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Hierarchical action control technique based on prediction time for autonomous omni-directional mobile robots

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1. Introduction

Recently, various essential technologies of an autonomous mobile robot such as a self localization scheme, an environmental map formation and path planning, learning algorithm and communication are developed in the area of robot. In addition, a variety of service robots which offers service with the actual environment with other moving objects, including people are proposed and developed(B. Graf, 2004; Asoh,2001; DeSouza,2002; Thrun,1999; R. Bischoff). A variety of tasks are required for such a service robot, but here we will focus on problems related to moving, which is the most fundamental and important of tasks. In the environment include humans, safe and efficient movement should be required. To deal with this problem, there have been a variety of mobile control techniques for the autonomous mobile robot. The visibility graph-like method and the Voronoi diagram method are the technique to design the pass which can reach a goal without colliding with obstacles on the basis of the advance knowledge of environment. However, it is not easy to work effectively with an actual environment where the unknown static or moving obstacles exist, because the complete knowledge regarding environment is needed. On the one hand, sensor based approach and reactive technique are the technique where recognizes the information of environment with the sensor and then decides behaviour in real time. Therefore it is the technique which is suited for actual environment.

This study proposes a hierarchical action control method for autonomous omni-directional mobile robot to achieve a smooth obstacle avoidance ensuring safety in the presence of moving obstacles including humans. The hierarchical control method considers various time scales for actions such as goal path planning, obstacle avoidance within the recognizable range, and emergency avoidance to deal with unexpected events. In the proposed method, several modules for each action are composed in parallel.

The vertical axis is the time scale in the control system. In the lowest module, the robot can move to the goal safely and efficiently by planning from the environment information which is obtained in advance. In the higher module, the robot moves more safely by using the estimated information about the obstacles to avoid them. By integrating the output of each module comprehensively, it is possible to realize a safe and efficient movement according to the situation. In this paper, as an example of the proposed moving control technique, we present a method based on virtual potential fields (Khatib, 1986; Brooks, 1986; Ge, 2002).

First, the module which generates the potential field based on each prediction time is formed hierarchically. Second, the virtual force which is derived from the respective potential fields is synthesized. Third, the velocity command is decided on the basis of the resultant force.

To verify the effectiveness of the proposed technique, some experiments using the real apparatus of an autonomous omni-directional robot have been carried out. Moreover, experimental results in an hospital environment are shown.

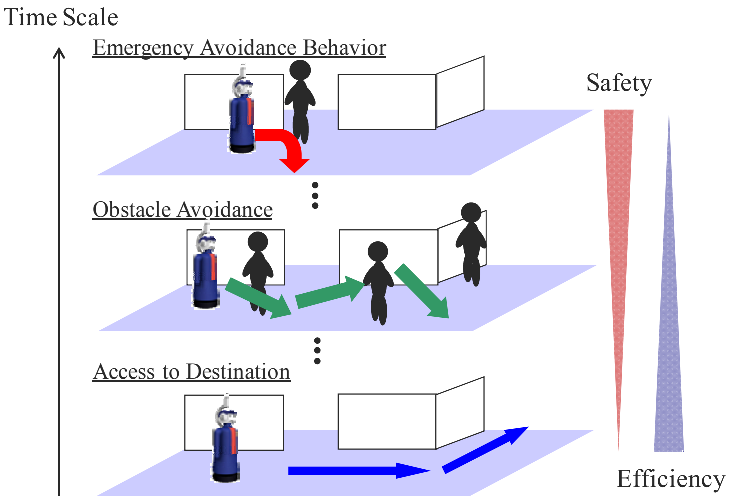


Fig. 1. Problem Establishment for Action of Service Robot

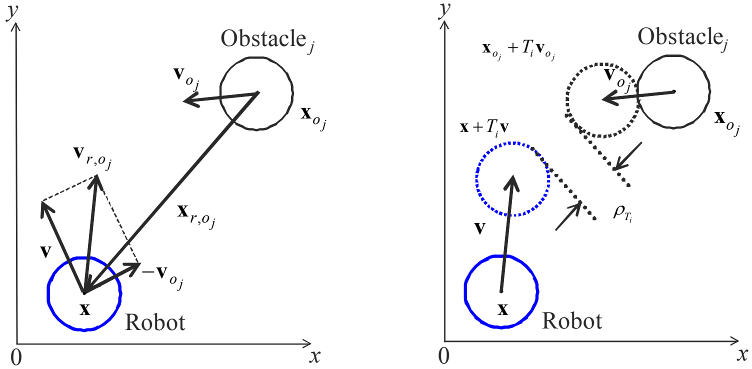


Fig. 2. World coordinate system and predicted shortest distance.

2. Important Hierarchical Action Control Method Considering Prediction Time of its Actions

2.1 Nomenclature

Symbol	Quantity
T_i	Prediction time
ρ_g	Distance between the robot and the goal
ρ_{T_i}	Predicted shortest distance between the robot and the obstacle
ρ_0	Minimum of repulsive potential
$\mathbf{x}$	Position vector of robot
$\mathbf{x}_\mathrm{g}$	Position vector of the goal
$\mathbf{x}_{o_j}$	Position vector of object O_j
$\mathbf{x}_{r,o_j}$	Position vector of the obstacle O_j relative to the robot
$\mathbf{v}$	Velocity vector of robot
$\mathbf{v}_{o_j}$	Velocity vector of object O_j
$\mathbf{v}_{r,o_j}$	Velocity vector of the obstacle O_j relative to the robot
$U_{o_j}^{T_i}$	Virtual potential about object O_j on each time scale
$\mathbf{F}_{o_j}^{T_i}$	Virtual force vector from $U_{o_j}^{T_i}$
i	Index of each time scale
j	Index of object
x	x-axis
y	y-axis

Table 1. Nomenclature

2.2 Concept

In this study, we address the issues concerning robots that are expected to move within general buildings, such as public spaces, offices, hospitals, or homes, with other moving objects, including people. A variety of tasks are required for such a service robot, but here we will focus on problems related to moving, which is the most fundamental and important of tasks. As the service robot comes in direct contact with humans, we must attach importance to safety to ensure that the robot will not harm humans, but the time it requires for its movements must be minimized as much as possible. It is desirable for the robot to reach its goal without colliding with obstacles, including humans. However, this type of environment includes events that are unpredictable at the design phase, and it is difficult to respond to various circumstances using a scenario-based method. Thus, we propose a moving control method that generates actions corresponding to the circumstances, by embedding a fundamental problem-solving method for moving into the control system.

We propose a hierarchical moving control method that considers the differences in time scale among actions to achieve both safe and effective movement; e.g., movement of the robot over the shortest distance can be realized based on prediction of the movements of objects, such as those that have a relatively large time scale, including structures in the environment that do not change, or moving obstacles that only move in a constant and predictable direction. However, in a dynamic environment with moving objects such as humans, spontaneous events may occur that cannot be predicted, and thus it is desirable to use very short-term predictions to realize safe movement. To realize movement over such short distances and safely, decision making regarding actions considering time scale differences is required. The hierarchical control method considers various time scales for actions in problems with various time scales, such as goal path planning, obstacle avoidance within the recognizable range, and emergency avoidance to avoid spontaneous events. The module is a potential function with the time scale as a design parameter, and generates a potential field.

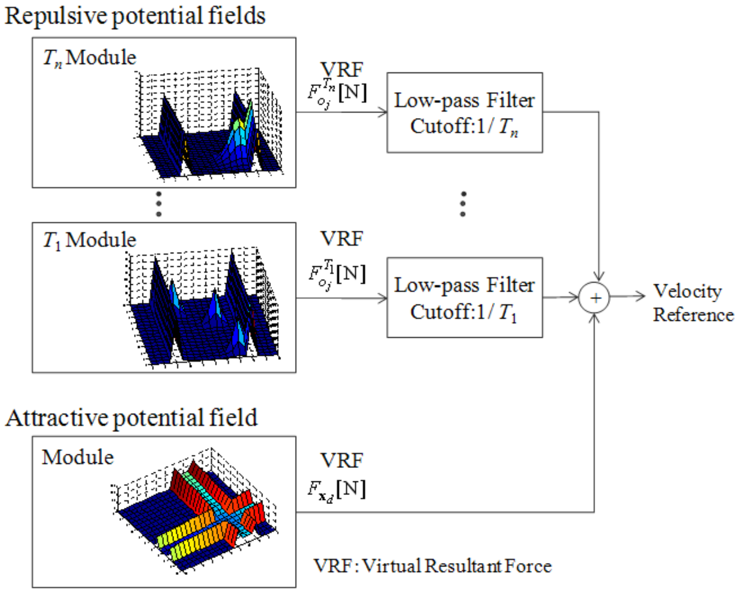


Fig. 3. Output of each module and integration.

2.3 Design Method

The module is a potential function with the prediction time as a parameter, and generates a potential field for each problem and virtual force on the robot is calculated. In this study, the proposed potential function was designed based on the repulsive potential reported by Khatib (Khatib, 1986).

$$U = U_{\mathbf{x}_g} + U_o \tag{1}$$

$$U_{\mathbf{x}_g} = k_a \rho_g \tag{2}$$

$$U_o = \sum U_{oj}^{T_i} \tag{3}$$

$$U_{o_j}^{T_i} = \begin{cases} \eta T_i \left(\dfrac{1}{\rho_{T_i}} - \dfrac{1}{\left\| T_i \mathbf{v}_{r,o_j} \right\| + \rho_0} \right)^{\frac{1}{T_i}} & , \rho_{T_i} \le \left\| T_i \mathbf{v}_{r,o_j} \right\| + \rho_0 \\ 0 & , \rho_{T_i} > \left\| T_i \mathbf{v}_{r,o_j} \right\| + \rho_0 \end{cases} \tag{4}$$

where $\mathbf{x}_g$ is the goal position and $U_{\mathbf{x}_g}$ is an attractive potential field. In the proposed method, a repulsive potential function in consideration with prediction time T_i is used.

ρ_{T_i} is the predicted shortest distance between the robot and the obstacle O_j at time scale T_i. This is determined by calculating the predicted positions of the robot and the obstacles after time T_i using the current velocity, and by calculating the shortest distances in these positional relationships.

$1 \big/ \left(\left\| T_i \mathbf{v}_{r,o_j} \right\| + \rho_0 \right)$ in Eq. (4) is a parameter that determines the range of the potential field in the repulsive potential of Khatib. ρ_0 is the limit distance of the potential field influence and η is a constant gain. By considering the relative velocity, the response of the robot is expected to change even if the relative position of the obstacle to the robot is the same. For example, when the relative velocity is large, the robot reacts more quickly.

The exponential part $1/T_i$ is the part of the equation that determines the priority level of the output of each module. When the robot faces an emergency situation, the time scale is small, and the output of the module with a small time scale is large. Thereby, the robot acts more rapidly.

A force for the position **x** of the robot is derived from the following equation.

$$\mathbf{F}(\mathbf{x}) = -\frac{\partial U}{\partial \mathbf{x}} \tag{5}$$

where $\dfrac{\partial U}{\partial \mathbf{x}}$ denotes the partial derivation vector of the total virtual potential U. From Eqs. (2) and (5), the attractive force allowing the position x of the robot to reach the goal position $\mathbf{x}_g$ is as follows:

$$\mathbf{F}_{\mathbf{x}_g} = -k_a \frac{\partial \rho_g}{\partial \mathbf{x}} \tag{6}$$

From Eqs. (4) and (5), the repulsive force to the obstacle O_j are as follows:

$$\mathbf{F}_{o_j}^{T_i} = \begin{cases} \eta \left(\dfrac{1}{\rho_{T_i}} - \dfrac{1}{\left\| T_i \mathbf{v}_{r,o_j} \right\| + \rho_0} \right)^{\frac{1}{T_i} - 1} \dfrac{1}{\rho_{T_i}^2} \dfrac{\partial \rho_{T_i}}{\partial \mathbf{x}} & , \rho_{T_i} \le \left\| T_i \mathbf{v}_{r,o_j} \right\| + \rho_0 \\ 0 & , \rho_{T_i} > \left\| T_i \mathbf{v}_{r,o_j} \right\| + \rho_0 \end{cases} \tag{7}$$

The command vector **F** of the robot is derived from the following equation.

$$\mathbf{F} = \mathbf{F}_{\mathbf{x}_g} + \mathbf{F}_o \tag{8}$$

When combining the virtual force derived from a potential field which is generated at each module, we consider the robot as a point mass. The velocity command with the same magnitude and direction is determined by combining the forces to the robot. In addition, the potential approach has a vibration problem caused by the magnitude of velocity and roughness of the control period. Thus, in the method, a low pass filter on each element of the virtual force output in each module is used to suppress such vibration as shown in Fig.3. It was confirmed that safe and effective motion is possible even in a situation where movement to the destination, avoiding moving obstacles, and emergency avoidance all coexist. In the simulations, each low pass filter uses the reciprocal of each prediction time as a cut-off frequency.

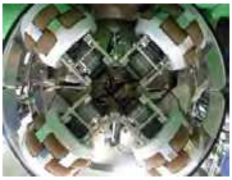


Fig. 4. Omni wheeled platform.

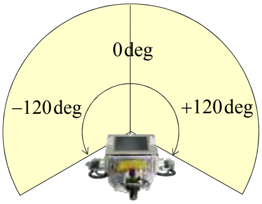


Fig. 5. The range of LRF.

3. Simulation Results

3.1 Simulation Environments

To verify the usefulness of the proposed method, several simulations were carried out. The method of the Khatib was used as a comparative method. In this study, several conditions based on the real robot are assumed.

1. The robot has an omni-directional wheel as shown in Fig.4 and thereby can move in all directions.
2. In order to recognize the environment, the robot has a laser range finder (LRF) which the measuring range is 4.0 m at the angle of the 240 degrees as shown in Fig.5.
3. The velocity of the obstacle can be estimated based on the information from LRF.

The proposed control system used in this study consists of three modules. The lowest module generates the attractive potential field and the repulsive potential field to the wall. The second module is the middle time scale T_1 module to avoid collision with the obstacles. The third module is the short time scale T_2 module to avoid collision with the sudden appearing obstacles. From the parameter studies, T_1=1.2 s and T_2=0.5 s are decided.

To verify the performance of the proposed method against two moving obstacles in different conditions, the simulation was carried out. Figure 6 shows the situation of the simulations. The initial position of the robot is (0 m, 0 m). The obstacle 1 moves straight forward to the robot from the initial position (0.2 m, 6.0 m). The obstacle 2 starts the movement from right to left as shown in Fig.4 when the robot comes close to the corner. The robot cannot recognize the obstacle 2 until just before. Therefore, the robot should deal with the situation instantaneously. The velocity of the robot and two obstacles are 1.3 m/s.

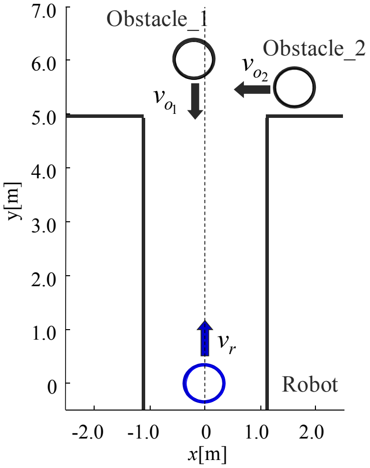


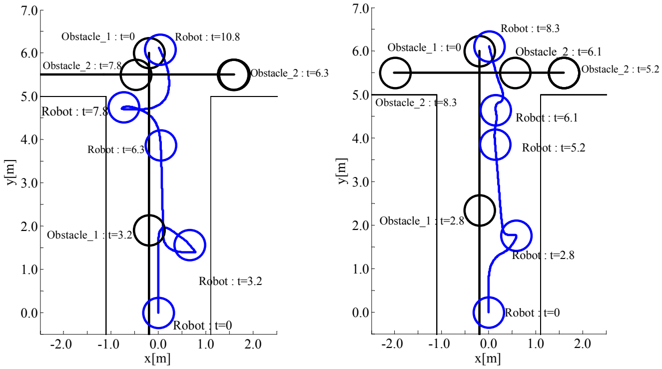
Fig. 6. Simulation Environment.

3.2 Simulation Results

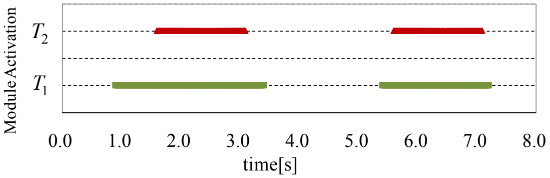
Figure 7 shows the simulation results. Figures 7(a) and (b) show the trajectories of the robot and two obstacles using the Khatib and the proposed methods respectively. Figure 7(c) shows the time history of the module activations.

From the result in Fig. 7(a), it was confirmed that the robot with the Khatib method can reach the goal without colliding with two moving obstacles. However, the robot moves backward to avoid the obstacle 1 and then starts the movement to the goal after the obstacle 1 passes over. In the case of the obstacle 2, the robot moves in the direction of movement of the obstacle 2 because the predicted information of the obstacle 2 is not used. Thereby, the arrival time to the goal is longer than our method.

On the other hand, it was confirmed in Fig. 7(b) that the robot can reach the goal earlier than the other method without colliding with two moving obstacles. The robot moves in the right direction in advance to avoid the obstacle 1 by considering the predicted information and thereby the efficient collision avoidance is performed. In the case of the obstacle 2, when the robot recognizes the obstacle 2, by generating the repulsive potential fields based on the estimated information of the obstacle 2, the robot stops until the obstacle 2 passes over, and then starts the movement to the goal. From Fig. 7(c), the robot can move without colliding with two moving obstacle 2 by acting on the T_2 module simultaneously with the T_1 module at about 6.0 s. From the results, it was confirmed that the robot with the proposed method can realize the safe and efficient movement according to the situation.



(a) Khatib method (b) The proposed method



(c) Time History of the Module Activations

Fig. 7. Simulation Result.

4. Experimental Results

4.1 Experimental Environment

To verify the effectiveness of the proposed method in the actual situation, the experiments using the real robot were carried out. The robot size is 0.55 m × 0.75 m × 1.25 m and the weight of the robot is about 60 kg. In order to recognize environment, though the stereo camera and the stemma camera, the laser range finder and the ultrasonic sensor are loaded, in this research the robot recognizes environment making use of only the laser range finder. The velocity limit of the robot is 0.5 m/s and the acceleration limit is 1.0 m/s^2.

Figure 8 shows the experimental environment to verify the effectiveness of the proposed method to a static obstacle. The initial position of the robot is (0 m, 0 m). The obstacle size is 0.20 m × 0.33 m × 0.50 m and its initial position is (-0.5 m, 3.0 m).

Figure 11 shows the experimental environment to verify the effectiveness of the proposed method to a moving obstacle. In this case, the moving obstacle appears through the blind corner at the velocity of 0.5 m/s when the robot comes close to the corner.

4.1 Experimental Results

Figures 9 (a), (b) and (c) show the trajectory of the robot by using the Khatib ($\rho_0 = 0.8$, $\eta = 0.064$), the Khatib ($\rho_0 = 1.5$, $\eta = 0.064$) and the proposed method respectively.

From the result in Fig. 9(a), it was confirmed that the robot comes close to the static obstacle because the repulsive potential fields for the obstacle is small. Fig. 9 (b) shows that the robot does not approach to the obstacle because the influence of the obstacle is large. In addition, because the robot receives the influence of repulsive forces from the wall, the robot is the stable state before it reaches the goal. On the other hand, it was confirmed in Fig. 9(c) that the robot with the proposed method can reach the goal earlier than other methods without colliding with the moving obstacle.

Figures 12 (a) and (b) show the trajectories of the robot and the moving obstacle by using the Khatib and the proposed method respectively. Figure 12(c) shows the time history of the module activations in the proposed method. Figure 12(a) shows the same result as the simulation. The robot can reach the goal without colliding with the obstacle. However, the robot moves in the direction of movement of the obstacle because the predicted information of the obstacle is not used. This movement of the robot is shown in Fig. 13. Thereby, the arrival time to the goal is longer than our method.

From the results in Figs. 12 (b) and 14, it was confirmed that when the robot recognizes the moving obstacle, the robot stops on the moment until the obstacle passes over, and then starts the movement to the goal. As shown in Fig.12(c), the robot can move without colliding with the moving obstacle by acting on the T_1 and T_2 modules at the same time at about 5.0 s.

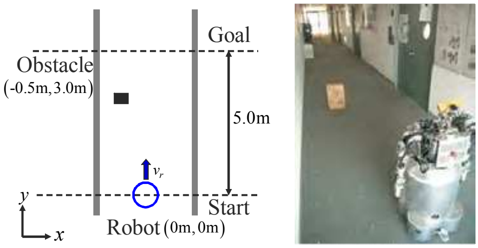
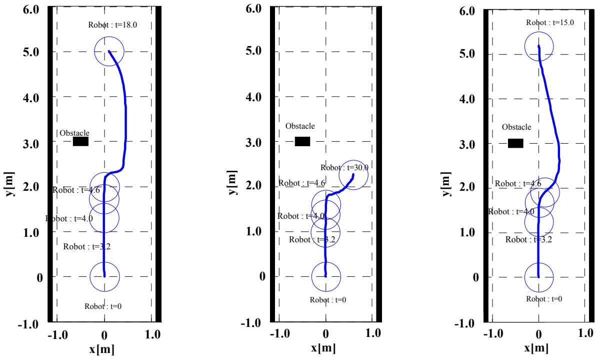
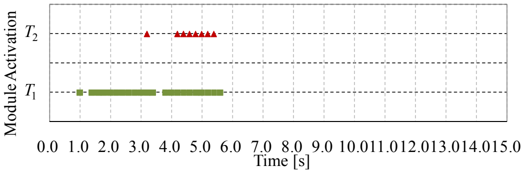


Fig. 8. Experimental Environment.



(a) $\rho_0 = 0.8, \eta = 0.064$ (b) $\rho_0 = 1.5, \eta = 0.064$ (c) The proposed method



(c) Time History of the Module Activations

Fig. 9. Experimental Result.

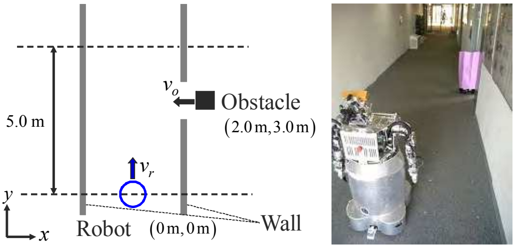
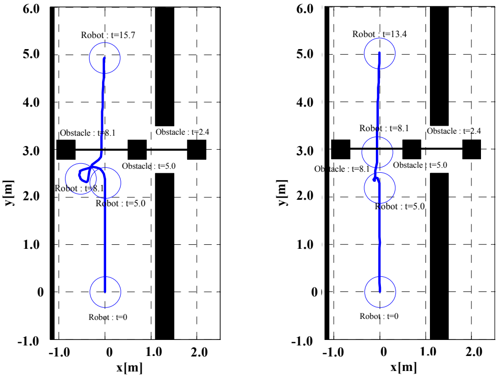
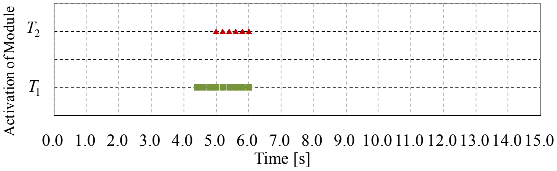


Fig. 10. Experimental Environment.



(a) Khatib method (b) Proposed method



(c) Time History of the Module Activations in the proposed method

Fig. 11. Experimental Result.

Fig. 12. Experimental Result.

(a) (b) (c) (d)

(e) (f) (g) (h)

Fig. 13. Experimental Result.

5. Conclusions

This study proposed the hierarchical action control method for an autonomous omni-directional mobile robot to realize safe and effective movement. In the method, the module with different prediction time processes in parallel, and the command velocity to the robot is decided by integrating them. As for each module, the selection condition is different according to relative position and velocity between the robot and the obstacle.

This study proposed the design procedure of the proposed method based on the virtual potential method. From the results of the numerical simulations and the experiments, it was confirmed that the robot can reach the goal efficiently without colliding with both the static and the moving obstacles by using the estimated information of them. Moreover, the robot can deal with the emergency situation adequately by acting on several modules simultaneously according to the situation. From the results, the effectiveness of the proposed method in dynamic environment was confirmed.

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Mobile robots navigation includes different interrelated activities: (i) perception, as obtaining and interpreting sensory information; (ii) exploration, as the strategy that guides the robot to select the next direction to go; (iii) mapping, involving the construction of a spatial representation by using the sensory information perceived; (iv) localization, as the strategy to estimate the robot position within the spatial map; (v) path planning, as the strategy to find a path towards a goal location being optimal or not; and (vi) path execution, where motor actions are determined and adapted to environmental changes. The book addresses those activities by integrating results from the research work of several authors all over the world. Research cases are documented in 32 chapters organized within 7 categories next described.

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