IEEE Int. Symposium on Industrial Electronics, Guimarães, Portugal, July 7-11, 1997

Complete Coverage Path Planning and Guidance for Cleaning Robots

R. Neumann de Carvalho, H.A. Vidal, P. Vieira, M.I. Ribeiro

Instituto Superior Técnico/Instituto de Sistemas e Robótica
IST - Torre Norte
Av. Rovisco Pais, 1
1096 LISBOA CODEX, Portugal

Abstract – **This paper describes a complete coverage path planning and guidance methodology for a mobile robot, having the automatic floor cleaning of large industrial areas as a target application. The proposed algorithms rely on the a priori knowledge of a 2D map of the environment and cope with unexpected obstacles not represented on the map. A template based approach is used to control the path execution, thus incorporating, in a natural way, the kinematic and the geometric model of the mobile robot on the path planning procedure.**

The novelty of the proposed approach is the capability of the path planner to deal with a priori mapped or unexpected obstacles in the middle of the working space. If unmapped obstacles permanently block the planned trajectory, the path tracking control avoids these obstacles.

The paper presents experimental results with a LABMATE mobile robot, confirming the feasibility of the total coverage path and the robustness of the path tracking behaviour based control.

I. INTRODUCTION

Path planning and path tracking strategies for mobile robot navigation are highly dependent on the target applications. Among those, floor cleaning in extended public or industrial areas raise very interesting research challenges when required to be autonomously fulfilled by mobile robots.

Cleaning tasks require a special kind of trajectory able to cover all the unoccupied areas in the specified cleaning environments. Paths that comply with this requirement are known as paths of total coverage. A few publications, [1], [2], [3] have discussed the application of mobile robots to floor cleaning tasks without the explicit knowledge of the geometry and complexity of the cleaning area. Some methods for generating a path of total coverage, based on a map of the area to be cleaned, have been presented in the near past. They use grid-based, [3], or template-based approaches, [1].

This paper describes a template based methodology for planning paths of total coverage. A 2D map of the environment is assumed to be known a priori. The system, implemented on a commercially available mobile platform, [8], exclusively relies on odometry and ultrasonic data, aiming at providing a low-cost navigation module that could be implemented on a future commercial vacuum-cleaner. The paper's novelty relative to previous related works, namely to [1], is an effective way to deal with obstacles lying in the middle of the cleaning area, either represented on the a priori map or unexpected. In both cases, ultrasonic data is used for obstacle detection. A behavior based path tracking is also a new approach in this type of application, leading to an increased robustness of the overall system relative to errors introduced by the sensors that support navigation and localization procedures.

The empty space to be cleaned is represented by a 2D-map, where the border and all the objects are represented, in a global frame, by the set of vertices that define the closed 2D-polygon of the corresponding contour. Although it is desirable that all the obstacles in the cleaning area are represented on this a priori map, the path tracking control copes with unexpected obstacles.

For a satisfactory coverage of the entire space, neighbor paths are required to have an overlaping area. Sequences of maneuvers consisting of a predefined number of line segments and arcs will be employed to generate the total coverage path. Each elementary path type is denoted as a template, the total path being a sequence of templates. The redundancy introduced by the overlap of parallel paths of successive templates will account for the swing out that exists during turns and for navigation errors. All templates take into consideration the parameters of the robot such as the minimum turning radius, [4], the robot width and the cleaning area. To account for vehicle dimensions and aiming at simplifying the path planning phase, the environment is previously enlarged so as to consider the robot as a point.

The paper organization is the following. Section II describes the various templates used to plan the entire path and the strategy for the best choice of the sequence of templates. The path tracking control is described in Section III, with a behavior based approach for the implementation of some templates. Section IV presents a brief overview of the implemented localization procedure. Section V describes the obstacle avoidance procedure for unexpected obstacles. Results obtained with a LABMATE mobile platform, are presented and discussed in Section VI. Conclusions and directions for further work are drawn in Section VII.

II. PATH PLANNER

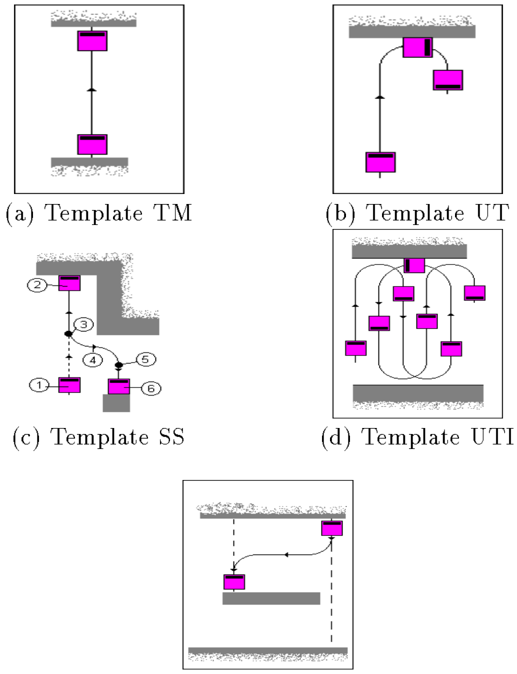
The complete coverage trajectory is planned as a sequence of pre-defined trajectories, denoted as templates, along the lines proposed in [1]. A set of five templates, TM (Towards Marker), UT (U turn), SS (Side Shift),UTI (U turn interlaced) and BT (Backtracker) is proposed as the minimum number to achieve a satisfactory floor coverage of an area which contains obstacles in its interior. The use of the BT template is a novel proposal with which the platform will cope with obstacles in the middle of the environment.

The set of templates, described in the sequel, are represented in Fig. 1, where the mobile platform is the grey square having a darker rectangle on its front part.

- **Template Towards Marker, TM:** Line segment that links two given points (Fig. 1 a). This template is the backbone of nearly all the other templates.
- **Template U-turn, UT:** Line segment followed by a U turn (Fig. 1 b). With the exception of TM, the execution of a UT template is fast when compared with all the other templates, due to the simplicity of the included maneuvers. The successive application of UT templates creates a snake trail pattern as represented in (Fig. 2). The platform minimum turning radius, and the required overlap between adjacent trails are the main geometric parameters associated with UT.
- **Template Side Shift, SS:** Side shift maneuver (Fig. 1 c). This template provides a tool for changing between adjacent tracks when the mobile robot has a minimum turning radius that prevents the use of a UT template to achieve that change. A Side Shift template can also be used when an environmental barrier such as a wall prevents the use of a UT template, this being the situation displayed in Fig. 1 c. The main drawback of this template is an high coverage redundancy.
- **Template U turn Interlaced, UTI:** Sequence of five interlaced UT templates (Fig. 1 d). It is well suited for robots with a large minimum turning radius and its application reduces the wheel slippage when compared to the UT template. This fact was experimentally observed during the tests carried out with the LABMATE mobile platform.
- **Template Backtracker, BT:** Sequence of 2 turns and 3 line segments (Fig. 1 e). This template is extremely useful when there are obstacles lying in the middle of the area to be cleaned. The backtracking movements supported by template BT, allow the mobile robot to clean areas not yet covered that would, otherwise, be left behind uncleaned, this being one of the novelties of the proposed methodology.

The complete coverage path-planning methodology is implemented iteratively, after an initial localization procedure. An human operator drives the platform to its initial location, and an estimated location is evaluated based on ultrasonic data. The main loop of execution is represented in Fig. 3.

At each iteration, and based on the previously cleaned area and the a priori map, the algorithm chooses the template to be applied, as explained later in this section. Before execution, the trajectory that will be generated by the chosen template has to be further decomposed in such a way that simple motion commands



(a) Template TM (b) Template UT (c) Template SS (d) Template UTI (e) Template BT

Fig. 1.: Templates.

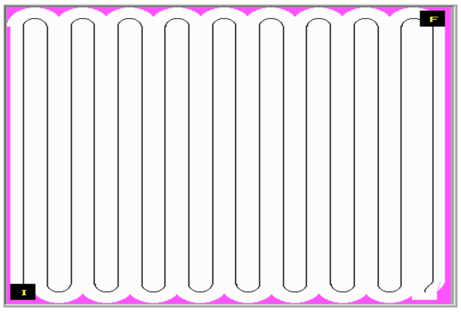


Fig. 2.: Successive UT templates, typical snake trail. I - initial point, F - final point.

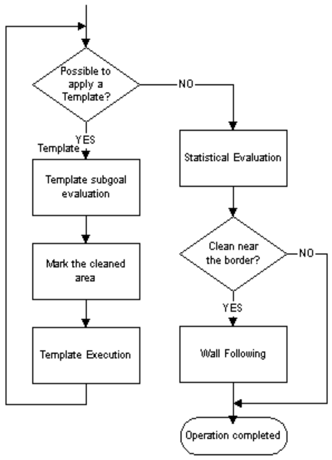


Fig. 3.: Main loop of the algorithm.

such as Move(x,y,forward) or Turn(θ,left,radius) can be dispatched to the mobile robot. This decomposition, achieved by the path tracking module, breaks up the templates into subgoals. The sub-goals of each template are the boundary points that separate line segments from turns, thus decomposing the template in a set of sub-templates (see [6] for details). Following template sub-goals evaluation, a prediction of the new cleaned area is carried out, followed by the template execution, which is achieved by the execution of each of its sub-templates. If no template can be applied, this means that all the area has already been cleaned or there is a deadlock situation. On both cases, a further procedure for wall following is implemented. This procedure, fully supported on ultrasonic data is described in [5], being based on a modified Potential Field Approach.

A heuristic formula is used for choosing the best template to apply at each stage, aiming at maximizing the total covered area. The template BT is the first one whose application is checked by the planner, because if any uncleaned space is left behind it must be covered before moving on, otherwise it will be left uncleaned. Next, the choice of an interlaced template (UTI) is trade aiming at reducing wheel slippage and consequently reducing odometry errors. Due to a fast execution time, the use of a UT template is checked next. The Side Shift template is the last one to be considered due to its high coverage redundancy. The TM template is used as a major component of all the other templates, given that all line segments are executed by TM templates.

To decide whether backtracking (BT) will really influence the percentage of the cleaning area to cover, a map of the area already cleaned is updated all over the process. Care was taken on the representation of the area already covered. The implemented method superimposes artificial 2D-objects to the map of the environment. These objects, which will be treated further on as obstacles, are inserted over the areas covered by the line segments of the templates. This way, the representation of the area already covered is totally adapted to each template and consequently to the method used for path planning. As displayed in Fig. 4 for the area cleaned by a UT template, the artificial obstacle is inserted over the line segment of the template. The length of the artificial obstacle is determined by the length of the line segment of the UT template, this clearly demonstrating the adaptation of the method used for marking the covered area to the variations in the length of the template.

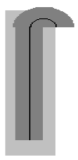


Fig. 4.: Artificial obstacle (light gray) inserted so as to mark the cleaned area of a UT template.

To assess the performance of the implemented methodology, the following measures of performance were defined: path length [m], specified area [m^2], covered area [m^2], ratio of actually covered area and specified cleaning area [%], redundant area [m^2] and operation time [s]. Due to the complexity of the motion pattern and the surrounding environment some of these parameters are evaluated using known methods from image processing. For example, the ratio of actually covered area is evaluated based on pixel counting.

III. PATH TRACKING

As explained in Section II, templates are executed by sequentially executing each of its sub-templates, which are defined by sub-goals. The flowchart of Fig. 5 illustrates the template execution algoritm.

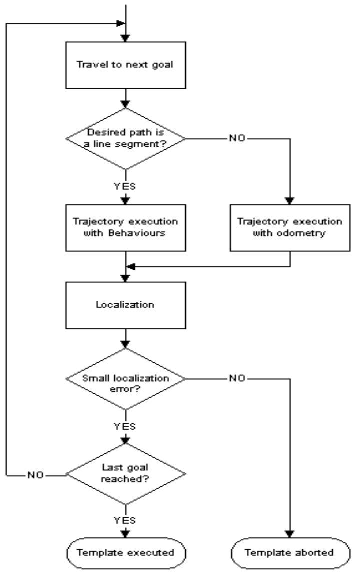


Fig. 5.: Template execution algorithm.

When the path to be followed towards the next subgoal is a line segment that ends near a mapped obstacle whose presence can be detected by the three front ultrasound sensors, a behavior based command is issued. In this case, the mobile robot follows a straight line until the presence of an obstacle is detected. Depending on the point at which detection occurs, a decision whether this is the expected obstacle of the environment or rather an unexpected one is taken. In the first case, the robot continues towards the the next-subgoal of the next planned sub-template. On the contrary, an obstacle avoidance procedure is implemented, as described in Section V. With this approach, the a priori map is not required to be very accurate and errors accumulated in the odometry system are less relevant, the overall robustness of the path tracking being greatly improved.

The behavior based approach just described implements a stopping criteria whenever the mobile robot is following a straight line included in a template, and, as represented in Fig. 6-a), the front sensors are expected to detect the obstacle. In the situation displayed in Fig. 6-b), the front sensors might not detect the obstacle due to specular reflection and beam width, and trajectory execution will exclusively rely on odometry.

Fig. 6.: Trajectory execution based on a) behaviours, b) odometry.

Stopping criteria for curves or straight lines not ending in mapped obstacles relies on traveled distance evaluated through odometry.

When the algorithm considers that the actual subgoal has been reachead, either using behaviours or odometry, the localisation procedure estimates, whenever possible, the platform's location and compares it with the predicted one obtained through the geometric characteristics of the executed sub-template and the a priori map. If the error is less then a pre-specified threshold, the next sub-template is executed. Otherwise, the template execution is aborted and, based on the estimated location, a new most appropriate template is chosen.

IV. LOCALIZATION

Localization is essential to correct the cumulative errors inherent to the odometry system, [8]. Using the a priori map and a model of the ultrasonic sensor, [5], [9], [10], a test is carried out at each subgoal, so as to determine if the real data acquired by the sensors is similar to the one predicted by the sonar model at the mobile robot location (position and orientation) estimate given by odometry. If the deviation between the predicted and the real measurements is less than a certain threshold, the real data is used to recalibrate the overall location of the mobile robot. Full details are given in [6].

This localization approach, based on low cost sensors and on the a priori map, requires no special modification on the environment, e.g. installation of bar codes. However, the implemented methodology introduces an overhead on path execution duration because localization has to be done with the vehicle stopped near an obstacle.

During experiments both position and orientation of the mobile platform were corrected using the proposed technique.

V. UNEXPECTED OBSTACLES

When the platform travels between two sub-goals that describe a line segment and an obstacle is detected by the set of installed sonars, the platform stops and the traveled distance is evaluated.

Using the knowledge of the distance to be travelled, evaluated during path planning, and the distance actually travelled and evaluated through odometry, the obstacle is either classified as expected, i.e., belonging to the environment map, or unexpected. The wall following method described in [5] and [7] is then used to overcome unexpected obstacles, as represented in Fig. 7, where 2 represents the point where the obstacle is first detected, 3 is an intermediate position along obstacle circumvention and 4 is the point where the planned trajectory is resumed.

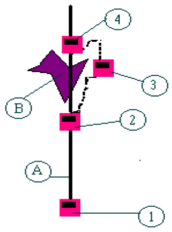


Fig. 7.: Contour following for obstacle circumvention.

The contour of the unexpected obstacles is followed at a pre-specified distance until a point over the original planned path is reached. If, after travelling a given distance, the mobile robot doesn't reach a point over the original planned path a new path is generated. Obstacle circumvention exclusively relies on ultrasonic data.

When the plataform travels between two sub-goals that describe an arc and a unexpected obstacle is detected no obstacle circumvention is executed and a new path is generated.

VI. RESULTS

Relevant experiments with the mobile robot LABMATE [8] were carried out. The platform, displayed in Fig. 8, has rectangular shape. Three ultrasound sensors are placed on each side for front, rear and lateral obstacle detection and contour following, while 5 sensors are installed on each corner.

Using a joystick the operator drives the robot to the vicinity of the chosen starting location. The localization procedure is then applied aiming at evaluating the vehicle's correct location. The total coverage path is evaluated and the robot starts its execution under the control of the path tracking module.

On the experiment displayed in Fig. 9, the initial and final locations are represented by I and F. The templates UT, BT, SS and TM were applied. The relevant performance parameters are displayed in Table 1.

The total area to be covered was 202.06 m^2 while the covered area was in fact 172.7 m^2 resulting in a coverage percentage of 85 %. This percentage will increase, should a wall following post procedure be applied.

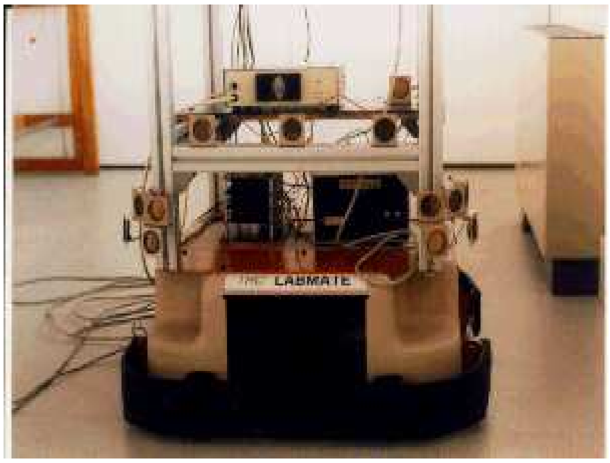


Fig. 8.: Labmate platform.

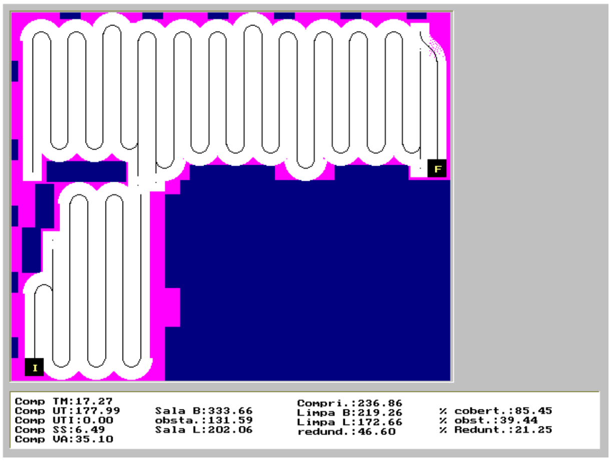


Fig. 9.: Trajectory generated for the Mobile Robot Lab. at ISR.

The localization detected deviations from the desired path up to 0.5 m. Processing time for location estimation is in the order of 5 to 10 s using a 486/66 MHz processor and the processing time associated with the selection of the next template takes 200 to 300 ms. The rather large interval between maneuvers results from the option taken of not firing the entire set of sonars when the robot is moving in a given direction. When the robot is moving forward, lateral and rear sensors are not fired. Instead, front, front-right and front-left sensors that most likely will detect unexpected obstacles are fired at given rate. The choice of the sensors to be fired on the next movement and the corresponding

Total Trajectory Length	236.9 m
Total Area to be Covered	202.06 m^2
Covered Area	172.7 m^2
Redundant Covered Area	46.6 m^2
Coverage Percentage	85.5%

Table 1.: Performance parameters.

initialization leads to an additional overhead.

A velocity of up to 200-400 mm/s during path tracking was obtained using the mobile robot LABMATE, which is adequate for the cleaning purpose.

As can be seen from Fig. 9 there are areas, near the border, which are not covered by the path planning algorithm. These areas can be covered by a final "Wall Following" path around the outer perimeter, [5].

The situation represented in Fig. 10 displays a test where the use of a BT template is required to clean the area left behind. For the sake of a clear understanding, the cleaned area covered by successive templates are represented with different gray levels. The platform starts at the point I with a UT template followed by another UT. Then, a UTI is apllied followed by a sequence of UT templates with extra TM apllied forward and backward (these extra TM templates significantly improve the overall covered area). At the right lowermost corner of the environment, a BT template is aplied driving the platform to point d where a new algorithm iteration will be applied. During the movement corresponding to BT, it is considered that no area is cleaned and therefore no area is marked as cleaned.

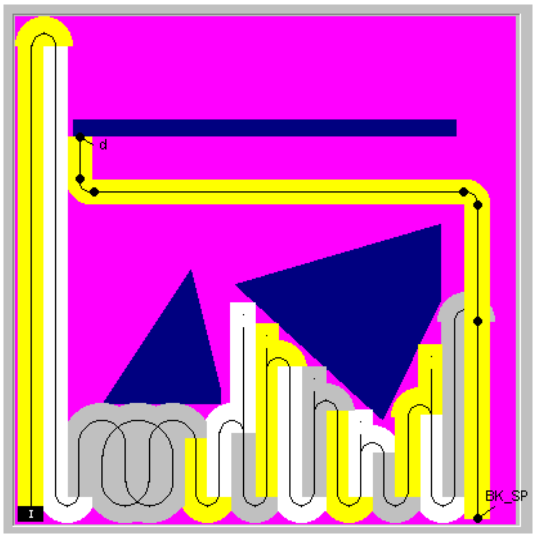


Fig. 10.: Use of a BT template to reach point d.

After the completion of the BT just referred, the total coverage planning proceeds, according to the methodology described in Fig. 3, yielding the coverages displayed in Figs. 11 and 12. Note that a second BT template has to be applied on the situation displayed in Fig. 11, aiming at cleaning the area above the horizontal uppermost obstacle.

Fig. 13 represents a deadlock situation within an obstacle with a C shape, from where the vehicle cannot escape. The use of a BT template will not solve the problem because all the area to the left of point F has already been marked as cleaned. Future work will handle this situation.

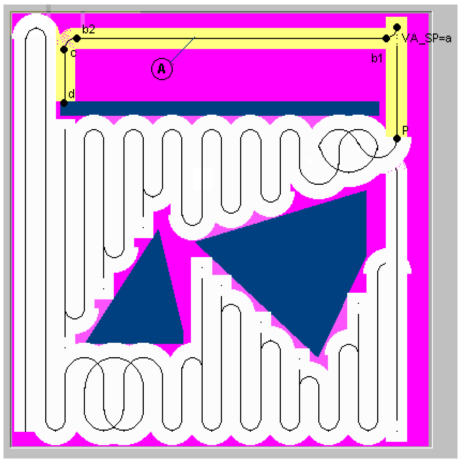


Fig. 11.: Requirement of a second BT template at point P and BT executed.

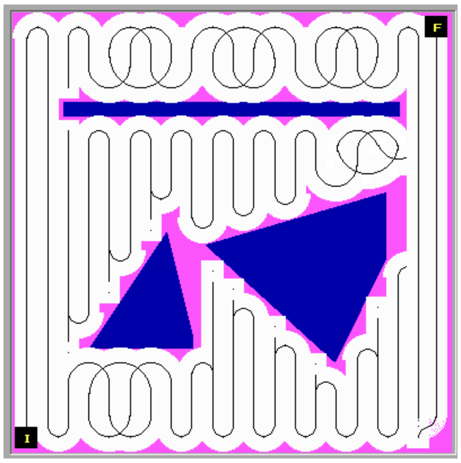


Fig. 12.: Complete coverage.

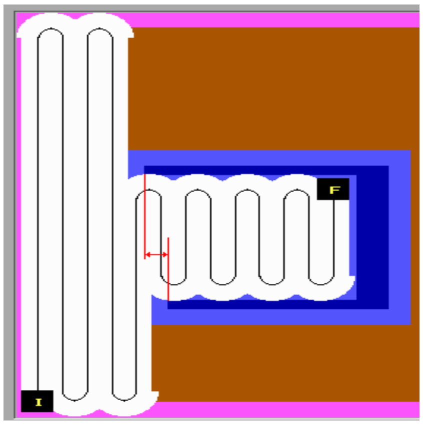


Fig. 13.: Obstacle with C shape and deadlock situation.

VII. CONCLUSIONS

Tests with the mobile robot LABMATE show that satisfactory floor coverage can be obtained using a template approach even when there are mapped or unmapped obstacles present in the interior of the cleaning area. The usage of the behavior based method was fundamental in improving the robustness of the path planner with small obstacles (up to 0.5 m in diameter) lined up against walls being detected as being part of the wall itself, thus not interfering with the execution of the path. The localization method applied is quite satisfactory showing that low cost methods are adequate for the proposed mission.

Further work will focus on solving more elaborate problems like the ones shown in Fig. 13, and in performing refinements on some of the templates, namely the Side Shift, aiming at reducing the redundancy covered area.

VIII. ACKNOWLEDGMENT

This work was partially supported by the project PRAXIS /3/3.1/TPR/23/94.

IX. REFERENCES

[1] Chistian Hofner, Günther Schmidt, "Path Planning and Guidance Techniques for an Autonomous Mobile Robot," *Robotics and Autonomous Systems*, vol.14, no. 2-3, May 1995, pp.199-212.

[2] Fumio Yasutomi, Daizo Takaoka, Makoto Yamada and Kazuyoshi Tsukamoto, "Cleaning Robot Control," in *Proceedings of the IEEE International Conference on Robotics and Automation*, 1988, vol.3, pp 1839-1841.

[3] A. Zelinsky, R. A. Jarvis, J. C. Byarne and S. Yuta, "Planning Paths of Complete Covarage of an Unstructured Enviroment by a Mobile Robot," in *Proceedings of the ICAR'93*, 1993, pp.533-538.

[4] Phillip John Mckerrow, *Introduction to Robotics*, 2nd edition, Addison Wesley, 1990.

[5] R. Neumann Carvalho, H. Vidal, P. Vieira, M. I. Ribeiro, "Wall Following an application to Automomous Robots," Internal Report (in Portuguese), Institute for Systems and Robotics, Lisbon, Portugal, Dec. 1995.

[6] R. Neumann Carvalho, H. Vidal, P. Vieira, M. I. Ribeiro, "Automatic Floor Cleaning based on Mobile Robots," Internal Report (in Portuguese), Institute for Systems and Robotics, Lisbon, Portugal, Dec. 1996.

[7] Maher Khatib, Raja Chatila, "An Extended Potential Field Approach for Mobile Robot Sensor Based Motion," in *Proceedings of the Inteligent Autonomous Systems*, IOS Press, 1995.

[8] "LABMATE^{TM} - User's Manual," Transitions Research Corporation^{TM}, 1991.

[9] "Proximity Subsystem User Manual," Transitions Research Corporation^{TM}",1991.

[10] "Ultrasonic ranging System," Polariod Corporation^{TM}, 1991.