M. Benreguieg, P. Hoppenot, H. Maaref, E. Colle, C. Barret: "Fuzzy navigation strategy : Application to two distinct autonomous mobile robots" - Robotica, vol. 15, pp. 609-615, 1997.

Fuzzy Navigation Strategy : Application to Two Distinct Autonomous Mobile Robots

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SUMMARY

Most of the motion controls of the mobile robots are based on the classical scheme planning-navigation-piloting. The navigation function the main part of which consists in obstacle avoidance, has to react with the shortest response time. The real time constraint hardly limits the complexity of sensor data processing. The described navigator is built around fuzzy logic controllers. Besides the well-known possibility of taking into account human know-how, the approach provides several contributions : a low sensitivity to erroneous or inaccurate measures and, if the inputs of the controllers are normalised, a well to do portability on various platform. To show these advantages, the same fuzzy navigator has been implemented on two mobile robots. Their mechanical structures are close, except for the size and the sensing system.

1. INTRODUCTION

Over the past few years, the research in autonomous mobile robot field gained an extensive interest. This is due chiefly to the necessity to replace human intervention in dangerous environments (nuclear, space,...), or to the wish to develop a help in some more classical tasks (cleaning, supervision, carriage,...).

Various methods for controlling mobile robot systems have been developed which are generally classified in two categories : global planning and local control.

Many works, based on the complete knowledge of the robot and the environment, use a global planning method such as artificial potential fields[1], connectivity graph, Voronoî diagram, cell decomposition[2,3],....These methods build some paths (set of subgoals) which are free of obstacles. Their main advantages are to prove the existence of a solution which permits to the robot to reach its destination and to generate a collision-free map-making. Thus, in this map, a global optimal solution can be achieved with the assistance of a cost function. The latter is related to either the global route between a start position to a goal position thanks to the A*-algorithm for example, or the time path or even the safe mission[4]. However, they have some well-known drawbacks. For example, an exact model of the environment is needed which unfortunately cannot be defined in most applications. A modification of the environment due to some new dynamic objects cannot be correctly handled.

The local methods are mainly used in unstructured environment. They might be called reactive strategies and are completely based on sensory information. So, an absolute localisation is not requisite and only the relative interactions between the robot and the environment have to be assessed. In these circumstances, a structural modelling of the environment is unnecessary, but the mobile robot has to react to its sensory inputs via a set of stimuli-response mechanism. In this scheme, the robot is generally expected to do only simple tasks. Numerous methods have been proposed[5-7].... However, they do not guarantee a solution for the mission because of deadlock problem occurrences. The reason is the robot does not have a high-level map-reading ability. For more efficiency and safety, perception tools have to be increased (several types of sensors including for example cameras) to get more pertinent information about the environment. But, these data are not easy to process under real time constraints. These constraints often lead to a degradation of the accuracy and the richness of the information.

The use of only one of these methods for the motion control of a mobile robot in a complex environment has turned out to be insufficient and hazardous. In fact, some constraints are added to their intrinsic drawbacks caused by :

-the imprecision or lack of knowledge in the system and environment behaviour

-the difficulties to represent correctly the environment and to locate the robot due to errors in the sensors data which are still far from perfect, taking in account the present day technologies.

A set of methodologies called qualitative or approximate reasoning have been developed to build a decision-making approach in systems where all uncertainties cannot be completely avoided or corrected. These methodologies attempt to capture some aspects of the human behaviour in system control. Their aim is to incorporate implicitly the uncertainties in the information gathering and reasoning process, rather than to determine explicitly them through numerical calculations or mathematical representations.

Some qualitative reasoning theories have been developed over the past few years[8] and currently one of the most used

for application to control systems is the theory of fuzzy sets[9]. The control based on this theory[10] provided satisfying results[11-12] in cases where classical control failed. As a fuzzy controller is built following the knowledge of experts, a complex or ill-defined system can be controlled without using an exact mathematical model.
Therefore, the fuzzy sets theory is a good candidate both to handle different sources of imprecision and to assign built-in guidance control enabling the robot to navigate through complex environments. In fact, we know from our own experience of human motion that it is necessary neither to know our own exact location nor to have a comprehensive knowledge of the whole scene. It can be sufficient for example to know if there is enough free space to get around an obstacle and to recognise marks indicating whether the passageway leads to the goal or not. Many application works of fuzzy logics in the mobile robot field have given promising results[13-16].

2. CONTROL ARCHITECTURE

To come close to human being behaviour, the efficient control of a mobile robot motion in complex environments needs a hierarchical strategy :

- a high level for planning path using global description of the world with possibly incomplete and/or imperfect knowledge ;
- a local level where the robot motion is based completely on the information of different sensors which cover the close area around the vehicle.

In that hybrid method the planner deduces subgoals from the known environment and the navigator realises local control (fig 1). The “ portability ”of the algorithm described in the next sections is proved by applying it to two different mobile robot architectures.

Figure 1. *Global scheme*

2.1. Planner : Visibility graph + A* Algorithm

The global method provides the planning of path using a visibility graph and the A* algorithm.
The visibility graph[2] is a set of straight lines connecting source (S), goal (G) points and obstacle vertices. Each point is connected to all viewed points without intersecting obstacles (fig.2). Then, an optimal path is searched with an A* algorithm in the generated graph, using the euclidian distance as a cost function. This path is a polygonal line connecting S to G ; it is the shortest collision free path from S to G.

Figure 2. *Optimal path*

This method is well adapted to generate a path (set of subgoals) for a robot represented by a point. In order to consider the whole ground space occupied by the robot, we need to extend the area of the obstacles. The growing is not greater than the robot’s half width to allow the navigation through narrow corridors.

2.2. Navigator

2.2.1. Avoidance behaviour

When the vehicle is moving towards the target (one of subgoals or final target) and the front sensors detect an obstacle on the path, an avoiding strategy is enabled. The selected method consists in reaching the middle of a collision-free space. The navigator is a fuzzy controller based on a set of rules such as :

rule R_i “ **If** R_n is x_i **and** L_n is y_i **Then** $C_{\omega a}$ is t_i
and if F_n is z_i **then** C_{va} is u_i “ .
Else

rule R_{i+1} “ **If**... ”

x_i, y_i, z_i, t_i and u_i are linguistic labels of a fuzzy partition of respectively the universes of discourse of the input R_n, L_n and Fn and the outputs $C_{\omega a}$ and C_{va}. The inputs variables are respectively the normalised measured distances on the right *R*, on the left *L* and in front F such as :

$$R_n = \frac{R}{R+L},\ L_n = \frac{L}{R+L} \text{ and } \begin{cases} \text{if } F < \sigma \text{ then } F_n = \dfrac{F}{\sigma} \\ else\ Fn = 1 \end{cases}$$

where σ defines the influence distance for obstacle avoidance.
Thanks to this normalisation, the universe of discourse adjust to the sensors range (fig.3).
The output variables are the angular ($C_{\omega a}$, fig 4) and the linear (C_{va}, fig 5) coefficients speed. The shape of the membership functions is triangular and the sum of the membership degrees for each variable is always equal to 1. The universes of discourse are normalised between -1 and 1 for $C\omega_a$, and between 0 and 1 for the other ones.

Figure 3. *Evolution of the partition of the universe of discourse*

Each universe of discourse is shared in five fuzzy subsets. The linguistic labels are defined as follows :

Z : *Zero*	NB : *Negative Big*
S : *Small*	NS : *Negative Small*
M : *Medium*	Z : *Zero*
B : *Big*	PS : *Positive Small*
VB : *Very Big*	PB : *Positive Big*

The whole control rules deduced from a human driver intuitive experience is represented by fifty rules shown in the two following decision tables (Table1 and Table2) : 25 rules determine the angular speed coefficient $C_{\omega a}$, and 25 rules determine the linear speed coefficient C_{va}.

Table 1. *Angular velocity coefficient rules*

An example of fuzzy rules is :

- **If** (R_n is *Very Big*) **and** (L_n is *Very Big*) **then** ($C_{\omega a}$ is *Zero*) **and if** (F_n is *Very Big*) **then** (C_{va} is *Very Big*).

- **If** (R_n is *Very Big*) **and** (L_n is *Small*) **then** ($C_{\omega a}$ is *Positive Big*) **and if** (F_n is *Zero*) **then** (C_{va} is *Zero*).

Table 2. *membership functions of the linear speed coefficient.*

Figure 4. *membership functions of the angular speed coefficient*

Figure 5. *Linear speed coefficient membership functions*

The operators are similar to those appearing in a Mamdani's controller : MIN for the composition of the input variables and for the fuzzy implication and MAX for the aggregation of the rules. In order to determine the crisp output actions $C_{\omega a}$ (Fig.4) and C_{va} (Fig.5), the center of gravity [10] is used as a defuzzification method.

$$C^j_{\omega a} = \frac{\sum_{i=1}^{n} C_{\omega ai} \times \mu_{C_{\omega ai}}}{\sum_{i=1}^{n} \mu_{C_{\omega ai}}} \qquad C^j_{va} = \frac{\sum_{i=1}^{m} C_{vai} \times \mu_{C_{vai}}}{\sum_{i=1}^{m} \mu_{C_{vai}}}$$

where *n* and *m* denote respectively the number of quantization levels of the fuzzy output actions $C_{\omega a}$ and C_{va}.

2.2.2. Goal-seeking behaviour

The robot is attracted by the following subgoal (SG^k). This latter produces an attractive force which guides the robot to its destination. The actions ($C_{\omega g}$ and C_{vg}) generated by this force are modulated by the inverse of the distance $\left(\left\|P,SG^k\right\|\right)$ between the center of the robot and the k^{th} subgoal (fig.6). θ_g is the angular deviation to face the goal. D is the distance of influence where no obstacle exists.

Figure 6. *Localisation of the robot* $(-\pi \le \theta \le +\pi)$

When the robot is far enough from the subgoal $\left(\left\|P,SG^k\right\| > D\right)$ the angular coefficient is proportional to $\frac{\theta_g}{\left\|P,SG^k\right\|}$ such as : $C_{\omega g} = \frac{C_g}{\left\|P,SG^k\right\|} \times \frac{D}{\pi}.\theta_g$. The proportionality coefficient C_g is chosen in such a way that the robot reaches a maximum angular speed for $\theta_g < \pi$ (fig.7). So it does not deviate to much from the line $\left(P,SG^k\right)$ direction.

Figure 7. *Attraction coefficient*

As soon as the robot reaches the influence zone (D diameter wide) the angular speed coefficient is such as : $C_{\omega g} = \frac{C_g}{\pi} \, . \, \theta_g$.

In both cases $C_{\omega g}$ is normalised such as : if $\left|C_{\omega g}\right| > 1$ then $C_{\omega g} = C_{\omega g} / \left|C_{\omega g}\right|$.

More the convergence-to-the-goal linear speed coefficient must satisfy the following equality : $C_{vg} = 1 - |C_{\omega g}|$. That one is automatically normalised.

2.2.3. Fusion of behaviours

If an obstacle is detected very close to the robot the obstacle avoidance has priority and the attraction is cancelled :

$$\textbf{If} \left\{ \begin{array}{c} ((\mathrm{Ln} \le 0.2) \text{ and } (\mathrm{Rn} \ge 0.4)) \\ \text{or} \\ ((\mathrm{Ln} \ge 0.4) \text{ and } (\mathrm{Rn} \le 0.2)) \\ \text{or} \\ (\mathrm{Fn} \le 0.2) \end{array} \right\} \textbf{ then } C\omega g = 0$$

The final linear speed V setpoint is such as :

$$\textbf{If } \left(\left\|P,SG^k\right\| < D\right) \text{ or } \left(\left\|P,SG^{k-1}\right\| < D\right)$$

$$\textbf{then } \mathrm{V} = \min(C_{va}, C_{vg}) \times \mathrm{V}_{\min} \ (m/s)$$

$$\textbf{else } \mathrm{V} = \min(C_{va}, C_{vg}) \times \mathrm{V}_{\max} \ (m/s)$$

The final angular speed Ω setpoint applied to the robot result of a linear combination between the obstacles avoidance and the subgoal attraction.

$$\Omega = (\alpha \times C_{\omega a} + \beta \times C_{\omega g}) \times \Omega_{\max} \qquad (\mathrm{rd/s})$$

where α and β are coefficients adjusted by experimentation to get the best trajectory generation.

2.3. Pilot

The robot's V (linear speed) and Ω (angular speed) are sent via a serial link to an onboard micro controller. The linear speeds of the right and left wheels are then calculated. A low level feedback loop is then performed on the robot itself by a PID controller.

3. PHYSICAL IMPLEMENTATION

3.1. Khepera

3.1.1. Physical structure

Khepera is a small mobile robot developed at Ecole Polytechnique Fédérale de Lausanne (EPFL) (fig.8).

Figure 8. *The miniature mobile robot " KHEPERA "*

Circular shape featuring 55mm in diameter, 30mm in height and 70g in weight [17]. It is supported by two wheels and two small teflon balls. The wheels are controlled by two DC motors with an incremental encoder (12 pulses per mm of robot displacement).

3.1.2. Perception

The robot possesses eight infrared sensors, which emit infrared light, measure the reflected light and return a corresponding value in the range [0, 1023]. They are disposed around the robot body and allow the measurement of distances in a short range from about 1 to 5 cm (fig.10).

3.1.3. The on-board computer is based on a Motorola 68331 micro-controller.

3.2. R.M.I.

3.2.1. Physical structure

R.M.I. (french acronym for Intelligent Mobile Robot) is a two back wheeled circular robot. It is twenty centimeters high, has twenty centimeters in radius and can carry about ten kilograms (fig.9).

The wheels are controlled by two DC motors with an incremental encoder (18 pulses per mm of robot displacement).

Figure 9. *The robot RMI.*

3.2.2. Perception

The robot carries eight ultrasonic Polaroid sensors around its body : seven in front, one behind (fig.11). The cone half-angle of the sensors is about 15 degrees. The accuracy is better than 3 centimeters for 3 meter measurement. A major drawback is the blind zone due to the fact that the transducer alternatively plays the part of the transmitter and the receiver. The blind zone at the present time is about 45 centimeters long but can be reduced to 16 centimeters by using a more complex control electronics. The range is about 10 meters.

3.2.3. The on-board computer is built around a set of processor boards. Each board is dedicated to a function : motors control, perception, planification and navigation.

Up to present time, the serial RS 232C communication has imposed a master-slave architecture. But a network-based solution is available now and allows the implementation of less hierarchical structures.

3.3. Fuzzy controller inputs

The previously described navigator uses actually three normalised inputs : front (F), left (L) and right (R). As both robots possess more than three sensors three virtual inputs have to be computed.

1) in the Khepera case, each input is the minimum value given by a set of infrared sensors :

front input F = Min(IR0, IR7),
right input R = Min(IR5, IR6, IR7),
left input L = Min(IR0, IR1, IR2).

Figure 10. *Infrared sensors layout of Khepera*

2)

Figure 11. *Ultrasonic sensors layou of RMI*

In the RMI case, each input is the minimum value given by a set of ultrasonic sensors :

front input F = Min(USd, USe, USf),
right input L = Min(USf, USg, USh),
left input R = Min(USb, USc, USd).

4. Experimentation Results

The experimentation aims to show the behaviour of the same navigator implemented on two different robots. Only the measures have been normalised by the range of the sensors. The experimental environment is composed of a room without or with an obstacle as furnitures. The task consists in getting through a doorway in that partially known environment. The robot is represented by a circle and the impact of the measures labelled for each sensor by a letter. From an ideal path given by the planner (fig.12) how do both robots operate ?

The following section describes the behaviour of both robots in two different configurations :

- without any obstacle
- with an unknown obstacle on the door side

Figure 12. *Planned path*

4.1. Khepera

The environment of Khepera is composed of a set of polygonal boxes representing the walls and the obstacles. The room is 55 cm long and 25 cm wide.

4.1.1.navigation without any obstacle (Fig.13)

Figure 13. *Navigation of Khepera without unknown obstacle*

As the range of the infrared sensors is limited to 5 cm, the robot cannot see all the walls. Since the inputs of the fuzzy controller belongs to the subset " Very Big " while the deviation belongs to the subset " Zero ", the robot converge to the subgoals at the maximum speed.

Only the significant measurements are drawn on the figure. Since the width of the door is about 11cm, the edges of the door are well-seen by the sensors.

4.1.2. navigation with an obstacle beside the door

As illustrated in figure 14 the obstacle is well identified by the sensors.

Thanks to the fuzzy navigator the robot avoids the obstacle in spite of the short range of the infrared sensors, 5cm. After obstacle avoidance the robot converges toward the next subgoal.

Figure 14. *Navigation of Khepera with an obstacle beside the door*

4.2. R.M.I.

The room is about four meters long and two and a half meters wide. The door is ninety centimeters wide.

4.2.1.navigation without any obstacle (Fig.15)

Figure 15. *Navigation of RMI without unknown obstacle*

Four points should be noticed.

i) the robot doesn’t actually follow the planned path. Indeed the obstacle avoidance module imposes the robot to follow the middle of the free space until it is close enough to the intermediate goal. The aim of the task is to reach the subgoal, not to follow the exact path.
ii) in spite of several wrong measurements generally due to multi-echoes, the fuzzy navigation succeeds the mission.
iii) the measurements, labelled for each sensor by a letter, provide an accurate information on the wall position. It allows to locate the robot precisely.
iv) the US_d-sensor detects the second stile of the door very soon. Even if the odometer gives an inaccurate robot position, it is possible to locate the robot and to get through the door.

4.2.2. navigation with an obstacle beside the door (Fig.16)

The obstacle is well-localised by the sensors and appears clearly in the environment representation. The obstacle avoidance doesn’t prevent the robot from getting through the door. The spatial layout of the sensors seems to be self-sufficient.

Figure 16. *Navigation with an obstacle beside the door*

5. CONCLUSION

Fuzzy navigator integrates heuristics copying human behaviour. That approach allows a priori a behaviour more independant of the mechanical structure of the mobile robot and a higher robustness to erroneous measres.
The originality of the navigator is to be divided into two fuzzy controllers. Angular and linear speed of the robot are generated separatly. Both actions are then combined in order to deduce each wheel angular speed.
The navigator has been implemented on two mobile robots.
In the case of the ultrasonic sensing system - generally due to multiple echoes - the rate of erroneous measures is high. Nevertheless the robot carries out its task of passing through a doorway in spite of obstacles unknown by the planner.
Besides the high insensitiveness to erroneous or inaccurate measures, the navigator presents the advantage to be easily portable to another platform. This has been shown by implementing the same fuzzy navigator on two different robots with the same adjustment parameters. Only the measures have been normalised by the range of the sensors. Indeed the normalisation of the fuzzy inputs ensures an homothetic invariance. So the size of the robot does not change the control. The higher semantic level of the inputs (left, right and front) allows the use of different types of sensors (ultrasonic and infrared).
We still have to validate the approach in a more complex environment such as a flat one. The treatment of some special cases such as chair legs, narrow doorway, frequent turns sets the problem of absolute localisation with a poor perception system.

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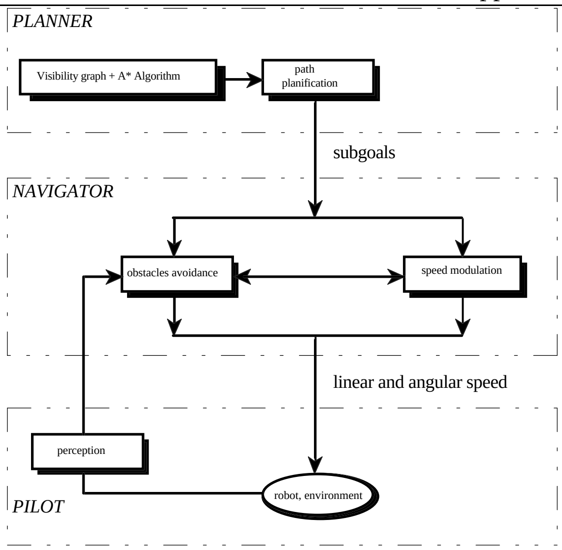

Figure 1. *Global scheme*

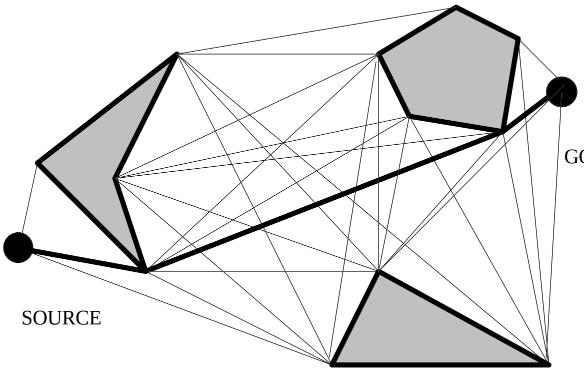

Figure 2. *Optimal path*

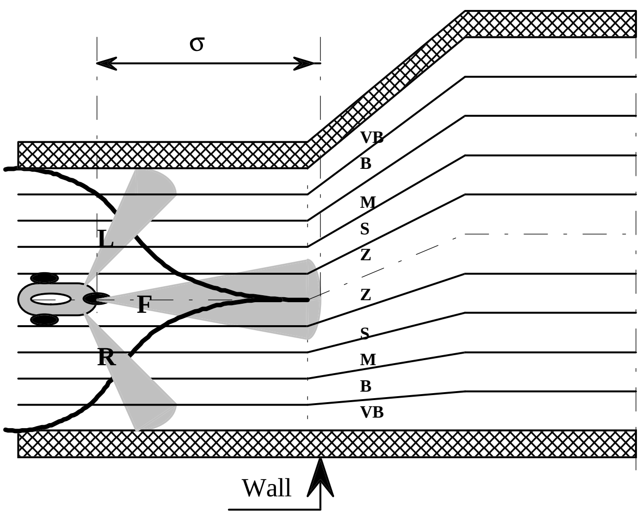

Figure 3. *Evolution of the partition of the universe of discourse*

R_n \ L_n	Z	S	M	B	VB
Z	**Z**	**PS**	**PS**	**PB**	**PB**
S	**NS**	**Z**	**PS**	**PS**	**PB**
M	**NS**	**NS**	**Z**	**PS**	**PS**
B	**NB**	**NS**	**NS**	**Z**	**PS**
VB	**NB**	**NB**	**NS**	**NS**	**Z**

Table 1. *Angular velocity coefficient rules*

ω \ F_n	Z	S	M	B	VB
NB	**Z**	**Z**	**S**	**S**	**S**
NS	**Z**	**S**	**S**	**B**	**B**
Z	**Z**	**S**	**M**	**B**	**VB**
PS	**Z**	**S**	**S**	**B**	**B**
PB	**Z**	**Z**	**S**	**S**	**S**

Table 2. *membership functions of the linear speed coefficient.*

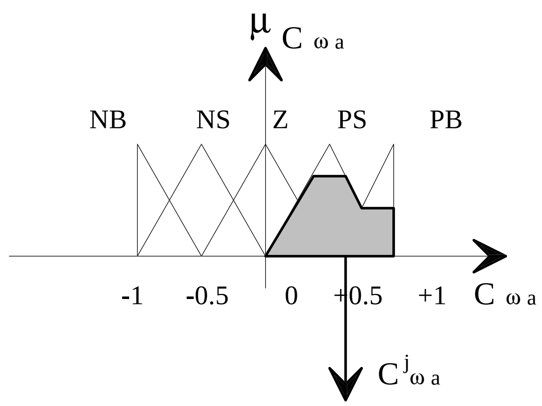

Figure 4. *membership functions of the angular speed coefficient*

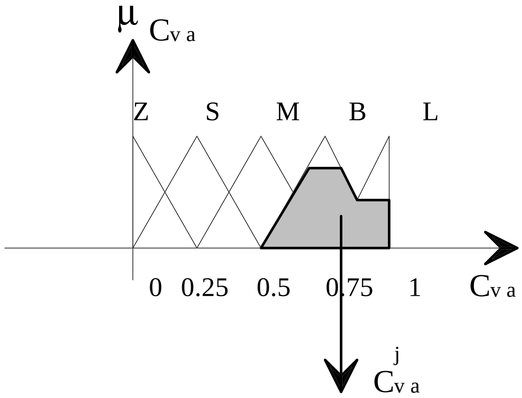

Figure 5. *Linear speed coefficient membership functions*

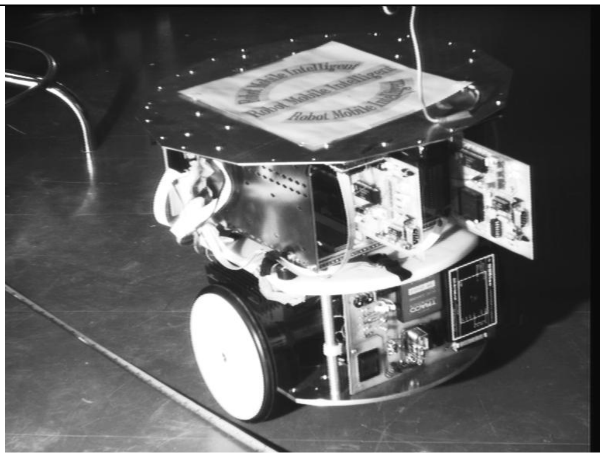

Figure 9. *The robot RMI.*

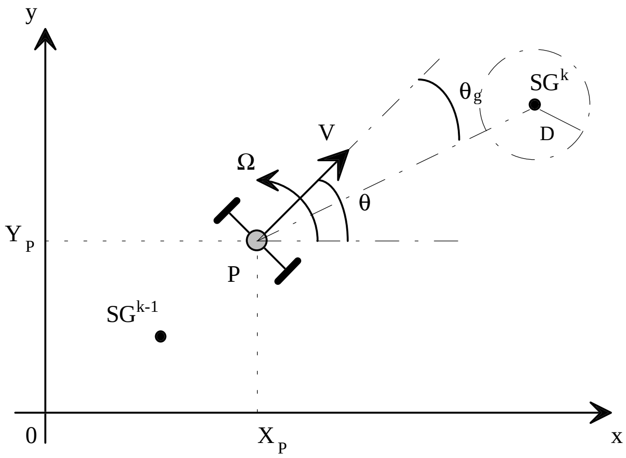

Figure 6. *Localisation of the robot* $(-\pi \leq \theta \leq +\pi)$

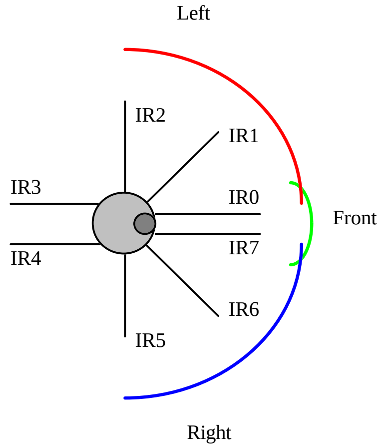

Figure 10. Infrared sensors layout of Khepera

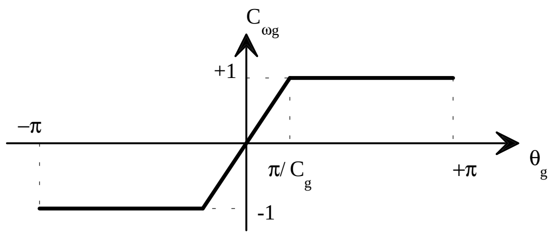

Figure 7. *Attraction coefficient*

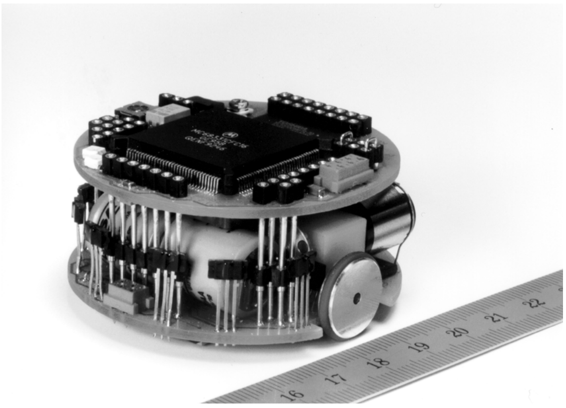

Figure 8. *The miniature mobile robot “ KHEPERA ”*

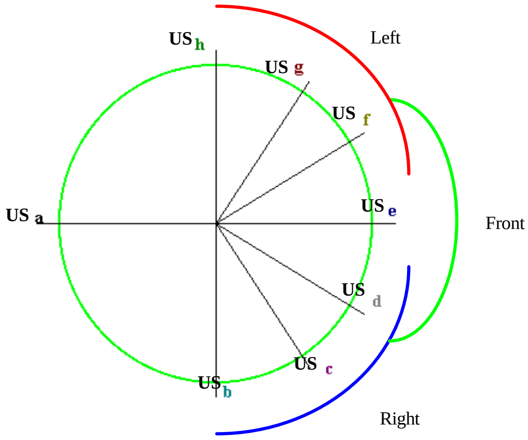

Figure 11. *Ultrasonic sensors layou of RMI*

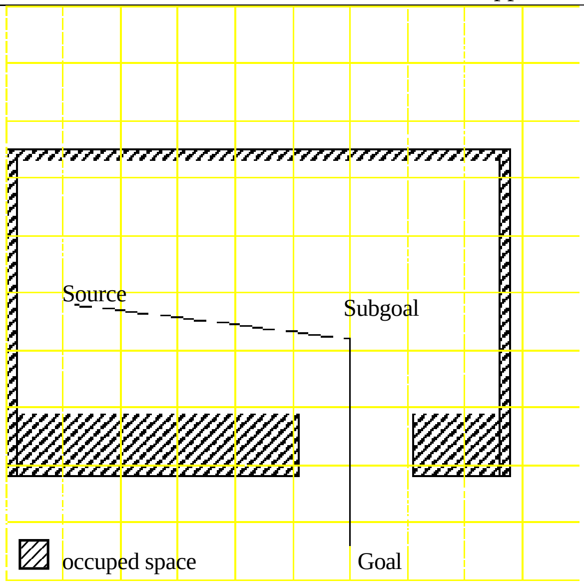

Figure 12. *Planned path*

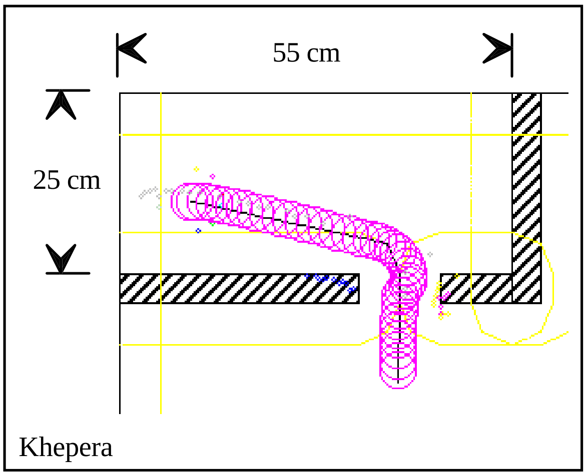

Figure 13. *Navigation of Khepera without unknown obstacle*

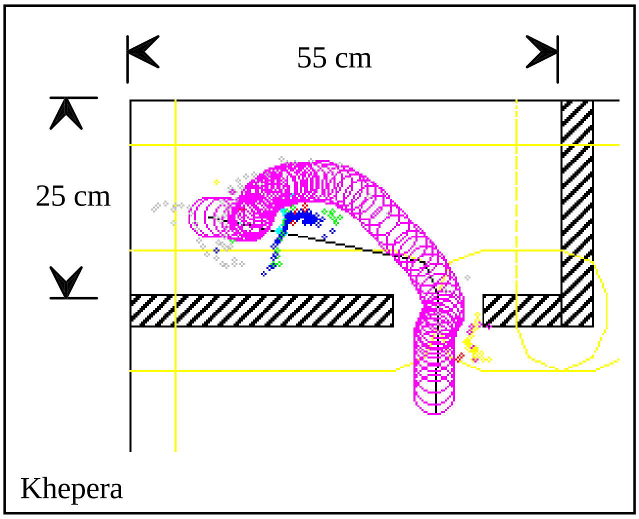

Figure 14. *Navigation of Khepera with an obstacle beside the door*

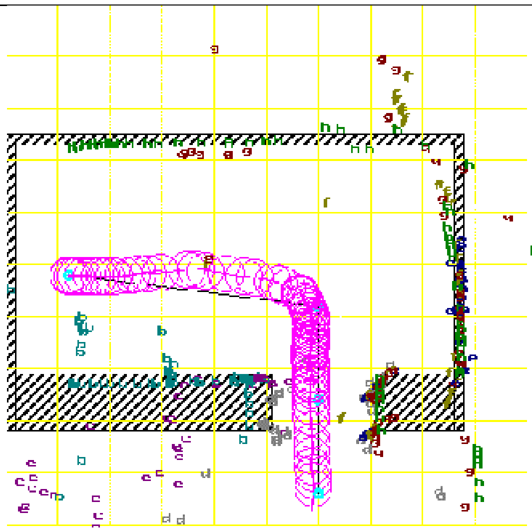

Figure 15. *Navigation of RMI without unknown obstacle*

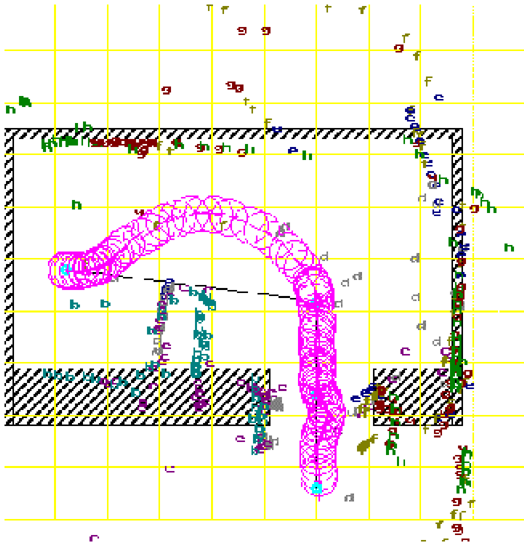

Figure 16. *Navigation with an obstacle beside the door*

Figure 1. *Global scheme*

Figure 2. *Optimal path*

Figure 3. *Evolution of the partition of the universe of discourse*

Figure 4. *Membership functions of the angular speed coefficient*

Figure 5. *Linear speed coefficient membership functions*

Figure 6. *Localisation of the robot* $(-\pi \leq \theta \leq +\pi)$

Figure 7. *Attraction coefficient*

Figure 8. *The miniature mobile robot " KHEPERA "*

Figure 9. *The robot RMI.*

Figure 10. *Infrared sensors layout of Khepera*

Figure 11. *Ultrasonic sensors layou of RMI*

Figure 12. *Planned path*

Figure 13. *Navigation of Khepera without unknown obstacle*

Figure 14. *Navigation of Khepera with an obstacle beside the door*

Figure 15. *Navigation of RMI without unknown obstacle*

Figure 16. Navigation with an obstacle beside the door

Table 1. *Angular velocity coefficient rules*

Table 2. *membership functions of the linear speed coefficient.*