Proceedings of the 1998 IEEE/RSJ
Intl. Conference on Intelligent Robots and Systems
Victoria, B.C., Canada • October 1998

An Advanced Planning and Navigation Approach for Autonomous Cleaning Robot Operations

G. Schmidt

Institute for Automatic Control Engineering
Technische Universität München
D-80290 München, Germany

C. Hofner

GANSOW GmbH & Co.-KG Maschinenbau
Industriestraße 22
D-59192 Bergkamen-Rünthe, Germany

Abstract

This paper presents an information processing scheme which increases the autonomy of floor caring robots in indoor applications, such as cleaning or inspection of industrial and public floor areas. An automatic planner generates a serpentine path pattern by repeated and appropriate concatenation of up to five basic motion macros. This nominal path is executed by a Cartesian motion controller. In case of unexpected obstacles the robot updates its internal geometric representation of the work area to be processed and replans its path. Due to obstacle avoidance, certain areas may remain unprocessed. Location and topology of such areas are automatically reconstructed for repeated follow-up floor caring in case of temporary obstacles. For this purpose connecting maneuvres and paths of complete floor coverage are incrementally planned and executed. Landmark localization at automatically preplanned reference points allows online modification of motion commands and guarantees precise long distance path tracking. Feasibility of the developed techniques has been demonstrated in various long-term experiments with the prototype mobile service robot MACROBE.

1 Introduction

Public services such as cleaning of terminals, platforms or halls will dominate in a growing affluent society. To meet the demands of high quality sevice at reasonable cost, competitive service companies have an increasing interest in applying innovative technologies ensuring economical benefits. Consequently there is a need for automation of such service tasks. In the past mobile robotics research has focused mainly on transportation and manipulation tasks, while service robots in floor cleaning tasks still seem to be an open and challenging field of investigation. Only a few publications have presented aspects of path planning and navigation for floor cleaning robots [2,3,11]. This situation stimulated the authors to develop an innovative information processing scheme that integrates important planning and guidance techniques for achieving most complete floor coverage with free navigating service robots. The proposed methods have been developed with the objective of practical application in real world indoor environments and refer to the automation of floor cleaning tasks. To identify a complete cleaning task, we destinguish the following operational phases:

1. *Initialization*
   a) Off-line path planning with respect to complete floor coverage
   b) Initialization of robot location prior to start of cleaning operation
2. *Nominal cleaning operation*
   a) Cycle of continuous path execution, perception and localization
   b) Event driven path adaptation, i.e. compensation of path tracking errors and path replanning in case of blockades
3. *Follow-up floor coverage*
   a) Extraction of uncleaned areas after completion of nominal cleaning process
   b) Planning and execution of
      1. point-to-point connecting maneuvres to guide robot to uncleaned areas
      2. appropriate paths to cover all accessible uncleaned areas.

This paper introduces the basic functions of a path planning and vehicle guidance scheme as a prerequisite for automatic follow-up floor coverage in case of temporaryly obstructed areas during the nominal cleaning process. The proposed approach contributes towards a greater level of autonomy and intelligence in task relevant behaviour of a cleaning robot. The human operator is relieved from manual guidance or path programming, which is still common in most cleaning robot applications [5,9,12,14, 15].

Section 2 outlines the operation of the proposed floor coverage path planner. Section 3 presents a brief discussion of corresponding guidance techniques, such as precise long distance path tracking and obstacle avoidance. In case of unexpected obstacles, complete floor coverage cannot be achieved in the course of the nominal cleaning process. To avoid manual cleaning of remaining un-

0-7803-4465-0/98 $10.00 © 1998 IEEE

cleaned areas, reconstruction of their topology and location is required. Related issues are discussed in section 4. The planning procedure for automatic follow-up floor coverage and completion of the cleaning task is presented in section 5. Section 6 demonstrates capabilities of the proposed information processing scheme through experiments performed with the prototype service robot MACROBE.

2 Floor Coverage Path Planner

As the path planner also contributes to nominal and follow-up floor coverage, its major features are summarized in this section. Detailed algorithms can be found in [7]. Planning is based on a geometric representation of the work space through 2D line segments and a geometric/kinematic model of the cleaning robot. A serpentine path pattern evolves from rule based concatenation of up to five basic motion macros. Kinematic restrictions of the robot are automatically considered by selecting appropriate macros. Each macro comprises a fixed sequence of line and circle segments to simplify trajectory parameterization. Every segment is described by an intermediate cartesian goal point, which is obtained from collision analysis in work space.

Each goal point specifies the set of parameters of a cartesian robot motion command. The automatically programmed path is stored and can be immediately executed by a cartesian motion controller [8]. In contrast to [11,16] the proposed approach is capable of planning of smooth floor coverage tracks for large scale service robots operating in areas of several thousand square meters, like railway platforms, airport terminals etc. Fig. 1 illustrates the application of the set of macros for path planning in a typical scenario. The algorithm of concatenation for achieving most complete work space coverage is described in [7]. In this example a robot without steering angle limitations was assumed, resulting in a serpentine path pattern composed of simple U-turns to guarantee a given overlap between neighbouring parallel tracks. Each track contains a set of intermediate cartesian goal points (x,y,Ψ), where (x,y) represent robot position and (Ψ) its orientation (see dots along the path in Fig. 1). Each goal point specifies the parameters for a motion command to be executed by a cartesian motion controller [8]. The geometric representation of the known workspace is based on closed 2D polygons. This layout is also visualized to the operator at the beginning of a cleaning operation for specification of both the desired start location and the cleaning area.

3 Vehicle Guidance

As robot navigation refers to a reference system B of the given layout, the robot must be able to initialize its proper start location before starting the cleaning operation. In the proposed approach the operator is expected to guide the robot manually in the vicinity of the start location S as selected in the layout. Corresponding locations may vary up to +/- 2m in position and up to +/- 45° in orientation with respect to S. Next, the robot determines its current position based on a landmark localization scheme as presented in [6].

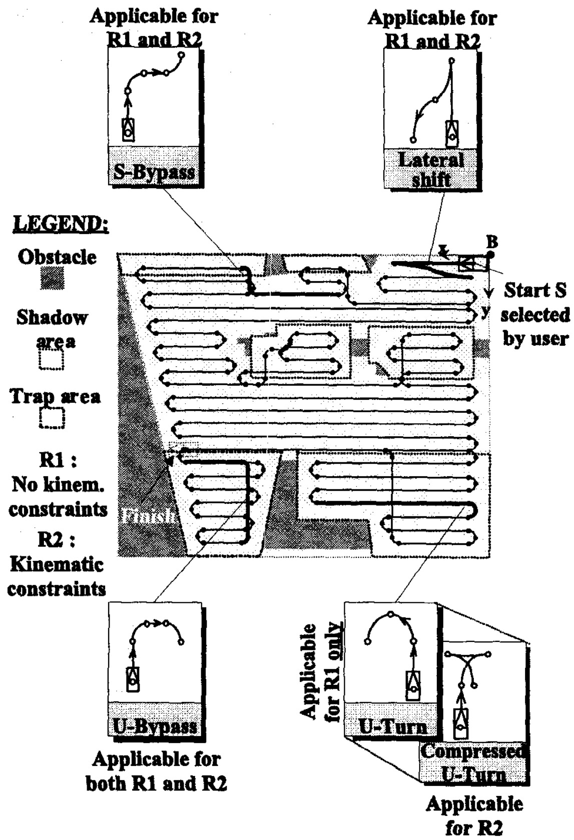

Fig. 1 : Path planning with macros and their concatenation with respect to generation of serpentine path pattern for most complete floor coverage

Subsequently, the robot plans and executes a local correction maneuvre [1] to access the first goal point of the off-line planned cleaning path. During nominal cleaning operation, the robot performs regular landmark localization to determine position and heading errors due to dead-reckoning uncertainties. For this purpose appropriate reference points are automatically selected along the path of complete coverage. The corresponding method is presented in [7]. Deviations from the planned path are compensated by modification of succeeding intermediate goal points of the motion program. This allows path tracking without updating of the robots dead-reckoning system. The relevance of path tracking becomes obvious in long-term operations of a mobile cleaning robot.

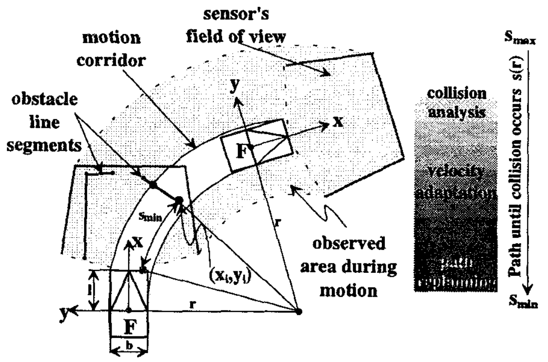

Fig. 2: Obstacle perception and navigation behaviour

To prevent the robot from colliding, tilting or falling, it must be capable to safely detect the freespace even along narrow winding U-turn sections of the cleaning path. To simplify updating of the a priori given layout, a 2D line segment representation of detected boundaries is used. Fig. 2 illustrates both the resulting field of view and the geometric representation of line segments as detected by a structured light CCD-sensor.

With respect to most complete floor coverage the robot approaches obstacles as close as possible. Obstacle contours are represented by 2D line segments both in the known layout and the local map obtained from sensor data. It is obvious that obstacle detection need not consider line segments located outside the current motion corridor. Only segments being part of the current motion corridor must be taken into account for calculatation of the collision distance s(r) according to Eqs. (1) and (2):

Collision distance while moving along a circular arc

$$s(r) = \begin{cases} r_k \left| \arcsin\left[\frac{x_i}{r_k}\right] - \arcsin\left[\frac{l}{r_k}\right] \right| & , r_k \geq r_{koll} \\ r_k \left| \arcsin\left[\frac{x_i}{r_k}\right] - \arccos\left[\frac{r_k - \frac{b}{2}}{r_k}\right] \right| & , r_k < r_{koll} \end{cases} \tag{1}$$

Collision distance while moving along a straight line

$$\lim_{r \to \infty} s(r) = \begin{cases} |x_i - l| & , r_k \geq r_{koll} \\ \infty & , r_k < r_{koll} \end{cases} \tag{2}$$

$$r_k = \sqrt{(r - y_i)^2 + x_i^2} \ , \ r_{koll} = \sqrt{(r - b/2)^2 + l^2}$$

The minimum collision distance s_{min} determines the robot's current velocity. Segments from known obstacles eventually disappear from the motion corridor (e.g. a wall is passed along a U-turn) and the robot speeds up again. This simple strategy allows to work with safety distances to obstacles of 150 mm without the necessity of path replanning. Unexpected obstacles however, permanently blocking the current motion corridor, cause the robot to stop. Prior to starting path replanning based on concatenation of motion macros) the layout is updated with sensor data from the detected obstruction, the current robot location and the boundaries of the already covered area.

The described nominal cleaning process is an event-driven cycle of perception, planning and execution. It terminates, when the robot has either completely executed a (re)planned path or when a feasible path could not be generated due to a complex obstacle configuration.

4 Reconstructing Topology of Uncleaned Areas

Depending on the obstacle configuration detected in the course of the nominal cleaning process, parts of the cleaning area may become temporarily inaccessible. Cleaning of such uncleaned areas can be implemented by the following method. First , the robot determines the topology of uncleaned areas and it subsequently starts automatic follow-up floor coverage.

In this section the basic idea of reconstructing the boundaries of uncleaned areas is presented. Since the robot stores every successfully executed motion command during the nominal cleaning process, it may reconstruct the already swept region based on the basic path elements "straight line" and "circular arc" (Fig. 3a). The swept region related to an executed motion command[1] is represented by a corridor polygon. It can be fused with the wrapping polygon (WPΣ) obtained from previous motion commands. The fusing technique is known from mapping procedures in exploration applications [10]. As Fig. 3b indicates, fusing is an incremental process, involving only two polygons for each new motion command. All line segments of a corridor polygon are concatenated clockwise. Fusion starts with point n1, which as a member of the latest polygon Ni and which is not enclosed by the already fused polygon Fi. Next all intersection points (ip1 to ip2) are calculated. While moving clockwise, all points ni are collected for NFi until the first intersection point (ip1) is detected. From this point all points fj are added to NFi until the next intersection point (ip2) indicates a change back to Ni. This process is continued until start point (n1) is reached again. Eventually, if all corridor polygons are fused, the actually covered area is topologically reconstructed with respect to reference system B.

To obtain the topology of uncleaned areas, it is necessary to define potential candidates for follow-up floor coverage. Two types of candidates exist according to the path planning technique described in section 1 : *Isolated areas and shadow areas*.

Isolated areas remain after the robot has completely passed obstacles as shown in Fig. 4a. To mark off such

[1] Each motion command is defined by two succeeding intermediate goal-points Gi and Gi+1.

areas, the presented polygon fusion technique is used. 4 intersection points exist in Fig. 4b between Ni and Fi. However, while reconstructing the fused polygon NFi only two of these points (ip3, ip4) were included in the fusion process. Now the following rule is defined: *If during the fusion of two corridor polygons any intersection points are left over, topology and location of an isolated area can be determined as follows :* Start with one point (e.g. f1*) being a member of the already fused polygon Fi. While moving counterclockwise, add all points of Fi to form the boundary dUAi of the isolated area UAi, until one of the remaining intersection points (e.g. ip1) is found. Change to polygon Ni and add the corresponding points to dUAi. Repeat this process, until start point (f1*) is reached (Fig. 4c). The set of collected points is stored as one "topological element" of a concatenated list (Fig. 4g).

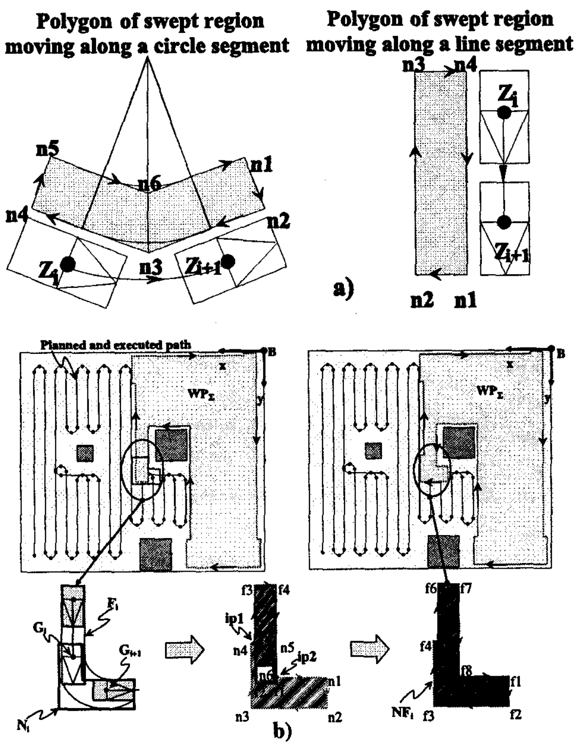

Fig. 3: Approximation of swept regions for basic path elements a), reconstruction of already covered area b)

To mark off shadow areas, polygon WPΣ must be compared with the boundary of the a priori known layout. For this purpose, search regions (squares in Fig. 4e) are centered around each point of WPΣ. The following rule is defined : *If there does not exist at least one corresponding point of the layout boundary in the search region of fi*, a shadow area can be determined as follows :* Calculate intersection point (ip1, Fig. 4f) between layout boundary and line segment defined by fi* (f11 of Fig. 4f) and its preceding point. Add fi* and all points of WPΣ to form the boundary dUAj of the shadow area UAj while moving counterclockwise along WPΣ. Repeat above steps for the case, that a corresponding point of the layout boundary can be found in the search region of another fi** (f20 of Fig. 4f). Add all points to dUAj while moving along the layout boundary until fi* is reached. The set of collected points represents another "topological element" of the concatenated list (Fig. 4g). As all uncleaned areas vary in size, the path planner of section 1 is applied to realize follow-up floor coverage. However, uncleaned areas ma turn out to be smaller than the requested minimum size for application of the proposed planner. In this case growing of the area boundary is performed as follows : A rectangle with length lNBi and width bNBi is defined to enclose the original boundary of an uncleaned area UAi. lNBi and bNBi are expanded symmetrically resulting in automatically generated layouts NBi* with length l*NBi and width b*NBi. The proposed floor coverage path planner is applied to the Nbi* areas (Fig. 5a). The l*NBi and b*NBi values are determined as follows:

$$l^*_{NBi} = \begin{cases} l_{NBi} & , l_{NBi} \geq \max\{r_h,\ r_f\} \\ l_{NBi} + 2\max\{r_h,\ r_f\} & \text{else} \end{cases} \tag{3}$$

$$r_{h,f} = \sqrt{(r_{turn} - b/2)^2 + l^2_{f,h}}$$

$$b^*_{NBi} = \begin{cases} b_{NBi} & , b_{NBi} \geq b/2 \\ b_{NBi} + b & \text{else} \end{cases} \tag{4}$$

lNBi > max{rh,rf}, where rh and rf denote the radius of the rear and front collision circle, allows the robot to cover the total uncleaned area along a straight track, before it changes to a neighbouring cleaning track. lNBi > b/2 meets the demands of complete coverage as the robot also passes the boundaries of UAi, which are located lateral to the alignment of the planned serpentine path pattern. Boundaries of the a priori known layout are automatically inserted to NBi*, if they are enclosed from the boundary dNBi*. Eventually the geometric representation NBi* substitutes the corresponding UAi of the topological memory.

5 Follow-Up Floor Coverage

The major steps to control a robot for follow-up floor coverage are illustrated in Figs. 5a to e. To start the floor coverage path planner, permitted start locations Si must be determined for the available layouts (NB1*..NB3* in Fig. 5a). For this purpose robot position and alignment is calculated according to the longest line segment of the boundary of each layout. The example in Fig. 5a shows 12 permissible start locations for the rectangular shaped, uncleaned areas.

To select the next uncleaned area, all euclidian distances are calculated for going from the current robot location Gf to each start location Si. In Fig. 5b, S12 is selected to be the nearest start location to Gf. Next an optimal connecting path CP1 from Gf to S12 is planned and executed. This task is solved by a local maneuvre planner [1], which optimizes path length with respect to the given kinematic restrictions of the robot and the accessible area from the a priori known layout. The actual path connecting Gf and S12 typically consists of circle-line-circle (CLC) or line-circle-line (LCL) maneuvres (Fig. 5b to d).

robot selects S6 to find a connecting path CP2 to NB2*. The described steps are repeated as long as all areas haven't been analyzed for access (Fig. 5b-d).

The incremental behaviour of planning and execution of both connecting paths and floor coverage paths is illustrated in Fig. 5e. Available start and goal locations are represented by the nodes of a selection tree. Its branches contain the euclidian distances for calculating local connecting maneuvres and the path lengths of serpentine patterns to realize follow-up floor coverage.

Up to this point it was assumed that the robot must not cope with permanent obstructions along any section of

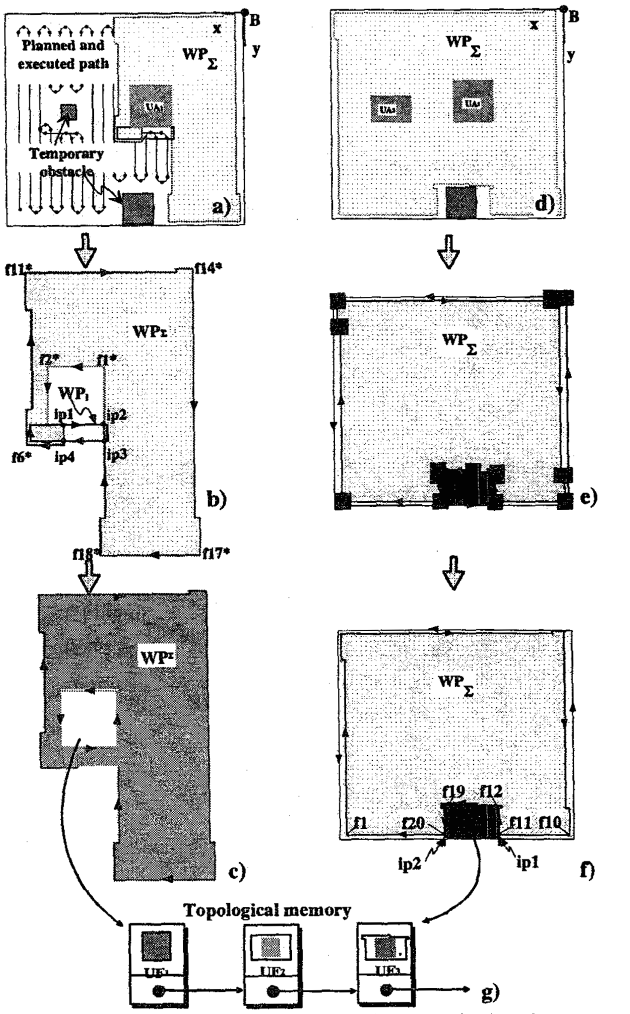

Fig. 4: Determining location and shape of isolated areas a) to c), shadow areas d) to f) and geometrical representation g)

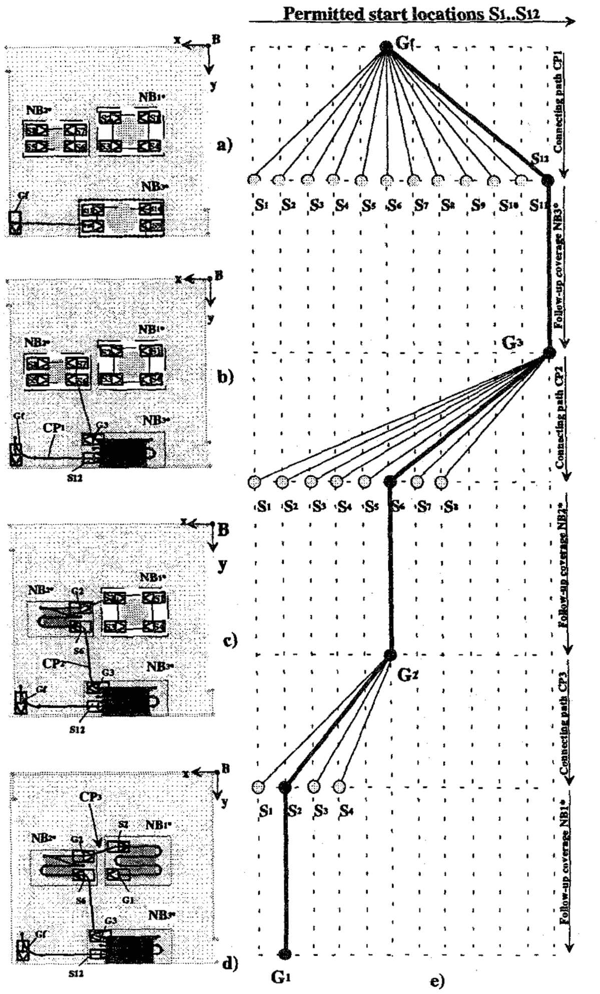

Fig. 5: Sequential follow-up coverage of three uncleaned areas

After the robot has reached S12, a path of complete floor coverage is planned. In case of successful execution, the robot is located at G3 and the corresponding layout NB3* is removed from the topological memory. From the remaining permitted start locations S1 to S8 the

the described incremental follow-up floor coverage procedure. If however a planned path is still blocked, e.g. the uncleaned area is occupied by a permanent obstacle, the robot stops, marks the inaccessible area for manual treatment and plans a new path to the closest among the remaining uncleaned areas. After completion of follow-up coverage, remaining uncleaned areas are displayed to the human operator. He can decide among several options : removing the area from the robot's memory, updating the original layout or commanding the robot to repeat follow-up coverage.

6 Experimental Results

The implementation of the proposed information processing scheme and experiments with the prototype service robot MACROBE are discussed in detail in [13].

7 Conclusions

This paper described approaches and procedures for increased autonomous operation of mobile robots in floor care tasks. The techniques developed are exceeding the current state-of-the-art by meeting requirements of long-term applicability in real-world indoor environments. The developed path planner is flexible with respect to the geometric layouts of large-scale cleaning areas and the kinematic/geometric features of the mobile robot. Planning times for motion paths with maximum floor coverage are in the order of seconds. This feature allows the same planner to be applied for on-line path replanning in case of obstacles. Another contribution of this paper is the development of a new technique for automatic reconstruction of uncleaned areas based on the robot's memory. Furthermore, a novel and systematic technique for planning of follow-up floor care operations of uncleaned floor patches is proposed. The presented procedures and algorithms for different types of planning and the corresponding sensor-based navigation and guidance techniques were implemented and tested with the prototype service robot MACROBE. The feasability of the approaches was demonstrated in various real-world long-term floor coverage experiments.

The authors are convinced, that the presented methods contribute to the development of more sophisticated robotic systems that will become available to service companies in the near future.

Acknowledgements

The work reported in this paper was supported by the Deutsche Forschungsgemeinschaft as part of the interdisciplinary research project „Information Processing Techniques in Autonomous Mobile Robots“ (SFB 331).

References

[1] Bott, W. „Automatische Planung und Ausführung lokaler Fahrmanöver für Roboterfahrzeuge“; PhD-Thesis in German, TU München, Germany, 1996

[2] Burhanpurkar, V.P. „Real World Application of a Low Cost High Performance Sensor System for Autonomous Mobile Robots“; Proc., Int. Conf. On Intelligent Robots and Systems (IROS '94), Munich, 1994, Vol. 3, pp. 1840

[3] Furuhashi, H. et al „Development of an Autonomous Cleaning Robot with an External Power Cable“; Proc., Int. Conference on Motion and Vibration Control, Yokohama, Japan, 1992, pp. 499

[4] Gilg, A. „Weitwinkel CCD-Lichtschnitt-Sensorsystem zur Führung eines mobilen Roboters mittels symbol-ischer Wegespezifikation“; PhD-Thesis in German, TU München, Germany, 1997

[5] HAKO GmbH. „Robomatic 80-Cleaning Robot“, Information brochures, Bad Oldesloe, Germany, 1994

[6] Hanebeck, U.D. „Lokalisierung eines mobilen Roboters mittels effizienter Auswertung von Sensordaten und mengenbasierter Zustandsschätzung“; PhD-Thesis in German, TU München, Germany, 1997

[7] Hofner, C. „Automatische Kursplanung und Fahrzeugführung für mobile Roboter bei flächendeckenden Bearbeitungsaufgaben“, PhD-Thesis in German, TU München, Germany, 1997

[8] Horn, J. „Cartesian Motion Control of a Mobile Robot“; Proc., Intelligent Vehicles Symp., Paris, 1994, pp. 443

[9] Kärcher GmbH. „BR 700 - Cleaning robot“, Information brochures, Winnenden, Germany, 1996

[10] Kampmann, P. „Ein topologisch strukturiertes Weltmodell als Kern eines Verfahrens zur Lösung von Navigationsaufgaben bei mobilen Robotern“; PhD-Thesis in German, TU München, Germany, 1991

[11] Kurabayashi, D. et al. „Cooperative Sweeping by Multiple Mobile Robots“; Proc. IEEE Int. Conf. On Robotics and Automation (ICRA '96), Minneapolis, U.S.A., 1996

[12] Schofield, M. et al. „Cleaning robots from concept to product - the users point of view“; Proc., 25th Int. Symposium on Industrial Robots (ISIR '94), Hannover, Germany, 1994

[13] Schmidt, G. et al. „An overall approach to improve task-relevant motion and guidance of cleaning robots“; Proc. IFAC Conf. on Intelligent Autonomous Vehicles (IAV'98), Madrid, Spain, 1998

[14] Villmer, F.-J. „Einsatzfelder und Applikationen von Dienstleistungsautomaten in der Reinigung“, Innovative Technologien für Dienstleistungen, Stuttgart, Germany, 1994, pp. 81

[15] Windsor Industries. „Robo-Scrub“, Information brochures, Colorado, U.S.A., 1994

[16] Zelinsky, A. „Planning Paths of Complete Coverage of an Unstructured Environment by a Mobile Robot“; International Journal of Robotics Research, MIT Press, 1994, Vol. 13, Nr. 4, pp. 315