Thesis Review Report

On

"Navigation of Mobile Robot using Fuzzy Logic Controller"

Submitted in partial fulfillment of the requirements

For the award of the of **Master of Technology**

In

Machine Design and Analysis

By

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CERTIFICATE

This is to certify the thesis which is being presented in the thesis entitled "**Navigation of Mobil Robot using Fuzzy Logic Controller**" is the bona fide work of *Bhuwaneshwar Chourasiya* who carried out under the Guidance of **Dr. D.R.K.Parhi** in partial fulfillment of the requirement for the award of the degree of **MASTER OF TECHNOLOGY** specialization **"Machine Design and Analysis"** and submitted in the **Department of Mechanical Engineering** of **National Institute of Technology Rourkela**, during the period 2006-2007.

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Bhuwaneshwar Chourasiya

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Synopsis

The most significant challenges confronting autonomous robotics lie in the area of automatic motion planning. The target is to be able to specify a task in a high-level language and have the robot automatically compile this specification into a set of low-level motion primitives to accomplish the task. Navigation of mobile robots in changing and dynamic unstructured environments like the outdoor environments needs to cope with large amounts of uncertainties that are inherent of natural environments. Thus navigation of mobile robots covers a large spectrum of different technologies and applications. It draws on some very ancient techniques, as well as some of the most advanced space science and engineering.

The overall aim of this research is to explore the application of artificial intelligence technique to navigate mobile robot using image processing. In this thesis work, fuzzy logic has been used to solve mobile robot navigation problems. This type of investigation is justified in this thesis.

The main goal of research on reactive navigation strategies is to allow autonomous units, equipped with relatively low-cost sensors and actuators, to perform complex tasks in uncertain or unknown environments. These technologies have a wide range of potential application fields, which include the exploration of inaccessible or hazardous environments, industrial automation, and also biomedicine. In this research area, the development of the decision and control strategies necessary for autonomous operation plays a central role.

In order to cope with these difficulties, we have developed a flexible and modular hardware platform that allows us to design and validate the fuzzy control algorithms for autonomous navigation directly on hardware benchmarks. The platform addresses the following key issues:

1. It allows us to perform real-time control of commercially-available mobile robots, overcoming the inherent limitation of low-cost sensors and actuators.

2. It exploits the potential of the widespread and versatile Matlab /Simulink programming environment.

3. It provides a tool for developing user-friendly graphical interfaces for real-time monitoring and parameter tuning in research and education experiments.

The thesis is divided into eight chapters. Following the introduction, Chapter 2 is devoted to a survey of the literature on mobile robot navigation. Chapter 3 discusses kinematics of mobile robots. Chapter 4 deals with the analysis of a proposed fuzzy logic technique with three types of membership functions to navigate mobile robots in a static as well as dynamic environment. Chapter 5 deals with architecture of mobile robot platform. Chapter 6 deals with how the fuzzy logic controller taking decisions to find target with avoiding obstacles. Chapter 7 consist of experimental setup, behavior of mobile robot, during reaching the target and simulation results. In Chapter 8 conclusions of the research are summarized and ideas for further work are suggested.

CHAPTER 1

INTRODUCTION

Introduction

This chapter gives an overview of the research work reported in the thesis. First, the background of the research and the chosen problem domain are outlined. Then, the objectives of this research work are described. Finally, an outline of the thesis content is provided.

1.1 Background

The most significant challenges confronting autonomous robotics lie in the area of automatic motion planning. The target is to be able to specify a task in a high-level language and have the robot automatically compile this specification into a set of low-level motion primitives to accomplish the task.

Navigation of mobile robots in changing and dynamic unstructured environments like the outdoor environments needs to cope with large amounts of uncertainties that are inherent of natural environments. Thus navigation of mobile robots covers a large spectrum of different technologies and applications. It draws on some very ancient techniques, as well as some of the most advanced space science and engineering.

The investigation in the field of navigation of mobile robot gained an extensive interest among the researchers and scientists since last two decade. This is due chiefly to the necessity to replace human intervention in dangerous environments (nuclear, space, military mission, harmful material handling, interplanetary explorations. and etc.) or the wish to develop a helpful device for some more classical tasks (Cleaning, supervision, carriage, etc.). In today's flexible manufacturing system environment, the autonomous mobile robot plays a very important role. It is used to transport the parts from one workstation to others, load unloads parts, remove any undesired objects from floors, and so on. Without autonomous mobile robot, the work stations, the CNC machines, machining centers will only be scattered and isolated machine tools, they will never become a manufacturing system. It is the mobile robot that connects the scattered machines tools into an integrated and coordinated unit, which can continuously, automatically and at a low cost, manufacture a variety of parts. So mobile robot navigation encompasses a number of skills, from high-level capabilities such as exploring the surrounding world, building a global map of the environment and planning a path towards a specific goal, to the execution of elementary low level action like avoiding collisions, following a wall or crossing a door. Numerous methods have been proposed, however, they don't guarantee a solution for the mission because of deadlock problem occurrences. The reason is that 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 sensor including for example cameras) to get more pertinent data of the environment. In fact, some constraints are added to their drawbacks caused by: the difficulties to represent correctly the environment and to locate the robot due to errors in the sensor data that are still far from perfect taking in account the present day technologies.

The goal of autonomous mobile robotics is to build physical systems that can move purposefully and without human intervention in unmodified environments i.e., in real world environments that have not been specifically engineered for the robot. The development of techniques for autonomous robot navigation constitutes one of the major trends in the current research in robotics. This trend is motivated by the current gap between the available technology and the new application demands. On the one hand current industrial robots have low flexibility autonomy typically; these robots perform pre-programmed sequences of operation in highly constrained environment and are not able to operate in new environments or to face unexpected questions. Despite the impressive advances in the field of autonomous robotics in recent years, a number of problem that remain inherent to these environments. First prior knowledge about the environment is in general incomplete and approximate. The effect of control actions is not completely reliable.

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 avoided or corrected. These methodologies attempt to capture some aspects of the human behavior 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.

Navigation of a machine is the control of motion of that machine from a start point to an end point in a workspace following a path that is either a curve or a series of jointed segments. Autonomous navigation systems are usually classified in the following categories according to the characteristics of the environment in which they have to move: structured or known environment, semi structured or partially known environment and unstructured or unknown environments.

Another classical way is to send the robot to discover its world and define some landmarks that can be used for navigation. In similar conditions, the robot relies heavily on its sensors, map making and updating. However, natural workspaces present a large amount of uncertainty, and mapping techniques are time and memory consuming techniques. Hence the need of an approach such as soft computing techniques can cope with all uncertainties and can deal with various situations without being provided or having to provide models and workspace maps. Soft computing techniques involve computations related to neural network, fuzzy logic technique, genetic algorithm, simulated annealing and others.

Many studies focus on behavior-based approaches, in which the reactivity to unforeseeable circumstances is achieved with computationally simple algorithms that process sensory information in real time by means of high level inference strategies. In this context, fuzzy logic (FL) is often adopted to overcome the difficulties of modeling the unstructured, dynamically-changing environment, which is difficult to express using mathematical equations. Recent examples include the coordination of robot soccer teams, and the navigation on rugged terrain. To cope with uncertainties and enhance the robustness of navigation, many researchers have adopted automatic learning techniques, which allow the FLC to exploit sensory data about the explored environment not only for autonomous navigation but also for the adaptation of decision and control algorithms. In particular, computational intelligence methods such as genetic algorithms, reinforcement learning and neural learning are extremely promising.

On the other hand, in contrast to the goal of enhancing robustness and adaptability in real-world environments, it can be noted that a considerable amount of research in the context of fuzzy navigation strategies, and mobile robotics in general, is still based on the design of sophisticated algorithms that are mainly validated with simulations of idealized environments. In particular, these conventional design procedures are based on a sequential schema that includes off-line problem description, model development, model-based design, simulation-based debugging and validation, followed by a final implementation on hardware, and subsequent trial-and-error refinement. Two fundamental limitations may compromise the effectiveness of such a sequential design procedure. Firstly, it is difficult to give a comprehensive description of unstructured navigation environments, and effectively take into account all the details of the unknown scenarios that can have a significant influence on decision and control algorithms. Secondly, simulations cannot easily take into account the effects of apparently negligible phenomena such as nonlinearities, noise, uncertainties, adverse operating conditions (e.g. poor lighting, defective hardware), and the interaction between concurrent real-time tasks devoted to sensor fusion, noise filtering, decision and control.

1.2 Aim and Objective of this Research

The overall aim of this research is to explore the application of artificial intelligence technique to navigate mobile robot using image processing . In this thesis work fuzzy logic have been used to solve mobile robot navigation problems. This type of investigation is justified in this thesis.

The main goal of research on reactive navigation strategies is to allow autonomous units, equipped with relatively low-cost sensors and actuators, to perform complex tasks in uncertain or unknown environments. These technologies have a wide range of potential application fields, which include the exploration of inaccessible or hazardous environments, industrial automation, and also biomedicine. In this research area, the development of the decision and control strategies necessary for autonomous operation plays a central role.

In order to cope with these difficulties, we have developed a flexible and modular hardware platform that allows us to design and validate the fuzzy control algorithms for autonomous navigation directly on hardware benchmarks. The platform addresses the following key issues:

1. It allows us to perform real-time control of commercially-available mobile robots, overcoming the inherent limitation of low-cost sensors and actuators.

2. It exploits the potential of the widespread and versatile Matlab /Simulink programming environment.

3. It provides a tool for developing user-friendly graphical interfaces for real-time monitoring and parameter tuning in research and education experiments.

1.3 Outline of the Thesis

The thesis is divided into eight chapters.

Following the introduction, Chapter 2 is devoted to a survey of the literature on mobile robot navigation.

Chapter 3 discusses kinematics of mobile robots.

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CHAPTER 2

LITERATURE SURVEY

Literature Survey

This chapter surveys the literature in the area of mobile robot navigation, focusing on intelligent systems techniques for navigation control.

Introduction

A motion planner is an essential component of a robot that interacts with the environment; without it a human operator has to constantly specify the motion for the robot. A significant amount of research has been done on the development of efficient motion-planning algorithms. The motion-planning problem has been solved in a theoretical sense for subsets of the general problem. Recently the coordination between mobile robots for obstacle avoidance and target seeking are carried out by the researchers and scientists using various methods. Soft computing techniques such as fuzzy logic, neural network and genetic algorithm are considered for expressing the subjective uncertainties in human mind. Humans have a remarkable capability to perform a wide variety of physical and mental tasks without any explicit measurements or computations. Examples of everyday tasks are driving in city traffic, parking a car, and cleaning of house. In performing such familiar tasks, humans use perceptions of time, distance, speed, shape, and other attributes of physical and mental objects. The ultimate goal of mobile robotics research is to endow the robots with high autonomous ability, of which navigation in an unknown environment is achieved by using on-line sensory information. A significant amount of research effort has been devoted to this area in the past decades few of which are surveyed below:

2.2 Mobile Robot Navigation

Navigation of a machine is the control of machine from a start point to end point in a workspace following a path that is either a curve or a series of jointed segments. Many researchers in the area of mobile robot navigation have developed two main navigation approaches. One is functional or horizontal decomposition [2] (Figure 2.1). The other is behavioral or vertical decomposition [3] (Figure 2.2). The former approach is sequential and involves modeling and planning. The latter approach is parallel and requires exploration and map building. Both approaches use many distinct sensory inputs and computational processes. Decisions such as left turn, right turn, run or stop are made on the basis of those inputs [4].

Levitt and Lawton [5] defined the aim of navigation control as providing answers to the following three questions: (a) Where am I? (b) Where are other places relative to me? (c) How do I get to other places from here? Question (a) is the problem of identifying the current location. Questions (b) and (c) relate to avoid obstacles and move towards target. To address both issues a mobile robot must have a way to perceive its environment. Some authors have proposed that one type of sensor devices such as sonar, laser, vision and infrared be adopted [6,7 and 8], where as others have recommended heterogeneous systems using different types of sensors [9,10, and 11].

Using the environment information perceived at each instant as well as data from previous instants, a strategy should be pursued to enable the robot to reach its target position without colliding obstacles. Researchers have used many techniques for obstacle avoidance [12, 13, 14, and 15]. Those techniques, together with the different sensors employed [16, and 17] will be reviewed below.

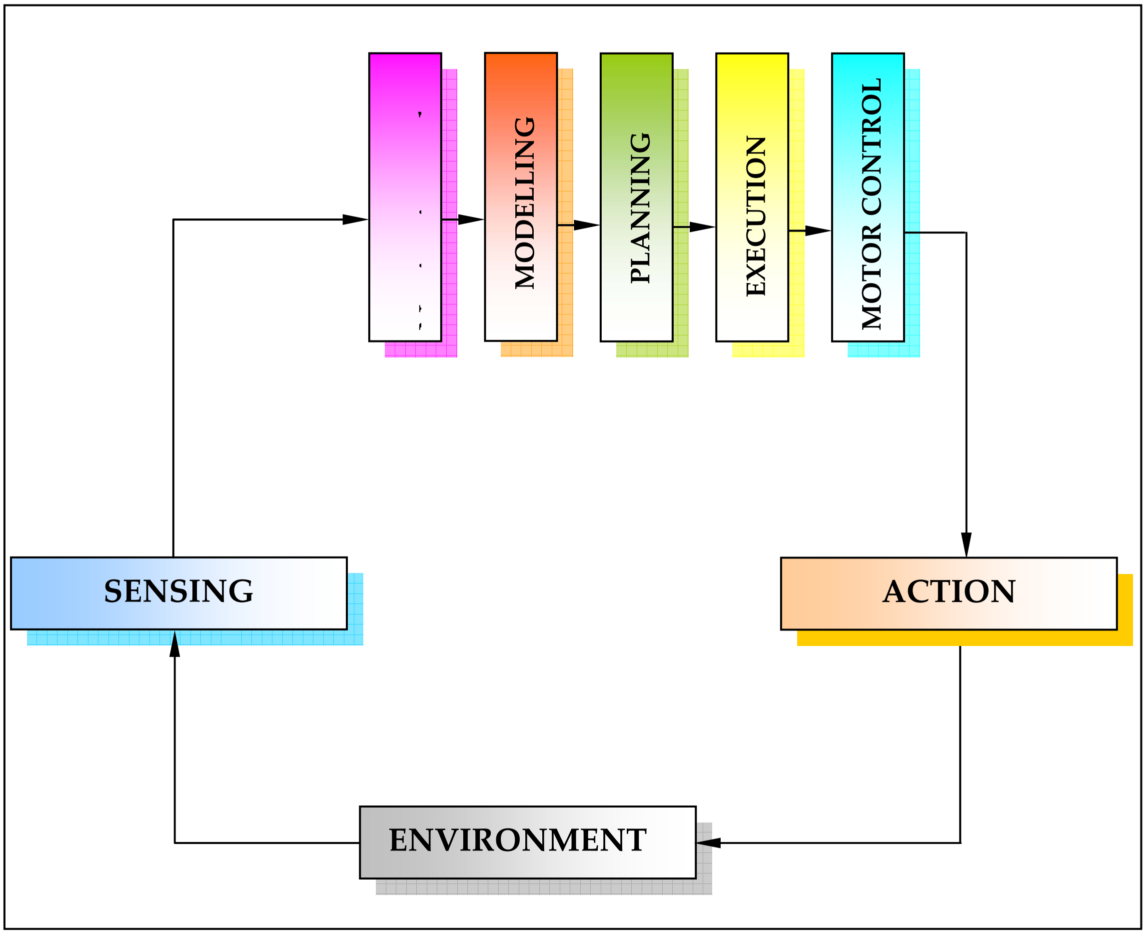


Figure 2.1. Flow diagram of the horizontal decomposition method for the navigation of a mobile robot.

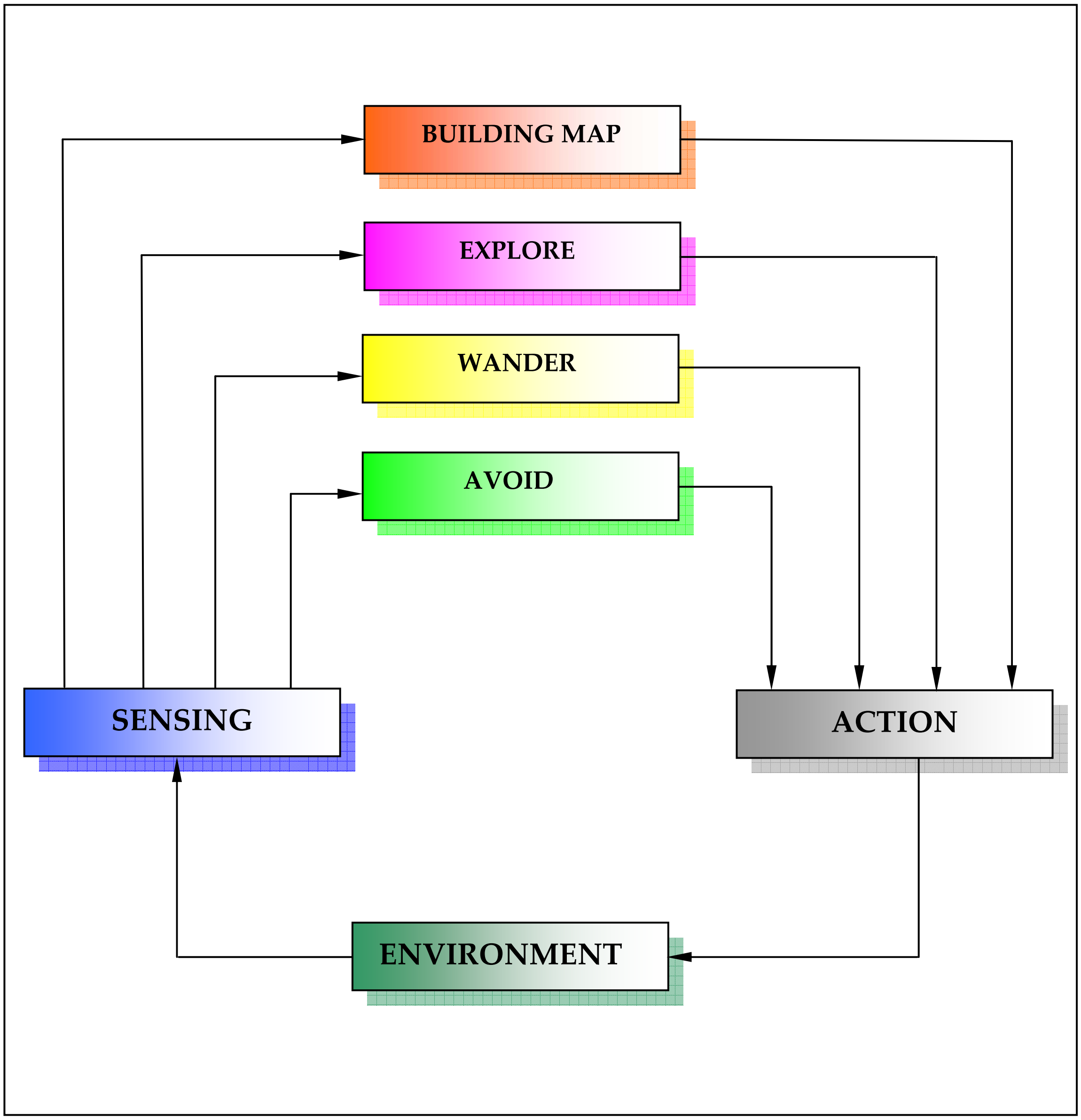


Figure 2.2. Flow diagram of the vertical decomposition method for the navigation of a mobile robot

2.3 Kinematics of Mobile Robots

2.3.1 Introduction

A wheeled mobile robot is a wheeled vehicle, which is capable of autonomous motion. An increasing interest in mobile manipulators observed recently in the literature has two sources: first, excellent performance characteristics of mobile manipulators, second, challenging motion planning and control problems [18].

2.3 .2 Kinematics for Mobile Robot Navigation

Alexander et al. [19] have developed the relationship between the rigid body motion of a robot and the steering and drive rates of wheels by. They have used the forward and inverse kinematics to a WMR with simple wheels that is maneuvering over a horizontal plane. Their method guarantees that rolling without skidding or sliding can occur in robot motion. Mester [20] has dealt with the modeling and control strategies of the motion of wheeled mobile robots. The model of the vehicle has two driving wheels and the angular velocities of the two wheels are independently controlled. He has analyzed the vehicle kinematics model and the control strategies using a feed forward compensator.

Chakraborty et al. [21] have studied the problem of kinematic slip for mobile robots moving on uneven terrain. A simulation result of their developed technique shows that the three-wheeled WMR with torus shaped wheels and passive joints can negotiate uneven terrain without slipping.

2.4 Fuzzy Logic Techniques

2.4.1 Introduction

Fuzzy control concepts are useful in both global and local path planning tasks for autonomous mobile objects. Humans have a remarkable capability to perform a wide variety of physical and mental task without any explicit measurements or computations. Examples of everyday tasks are driving in city traffic, parking a car, and cleaning of house. In performing such familiar tasks, humans use perceptions of time, distance, speed, shape, and other attributes of physical and mental objects. Perceptions are described by propositions drawn from a natural language, in which the boundaries of perceived classes are fuzzy. It is highly desirable to capture the expertise of a human mind and to utilize the knowledge to develop autonomous navigation strategies for mobile robots. Fuzzy logic provides a means toward accomplishing this goal. Fuzzy logic provides a formal methodology for representing and implementing the human expert's heuristic knowledge and perception-base actions. Using the fuzzy logic framework, the attributes of human reasoning and decision-making can be formulated by a set of simple and intuitive *IF (antecedent)–THEN (consequent)* rules, coupled with easily understandable and natural linguistic representations.

2.4.2Fuzzy Logic Technique for Mobile Robot Navigation

The automatic motion-planning problem in robotics and computer aided manufacturing has been studied extensively. Although planning a sequence of motions to bring together parts in a specific configuration has become essential for several applications, the traditional solutions for path planning have failed for complicated environments as they result computationally infeasible and restricted to their performance Latombe [22] and

Fraichard [23]. Many researchers have used fuzzy logic techniques in mobile robot navigation. Examples of work relating to fuzzy logic for the navigation of mobile robot are described below:

Motivated by Zadeh [24] and explored by Mamdani et al [25] and Kickert et al [26], many researchers have used fuzzy logic techniques successfully in numerous control systems such as control of mobile robot navigation. Examples of work relating to fuzzy logic for the navigation of mobile robot are described below:

Langer et al. [27] focus on the development of a navigation system that generates recommendations for vehicle steering, based on the distribution of untraversable terrain regions. A new design for behavior-based navigation of field mobile robots on challenging terrain using a fuzzy logic approach and a novel measure of terrain traversability have been developed by [28] Seraji et al.

Li et al. [29] have designed and implemented an autonomous car-like mobile robot (CLMR) control system, where they have set up the host computer, communication module, CLMR, and vision system. They have used fuzzy garage-parking control (FGPC) and fuzzy parallel-parking control (FPPC) to maneuver the steering angle of the CLMR. Li et al. [30] have used the concepts of car maneuvers, fuzzy logic control (FLC), and sensor-based behaviors to implement the human-like driving skills by an autonomous car-like mobile robot. They have used four kinds of FLCs, fuzzy wall-following control, fuzzy corner control, fuzzy garage-parking control, and fuzzy parallel-parking control, are synthesized to accomplish the autonomous fuzzy behavior control (AFBC). They have presented computer simulation results to illustrate the effectiveness of their proposed control schemes and demonstrate the feasibility in practical car maneuvers.

Baturone et al. [31] have described the design and implementation of a fuzzy control system for car-like autonomous vehicle. They have addressed problem for diagonal parking in a constrained motion. A grey-fuzzy controller (GFC) is developed by them for motion control of the tracker, in which dynamic models of the target and tracker are not required a priori. Ohkita M. et al. [32] have control an autonomous mobile robot for the flush parking. They have used fuzzy rules that are derived by modeling driving actions of a car. The drive control of an autonomous mobile robot is a new approach to recognize and to adapt to surrounding environment. Maeda [33] have developed fuzzy control based on forecast learning. They had shown their results in simulation as well as experiment mode to drive the control of the robot. An approach for building multi-input and single-output fuzzy models have been proposed by Joo et al. [34] and applied to construct a fuzzy model for the navigation control of a mobile robot. Xu et al. [35] have presented Real-time fuzzy reactive control for automatic navigation of an intelligent mobile robot in an unknown and changing environment. The reactive rule base governing the robot behavior is synthesized corresponding to the various situations defined by the instant robot motion, environment and target information. Simulation and experimental results have presented by the authors to validate their approach.

Lee et al. [36] have proposed fuzzy algorithm to navigate a mobile robotῳῳ from a given initial configuration to a desired final configuration in an unknown environment filled with obstacles. The mobile robot is equipped with an electronic compass and two optical encoders for dead-reckoning, and two ultrasonic modules for self-localization and environment recognition. From the readings of sensors at every sampling instant, the proposed fuzzy algorithm will determine the priorities of thirteen possible heading directions. Then the robot is driven to an intermediate configuration along the heading direction that has the highest priority. The navigation procedure will be iterated until a collision-free path between the initial and the final configurations is found. To show the feasibility of the proposed method, in addition to computer simulation, experimental results also demonstrated by the author.

Kodagoda et al. [37] have proposed a control structure for uncoupled longitudinal and lateral control of an autonomous guided vehicle. Longitudinal control is achieved via two uncoupled fuzzy controllers, *viz.*, a fuzzy drive controller and a fuzzy braking controller switched appropriately by a supervisory controller. Fukuda et al. [38] proposed an integrated structure for intelligent robotic systems based on a fuzzy controller. They have focused mainly on the perception capability based on the sensory network. Benreguieg et al. [39] have used navigator having two fuzzy controllers, one is angular another is linear speed. Their navigation function consisting of obstacle avoidance and react with the shortest response time. They have demonstrated their techniques on two distinct autonomous mobile robots. Beaufrere et al. [40] have solved the problem of navigation for a single mobile robot in a totally unknown environment using fuzzy logic. They have shown their results in simulation as well as in experimental validation on a single mobile robot.

A fuzzy logic based real time navigation controller is described by Liu et al. [41]. Their controller combines the path planning and trajectory following as an integrated and coordinated unit so that it executes maneuvers such as docking and obstacle avoidance on line. Pratihar et al. [42] have developed a collision-free path for multiple robots using genetic-fuzzy systems.

Demirli et al. [43] have introduced a new fuzzy logic-based approach for dynamic localization of mobile robots. They have used sonar data collected from a ring of sonar sensors mounted around the robot. The angular uncertainty and radial imprecision of sonar data are modeled by possibility distributions. Combining information from adjacent sensors reduces the uncertainty in sonar readings. The reduced models of uncertainty are used to construct a local fuzzy composite map of the environment. The local fuzzy composite map is fitted to the given global map of the environment to identify robot's location. Their proposed algorithm is implemented on a mobile robot and the results are reported. Khatib et al. [44] have used a data-driven fuzzy approach for solving the motion-planning problem of a mobile robot in the presence of moving obstacles. The approach consists of devising a general method for the derivation of input–output data to construct a fuzzy logic controller (FLC) off-line. The FLC is constructed based on the use of a recently developed data-driven and efficient fuzzy controller-modelling algorithm and it can then be used on-line by the robot to navigate among moving obstacles. They have compared their results with those obtained by fuzzy-genetic and another hybrid and data-driven design. Abdessemed et al. [45] have presented the theoretical development of a complete navigation problem of an autonomous mobile robot. The situation for which the vehicle tries to reach the endpoint is treated using a fuzzy logic controller. They have solved the problem of extracting the optimized IF–THEN rule base is solved using an evolutionary algorithm. They have developed a new approach based on fuzzy concepts to avoid any collision with the surrounding environment when this latter becomes relatively complex. Simulation results show that the designed fuzzy controller achieves effectively any movement control of the vehicle from its current position to its end motion and without any collision. Godjevec [46] outlined some linguistic rules for navigation of a mobile robot. He used fuzzy logic technique to implement the rules. He showed numerical examples for the navigation of a single mobile robot in a simple environment condition.

CHAPTER 3

KINEMATICS OF MOBILE ROBOT

Kinematics of Mobile Robot

In this chapter, the kinematics analysis of a wheeled mobile robot is carried out in which robot ride on a system of wheels and castors. With the help of the velocities of right wheel and left wheel, the steering angle is calculated to avoid obstacles near around the robot.

3.1 Introduction

A four wheeled mobile robot is modeled here as a planar rigid body with two driving wheels, arranged parallel to each other and 'B' distances apart, which are driven separately by two independent motors and two castors is provided for stability of the robot. The front wheels are a castor wheels. The connections between the rigid body motion of the robot and the angular velocity of the robot and driving controls of the wheels are developed. In particular, conditions are obtained that guarantee that rolling without slipping can occur. The simplest wheel configuration that permits control of arbitrary rigid body motions is determined.

3.2 Configuration of Mobile Robot

The mobile robot system in this study consists of two subsystems. They are driving subsystem and sensing subsystem.

Two driving configurations are used in today's mobile robot, steer drive and differential drive. The former uses two driving wheels to make the vehicle move forward and backward, and another separate steering mechanism to control its heading angle. Since the driving action is independent of the steering action, the motion control of the vehicle is somewhat easy. However due to physical constraints, this configuration cannot make turning in a very small radius, which need more floor space for vehicle turning.

The differential drive on the other hand has two independent drive wheels arranged parallel to each other. Their speed can be controlled separately. Thus the mechanism is able to not only drive the vehicle forward and backward, but also steer its heading angle by differentiating their speed. Even though this configuration requires a somewhat more complex control strategy than the steer drive configuration, its capability of making a small radius turning, even making a turning on the spot makes it the first choice in most researchers. In this research a differential drive configuration is used as shown in figure 3.1.

3.3 Kinematics Model

3.3.1 Assumption considered for analyzing path constrained of a wheeled mobile robot

- There are two identical castors in front of the mobile robot.
- There is no transitional slip between the wheels and the surface.
- Here is enough rotational friction between the wheel and the surface; so, the wheels can rotate without disturbance.
- The two driving wheels are identical.

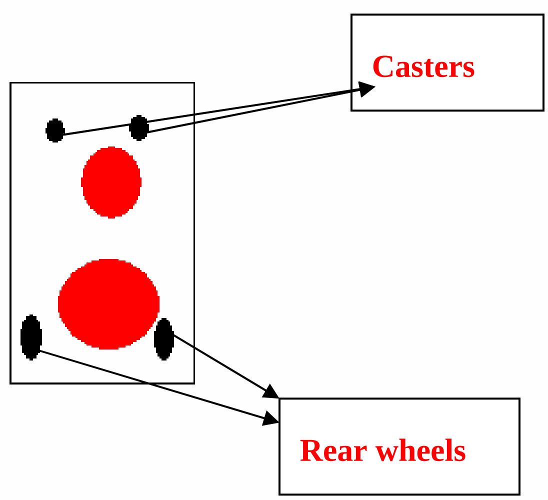


Figure 3.1.Top view of four wheel mobile Robot

To consider the kinematics model of an robot, it is assumed that the robot is placed on a plane surface with the inertial orthonormal basis (Xg,Yg,Zg), see Fig. 3.2. A local coordinate frame denoted by (xl, yl, zl) is assigned to the robot at its center of mass (COM). According to Fig. 3.2, the coordinates of COM in the inertial frame can be written as COM = (X, Y, Z). Since in this thesis the plane motion is considered only, the Z-coordinate of COM is constant (Z = const).

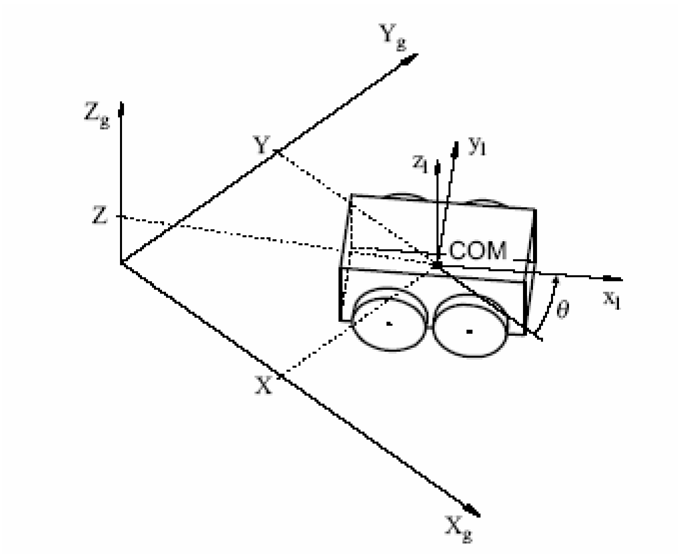


Fig. 3.2. Mobile robot in the inertial frame.

Suppose that the robot moves on a plane with linear velocity expressed in the local frame as v = [vx, vy , 0]T and rotates with an angular velocity vector ω = [0 0 ω]T .
If q = [X Y θ]T is the state vector describing generalized coordinates of the robot (i.e., the COM position, X and Y , and the orientation θ of the local coordinate frame with respect to the inertial frame), then ˙q = [˙X ˙Y˙ θ]T denotes the vector of generalized velocities. From Fig. 3.3 it can be noted that the variables ˙X and ˙Y are related to the coordinates of the local velocity vector as follows

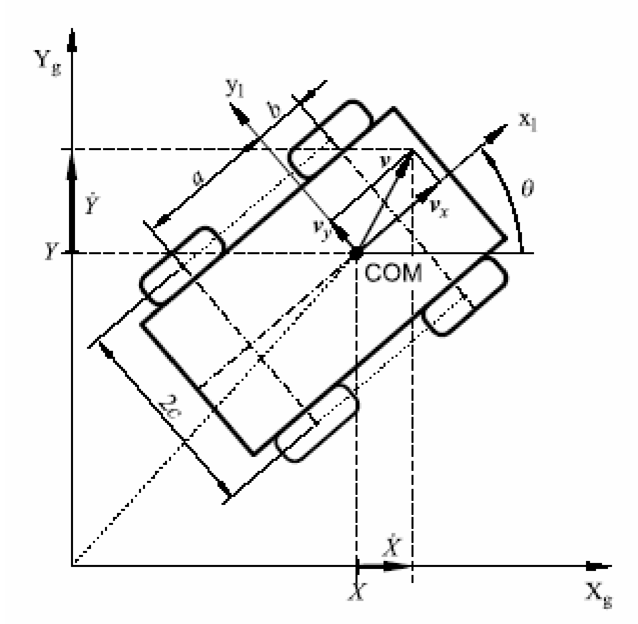


Fig. 3.3. Free body diagram.

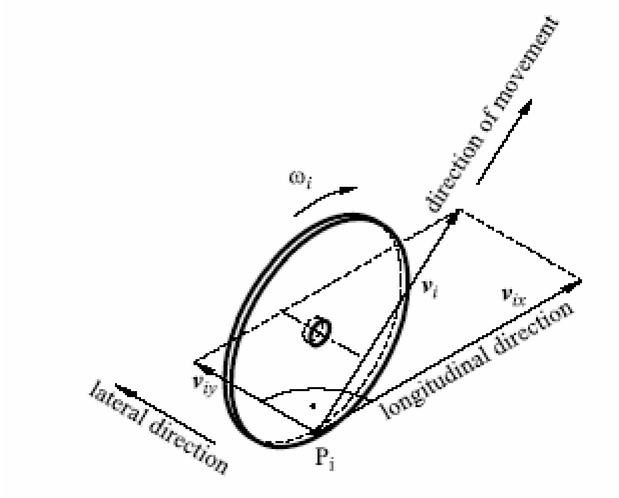


Fig.3.4. Velocities of one wheel.

$$\begin{bmatrix} \dot{X} \\ \dot{Y} \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} v_x \\ v_y \end{bmatrix} \qquad \text{………………(3.1)}$$

Furthermore, because of the planar motion, one can write $\dot{\theta} = \omega$.

It is obvious that Eqn. (3.1) does not impose any restrictions on the mobile obot plane movement, since it describes free-body kinematics only. Therefore it is necessary to analyze the relationship between wheel velocities and local velocities.

Suppose that the i-th wheel rotates with an angular velocity !i (t), where i = 1, 2, . . . , 4, which can be seen as a control input. For simplicity, the thickness of the wheel is neglected and is assumed to be in contact with the plane at point Pi as illustrated in Fig. 3.4. In contrast to most wheeled vehicles, the lateral velocity of the mobile robot, viy, is generally nonzero. This property comes from the mechanical structure of the mobile robot that makes lateral skidding necessary if the vehicle changes its orientation.

Therefore the wheels are tangent to the path only if ω = 0, i.e., when the robot moves along a straight line.

In this description we consider only a simplified case of the mobile robot movement for which the longitudinal slip between the wheels and the surface can be neglected. The following relation can be developed:

vix=ri*ωi…………………….(3.2)

where vix is the longitudinal component of the total velocity vector vi of the i-th wheel expressed in the local frame and ri denotes the so-called effective rolling radius of that wheel.

To develop a kinematic model, it is necessary to take into consideration all wheels together. In Fig. 3.5, the radius vectors di = [dix diy]T and dC = [dCx dCy]T

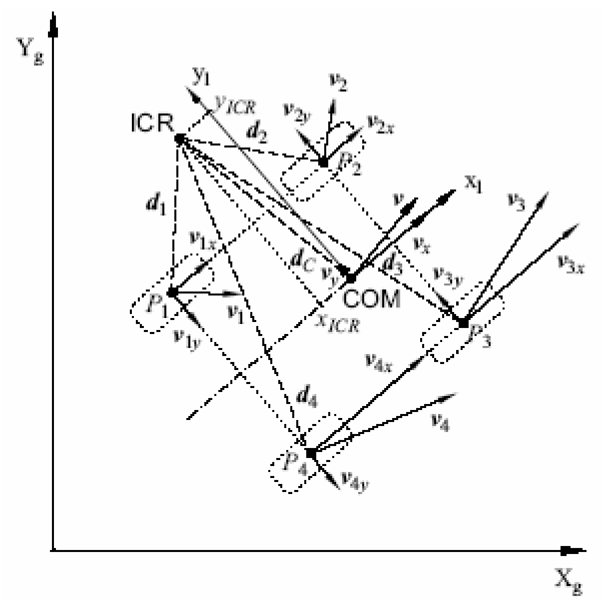


Fig. 3.5. Wheel velocities.

are defined with respect to the local frame from the instantaneous center of rotation (ICR). Consequently, based on the geometry of Fig. 3.5, the following expression can be deduced:

$$\frac{\|v_i\|}{\|d_i\|} = \frac{\|v\|}{\|d_C\|} = |\omega| \qquad \text{………………(3.3)}$$

or, in a more detailed form,

$$\frac{v_{ix}}{-d_{iy}} = \frac{v_x}{-d_{Cy}} = \frac{v_{iy}}{d_{ix}} = \frac{v_y}{d_{Cx}} = \omega, \qquad \text{………………..(3.4)}$$

where the symbol ||·|| denotes the Euclidean norm.

Defining the coordinates of the ICR in the local frame as

ICR = (xICR, yICR) = (−dxC, −dyC) ………….(3.5)

allows us to rewrite (4) as follows:

$$\frac{v_x}{y_{\text{ICR}}} = -\frac{v_y}{x_{\text{ICR}}} = \omega. \qquad \text{………………….(3.6)}$$

From Fig. 3.5 it is clear that the coordinates of vectors di satisfy the following relationships:

{d1y = d2y = dCy + c,

d3y = d4y = dCy − c,

d1x = d4x = dCx − a,

d2x = d3x = dCx + b,}……………….(3.7)

where a, b and c are positive kinematic parameters of the robot depicted in Fig. 3.3. After combining Eqns. 3.(4)and (3.7), the following relationships between wheel velocities can be obtained:

{vL = v1x = v2x,

vR = v3x = v4x,

vF = v2y = v3y,

vB = v1y = v4y,}………………….3.(8)

where vL and vR denote the longitudinal coordinates of the left and right wheel velocities, vF and vB are the lateral coordinates of the velocities of the front and rear wheels, respectively.

Using (3.4)–(3.8) it is possible to obtain the following transformation describing the relationship between the wheel velocities and the velocity of the robot:

$$\begin{bmatrix} v_L \\ v_R \\ v_F \\ v_B \end{bmatrix} = \begin{bmatrix} 1 & -c \\ 1 & c \\ 0 & -x_{\mathrm{ICR}} + b \\ 0 & -x_{\mathrm{ICR}} - a \end{bmatrix} \begin{bmatrix} v_x \\ \omega \end{bmatrix}. \qquad \ldots\ldots\ldots\ldots\ldots\ldots(3.9)$$

In accordance with (3.2) and (3.8), assuming that the effective radius is ri = r for each wheel, we can write

$$\omega_w = \begin{bmatrix} \omega_L \\ \omega_R \end{bmatrix} = \frac{1}{r} \begin{bmatrix} v_L \\ v_R \end{bmatrix}, \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots..(3.10)$$

where ωL are ωR are the angular velocities of the left and right wheels, respectively.

Combining (3.9) and (3.10), the following approximated relations between the angular wheel velocities and the velocities of the robot can be developed:

$$\eta = \begin{bmatrix} v_x \\ \omega \end{bmatrix} = r \begin{bmatrix} \dfrac{\omega_L + \omega_R}{2} \\ \dfrac{-\omega_L + \omega_R}{2c} \end{bmatrix}, \qquad \ldots\ldots\ldots\ldots\ldots(3.11)$$

where η is a new control input introduced at the kinematic level.

From the last equation it is clear that, theoretically, the pair of velocities ωL and ωR can be treated as a control kinematic input signal as well as velocities vx and ω.

However, the accuracy of the relation (3.11) mostly depends on the longitudinal slip and can be valid only if this phenomenon is not dominant.

CHAPTER 4

FUZZY LOGIC TECHNIQUE

FUZZY LOGIC TECHNIQUE

4.1 Introduction

Navigation of mobile robot in presence of static and moving obstacles using different types of Fuzzy Logic Controller (FLC) is discussed. This task could be carried out specifying a set of fuzzy rules taking into account the different situations found by the mobile robots. The approach is to extract a set of fuzzy rule set from a set of trajectories provided by human. For this purposes the input to all the FLC are left obstacle distance, right obstacle distance, front obstacle distance and target angle considered. The output from FLC is left wheel velocity and right wheel velocity of mobile robots is in use. The fuzzy rules help the robots to avoid obstacles and find targets. Results were presented to demonstrate the performance of the proposed approach.

4.2Control Architecture

4.2.1 Analysis of Obstacle Avoidance and Target Seeking Behavior

The robots used here are rear wheel drive having two rear wheels, namely left and right rear wheel. The mobile robot considered in this thesis is a point robot for simulation mode. Its dimension is 1 X 1 $pixel^2$. Each robot has an array of sensors for measuring the distances around it and locating the target i.e., front obstacle distance (FD), left obstacle distance (LD), right obstacle distance (RD) and detecting the bearing of target (HA). The distance between the robots and obstacles act as repulsive forces for avoiding the obstacles, and the bearing of the target acts as an attractive force between robots and target.

In this research three types of membership functions are considered. First one is of three-membership function having two trapezoidal members and one triangular member. Linguistic variables such as “far”, “medium” and “near” are taken for three-membership function. Five membership function is considered with all are of triangular member. Here linguistic variables like “very near”, “near”, “medium”, “far” and “very far” are considered. Finally Gaussian membership function is considered with “very near”,

"near", "medium", "far" and "very far" as linguistic variables for navigation of mobile robot.

Some of the fuzzy control rules are activated according to the information acquired by the robot using vision sensor. The outputs of the activated rules are weighted by fuzzy reasoning and the velocities of the rear driving wheels of the robot are calculated. . Left wheel velocity and right wheel velocity are denoted as leftvelo (LV) and rightvelo (RV) respectively (Table 4.1). Similarly leftdist, rightdist, and frontdist are defined for the distances left obstacle distance (LD), right obstacle distance (RD) and front obstacle distance (FD) respectively.

Linguistic variables such as "pos" (positive) "zero" and "neg" (negative) are defined for the bearing of heading angle (HA) with respect to target. The term "notargetconsider" is used if there is no target in the environment. Linguistic variables like "fast"; "medium" and "slow" are defined for left wheel velocity and right wheel velocity for three-membership function. Terms like "very slow", "slow", "medium", "fast", and "very fast" are considered for left wheel velocity and right wheel velocity for five-membership functions. Similarly linguistic variables such as "more pos" (more positive),"pos" (positive) "zero", "neg" (negative) and "more neg" (more negative) are defined for the bearing of heading angle (HA) with respect to target. The parameters defining the functions are listed in Table 4.1. The membership functions described above are shown in Figure 4.1.

(a)Parameters for Left and Right Obstacle

Variables	**Very Near (Meter)**	**Near (Meter)**	**Medium (Meter)**	**Far (Meter)**	**Very Far (Meter)**
Left Obstacles Distances Right Obstacles Distances and Front Obstacles Distances	0.0	1.0	2.0	3.0	4.0
	1.0	2.0	3.0	4.0	5.0
	2.0	3.0	4.0	5.0	6.0

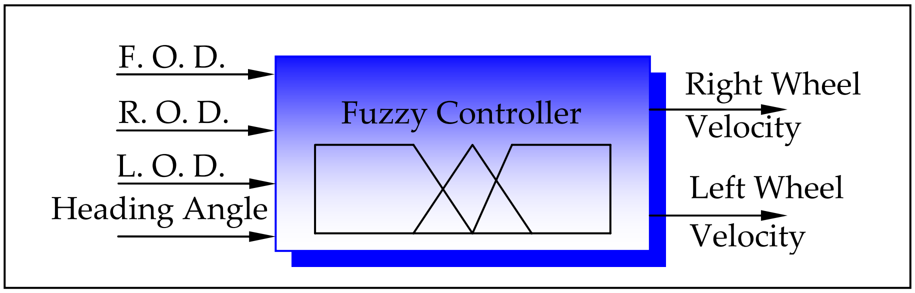
(b)Parameters for Heading Angle

Variables	More Negative (Degree)	Negative (Degree)	Zero (Degree)	More Positive (Degree)	Positive (Degree)
Left Obstacles Distances and Right Obstacles Distances	-180	-120	-20	0	20
	-120	-20	0	20	120
	-20	0	20	120	180

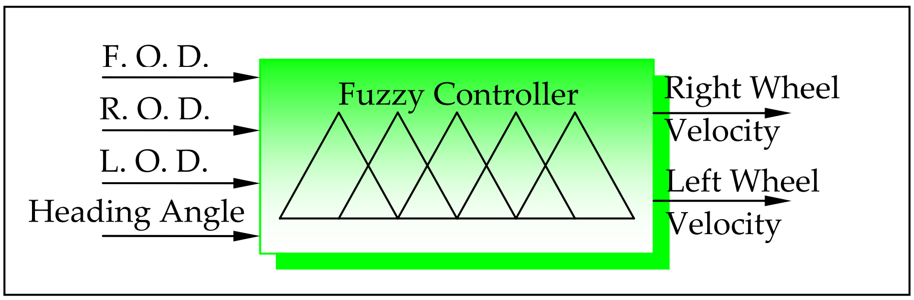
(c) Parameters for Heading Angle

Variables	Very Slow (Meter/Sec)	Slow (Meter/Sec)	Medium (Meter/Sec)	Fast (Meter/Sec)	Very Fast (Meter/Sec)
Left Wheel Velocity and Right Wheel Velocity	0.0	0.5	1.0	1.5	2.0
	0.5	1.0	1.5	2.0	2.5
	1.0	1.5	2.0	2.5	3.0

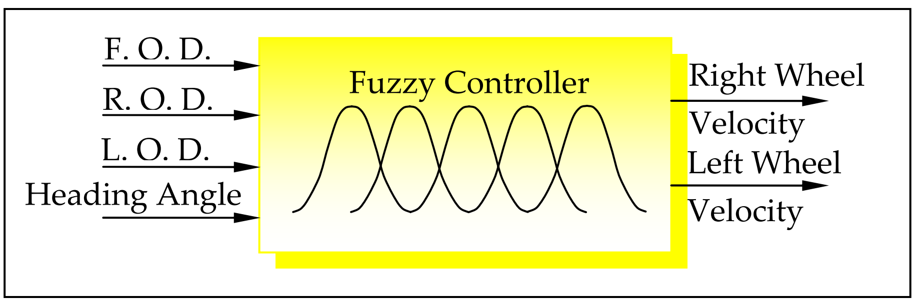
Table 4.1. Parameters of fuzzy membership functions



Three-Membership Fuzzy Controller for Mobile Robot Navigation



Five-Membership Fuzzy Controller for Mobile Robot Navigation



Gaussian Fuzzy Controller for Mobile Robot Navigation

0.6

F. O. D. = Front Obstacle Distance, L. O. D. = Left Obstacle Distance and

R. O. D. = Right Obstacle Distance

Figure 4.1. Fuzzy Controllers for Mobile Robot Navigation

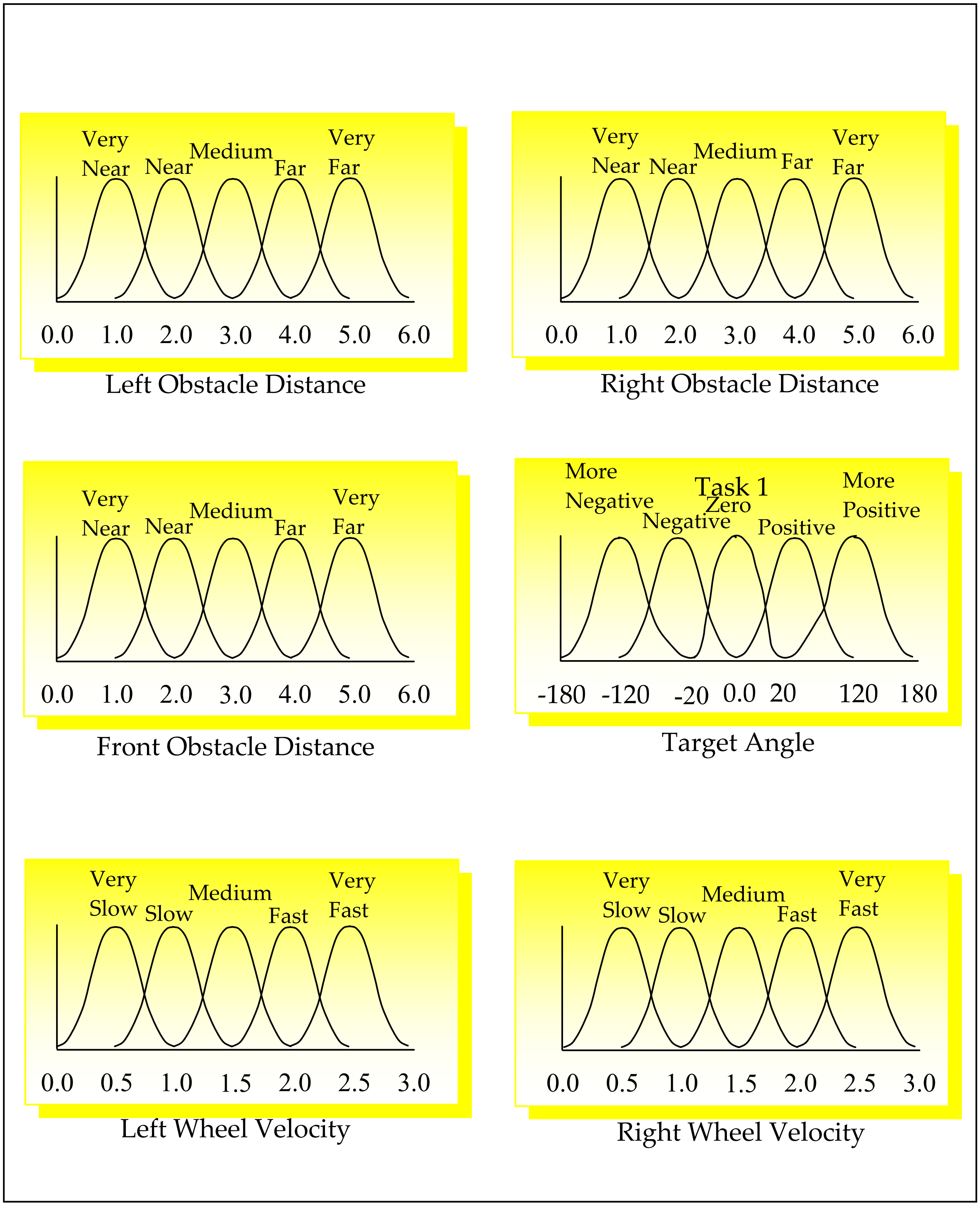


Figure 4.2. Fuzzy membership functions

Fuzzy Mechanism for Mobile Robot Navigation

Based on the subsets the fuzzy control rules are defined as follows:

$$\text{If (LD is } LD_i \wedge \text{ FD is } FD_j \wedge \text{ RD is } RD_k \wedge \text{ HA is } HA_l) \tag{4.1}$$

Then LV is LV_{ijkl} and RV is RV_{ijkl}

Where i = 1 to 3, j = 1 to 3, k = 1 to 3 and l = 1 to 3 because LD, FD, RD and HA have three membership functions each.

And for five membership function i = 1 to 5, j = 1 to 5, k = 1 to 5 and l = 1 to 5

From equation (4.1) two rules can be written:

$$\left.\begin{array}{l}\text{If (LD is } LD_i \text{ and FD is } FD_j \text{ and RD is } RD_k \text{ and HA is } HA_l) \\ \text{Then } LV = LV_{ijkl} \\ \text{And} \\ \text{If (LD is } LD_i \text{ and FD is } FD_j \text{ and RD is } RD_k \text{ and HA is } HA_l) \\ \text{Then } RV = RV_{ijkl} \\ \text{A factor } W_{ijkl} \text{ is defined for the rules as follows:}\end{array}\right\} \tag{4.2}$$

$$W_{ijkl} = \mu_{LD_i}(dis_i) \wedge \mu_{FD_j}(dis_j) \wedge \mu_{RD_k}(dis_k) \wedge \mu_{HA_l}(ang_l) \tag{4.3}$$

Where dis_i, dis_j, and dis_k are the measured distances, and ang_l is the value of the heading angle.

The membership values of the left wheel and right wheel velocities vel_{LV} and vel_{RV} are given by:

$$\left.\begin{array}{ll}\mu_{LV'_{ijkl}}(vel) = W_{ijkl} \wedge \mu_{LV_{ijkl}}(vel_{LV}) & \forall_{vel} \in LV \\ \mu_{RV'_{ijkl}}(vel) = W_{ijkl} \wedge \mu_{RV_{ijkl}}(vel_{RV}) & \forall_{vel} \in RV\end{array}\right\} \tag{4.4}$$

The overall conclusion by combining the outputs of all the fuzzy rules can be written as follows:

$$\left.\begin{array}{l}\mu_{LV}(vel) = \mu_{LV'_{1111}}(vel_{LV}) \vee \ldots \vee \mu_{LV'_{ijkl}}(vel_{LV}) \vee \ldots \vee \mu_{LV'_{3333}}(vel_{LV}) \\ \mu_{RV}(vel) = \mu_{RV'_{1111}}(vel_{RV}) \vee \ldots \vee \mu_{RV'_{ijkl}}(vel_{RV}) \vee \ldots \vee \mu_{RV'_{3333}}(vel_{RV})\end{array}\right\} \tag{4.5}$$

Equation (4.5) is for three membership functions. For five-membership function the fuzzy rules are written as:

$$\left.\begin{array}{l}\mu_{LV}(vel) = \mu_{LV'_{1111}}(vel_{LV}) \vee \ldots \vee \mu_{LV'_{ijkl}}(vel_{LV}) \vee \ldots \vee \mu_{LV'_{5555}}(vel_{LV}) \\ \end{array}\right\} \tag{4.6}$$

$$\mu_{RV}(\text{vel}) = \mu_{RV'_{1111}}(\text{vel}_{RV}) \vee \ldots \vee \mu_{RV'_{ijkl}}(\text{vel}_{RV}) \vee \ldots \vee \mu_{RV'_{5555}}(\text{vel}_{RV})$$

The crisp values of Left Wheel Velocity and Right Wheel Velocity are computed using center of gravity method is:

$$\left.\begin{aligned} \text{Left Wheel Velocity} &= \text{LV} = \frac{\int \text{vel} \cdot \mu_{LV}(\text{vel}) \cdot d(\text{vel})}{\int \mu_{LV}(\text{vel}) \cdot d(\text{vel})} \\ \text{Right Wheel Velocity} &= \text{RV} = \frac{\int \text{vel} \cdot \mu_{RV}(\text{vel}) \cdot d(\text{vel})}{\int \mu_{RV}(\text{vel}) \cdot d(\text{vel})} \end{aligned}\right\} \quad (4.7)$$

CHAPTER 5

PLATFORM ARCHITECTURE OF MOBILE ROBOT

5. PLATFORM ARCHITECTURE OF MOBILE ROBOT

The design of a new fuzzy logic-based navigation algorithm for autonomous robots is illustrated which effectively achieves correct environment modeling and noisy and uncertain sensory data processing on low-cost hardware equipment. We have devised a hierarchical control strategy in which three different reactive behaviors [1] are fused in a single control law by means of a fuzzy supervisor guaranteeing robot safety and task accomplishment. Due to the inherent transparency of fuzzy logic, the proposed algorithm is computationally light, easily reconfigurable and well-performing in a wide range of differing operating conditions and environments.

Our platform is based on the widespread mobile robot developed at National Institute of Technology Rourkela. The robot is a differential-drive mobile robot that is particularly useful for rapid initial testing in real world environments; a robot has four wheels, each driven by a dc motor with 30 rpm. The built-in motor controller accepts either position or speed commands.

The RS232 serial wire-link between the robot and the terminal unit enables the remote control of all mobile robot functions, thus making it possible to run directly on the remote unit any navigation strategy compatible with the limited speed of serial communication.
Communication between the remote terminal and the robot is carried out by sending and receiving ASCII messages. The terminal plays the role of the master and initiates the communication; the robot plays the role of slave and answers only when requested.
Every interaction between the terminal unit and robot is composed of:

In our platform, we used a dSPACE microcontroller board (DS1104) [3] as the interface device between the PC and the mobile robot .The DS1104 is a general-purpose rapid prototyping control board, fully programmable in a Matlab/Simulink environment through *Real-Time Workshop* (RTW) routines. The operating system of the DS1104 includes a set of specific libraries (the *mlib/mtrace* software) that allow users to set up a real-time communication between the board and the Matlabroutines simultaneously running on the PC. Moreover, the software includes a graphical object-oriented package (the *Control Desk*) to develop user-friendly control panels for on-line monitoring and supervision. Finally, the board features a RS232 serial port directly programmable using the *serial communication* Simulink blocks. The latter allows users to implement any ASCII-based communication protocol.

In our platform, the serial communication for the DS1104 board is developed and configured in Simulink employing the RTI serial interface library. In order to send a command to the mobile robot, all the symbols must be translated in ASCII 8 bit unsigned integers (uint8). After this, the Simulink serial transmit block is used for sending the obtained bytes to the mobile robot. Similarly, the bytes received from the serial port can be read through the Simulink serial receive block.

To increase the autonomy of the mobile robot and the versatility of the platform, the equipment is completed with a top-view web-cam connected to the PC with a USB interface that provides visual information to the control system. The RGB images from the web cam are processed directly into Matlab using color detection codes (Image Processing Toolbox and Image Acquisition Toolbox) [5]. It can be seen that the use of a single programming environment simplifies the processing visual information and its use in the control strategy. In this way, the mobile robot and target positions are continuously passed to the control algorithm running on the dSpace board through the mlib/mtrace interfaces.

On the other hand, since the vision algorithm runs in Matlab under the Windows operating system, exact real time cannot be guaranteed. However, it is important to note that, considering the limited speed of the robot, this limitation is not particularly significant. If the sampling time of the vision system Tv is chosen sufficiently higher than the average image processing time interval, the information received from the camera is always available on time. For our experiments, we chose Tv=200 ms while the sampling time of the control system was Tc=20 ms.

In Fig.5.1, a block diagram of the overall test bed architecture is shown. The continuous line represents a physical connection between hardware units while the dotted line represents a data exchange between software modules.

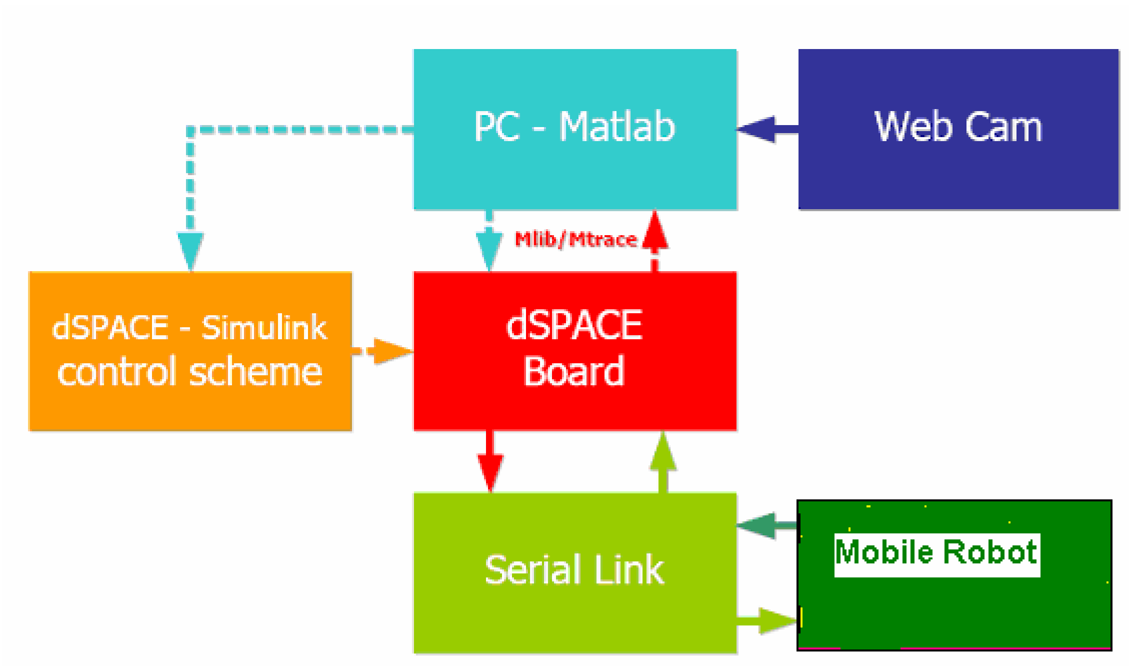


Fig. 5.1 - Overall configuration of the proposed test bed architecture.

CHAPTER 6

FUZZY DECISIONS AND CONTROL ALGORITHM DESIGN

FUZZY DECISIONS AND CONTROL ALGORITHM DESIGN

The robot operates in a 2 ×2.4 m2 arena (viewed entirely by the web cam) with moving obstacles and a target to be reached. The positions of the target and of the obstacles are not known in advance; therefore the navigation algorithm has to implement a reactive paradigm relying only on sensory information.

At first, two simple behaviors, namely *reach the target* and *avoid obstacles*, are carried out with two different fuzzy controllers, hereinafter called FLC1 and FLC2 respectively. The *reach the target* behavior as well as *avoid obstacles* behavior depends on artificial vision information and is the primary task for the mobile robot It has the highest priority and takes place only if an obstacle appears on the robot path. Subsequently, a fuzzy supervisor takes charge to combine the reference wheel speeds calculated by each FLC following a priority code. The final commanded speeds are sent to the built in speed control loop of the robot. These controllers are sufficient to guarantee satisfactory navigation performances for the mobile robot in most of the navigation tasks. The *explore the environment* behavior makes the mobile robot mark regions already visited and look for unexplored areas. The mobile robot is endowed with a type of spatial local memory, which is used by a further fuzzy controller, henceforth called FLC3, to localize and avoid the box canyons. The structure of the whole control scheme is shown in Fig.6.1.

The modular architecture of our controller has the following main advantages with respect to a monolithic solution:

1. Debugging and tuning operations are faster and easier since each behavior is described by few rules and inputs;
2. The final structure is more flexible as new simple behaviors can easily be added in order to expand mobile robot skills.

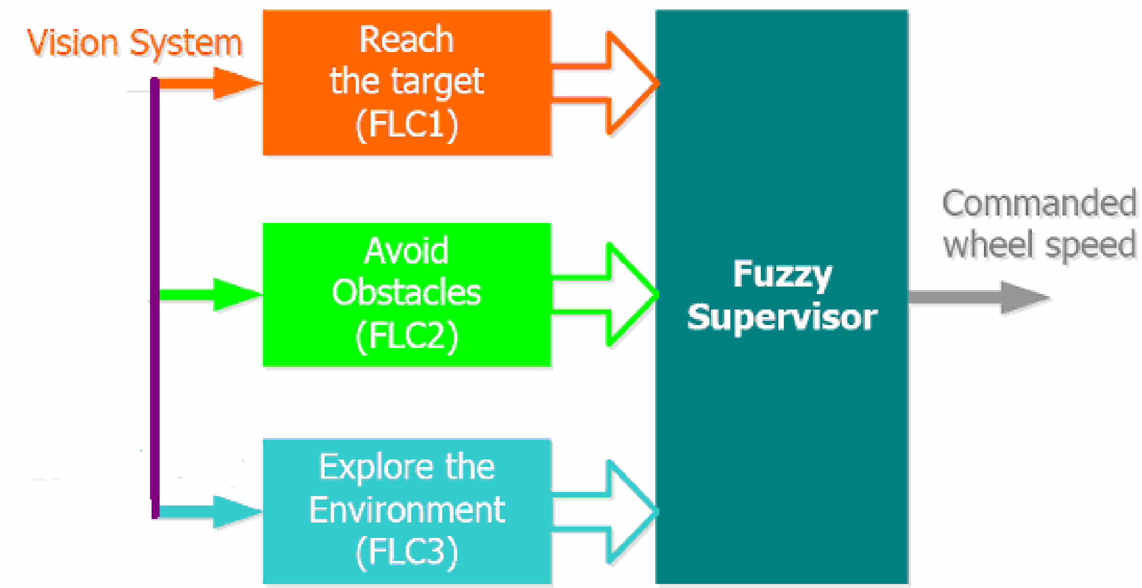


Fig.6.1- Behavior based control scheme.

6.1 Reach the target

This behavior reacts to the stimuli of the vision system, providing information about the relative position between mobile robot and target. The behavior ignores the presence and position of obstacles. The robot is equipped with two different diameter circles of same color on top for position and orientation detection, and the target is marked with a red ball. The image processing is based on conventional colour coding on RGB formats using the Matlab image Processing Toolbox. The information captured by the vision system is updated every 200 ms and passed through mlib/mtrace to the FLC1 which is running on the dSpace board. In this behavior, the robot firstly turns until it is aligned to the target, and then moves in a straight line. The information on the distance (DIST) between robot and target, and the alignment error (DIR) of the robot is provided by the vision system passed as inputs to FLC1.

6.2 Obstacle Avoidance

The distance between the robot and the target causes the robot seeking towards the target when the robot is very close to the target. Similarly when the robot is very close to an obstacle, because of it the robot must change its speed and heading angle to avoid the obstacle. Some of the fuzzy rules used for obstacle avoidance by robots are listed in Table 6.1 to Table 6.5. All the rules in those tables have been obtained heuristically using common sense.

Some rules mentioned in Table 1 cater for extreme conditions when the obstacles have to be avoided as quickly as possible. This is for three-membership function. Rule 06 mentioned in the Table 1 describes if the left obstacle distance is “near”, right obstacle distance is “far”, front obstacle distance is “medium” and no unobstructed target is around the robot, then the robot should turn to right side as soon as possible to avoid collision with the left obstacle. For the above condition the left wheel velocity should increase fast and right wheel velocity should decrease slowly.

Similarly some rules mentioned in Table 6.2 are used for extreme conditions when the obstacles have to be avoided as soon as possible. These rules are for five-membership function.

For example in rule 12, the left obstacle distance is “ very far”, right obstacle distance is “near”, front obstacle distance is “ very near” and no target is located around the robot, then the robot should turn to left side to avoid collision with the obstacle in front and towards right of it. For the above condition the right wheel velocity should increase very fast and left wheel velocity should decrease very slowly.

6.2.1 Control Steering Action for Target

The objective of the robots is to reach the target efficiently. If the robot senses a target, it will decide whether it can reach the target or there is any obstacle that will obstruct the path. If there is no obstacle on the path leading to the target, the robot will find its desired path and proceed towards it. Fuzzy rules 21 to 26 are for three-membership function (Table 6.3) for target finding. Table 6.3 describes rules for five-membership function to locate the target. Here also the fuzzy rules were obtained heuristically.

Rule number 22 states that if the left obstacle distance is "near", front obstacle distance is "medium" and right obstacle distance is "far" and the robot detects a target located on the right side (positive), then the robot should turn right as soon as possible. To do this, the left wheel velocity of the robot should increase fast and the right wheel velocity should decrease slowly.

The velocities are found from the fuzzy rules described in the below table. With the above-mentioned obstacles, there will be 2 X 2 X 2 = 8 fuzzy rules (Fig. 6.1) activated to control the left wheel velocity and right wheel velocity of the robot. The resultant velocities are given in fig. 6.3, from which the crisp values can be determined.

Sr.No.	Front Obstacle Distance	Left Obstacle Distance	Right Obstacle Distance	Left wheel Velocity	Right wheel Velocity
1	Near	Very Near	very Far	Very Fast	Very Slow
2	Near	Very Near	Far	Fast	Slow
3	Medium	Very Near	Very Far	Very Fast	Very Slow
4	Medium	Very Near	Far	Fast	Medium
5	Near	Near	Very Far	Medium	Very Slow
6	Near	Near	Far	Slow	Very Slow
7	Medium	Near	Very Slow	Very fast	Very Slow
8	Medium	Near	Far	Fast	slow

Table 6.1 fuzzy rules

In all the rules heading angle is taken as 0.

Fuzzy Rule No.	Action	leftdist	frontdist	rightdist	heading angle	leftvelo	right velo
01	OA	Near	Near	Near	NoTargetConsidered	Slow	Slow
02	OA	Near	Near	Med.	NoTargetConsidered	Med	Slow
03	OA	Near	Near	Far	NoTargetConsidered	Fast	Slow
04	OA	Near	Med.	Near	NoTargetConsidered	Slow	Slow
05	OA	Near	Med.	Med.	NoTargetConsidered	Fast	Med.
06	OA	Near	Med.	Far	NoTargetConsidered	Fast	Slow
07	OA	Near	Far	Near	NoTargetConsidered	Slow	Slow
08	OA	Near	Far	Med.	NoTargetConsidered	Fast	Med.
09	OA	Near	Far	Far	NoTargetConsidered	Fast	Slow
10	OA	Med.	Near	Near	NoTargetConsidered	Med.	Fast

Table 6.1. Obstacle avoidance for three-membership function.

Fuzzy Rule No.	Action	leftdist	frontdist	rightdist	heading angle	leftvelo	right velo
11	OA	VN	VN	VN	NoTargetConsidered	VS	VS
12	OA	VF	VN	Near	NoTargetConsidered	VS	VF
13	OA	VN	VN	Med.	NoTargetConsidered	Fast	VS
14	OA	VN	VN	Far	NoTargetConsidered	Fast	Slow
15	OA	VN	VN	VF	NoTargetConsidered	VF	VS
16	OA	VN	Near	VN	NoTargetConsidered	Slow	Slow
17	OA	VN	Near	Near	NoTargetConsidered	Slow	VS
18	OA	VN	Near	Medium	NoTargetConsidered	Fast	Slow
19	OA	VN	Near	Far	NoTargetConsidered	Fast	Slow
20	OA	VN	Near	Very Far	NoTargetConsidered	VF	VS

Table 6.2. Obstacle avoidance for five-membership function.

Fuzzy Rule No.	Action	leftdist	frontdist	rightdist	heading angle	leftvelo	rightvelo
21	TS	Near	Far	Med.	Positive	Fast	Slow
22	TS	Near	Med.	Far	Positive	Fast	Slow
23	TS	Near	Med.	Near	Negative	Slow	Fast
24	TS	Far	Near	Med.	Negative	Slow	Fast
25	TS	Far	Med.	Near	Positive	Fast	Slow
26	TS	Far	Far	Far	Negative	Slow	Fast

Table 6.3. Target seeking for three-membership function.

Fuzzy Rule No.	Action	leftdist	Frontdist	rightdist	heading angle	leftvelo	right velo
27	TS	VN	Far	Near	Positive	Slow	VS
28	TS	VN	Med.	VF	Positive	VF	VS
29	TS	Near	Far	Far	Positive	Fast	Slow
30	TS	Med.	Far	Near	Negative	Slow	Med.
31	TS	Far	Med.	Near	Negative	Med.	Fast
32	TS	Far	Very Far	Near	Negative	Med.	VF

Table 6.4. Target seeking for five-membership function.

Note: OA = Obstacle Avoidance, Med. = Medium, frontdist = front obstacle distance, rightdist = right obstacle distance, leftdist = left obstacle distance, leftvelo = left wheel velocity, rightvelo = right wheel velocity, TS = Target Seeking, Positive = Right Turn, Negative = Left Turn, VF = Very Fast, VN = Very Near and VS = Very Slow. In Figure 6.2 left, front and right obstacle distances are 1.2, 2.4 and 4.6 respectively. There is no target present in the environment. The resultant right wheel and left wheel velocity are shown in Figure 6.3.

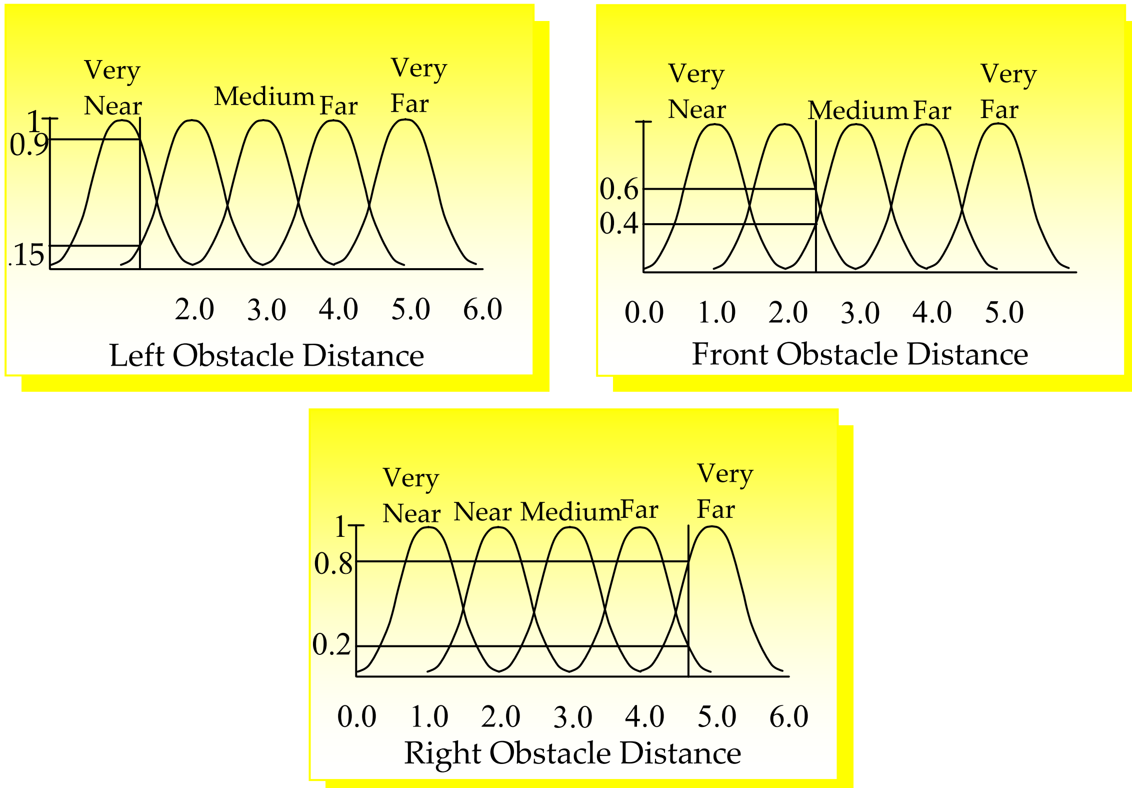
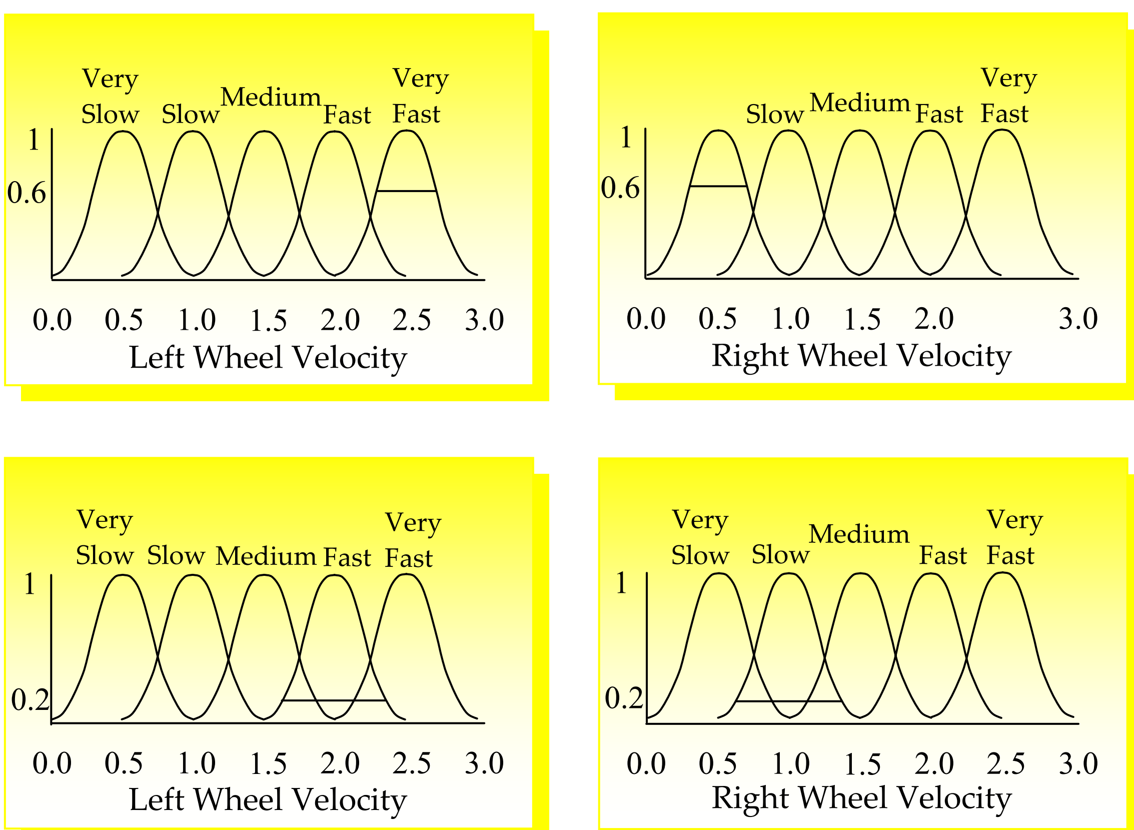
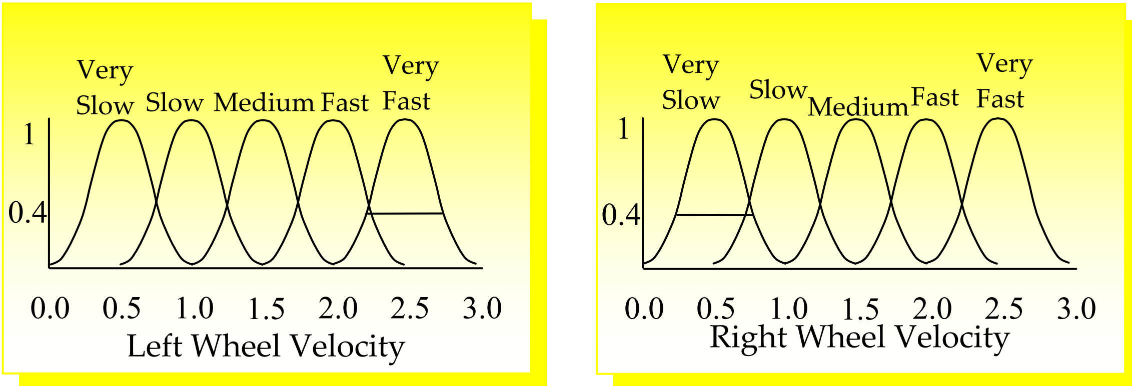


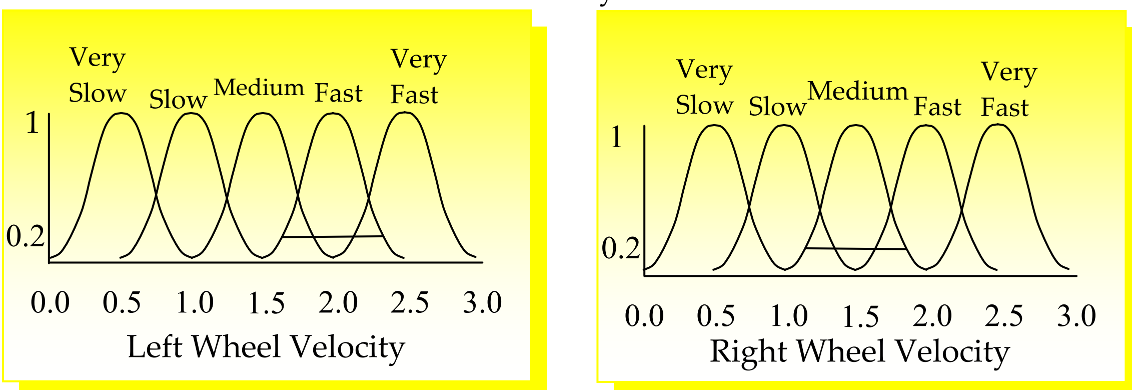
Figure 6.2 Left, Front and Right Obstacles



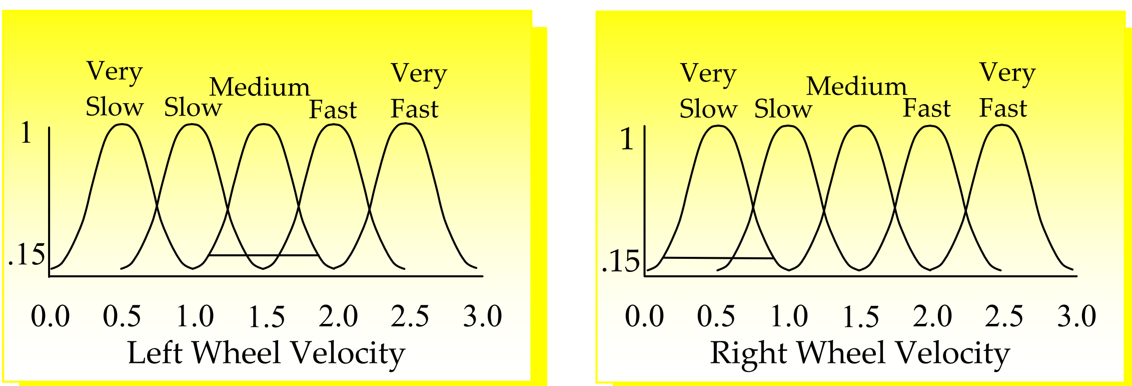
“Second combination of fuzzy rule is activated”



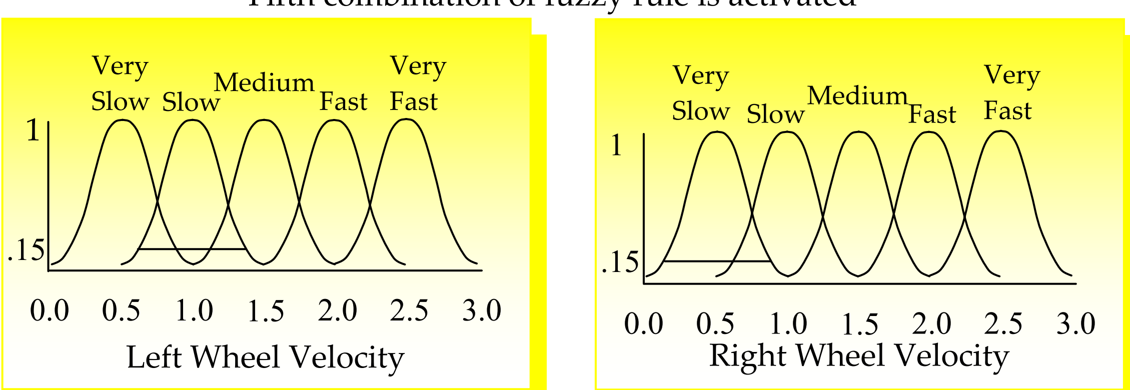
“Third combination of fuzzy rule is activated”



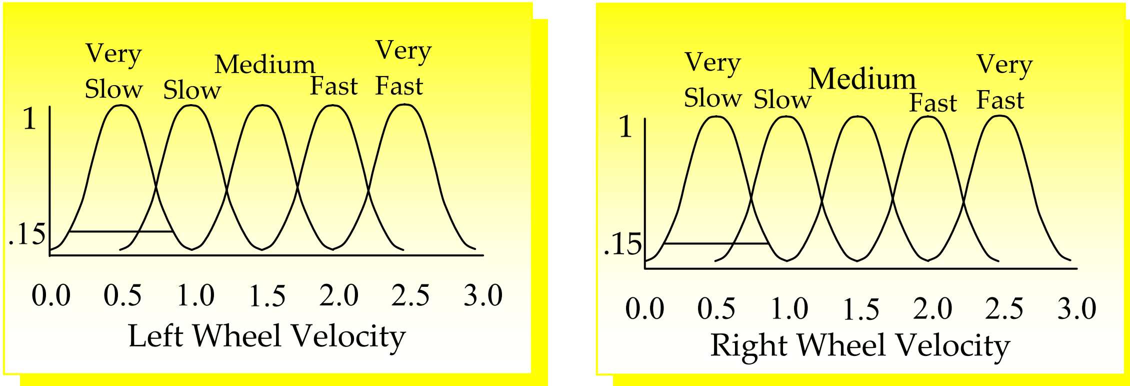
“Fourth combination of fuzzy rule is activated”



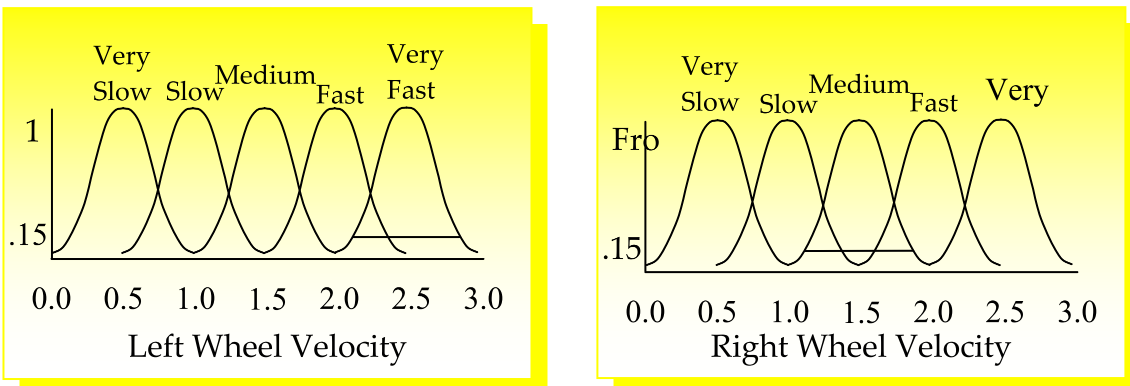
“Fifth combination of fuzzy rule is activated”



“Sixth combination of fuzzy rule is activated”



"Seventh combination of fuzzy rule is activated"



"Eighth combination of fuzzy rule is activated"

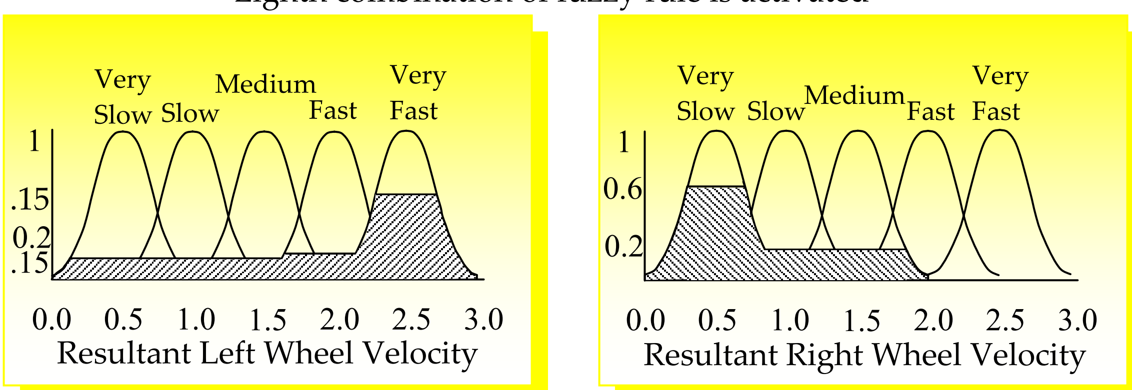


Figure 6.3. Resultant Left and Right Wheel Velocity

6.3 Explore the environment

1. Using the information provided by the web cam, the arena is divided into a point grid corresponding to a matrix, the elements of which record the number of times the corresponding square patch has been visited. Each time the robot enters a square patch, the corresponding matrix element is increased by one. The dimension of each square patch is about 25x25 mm

2. An exploration index, representing how often the actual area has been visited by the robot, is then calculated considering the value of the element corresponding to the actual position of the robot. It is then necessary to define the proper correspondence between the elements of the exploration matrix and the arena square patches according to the actual orientation of the robot.

6.4 **Fuzzy supervisor**

In order to safely reach the target, a fuzzy supervisor determines the priority of execution for the three elementary behaviors. This approach is well suited to the task of behavior arbitration as it offers a transparent and extremely effective solution based on high level linguistic decision rules.

The fuzzy supervisor carries out this task according to the proximity of obstacles and the exploration requirements.

In every intermediate condition the supervisor will perform a fusion of the three FLCs blending their outputs to achieve a safe navigation toward the target.

CHAPTER 7

EXPERIMENTAL SETUP AND SIMULATION RESULTS

7.1 BEHAVIOR OF MOBILE ROBOT DURNG SEARCHING THE TARGET

Several navigation experiments were conducted in an arena with black obstacles (detectable to the camera) and a red ball representing the target that the robot has to reach. Fig.7.1 depicts the control scheme in which serial communication and fuzzy logic controllers are managed through specific Simulink blocks. The overall tuning of the control scheme can easily be performed by directly changing the parameters in the Simulink scheme, and executing new experiments until the desired robot behavior is obtained.

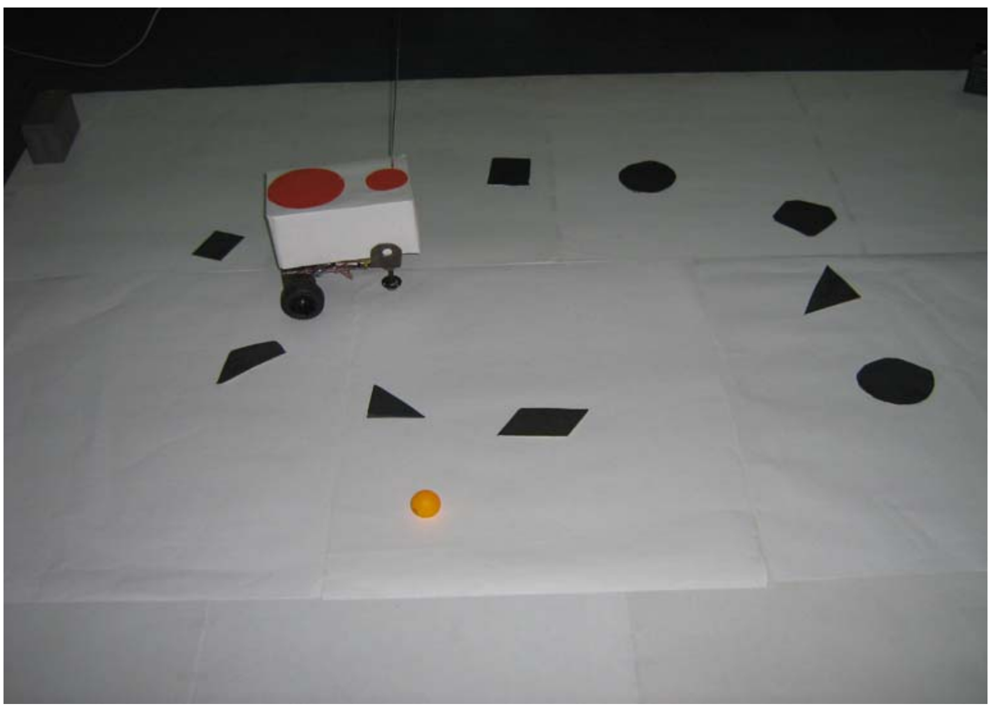


Fig.7.1 –The view of the robot environment

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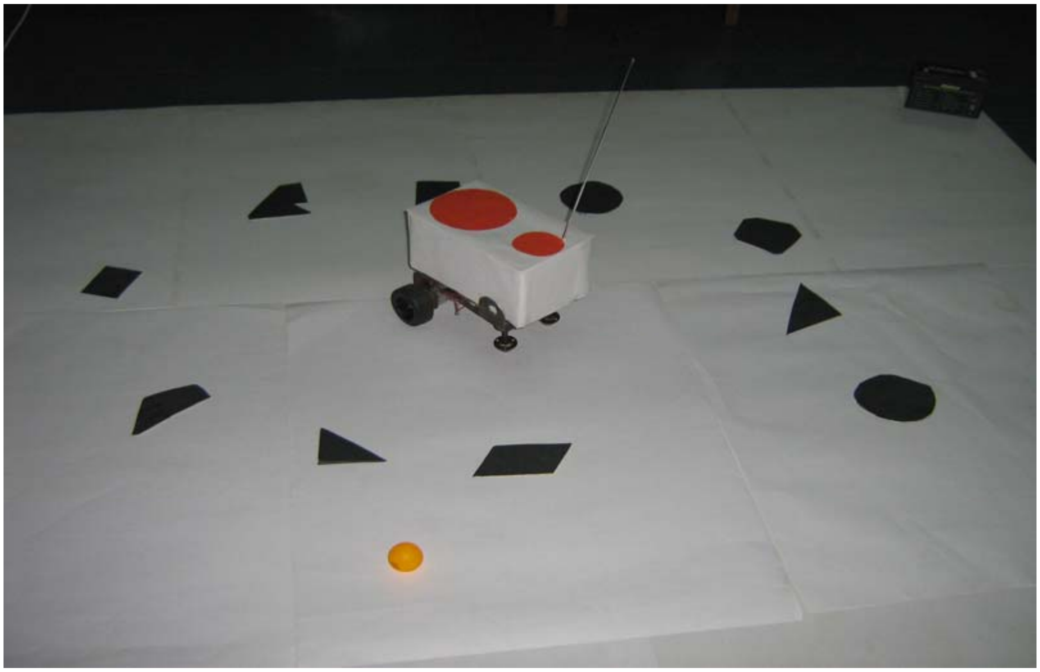

Fig.7.2 - Real time control scheme developed in Simulink

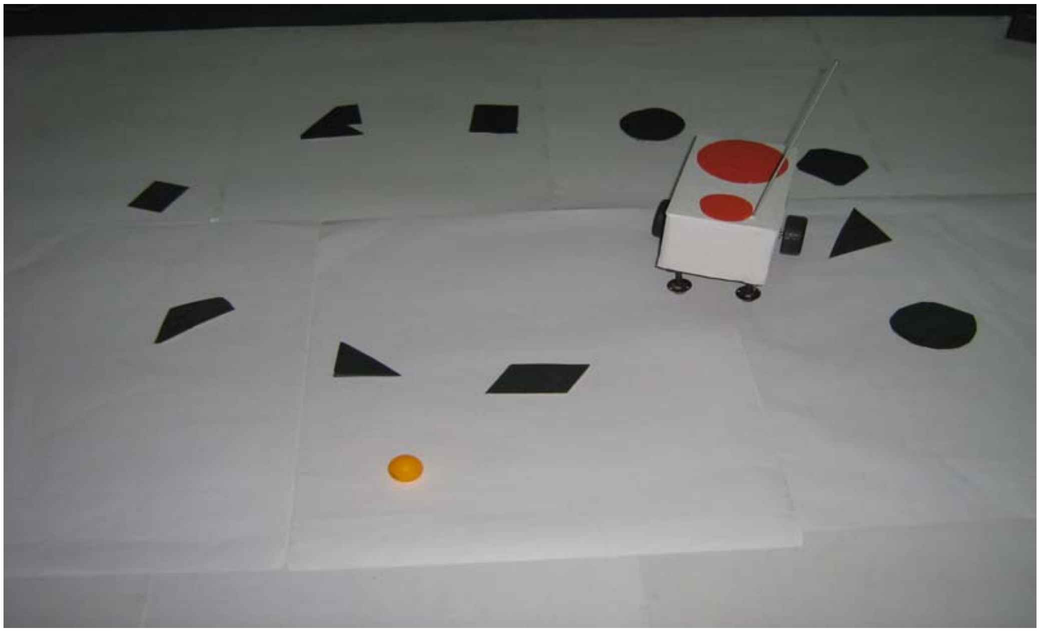

Fig.7.3-Robot moving towards target

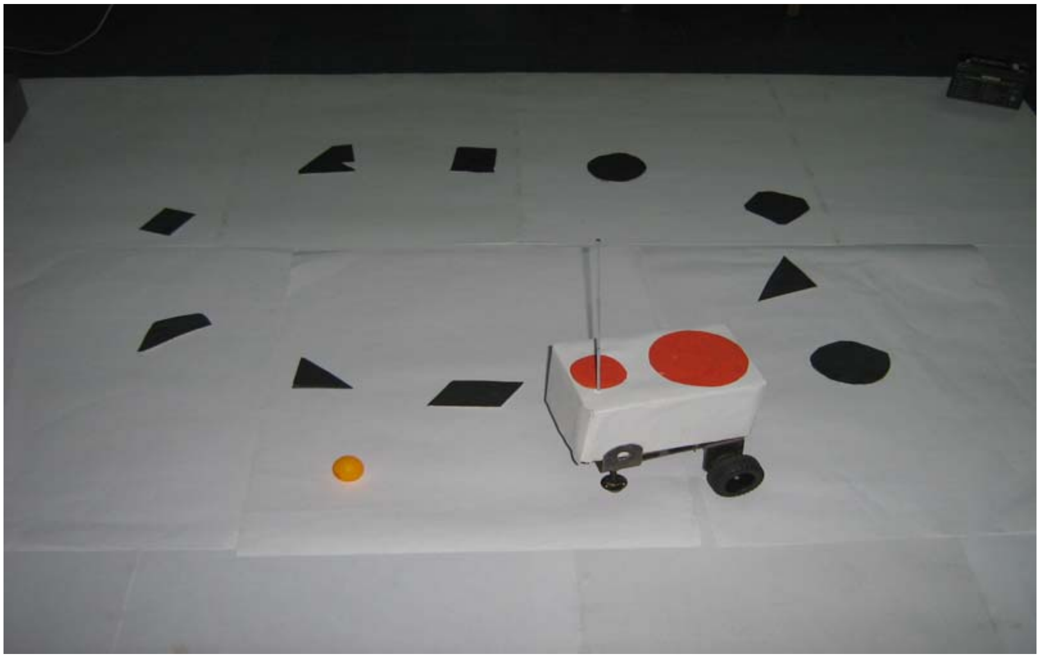

Fig. 7.4 Robot moving towards target

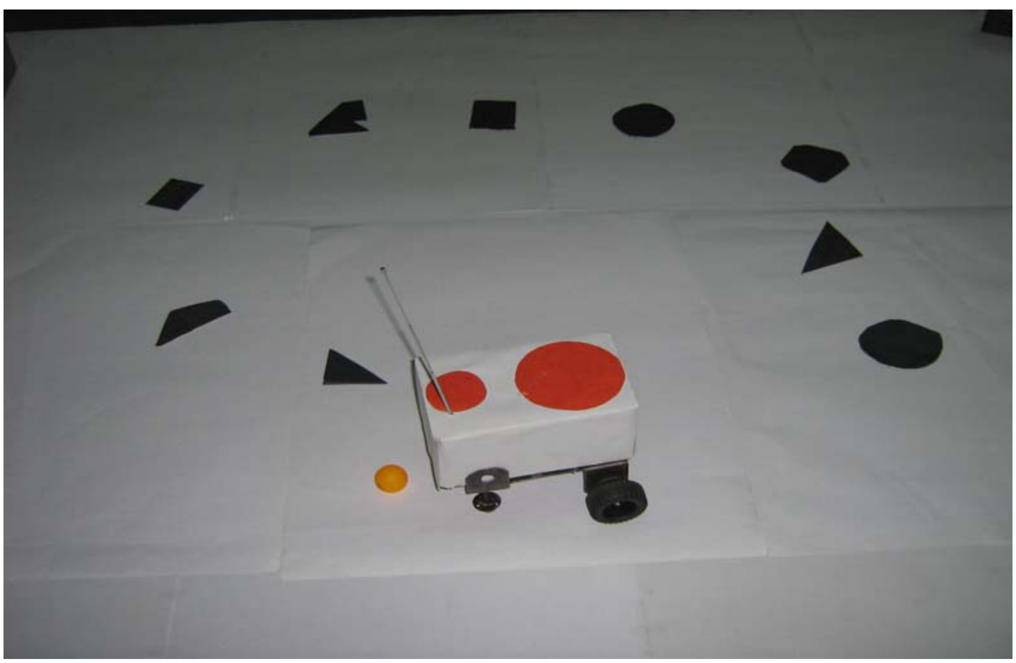

Fig. 7.5 Robot finds the target

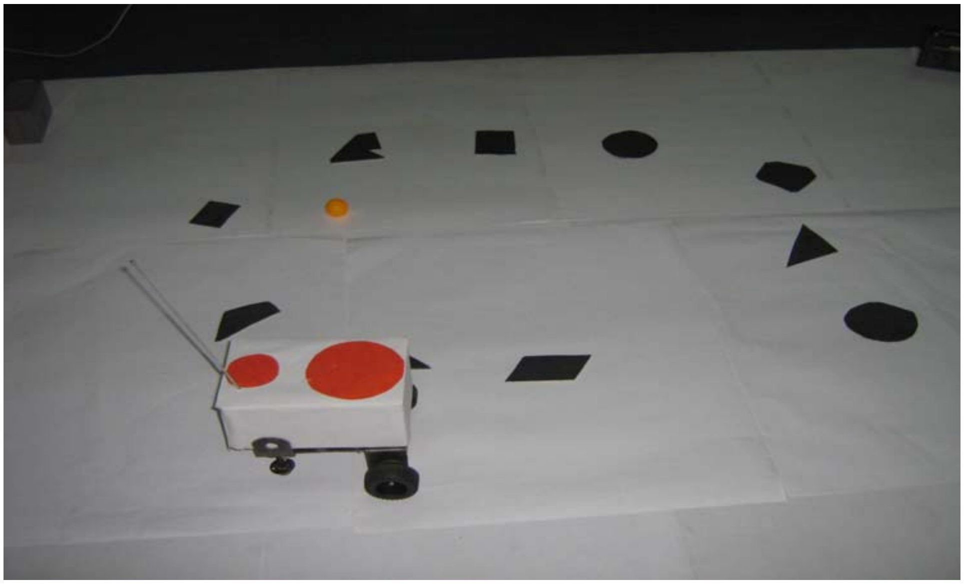

Fig.7.6 Different position of target

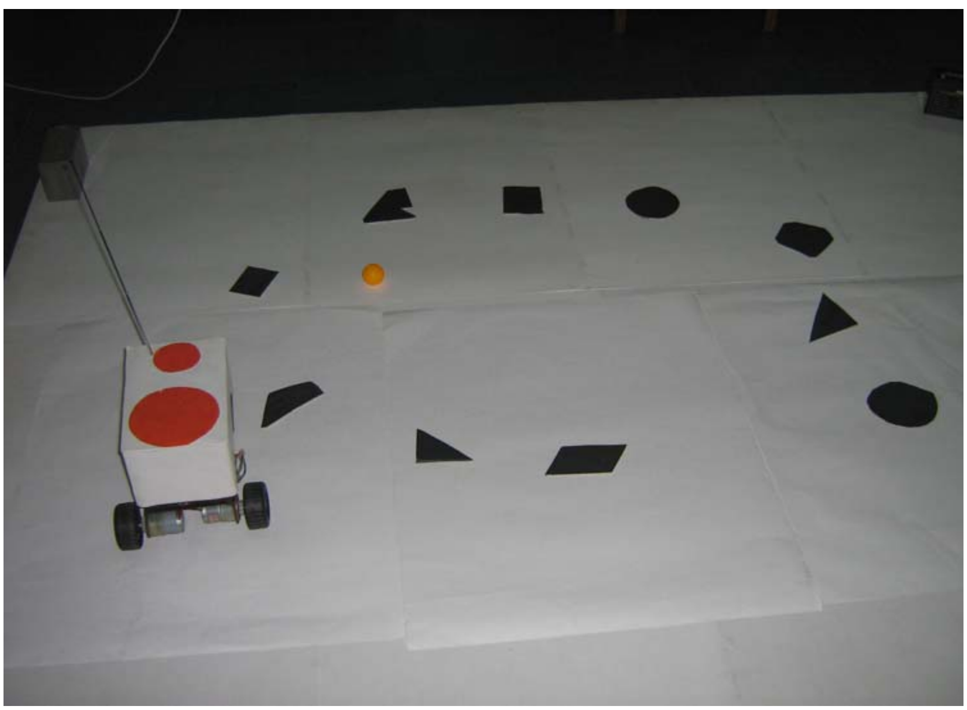

Fig. 7.7 – Robot trying to towards target

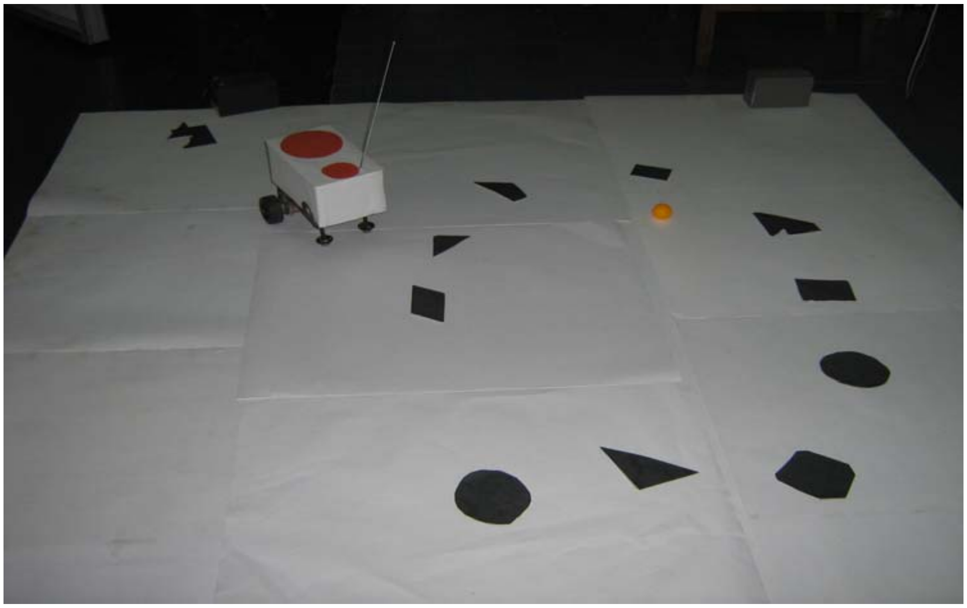

Fig. 7.8- Robot avoiding the obstacles

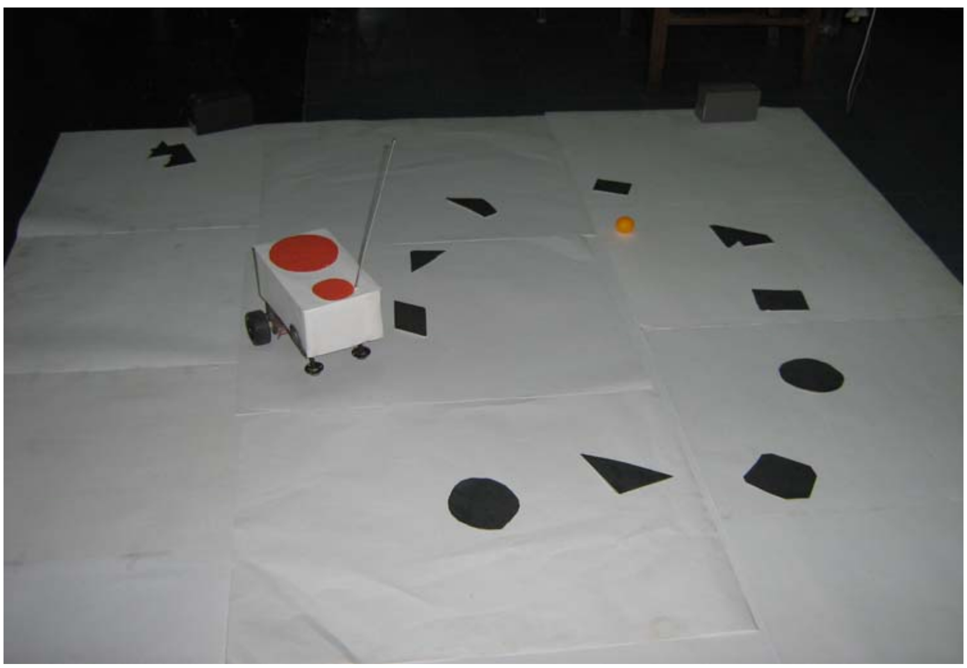

Fig. 7.9- Robot trying to move towards target with avoiding obstacles

Fig. 7.10-Robot enters in middle part of arena

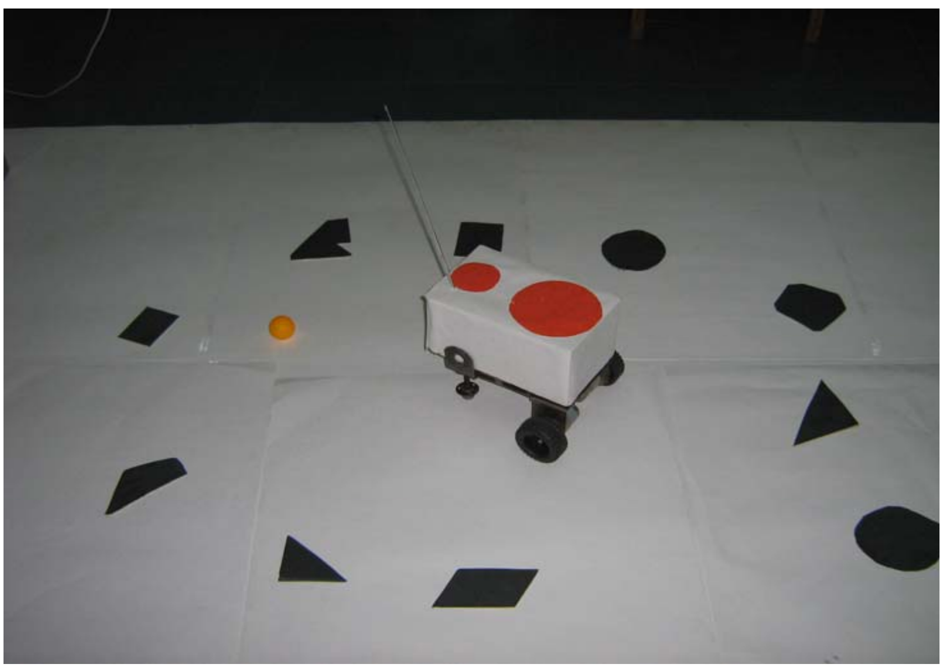

Fig. 7.11-Robot moving towards target

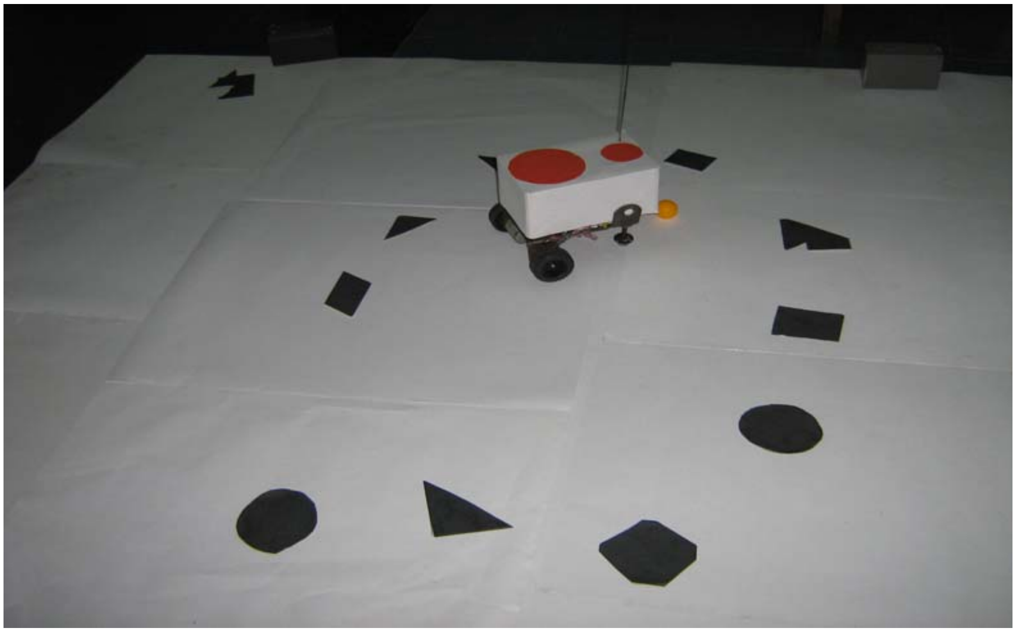

Fig. 7.12- Robot reached on target

SIMULATION RESULTS

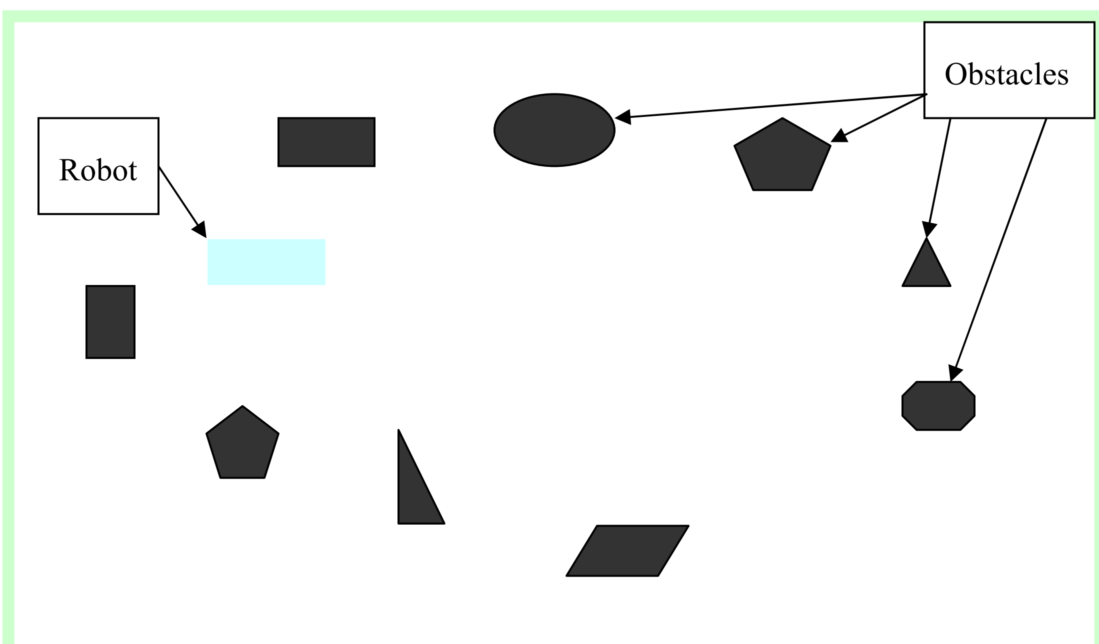

Fig.-7.13. Environment of Mobile Robot

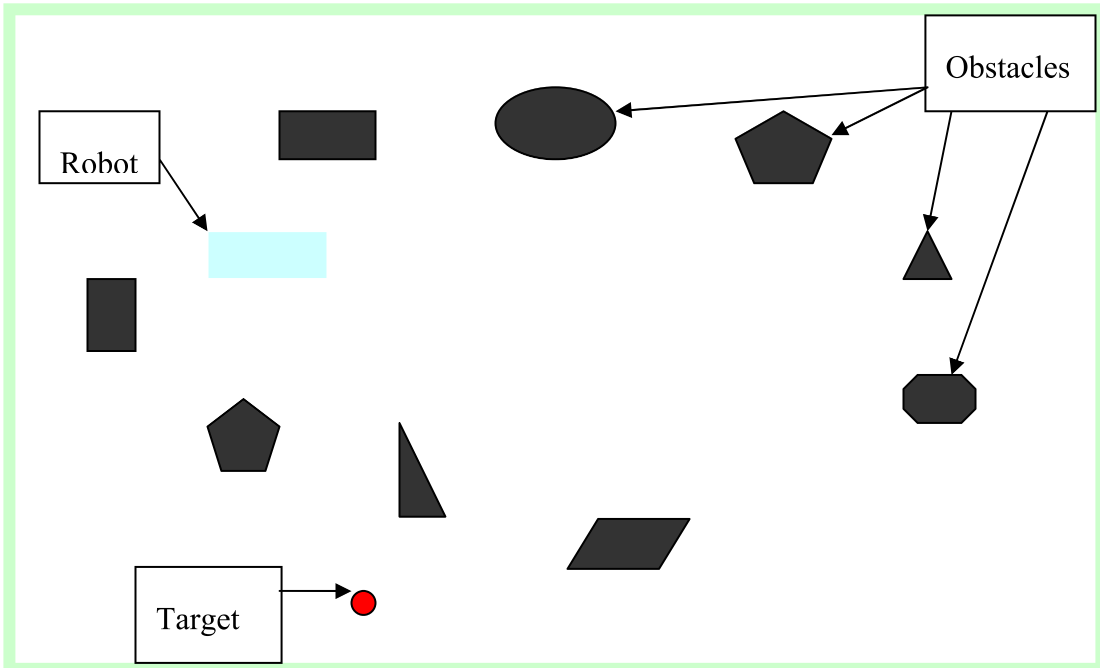

Fig.-7.14.Simulation result for first position of target

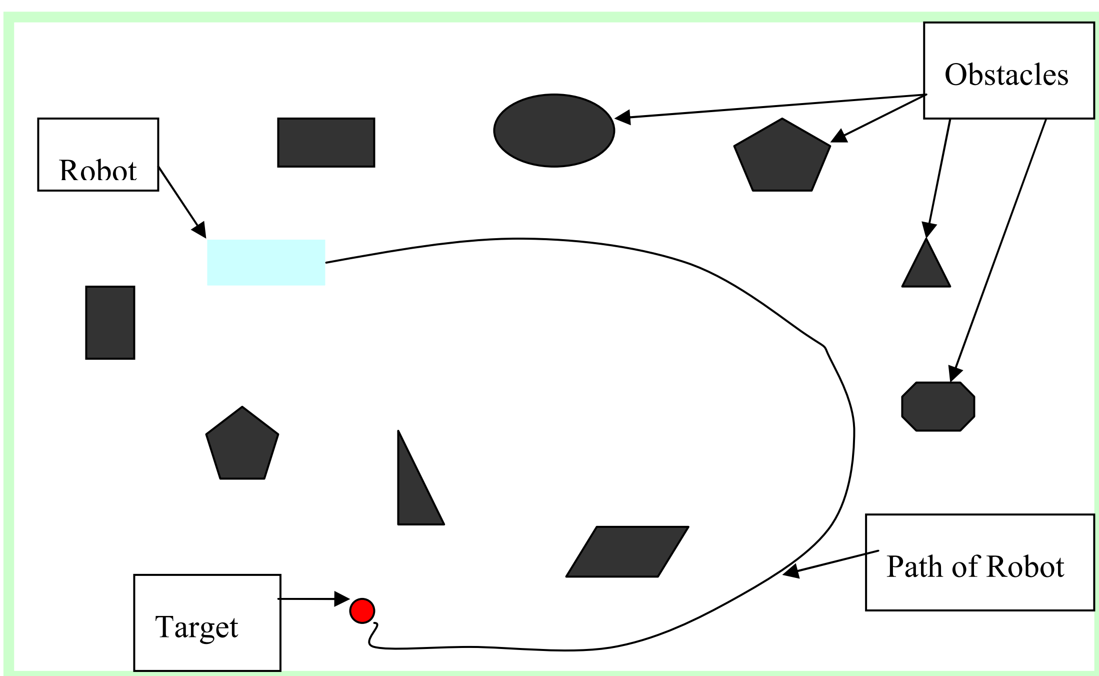

Fig.-7.15.Simulation result after reaching the first position of target

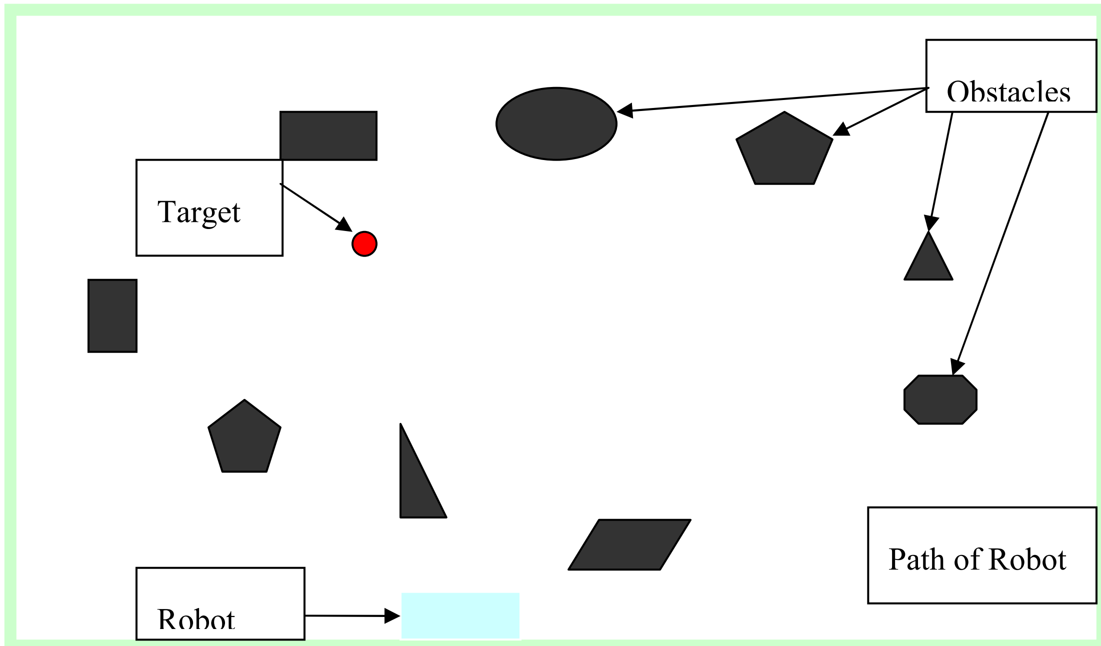

Fig. - 7.16.Simulation result for second position of target

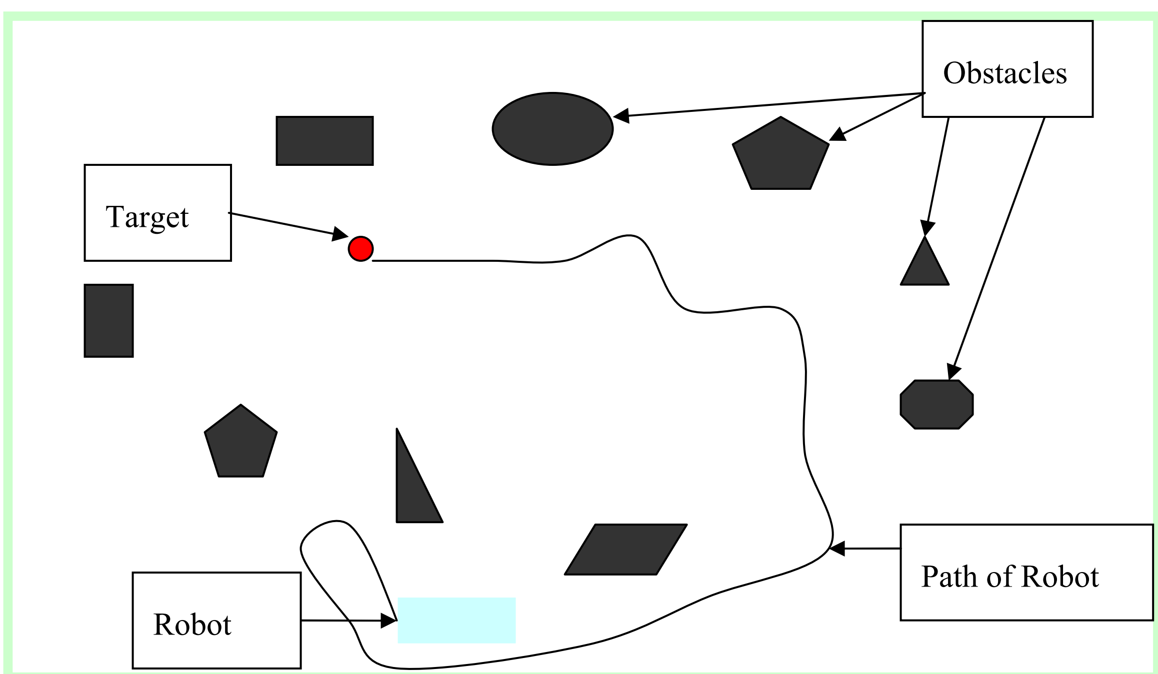

Fig.-7.17. Simulation result after reaching the second position of target

For brevity, we focus on a sample experiment, chosen to enlighten the particular effectiveness of the hierarchical fuzzy control strategy. From Fig.7.1-Fig. 7.12 shows the performance of the robot during the navigation experiment.

Finally we want to remark that developing the navigation control code directly on the hardware platform allowed us to gain useful insights on the adopted fuzzy design strategies. For instance, in our test, we noted that it was extremely simple to implement each of the three independent behaviors correctly, while the development of the supervisory strategy was more difficult than in preliminary simulations.

In particular, the navigation strategy proved to be extremely sensitive to the balance between *avoid obstacle* and *reach the target* behaviors. If the former behavior is emphasized, the robot tends to move away from obstacles, even though they are not directly on its path to the target, and become unable to move through narrow passages (exhibiting winding paths).

On the contrary, if the *reach the target* behavior is emphasized, the robot tends to cross narrow passages with agility, following straight paths, at the cost of a decreased ability to avoid collisions at the same speed. The platform allowed us to perform without difficulty a sufficient number of experiments necessary to find the appropriate trade off between robot speed (avoid obstacle priority) and smoothness of paths traveled (reach the target priority), and therefore achieve the presented satisfactory results.

CHAPTER 8

CONCLUSIONS AND FUTURE WORK

Conclusions and Future Work

The aim of this thesis work has been to investigate effective techniques for controlling the navigation of multiple mobile robots in a cluttered environment.

This chapter summaries the main contributions and conclusions of the research and proposed ideas for further work.

8.1 Conclusions

8.1.1 Contributions

. By using kinematics of mobile robot right wheel velocity and left wheel velocity of the mobile robot is calculated. From the wheel velocities steering angle is calculated.

A fuzzy logic technique has been developed using three types of membership functions. The fuzzy rules considered for all the three membership functions are deployed for mobile robot. The fuzzy logic controller utilizing Gaussian membership is best among the three types of membership functions for navigation of mobile robot in an unknown environment.

We have used the Matlab-Simulink software package a key element in freeing the designer from low-level hardware and software issues so as to focus on experimental implementations from a control engineer perspective.

The serial output of the mobile manipulator was then connected to a Bluetooth device for wireless serial communication with the dSpace board. The software modules (Simulink, Control Desk) were obtained by slightly modifying those developed for the robot, and also the fine-tuning of the navigation strategy was carried out without difficulty.

In fact, the image processing algorithms are the most time-demanding tasks in the present version of the platform, and constitute the most limiting constraint for the maximum safe-navigation speed.

8.1.2 Conclusions

From the simulation results and the experimental results, it is concluded that the developed simple fuzzy controller with Gaussian membership is able to control the navigation of mobile robot in an unknown cluttered workspace.

The software/hardware platform can be profitable for the standardization of laboratory equipment (making it possible to share and reutilize software and hardware easily), as well as for the development of virtual laboratories (remotely-controlled experiences for research and education using Internet can also be set up using the available toolboxes).

8.1.3 Future Work

The following are suggestions fro further investigation:

- In the current research work, the technique developed for mobile robot navigation enable the robot to avoid each other and static obstacles. However, further development of the techniques is required for the avoidance of moving obstacles other than the stable obstacles. These obstacles may be animals, moving equipments etc.
- Co-ordination between the robots for co-operative task with static as well as moving obstacles.
- Further work needs to be undertaken in the area of optimizing the number of robots reaching and handling a particular object.
- The navigational technique developed in this research work is capable of detecting and reaching static target. Further modifications in this navigational technique may be carried out so that the robot can not only detect dynamic target but also reach them using an optimum path.
- Future work on the research project will include the extension of the control approach to communities of mobile robots, endowed with a specific set of behaviors including coordination functions

REFERENCES

[1] Nilsson N. J., "Shakey the Robot", *SRI International*, *Technical Note 323*, CA, 1984.

[2] Cameron S., and Probert P., "Advanced Guided Vehicles Aspects of the Oxford AGV Project", *World Scientific,* London, 1994.

[3] Brooks R. A., "A Robust Layred Control System for a Mobile Robot", *IEEE Transction on Robotics and Automation,* 1986, Number 2 (1), pp. 14 – 23.

[4] Trullier O., Wiener S. I., and Berthoz A., "Biologically based artificial navigation systems: review and prospects", *Progress in Neurobiology*, 1997, Number 51(5), pp. 483 – 544.

[5] Levitt T. S., and Lawton D. T., "Qualitative navigation for mobile robots", *Artificial Intelligence,* 1990, Vol. 44, pp. 305 – 360.

[6] Feng L., Borenstein J., and Everett H. R., "Where am I? Sensors and methods for autonomous mobile robot positioning, *Technical Report, University of Michigan*, MI, 1994.

[7] Crowley J.L.,and Coutaj J.,"Navigation et modelisation pour un robot mobile",Technique et Science Informatiques,1986,Number 5(5),pp.391-402.

[8] Borenstein J., and Koren Y., "Noise reflection for ultrasonic sensors in mobile robot application", *of IEEE Conference on Robotics and Automation*, Nice, France, 1992, pp. 1727 – 1732.

[9] Buchberger M., Jorg K., and Puttkamer E. V., "Laserradar and sonar based world modeling and motion control for fast obstacle avoidance of the autonomous

mobile robot MOBOT-IV", *IEEE Conference on Robotics and Automation*, Atlanta, Georgia, 1993, pp. 534 – 540.

[10] Tsoukalas L. H., Houstics E. N., and Jones G. V., "Neurofuzzy motion planners for intelligent robots", *Journal of intelligent and Robotic Systems*, 1997, Vol. 19(3), pp. 339 – 356.

[11] Lozana-Perez T., and Wesley M. A., "An algorithm for planning collision free paths among polyhedral obstacles", *ACM22*, 1979, number 10, pp. 560 – 570.

[12] Khatib O., "Real-time obstacle avoidance for manipulators and mobile robots", " *IEEE Conference on Robotics and Automation*, 1985, pp. 500 – 505.

[13] Guldner J., Utkin V. I., and Hushimoto H., "Robot obstacle avoidance in n-dimensional space using planar harmonic artificial potential fields", *ASME Transactions, Journal of Dynamic Systems Measurement and Control*, 1997, Vol. 19(2), pp. 160 – 166.

[14] Shkel A. M., and Lumelsky V. J., "The joggers problem: Control of dynamics in real-time motion planning", *Automatica*, 1997, Vol. 33(7), pp. 1219 – 1233.

[15] Luo R. C., and Kay M. G., "Multisensor integration and fusion in intelligent system", *IEEE Transactions on Systems, Man and Cybernetics*, 1989, Vol. 19(5), pp. 901 – 931.

[16] Lin I. S., Wallner F., and Dillmann R., "Interactive control and environment modelling for a mobile robot based on multi sensor perceptions", *Robotics and Autonomous Systems*, 1996, Vol. 18(3), pp. 301 – 310.

[17] Fox D., Burgard W., and Thrun S., "The dynamic window approach to collision avoidance", *IEEE Robotics and Automation Magazine*, 1997, Vol. 4(1), pp. 23 – 33.

[18] Yamamoto Y., and Yun X., "Coordinating Locomotion and Manipulation of a Mobile Manipulator", *IEEE Transactions on Robotics and Automation*, 1994, Vol. 39, pp. 1326–1332.

[19] Alexander J.C., and Maddocks J.H. "On the Kinematics of Wheeled Mobile Robots", *The International Journal of Robotics Research*, 1989, Vol. 8(5), pp. 15-27.

[20] Mester G., "Motion Control of Wheeled Mobile Robots", *4th Serbian-Hungarian Joint Symposium on Intelligent Systems*, 2006, pp. 119 – 130.

[21] Chakraborty N., and Ghosal A., "Kinematics of Wheeled Mobile Robots on Uneven Terrain", *Mechanism and Machine Theory*, 2004, Vol. 39, pp. 1273 – 1287.

[22] Latombe J.C., "Robot Motion Planning, Boston", MA, USA: Kluwer Academic Publishers, 1991.

[23] Fraichard T., and Garnier P., "A fuzzy Motion Controller for a Car-like Vehicle", *IEEE-RSJ International Conference on Intelligent Robots and Systems*, 1996, Vol. 3, pp. 1171–1178.

[24] Zadeh L. A., "Fuzzy Sets", *Journal of Information and Control*, 1965, Vol. 8, pp. 338 – 353.

[25] Mamdani E. H., and Assilian S., “An Experiment in Linguistic Synthesis with a Fuzzy Logic Controller”, *International Journal of Man Machine Studies*, 1975, Vol. 7(1), pp. 1-13.

[26] Kickert W.J.M., and Mamdani E. H., “Analysis of a Fuzzy Logic Controller”, *Fuzzy Set and Systems*, 1978, Vol. 12, pp. 29-44.

[27] Langer D., Rosenblatt J. K., and Hebert M., “A behavior-based system for off-road navigation”, *IEEE Transactions on Robotics and Automation,* 1994, Vol. 10, pp. 776-783.

[28] Seraji H., and Howard A., “Behavior-based robot navigation on challenging terrain: A fuzzy logic approach”, *IEEE transactions on robotics and automation*, 2002, Vol. 18(3), pp. 308-321.

[29] Li S. Tzuu-Hseng and Chang S. J., “Autonomous fuzzy parking control of a car-like mobile robot”, *IEEE Transactions on Systems, Man, and Cybernetics*, 2003, Vol. 33(4), pp. 451 - 465.

[30] Li S. Tzuu-Hseng, Chang S. J. and Chen Yi-Xiang, “Implementation of human-like driving skills by autonomous fuzzy behavior control on an FPGA-based car-like mobile robot”, *IEEE Transactions on Industrial Electronics*, 2003, Vol. 50(5), pp. 867 - 880.

[31] Baturone H., Francisco J., Moreno-Velo, Santiago Sanchez-Solano, and Ollero A., “Automatic design of fuzzy controllers for car-like autonomous robots”, *IEEE Transactions on Fuzzy Systems*, 2004, Vol. 12(4), pp. 447 - 464.

[32] Ohkita M., Miyata H., and Miura M., "Travelling experiment of an autonomous mobile robot for a flush parking", *IEEE International conference on fuzzy systems,* 1993, pp. 327 – 332.

[33] Maeda M., Shimakawa M., and Murakami S., "Predictive fuzzy control of an autonomous mobile robot with forecast learning function", *Fuzzy Sets and Systems*, 1995, Vol. 72(1), pp. 51-60.

[34] Joo Y. H., Hwang H. S., Kim K. B., and Woo K. B., "Fuzzy system modeling by fuzzy partition and GA hybrid schemes", *Fuzzy Sets and Systems*, 1997, Vol. 86(3), pp. 279-288.

[35] Xu W. L., Tso S. K., and Fung Y. H., "Fuzzy reactive control of a mobile robot incorporating a real/virtual target switching strategy", *Robotics and Autonomous Systems*, 1998, Vol. 23, pp. 171-186.

[36] Lee T-L., and Wu C-J., "Fuzzy motion planning of mobile robots in unknown environments", *Journal of Intelligent and Robotic Systems,* 2003, Vol. 37(2), pp. 177 – 191.

[37] Kodagoda K. R. S., Wijesoma W. S., and Teoh E. K., "Fuzzy speed and streering control of an AGV", *IEEE Transactions on Control Systems Technology*, 2002, Vol. 10(1), pp. 112 – 120.

[38] Fukuda T., and Kubota N., "An intelligent robotic system based on a fuzzy approach", *Proceedings of the IEEE*, 1999, Vol. 87, pp. 1448 - 1470.

[39] Benreguieg M., Hoppenot P., Maaref H., Colle E., and Barret C, "Fuzzy navigation strategy: application to two distinct autonomous mobile robots", *Robotica*, 1997, Vol. 15, pp. 609-615.

[40] Beaufrere B., and Zeghloul S., "A mobile robot navigation method using a fuzzy logic approach", *Robotica*, 1995, Vol. 13, pp. 437 – 448.

[41] Liu K., and Lewis F. L., "Fuzzy logic based navigation and maneuvering for a mobile robot system", *IEEE Mediterranean Symposium New Directions in Control and Automation*, 1994, pp. 555-562.

[42] Pratihar D. K., and Bibel W., "Near-optimal, collision-free path generation for multiple robots working in the same workspace using a genetic-fuzzy systems", *Machine Intelligence and Robotic Control*, 2003, Vol. 5(2), pp. 45—58.

[43] Demirli K., and Molhim M., "Fuzzy dynamic localization for mobile robots", *Fuzzy Sets and Systems*, 2004, Vol. 144, pp. 251–283.

[44] Khatib-Al M., and Saade J. J., "An efficient data-driven fuzzy approach to the motion planning problem of a mobile robot", *Fuzzy Sets and Systems*, 2003, Vol. 134, pp. 65–82.

[45] Abdessemed F., Benmahammed K., and Monacelli E., "A fuzzy-based reactive controller for a non-holonomic mobile robot", *Robotics and Autonomous Systems*, 2004, Vol. 47, pp. 31–46.

[46] Godjevac J., "Fuzzy systems and neural networks", *Intelligent Automation and Soft Computing*, 1998, Vol. 4(1), pp. 27 – 37.