ECC 95 European Control Conference, Rome, September 5-8 1995

Reactive Motion Control for an Omnidirectional Mobile Robot

Igor E. Paromtchik and Uwe M. Nassal

Institute for Real-Time Computer Systems and Robotics
University of Karlsruhe, Kaiserstr. 12, Build. 40.28, D-76128 Karlsruhe, Germany
Fax: +49/721/60 67 40, Tel: +49/721/608 42 63
e-mail: {paromt,nassal}@ira.uka.de

Abstract

This paper presents the developed practical approach to reactive motion control for the omnidirectional mobile vehicle of the Karlsruhe Autonomous Mobile Robot (KAMRO). The reactive control is based on the ultrasonic sensory information processing and is a supplement to the usual motion control of the vehicle. The geometrical path planner on the base of the environmental model generates global subgoals which define the coarse global path to a goal. To realize the planned motion within an environment where unknown obstacles may occur, the reactive control operates with the introduced preference functions of the vehicle and its global subgoal. The preference functions combined with the processing of sensory information provide the computation of the local subgoals leading the vehicle to its global subgoals or providing an obstacle avoidance. The developed approach is discussed and illustrated by the obtained experimental results.

Key Words: reactive control, mobile robots, obstacle avoidance.

1: Introduction

Real-time reactive behaviour is a substantially necessary feature of mobile robots. This provides their autonomous operation within an environment which may be dynamically changed from initial conditions described in an environmental model [1-3]. In the recent years, various research groups have been developing methods of reactive control for mobile robots. Mainly, these methods may be divided into two groups in dependence of whether they operate within a fully known environment or in the case of a partially known (or totally unknown) environment [3-5]. In the latter case the mobile vehicle does not posses enough information from its environmental model to generate a path to a goal without collisions with obstacles which are not included in the model. To avoid collisions, the sensory information about the environment is gathered and processed. Various vision systems were developed and are being studied to solve this task [6]. Such methods require significant computations and are complex for an on-line implementation. For practical realizations of reactive control ultrasonic sensor systems are mostly used [7, 8]. The ultrasonic sensor information is processed in different ways to obtain, e.g. a grid representation of the free space [7]. Then, the potential field method [9] or its modifications [10-13] are applied to compute a free path. The approaches within the frameworks of the potential field method have two main problems - undesired local minima and the necessity to generate arbitrarily large repulsive potential at boundaries of obstacles to avoid collisions. To solve both problems, the navigation functions were considered [10]. The wave propagation technique [14], diffusion method [15], distance field algorithm [16, 17] or probability approach [18] are used for navigation of the mobile robots. Navigation of mobile robots is carried out with the use of an environmental map [19] or without creation of such a map [4]. Architectural concepts regarding the integration of a high-level motion planning with low-level reactive behaviours [22] allow to improve the robustness and capabilities of autonomous mobile robots. The reactive behaviours provide a reasonable means to develop a reactive motion control for mobile robots. In our paper the reactive motion control along a preplanned coarse global path is considered. The global path is computed off-line on the base of the environmental model. The reactive control operates with the ultrasonic sensory information and provides the collision-free motion of the vehicle in a partially known environment.

2: Mobile Robot KAMRO

The KAMRO mobile robot is being developed to solve transport and assembly operations within a manufacturing environment. The robot's hardware consists of the mobile vehicle, two manipulators, a vision system to carry out comprehensive assembly operations and an ultrasonic sensor system used for reactive motion control. The KAMRO mobile vehicle moves by means of its four omnidirectional MECANUM-wheels which are position controlled. There are also two PUMA 200 manipulators in a hanging configuration on the vehicle. The manipulators are under position/force control. The vision system includes three CCD-cameras and the ultrasonic sensory system consists of 16 ultrasonic sensors situated on the sides and corners of the mobile platform. The hardware and control architecture of the KAMRO mobile robot is described in [1, 2, 20, 21].

The overall structure of the KAMRO navigation system is designed as a hierarchical planning system and is shown in Fig. 1. The central module is running on a SUN-Workstation and serves as a user interface for monitoring and control as well as an interface to the task level planner of the KAMRO [20]. For a task given to this module by the user or the task level planner, an integrated off-line global path planner computes a sequence of global subgoals. The corresponding algorithm is based on a convex polygon description of free space which is computed within a world model editor. A heuristic search algorithm provides a coarse global path in this graph of convex polygons. In a final step this path is refined where distances to edges in the neighbourhood of objects are maximized and the feasibility to pass a region is ensured. If the fine planner notices that the path is not feasible, the coarse planner is called again to replan the global path.

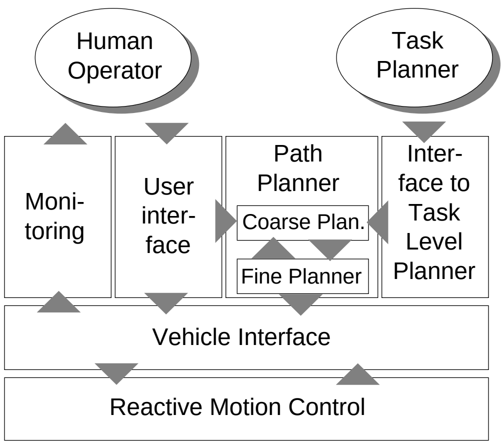

Figure 1: Overall structure of the navigation system

The vehicle's interface transmits *implicit commands* to the reactive motion control and receives status information concerning the current position and orientation as well as the velocity and the sensory data. The monitoring module displays this current information in a top view to inform the user on the current location and sensor image of the vehicle. The reactive motion control receives the *implicit motion* commands and executes them based on the current sensor information. The execution can be described as a transformation from *implicit motion commands* to *explicit motion commands* which completely specify the trajectory of the vehicle. Examples for implicit motion commands are *move* and *dock*. The *move* command specifies the position of the global subgoal that has been computed by the off-line planner. The *dock* command specifies the geometry of a bay, where the vehicle has to arrive a definite position and orientation relative to this bay.

3: Reactive motion control

To execute the planned motion, the control system of the KAMRO mobile vehicle receives its subgoals and the final goal position from the global path planner [2]. The planner operates off-line on the base of a two-dimensional environmental model. The path planner generates positions of the vehicle in the *(x,y)*-plane as a sequence of $(x_{s,i}, y_{s,i})$ - points where *s* denotes "subgoal" and *i* denotes "number of subgoal". These positions, further called "global subgoals", are presented as a list of global subgoals. The last global subgoal in this list is the final goal position for the vehicle. In this sense, computed global subgoals correspond to coarse paths. The control system of the vehicle, using the sensory information about its position/orientation and distances to the surrounding objects, has to carry out reactive control including the local path planning within such a coarse path to compute the local subgoals leading to the current (or next) global subgoal. This is substantially necessary if the vehicle can not follow the global path because of the proximity of objects. In the case of unexpected obstacles which were not primarily included in the environmental model, the use of reactive control with the ultrasonic sensory information processing and local path planning is especially necessary.

The reactive motion control was designed to provide the mobile vehicle with a feature of the fast and robust reaction if unexpected obstacles appear on its path or in its proximity. To get this feature, the control system of the vehicle uses the ultrasonic sensory system and the local path planning. The latter results in the additional subgoals, further called "local subgoals" for the vehicle; they lead the vehicle to its current subgoal or, in the case of obstacles, provide an obstacle avoidance. Thus the control system of the vehicle deals with two kinds of subgoals - *global* subgoals computed off-line by the global path planner and *local* subgoals computed on-line by the local path planner operating within the reactive motion control. If there are no obstacles, the local subgoals lead the vehicle to its current global subgoal. When the vehicle has achieved the neighbourhood of radius *r* to its current global subgoal, the control system receives the new global subgoal taken from the list of global subgoals. The value of this radius depends on the necessary accuracy of following the precomputed global path.

The reactive motion control is carried out with a sampling period defined by the period of renewing the ultrasonic data. It is not necessary to recompute the local subgoals, if the ultrasonic sensor data are not renewed yet. This also means that the technical specifications of the ultrasonic sensor system impose hard limitations on the velocity of the vehicle. The reactions of the control system depend on the receiving the correct range information from the ultrasonic sensors. The current ultrasonic sensory system of the KAMRO is able to renew the sensory data with a frequency of 1 Hz and the local subgoals of the vehicle are generated with the same frequency.

If obstacles are on the path of the vehicle so that it can not achieve its current global subgoal (i.e. an obstacle is situated at this position or very near to it), this subgoal is deleted from the list of global subgoals. Then, the next global subgoal is taken from this list. If the global subgoal to be deleted is the final goal position, i.e. if the goal position is occupied, the vehicle signals this event to the task level planner. Then, the adequate corrections in the goal position/orientation or in sequence of operations will be made.

Since the control system of the vehicle receives the global subgoals as $(x_{s,i}, y_{s,i})$-points, the orientations $\alpha_{s,i}$ of the vehicle at the global subgoals must be computed. These angles are used to keep the velocity vector of the vehicle being directed to its current global subgoal. During the motion to the current global subgoal the vehicle has such a reference orientation that it moves like a car keeping its orientation near tangent to the trajectory [21]. If there is not enough space available to hold such an orientation, the vehicle can move to its left or right side directions keeping its current orientation. This is possible because of the omnidirectional MECANUM wheels. To move through a sequence of narrow passages, this capability is used within the reactive motion control.

4: Reactive control based on the ultrasonic sensory information

The ultrasonic sensors are situated at the sides and corners of the vehicle as shown in Fig. 2. To examine only those areas that are relevant for collision avoidance and in order to decrease the influence of the noisy sensor data, the maximal measured distance is defined as r_{max}. If the measured values exceed this maximal one, i.e. $r_j \geq r_{max}$ where j denotes a sensor number, then it is set: $r_j = r_{max}$. Then, using the measured distances to objects around the vehicle, the weights of measurements are computed:

$$weight\_of\_measurement(j) = w_j = r_j / r_{max}, \; 0 \leq w_j \leq 1.$$

The deviation between the global subgoal and current position of the vehicle in the *(x, y)*-plane is found as

$$\mathbf{d}_{subgoal} = \mathbf{x}_{subgoal} - \mathbf{x}_{vehicle}, \tag{1}$$

where $\mathbf{x}_{subgoal}$ and $\mathbf{x}_{vehicle}$ are vectors of the subgoal and current positions of the vehicle in the world coordinates respectively. The vector $\mathbf{d}_{subgoal}$ gives the direction to the subgoal relative to the current position of the vehicle. The current direction of the vehicle in the *(x, y)*-plane is

$$\mathbf{d}_{vehicle} = (cos\alpha, \; sin\alpha)^T, \tag{2}$$

where α is current orientation angle of the vehicle in the world coordinates. From (1) and (2) one can receive the deviation angle ε between $\mathbf{d}_{subgoal}$ and $\mathbf{d}_{vehicle}$. This angle is considered as an orientation error which has to be compensated in order to direct the vehicle to its current global subgoal and thus $\mathbf{d}_{subgoal}$ and $\mathbf{d}_{vehicle}$ will coincide.

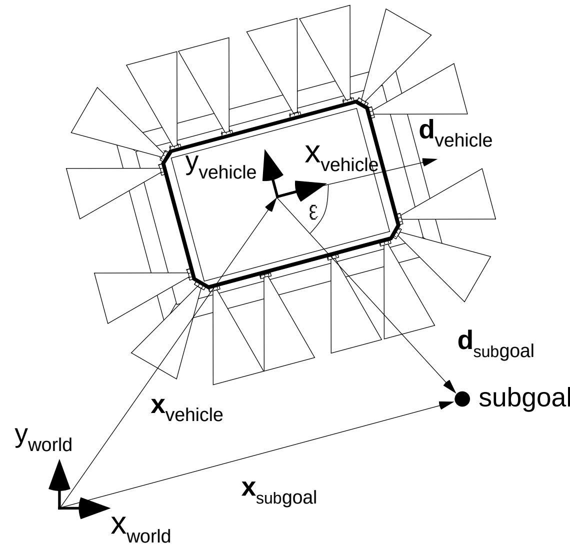

Figure 2: Representation of the coordinate systems

Based on the ultrasonic sensors configuration, eight possible directions of the vehicle's motion are considered, as it is shown in Fig. 3. The processing of the sensory information results in the *weight_of _measurement(k)*; $k \in \{0, \pm 1, \pm 2, \pm 3, \pm 4\}$ computed for each of these directions. The weights of measurements provide the normalized distance information about the free space around the vehicle. This information is used for the reactive motion control including two contradictory tasks - path following and obstacle avoidance. Mainly, the two tasks deal with the same problem of computing the direction of the vehicle's motion. In the case of path following the necessary direction is automatically computed by means of a spline-interpolation. But in the case of obstacles a preferable direction of the motion has to be computed.

To find the most preferable direction from the possible directions, shown in Fig. 3, the following preference functions of the vehicle and its global subgoal are introduced:

$$f_{vehicle}(k) = exp(-k^2 / 8), \quad k = 0, \pm 1, \pm 2, \pm 3, \pm 4, \tag{3}$$

$$f_{subgoal}(k, \; \varepsilon) = exp\{-(k\pi + 4\varepsilon)^2 / (8\pi^2)\}, \quad k = 0, \pm 1, \pm 2, \pm 3, \pm 4, \tag{4}$$

where k denotes "number of direction"; values of these functions are between 0 and 1. The directions for $k = 0, \pm 1, \pm 2, \pm 3, \pm 4$ are considered relative to the current position/orientation of the vehicle and are shown in Fig. 3. The preference function (3) gives weights of the possible directions of the motion relative to the current vehicle's direction so that:

- current direction ($k=0$) is the most preferable ("very large preference"),
- directions of ±45° ($k=\pm 1$) are preferable ("large preference"),
- directions of ±90° ($k=\pm 2$) are not very preferable ("middle preference"),
- directions of ±135° ($k=\pm 3$) are not very desirable ("small preference"),
- directions of ±180° ($k=\pm 4$) are not desirable (backward motion) but possible ("very small preference").

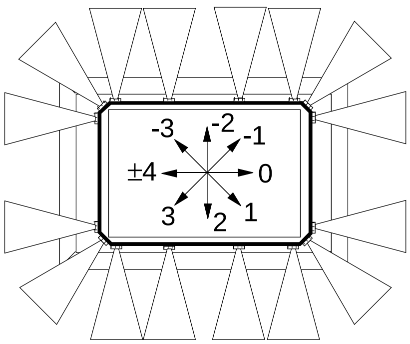

Figure 3: Interpretation of directions for the vehicle

The same explanation is used for the preference function (4) of a subgoal. In the case of $\varepsilon = 0$, the both preference functions coincide. From (4) it follows that $f_{vehicle}$ has always the same values for the same directions relative to the vehicle's current direction. But the values for $f_{subgoal}$ are dependent on the angle ε between $\mathbf{d}_{subgoal}$ and $\mathbf{d}_{vehicle}$. The both preference functions with a deviation $\varepsilon = 45^\circ$ are shown in Fig. 4.

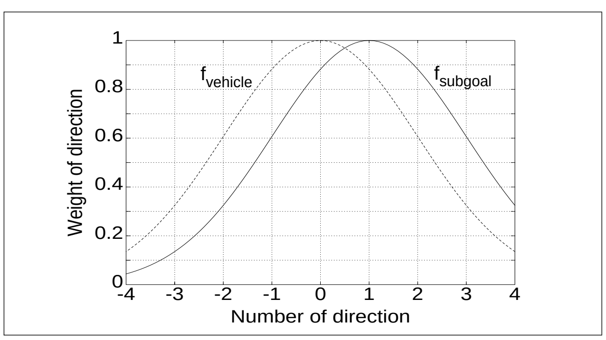

Figure 4: Preference functions

The $weight\_of\_measurement(k)$; $k \in \{0, \pm 1, \pm 2, \pm 3, \pm 4\}$ computed on the base of the ultrasonic sensory data, "modulate" the preference functions (3), (4) and this results in the following weights of directions:

$$weight\_of\_direction(k) = \begin{cases} weight\_of\_measurement(k) \cdot \\ \quad f_{subgoal}(k, \varepsilon), \text{ if path is free}, \\ weight\_of\_measurement(k) \cdot \\ \quad f_{vehicle}(k), \text{ if path is not free}. \end{cases} \tag{5}$$

The resulting direction, i.e. its *number_of_direction*, is found as a number corresponding to the maximal value of the *weight_of_direction(k)* for all k:

$$number\_of\_direction = i \quad \text{with} \quad weight\_of\_direction(i) = \max_k (weight\_of\_direction(k)) \tag{6}$$

If an obstacle is detected in any direction, the weight of this direction is being decreased when the vehicle is approaching the obstacle. Since the direction with the maximal value of the preference function is always taken as the further direction of motion, the decrease of the weight for the current direction because of the obstacle will cause the vehicle to rotate and change its current direction to avoid collisions with the obstacle.

As it follows from (5), only one of the preference functions is applied at each moment to define a direction of the further motion. Which function is used depends on the results of the processing of the sensor data. If the sensor data show that the path to the current global subgoal is free, the preference function of a subgoal is applied and the local subgoals lead the vehicle to its current global subgoal. In the opposite case the preference function of the vehicle is used, the current global subgoal is not taken into account and the vehicle moves in the direction which is not occupied by objects. After the vehicle has moved around the obstacle and when the sensor data shows that the path leading to the current subgoal is free, the preference function (4) is applied to control the vehicle. It results in a rotation of the vehicle to get the orientation corresponding to the direction to this subgoal. There are also situations when the vehicle can achieve its global subgoal with a specific orientation only because of the environmental objects or obstacles. In this case the appropriate orientation is obtained automatically by the reactive control using the ultrasonic sensory data and the vehicle moves to its current global subgoal keeping this orientation.

Generally, there are three areas to be considered within the reactive control: *far area*, *area of obstacle avoidance* and *near area*. Objects situated in the *far area* do not produce any influence on the vehicle's motion - they are too far and are not considered within the reactive control. Borders of the *obstacle avoidance area* and the *near area* are dependent on the current velocity and possible (or maximal) acceleration of the vehicle. The reactive control operates within the *obstacle avoidance area* and the *near area*. If an obstacle is situated in the *near area* of the vehicle, the reactive control pushes the vehicle to the opposite side (if it is free) or commands to stop the vehicle in order to avoid a collision.

The velocity of the vehicle is a function of the minimal measured distance between the vehicle and the surrounding objects so that the vehicle speeds down in the neighbourhood of objects to prevent possible collisions and it speeds up while moving away from objects.

5: Experimental results

The developed practical approach to reactive motion control is currently used to control the KAMRO mobile vehicle within a manufacturing environment. A rather simple example of the vehicle's motion in the case of an unknown obstacle situated on the preplanned path, is shown in Fig. 5 to illustrate the algorithms. The preplanned reference trajectory was received from the global path planner as a straight line. Because of the obstacle detected by the ultrasonic sensor system, a segment of this reference trajectory was modified into a curve to avoid a collision with the obstacle. During this motion the orientation of the vehicle was near tangent to its trajectory.

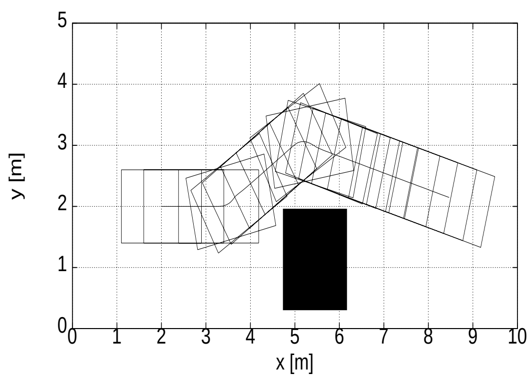

Figure 5: Motion during obstacle avoidance

The corresponding preference function of a subgoal is shown in Fig. 6. It is obvious that during obstacle avoidance this function has a shift to the right side. This shift corresponds to the deviation ε between the current direction of the vehicle's motion $\mathbf{d}_{vehicle}$ and the direction to the subgoal $\mathbf{d}_{subgoal}$. Since the obstacle has been detected on the way of the motion, the preference function of the vehicle is used to compute the *weight_of_direction* in accordance with (5). The vehicle moves to a free area so that its direction of the motion minimally differs from the current direction.

The computed values of the *number_of_direction* during this motion are presented in Fig. 7. First, the *number_of_direction* is changed from 0 to -1 when the obstacle has been detected. This corresponds to the rotation of the vehicle to the left side relative to the obstacle. This rotation is carried out until no obstacles are detected in front of the vehicle and it can move forward without collisions. Then, the vehicle moves forward with the *number_of_direction* = 0 until the sensor data show that the way to the subgoal is free. Now, the preference function of the current global subgoal is used and the *number_of_direction* is changed from 0 to 1. This corresponds to the rotation of the vehicle to the right side relative to the obstacle. This rotation is made until the vehicle's direction of the motion coincides with the direction to the subgoal. Then, using *number_of_direction* = 0, the vehicle moves to the subgoal and the shift of the preference function in Fig. 6 is eliminated. These results give an example of operation of the developed reactive motion control in the case of obstacle avoidance.

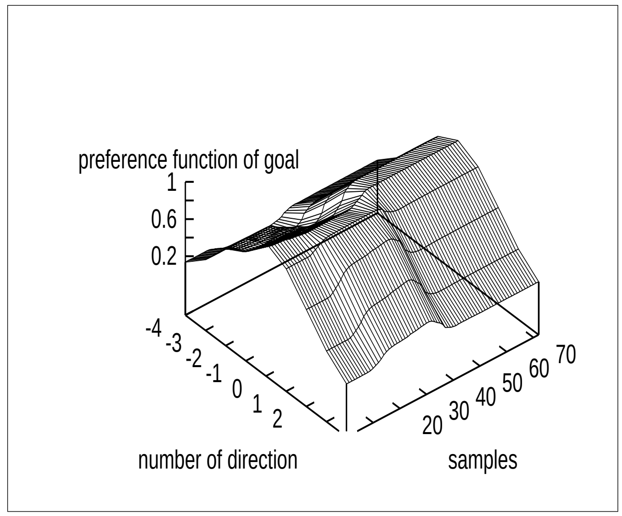

Figure 6: Preference function of subgoal during the obstacle avoidance

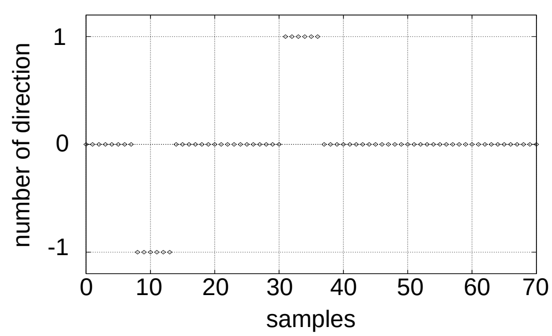

Figure 7: *Number_of_direction* during the obstacle avoidance

To guarantee the collision-free motion of the vehicle, an accumulation of the ultrasonic measurements is used. This means that a new direction is taken if it is confirmed (sequentially a few times) that the corresponding area is free. At the same time, if the current direction of the motion is not confirmed as free, a correction is done immediately. This provides the reliable motion of the vehicle.

6: Conclusion

A practical approach to reactive motion control based on the ultrasonic sensory information processing was developed for an omnidirectional mobile robot. To control the vehicle and provide its collision-free motion, the preference functions of the vehicle and its global subgoal were introduced. These functions combined with the ultrasonic sensor data were used to compute the reasonable direction of the vehicle's motion. The developed approach was experimentally verified and the obtained results were presented and discussed. The results have proved robustness and applicability of the considered reactive control to increase the capabilities of autonomous operation of the mobile robots. Currently, a local map based on the ultrasonic data and the environmental model is being worked out to wide the developed approach for the case of dynamic obstacles and complex manufacturing environments.

Acknowledgement

This work was performed at the Institute for Real-Time Computer Systems and Robotics, Prof. Dr.-Ing. U. Rembold and Prof. Dr.-Ing. R. Dillmann, University of Karlsruhe. The research work was funded by the "Sonderforschungsbereich Künstliche Intelligenz" of the Deutsche Forschungsgemeinschaft.

References

[1] Hoermann, A., and Rembold, U.: Development of an Advanced Robot for Autonomous Assembly, *Proc. of the IEEE Int. Conf. on Robotics and Automation, Sacramento, California, April 1991*, pp. 2452 - 2457.

[2] Hugel, T.: Real-Time Control of an Omnidirectional Mobile Robot with Sensor-Based Reactive Components, *Ph.D.-Thesis (in German), University of Karlsruhe*, 1992.

[3] Arkin, R.: Towards the Unification of Navigational Planning and Reactive Control, *Proc. of the AAAI Spring Symp. Robot Navigation Working Notes, March 1989*, pp. 1 - 5.

[4] Lumelsky, V.J., and Stepanov, A.A.: Path Planning Strategies for a Point Mobile Automation Moving Amidst Unknown Obstacles of Arbitrary Shape, *Algorithmica, Vol. 2, No. 4, 1987*, pp. 211 - 215.

[5] Brooks, R.: Intelligence Without Representation, *Artificial Intelligence J., Vol. 47, 1991*, pp. 139 - 159.

[6] Takeuchi, T., Nagai, Y., and Enomoto, N.: Fuzzy Control of a Mobile Robot for Obstacle Avoidance, *Information Sciences, Vol. 45, No. 2, 1988*, pp. 231 - 248.

[7] Borenstein, J., and Koren, Y.: Real-time Obstacle Avoidance for Fast Mobile Robots in Cluttered Environment, *Proc. of the IEEE Int. Conf. on Robotics and Automation, Cincinnati, Ohio, 1990*, pp. 572 - 577.

[8] Crowley, J.L.: World Modelling and Position Estimation for a Mobile Robot Using Ultrasonic Ranging, *Proc. of the IEEE Int. Conf. on Robotics and Automation, 1989*, pp. 674 - 680.

[9] Khatib, O.: Real-time Obstacle Avoidance for Manipulators and Mobile Robots, *Int. Journal of Robotics Research, Vol. 5, No. 1, 1986*, pp. 90 - 98.

[10] Khatib, M., Chatila, R.: An Extended Potential Field Approach For Mobile Robot Sensor Based Motions, *4th International Conference on Intelligent Autonomous Systems - IAS-4, Karlsruhe, March 27-30 1995*, pp. 490 - 496.

[11] Rimon, E., and Koditschek, D.E.: Exact Robot Navigation Using Artificial Potential Functions, *IEEE Trans. on Robotics and Automation, Vol. 8, No. 5, Oct. 1992*, pp. 501 - 518.

[12] Koren, Y., and Borenstein, J.: Potential Field Methods and their Inherent Limitations for Mobile Robot Navigation, *Proc. of the Int. Conf. on Robotics and Automation, April 1991*, pp. 1398 - 1404.

[13] Kim, J.-O., and Khosla, P.: Real-time Obstacle Avoidance Using Harmonic Potential Functions, *IEEE Transactions on Robotics and Automation, Vol. 8, No. 3, June 1992*, pp. 338 - 349.

[14] Barraquand, J., and Latombe, J.-C.: Robot Motion Planning: A Distributed Representation Approach, *Int. Journal of Robotics Research, Vol. 10, No. 6, 1991*, pp. 628 - 649.

[15] Schmidt, G.K., and Azarm, K.: Physical Analogies for Rapid Robot Motion Planning and Execution in Dynamic Environment, Proc. of the *IMACS/SICE Int. Symp. on Robotics, Mechatronics and Manufacturing Systems'92, Kobe, Japan, Sept. 16 - 20 , 1992*, pp. 609 - 614.

[16] Mataric, M.J.: Integration of Representation into Goal-driven Behaviour-based Robots, *IEEE Trans. on Robotics and Automation, Vol. 8, No. 3, June 1992*, pp. 304 - 312.

[17] Dillmann, R., Kreuziger, J., and Wallner, F.: PRIAMOS: An Experimental Platform for Reflexive Navigation, *Robotics and Autonomous Systems, No. 11, 1993*, pp. 195 - 203.

[18] Hu, H., Brady, M., and Probert, P.: A Decision Theoretic Approach to Real-time Obstacle Avoidance for a Mobile Robot, *Proc. of the IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, Yokohama, Japan, July 26-30, 1993* , pp. 1457 - 1464.

[19] Chatila, R., and Laumond, J.-P.: Position Referencing and Consistent World Modelling for Mobile Robots, *Proc. of the IEEE Int. Conf. on Robotics and Automation, March 1985*, pp. 138 - 145.

[20] Damm, M., Kappey, D., Schloen, J., Rembold, U., and Dillmann, R.: A Multi-Sensor and Adaptive Real-time Control Architecture for an Autonomous Robot, *Proc. of the Int. Conf. on Intelligent Autonomous Systems IAS-3, Pittsburgh, Penn., Feb. 15-18, 1993*, pp. 439 - 448.

[21] Paromtchik, I.E., and Rembold, U.: A Practical Approach to Motion Generation and Control for an Omnidirectional Mobile Robot, *Proc. of the IEEE Int. Conf. on Robotics and Automation, San Diego, California, May 8 - 13, 1994*, pp. 2790 - 2795.

[22] Payton, D.W., Rosenblatt, J.K., and Keirsey, D.M.: Plan Guided Reaction, *IEEE Trans. on Systems, Man and Cybernetics, Vol. 20, No. 6, 1990, pp. 1370-1382.*