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Robot Control by Fuzzy Logic

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1. Introduction

Fuzzy set theory, originally developed by Lotfi Zadeh in the 1960's, has become a popular tool for control applications in recent years (Zadeh, 1965).

Fuzzy control has been used extensively in applications such as servomotor and process control. One of its main benefits is that it can incorporate a human being's expert knowledge about how to control a system, without that a person need to have a mathematical description of the problem.

Many robots in the literature have used fuzzy logic (Song & Tay, 1992), (Khatib, 1986), (Yan et al., 1994) etc. Computer simulations by Ishikawa feature a mobile robot that navigates using a planned path and fuzzy logic. Fuzzy logic is used to keep the robot on the path, except when the danger of collision arises. In this case, a fuzzy controller for obstacle avoidance takes over.

Konolige, et al. use fuzzy control in conjunction with modeling and planning techniques to provide reactive guidance of their robot. Sonar is used by robot to construct a cellular map of its environment.

Sugeno developed a fuzzy control system for a model car capable of driving inside a fenced-in track. Ultrasonic sensors mounted on a pivoting frame measured the car's orientation and distance to the fences. Fuzzy rules were used to guide the car parallel to the fence and turn corners (Sugeno et al., 1989).

The most known fuzzy models in the literature are Mamdani fuzzy model and Takagi-Sugeno-Kang (TSK) fuzzy model. The control strategy based on Mamdani model has the linguistic expression (Mamdani, 1981):

Rule k: IF condition C1 AND condition C2 \Leftarrow Fuzzy sets
 THEN decision D_k \Leftarrow Fuzzy sets

The TSK models are formed by logical rules that have a fuzzy antecedent part and functional consequent (Sugeno, 1985):

Rule i: IF x_1 is C_{1i} AND x_2 is C_{2i} AND \Leftarrow Fuzzy sets
 THEN $u_i = f_i(x_1, x_2, \dots, x_n)$ \Leftarrow Non fuzzy sets

where C_{ij} , $j = (1, p)$, $i = (1, n)$ are linguistic labels defined as reference fuzzy sets over the input spaces (X_1, X_2, \dots) , x_1, x_2, \dots are the values of input variables and u_i is the crisp output inferred by the fuzzy model as a nonlinear functional.

The advantage of the TSK model lies in the possibility to decompose a complex system into simpler subsystems. The TSK model allows to use a fuzzy decomposition and an interpolative reasoning mechanism. In some cases this method can use a decomposition in linear subsystems.

2. Robot control system by fuzzy logic

2.1 Control methodology

Consider the conventional control system of a robot (Fig. 2. 1) which is based on the control of the error by using standard controllers like PI, PID.

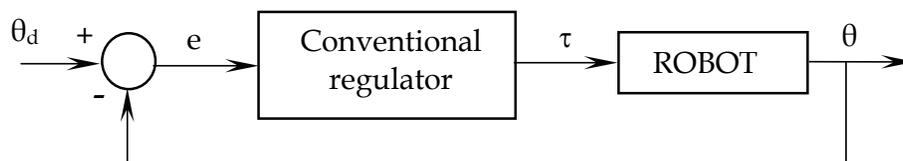


Fig. 2. 1. Conventional control system

$$e(t) = \theta_d(t) - \theta(t) \quad (2.1)$$

The control strategy determines the torque of the robot arm so that the steady error converges to zero

$$e_s = \lim_{t \rightarrow \infty} e(t) = 0 \quad (2.2)$$

We can conclude that in the classical approach, the basic decisions imply the use of simple feedback control loops, loop interactions, internal feedbacks by cascade controllers and multimode controllers.

The basic idea of Fuzzy Logic Control (FLC) centre on the labelling process in which the reading of a sensor is translated into a label as performed by human expert controllers (Yan et al., 1994), (Van der Rhee, 1990), (Gupta et al., 1979). The general structure of a fuzzy logic control is presented in Fig. 2. 2.

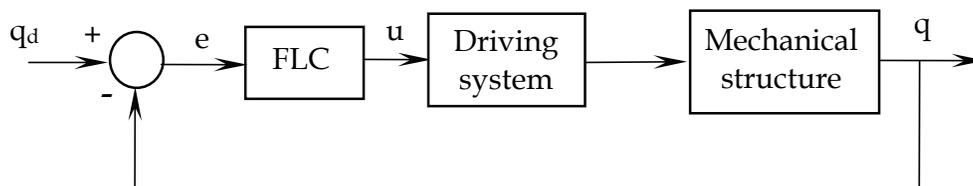


Fig. 2. 2. General structure of a fuzzy logic control

The main component is represented by the Fuzzy Logic Controller (FLC) that generates the control law by a knowledge-based system consisting of IF ... THEN rules with vague predicates and a fuzzy logic inference mechanism (Jager & Filev, 1994), (Yan et al., 1994), (Gupta et al., 1979), (Dubois & Prade, 1979). A FLC will implement a control law as an error function in order to secure the desired performances of the system. It contains three main components: the fuzzifier, the inference system and the defuzzifier.

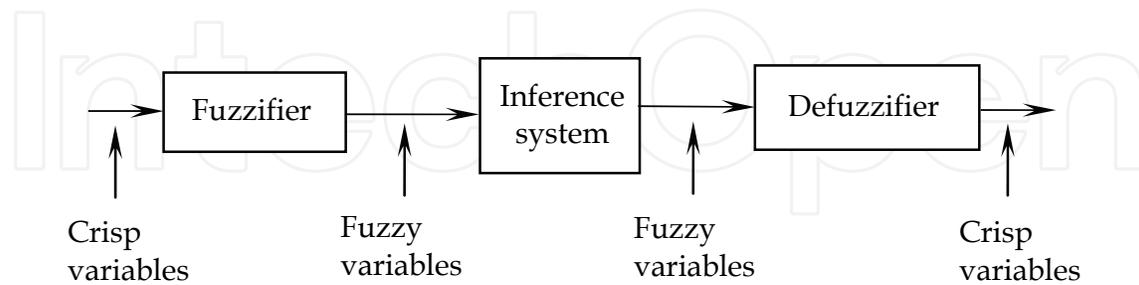


Fig. 2. 3. The structure of the fuzzy logic control

The fuzzifier has the role to convert the measurements of the error into fuzzy data.

In the inference system, linguistic and physical variables are defined. For the each physical variable, the universe of discourse, the set of linguistic variables, the membership functions and parameters are specified. One option giving more resolution to the current value of the physical variable is to normalize the universe of discourse. The rules express the relation between linguistic variables and derive from human experience-based relations, generalization of algorithmic non fully satisfactory control laws, training and learning (Gupta et al., 1979), (Dubois & Prade, 1979). The typical rules are the state evaluation rules where one or more antecedent facts imply a consequent fact.

Defuzzifier combines the reasoning process conclusions into a final control action. Different models may be applied, such as: the most significant value of the greatest membership function, the computation of the averaging the membership function peak values or the weighted average of all the concluded membership functions.

The FLC generates a control law in a general form:

$$u(k) = F(e(k), e(k-1), \dots, e(k-p), u(k-1), u(k-2), \dots, u(k-p)) \quad (2.3)$$

Technical constraints limit the dimension of vectors. Also, the typical FLC uses the error change

$$\Delta e(k) = e(k) - e(k-1) \quad (2.4)$$

and for the control

$$\Delta u(k) = u(k) - u(k-1) \quad (2.5)$$

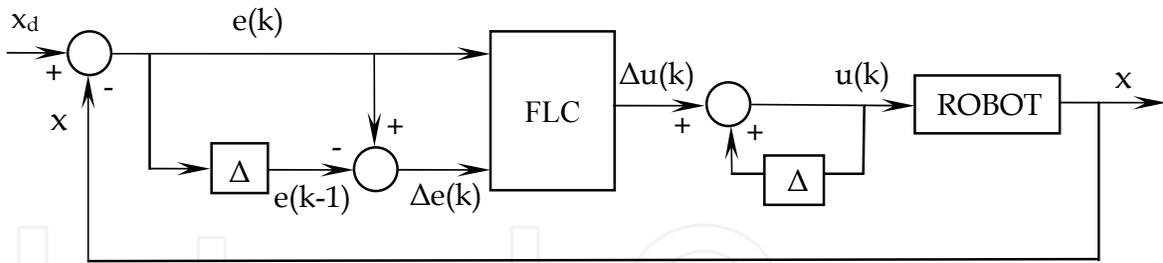


Fig. 2. 4. The structure of the robot control by fuzzy logic

Such a control law can be written as (2.6) and (2.7) (Gupta et al., 1979), (Dubois & Prade, 1979) and it is represented in Fig. 2. 4.

$$\Delta u(k) = F(e(k), \Delta e(k)) \quad (2.6)$$

$$u(k) = u(k-1) + \Delta u(k) \quad (2.7)$$

The error $e(k)$ and its change $\Delta e(k)$ define the inputs included in the antecedents of the rules and the change of the control $\Delta u(k)$ represents the output included in the consequents.

The methodology which will be applied for the control system of the robot arm is:

- Convert from numeric data to linguistic data by fuzzification techniques
- Form a knowledge-based system composed by a data base and a knowledge-base.
- Calculate the firing levels of the rules for crisp inputs.
- Generate the membership function of the output fuzzy set for the rule base.
- Calculate the crisp output by defuzzification

2.2 Control System

Consider the dynamic model of the arm defined by the equation

$$\dot{x} = f(x) + b(x)u \quad (2.8)$$

where x represents the state variable, a $(n \times 1)$ vector, and u is control variable. The desired state of the motion is defined as:

$$x_d = [x_d, \dot{x}_d, \dots, d_d^{(n-1)}]^T \quad (2.9)$$

and the error will be

$$e^* = [x - x_d, \dot{x} - \dot{x}_d, \dots, x^{(n)} - x_d^{(n)}]^T \quad (2.10)$$

consider the surface given by the relation

$$s = e^* + \sigma \dot{e}^* \tag{2.11}$$

where

$$\sigma = \text{diag}(\sigma_1, \sigma_2, \dots, \sigma_n) \tag{2.12}$$

is a diagonal positive definite matrix. The surface

$$S(x) = 0 \tag{2.13}$$

defines the switching surface of the system. For $n = 1$, the switching surface becomes a switching line (Fig. 2.5)

$$s = e + \sigma \dot{e} \tag{2.14}$$

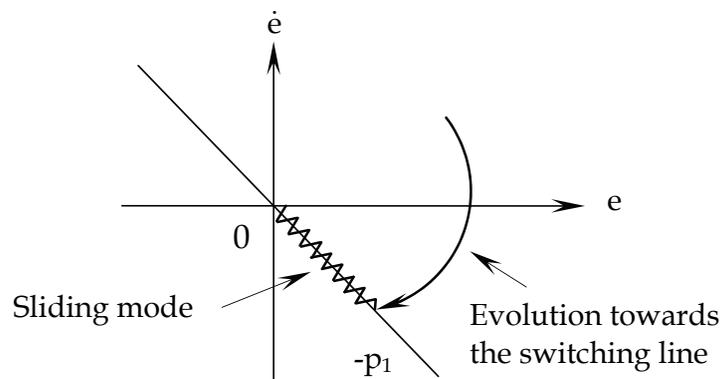


Fig. 2.5. Trajectory in a variable structure control

The control strategy is given by (Dubois & Prade, 1979).

$$u = -k \text{sgn}(s) \tag{2.15}$$

Assuming a simplified form of the equation (2.8) as

$$m\ddot{x} + k\dot{x} = u \tag{2.16}$$

from (2.14) one obtains

$$\ddot{e} = \dot{s} - \sigma \dot{e} \tag{2.17}$$

For a desired position $x_d, \dot{x}_d, \ddot{x}_d$ this relation can be written as

$$\dot{s} = -\frac{k}{m}s + H - \frac{1}{m}u \quad (2.18)$$

where

$$H(e, x_d, \dot{e}, \dot{x}_d, \ddot{x}_d) = \sigma e + \sigma \frac{k}{m}e + \ddot{x}_d - \frac{k}{m}\dot{x}_d \quad (2.19)$$

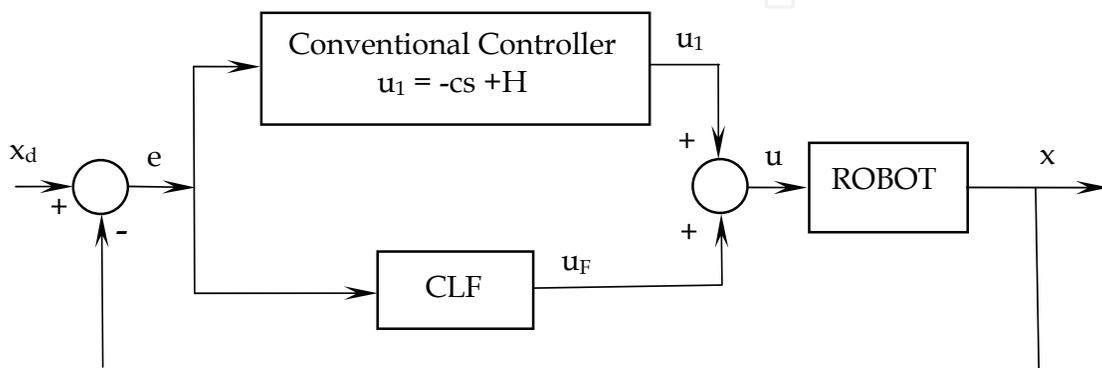


Fig. 2.6. Control system of the robot

We shall consider the control law of the form

$$u = -cs + m(H + u_F) \quad (2.20)$$

where c is a positive constant, $c > 0$, the second component mH compensates the terms determined by the error and desired position (2.19) and the last component is given by a FLC (Fig. 2.6). The stability analysis of the control system is discussed following Lyapunov's direct method. The Lyapunov function is selected as

$$V = \frac{1}{2}s^2 \quad (2.21)$$

hence

$$\dot{V} = ss \quad (2.22)$$

and, from the relation (2.18) one has

$$\dot{V} = \frac{s^2}{m}(-k + c) + su_F \quad (2.23)$$

Thus, the dynamic system (2.16), (2.20) is globally asymptotical stable if

$$\dot{V} < 0 \tag{2.24}$$

One finds that

$$c < k \tag{2.25}$$

$$u_F = -\alpha \operatorname{sgn} s \tag{2.26}$$

The last relation (2.26) determines the control law of FLC. Consider the membership functions for e , \dot{e} and u represented in Fig. 2.7 and Fig. 2.8 where the linguistic labels NB, NM, Z, PM, PB denote: NEGATIVE BIG, NEGATIVE MEDIUM, ZERO, POSITIVE MEDIUM and POSITIVE BIG, respectively.

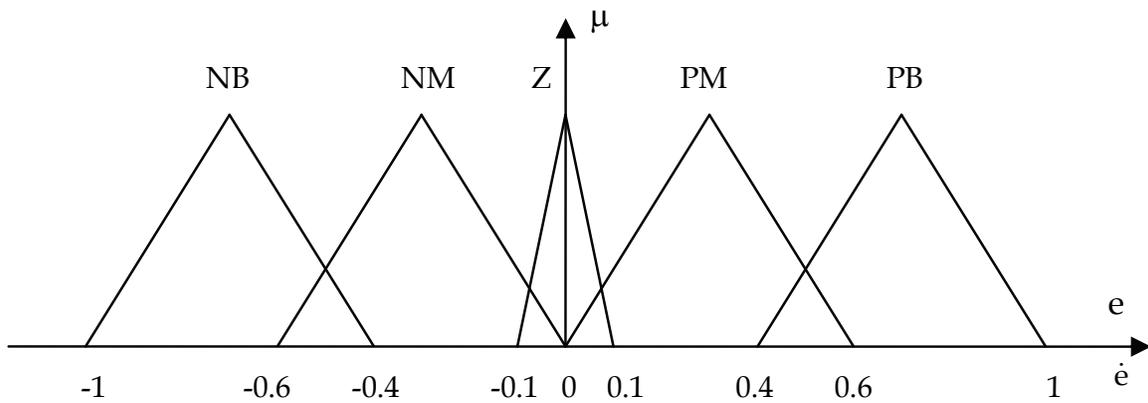


Fig. 2.7. Membership functions for e and \dot{e}

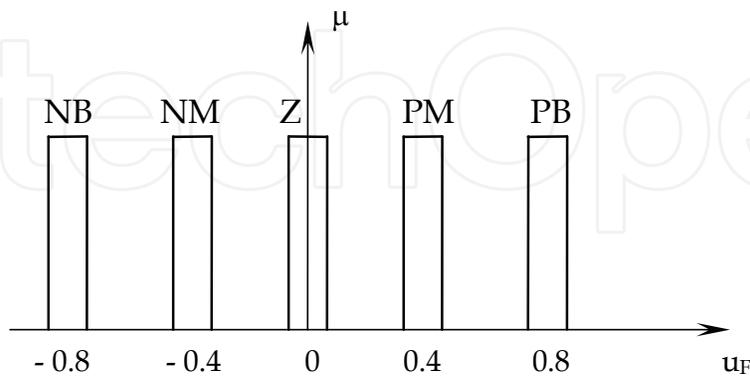


Fig. 2.8. Membership functions for u_F .

The rule base, represented in Table 2.1 is obtained from the relation (2.26).

$\dot{e} \backslash e$	NB	NM	Z	PM	PB
PB	Z	NM	NM	NB	NB
PM	PM	Z	NM	NM	NB
Z	PM	PM	Z	NM	NM
NM	PB	PM	PM	Z	NM
NB	PB	PB	PM	PM	Z

Table 2.1. Rule base for u_F

The rule base for u_F is the following:

Rule 1: IF e is NB AND \dot{e} is PB
THEN u_F is Z

Rule 2: IF e is NB AND \dot{e} is PM
THEN u_F is PM

.....
Rule 25: IF e is NB AND \dot{e} is PB
THEN u_F is Z

3. Mobile robot control system based on artificial potential field method and fuzzy logic

3.1 Artificial potential field approach

Potential field was originally developed as on-line collision avoidance approach, applicable when the robot does not have a prior model of the obstacles, but senses them during motion execution (Khatib, 1986). Using a prior model of the workspace, it can be turned into a systematic motion planning approach. Potential field methods are often referred to as "local methods". This comes from the fact that most potential functions are defined in such a way that their values at any configuration do not depend on the distribution and shapes of the obstacles beyond some limited neighborhood around the configuration. The potential functions are based upon the following general idea: the robot should be attracted toward its goal configuration, while being repulsed by the obstacles. Let us consider the following dynamic linear system with can derive from a simplified model of the mobile robot:

$$\dot{\mathbf{x}} = \mathbf{A} \mathbf{x} + \mathbf{B} \mathbf{F} \quad (3.1)$$

where $\mathbf{x} = [x_1, \dots, x_n, \dot{x}_1, \dots, \dot{x}_n]^T \in \mathbf{R}^{2n}$ is the state variable vector

$\mathbf{F} = \mathbf{u} \in \mathbf{R}^{2n}$ is the input vector

$$\mathbf{A} = \begin{bmatrix} \mathbf{0}_{n \times n} & \mathbf{I}_{n \times n} \\ \mathbf{0}_{n \times n} & \mathbf{0}_{n \times n} \end{bmatrix}; \mathbf{B} = \begin{bmatrix} \mathbf{0}_{n \times n} \\ \mathbf{I}_{n \times n} \end{bmatrix} \quad (3.2)$$

$\mathbf{0}_{n \times n} \in \mathbf{R}^{n \times n}$ is the zero matrix

$\mathbf{I}_{n \times n} \in \mathbf{R}^{n \times n}$ is the unit matrix

We can stabilize the system (3.1) toward the equilibrium point $[x_1 \dots x_n]^T = [x_{T1} \dots x_{Tn}]^T$ by using the artificial potential field (artificial potential Π which generates artificial force system \mathbf{F}).

$$\mathbf{F}(t) = \frac{\partial W_p(\mathbf{x})}{\partial \mathbf{x}} - \mathbf{F}_d - \frac{\partial \Pi(\mathbf{x})}{\partial \mathbf{x}} \quad (3.3)$$

where the first term compensates the gravitational potential, the second term assures the damping control and the last component defines the new artificial potential introduced in order to assure the motion to the desired position.

$$\frac{\partial \Pi(\mathbf{x})}{\partial \mathbf{x}} = \left[\frac{\partial \Pi(\mathbf{x})}{\partial x_1}, \frac{\partial \Pi(\mathbf{x})}{\partial x_2}, \dots, \frac{\partial \Pi(\mathbf{x})}{\partial x_n} \right]^T \quad (3.4)$$

In order to make the robot be attracted toward its goal configuration, while being repulsed from the obstacles, Π is constructed as the sum of two elementary potential functions:

$$\Pi(\mathbf{x}) = \Pi_A(\mathbf{x}) + \Pi_R(\mathbf{x}) \quad (3.5)$$

where: $\Pi_A(\mathbf{x})$ is the *attractor potential* and it is associated with the goal coordinates and it isn't dependent of the obstacle regions.

$\Pi_R(\mathbf{x})$ is the *repulsive potential* and it is associated with the obstacle regions and it isn't dependent of the goal coordinates.

In this case, the force $\mathbf{F}(t)$ is a sum of two components: the *attractive force* and the *repulsive force*:

$$\mathbf{F}(t) = \mathbf{F}_A(t) + \mathbf{F}_R(t) \quad (3.6)$$

3.2 Attractor potential artificial field

The artificial potential is a potential function whose points of minimum are attractors for a controlled system. It was shown (Takegaki & Arimoto, 1981), (Douskaia, 1998), (Masoud & Masoud, 2000), (Tsugi et al., 2002) that the control of robot motion to a desired point is possible if the function has a minimum in the desired point. The attractor potential Π_A can be defined as a functional of position coordinates \mathbf{x} in this mode:

$$\Pi_A : \Omega \rightarrow \mathbf{R}; \Omega = \mathbf{R}^n \quad (3.7)$$

$$\Pi_A(\mathbf{x}) = \frac{1}{2} \sum_{i=1}^n \left[k_i (x_i - x_{Ti})^2 + k_{n+i} \dot{x}_i^2 \right] \Sigma = \frac{1}{2} \mathbf{x}^T \mathbf{K} \mathbf{x} \quad (3.8)$$

where

$$\mathbf{K} = \text{diag} (k_1, k_2, \dots, k_{2n}),$$

$$k_i > 0 \ (i = 1, \dots, 2n) \quad (3.9)$$

The function $\Pi_A(\mathbf{x})$ is positive or null and attains its minimum at \mathbf{x}_T , where $\Pi_A(\mathbf{x}_T) = 0$. $\Pi_A(\mathbf{x})$ defined in this mode has good stabilizing characteristics (Khatib, 1986), since it generates a force \mathbf{F}_A that converges linearly toward 0 when the robot coordinates get closer the goal coordinates:

$$\mathbf{F}_A(\mathbf{x}) = k(\mathbf{x} - \mathbf{x}_T) \quad (3.10)$$

Asymptotic stabilization of the robot can be achieved by adding dissipative forces proportional to the velocity $\dot{\mathbf{x}}$.

3.3 Repulsive potential artificial field

The main idea underlying the definition of the repulsive potential is to create a potential barrier around the obstacle region that cannot be traversed by the robot trajectory. In addition, it is usually desirable that the repulsive potential not affect the motion of the robot when it is sufficiently far away from obstacles. One way to achieve these constraints is to define the repulsive potential function as follows (Latombe, 1991):

$$\Pi_R(\mathbf{x}) = \begin{cases} \frac{1}{2} k \left(\frac{1}{d(\mathbf{x})} - \frac{1}{d_0} \right)^2 & \text{if } d(\mathbf{x}) \leq d_0 \\ 0 & \text{if } d(\mathbf{x}) > d_0 \end{cases} \quad (3.11)$$

where k is a positive coefficient, $d(\mathbf{x})$ denotes the distance from \mathbf{x} to obstacle and d_0 is a positive constant called *distance of influence* of the obstacle. In this case $\mathbf{F}_R(\mathbf{x})$ becomes:

$$\mathbf{F}_R(\mathbf{x}) = \begin{cases} k \left(\frac{1}{d(\mathbf{x})} - \frac{1}{d_0} \right) \frac{1}{d^2(\mathbf{x})} \frac{\partial d(\mathbf{x})}{\partial \mathbf{x}} & \text{if } d(\mathbf{x}) \leq d_0 \\ 0 & \text{if } d(\mathbf{x}) > d_0 \end{cases} \quad (3.12)$$

For those cases when the obstacle region isn't a convex surface we can decompose this region in a number (N) of convex surfaces (possibly overlapping) with one repulsive potential associated with each component obtaining N repulsive potentials and N repulsive forces. The repulsive force is the sum of the repulsive forces created by each potential associated with a sub-region.

3.4 Dynamic model of the system

The mobile robot is represented as a point in configuration space or as a particle under the influence of an artificial potential field Π whose local variations are expected to reflect the

“structure” of the space. Usually, the Lagrange method is used to determinate the dynamic model:

$$\frac{d}{dt} \left(\frac{\partial L(\mathbf{q}, \dot{\mathbf{q}})}{\partial \dot{\mathbf{q}}} \right) - \frac{\partial L(\mathbf{q}, \dot{\mathbf{q}})}{\partial \mathbf{q}} = \mathbf{F} \quad (3.13)$$

or

$$\frac{d}{dt} \left(\frac{\partial W_C(\mathbf{q}, \dot{\mathbf{q}})}{\partial \dot{\mathbf{q}}} \right) - \frac{\partial W_C(\mathbf{q}, \dot{\mathbf{q}})}{\partial \mathbf{q}} + \frac{\partial W_P(\mathbf{q})}{\partial \mathbf{q}} = \mathbf{F} \quad (3.14)$$

where:

$$\begin{aligned} \mathbf{L} &= W_C - W_P \text{ is Lagrange function} \\ W_C &- \text{total kinetic energy} \\ W_P &- \text{total potential energy} \\ \mathbf{q} &= [x \ y]^T - \text{coordinate vector} \\ \mathbf{F} &= [F_X \ F_Y]^T - \text{force vector} \end{aligned} \quad (3.15)$$

The dynamics of the mobile robot becomes:

$$m\ddot{x} + \mu mg - k_f \dot{x} = F_X \quad (3.16)$$

$$m\ddot{y} + \mu mg - k_f \dot{y} = F_Y \quad (3.17)$$

The artificial potential forces which are the control forces are:

$$F_X = -k_1 \dot{x} - \frac{\partial \Pi}{\partial x} \quad (3.18)$$

$$F_Y = -k_1 \dot{y} - \frac{\partial \Pi}{\partial y} \quad (3.19)$$

The dynamical model of the system is:

$$m\ddot{x} + \mu mg - k_f \dot{x} = -k_1 \dot{x} - \frac{\partial \Pi}{\partial x} \quad (3.20)$$

$$m\ddot{y} + \mu mg - k_f \dot{y} = -k_1 \dot{y} - \frac{\partial \Pi}{\partial y} \quad (3.21)$$

where:

$$\Pi = \Pi_A + \Pi_R \quad (3.22)$$

The potential function is typically (but not necessarily) defined over free space as the sum of an *attractive* potential pulling the robot toward the goal configuration and a *repulsive* potential pushing the robot away from the obstacles.

3.5 Fuzzy controller

We denote by $\mathbf{x} = [x, y]^T$ the trajectory coordinates of the mobile robot in XOY plane and let e be the error between the desired position and mobile robot position.

$$\mathbf{e} = \mathbf{x}_T - \mathbf{x} \quad (3.23)$$

The switching line σ in the real error plan is defined as

$$\sigma(\dot{e}, e) = \dot{e} + me \quad (3.24)$$

A possible trajectory in the (\dot{e}, e) plane is presented in Fig. 3.1.

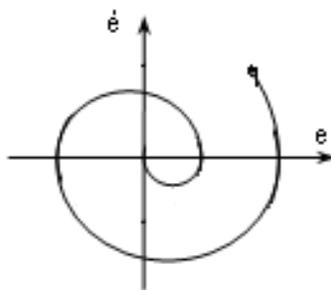


Fig. 3.1. System evolution

We can consider that the final point is attained when the origin O is reached. A great control procedure, DSMC (Ivanescu, 1996) can be obtained if the trajectory toward the moving target has the form as in Fig. 3. 2.

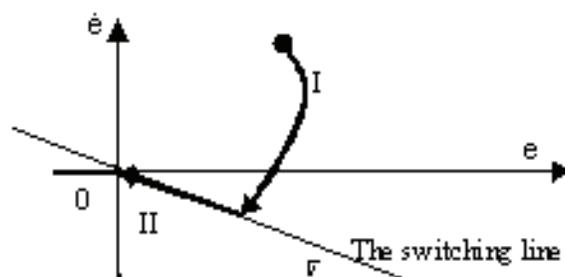


Fig. 3. 2. DSMC procedure

When trajectory in the (\dot{e}, e) plane penetrates the switching line, the motion is forced toward the origin, directly on the switching line. The condition which ensure this motion are given in (Ivanescu, 2001). The fuzzy logic controller used here has two inputs and one output. The displacement and speed data are obtained from sensors mounted on the mobile robot. The displacement error and velocity error are taken as the two inputs while the control force is considered to be the output. For all the inputs and the output the range of operation is considered to be from -1 to +1 (normalized values). The fuzzy sets used for the three variables are presented in Fig. 3. 3.

The linguistic control rules are written using the relation (3.24) and Fig. 3.2 and are presented in Table 3.1.

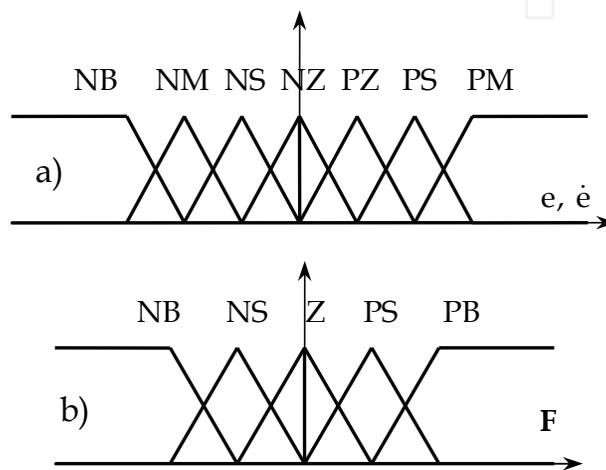


Fig. 3. 3. The fuzzy sets for the inputs and the output variables

\dot{e}/e	NB	NM	NS	NZ	PZ	PS	PM	PB
PB	Z	NS	NS	NB	NB	NB	NB	NB
PM	PS	Z	NS	NS	NB	NB	NB	NB
PS	PS	PS	Z	NS	NS	NB	NB	NB
PZ	PB	PS	PS	Z	NS	NS	NB	NB
NZ	PB	PB	PS	PS	Z	NS	NS	NB
NS	PB	PB	PB	PS	PS	Z	NS	NS
NM	PB	PB	PB	PB	PS	PS	Z	S
NB	PB	PB	PB	PB	PB	PS	PS	Z

Table 3.1. The linguistic control rules

3.6 Simulations

We propose the mobile robot to move from initial point $(x, y) = (0, 0)$ to final point $(x_T, y_T) = (7, 5)$. First, we consider that aren't any obstacles in moving area and the mobile robot is driven toward goal point by attractor artificial potential field (Fig.3.4).

$$\Pi(x) = \Pi_A(x) = \frac{1}{2} [(x - 7)^2 + (y - 5)^2] \tag{3.25}$$

$$\Pi_R(\mathbf{x}) = \begin{cases} \frac{1}{2} \left(\frac{1}{\sqrt{(x-4)^2 + (y-3)^2}} - 1 \right)^2 & \text{if } \sqrt{(x-4)^2 + (y-3)^2} \leq 1 \\ 0 & \text{if } \sqrt{(x-4)^2 + (y-3)^2} > 1 \end{cases} \quad (3.26)$$

Second, we consider that there is a dot obstacle, in $(x_R, y_R) = (4, 3)$, with *distance of influence* $d_0 = 0.4$. The expression for repulsive potential is (3.26). The trajectory is shown in Fig. 3.5.

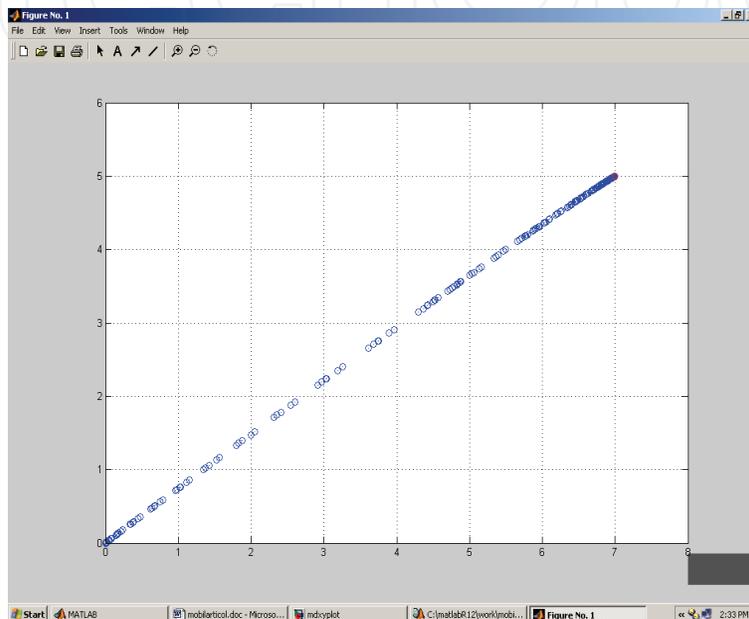


Fig. 3.4. The robot trajectory without obstacles

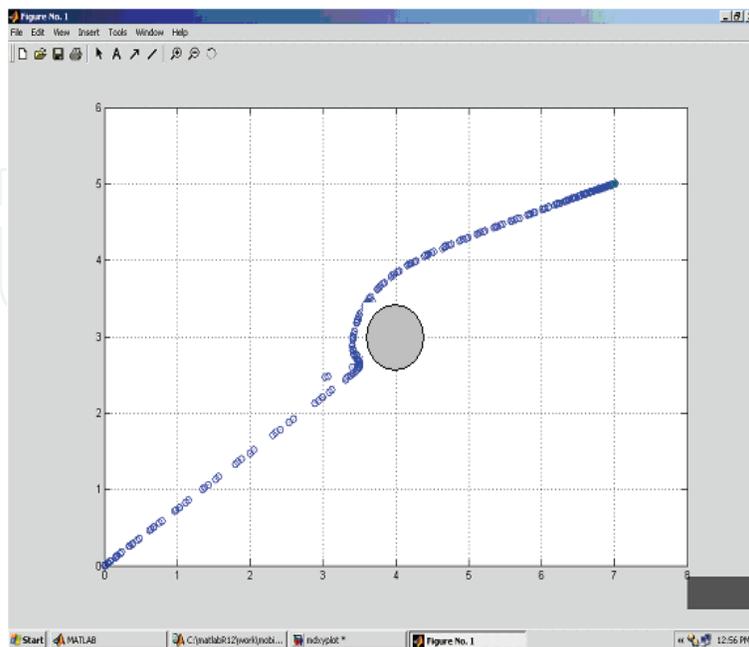


Fig. 3.5. The constrained robot trajectory by one obstacle

4. Fuzzy logic algorithm for mobile robot control next to obstacle boundaries

4.1 Control algorithm

In this section a new fuzzy control algorithm for mobile robots is presented. The robots are moving next to the obstacle boundaries, avoiding the collisions with them.

The mobile robot is equipped with a sensorial system to measure the distance between the robot and object that permits to detect 5 proximity levels (PL): PL1, PL2, PL3, PL4, and PL5. Fig. 4.1a presents the obstacle (object) boundary and the five proximity levels and Fig. 4.1b presents the two degrees of freedom of the locomotion system of the mobile robot. This can move either on the two rectangular directions or on the diagonals (if the two degrees of freedom work instantaneous).

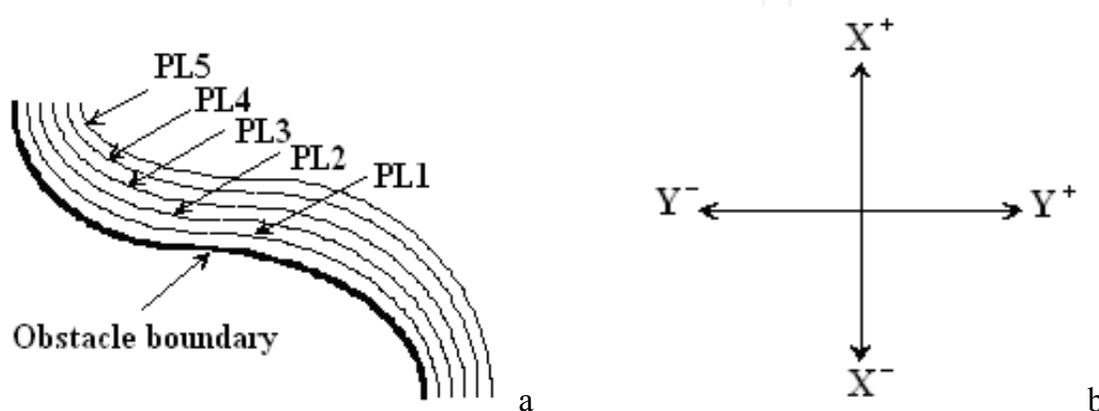


Fig. 4.1. The proximity levels and the degrees of freedom of the robot motion

The goal of the proposed control algorithm is to move the robot near the object boundary with collision avoidance. Fig. 4.2 shows four motion cycles (programs) which are followed by the mobile robot on the trajectory (P1, P2, P3, and P4). Inside every cycle are presented the directions of the movements (with arrows) for every reached proximity level. For example, if the mobile robot is moving inside first motion cycle (cycle 1 or program P1) and is reached PL3, the direction is on Y-axis (sense plus) (see Fig. 4.1b, too).

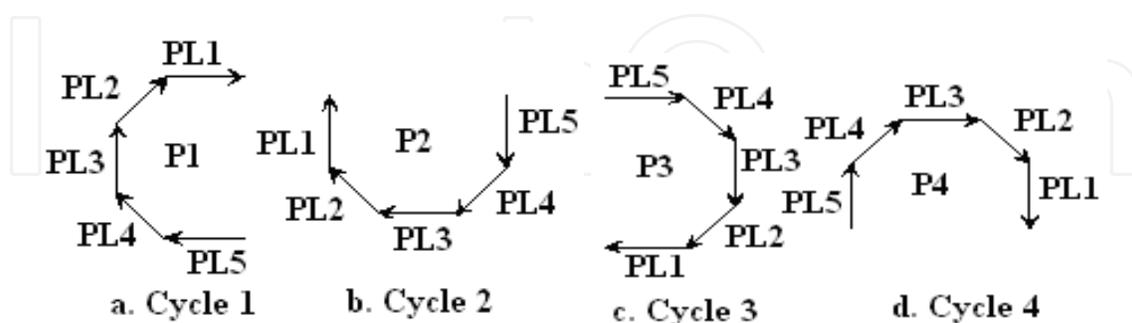


Fig. 4.2. The four motion cycles (programs)

In Fig. 4.3 we can see the sequence of the programs. One program is changed when are reached the proximity levels PL1 or PL5. If PL5 is reached the order of changing is: P1→P2→P3→P4→P1→ If PL1 is reached the sequence of changing becomes: P4→P3→P2→P1→P4→

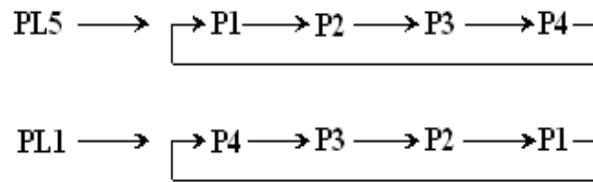


Fig. 4.3. The sequence of the programs

The motion control algorithm is presented in Fig. 4.4 by a flowchart of the evolution of the functional cycles (programs). We can see that if inside a program the proximity levels PL2, PL3 or PL4 are reached, the program is not changed. If PL1 or PL5 proximity levels are reached, the program is changed. The flowchart is built on the base of the rules presented in Fig. 4.2 and Fig. 4.3.

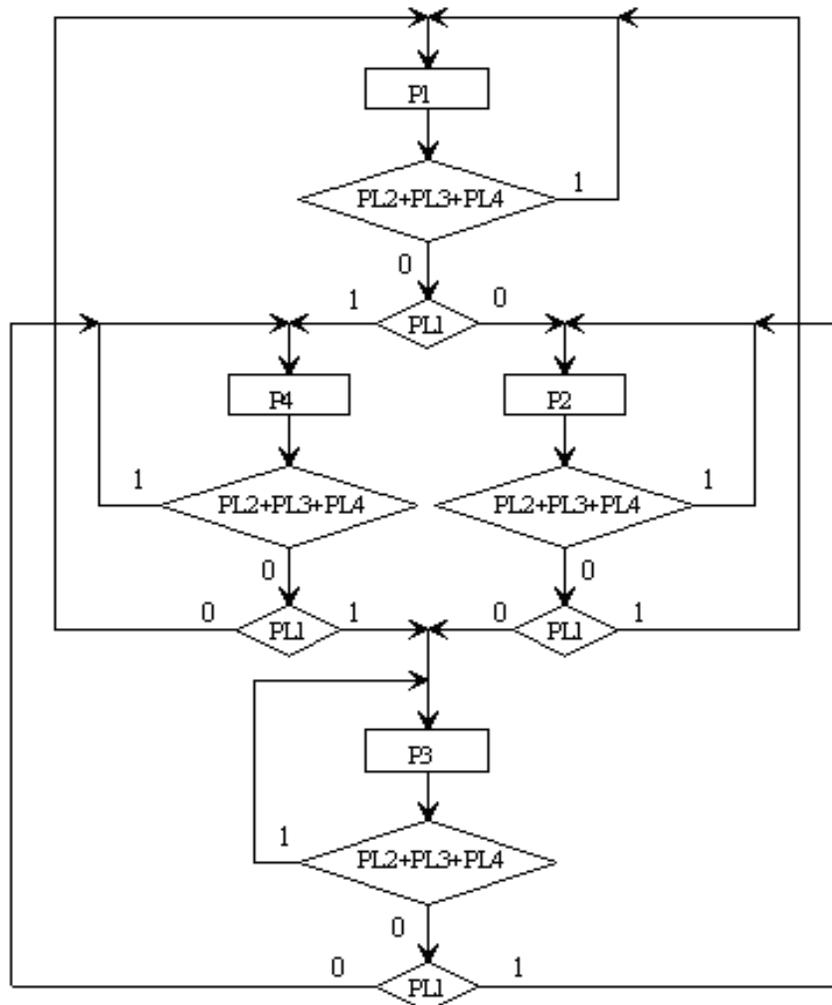


Fig. 4.4 The flowchart of the evolution of the functional cycles (programs)

4.2 Fuzzy algorithm

The fuzzy controller for the mobile robots based on the algorithm presented above is simple. Most fuzzy control applications, such as servo controllers, feature only two or three inputs to the rule base. This makes the control surface simple enough for the programmer to define

explicitly with the fuzzy rules. The above robot example uses this principle, in order to explore the feasibility of using fuzzy control for its tasks. Fig. 4.5 presents the inputs (distance-proximity levels and the program on k step) and the outputs (movement on X and Y axes and the program on k+1 step) of the fuzzy algorithm.

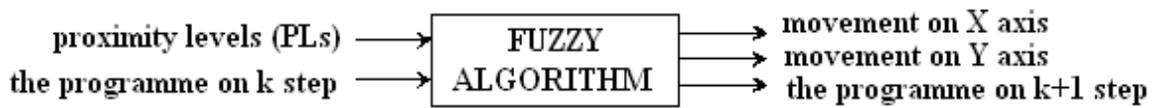
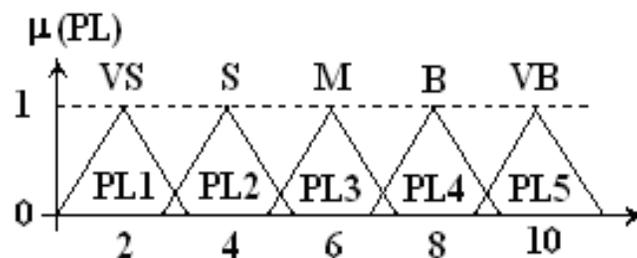
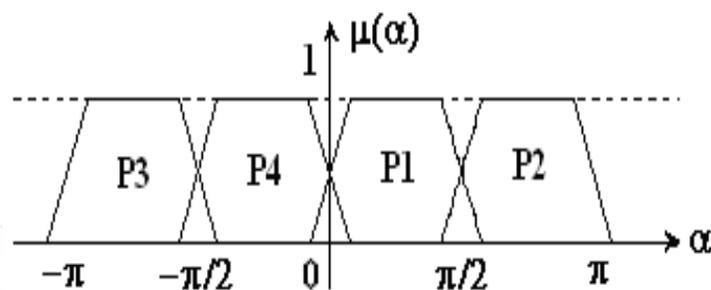


Fig. 4.5. The inputs and outputs of the fuzzy algorithm

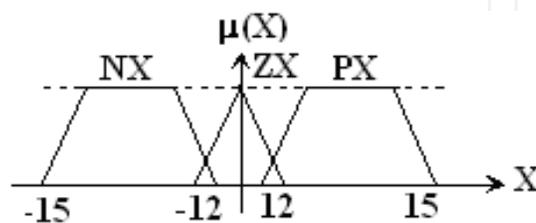
For the linguistic variable “distance proximity level” we establish to follow five linguistic terms: “VS-very small”, “S-small”, “M-medium”, “B-big”, and “VB-very big”. Fig. 4.6a shows the membership functions of the proximity levels (distance) measured with the sensors and Fig. 4.6b shows the membership functions of the angle (the programs). If the object is like a circle every program is proper for a quarter of the circle.



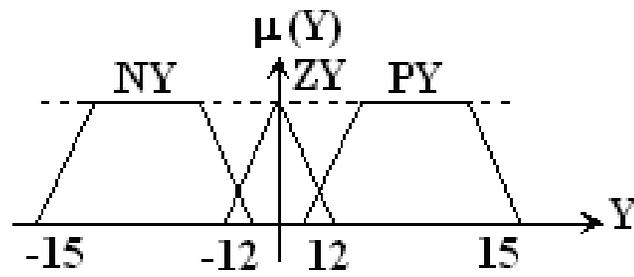
a) Membership functions of the proximity levels (distance) measured with the sensors



b) Membership functions of the angle (the programs)



c) Membership functions of the X commands



d) Membership functions of the Y commands

Fig. 4.6 Membership functions of the I/O variables

Fig. 4.6c and Fig. 4.6d present the membership functions of the X, respectively Y commands (linguistic variables). The linguistic terms are: NX-negative X, ZX-zero X, PX-positive X, and NY, ZY, PY respectively.

	VS	S	M	B	VB
P1	P4	P1	P1	P1	P2
P2	P1	P2	P2	P2	P3
P3	P2	P3	P3	P3	P4
P4	P3	P4	P4	P4	P1

Table 4.1. Fuzzy rules for evolution of the programs

	VS	S	M	B	VB
P1	PX	PX	ZX	NX	NX
P2	ZX	NX	NX	NX	ZX
P3	NX	NX	ZX	PX	PX
P4	ZX	PX	PX	PX	ZX

Table 4.2. Fuzzy rules for the motion on X-axis

	VS	S	M	B	VB
P1	ZY	PY	PY	PY	ZY
P2	PY	PY	ZY	NY	NY
P3	ZY	NY	NY	NY	ZY
P4	NY	NY	ZY	PY	PY

Table 4.3. Fuzzy rules for the motion on Y-axis

Table 4.1 describes the fuzzy rules for evolution (transition) of the programs and Table 4.2 and Table 4.3 describe the fuzzy rules for the motion on X-axis and Y-axis, respectively. Table 1 implements the sequence of the programs (see Fig. 4.2 and Fig. 4.4) and Table 4.2 and Table 4.3 implement the motion cycles (see Fig. 4.2 and Fig. 4.4).

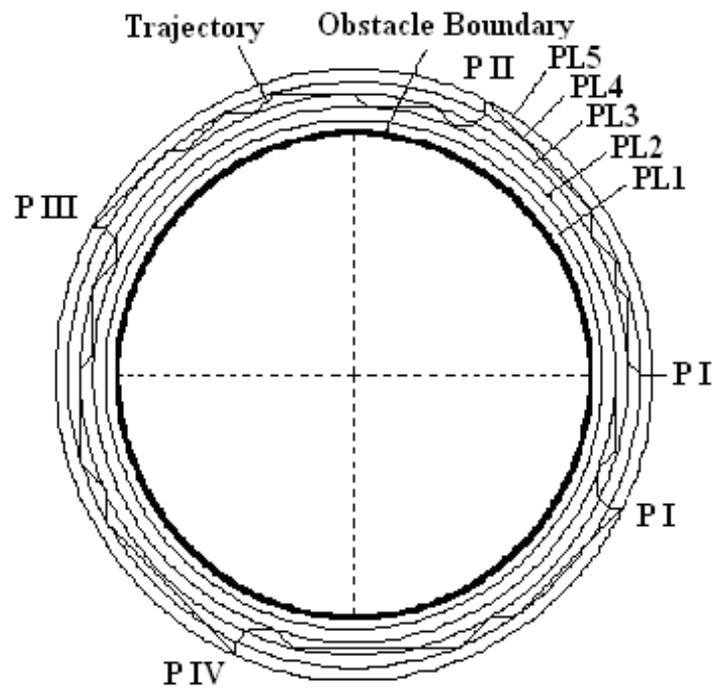


Fig. 4.7. The trajectory of the mobile robot around a circular obstacle

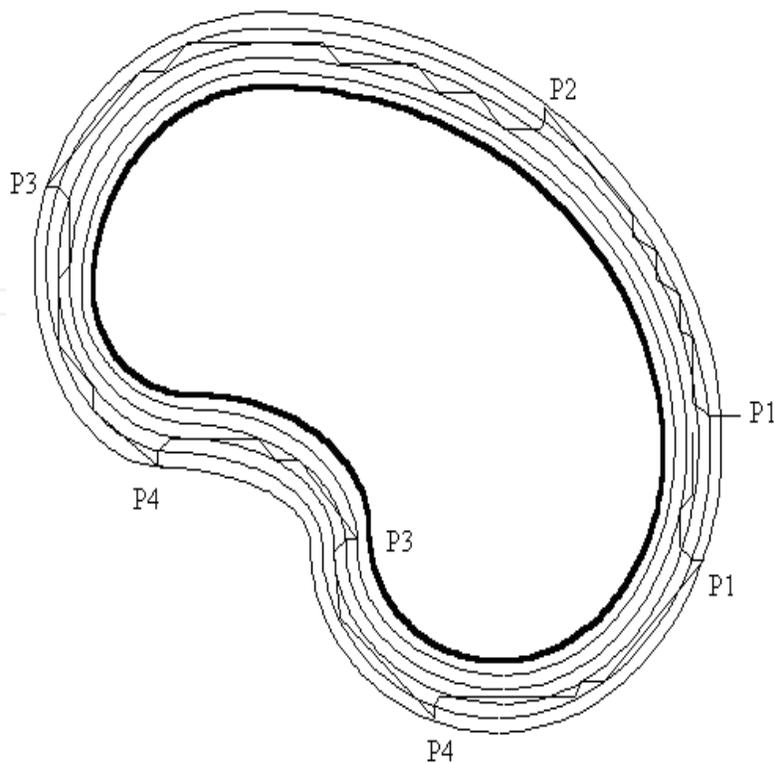


Fig. 4.8. The trajectory of the mobile robot around a irregular obstacle

4.3 Simulations

In the simulations can be seen the mobile robot trajectory around an obstacle (object) with circular boundaries (Fig. 4.7) and around an obstacle (object) with irregular boundaries (Fig. 4.8). One program is changed when are reached the proximity levels PL1 or PL5. If PL5 is reached the order of changing becomes as follows: $P1 \rightarrow P2 \rightarrow P3 \rightarrow P4 \rightarrow \dots$. If PL1 is reached the order of changing is becomes follows: $P4 \rightarrow P3 \rightarrow P2 \rightarrow P1 \rightarrow P4 \rightarrow \dots$.

5. Conclusions

The section 3 presents a new control method for mobile robots moving in its work field which is based on fuzzy logic and artificial potential field. First, the artificial potential field method is presented. The section treats unconstrained movement based on attractive artificial potential field and after that discuss the constrained movement based on attractive and repulsive artificial potential field. A fuzzy controller is designed. Finally, some applications are presented.

The section 4 presents a fuzzy control algorithm for mobile robots which are moving next to the obstacle boundaries, avoiding the collisions with them. Four motion cycles (programs) depending on the proximity levels and followed by the mobile robot on the trajectory (P1, P2, P3, and P4) are shown. The directions of the movements corresponding to every cycle, for every reached proximity level are presented. The sequence of the programs depending on the reached proximity levels is indicated. The motion control algorithm is presented by a flowchart showing the evolution of the functional cycles (programs). The fuzzy rules for evolution (transition) of the programs and for the motion on X-axis and Y-axis respectively are described. The fuzzy controller for the mobile robots based on the algorithm presented above is simple. Finally, some simulations are presented. If the object is like a circle, every program is proper for a quarter of the circle.

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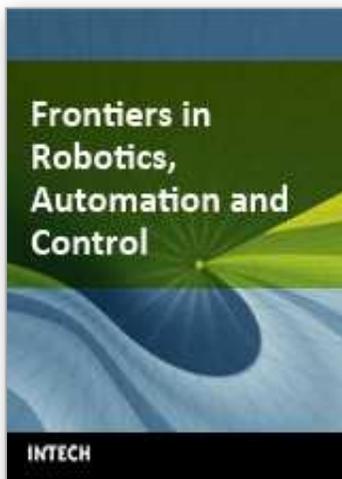
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