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W a r s z a w a

EUROPEAN TELEMAN-IMPACT PECO PROJECT - results reached by PIAP

The results reached by PIAP in the Teleman-Impact European Project are presented. The basic objectives of the Project PIAP's part, entitled: „Free space and obstacle mapping with a Laser Range Finder" (LRF), were: to evaluate the LRF performance and to define the capabilities of this sensor for the environment's maps making for navigation purposes, to elaborate the appropriate programmes as well as to make tests and to validate the LRF working together with the relevant software. The methods used and the main algorithms applied in the Project are also briefly described.

1. OBJECTIVES OF THE PIAP's PROJECT PART

Description of the Work

The PIAP's contribution dealt with the perception of the industrial environment by a mobile robot. The objective was to model this environment in free space and occupied space for navigation purposes. A laser range finder, scanning in a spiral way at a high speed, should be used. The distance and reflectivity data should be processed in order to provide the environment map used to navigate the mobile robot.

The following activities were planned, as listed below:

• experiments with data acquisition and evaluation of the performances of the scanning laser range finder in a relevant test environment (industrial - nuclear site) in France or Belgium. In Poland an industrial robotics site will be set up for subsequent experimentation and validation,

• defining the capabilities of such a sensor for navigation purposes by mobile robots in industrial environments, i.e. for providing data used to create a 2D map of the free space and obstacles,

• software implementation for processing the distance and reflectance information in order to produce the 2D map, based on occupancy grids with Bayesian-like fusion of data,

• studying the possibility and methods for creating a 3D map of the terrain, implementation of a prototype software and experiments with this software,

• validation of the developed software in a relevant industrial environment with a mobile robot,

• reporting on the work, methods, software and achieved results.

Objectives of the Work

To design, implement and test methods of perception for mobile robots, using range data provided by a commercially-available, spiral-scanning laser sensor. This data should be processed to enable free-space mapping of the mobile robot's environment for navigation purposes.

Expected Achievements

(i). Validated methods for processing range and reflectance data from laser range-finding sensors (free space/obstacle classification; terrain elevation modelling) in a relevant environment.

(ii). Validated methods for free-space mapping of a mobile robot's environment for navigation purposes. Experiments should be performed with a real mobile robot provided from outside this PIAP's Project part.

2. WORK PERFORMED

PIAP's Project part started 1 April 1994 and was finished 31 May 1996.

The works were carried out, basing on the subsequent tasks, initially formulated and accepted by the Coordinator - EDF (Electricité de France) and the collaborating ULB (Université Libre de Bruxelles).

During the Project, the tasks were subsequently updated by PIAP, EDF and ULB and all the reached results were currently and regularly reported by PIAP.

The actual Project tasks list contained the following main points:

1. PIAP's project tasks definition & breakdown,
2. PIAP's project tasks specification,
3. Laser Range Finder (LRF) evaluation,
4. LRF improvement to handle tilt angles (second TRC software release),
5. 2D local and composite map building software,
6. Local and composite crossability map building software, (using LRF tilt information),
7. Local and composite elevation map building software,
8. Map building tests, demonstrations and final Project report to EDF.

During the first phase of the project, the following equipment and software, in accordance with ULB suggestions, accepted by EDF, was purchased:

- PC Pentium, 90 MHz, and user software, from Polish dealers,
- LRF from TRC (now: HelpMate inc.) company., USA,

- DSP board and relevant system software from LSI, England,
- Virtuoso system software for DSP from Eonic (former ICI), Belgium,
- Ethernet card to PC for PC-LRF data transmission.

All the above tasks, 1-7, have been completed. Unfortunately, just before the planned date of the final experiments at PIAP's robotics laboratory and experiments in EDF industrial environment, LRF broke down and the task 7 was modified (to the extent of the demo without the LRF's tilting movement). However, before the LRF failure occurred, the software for building 2.5D composite maps (elevation and crossability) was completed and tested in the structured artificial world of cartoon blocks.

The task 5 was finally tested and demonstrated at the ULB also to the EDF, where the LRF was integrated with the mobile robot Cerberus, building the composite occupancy grid map of the unknown room.

The work connected with the LRF use, in this time only one such kind of the laser sensors, with scanning beam in horizontal and vertical planes, market available and for the reasonable price, was very time and effort consuming, in the extent much more than expected. Due to a very short time from the moment when the second (not prototypal) LRF system software was delivered, to the end of the Project, a big effort was spent to make the software in time. The LRF was delivered in December 1994. It was released as a piece of the prototype series. The LRF started to work in mid March, 1995. It was equipped then with the prototype software version, enabling the measurements of the distance, but providing an information only on the scanning beam azimuth angle. It was enough, however, for 2D map making and this data was used for 2D occupancy grid maps, local as well as the composite ones.

The tests and measurements of LRF were carried out, showing that some parameters differ from the values declared in the LRF's technical specification. In September 1995 the new (not prototype) LRF system software was delivered. This software provided the data on the scanning beam vertical (tilt) angle and allowed to work on the 2.5D map making. Because the latest experiments and demonstrations with 2D map making software were carried on until February, 1996 (demo at ULB), the new LRF's system software could be embedded and started in March this year.

After the new version of the LRF software was embedded and started-up, the new series of some LRF's tests were carried out.

An additional work was needed to be done to change the graphical part of the map making software (made for prototype LRF's software version for Borland C environment), in order to meet the requirement of the Microsoft C (producer of LRF couldn't make the compilation of the system software using Borland C) environment for which the second LRF software version was made.

With the second version of the LRF system software, the series of map making software packages were worked-out:

- 2D maps maker with the new LRF software version was rebuilt.
- Software for building 2.5D models, including:
  - crossability local maps,
  - elevation local maps,
  - crossability composite maps,
  - elevation composite maps,
  - interface to commercially available "Mathematica" package for 3D (axonometric) presentation of 2.5D maps.

All these map making packages were tested using working LRF. The crossability and elevation map makers were tested in laboratory, just before the a/m serious LRF failure.

The time of the cycle of the composite map updating is quick enough to work in a real-time, providing that the mobile robot does not speed over 3 m/s.

During the very first part of the work with LRF, PIAP gained the consultations from the specialists in laser technology at Warsaw University of Technology and Military Technical Academy.

The original software for making maps was prepared in collaboration with scientists from the Institute of Fundamental Technological Research of Polish Academy of Sciences.

The work on the DSP, made with the RS-232 output, necessary for the maps transmission to navigating package, was continued until the end of the Project. It should be continued further, outside and after the end of the Project, since the DSP board doesn't work with RS-232, despite of repair/adjustment made at producer.

Virtuoso system software also does not work with DSP board so far. The necessary further work should be undertaken, also outside and after the project end, after the DSP board is workable.

3. RESULTS REACHED

Only the LRF of HelpMate was commercially, market available and of reasonable price - ca. 8000 USD. It was tested and examined practically in the process of the mobile robot environment map making. The main parameters of LRF, as declared in the technical specification, are attached as Table 1. The most important difference between declared and the reality is the available range of distance measurement. Instead of the 0-12m., it is, practically limited, to 4m., depending on the kind of surface observed. The disadvantages of this LRF are:

- strong dependency of the distance measurement range on the surface colour and texture; there exists a certain critical laser beam incidence angle, different for different surfaces, being the boundary one, where for the bigger angles the surface is not visible at all (we may say for short that the laser beam is "sliding" on the surface and too small amount of it's energy is reflected and coming back to the sensing part). The curves of critical incidence angle (CIA) for some materials are hereby attached as the Fig. 1 and Fig 2.

- low reliability of the external electrical connections or/and the bugs in the system software part serving the Ethernet interface, causing the interruptions of the data transmission too often,
- lack of the compact supplier, designed accordingly to the requirements of the LRF, which has to be provided with 4 different voltages.

The real advantages of LRF with the newest software release are:

- good accuracy,
- high scanning rate,
- high throughput of the Ethernet interface, transmitting the distance readouts,
- some interesting and useful options in the system software as e.g. the local filtering, planar projection,
- possibility to work with LRF in both position: normal and upside down,
- a large azimuth scanning range: 360°.

During the works on the second LRF system software application to 2.5D map making, it turned out that the tilt angle/azimuth angle relating characteristic was very inexact which caused that visible contours were fuzzy or even doubled. After that observation the more exact, however linearised, characteristic was delivered by HelpMate and the maps being done improved remarkably.

The conclusion, after the tests, analysis and experiments with map making, carried out in the project with this LRF use, is that this laser device is good enough to be used for mobile robot navigation, at least in indoor environment including industrial one.

Of course, it would be very interesting to have, in the future, the increased distance measurement range, and then to be able to experiment with the outdoor applications and/or with higher speed mobile robots. It is also very advisable to reach the lower LRF distance measurements dependency on the surface kind, however the high performance of the composite maps software compensates this laser sensor's disadvantages remarkably.

For making the field tests of LRF map making in integration with mobile robot, the portable, based on the 486DX, 90 MHz NoteBook, sub-system has been created. The structure of this sub-system is shown as the Fig. 3. LRF is mounted on the vehicle's deck and connected with Notebook through Ethernet interface. Notebook is also connected with the mobile robot positioning system through RS serial port, enabling this way to make the maps automatically. Pictures at Fig. 4 show the LRF and robots used for map making process, i.e. the Cerberus cart at ULB and the Pioneer 1 vehicle of Warsaw University of Technology at Warsaw Academy of Science's laboratories. The compact mobile robot Pioneer 1 is very convenient for tests at any field, since it is easy to be transported due to small dimensions and a little weight. It was prepared as a part of portable subsystem for the tests of the map making at any place.. Pioneer 1 cart, though wheel driven has a very accurate odometer. This resulted in the good and exact maps created with use of this robot.

As the result of the Project, the set of map making software (MMS) packages were made and tested. MMS enables to model the mobile robot environment, perceived by the laser sensor, working at high sampling rate and transmitting the data with the use of the high throughput Ethernet interface. At the beginning of the Project, only the 2D and 2.5D MMS was planned. The 3D was planned to be limited to exploratory research. During the work, it turned out to be very important to have for navigation purposes the crossability kind of maps to show the areas accessible for mobile robot, and altitude kind of maps for good orientation of the vehicle teleoperating operator. The composite versions of these maps could be useful for teleoperation as well as for autonomous navigation.

This kind of maps is based on redundant information and compensates the most important LRF disadvantage, i.e.: the poor sensing of the dark and/or glittering surfaces and surfaces positioned at bigger than (characteristic for a surface colour and texture) a/m critical (boundary) laser beam incidence angle. Fig. 5 shows the 2D local maps made with the first version of LRF system software, giving the limited, 180 degrees planar scanning range. The pictures of 2D composite maps building process, for two different environment of „unknown" places at ULB are shown as the Fig. 6 and Fig. 7. The presentation of the maps is user friendly. User can choose many useful options from graphic menu, using mouse or keypad. These are e.g. the probability of LRF measurement accuracy, the colours representing the free, occupied, occluded (beyond the obstacles) and unknown (no returned, reflected signals-LRF gives zero distance readouts) areas.

In these MMS packages the LRF tilt angle data is included into processing algorithm. For the terrain profile sensing, LRF was mounted upside down on the mobile robot deck and scanned in spiral way the surrounding environment: horizontally - 360° and vertically: from horizontal plane to 45° down. The elevation map is stored in a format accepted by package "Mathematica" used to present these maps in axonometry.

The basic experiments with laser and map making software were made mostly in the PIAP's robotics laboratory, where there were a lot of equipment like industrial robots's manipulators lacquered with the orange colour and theirs control cubicles, also metallic, but of glittering surface, dark grey coloured. The manipulators are very well sensed by LRF, while the robots's control cubicles have a very low CIA and therefore the best picture of such environment is formed when using the composite maps.

Map building is a dynamic process, which needs the pre-processing of data stream supplied by external sensors in a real-time. In general, this data refers to observations taken from different positions along the path followed by a vehicle. This requires a mechanism for integrating local views into a common reference frame. The problem was splitted into two concurrent operations: performing a local map by scans from one place, and updating a global map by projecting a local map into a global one (called composite map) with respect to a current vehicle's position. In order to meet the real-time restrictions and consider the limited reliability of sensors, an *occupancy grid method* for world modelling was used. Such representation can be applied directly in path planning navigation, collision avoidance, and in assisting of teleoperations.

In the framework of the Project the robot independent sub-system enabling to build plane and spatial composite maps has been designed. Due to real-time restrictions, instead of full 3D occupancy cubic grid, a 2D planar map, composed of grids, described by theirs heights and crossability status's was used (2.5D). It allowed to build a full local view (azimuth scanning range 360°) and to project it into a composite map in a time loop less than 100 ms. This in turn enabled to build the map on-line, while the robot was riding with a speed up to 3 m/s. It was estimated that 3D model of the environment map would decrease the robot's speed about 10 times which make such a approach useless for navigation.

2D representation

The robot's environment is represented as a grid of cells. Each cell is described within a certain number, which refers to the specific state i.e. *occupied, free* or *unknown*. The local map contains information about the robot's environment, which is directly perceivable. Therefore, the local grid is centred on the vehicle's frame. While the robot stays in a certain point within a certain tolerance, the sensory data is collected in a sense of updating cells' states. To describe these states, the theory of probability was employed. Thus, the two probabilities were defined, which express whether the cell is occupied by an obstacle - P_{occ}, or if it is free - P_{emp}. These are two events excluding each other so $P_{occ} + P_{emp} = 1$. Initially predefined state of each cell is *unknown*, which means that $P_{occ} = P_{emp} = 0.5$ for each cell.

Knowing the robot's position and the sensor indication, one can determine states of cells, placed along the current scanning direction. Thus, the cell on the endpoint of the sensor beam, is assumed to be *occupied* within a certain probability, depending on the sensor's *probability factor*. All cells between the sensor and the endpoint of its beam are treated as *free* within the same probability, and consequently, cells behind the endpoint stay *unknown*. During a scanning process, the states of cells are continuously updated according to the Bayesian formula:

$$P_{occ}^{new} = \frac{P_{occ}^{old} \cdot P_{occ}}{P_{occ}^{old} \cdot P_{occ} + P_{emp}^{old} \cdot P_{emp}} \tag{1}$$

where:

P_{occ}^{old}, P_{emp}^{old} probabilities that the particular cell is occupied or free. They express the gathered knowledge about the cell's state and fulfil a condition: $P_{occ}^{old} = 1 - P_{emp}^{old}$,

P_{occ}, P_{emp} probabilities of the occupancy cell's state - they refer to cells along measurement direction and express temporary states only. These probabilities are known and represent the sensor's model,

P_{occ}^{new}, P_{emp}^{new} probabilities express cells' states after a current measurement. These are a result of an ongoing aggregation process and, according to the theory of probability, meet the condition: $P_{occ}^{new} = 1 - P_{emp}^{new}$.

The aggregation loop is performed for each cell of a local map and takes most of processing time. Therefore, in order to increase the efficiency of the algorithm, the Bayesian formula was tabulated in two tables. In order to avoid collisions with static and dynamic obstacles the updating process of the local certainty grid has two important characteristics: on the one hand, the updating process is very fast so that it runs continuously. On the other hand the data of the local map becomes outdated because it is not relevant to the real robot's pose and consequently has to be refreshed with a frequency depending on the vehicle's speed.

The updating process of the global certainty integrates the data of the local certainty grid into the global one. The global map results from the superposition of local models, obtained for subsequent scans and takes into account the robot's pose and its uncertainty. Initial states of the global certainty grid are referred to as *unknown*. In the updating process, the cells from local map are projected into the global one, where corresponding cells are updated according to the formula (1).

To tests the designed sub-system, it was installed on the ULB Cerberus robot and there were the series of experiments in a real unstructured environment conducted. The performed experiments consisted in building the global 2D occupancy grid map during exploration of unknown rooms. Cerberus with LRF installed on the deck, was controlled "by hand" (joy-stick) by the operator who did manoeuvres, based both: on the grid maps, being updated in a real time and on images from CCD camera. The current vehicle's position was provided to the sub-system via serial port by the dead reckoning system within an uncertainty.

The presented sub-system enabled to make 2D occupancy grid maps, based on LRF readouts end external positioning system. The communication through a serial port makes the sub-system portable and independent of robot's on-board equipment. A very efficient, short time updating mechanism allows a robot to ride with a speed up to 3 m/s and investigate the map building process on an operator's console.

Comparing usefulness and reliability of the sub-system with vision in tele-operating, it was found that 2D occupancy grid map, performing on-line with its graphic interface is a convenient way of representation of an environment and enables an operator to control the vehicle even more efficiently than using stereo vision.

2.5D representation

The essence of this representation lies in computation of the elevation (e^{ij}) of each grid (i, j), based on measured distances to the detected obstacles, on the pan and tilt angles:

$$e_{ij}^{(n)} = f(d^n, \alpha^{(n)}, \varphi^{(n)})$$

The base problem is the determination of heights of occluded grids. The 2 approximation methods (linear progressing and discrete minimisation) which enable to obtain the elevation for each raster were investigated. The Local Cartesian Elevation Map (LCEM), composing of such grids, is used in the process of building the Composite Elevation Map (CEM). The rule base system to aggregate grid heights, which distinguished known, occluded and unknown status's of particular cells was employed.

The local and composite Crossability Maps (CM) are build using LCEM or CEM with respect to a current position. In this representation the cell may have three values, describing if the cell is traversable, non-traversable or unknown. The grid is traversable if the derivative of the elevation along the specified line (direction) is less than the assumed threshold. Otherwise the grid is non-traversable. If one of the cells, whose elevations are used for calculation of the derivative, is unknown, then status of the adequate cell is unknown too.

In order to illustrate 2.5D representation, the CEM of the artificial environment composed of carton boxes was built. Due to real LRF failure it was necessary to use the laser simulator program to generate readings which were provided to the sub-system. The robot was wandered around virtual world, scanning the environment and building on-line 2.5D composite maps. The enclosed pictures at a Fig. 8 show obtained results. At the Fig. 9, 10 and 11 there are presented the environment 2.5D maps in axonometry-for the same example of surrounding, however projected by „Mathematica" package from three different points of view.

4. SUMMARY

Summarising, the objectives of the PIAP's Project part have been achieved i.e. the methods of perception for mobile robots, using range data provided by a commercially-available, spiral-scanning laser sensor were designed, implemented and tested.

The expected results were achieved, and in particular:

• the methods for processing range and reflectance data from laser range-finding sensors (free space/obstacle classification; terrain elevation modelling) in a relevant environment,

• the methods for free-space mapping of a mobile robot's environment for navigation purposes, were attained and the experiments with the real mobile robots were performed.

5. CONCLUSIONS AND POSSIBLE FUTURE WORK

The biggest challenges were the problems connected with the purchased equipment and it's system software, considering the relatively short time of the Project realization in PIAP.

The good LRF testing and application knowledge and experience were collected.

The knowledge and experience in the appropriate methods application, programming and validation of the mobile robot environment map making were gained.

The prepared software packages can be useful in existing navigation systems.

In the future, some work should be continued, in order to:

• reach the improved, substantially more reliable state of this LRF, including the latest, third version of it's system software,

• connect the map making software with various navigation systems,

• reach the DSP board and Virtuoso DSP OS working with the mapping and navigating software packages,

• examine the fully 3D representation of the environment, using for calculations the DSP and Virtuoso,

• make the software for automatic matching the local/composite maps and global ones, introduced to the mobile robot system through standard CAD, and to use the results in autonomous navigation.

A part of the above listed work is intended to be continued in the framework of the national grant "The investigation of the methods, and laser technique application for the mobile robot navigation support", N° 8T11A 025 09.

6. ACKNOWLEGMENTS

During the Project realisation, PIAP obtained the substantial and effective organisational and some, necessary technical help and advice from EDF co-ordinator Mr. Leon Piotrowski, as well as from ULB specialists: Mr. Lionel Anciaux at the beginning and especially valuable, very creative and in the same time practical from Mr. Marc Halbach, during the latest and most important phases of the work. The good co-operation in the research, technical and organisational aspects of the R&D project realisation has been established between EDF, ULB and PIAP.

PIAP is very grateful EDF and ULB for the assistance delivered.

The main contribution to the PIAP Project results was delivered by: Dunaj J. , Lichodziejewski C. , Petz M. , Pilat Z. , Racz J.,*) Sawwa R. , Siemiątkowska B.*)

Author also appreciates the comments and suggestions of Prof. A. Maslowski on the Project tasks execution.

PUBLICATIONS

[1] M. Petz, R. Sawwa: "A 2D scanning range finder for mobile robot navigation". Presented at "Teleman Telerobotics Conference", July 1995, Noordvijkerhout, Holland.

[2] J. Dunaj, M. Petz, R. Sawwa: "The investigation of the Laser Range Finder application for the mobile robot navigation and remarks on the potential use of LRF in the industry". Paper at Conference: "Robotics in Theory and Practice", Prešov, Slovakia, September, 1995.

[3] J. Racz, B. Siemiatkowska, R. Sawwa, M. Petz: "Building 2D local maps based on laser readouts". Paper at Conference: " Methods and Models in Automation and Robotics". Miedzyzdroje, Poland, September 1996.

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*) Institute of Fundamental Technological Research, Polish Academy of Sciences.

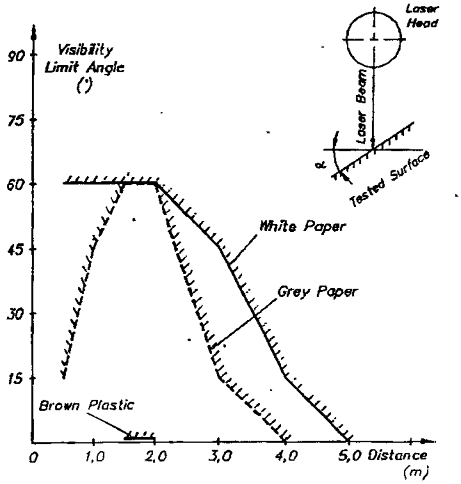


Fig. 1. Curves of Critical Incidence Angle

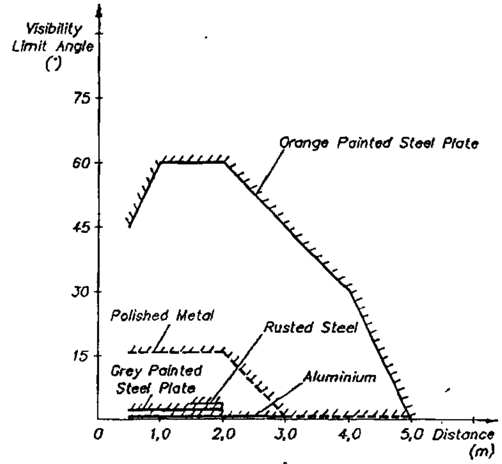


Fig. 2. Curves of Critical Incidence Angle

Table 1.

Range	0 to 12m
Wavelength	infrared (780 nm)
Optical Output Power	6 mW maximum
Resolution	5 mm
Accuracy	25 mm
Sampling Rate	25 Khz
Field of View	360° azimuth, 45° elevation
Angular Resolution	0.18°
Horizontal Sweep Rate	200-900 rpm
Vertical Nod Rate	one cycle per 10 revolutions
Enclosure	13x13x35 cm scan unit
	30x26x5 cm electronics
Weight	2 kG

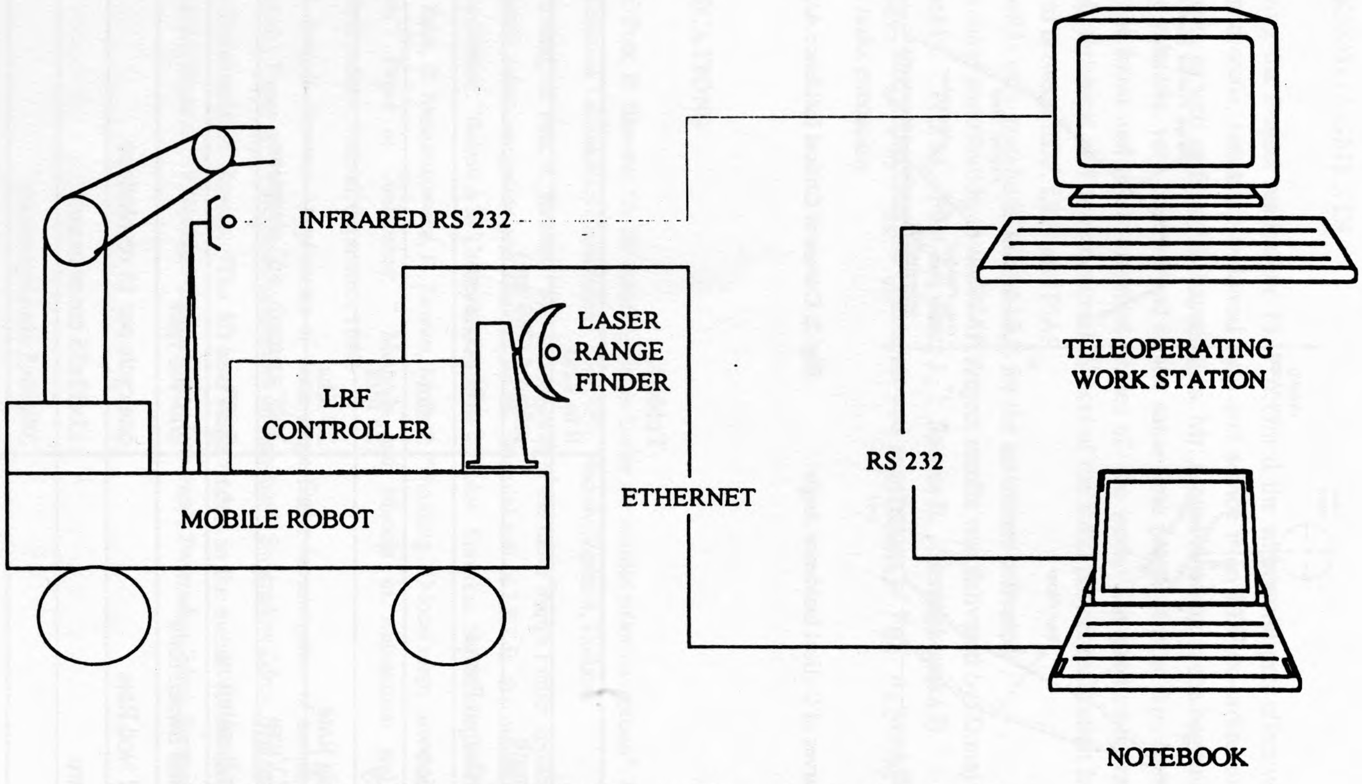


Fig. 3. Structure of the integrated mobile system for environment map making

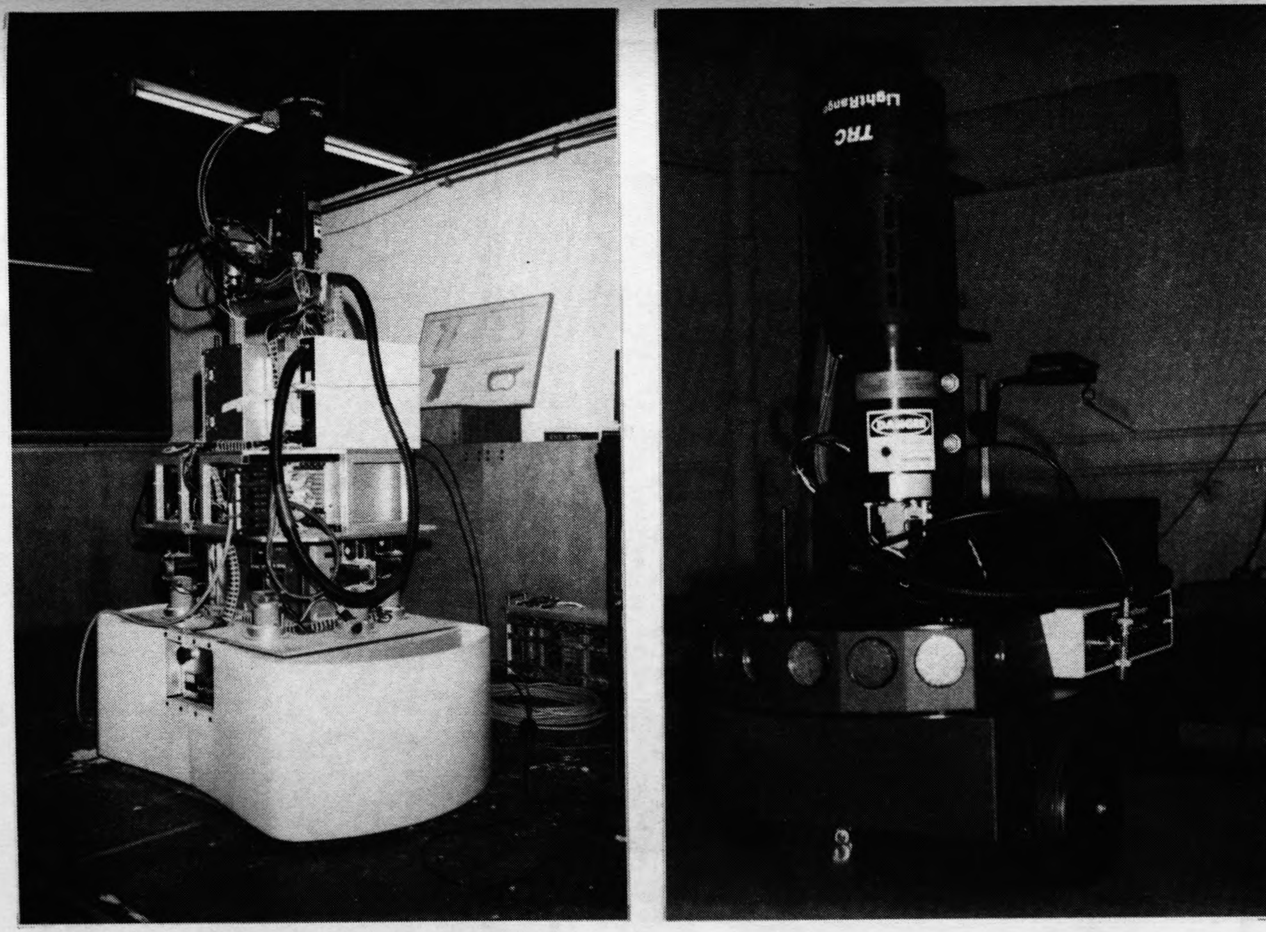
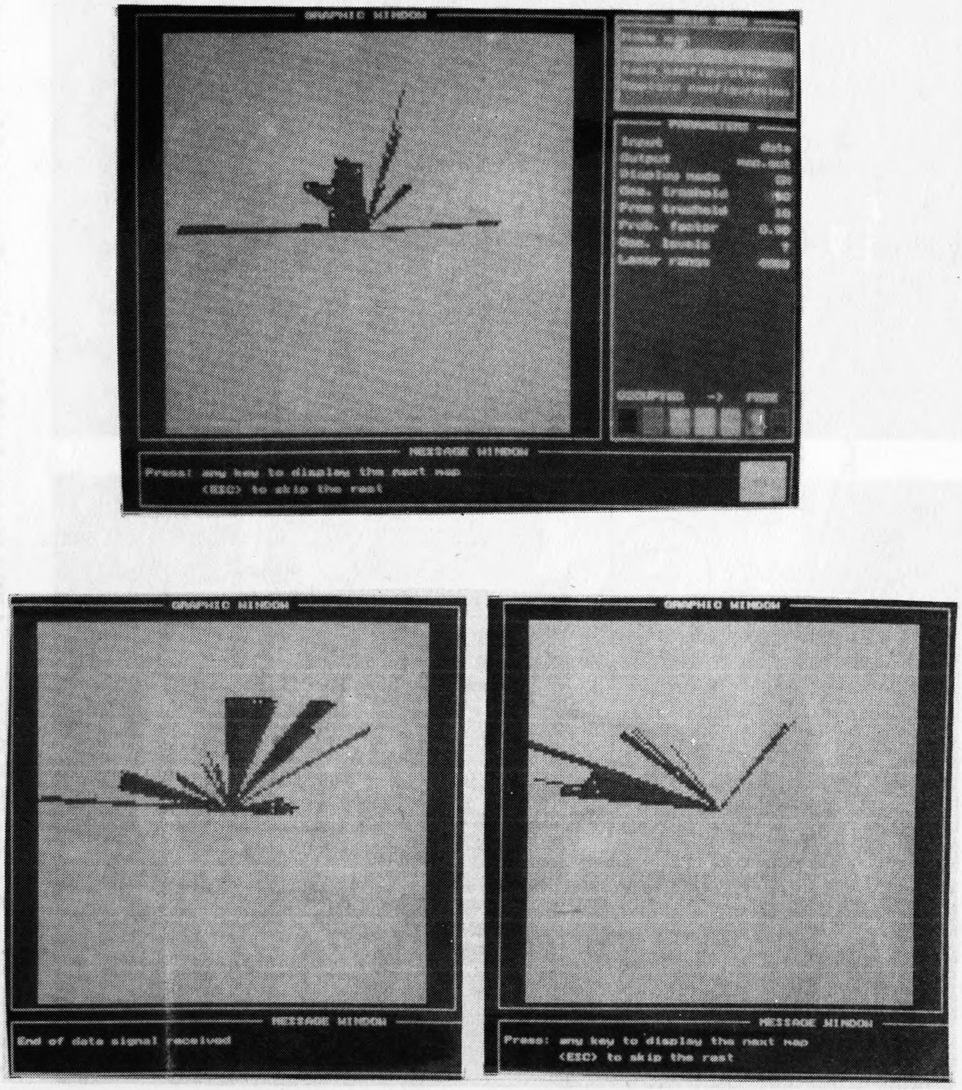


Fig. 4. Real Mobile Robots - ULB Celebrus and RWI Pioneer 1 with laser range finger used for environment map making

ENVIRONMENT 2D
LOKAL MAPS

Fig. 5. 2D range maps obtained from a scanning laser range finder



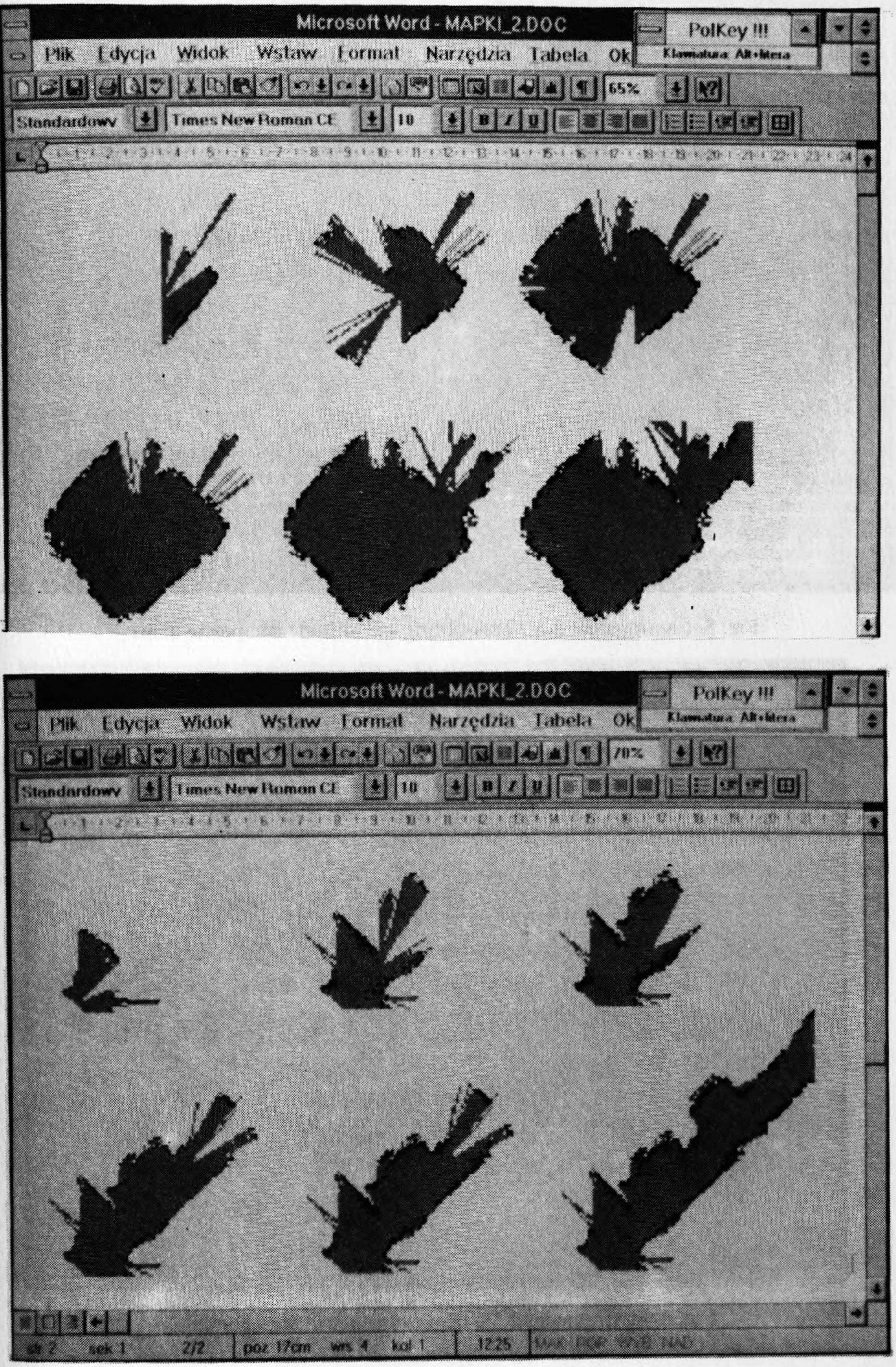


Fig. 6 i 7. Sequence of consolidated 2D range maps obtained from a scanning laser range finder carried by a mobile robot

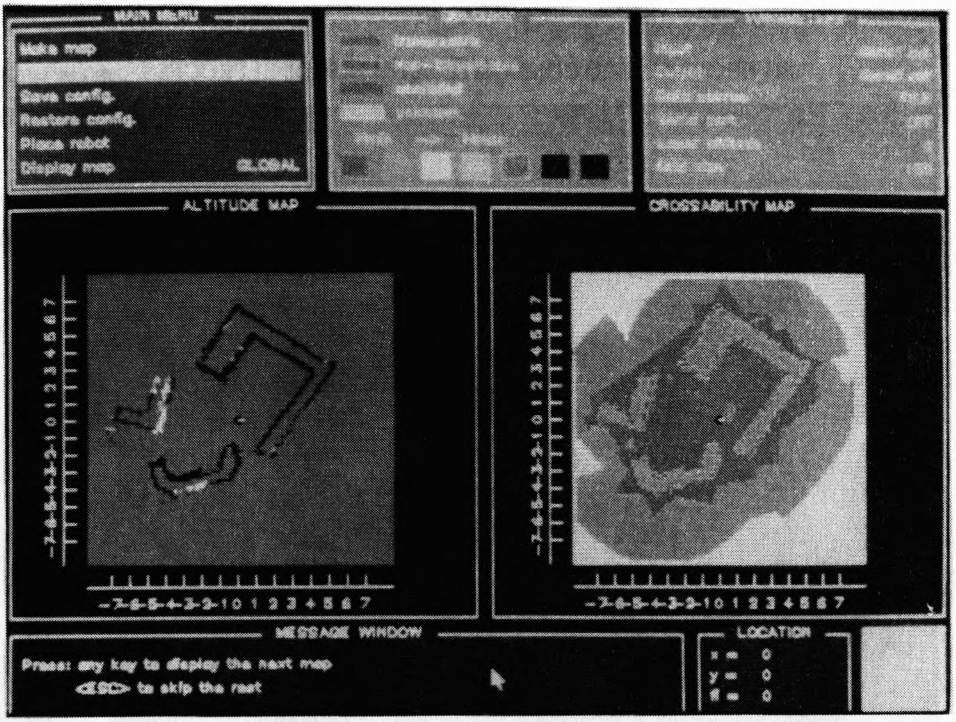


Fig. 8. Environment 2.5D crossability and altitude composite maps

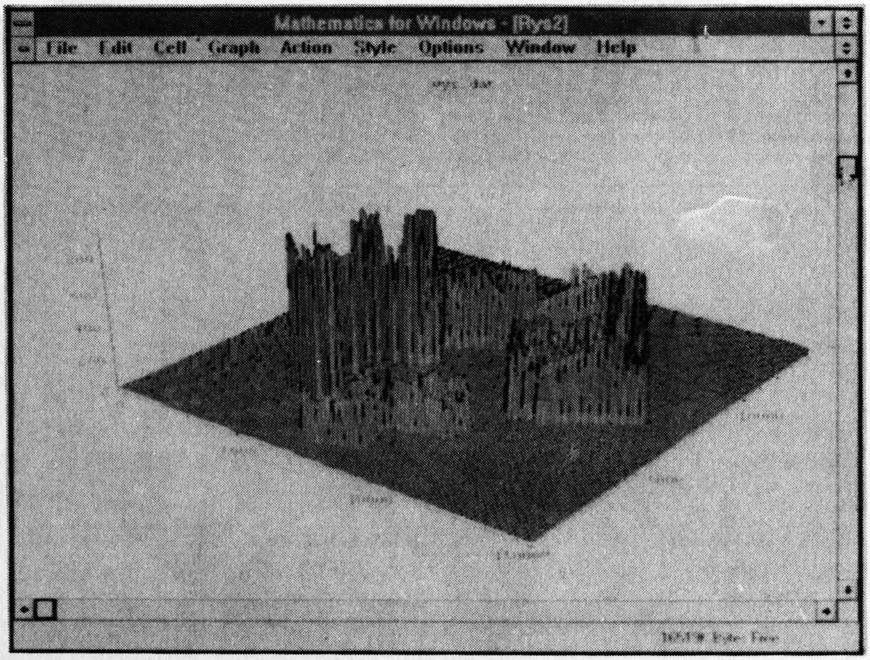


Fig. 9. Environment 2.5D map exonometric presentation

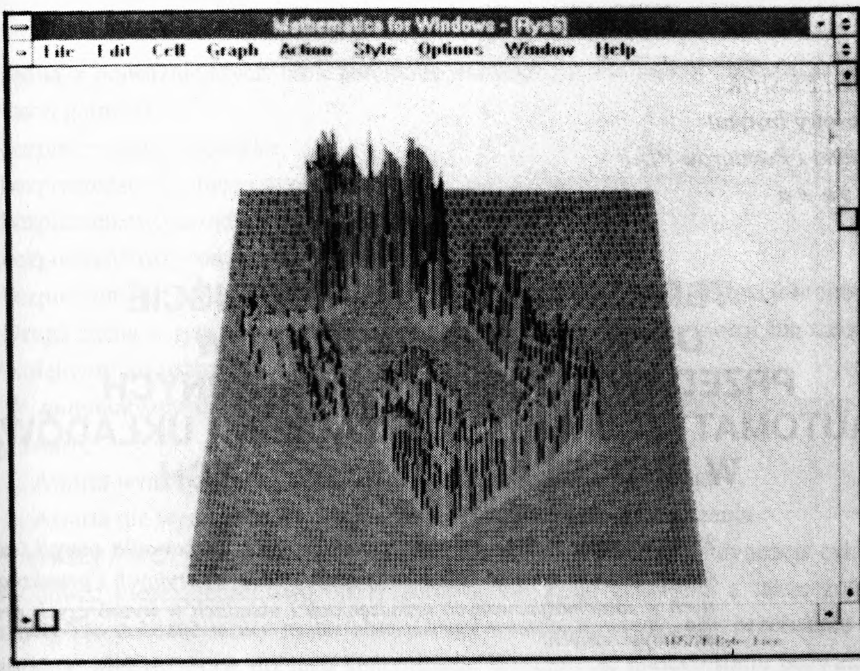


Fig. 10. Environment 2.5D map exonometric presentation

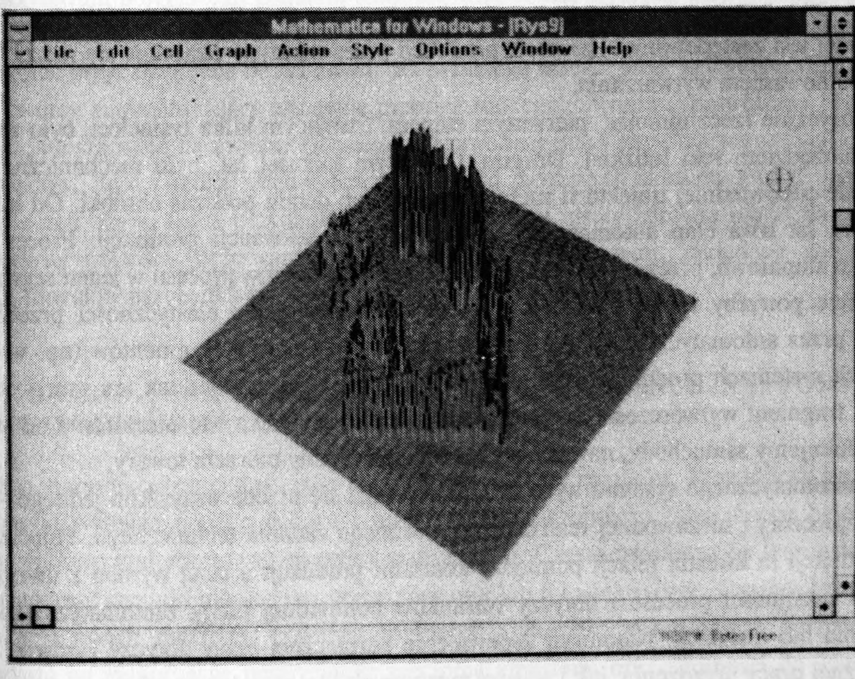


Fig. 11. Environment 2.5D map exonometric presentation