a plan map) of spaces from sensor data, along with capabilities for position correction and navigation. The demonstration essentially was a robot system achieved by marrying those existing capabilities.

The problem was to demonstrate plan mapping of a mine space using sonar sensors, a mobile robot base, and artificial-intelligence software to assemble the map. The objectives of the system include:

- A mapping accurate and reliable enough for practical use.
- An intelligent interpretation system which would correct for errors, account for transient conditions, and so on.

- A system with the capabilities for fully autonomous (hands-off) system operations.

- A system with the additional functions of navigation within the mapped space.

These objectives were all met in the system which was assembled, although the demonstration was not extensive enough to demonstrate each and every feature.

Overview of Robotic System

Figure 1 pictures the three main components of the robotic system, titled as follows: 1) Sonar Ring 2) RI software 3) TERREGATOR

Each major component is discussed in turn, especially in its suitability to the mine-mapping demonstration.

Sonar Ring: The "sonar ring" assembly is a product developed by Denning Mobile Robots, Inc. Figure 2 shows it composed of a set of 24 sonar sensors, a power supply, and a Z-80 based microprocessor with driving software, communicating to the RI software via an RS-232 link. As used in this demonstration, upon sequential command it triggers each sonar unit, reporting a string of 24 distance readings in feet. The nominal accuracy of each sensor as used is 0.1 foot, and a single sweep under this configuration takes roughly five seconds. This sensor assembly was used essentially as supplied. The only attention directed at it by CECRL was in ruggedizing of connectors.

The sensing technology processes the time for receipt of a reflected sonar signal, and is effective to a range of some 30 feet. It is well-suited to mine mapping for these reasons:

1. Features (walls) are typically spaced within the operating radius of the sensors.

2. Walls act as reliable reflectors of signals, and do not introduce ghost images or virtual images which may be created by other materials such as glass or polished metal.

RI Software: This title is used for the Robotics Institute software written by J. Crowley and his staff, which performs the mapping and navigation. One portion of the software is written in PASCAL and was run on a PERQ microcomputer with internal hard disk. (Comparable software can be downloaded and run from a microprocessor board; while this was not undertaken for this USBM demonstration, it has been performed in other Robotics Institute demonstrations.) The PERQ software totals some 50 modules occupying some 2 Mb of memory. Another portion of the software, originally developed by T. Wood, has the function of local navigation : interfacing with the robot movement commands. That local navigation software is a C-language program downloaded and residing on the robot itself. In this case the local navigation program was customized for the TERREGATOR, and was written by Wood and K. Lee.

The RI software is at the center of all system operations. Specifically:

- The user enters instructions into and is reported results from the PERQ running the RI software.
- The sonar ring reports its distance readings only to the RI software.
- The TERREGATOR receives its commands only from (and reports its actions only to) the RI software.

The system provides for mapping, which is the acquisition and intepretation of sonar data, building and maintaining of the composite local model, and navigation, which is path planning and execution. The basic functions in mapping can be partly summarized as:

- Extracting from sonar ring data the location and extent of flat wall segments.
- The composite identification of a space from multiple measurements.
- The identification of corners.
- The correction of position error.
- The correction of spurious readings.
- The overall assembly of a map.

The basic functions in navigation can be partly summarized as:

- Checking for a freepath before any move is executed.
- Maintaining or generating a network of positions, defined within the map created by the local composite model.
- Planning and executing moves on that network.
- Correction for positioning errors.

- Avoidance of collisions.

TERREGATOR: The TERREGATOR is an autonomous mobile base designed to interact with experimental navigation systems (as it did in its marriage to the RI software) while presenting motion capabilities appropriate for testing in actual mine or construction site environments. It is a six wheel skid steered vehicle, powered by two separate 1.5 hp DC motors, one for each side. Each motor is controlled by a GALIL board sensing an encoder mounted on the motor shaft. The two GALIL boards are independent. They are commanded by an OMNIBYTE microprocessor board (M68000-based) which contains the software representing the TERREGATOR command set.

The OMNIBYTE commonly maintains downloaded C-language programs to provide a set of commands, which in this demonstration are issued by the RI software. In this demonstration a portion of the RI software, the local navigator, was developed for and also resident on the TERREGATOR OMNIBYTE board. The simplest TERREGATOR commands are exemplified as MOVE (n) and TURN (n), as follows:

> MOVE (n) - The argument n is the distance in millimeters for the TERREGATOR to move. The OMNIBYTE program converts n to the corresponding number of encoder counts, and issues the appropriate commands to the left and right GALIL boards.
>
> TURN (n) - The argument n is the angle in degrees for the TERREGATOR to turn. The turn is servo-ed to an onboard gyro which is read within a program loop.

In practice the OMNIBYTE software set is extensive, allowing for interrupts, velocity or position modes, sampling while moving, coupled moving and turning, smooth continuous motions, path planning and so on. These various capabilities have all been exercized in various TERREGATOR missions. In this USBM demonstration the actual command set was a simple (but customized) version of the MOVE/TURN pair which was formulated to mate with the pre-existing RI software, and which was phrased in global x-y coordinates.

In summary, the TERREGATOR executes MOVEs by encoder counting, and executes TURNs within a sensor loop. All actions are under OMNIBYTE program control only; there is no analog drive for the machine. By design the TERREGATOR is a modular realization of a mobile test base. In principle encoders could be emplaced on any motor-controlled base and the OMNIBYTE software employed.

The TERREGATOR contains an on-board generator, cage capacity, and radio telemetry to function as an untethered autonomous vehicle. In this demonstration the additional burden of untethered operations was not justified, so a tether supplying power and RS-232 communication to the PERQ was employed. Note that the most essential portion of the demonstration was observation of the mapping process on the monitor. Had a fully autonomous version been deployed it still would have necessitated addition of such a monitor station.

The TERREGATOR was suitable to the USBM mine-mapping demonstration in two key ways:

- The TERREGATOR is mechanically robust, capable of maneuvering over obstacles (such as rails) and ground irregularities. To our knowledge, no other available mobile base for robotic vehicular experimentation could have executed in the mine environment. In this way the TERREGATOR is fully representative of motion capabilities in an equipment base (tramming mode) adapted for intelligent robotic control.
- The system architecture of TERREGATOR motion control permitted the ready interfacing with the RI mapping/navigation software.

<u>Functional</u> <u>Description</u> <u>of</u> <u>Mapping/Navigation</u> <u>Software</u>

System operation is available in a number of modes including:

- <u>Active</u> <u>learn</u> <u>mode</u>: The robot systematically follows walls, maps the space autonomously, and builds its own network of stations for later reference. This is a fully autonomous mode which has been tested in simulation and in laboratory experiments.
- <u>Passive</u> <u>learn</u> <u>mode</u>: An operator specifies points (in the sensor-based map) to the RI software for the robot to traverse. This mode exercizes the same sensing, interpretation, and navigation functions as the fully autonomous mode but keeps an operator in the loop. This mode was selected for the USBM demonstration, considering that the deployment was the first in such a committing envrionment.

The mapping function is accomplished by a software module which <u>identifies</u> <u>wall</u> <u>segments</u> from sonar data. It is a composite model because it is assembled from multiple sensors and from multiple readings, including many taken from different positions. It is far more involved than connecting raw data points. The emphasis upon the interpretation function further endows the system with two desirable (and in fact necessary) features:

- A transient sample, as created by a human walking through the field, or by a freak reflection, is justifiably ignored.
- In a sequence of robot moves, if the measured position differs from the intended position, an updating and re-orientation is accomplished.

It should be emphasized that these capabilities derive from the fundamental design of the mapping software.

Upon presentation of the 24 distance readings, the software seeks those sequences of nearby points which, within certain bounds on linearity, define a (straight) wall segment. Nearby points are selected because they represent the wall portion closest to the robot and normal to the sonar pattern; these points are most important because they are the most accurately ranged.

Figure 3 simulates a typical display, representative of the results obtained in the demonstration. The main window contains the overall map, pictured after some 13 moves of the robot. The actual display contains the map (bold lines), the network of stations (as shown), and the current robot position. The sonar pattern (not shown in this Figure) appears on the display as a ray sweeping outward and rotating about the current robot location. The main window in Figure 3 has had added to it a depiction of the actual wall geometry and an overlay of the raw data connected point-to-point. Figure 3 also contains our explanatory comments which are, of course, not present on the actual display. Note that the sonar far points limit the pattern when directed down an open zone.

The local model window contains the raw data (point-to-point) as shown. In this window the segments which are identified, reinforced, or extended during that scan are delineated. This is pictured in Figure 3 as the four short segments shown in bold line; the "construction lines" normal to them are also pictured. The videotape of this demonstration includes footage corresponding closely to the point in the demonstration represented by Figure 3. The scan and interpretation are taken repeatedly. Continued appearance of the features reinforces the model segments, while disappearance leads to their removal. In this way transient or freak readings are eliminated.

Robot moves are ordered either by the operator (passive learn mode) or autonomously ("wall-following", or active learn mode). A new raw data map is assembled, overlaid on the existing model. In this fashion wall segments are extended, corners are identified, and a full map is created. The intepretation logic uses a number of matching criteria to identify wall segments and to connect (or extend) then.

A number of functions are involved with any local move. First, the proposed path of the robot body is checked against the composite local model to see if a freepath exists. A check is also performed against the sonar (raw data) horizon. During the move the sensor data is taken and continuously interpreted to maintain the path trajectory as planned. As mentioned earlier, the position at the end of the move is then intepreted in light of sensor data. These functions are all followed graphically on the main display window.

Global path information is maintained in the network connecting the stations. The robot system assembles the network and maintains its geometry, including the mapped features relative to the network stations. The system then permits the robot to navigate itself to any point on the network. This capability is present also for multiply connected networks (not shown) in which more than one path to a goal position may exist.

Experimental Plan and Results

The demonstration and experiment fulfilled the following objectives:

- To assemble a system integrating the sonar ring, the RI software, and the TERREGATOR to perform intelligent (autonomous) mapping and navigation.
- To configure the system with sufficient mechanical and electrical ruggedness to function in a coal mine demonstration.
- To test the quality of raw data and interpreted data from a typical mine room; specifically to judge whether the accuracy is sufficient for practical equipment motion.
- To test the mapping and navigation functions in the actual mine environment; specifically to judge whether autonomous mapping and autonomous tramming (navigation) are feasible.

All of these objectives were met, and experimental observations were positive. While the scope of the demonstration was of necessity limited, it was sufficient to answer the objectives stated.

The demonstration was performed on 29 March 1985 in the Safety Research Coal

Mine at Bruceton. A base station for the PERQ was established in the first-aid room at B-butt and entry 7. The TERREGATOR (with sonar ring mounted) was run under its generator power the quarter mile from the portal to a starting position in B-butt. At that point it was connected to the power and RS-232 tether.

Figure 4 depicts the region of B-butt and entry 7 which constituted the actual demonstration. Moving of equipment (with spares) and setup required some 90 minutes of effort by seven C-MU personnel, assisted by Bruceton personnel. The run then proceeded for approximately 90 minutes, followed by some 60 minutes spent in removal from the site.

The demonstration started with the first sonar scan taken at position 1. From observing the monitor, two things were clear:

1. The raw data itself represented a recognizable mapping of mine wall locations.

2. Extraction of wall segments for the local composite model was reliable.

At that instant it was apparent that the sensor and mapping technology were performing well. The sense of reliability in the model was such that the operator could confidently enter a new goal position on the display, basing the position solely on the composite local model itself.

A series of 17 goal positions were transmitted, in the course of which the robot mapped some 30 feet of B-butt, establishing a map and creating a network of those 17 positions. The map was extended flawlessly, and the integrated system, with robot movement, performed perfectly.

The robot was then reversed and headed through a turn into entry 7. Mechanical performance was very satisfying in observing gyro control of a turn over a series of rails. Mapping functions during this phase continued to perform flawlessly. The demonstration ended when a software time-out required a restart; time for the demonstration had largely been exhausted anyway.

The system demonstrated the following problems during its development and deployment:

1. <u>Processor reliability</u>: The many processors involved have individual suspectibility to failure through mechanical stress, power fluctuations and so on. Similarly the many connections create mechanical suspectibility to failure. In the course of development these problems were encountered

and installations were ruggedized. Continued work in this environment should be preceded by a change over to a more rugged processor than the PERQ.

2. Software display bugs: The RI software contained bugs localized in its display function. In the act of scrolling certain line segments were lost from the display. Similarly, the routine which would have stored the display history for subsequent replay failed to perform.

3. Sonar functions: The time for a single scan (several seconds) is constrained by the existing configuration. Similarly, a finer array of narrow beam sensors (48 instead of 24) is judged to offer a precision which could be profitably interpreted by the supporting software.

4. System scope: The system has not been tested for mapping an extensive region. It is suspected that software errors would probably surface under such a trial.

Conclusions

The project produced a noteworthy demonstration of current research-status autonomous vehicle motion in an unstructured environment. The positive conclusions can be phrased as follows:

- Sonar sensing can be used to locate mine wall surfaces with a precision appropriate for practical applications.
- The RI mapping and navigation software is effective in such an application.
- A robust mechanical capability for motion is required; the TERREGATOR provides that minimum capability, but is limited to a research/experimental role.
- Configuring an integrated system from existing capabilities is itself a many man-month task for highly capable researchers; it is far from being a common resource or capability.
- The resulting systems are complex in terms of software, processing hardware, mechanical systems, and so on. As such they will continue to present a challenging research mission.
- Nonetheless, a successful basis exists for continued experimentation and demonstration of robotic capabilities.

It is recommended that researchers use this experiment first as a calibration of what is feasible. For instance, it is realistic to propose now a more substantive deployment of such a technology. With a run time in the hundreds of hours (as opposed to the 90 minutes in this demonstration) it should be possible to test the technology against realistic limits of accuracy, range, and complexity. Such a suggestion could not have been made prior to the successful experience in this effort. The positive nature of the findings indicates that sonar mapping has realistic potential as the primary sensing mode for mine equipment location. (Conditions of noise, dust, or spray have not yet been considered.)

Acknowledgements

We are indebted to scores of people. The TERREGATOR capability itself resulted from many months of devoted effort by some dozen or more individuals. The RI software represents years of work performed and directed by Jim Crowley. Its availability stems from the investment that he, his research assistants, and his sponsors made before us.

Many of the lessons learned in using the TERREGATOR have come through the work of other RI teams with missions for other sponsors. Many of these individuals labored on this demonstration, including Chuck Thorpe and Kevin Dowling who appear in the videotape.

Many USBM personnel worked at the Bruceton end to make this demonstration feasible. Numerous details of technical co-ordination were resolved by Bill Schiffbauer and made possible by the mine staff. Tom Fisher and George Schnakenberg provided their guidance and support.

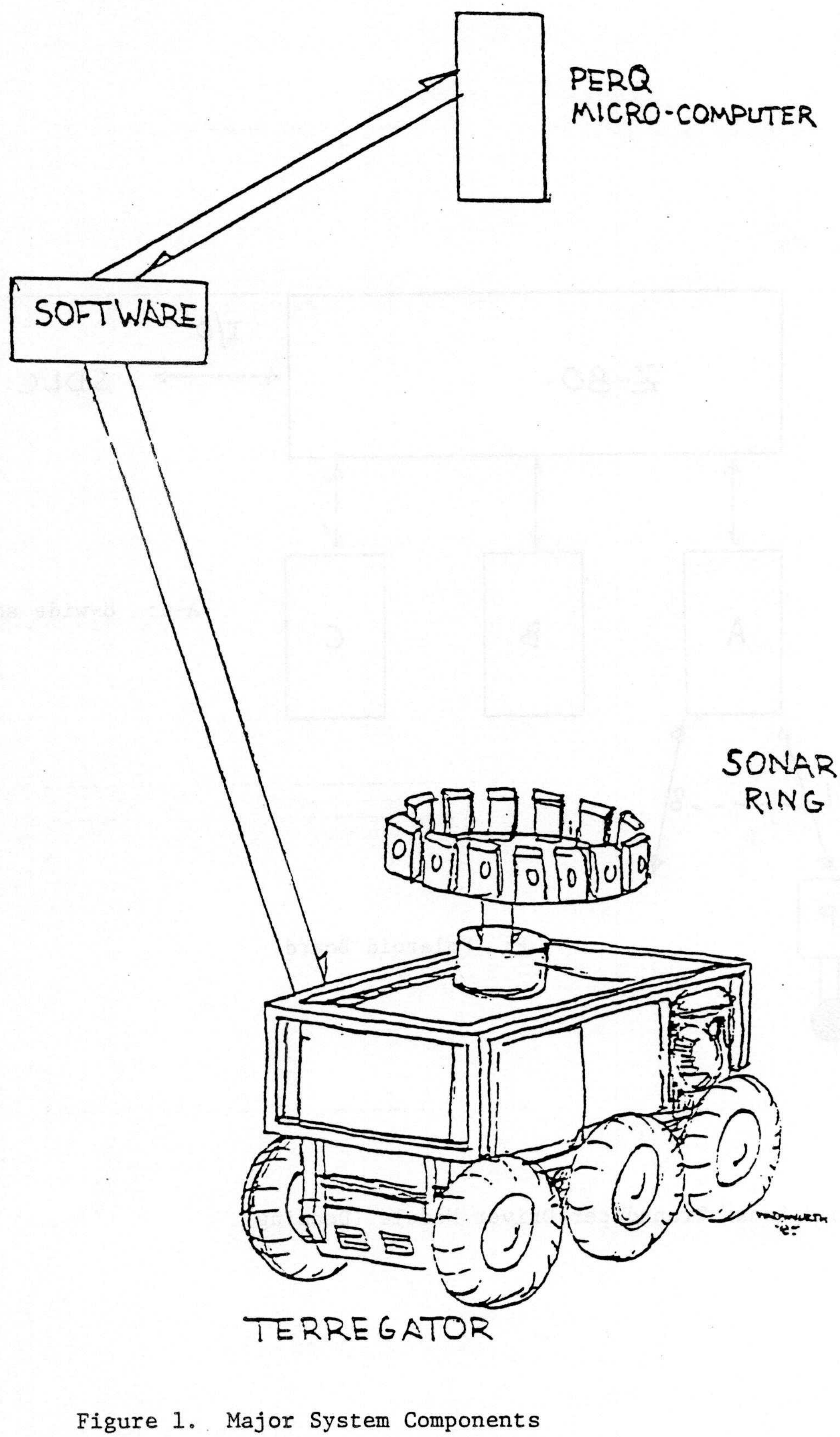

Figure 1. Major System Components

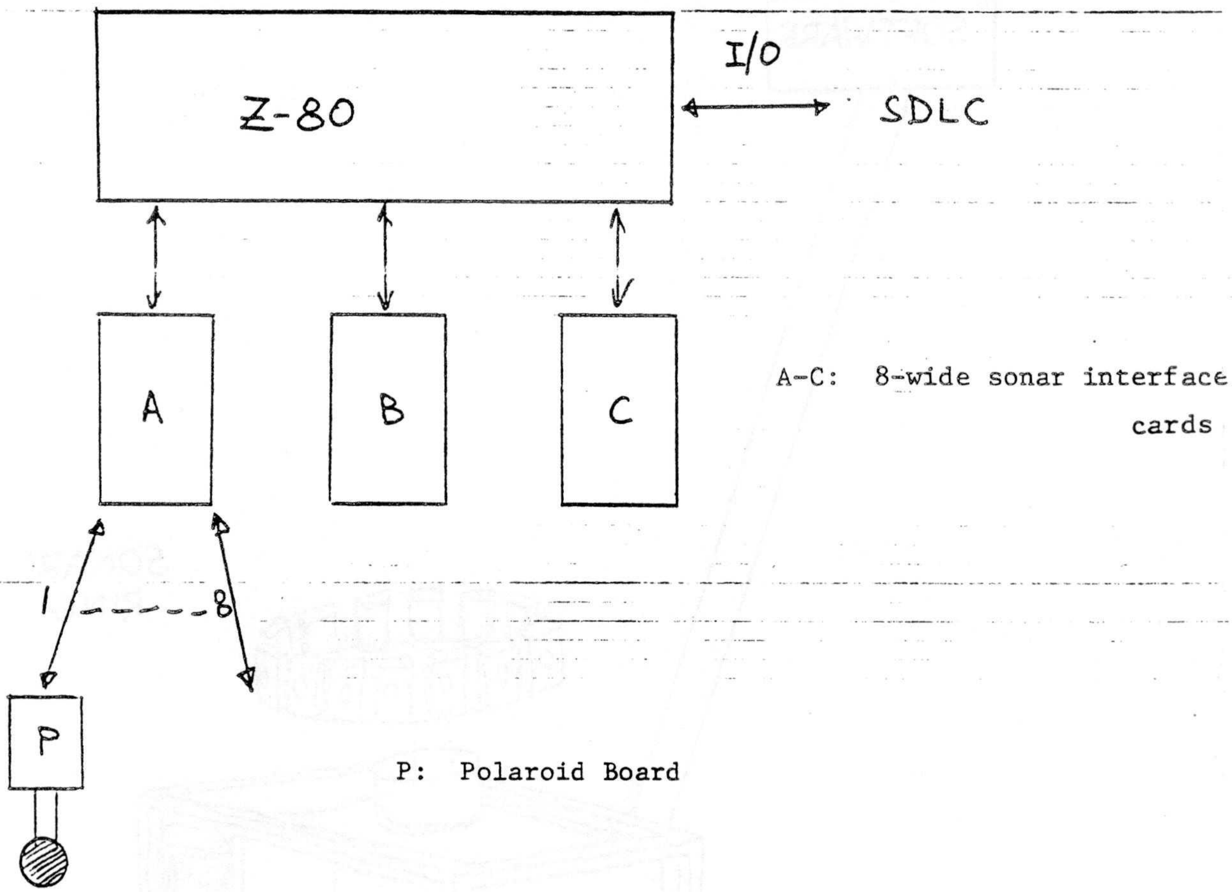

Figure 2. Polaroid Sonar Transducer Driver Module (Denning)

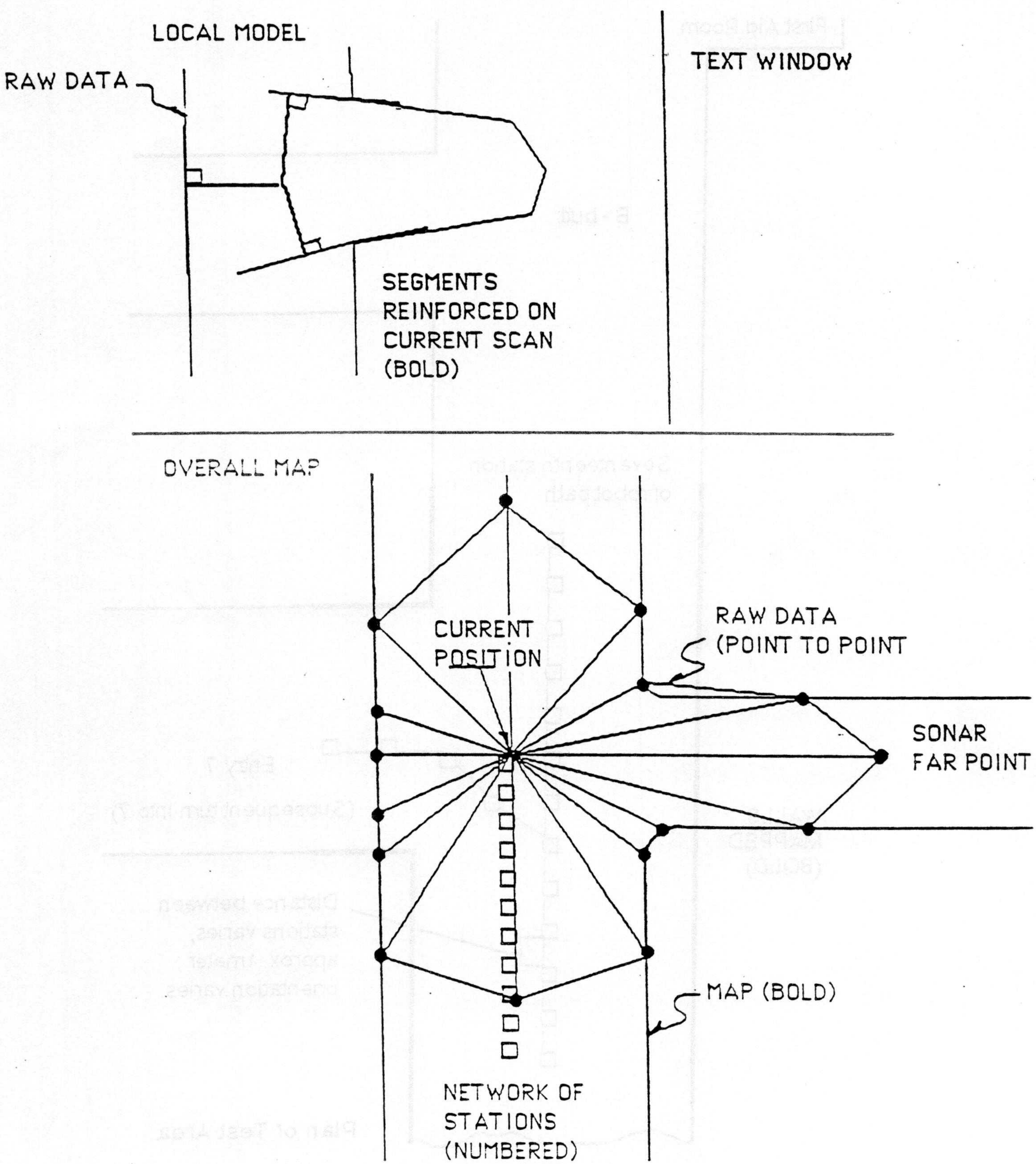

Figure 3. SIMULATED PERQ DISPLAY

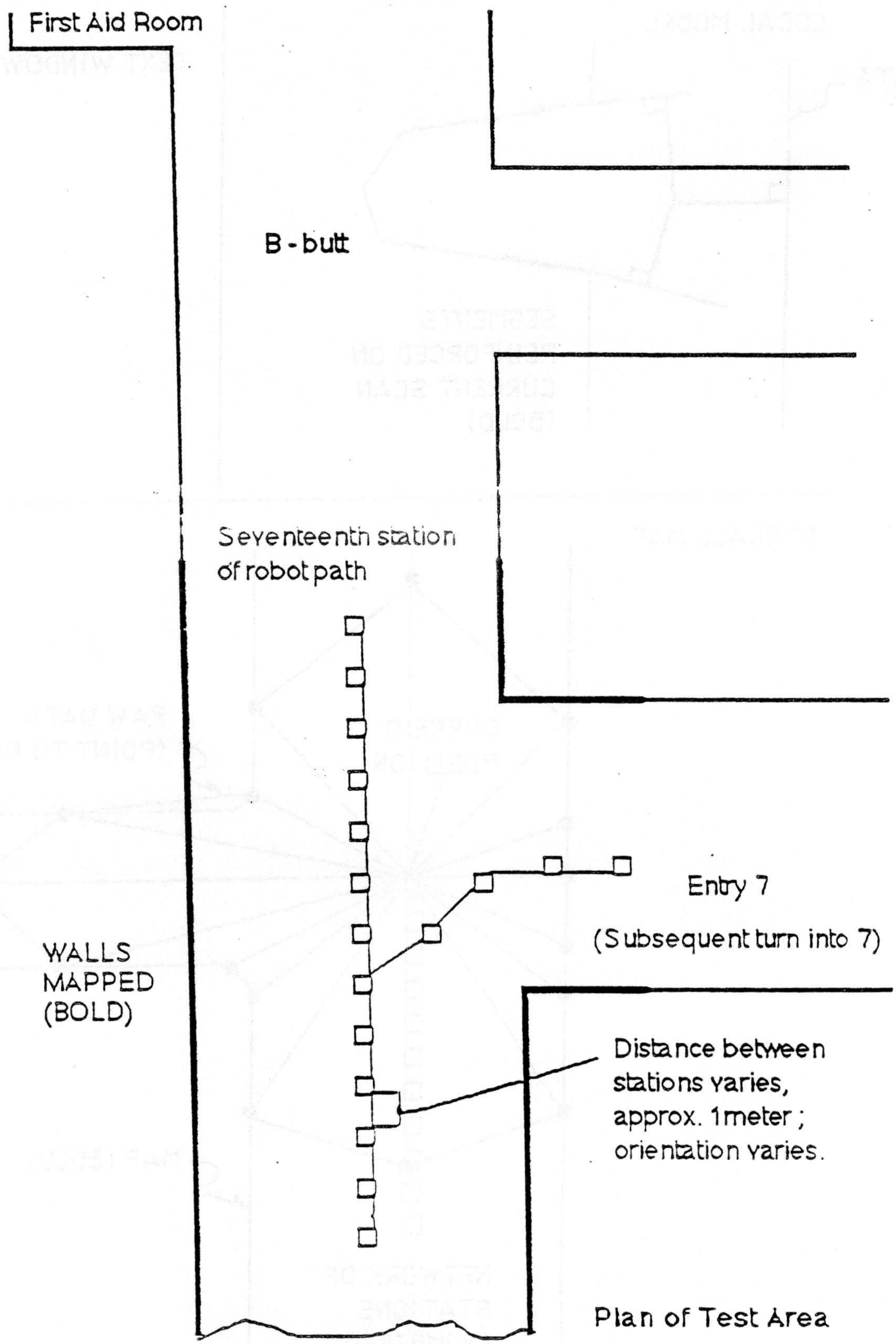
First Aid Room
B - butt
Seventeenth station
of robot path
Entry 7
(Subsequent turn into 7)
WALLS
MAPPED
(BOLD)
Distance between
stations varies,
approx. 1meter ;
orientation varies.
Plan of Test Area

Figure 4.