

DESIGN AND CONTROL OF A SELF-PARKING MODEL CAR

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DESIGN AND CONTROL OF A SELF-PARKING MODEL CAR

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Approval of the Graduate School of Natural and Applied Sciences

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ABSTRACT

DESIGN AND CONTROL OF A SELF-PARKING MODEL CAR

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A fuzzy logic control algorithm for self parking of a model car has been developed and an embedded controller hardware has been designed, manufactured and programmed to control parking maneuvers of a model car within the scope of this thesis study.

The model car chassis consists of a DC motor actuated traction system and a servomotor actuated steering mechanism. Position data and parking place data is obtained by a sensory system. A stepper motor driven rotary table is designed and assembled to the model car chassis for positioning of the sensory system. The controller hardware includes all the required peripherals for interfacing to the motors and sensory system.

A visual computer program running in PC environment is developed in order to simulate the control characteristics of the fuzzy logic algorithm. The program allows the user to generate fuzzy sets and fuzzy set members and allows the user to define membership functions and fuzzy rules. Once an appropriate

control characteristic is obtained, all the parameters can be exported to a file in order to be downloaded to the controller.

Keywords: Fuzzy Logic, Self-parking

ÖZ

KENDİ KENDİNE PARK EDEN BİR MODEL ARABANIN TASARLANMASI VE DENETLENMESİ

AVĞAN, Utku

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Bu tez çalışması kapsamında bir model arabanın kendi kendine park edebilmesi için bir bulanık mantık algoritması geliştirilmiş ve model arabanın park etme manevralarının denetlenebilmesi için bir iliştilirilmiş kontrol donanımı tasarlanıp, imal edilmiş ve programlanmıştır.

Model arabanın gövdesi DC motorla hareket ettirilen bir çekiş sistemi ve servomotorla hareket ettirilen bir direksiyon mekanizmasından oluşmaktadır. Konum bilgisi ve park edilecek yer bilgisi bir algılayıcı sistemle elde edilmektedir. Algılayıcı sistemin konumlandırılması için adım motorla hareket eden bir döner tabla tasarlanmış ve model araba gövdesi ile birleştirilmiştir. Denetim donanımı, motorlarla ve algılayıcı sistemle iletişimde gerekli olan tüm çevresel arabirimleri içermektedir.

Bulanık mantık algoritmasının denetim davranışlarını inceleyebilmek için PC ortamında çalışan bir görsel bilgisayar programı geliştirilmiştir. Program kullanıcıya bulanık mantık kümeleri ve küme elemanları oluşturabilme, aitlik

fonksiyonları ve bulanık mantık kuralları tanımlayabilme imkanı tanır. Uygun bir denetim davranışı elde edildiğinde bütün parametreler denetim donanımına yüklenmek üzere bir dosyaya gönderilebilir.

Anahtar kelimeler: Bulanık Mantık, Kendi Kendine Park Etme

To My Family

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I would like to thank to Prof. Dr. Tuna Balkan and Prof. Dr. Y. Samim Ünlüsoy for their guidance and support throughout the study. Thanks are given to Asst. Prof. Dr. E. İlhan Konukseven for his suggestions and discussions. The assistance of my friends Asst. Kaan Berker, Asst. Halil Bil and Asst. Ali E. Turgut is acknowledged. I express sincere appreciation to my family for their love and patience.

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CHAPTER 1

INTRODUCTION

1.1 Definition of the Problem

The problem can be defined as, “developing a system that will manage to generate the necessary parking maneuvers of a model car to park vertically at an arbitrary and marked position in a closed parking bay without hitting the boundaries of the environment”. Design of a fuzzy logic control system is aimed in this thesis study for the solution of the given problem.

Excluding the model car chassis, the system that will be designed and manufactured within the scope of this thesis study consists of the following components:

- A mechanical section consisting of a sensory housing group with its positioning equipment.
- An electrical section consisting of an embedded controller hardware which includes a microcontroller and all the necessary interfacing peripherals and a sensory system.
- A software section consisting of the assembly code of the microcontroller that will interface with the peripherals and handle the fuzzy logic calculations; and a computer program for PC environment to simplify the development, simulation and tuning of the fuzzy control system.

1.2 Literature Survey and Previous Research

Population increase in large cities results an increase in the number of vehicles used by the community which causes an increasing demand for parking bays. So closed parking bays are very common in city life. Parking of a car in a parking lot may be agreed to be one of the most complex parts of the driving action. By the help of the improvements in computer technology, automatic control of local vehicle maneuvers to obtain a self-parking action is no more a fantasy. Most of the researches about this subject are done to develop a self-parking strategy and some to develop driver aid systems. The studies about self-navigating cars and mobile robots are also important because of the similar control techniques that are used.

One of the studies about this subject is done in the München Technical University of Germany by Daxwanger and Schmidt [1]. In this study the acquisition and transfer of an experienced driver's skills to an automatic parking controller is performed. The interesting part of this study is the way of taking input information and approaches to cloning the skills of an expert driver. A CCD video image sensor is employed to collect data from the environment. The image sensor is composed of a gray-scale CCD camera which is combined with an aspheric mirror to perform an inverse perspective mapping of the scene in front of the vehicle. By the help of this set-up a 4 m x 4 m field of view is obtained. An integrated sensor-processing unit is also utilized to generate a gradient image of the view to process data. No other information, such as the vehicle position relative to the goal location, is needed as extra input. In this study two approaches clone the skills of an expert driver are proposed and compared. A human driver is able to demonstrate his skills by parking a car in the parking bay instead of explicitly describing his information processing while generating an adequate steering action from visual information for parking. Imitating this "black-box" behavior and using the same obvious inputs and outputs leads to a direct neural control architecture as the first approach. On the other hand, the expert driver may be able to describe his parking strategy roughly in terms of linguistic rules, which leads to a parking strategy that can be implemented by means of a fuzzy network as the second approach. A robot vehicle, which has car-like

kinematics with one steering wheel and a driven rigid axle, is employed to get the experimental performance of the control architectures. The results are satisfactory with a cost of high signal processing requirements of the input data.

Another interesting study about this subject is performed in Tottori University of Japan by Ohkita [2]. In this study fuzzy control theory is used for controlling an autonomous mobile robot with four wheels for parallel parking and fuzzy rules are derived by modeling driving actions of the conventional car. Six supersonic transducers are used for recognizing the position and attitude of the robot. A stepper motor is also employed to control and move the sensors to keep the suitable angle to the wall for preventing the occurrence of dead angles. The configuration of the supersonic transducer units of this study is presented in Figure 1.1.

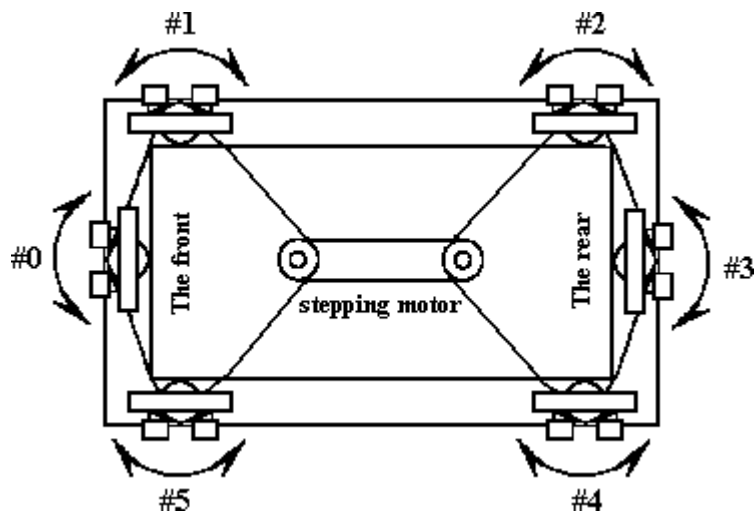


Figure 1.1. Configuration of the Supersonic Transducer Units

In the study of Ohkita, three microprocessors are used for calculations and peripheral access. This kind of architecture seems bulky when combined with the number of the sensors. But using so many sensors has an advantage of an increase in sampling rate of the input data when compared to a positioned single sensor system. The fuzzy reasoning of the system is composed of three fuzzy rule groups each with three, five and seven rules respectively. The active rule group is

determined according to the current state of the mobile robot. The performance of this system is satisfactory except the behaviors of the system during the absence of the walls. To overcome this problem, utilization of gyro-sensors and a CCD camera is recommended by the authors.

Parking motion control of a car-like robot is discussed in the study of Motoji and Akira [3]. The constraints of steering operation and obstacle avoidance with a garage and walls are also considered and a motion planning and control method that is using a fuzzy neural network is presented. The fuzzy neural network system for parking motion is made to learn good motions by human operations to generate motion control strategy of parking and the system is used for parking motion planning and control. A similar study is performed by Moran and Nagai [4]. A new design method of autonomous parking systems by integrating fuzzy systems and neural networks is presented. In this study a fuzzy driver is designed that is based on the experience of a human driver and it is refined by designing a fuzzy-neuro driver. Then the performance of both the fuzzy driver and fuzzy-neuro driver are analyzed and compared.

Another study about this subject is performed by Kong and Kosko [5]. In this study a fuzzy and a neural truck backer-upper control system are designed and compared. Vertical parking at the middle of one of the walls of a parking bay is performed by using a fuzzy control system with just 25 rules. The results are satisfactory except some dead points.

In the study of Fraichard and Garnier [6] a motion control architecture for a car-like vehicle intended to move in dynamic and partially known environments is presented. The system is designed as a fuzzy controller and it is implemented and tested on a real computer-controlled car, equipped with sensors of limited precision and reliability. A Motorola VME bus with an MVME 162 CPU board (68040 processor) is employed as the controller of the vehicle. Three servo-motors and a three-phase controller are driven with this board. The steering wheel is controlled with one of the servo-motors, the other two are used for the brakes. The three-phase

controller is used to drive the electric motor of the car for traction. The steering angle is measured with an optical encoder and two optical encoders are also mounted on the rear wheels to obtain the longitudinal velocity of the car and a motion estimation. The system is equipped with a range measurement system of 14 Polaroid 9000 ultrasonic sensors whose layout is presented in Figure 1.2.

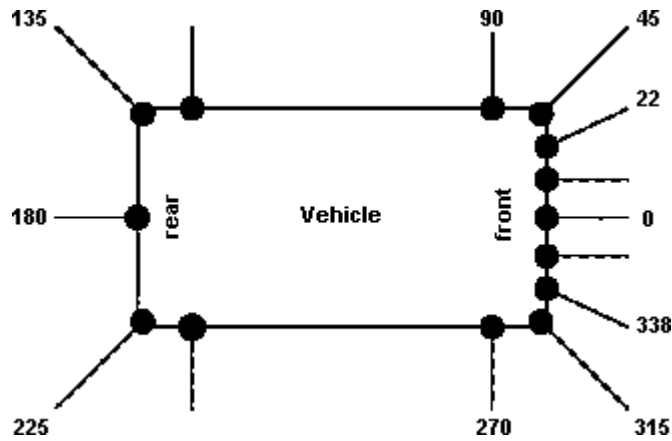


Figure 1.2. Layout of the ultrasonic sensors

Nowadays the usage of ultrasonic sensors for driver parking aid systems is popular. The layout of these sensors are similar with the sensor layout of the rear part of the vehicle that is presented in Figure 1.2. It is also possible to use these sensors for designing intelligent types of these driver parking aid systems that will generate the parking maneuvers automatically. Some commercial research studies are also done by the car manufacturers.

1.3 The Objective of the Thesis

The objective of this thesis study is the design, construction and performance testing of a vehicle system that has car-like kinematics and an embedded fuzzy controller for this vehicle that will manage self-parking action. An expected parking action is presented in Figure 1.3.

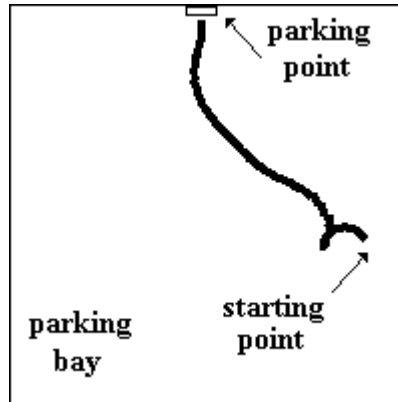


Figure 1.3. Expected parking action

Implementing fuzzy logic control to embedded control systems is a popular trend. Generally commercial fuzzy controller development tools are used during the fuzzy control system design process for embedded systems. This thesis study is a good example with its hardware architecture and user friendly computer software for fuzzy system design for an embedded system and it may be a good alternative to the commercial development tools for embedded systems.

1.4 The Scope of the Thesis

A literature survey about the problem is carried out at the beginning of the study. Previous researches about the topic are examined and position data collection and control types are presented in Chapter 1.

In Chapter 2, components of the system are explained. All the details about the mechanical and electrical parts of the system are presented. Technical specifications of the sensors and actuators are given. Electrical hardware design is performed and interfacing to the environment is performed.

General information about fuzzy logic and fuzzy control is given briefly in Chapter 3. Fuzzy control system of the self-parking model car is explained. The

governing fuzzy sets of the system are discussed and membership functions are presented. After the definition of the sets and functions, rule maps of the system are given. After all of these, the software and hardware architectures of the embedded fuzzy engine of the system are explained in detail and software flow diagrams about fuzzification, rule application and defuzzification stages are presented.

Information about the simulation process and the simulation program is given in Chapter 4 and the performance of the system is tested by executing three parking scenarios. The position data is collected from the parking bay and parking maneuvers are visualized for comparison with the simulation results of the computer program about the maneuvers of the system. The results and failures of the system are discussed.

As the final step of the study, the developed self-parking vehicle system is discussed and future recommendations about this study are stated in Chapter 5.

CHAPTER 2

COMPONENTS OF THE SYSTEM

2.1 Overview of the System

In this chapter a detailed description of the system components will be performed. The system can be examined mainly in two sub-divisions. First one is the mechanical section, which is composed of a model car chassis and a sensory housing group with its positioning equipment. Second one is the electrical section, which is composed of an embedded controller hardware which includes a microcontroller and all the necessary interfacing peripherals and a sensory system. A photograph of the developed system is given in Figure 2.1.

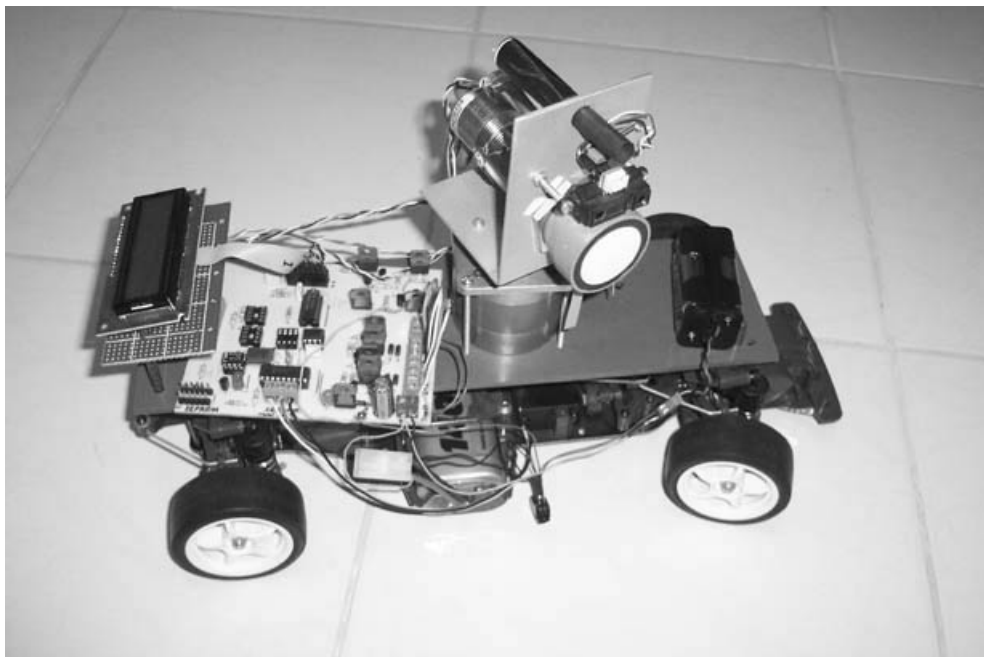


Figure 2.1. Photograph of the system

The mechanical section of the system includes a model car chassis and a sensory housing group with its positioning equipment that is mounted on the model car chassis. The model car chassis is of type TA03F pro belt driven 4WD from Tamiya Plastic Model Company, Japan. It is a 1/10 scale 4WD racing car chassis, but in this thesis study, the car will be actuated with rear wheel drive. The length and width of the model car chassis are 39 cm and 18 cm respectively. Distance between the axles is 26 cm and the turning radius is 98 cm. The average speed of the car is 2.5 cm/s with the selected motor. The final weight of the car is measured to be 2.5 kg at the end of the study.

The sensory housing group is composed of a base plate which is made of PVC, an aluminum rotary table, a stepper motor and its coupling and a shield for direction sensor in order to obtain directional characteristics. A general view of the sensory housing group with the sensors mounted on can be seen in Figure 2.2.

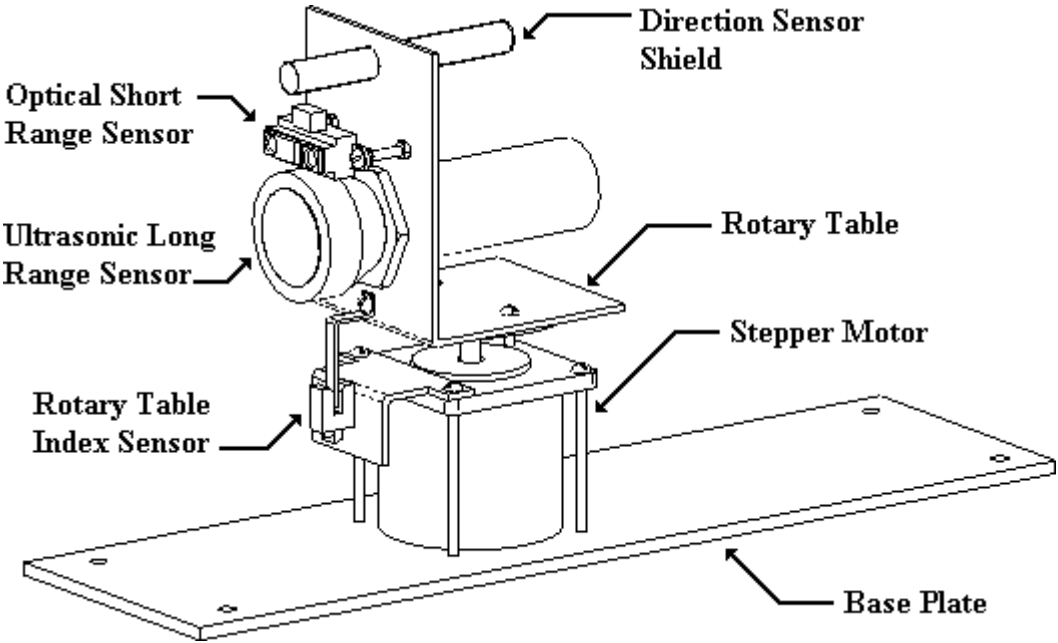


Figure 2.2. General view of the sensory housing group

The sensory housing group is mounted on the car chassis through the holes on the base plate. The sketch of the car chassis showing the base plate mounting pins is presented in Figure 2.3.

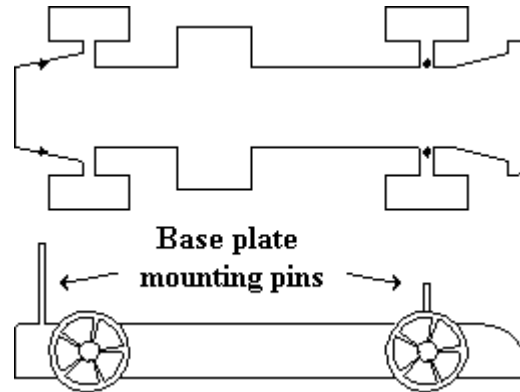


Figure 2.3. Sketch of the car chassis

Interfacing to the environment and fuzzy logic calculations are performed by the microcontroller, so it is the core of the system. Controlling action starts with the scanning of the parking bay. Rotary table is activated by the actuation of the stepper motor. Since the sensory system is mounted on the rotary table, all the position data and parking place data can be obtained by a 360° degree rotation of it. After gathering inputs to the system, the crisp values corresponding to the fuzzy variables are fuzzified into sets of (fuzzy set, membership degree) couples by matching the crisp values against the membership functions of each fuzzy set of the fuzzy variables. This is the fuzzification stage. Then comes the rule application and defuzzification stages where the calculated grade of membership values are processed with the preloaded rules in order to obtain steering and direction of motion information. These values are the outputs of the fuzzy controller and they are fed to the steering servo motor and DC traction motor respectively to generate the parking maneuver. This controlling action is repeated until the parking process is completed.

Information related to the design of both the mechanical and electrical components of the developed system can be found in the following sections.

2.2 Components of the System

2.2.1 The Mechanical Section

In this section the components of the sensory housing group will be explained. This part of the system is composed of a base plate, a rotary table, a stepper motor and its coupling and a shield for direction sensor.

Base plate is the component which holds all the other components and it is used to mount the sensory housing group on the model car chassis. Technical drawing of this component can be seen in Figure 2.4. Since the electrical hardware is also placed on the base plate, a nonconducting material should be used for manufacturing this component. For this purpose it is manufactured from 4 mm width PVC plate.

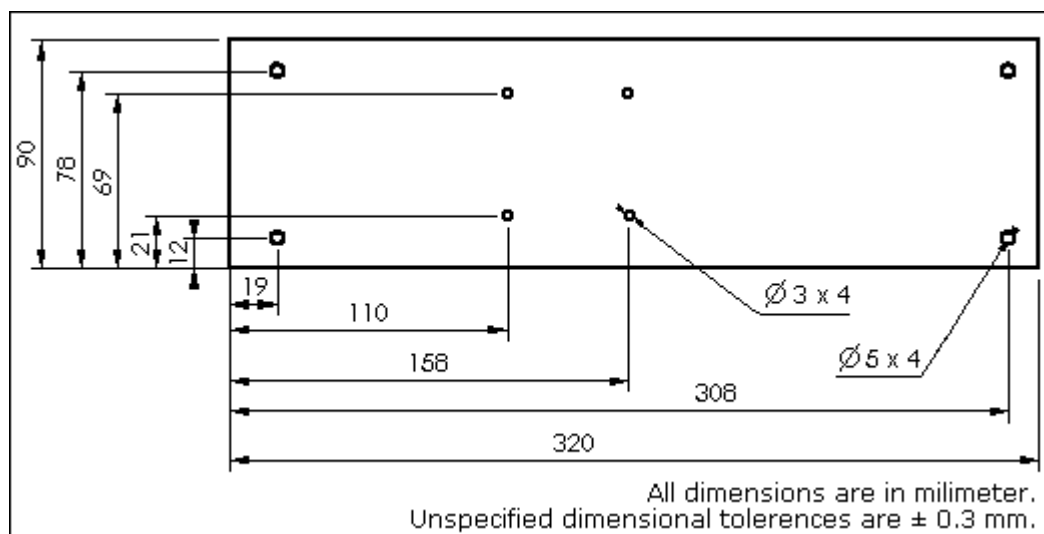


Figure 2.4. Technical drawing of the base plate

An L-shape rotary table is manufactured for housing the sensors. This component is actuated with a stepper motor and it is connected to the motor with a coupling element. Technical drawings of the rotary table and the coupling element can be seen in Figure 2.5 and in Figure 2.6 respectively.

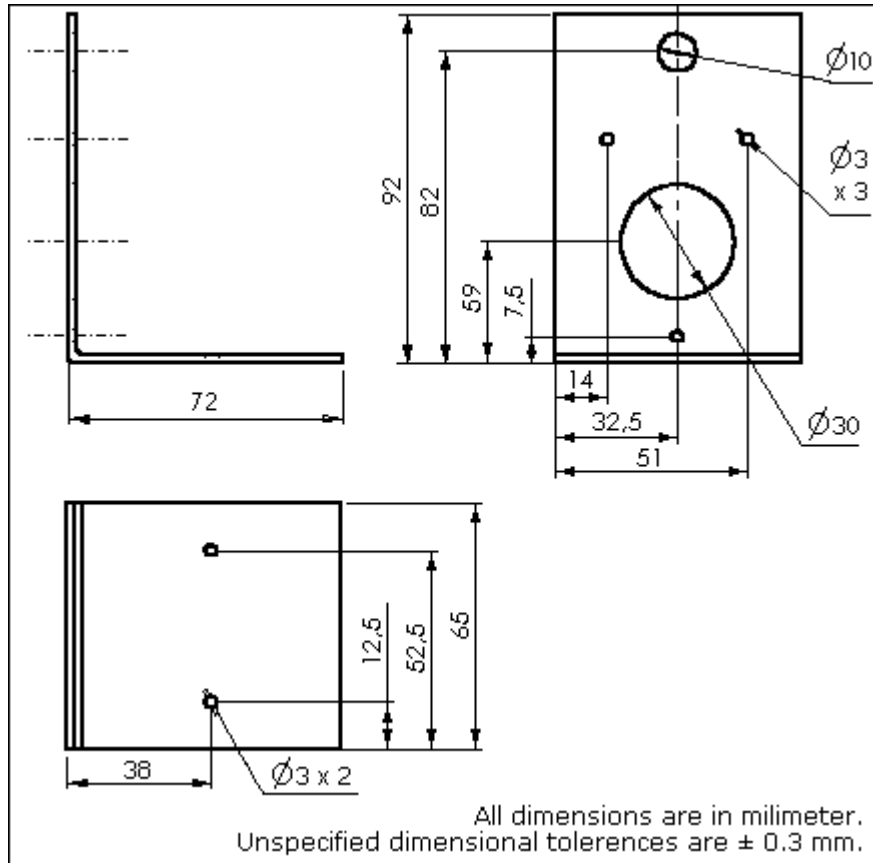


Figure 2.5. Technical drawing of the rotary table

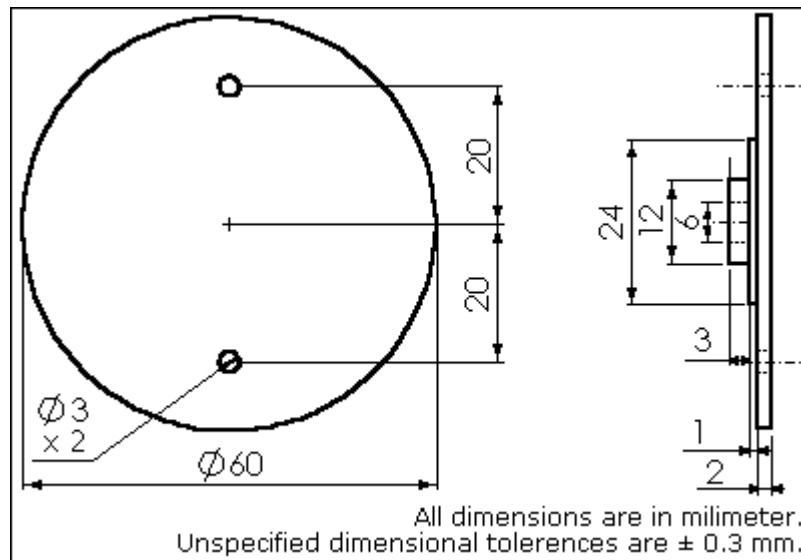


Figure 2.6. Technical drawing of the coupling element

The material of the rotary table is 2 mm width sheet aluminum. This part is mounted to the coupling element by two M3 screws. The coupling element is machined from polyethylene.

A table index sensor is used for preventing the possibility of the cumulation of positioning errors of the rotary table due to miss of step pulses. With this sensor the absolute position of the rotary table can be determined at a fixed angle. This sensor is a slot type IR optical interrupter switch and the position of the table is determined by the breaking of the IR light by a tiny piece of aluminum mounted on the rotary table. A component is manufactured from 0.5 mm width sheet aluminum for mounting this sensor to the stepper motor body. The technical drawing of this part can be seen in Figure 2.7.

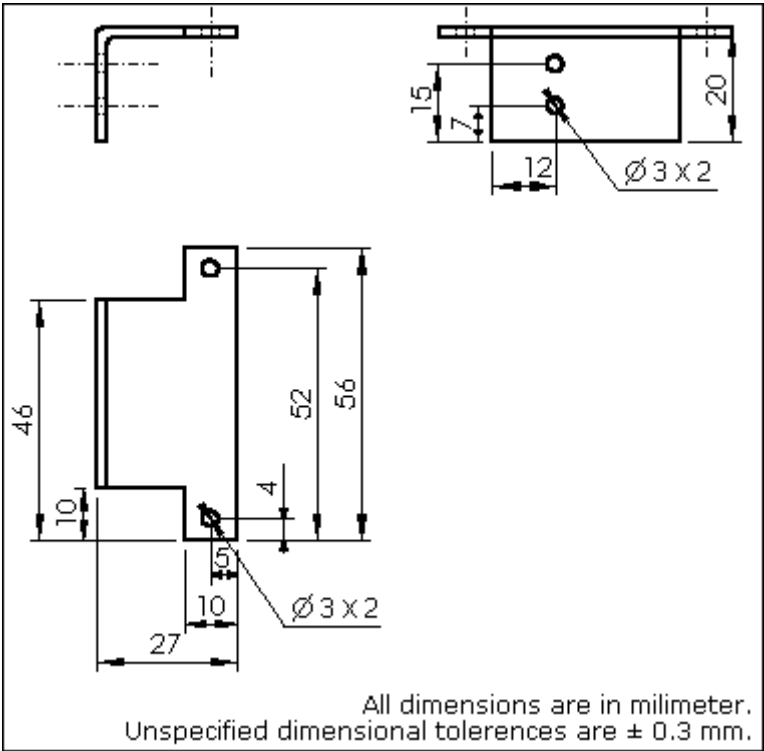


Figure 2.7. Technical drawing of the index sensor holder

2.2.2 The Electrical Section

In this section the designed controller hardware and its interfacing peripherals with sensors and motors will be explained with the characteristics of the components. In Figure 2.8 the block diagram of the hardware is presented.

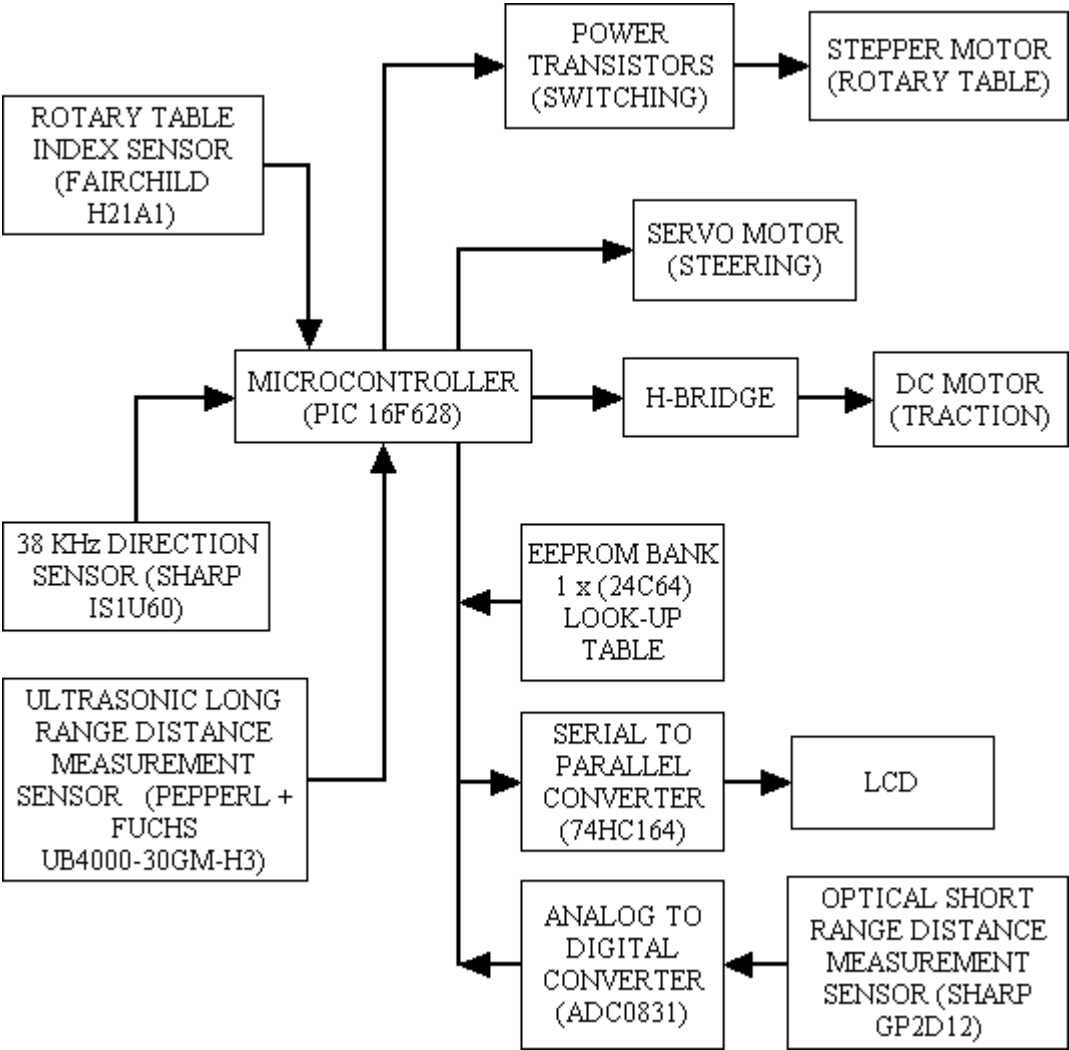


Figure 2.8. Block diagram of the hardware

A block diagram representation of the control system is presented in Figure 2.9.

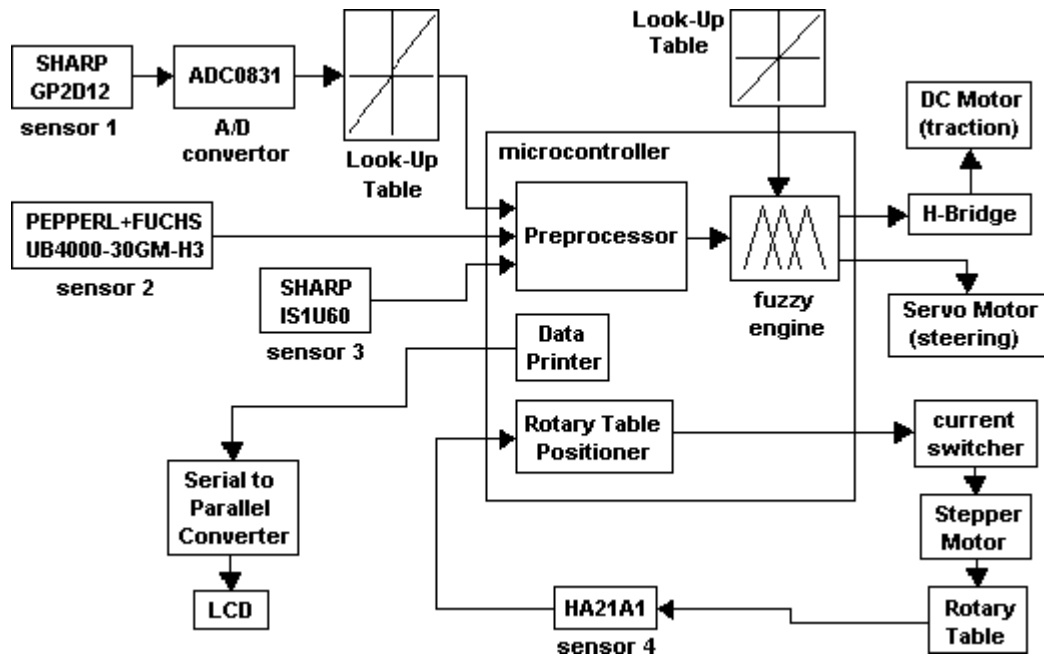


Figure 2.9. Block diagram of the control system

Selection of the microcontroller is an important step in the design. Because the microcontroller is the core of the hardware. There are many alternatives in the market. Motorola 68HCXX series, Intel 8251, Arizona Microchip PIC 16F series and Atmel AT 89 C series can be given as alternatives. Among these microcontroller families there is one with built in fuzzy logic instructions. It is 68HC12, which is a powerful and fast math capable 16 bit microcontroller from Motorola. However, due to the background of the owner of this study about coding with assembly language for Microchip PIC 16F series, a microcontroller from this company is selected as the development platform. Microchip PIC 16F series include many microcontroller types. Among them the selection of the one which has the necessary and enough properties is aimed. The selected microcontroller is PIC16F628 [7]. Some important properties of this 8-bit RISC architecture microcontroller are,

- 35 single word instructions for programming,
- 4 MHz clock frequency, 1 μ s instruction cycle,
- Eight-level deep hardware stack,
- 100,000 erase/write cycles, 2K Flash program memory,
- 10,000,000 erase/write cycles, 128 bytes EEPROM data memory,
- 224 bytes of data RAM,
- 13 I/O pins with individual direction control in crystal oscillator mode.
- DIP18 package,

The schematic diagram of microcontroller block of the designed hardware can be seen in Figure 2.10. As it can be observed from the figure, programming of this component is performed through three pins.

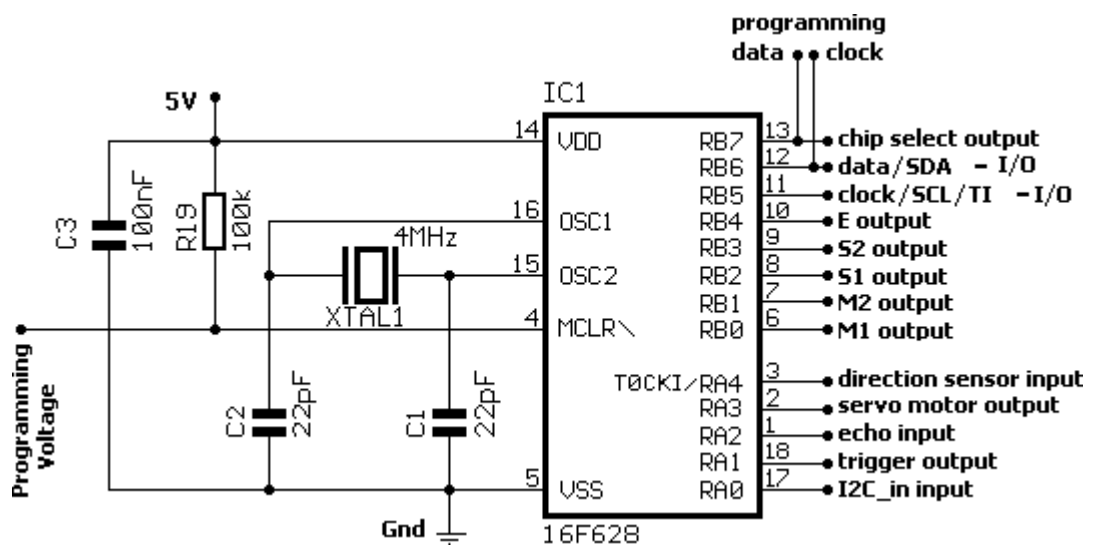


Figure 2.10. Microcontroller block

The system is composed of a DC motor, a stepper motor, a servo motor, an EEPROM, an analog to digital converter, an LCD and 4 sensors. So the number of I/O pins of the microcontroller is an important parameter in the circuit design. Because of this fact, interfacing to some of these parts is performed through a serial bus for pin saving and for printed circuit board simplification. In Figure 2.11 the block diagram of this serial bus is presented.

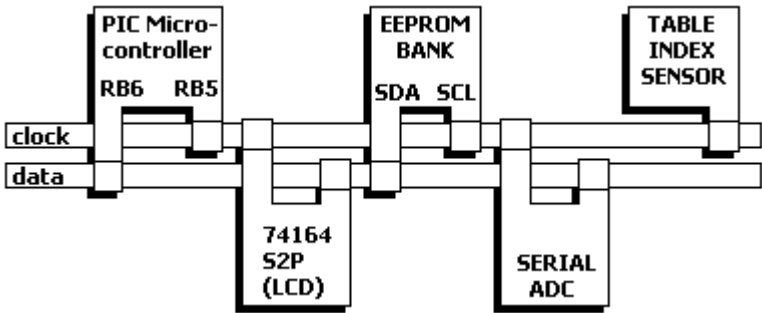


Figure 2.11. The serial bus

The advantage of this data bus design is, its capability of housing a serial synchronous bi-directional data transfer protocol and an I²C (Inter-IC) data transfer protocol on the same serial lines without interfering each other. This is due to the difference between signal timings and sequences of the protocols. Clock line of this serial bus is also used as an input line for table index sensor.

An alphanumeric LCD module is added to the hardware in order to simplify debugging stage of code development by displaying intermediate results. The LCD module is also used for displaying the results of measurements and outputs of the algorithms. It is a 2 line model with 16 characters per line. An industry standard LCD controller, HD44780 by Hitachi Semiconductor [8], constitutes the core of this component. Interfacing to this LCD module can be done by an 8 bit or 4 bit parallel bus, a read signal through the E pin and a command select signal (RS). But the lack of spare I/O pins in the microcontroller brings the necessity of another solution. A serial to parallel converter is utilized to expand 2 I/O pins to 8 lines of parallel data.

parameters are changed rather than the executing portion of the code. But this is not the case in a separate data storage element. Once the executing portion of the code is developed and it is made to process a general data, during the tuning process of the system the only thing that is needed to be changed is the memory map of the storage element. Due to these facts a separate data storage element, 24C64 is utilized in the design [9]. This is a small 8 pin, 64 Kbits serial EEPROM with I²C (Inter-IC) interface. Small package and serial interface simplifies the printed circuit board of the controller and fits to the serial bus design. Being cascadable for up to eight devices by hardware addressing is another advantage of this component which enables the expand of data storage area for further improvements without hardware modification. So by taking into account of this possibility, the hardware is organized as an EEPROM bank and 3 extra slots are placed in the PCB. The schematic diagram of the EEPROM bank can be seen in Figure 2.13.

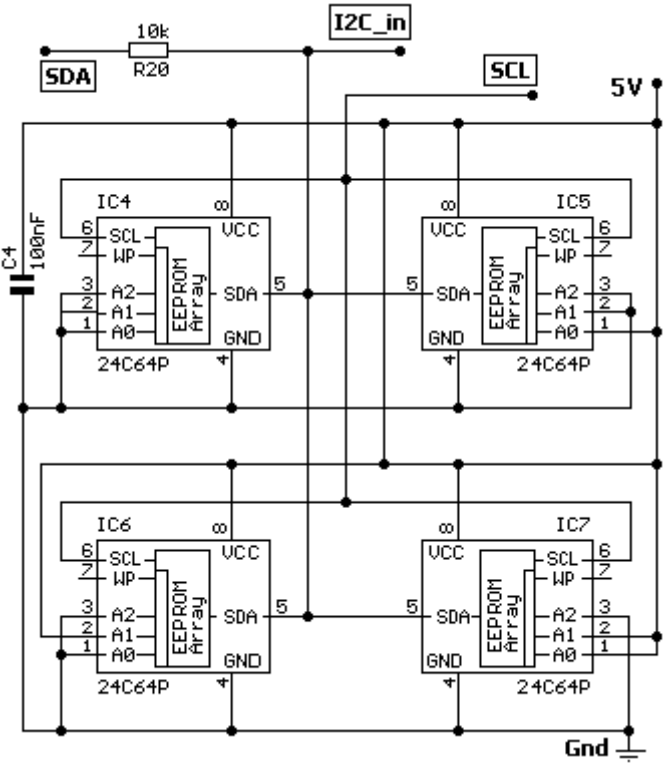


Figure 2.13. EEPROM bank

A gearbox coupled DC motor is used for the traction of the model car chassis. This motor is of type 1.61.065.405 from Buehler Motor. Technical drawing and specifications of this motor are given in Figure 2.14 and in Table 2.1 respectively.

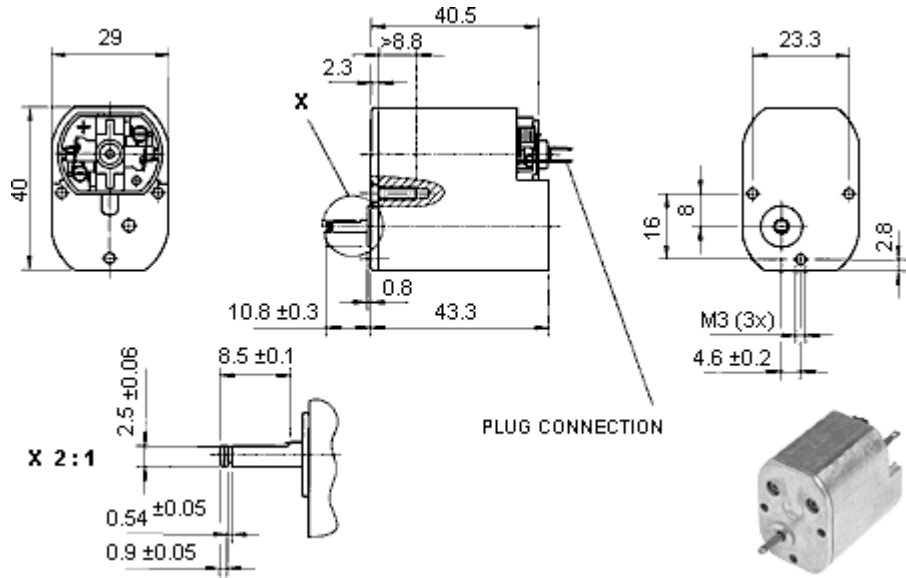


Figure 2.14. Technical drawing of the DC motor

Table 2.1. Technical specifications of the gearbox coupled DC motor

Type	3 Segment Brush, Permanent Magnet
Nominal Operating Voltage	6 V
Rated Torque	150 mNm
Rated Speed	34 rpm
Rated Current	280 mA
No Load Speed	44 rpm
Gear Ratio	116.9 (6 stages)
Weight	Approx. 150 g

The need of changing the direction of motion of the car during parking maneuvers brings the necessity of reversing the direction of rotation of the motor. So an H-Bridge circuit is designed and utilized instead of directly switching the motor current. With this circuit the direction of motor current can be changed by cross excitation of darlington power transistors directly from the I/O pins of the microcontroller. Switching time adjustment is also a very important design parameter to reduce the loss of power. The power transistors should be switched on slowly and switched off quickly in order to reduce leakage currents. These timing problems are handled by the small signal transistors. The schematic diagram of the H-Bridge is presented in Figure 2.15.

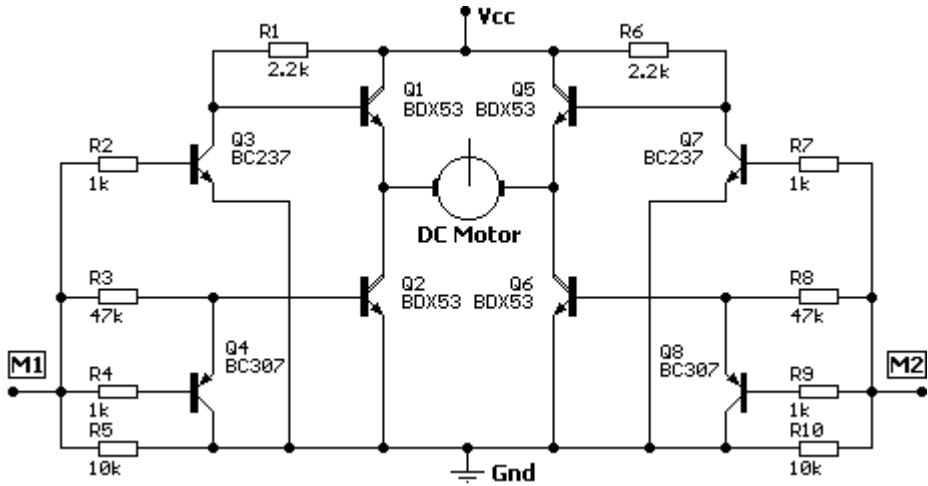


Figure 2.15. H-Bridge

This is an inverting H-Bridge and the input signals are TTL compatible. When the input line is in low state, output is in high state. For driving the DC motor, one of the signals at M1 and M2 should be high and the other low. Inverting the signals at this instant reverses the direction of the current so the rotation. Same logic states at inputs result a braking action.

A common problem in switching inductive loads is the induced currents due to switching. So freewheeling diodes are needed to short these currents for

protecting switching circuitry. In this type of connection of power transistors the internal diodes of power transistors can be utilized for this purpose and this design is an example to this property. But it is not the case in the circuits where directly switching of the currents is performed with power transistors as the switching circuit used in stepper motor driving in this thesis study.

As it is mentioned before, in this study a stepper motor is used to direct the sensory system to collect position data from all the sides of the car. For this purpose a unipolar type stepper motor of type Astrosyn 23LM-K33L04 from Minebea Co Ltd. Japan, is selected. The resolution of the motor is 1.8 deg/step and its ratings are 12.0 V/Phase and 0.42 A/Phase. The technical drawing of the stepper motor is presented in Figure 2.16.

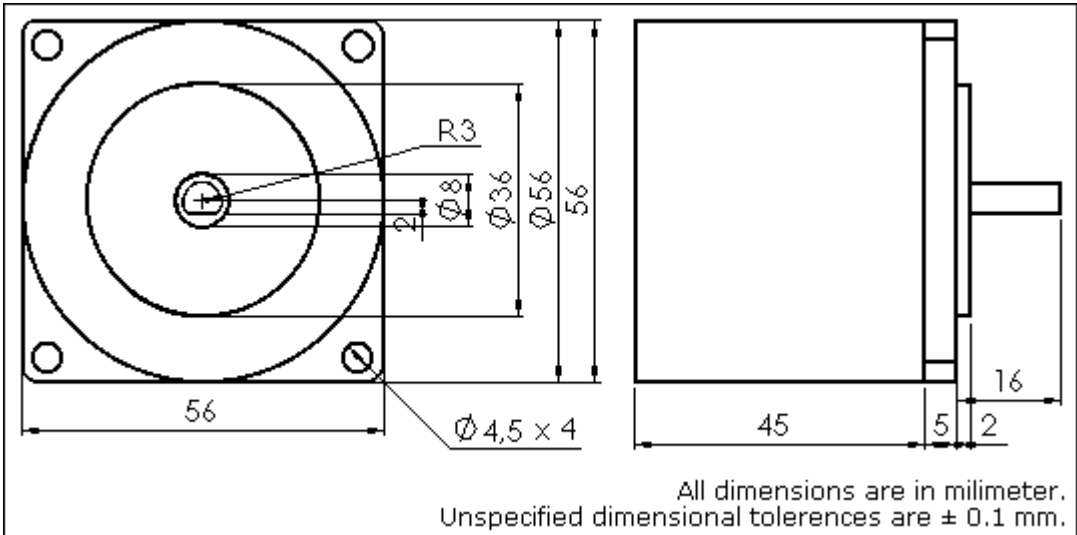


Figure 2.16. Technical drawing of the stepper motor

Stepper motor is a good solution to the problem of precise positioning without any feedback from the system. The internal structure of a unipolar type stepper motor and the logic behind stepper motor driving is presented in Figure 2.17.

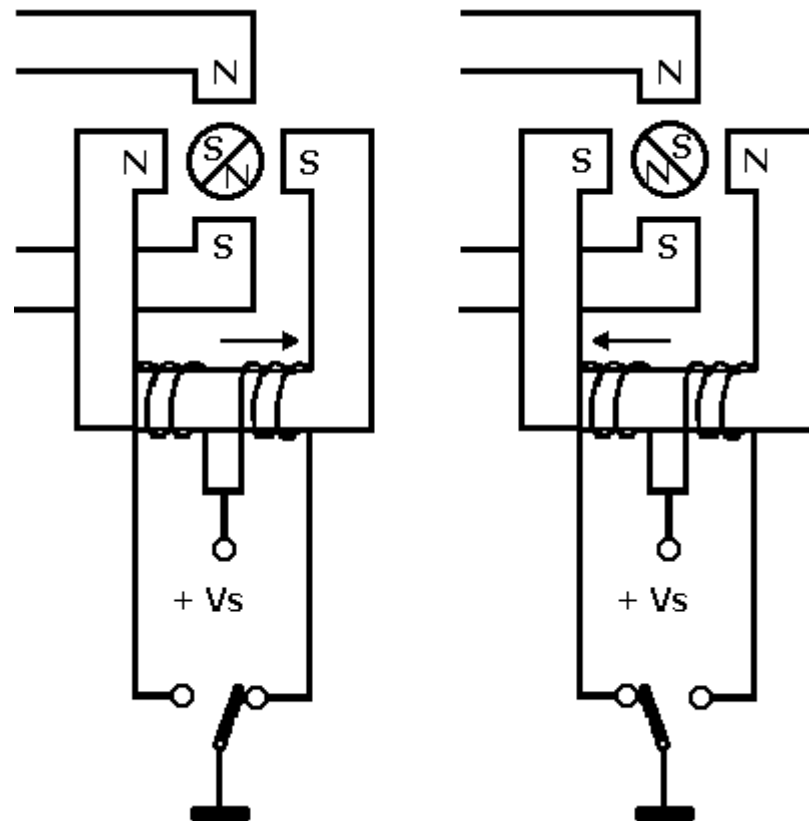


Figure 2.17. The internal structure of a unipolar type stepper motor

The stepper motor structure presented in the figure has a resolution of 4 steps/revolution. This is a simplified representation. In a real stepper motor with more resolution, the polar states in the rotor and stator repeat themselves successively. This property directly determines the resolution of the stepper motor. As it can be observed from Figure 2.17, one step movement of the rotor is obtained by a 90° circular rotation of the polar state of the stator. In order to get this kind of a polar state rotation, stepper motor coils should be excited with a special type of waveform. There must be 90° phase difference between the driving signals. In Figure 2.18 a sample form of the signal to be applied to the switches in Figure 2.17 is presented.

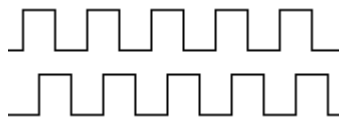


Figure 2.18. Stepper motor driving waveform

As it can be seen from the figure, the first signal is leading 90°. If the first signal is made to be lagging 90°, a change of direction of rotation occurs. Each logical state change in this waveform causes one step movement of the rotor. In other words, each cycle results 4 steps of movement. The schematic diagram of the stepper motor coil switching circuit which is driven by the above given waveform is presented in Figure 2.19.

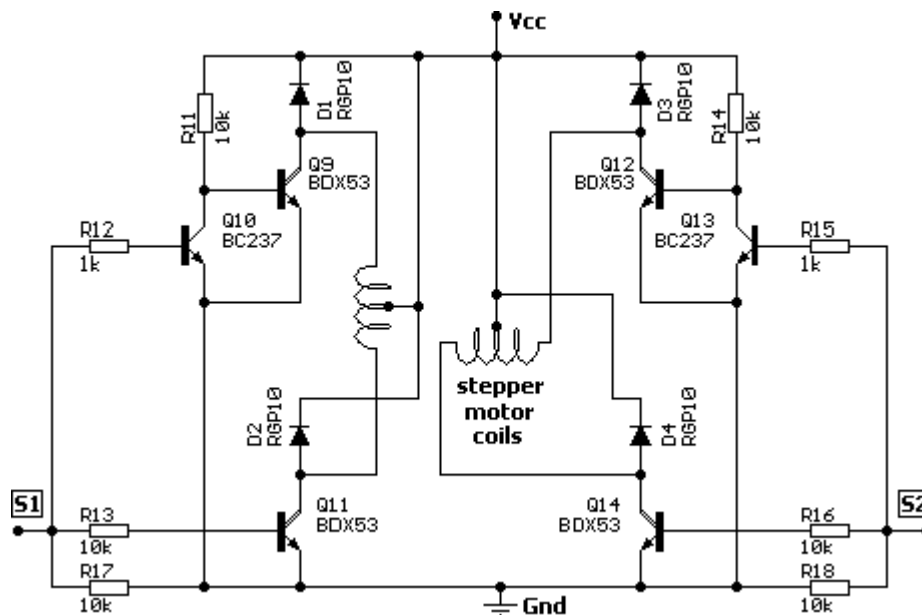


Figure 2.19. Stepper motor coil switching circuit

The nature of the switches in Figure 2.17 brings about 4 signals where 2 of them are the inverted form of the explained waveform. The lack of spare I/O pins in the microcontroller brings the necessity of generating only the master signal with

two I/O pins and obtaining the inverted forms by some other way. The inverted forms of these signals are generated by using two small signal transistors which are embedded into the circuit design. Darlington power transistors are used in the current switching circuit in order to directly drive the transistors from the TTL output of the microcontroller. Freewheeling fast recovery diodes are used in this design because of the reason which is mentioned before in the H-Bridge section.

As it is mentioned before, four sensors are utilized in this system. One of them is used for preventing the possibility of the cumulation of positioning errors of the rotary table due to miss of step pulses and the other three of them are used for determining the position of the car and the place of the parking place. These three sensors are mounted on a rotary table to be directed to the desired direction. Two of these sensors are utilized for distance measurement. One of them is an ultrasonic sensor and it is used for long range distance measurement. The other one is an optical sensor and it is used for short range distance measurement. Allocation of two sensors for distance measurement is due to the limitations of both sensors. Each sensor has its own detection range and the union of these detection ranges covers the needed measurement range.

The utilized ultrasonic sensor is UB 4000-30GM-H3 from Pepperl + Fuchs, Mannheim, Germany [10]. Technical drawing and the photograph of this sensor can be seen in Figure 2.20.

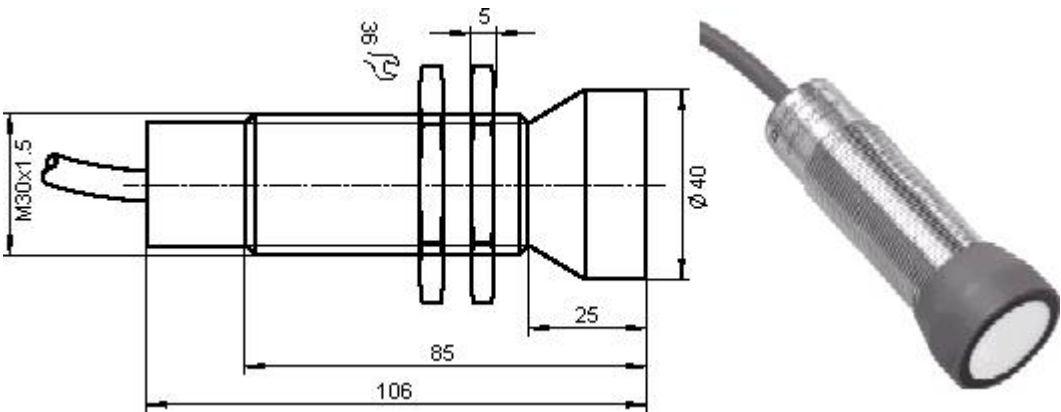


Figure 2.20. Technical drawing and the photograph of the ultrasonic sensor

The principal of operation and technical specifications of this sensor are presented in Figure 2.21 and in Table 2.2 respectively.

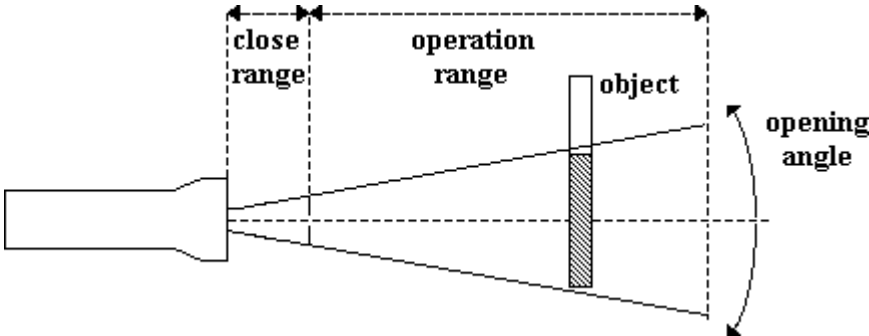


Figure 2.21. Operation of ultrasonic sensor

Table 2.2. Technical specifications of the ultrasonic sensor

Detection Range	500 mm ... 4000 mm
Unusable Area	0 mm ... 500 mm
Sonic Beam Divergence Angle	Approx. 5° at -3 dB
Transducer Frequency	85 kHz
Operating Voltage (U_B)	10V DC ... 30V DC
Quiescent Current	<30 mA
Input type	Emitter pulse (open collector)
Input Pulse Duration	40 μs < 500 μs
Output type	Echo propagation time output
Output High Level	U _B - 3V

This sensor is a transducer that operates with piezoceramics as sound transmitter and receiver. During operation, a packet of sonic pulses is transmitted and the echo pulse is converted into voltage by the integrated controller of the

sensor and the distance is computed from the echo time and the velocity of sound. The transmitted pulse duration and the decay time of the sonic transducer result in a blind zone in which the ultrasonic sensor cannot detect an object. During this time the receiver is disabled in order to prevent the self-excitation of the receiver by the generated sonic pulse instead of echo. The needed signal waveforms for interfacing this sensor are presented in Figure 2.22.

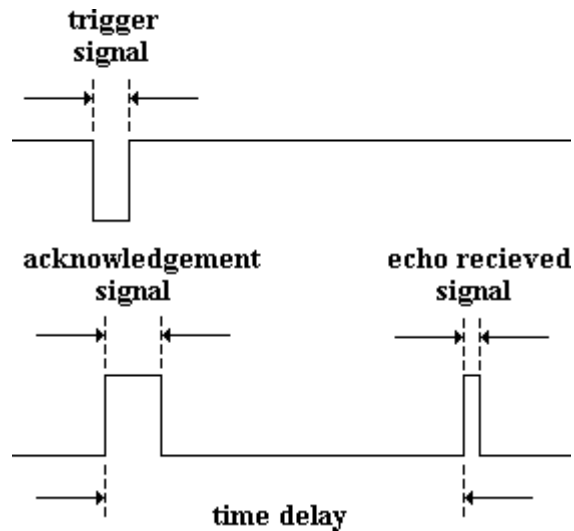


Figure 2.22. Ultrasonic sensor interfacing waveforms

The output of this sensor is in the form of pulses representing echo time delay, but the signal levels in the output is not TTL compatible. A small signal transistor is utilized for level shifting to overcome this problem. The schematic diagram of this signal conditioning and interfacing circuit is given in Figure 2.23.

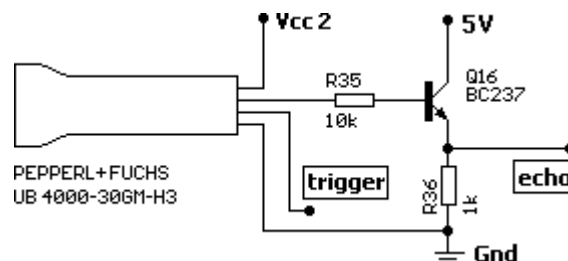


Figure 2.23. Ultrasonic sensor interfacing circuit

The thick gray cable of this sensor houses four colored cables for interfacing. The blue cable is connected to ground, the brown cable is connected to Vcc, the black cable is connected to trigger and the white cable is connected to the circuit through 10k resistor for echo.

Low sonic beam divergence angle property makes this sensor a powerful device for orientation measurement because ultrasound echo detection is only performed when the alignment of sonic beam and object is near to vertical.

The second sensor for distance measurement is GP2D12 from Sharp, JAPAN [11]. This sensor is an optical distance measurement sensor and it is utilized for short range distance measurements. Sharp's GP2D12 is a general purpose type distance measuring sensor which consists of a position sensitive detector, an infrared emitting diode and a signal processing circuit. It computes the range to an object based on triangulation principle which is presented in Figure 2.24. This enables to detect the range without any influence on the color of reflective objects, reflectivity and the illumination of surroundings. But when compared to the ultrasonic distance measurement sensor, this one has a much wider measurement angle which makes this sensor a poor device for orientation measurement.

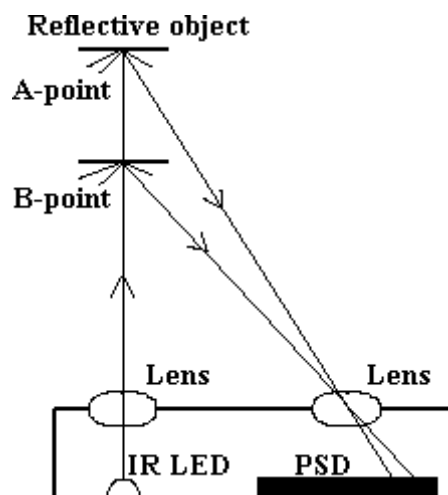


Figure 2.24. The principal of triangulation

Technical drawing and specifications of this sensor are presented in Figure 2.25 and in Table 2.3 respectively.

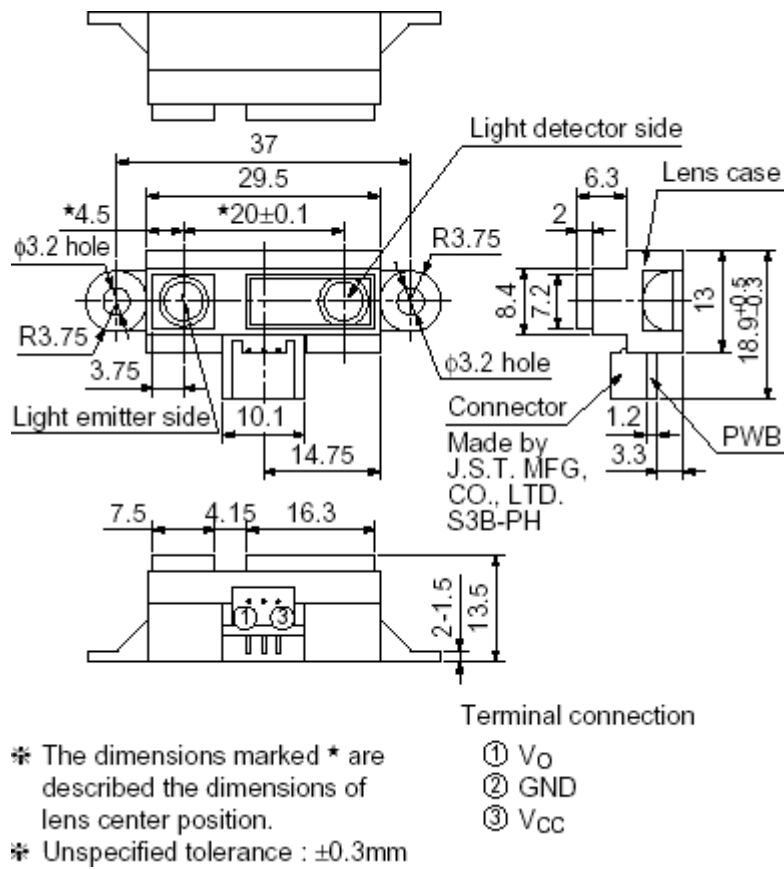


Figure 2.25. Technical drawing of Sharp GP2D12

Table 2.3. Technical specifications of Sharp GP2D12

Detection Range	10 cm ... 80 cm
Operating Voltage	4.5V ... 5.5V
Average Dissipation Current	50 mA (max)
Output Type	Analog
Update Frequency	25 Hz
Max Admissible Measurement Angle on a Flat Surface	$> 40^\circ$

The output voltage of this sensor inversely varies with the distance and it can be seen in Figure 2.26 as an analog output voltage versus distance to the object graphic that is given for two surface colors. Surface color insensitivity of the sensor can be observed in the graphic.

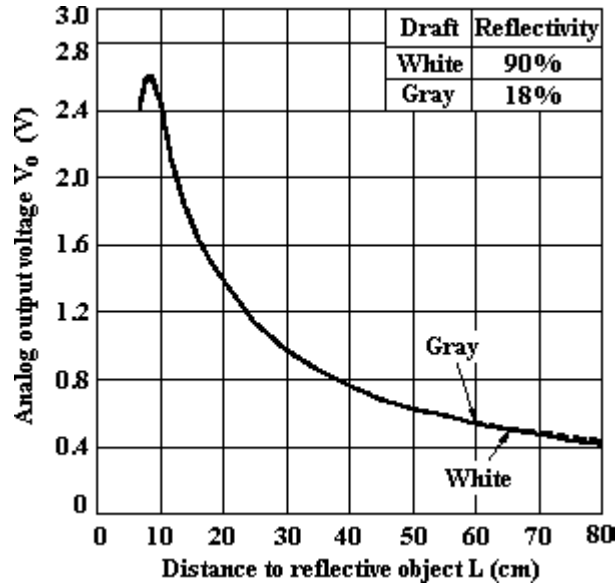


Figure 2.26. Output of Sharp GP2D12

An analog to digital converter is included to the design for measuring this voltage. The selected component is ADC0831 from, National Semiconductor [12]. This is an 8-bit serial ADC and interfacing to this component is with a serial synchronous data transfer protocol. The schematic diagram about the ADC and its connection to the distance measurement sensor is presented in Figure 2.27.

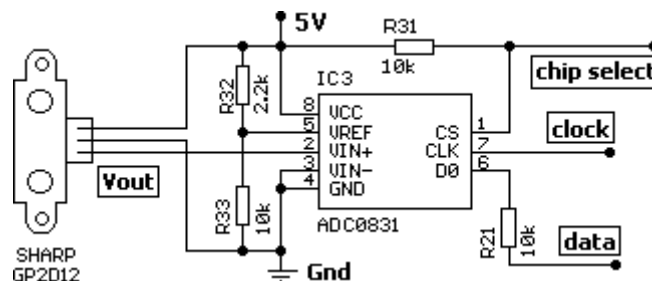


Figure 2.27. Analog to digital converter

The resolution of the ADC is selected to be 8 bits as previously mentioned. This resolution is sufficient for measuring distances between 10 and 60 centimeters with 1 centimeter resolution.

Implementation of this component to the serial bus of the system can be managed with the help of the chip selection feature of this IC. This kind of a design results I/O pin saving and decrease in the complexity of the printed circuit board as mentioned before.

The result of measurement that is read from the ADC is a number between 0 and 255. Due to the output characteristics of the sensor, these numbers are also nonlinear. There are two possibilities for linearizing the results and obtaining the corresponding cm values. One of them is defining a function for converting the 8 bit result to its cm equivalent and the other one is generating a look-up table. The output of the sensor can be expressed as

$$R = K_1 \cdot \text{atan}(S / D) + K_2 \quad (2.1)$$

where

R : 8 bit result

K₁ : A multiplicative constant to bring the result into the range of 0 to 255

K₂ : Offset

S : Lens separation of the sensor

D : Distance to be measured

This formula comes from trigonometry, as applied to the triangulation triangle in Figure 2.24. Lens separation of the sensor is 2 cm. A successful curve is obtained to give distance values in cm when 1600 for K₁ and – 3 for K₂ is used. This curve will be given later. Calculating distance by using this equation needs a lot of trigonometric calculations and time consuming mathematical operations that

are hard to be handled by a tiny microcontroller. Instead of this method, using a look-up table may give better performance when there is no problem for the storage of the look-up table data. Again the EEPROM of the system can be used instead of the program memory space. The EEPROM of the system has an 8 kB data storage space. Some part of this memory area is allocated for storing the fuzzy logic rules and membership function limits and the rest is free for any arbitrary usage. So a 256 entries look-up table is implemented and stored in the EEPROM. The values in this look-up table are obtained experimentally and they are presented in Table 2.4.

Table 2.4. 256 entries look-up table obtained from experimental study

H \ L	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	80	79	78	77
3	75	72	70	68	64	62	61	60	59	58	56	55	52	50	48	47
4	46	46	45	45	44	44	43	42	40	40	40	40	39	39	39	39
5	38	38	37	37	36	36	35	34	33	32	31	31	30	30	30	30
6	29	29	29	29	29	29	28	28	27	27	27	26	26	26	25	25
7	25	24	24	24	24	23	23	23	23	23	22	22	22	22	22	22
8	21	21	21	21	21	20	20	20	20	20	20	20	20	19	19	19
9	19	19	19	18	18	18	18	18	18	18	17	17	17	17	17	16
A	16	16	16	16	16	16	15	15	15	15	15	15	15	15	15	15
B	14	14	14	14	14	14	14	14	14	14	13	13	13	13	13	13
C	13	13	13	13	13	12	12	12	12	12	12	12	12	12	12	12
D	12	12	12	11	11	11	11	11	11	11	11	11	11	11	11	11
E	11	11	11	11	11	11	11	10	10	10	10	10	10	10	10	10
F	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10

The first column and the first row of this table give the high and low portions of the hexadecimal form of the measurement that is obtained from the ADC respectively. The corresponding numbers are the distances in cm. Since the EEPROM has an 8 kB data storage area, 2 bytes are needed for addressing the memory cells. When the high byte of the address is defined, the low byte of the

address can easily point to the 256 numbers of the look-up table that is given above. So during the execution of the code, microcontroller directly moves the value obtained from the ADC to the low byte of the address and moves the fixed index number to the high byte of the address and loads the corresponding value, so the corresponding distance in cm, from the EEPROM. The hexadecimal form of this fixed index number is 11. The graphical representation of the given table and the curve that is obtained by using the given formula is presented in Figure 2.28.

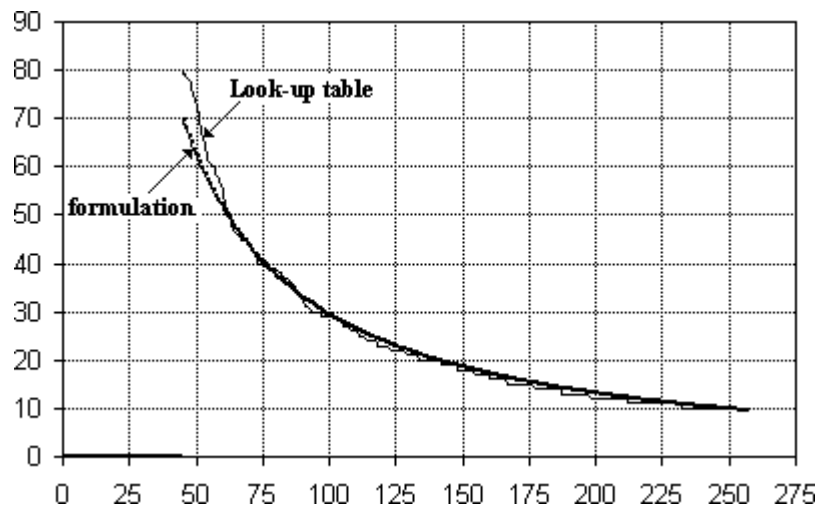


Figure 2.28. Graphical representation of the look-up table and the curve

This kind of a table access method significantly simplifies the distance measurement process with this sensor and reduces the amount of program code which is needed for this measurement.

The last of the sensors which are on the rotary table is the direction sensor which is utilized for determination of the place of the parking place in the parking bay. There is an IR signal emission at the parking place and this sensor is utilized for the detection of this sign. The sensor is IS1U60 from Sharp [13]. It is actually an optical integrated circuit that is containing a photodiode, an amplifier, a band pass filter which is tuned to 38 kHz and a demodulator. This frequency is the carrier signal and the component detects the presence of the IR light oscillations at this

frequency. This component is generally used as a receiver in remote control applications in household devices so it has a wide detection angle. It is even sensitive to the reflected portions of the signals coming from backside. Due to this property, usage of this device without any extra elements is not suitable for detection of direction. For this fact, this sensor is shielded with a tubular part in order to obtain directional characteristics. Only the direct light coming from the front side of this shield can effect the sensor. The tubular shield is made of dark colored paper. It is 80 mm long and 10 mm in diameter. One side of this tubular part is closed and the other side is open for the entrance of the IR light. The sensor is placed inside at 20 mm away from the closed side and this group is also mounted on the rotary table. The technical drawing of this sensor is given in Figure 2.29.

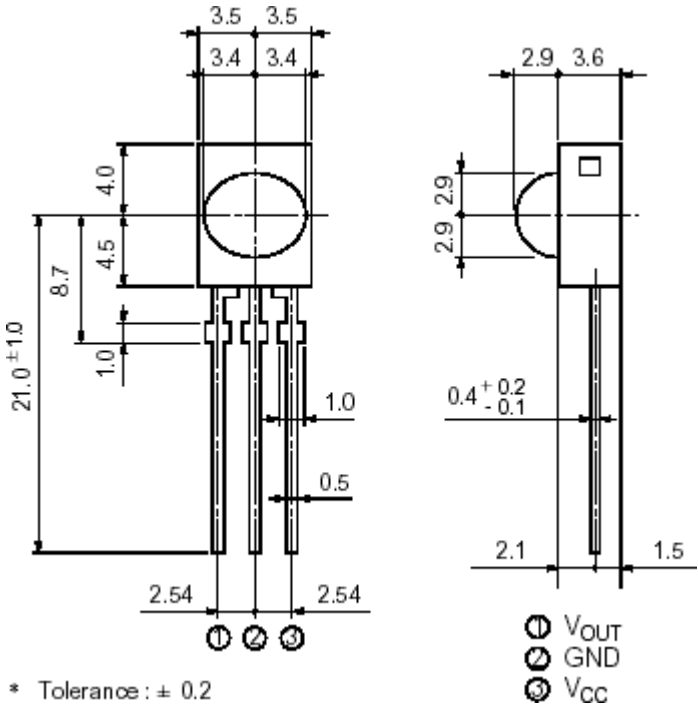


Figure 2.29. Technical drawing of Sharp IS1U60

The output of this sensor is an analog signal in the range of 0 to 5 volts. In the normal state the output is at 5 volts. In the presence of the carrier signal the output falls. Since a high order filter is equipped in the sensor, the falling

characteristics of the output is quite sensitive to the received frequency. So the usage of the level of the signal is useless. Instead, the high and low states of the output according to a threshold value is a meaningful output as in the other application areas of this sensor. This kind of an output can be obtained by the application of this analog signal to the input of a schmitt trigger. This is a logic component for converting analog signals to digital signals by comparing the input with a fixed internal threshold value. RA4 pin of the microcontroller can be programmed as a schmitt trigger input and this property prevents utilizing a spare part for this purpose. Another disadvantage of this sensor is its low immunity to the surrounding noise due to the high amplification gain of its built-in amplifier. A low-pass filter is added to the output stage of this sensor in order to overcome this problem. This addition decreases the time response of the sensor a little, but this property is not important if the sensor is used for ordinary signal receptions instead of modulated data receptions. The schematic diagram for interfacing to this sensor is presented in Figure 2.30.

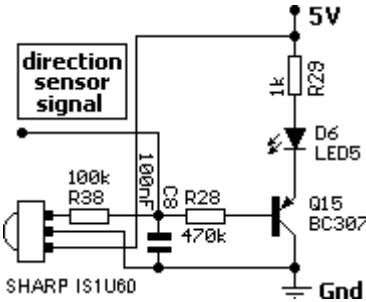


Figure 2.30. Direction sensor interfacing circuit

As it can be seen from the figure, a led is also added to the design. This led is for visualizing the state of the sensor. Since the output of the sensor is a weak signal, the current of the led is supplied through a small signal transistor.

The last sensor in the system is the rotary table index sensor. This sensor is H21A1 from Fairchild Semiconductor [14]. It is an optical interrupter switch, which is composed of an IR led and a phototransistor that are packed in a slotted form.

This sensor is utilized to generate an index signal for the rotary table as the index signals of optical encoders. This signal is needed to position the rotary table at power on and to prevent the possibility of the cumulation of positioning errors of the rotary table due to miss of step pulses caused by the cabling of the sensors on the rotary table and other reasons. The schematic diagram for the connection of this sensor can be seen in Figure 2.31.

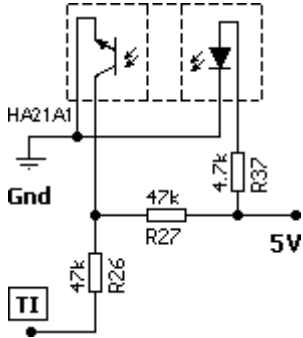


Figure 2.31. Rotary table index sensor interfacing circuit

The steering output that is generated by the fuzzy logic controller is fed to a servomotor for actuating the steering mechanism. The servomotor, which is supplied by the manufacturer of the model car chassis, is S3003 from Futaba. The driving circuit of this motor is included in its casing. A sequence of pulses is needed to position the output shaft of the motor. The width of the pulses determines the position of the shaft. In Figure 2.32 the driving signal needed to activate the servomotor and the width of this signal can be seen.

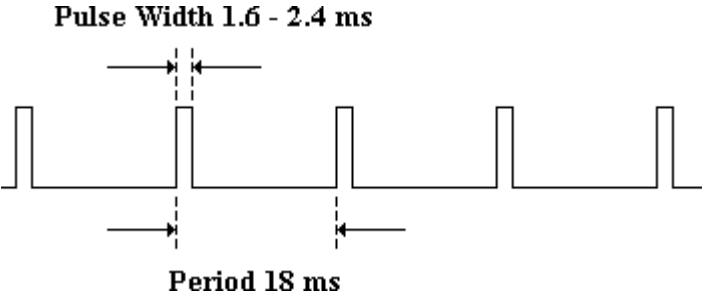


Figure 2.32. Servomotor driving signal

A sequence of pulses with a 1.6 ms width brings the steering mechanism to the left most position, where a sequence of 2.4 ms width of pulses brings it to the right most position. A sequence of 2 ms width of pulses results positioning of the mechanism to the center position. The values between these values affect the mechanism accordingly.

For most of the electrical components of the system 5 volts is needed as the supply voltage. A voltage regulator IC is equipped to generate this voltage. Also a filter with a capacitor and a diode is added to the design to prevent the interference of the switched motor currents with the logic parts of the controller circuit. A 7.2 V battery pack is supplied by the manufacturer of the car chassis. During the studies it is observed that after some operation time the voltage of this battery pack falls a little when power is supplied to the current consuming parts of the system such as motors. As a result of this, the voltage regulator IC fails to stabilize the 5 V output with such low input voltage. An additional 6 V battery is connected serially to the battery pack of the system resulting a voltage around 13 V to prevent this failure. This relatively high voltage is used directly for ultrasonic distance measurement sensor and the digital parts of the system including the remaining sensors through voltage regulator. The high current for the motors is supplied from the 7.2 V battery pack. The schematic diagram of the voltage regulation part of the overall circuit is presented in Figure 2.33.

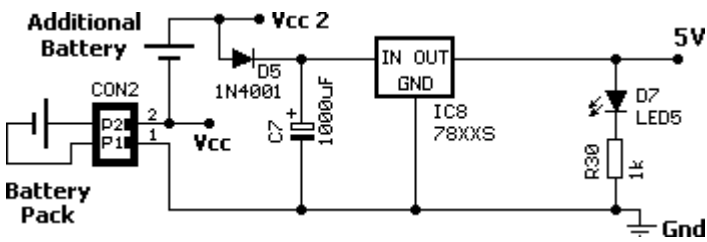


Figure 2.33. Voltage regulator

A printed circuit board is designed and manufactured for this system. Eagle Layout Editor v3.55 [15], which is a computer program for printed circuit design, is used for this process. This printed circuit board is presented in Figure 2.34.

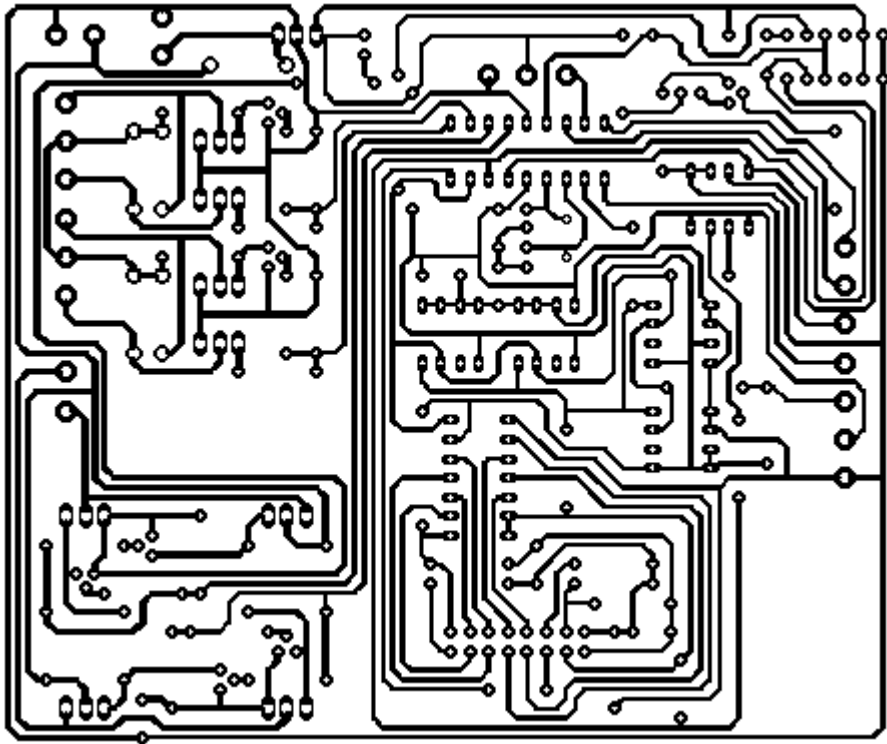


Figure 2.34. Printed circuit board

Connectors are added to the design in order to simplify the installation and cabling process. Two ports each with six pins are also added to the design for interfacing to the programming circuit for the microcontroller and the EEPROM. The layout of the components and the terminal connections of the circuit are given and the designed hardware blocks of the system are presented in Figure 2.35

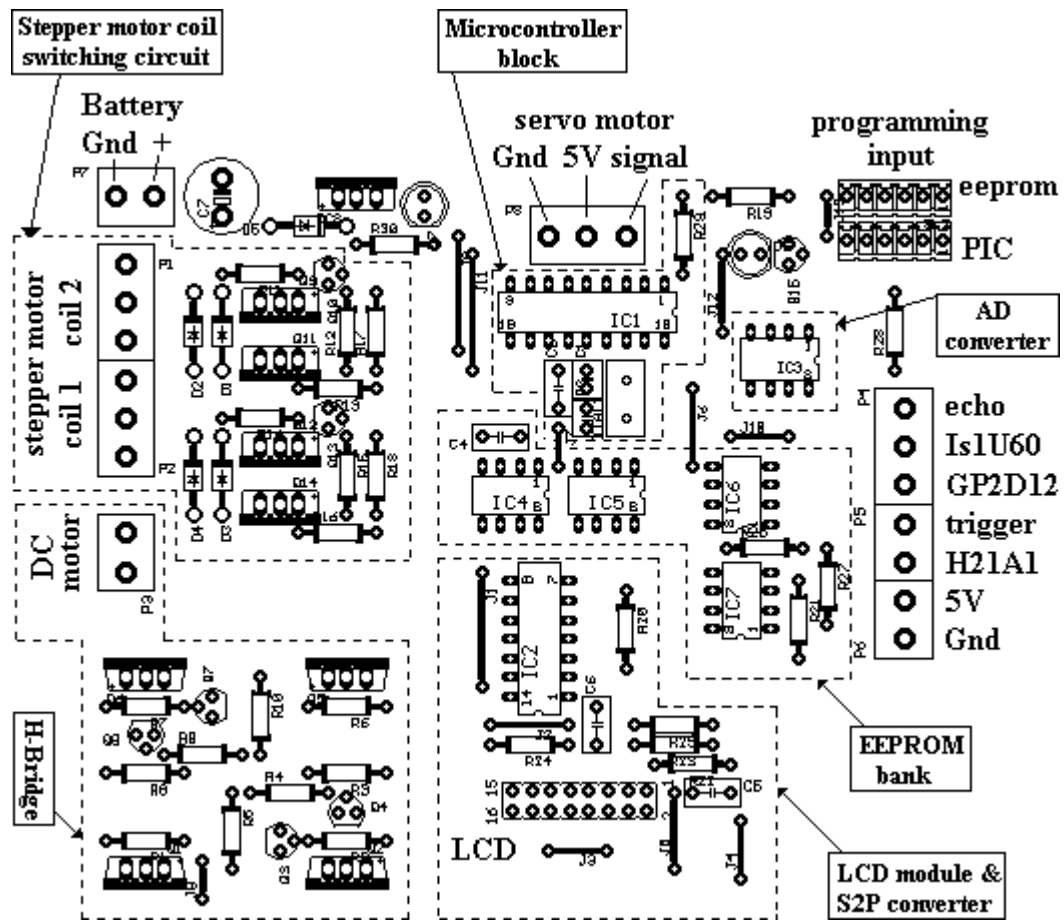


Figure 2.35. Layout of the components

A programming hardware is also developed for this system in order to download the codes for the microcontroller and the EEPROM. This circuit can either be connected to the microcontroller or the EEPROM through 6 pin ports. The input is done from the parallel port of a PC. The hexadecimal files are downloaded to the memories of the components by using a software. The power needed for the programming circuit is taken from the main circuit, so no additional power supply is needed. The programming circuit generates high programming voltage (12 V) for the microcontroller with its built in DC/DC converter. The schematic diagram of the programming circuit is presented in Figure 2.36.

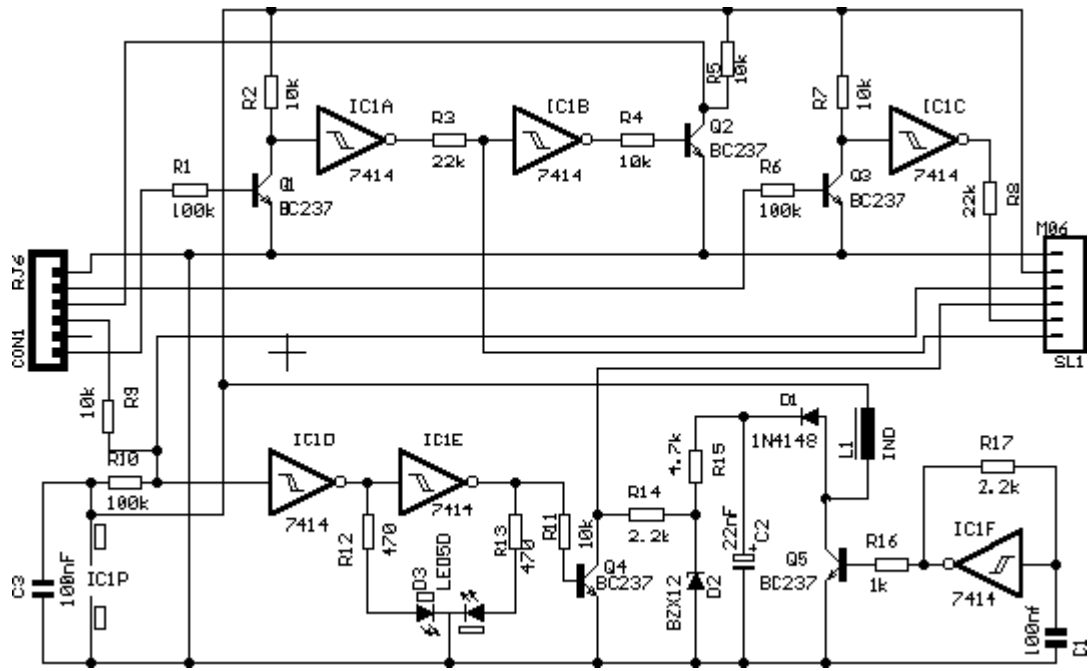


Figure 2.36. Schematic diagram of the programming circuit

The photograph of the designed printed circuit boards is presented in Figure 2.37.

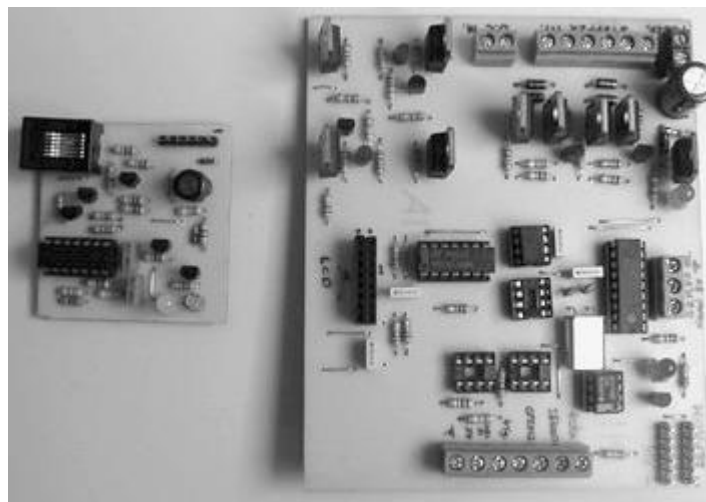


Figure 2.37. The photograph of the designed printed circuit boards

CHAPTER 3

FUZZY LOGIC CONTROL

3.1 Introduction

In this chapter, principles of fuzzy logic control will be explained briefly and a control architecture will be developed to control the parking maneuvers of a model car in a partially known environment. The characteristics of the system will be observed in a computer program that is developed for simulation purposes and in the last stage the developed control architecture will be embedded in a microcontroller to observe the characteristics in real world.

3.2 Fuzzy Theory

3.2.1 Fuzzy Logic

Fuzzy Logic is basically a multivalued logic that offers a better way of representing reality by allowing intermediate values to be defined between conventional evaluations like true/false, yes/no, black/white, etc. In fuzzy logic, a statement is true to various degrees, ranging from completely true through half-truth to completely false. By the help of fuzzy logic, linguistic notions like rather warm or pretty cold can be formulated mathematically and processed by computers allowing a more human-like way of thinking in the programming of computers. Fuzzy Logic was initiated in 1965 by Prof. Lotfi Zadeh of the University of California in Berkeley.

In conventional logic, the statement (A AND B) is true only if both A and B are individually true; otherwise, the statement (A AND B) is false. In fuzzy logic, if

the fuzzy truth values of A and B are separately known, the truth of (A AND B) together is the minimum of the truth values of A and B. A similar explanation can be done for the "OR" operator where the result is the maximum of the truth values. This kind of fuzzy logic calculation doesn't cause ambiguity when the truth values are equal to one or zero, the truth values of conventional logic. Actually this is the case in the conventional logic where the result of the "AND" operator is again the minimum of ones and zeros and the result of the "OR" operator is the maximum of the ones and zeros.

3.2.2 Fuzzy Sets

In mathematics, a set is simply a collection of things. The things can be anything; numbers, names of autos, properties etc. In the sets theory, an element either belongs or does not belong to a set, similar to the idea in logic that statements are either true or false. On the other hand a fuzzy set is one to which objects can belong to different degrees, called grades of membership. The set of acceptable temperatures for comfort may be a good example to a fuzzy set. If the temperature is 26°, it can be said that, "26° is an acceptable temperature for comfort." A truth value of 0.80 might be assigned to this statement and could be translated into set terminology as follows: "26° is a member of the set of acceptable temperatures for comfort. Then for 26° the grade of membership to the set of acceptable temperatures for comfort is 0.8. The outlines of fuzzy sets are not "crisp", but "fuzzy" or "gradual". A visual representation of this gradual set boundary is presented in Figure 3.1.

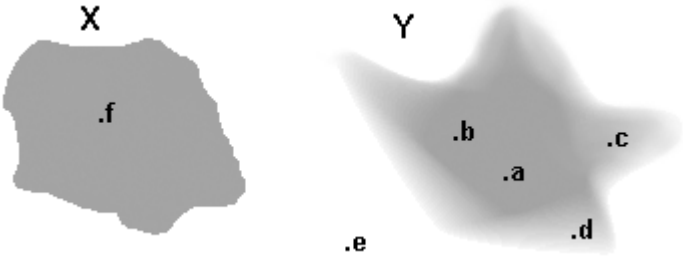


Figure 3.1. Crisp outline of an ordinary set vs. gradual outline of a fuzzy set

As it can be observed from the figure, X is an ordinary set and Y is a fuzzy set and the membership states of the elements are as follows:

f belongs to X.

e belongs neither to X nor Y.

a and b belong completely to Y.

c belongs partially to Y.

d belongs partially to Y.

3.2.3 Membership Functions

Membership functions are functions that characterize their associated fuzzy sets by associating to any input value its degree of membership to the fuzzy sets. They can be accepted as bridges between the numbers and the linguistic terms of the fuzzy sets. Membership functions operate over the range of real numbers [0.0, 1.0] and may be of type singleton, triangular, trapezoidal or the other complex curves. A membership function group that is defining the speed of a car is presented as an example in Figure 3.2.

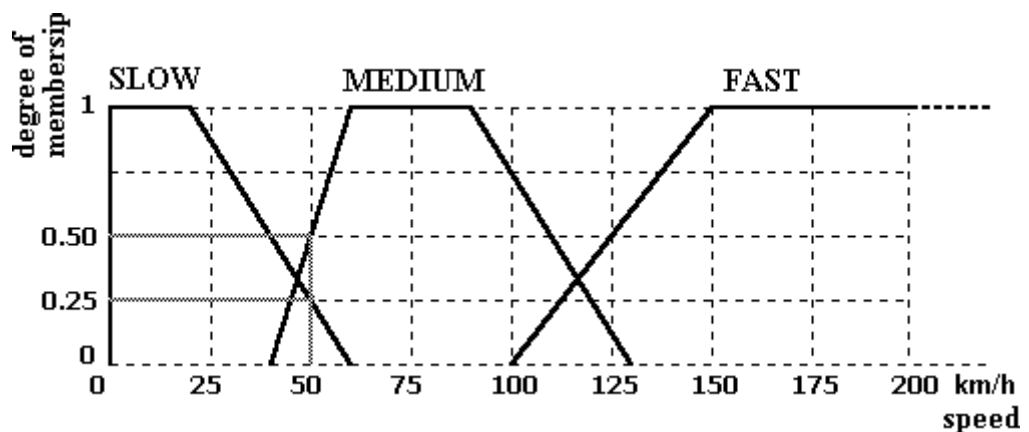


Figure 3.2. Membership functions for a fuzzy set of speed descriptors

3.2.4 Fuzzification

In Figure 3.2. it can be observed that 50 km/h is a member of the set of slow with a grade of membership of 0.25. It also belongs to the set of medium with a grade of membership of 0.50. So it can be said that membership functions are employed for transformation between numerical values and linguistic values. In fuzzy theory this kind of a transformation is named as fuzzification.

3.2.5 Rule-Based Reasoning

Fuzzy rule-based reasoning is a tool which is used to formalize and implement a human's method of reasoning and emulate a human-like way of thinking. It is generally composed of several IF-THEN rules which rely on a knowledge base derived from human expertise. The left-hand side of the rule, or the IF part, is called as the antecedent; the right-hand side, or the THEN part, is called the consequent. In a fuzzy rule-based system, the confidence with which the data match the antecedent is calculated and the consequent actions are carried out. The confidence with which these actions are taken depends on the antecedent confidence.

3.2.6 Defuzzification

The results of the rule-based reasoning are again in the form of fuzzy sets. These results are in linguistic terms and they cannot be directly used to generate the outputs of the real world. Another stage for conversion of the variables is needed. This is the defuzzification stage. Defuzzification is the reverse process of fuzzification. In other words it is a transformation from the "fuzzy world" to the "real world". Representative values that correspond to each fuzzy set member are needed for the process of defuzzifying a fuzzy set. There are some methods for the choice of representative values but the most common one is the calculation of the center of gravity of the fuzzy set. In the defuzzification process, the representative value for each fuzzy set member is multiplied by the confidence in that member, the products are summed, and the sum is divided by the sum of the confidences.

3.3 Fuzzy Control

Fuzzy control is the most important application of fuzzy theory. The principle of this type control is rather different than conventional control strategies. In fuzzy control expert knowledge is used instead of differential equations or mathematical models to describe a system. This knowledge can be expressed in a very natural way by using linguistic variables, which are described by fuzzy sets.

The employment of fuzzy control is recommendable for the following situations:

- When the process is very complex and there is no simple mathematical model.
- When the process is highly nonlinear.
- If the processing of (linguistically formulated) expert knowledge is to be performed.

The employment of fuzzy control is not a good idea for the following situations:

- When conventional control theory yields a satisfying result.
- When an easily solvable and adequate mathematical model already exists.
- When the problem is not solvable.

During parking maneuvers the logic behind the decisions of a human driver are complex and hard to model mathematically. The same is true for the model car of interest. This reason match with the recommendable situations that were given above. Also fuzzy logic based control strategies are capable of handling imprecisions and uncertainties that are prevailing in the system due to the sensory system and the nature of the system. All these facts makes the employment of a fuzzy algorithm with a rule-based reasoning reasonable.

3.4 Fuzzy Control Strategy

Overall structure of the problem and its solution should be created before developing a fuzzy control strategy. To do this, first the problem itself and the purpose of the project should be defined. This definition should be made as simply and clearly as possible. The purpose should be worded so as to make possible testing whether or not the purpose has been achieved by the final system. Next, the range of possible conclusions that might be reached in particular instances of the problem should be laid out. After defining the purpose and the range of conclusions, the data that will be needed to reach the conclusions, and thus to achieve the purpose should be considered. Defining the input and output data is the most important step of all in developing a fuzzy control strategy. If the input data is sufficient to determine the data to be output, the problem of defining the reasoning process to relate input data to proper output data by defining rules may be handled. The rules will be based on comparisons of the input data to values. Once the rules are defined the next step is tuning the system for performance.

Considering the given outline, the problem of interest may be expressed as follows: “Developing a control system that will manage to generate the necessary parking maneuvers of a model car to park vertically at an arbitrary and marked position in a closed parking bay without hitting the boundaries of the environment”. In Figure 3.3 the overview of the parking bay is presented.

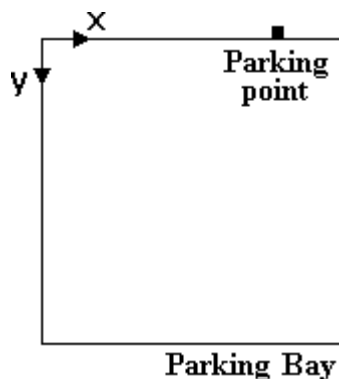


Figure 3.3. Overview of the parking bay

Size of the parking bay is fixed to 2m x 2m to simplify the design. The output of the controller is the direction of movement and the steering angle due to the nature of the problem. But determination of the input data to the controller is not as easy as the determination of the outputs. This is the most important stage of the design, because performance and complexity of the system is directly proportional with these parameters. One of the inputs is the position of the model car and the other one is the position of the marked parking point. The position of the car in the parking bay is determined relative to the car because the measurements are taken by a sensory system, which is mounted on the car chassis. The position parameters are the distance to the left side wall (x-pos.), the distance to the front wall (y-pos.), and the orientation of the car chassis relative to the front wall. These three position defining parameters are necessary and sufficient to determine the position of the car. On the other hand the position of the parking point is determined by the angle between the car axis and the marked point of the parking bay. These parameters are presented in Figure 3.4.

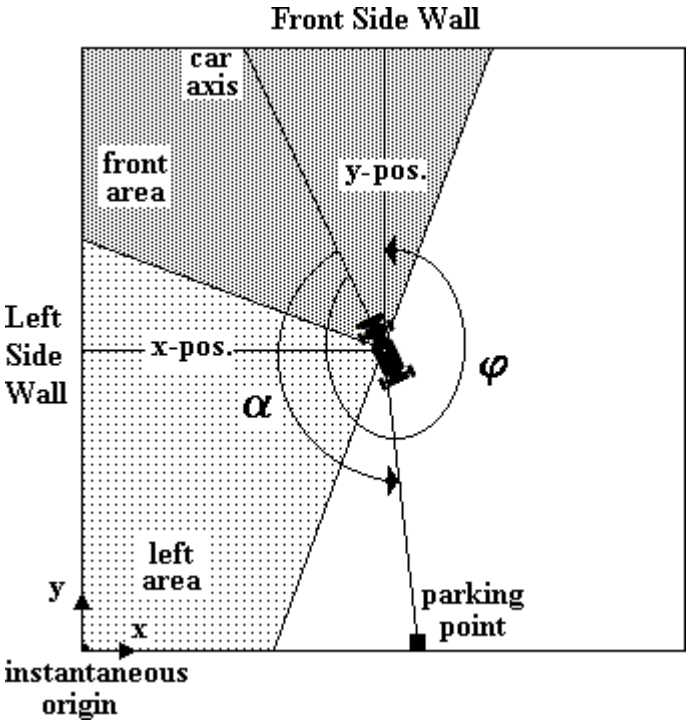


Figure 3.4. Position defining parameters

The 90^0 cones in front of the car and at the left side of the car are named as the front and left areas respectively. In these ranges, the vertical distance values with respect to the walls are defined as the x-position and y-position. The angle between the car axis and the front distance line is the orientation angle (φ), and this angle is employed to represent the orientation of the car with respect to the current front side wall. The second angular parameter in the system is the index angle (α). This angle is defined to represent the angle between the car axis and the index signal that is emitted from the parking point. As it is mentioned before, all the parameters in the system are relative to the car axis. This unavoidable fact is the nature of the system due to the way of collecting data and results some difficulties due to the varying origin with respect to the car. At any instant of collecting data during the maneuver, anyone of the four walls in the parking bay may be accepted as the front wall according to the car axis. This acceptance causes the definition of a new origin for the parking bay.

The number of the input parameters in the system is equal to the number of the input fuzzy sets that will be defined for the fuzzy control of the system. So at the beginning four fuzzy sets are defined as follows: x-position, y-position, orientation and index angle. Number of elements in each fuzzy set is an important parameter that determines the performance and designates the number of the fuzzy rules in the system. In the design, the x-position and y-position sets are made to be composed of three and four elements respectively. Since a vertical parking is aimed, allocating four elements in the y-position set increases the precision of the control. As the x-position set, three elements are assigned to the orientation set. Three elements may not seem to be enough for the orientation parameter, but due to the varying origin fact, the orientation of the car chassis is defined in $[-45^0..45^0]$ range. Beyond this range the instantaneous origin changes resulting a new front side wall so a new orientation value. As a result, narrowing of the range makes three elements sufficient for expressing this parameter. As it is mentioned before, the fourth and the last parameter in the system is the index angle. Five elements are allocated in the index angle set.

The controller output is composed of two items. These are the direction of movement and the steering angle. Among these items only steering angle output may be expressed with a fuzzy set because it is a continuous type variable. On the other hand, direction of movement is a crisp variable due to its restricted domain with two elements, forward or backward.

After the definition of the fuzzy sets in the system, all of them are presented in a tabular form in Table 3.1 with their elements.

Table 3.1. Initial fuzzy sets and their elements

x-position	y-position	orientation (ϕ)	index angle (α)	steering angle (θ)
Left	Up	Right	Vertical	Right Big
Center	Up Center	Vertical	Right Vertical	Right Small
Right	Center	Left	Right Below	Zero
	Down		Left Below	Left Small
			Left Vertical	Left Big

The number of the fuzzy rules in the system can be obtained by multiplication of the number of elements of each input fuzzy set which results 180 rules. All linguistic input variables are connected with an ‘AND’ operator. 180 rules for such a system may be accepted to be a bulky system but it is tried.

The elements of these fuzzy sets are the linguistic variables of the system and they are connected to the real numbers by membership functions. Definition of membership functions is an important issue which directly affects the characteristics of the system. By adjusting the shapes of these functions the system can either be made to handle many uncertainties with a cost of low precision or it can be made to

get high precision results with a cost of low flexibility. While defining a membership function these two options should be compromised in order to get an acceptable fuzzy system.

After all the membership functions and fuzzy rules are defined for the system which is mentioned above, a simulation is performed in the computer program. The results are seem to be not so satisfactory for a fuzzy system with 180 rules. Then another strategy is developed. It is observed that the presence of the x-position as an input variable for parking action is unnecessary. Index angle parameter is sufficient for this purpose. The x-position parameter is needed only for avoiding the walls. So reasoning process of the system is divided into two parts. One of these parts is the parking maneuver deciding part and the other one is the wall avoidance part. For the first part only three input parameters are found to be sufficient. These parameters are y-position, orientation and index angle respectively. The reduction of input parameters significantly decreases the number of the rules. This brings the opportunity of increasing the number of elements of some fuzzy sets for obtaining more precise results. After all these changes, the resulting fuzzy sets and their members for parking maneuver deciding part of the system is presented in a tabular form in Table 3.2.

Table 3.2. Final fuzzy sets and their elements

x-position	y-position	orientation (ϕ)	index angle (α)	steering angle (θ)
Any	Up	Right	Vertical	Right Big
	Up Center	Vertical	Right Vertical	Right Small
	Center	Left	Right Side	Zero
	Down		Right Below	Left Small
			Left Below	Left Big
			Left Side	
			Left Vertical	

x-position parameter still seems to be an input parameter for the parking reasoning part of the system but this is not so. It is included for the code compatibility with the previous version. By manipulating the membership functions this parameter is made to be ineffective. This configuration results 84 fuzzy rules for the parking maneuver deciding portion of the system. All the linguistic input variables are again connected with an ‘AND’ operator. Wall avoidance is performed by two if-then statements which are used to check the critical positions of the car. If the position of the car is critical from wall avoidance point of view, the execution of fuzzy parking reasoning is paused and the necessary maneuver is performed to avoid collision. If the new position is found not to be critical, fuzzy parking reasoning is resumed.

A termination criteria for fuzzy parking action is added to the controller. This is again performed by an if-then statement which is used to check the acceptable state of the car at the parking point.

This type of a reasoning performs well in the computer simulations. The membership functions of the system are presented in Figures 3.5, 3.6, 3.7, 3.8 and 3.9.

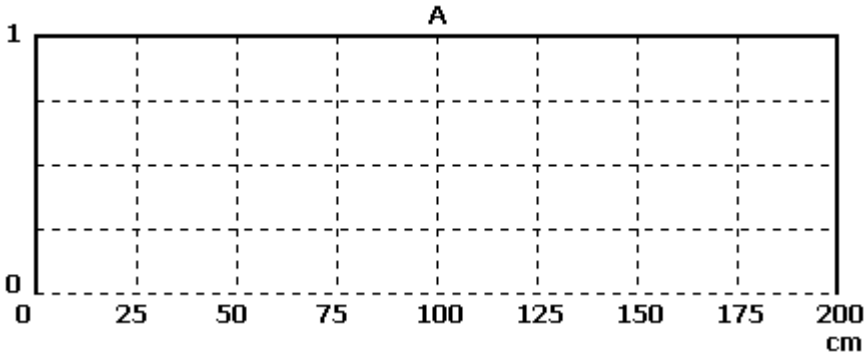


Figure 3.5. Membership function for the variable x-position

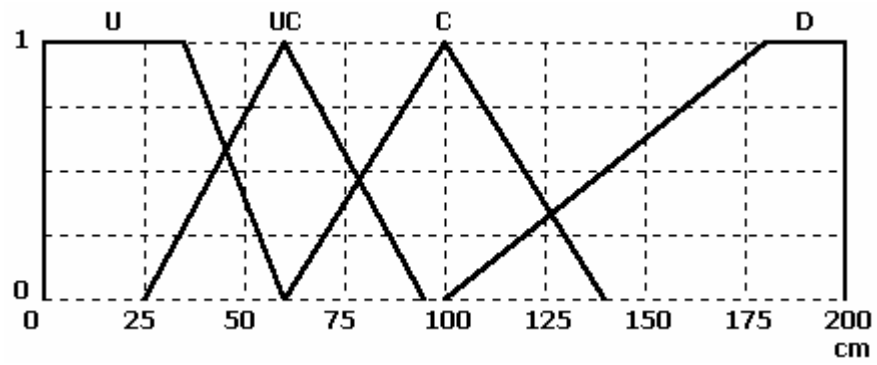


Figure 3.6. Membership functions for the variable y-position

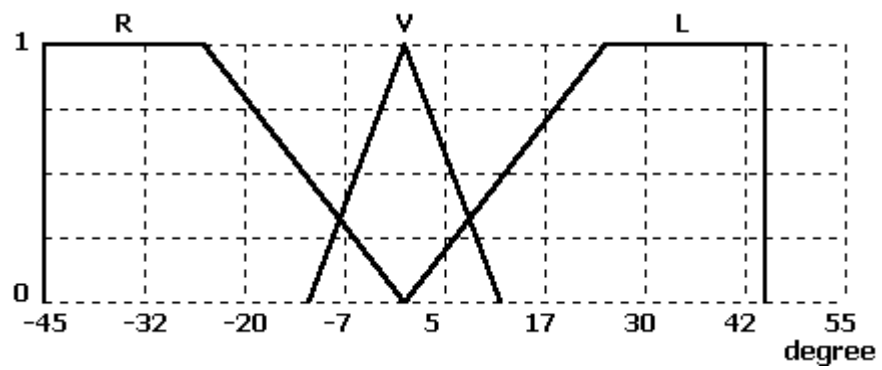


Figure 3.7. Membership functions for the variable orientation (ϕ)

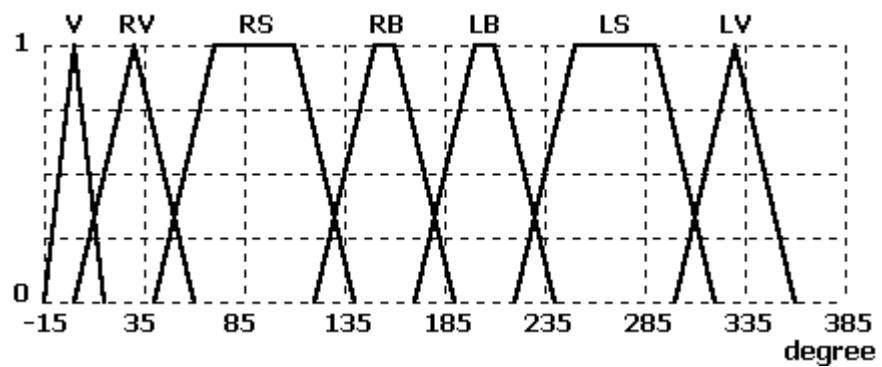


Figure 3.8. Membership functions for the variable index angle (α)

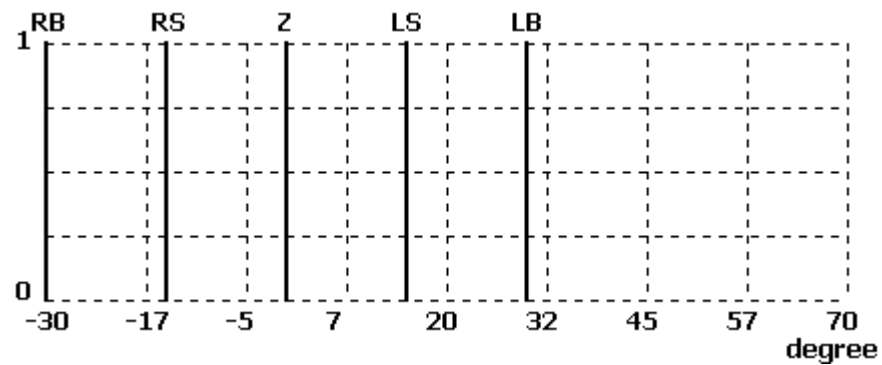


Figure 3.9. Membership functions for the variable steering angle (θ)

Membership functions of steering angle are singleton type because it is an output variable and the constant values of its functions are used for defuzzification purposes.

The ranges and resolutions of the variables in the real application are a bit different from the situation that is presented above. Angle defining input fuzzy sets are in the range of $[0..100]$ where 0 corresponds to 0° and 100 corresponds to 360° . This conversion is due to the low resolution of angular measurements resulting from the 5° cone angle limitation of the ultrasonic distance measurement sensor and index angle sensor. The range and the resolution of the angle defining output fuzzy set, steering angle, is a bit different from the other angular fuzzy sets. It is again in the range of $[0..100]$ because only 7 bits are reserved for the storage of this variable but 0 corresponds to -30° and 100 corresponds to 30° in this case. All the calculations in the real application are performed by using unsigned integer mathematics so the angular fuzzy sets are always positive in the real application. Since control characteristics including the fuzzy rules and membership function limits are downloaded to the look-up table of the controller hardware by the simulation program, the range and sign conversions are performed automatically by this software before the downloading process. All the fuzzy calculations in the simulation program are also performed with these variable resolutions and ranges in order to obtain similar results with the real controller. But the calculations related to

the vehicle kinematics are performed with real numbers in order to calculate the positions of the vehicle correctly in the simulation. There is not a range or sign conversion for distance defining membership functions. They are downloaded as they are. In the real system if a distance value that is greater than the upper limit (200 cm) is measured, this value is set to 200 cm. The system characteristics are not affected due to this assumption because the maneuvers are rough around these distance values.

Fuzzy rule maps of the system are presented in Figures 3.10, 3.11, 3.12, and 3.13. The terms which are given with capital letters are representing the elements of the fuzzy set steering angle. The lower case terms are representing the direction of motion as ‘f’ meaning forward and ‘b’ meaning backward.

XPOS = Any YPOS = Down

		α						
		V	RV	RS	RB	LB	LS	LV
ϕ	R	RS-f	LB-f	LB-f	LB-f	RB-f	RB-f	Z-f
	V	Z-f	LB-f	LB-f	Z-f	RB-f	RB-f	RB-f
	L	LS-f	Z-f	LB-f	RS-f	RB-f	RB-f	RB-f

Figure 3.10. Fuzzy rule map 1

XPOS = Any YPOS = Center

		α						
		V	RV	RS	RB	LB	LS	LV
ϕ	R	RS-f	LB-f	LB-f	RB-f	LB-b	LB-b	Z-f
	V	Z-f	LB-f	RB-b	LS-f	Z-f	LB-b	RB-f
	L	LS-f	Z-f	RB-b	LS-f	LB-f	RB-f	RS-f

Figure 3.11. Fuzzy rule map 2

XPOS = Any YPOS = Up Center

		α						
		V	RV	RS	RB	LB	LS	LV
ϕ	R	RS-f	LB-f	LB-f	LB-f	LB-b	LB-b	RS-f
	V	Z-f	LB-f	RB-b	RB-b	LB-b	LS-b	RB-f
	L	RS-f	LS-f	RB-b	RB-b	LB-f	RB-f	RB-f

Figure 3.12. Fuzzy rule map 3

XPOS = Any YPOS = Up

		α						
		V	RV	RS	RB	LB	LS	LV
ϕ	R	LS-f	LB-f	RB-b	RB-b	RB-b	LB-b	RB-f
	V	Z-f	LB-b	RB-b	RB-b	LB-b	LB-b	RB-b
	L	RB-f	LB-f	RB-b	RB-b	LB-b	LB-b	LS-b

Figure 3.13. Fuzzy rule map 4

3.5 Data Structure of the Fuzzy Engine of the Controller

An 8-bit EEPROM bank is utilized as the look-up table of the controller hardware. Its default capacity is 8 Kbytes and this value can be extended up to 64 Kbytes. This component may be defined as an array that is storing 8192 numbers where the stored numbers can vary between 0 and 255. Access to any of these numbers is performed by sending the address value of the number of concern to the component. This address value is varying between 0 and 8191, so it is a 13-bit number.

The direction of movement data and the steering data of each rule are encoded into an 8-bit number for the storage process of the rules. Only 1 bit is sufficient for the direction of movement data because this variable has two possible

values. But at least 7 bits are needed for expressing steering data because this variable is varying between 0 and 100. All of the rules in the system are encoded to 8-bit numbers with the given method so the consequent parts of the if-then rules are represented by these numbers that will be stored in the look-up table. Encoding structure of the consequent parts of the rules is presented in Figure 3.14.

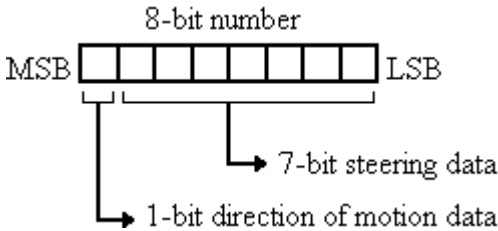


Figure 3.14. Encoding structure of the consequent parts of the rules

Since all of the linguistic variables of the system are connected to each other with an ‘AND’ operator, a similar encoding structure is applied to the antecedent parts of the if-then rules. The numbers that are obtained at the end of this encoding process are used as the address values of the encoded numbers of the consequent parts of the rules which are obtained before. 3 bits are allocated for each fuzzy set which reserves a maximum of eight elements for each fuzzy set. By default the address allocation of the look-up table hardware has a maximum value of 13 bits which is capable of defining four fuzzy sets with a cost of 12 bits. So by the combination of packs of 3-bit fuzzy sets, a 12-bit address number is encoded. By using this number, four fuzzy sets each with a maximum of eight elements can be identified. This gives the opportunity of defining a maximum of 4096 if-then rules each generated with an ‘AND’ operator. This value is a huge number but most of the time the elements of the fuzzy sets are less than eight and two or three fuzzy sets are sufficient to define a system. When a code is developed to process this look-up table data as a fuzzy engine, it takes minutes to design a completely different system. The structure of this type of encoding may be customized for different applications by changing the allocation of the bits. But the disadvantage of this action is the necessity of changing the code that will process this look-up table data

at the same time. Encoding structure of the antecedent parts of the rules is presented in Figure 3.15.

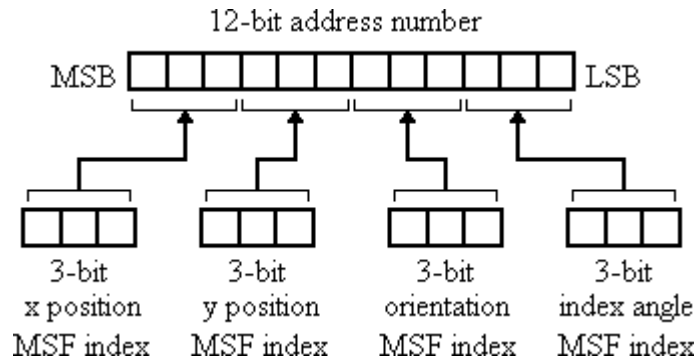


Figure 3.15. Encoding structure of the antecedent parts of the rules

A sample rule formation is presented in Figure 3.16.

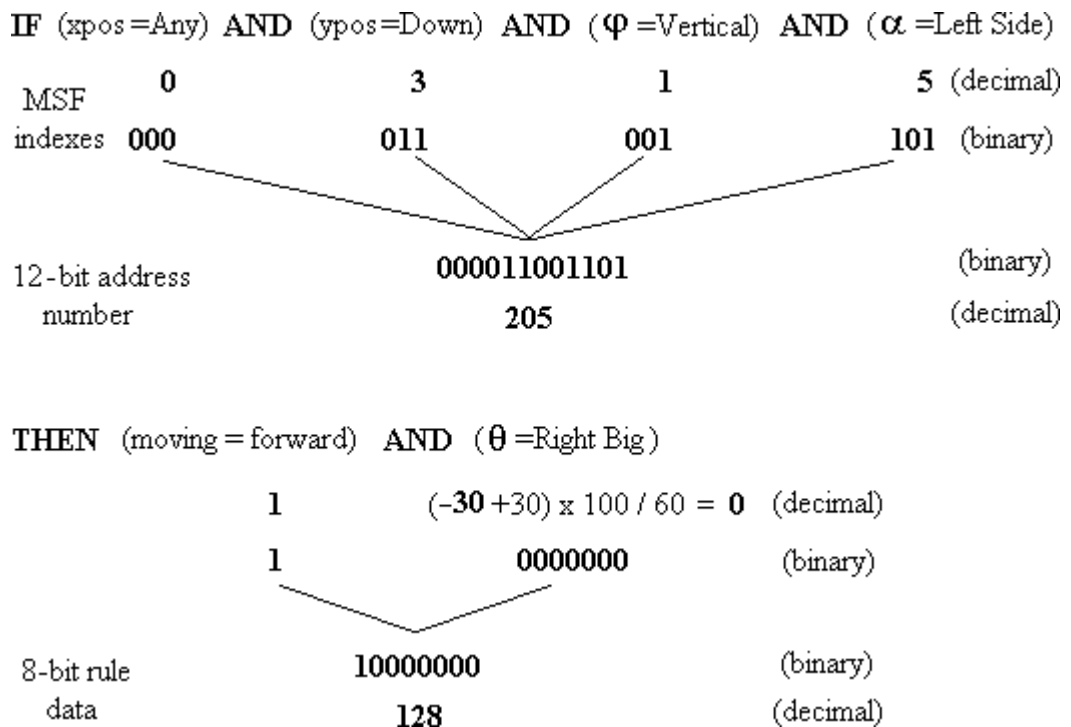


Figure 3.16. Sample rule formation

As it can be seen in Figure 3.16, two numbers are generated which are storing the encoded data of the rule. In the look-up table, 128 will be located at the address location 205. While generating the 12-bit address number, membership function indexes are used. These indexes are counted from 0 with the order that is given in Table 3.2. During the 8-bit rule data generation process, steering angle range is adjusted as it is mentioned before. -30° steering angle is transformed to 0.

The look-up table of the controller hardware is also used for storing the membership functions and a minor look-up table for one of the sensors apart from the fuzzy rules. The memory map of this component which is showing the reserved memory locations is presented in Figure 3.17.

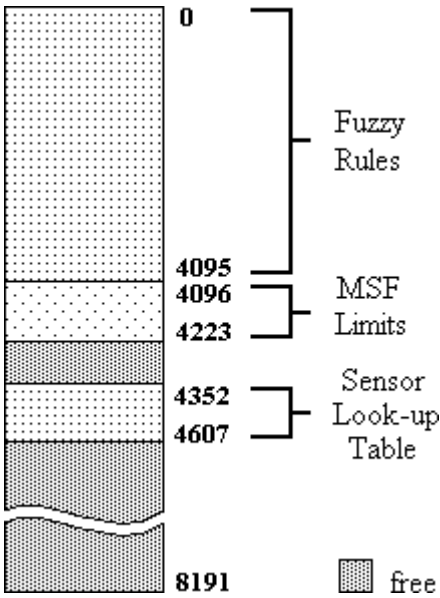


Figure 3.17. Memory map of the look-up table component

3.6 Operation of the Fuzzy Engine of the Controller

The developed code of the microcontroller is capable of processing the previously defined format of the look-up table. Block diagram representations of the fuzzification, rule application and defuzzification algorithms of the microcontroller are presented in Figure 3.18 and Figure 3.19 respectively.

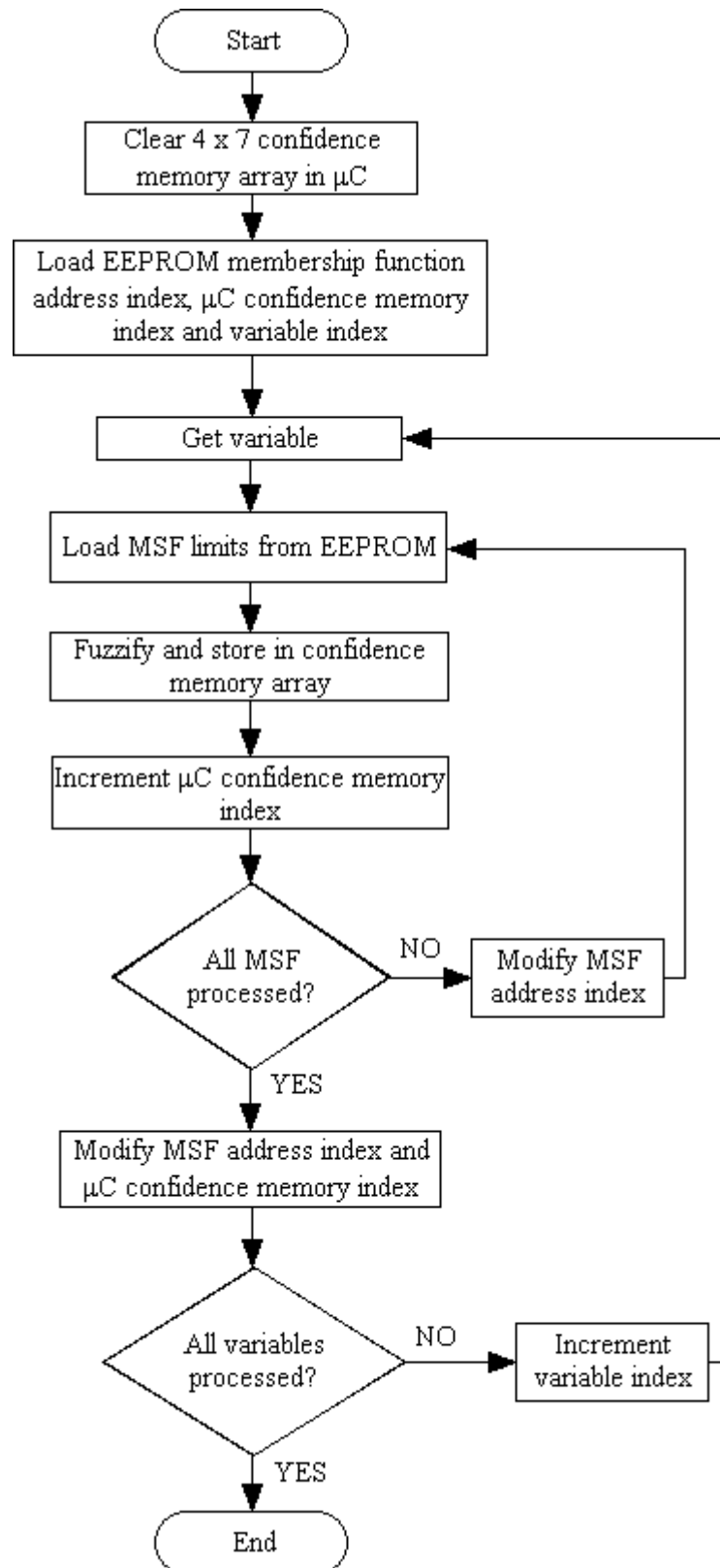


Figure 3.18. Fuzzification algorithm

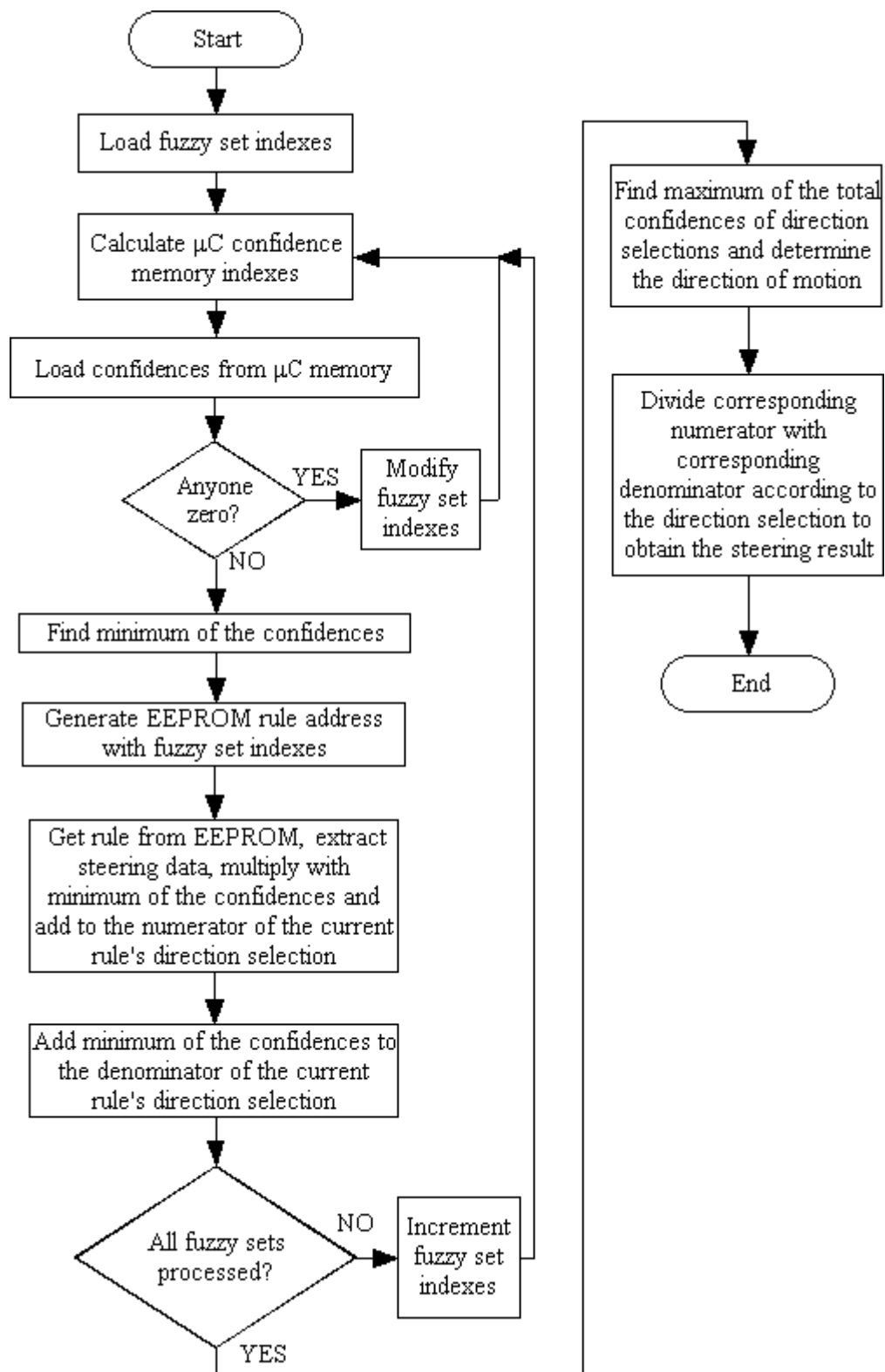


Figure 3.19. Rule application and defuzzification algorithm

Control action start with making measurements to find the position of the car. Then variables in the system are subjected to the fuzzification process. Although encoding structure of the rules permits allocation of eight members for each fuzzy set, due to the maximum number of elements in the fuzzy sets of the system, only seven fuzzy set members for each of the four fuzzy sets are supported. Generally indirect access to microcontroller memory through pointers is performed during calculations to decrease the amount of program memory requirements and to get a powerful and fast executing code. Rule application portion of the code uses the confidence levels that are prepared by the fuzzification routine. Address numbers are generated with the valid fuzzy set indexes and values at these locations of the look-up table are decoded and subjected to the defuzzification process in order to get the results. Defuzzification is transformation from linguistic space to a space of non-fuzzy, crisp control actions. The center of area method is used for the defuzzification process. Since the output fuzzy set is composed of singleton membership functions, their representative values are used as the center of area and each of them is multiplied by the confidence in that member, the products are summed, and the sum is divided by the sum of the confidences. But at the beginning of this process, the direction of motion is determined by comparing the backward and forward maneuver confidences. Then the steering information of the rules that belong to the discarded direction maneuvers are filtered and steering information is obtained by the application of defuzzification process to the remaining rules as described above. After all these calculations the results are fed to the steering servo motor and DC traction motor to generate the parking maneuver.

As it is mentioned before, position data is collected by positioning the sensors with a stepper motor. Because of the nature of collecting data from environment, data collecting phase of the control loop must be performed while there is no motion. This fact results a discrete behavior in parking. At each step the car is stopped, measurements are made, inputs are processed and outputs are performed and maintained until the next step. This control strategy is repeated until an acceptable state is obtained.

CHAPTER 4

SIMULATION AND PERFORMANCE TEST OF THE SYSTEM

4.1 Introduction

In this chapter, information related to the simulation of the system and the computer program will be given and performance tests of the system will be carried out. Performance tests are based on the final position of the model car after the self-parking cycle. Three successful parking scenarios will be presented with the position data that is obtained from the parking lot during the maneuvers and simulation results for these scenarios will also be given.

4.2 Simulation of the system

4.2.1 Kinematics of the car

A four wheeled front wheel steered car-like vehicle has complex kinematics. The route of the car is dependent on the steering angle, dimensions and speed of the car. Increasing speed increases the turning radius at a fixed steering angle for an under steer vehicle. This is due to the slip of the front wheels that causes a force for turning the car body during the maneuvers. Parking action of a car occurs at low speeds, so the effect of the speed can be ignored for the estimation of the route of the car during parking maneuvers. This kind of an approach significantly decreases the complexity of the problem and governing equations of the kinematics of the car can be expressed using simple trigonometric relations. Parameters of the simplified kinematics of the car are presented in Figure 4.1.

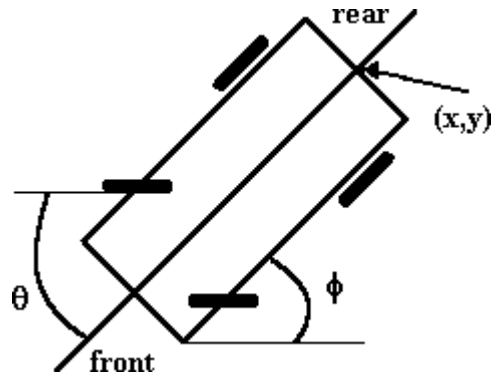


Figure 4.1. Parameters of the car

Governing equations of the kinematics of the car can be expressed as

$$\phi' = \phi + \theta \quad (4.1)$$

$$x' = x + r \cdot \cos(\phi') \quad (4.2)$$

$$y' = y - r \cdot \sin(\phi') \quad (4.3)$$

where

ϕ : Orientation of the car

θ : Steering angle

x : x-position of the car

y : y-position of the car

r : Wheelbase of the car

Equations (4.2) and (4.3) about x-position and y-position of the car are valid if the direction of motion is forward. If direction of motion is backward the new forms of these equations can be expressed as

$$x' = x - r \cdot \cos(\phi') \quad (4.2)$$

$$y^1 = y + r \cdot \sin(\phi^1) \quad (4.3)$$

4.2.2 Simulation program

By using the equations that are given above, a computer program is developed with Borland Delphi 6.0 [16]. This program is used for simulation purposes. Other facilities of the program are defining and storing all the parameters of a fuzzy control system in a user friendly manner, testing the system visually, exporting the membership functions and rule maps as image files and exporting the characteristics of the system for downloading to the controller hardware of the self-parking model car system. The program allows the user to position the car and the parking point to the desired position. The main window of the simulation program is given in Figure 4.2.

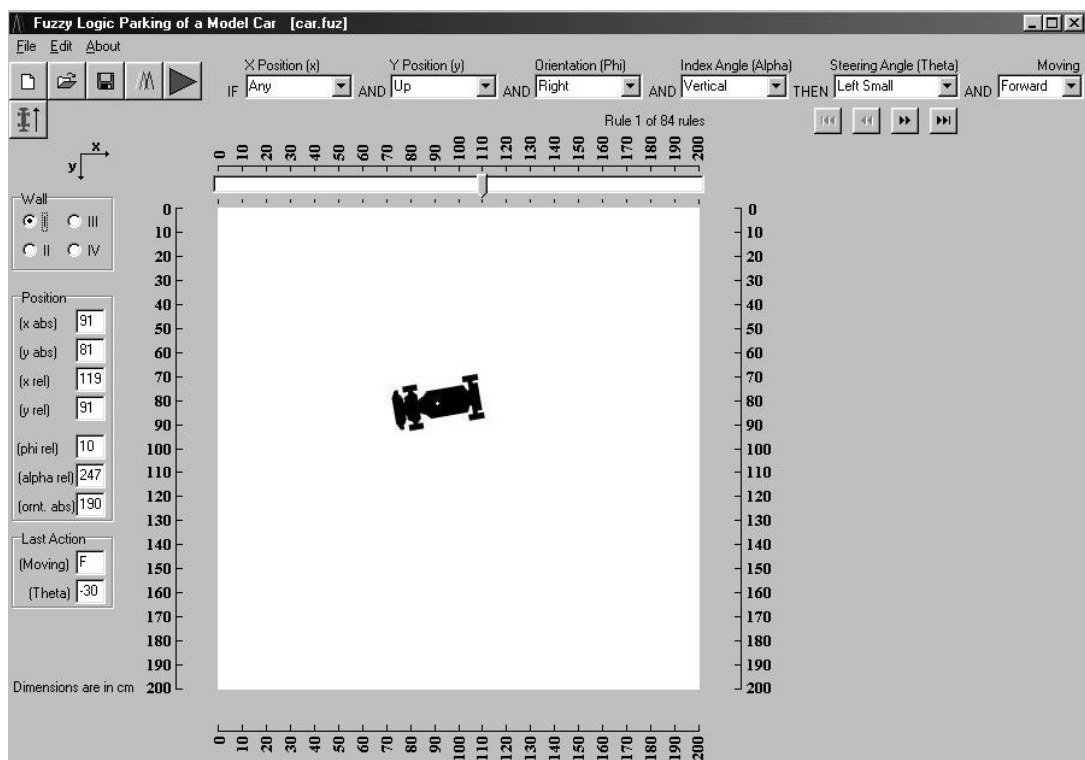


Figure 4.2. The main window of the simulation program

The program windows related to the fuzzy variable configuration, membership function definition and rule map export are presented in Figure 4.3, in Figure 4.4 and in Figure 4.5 respectively.

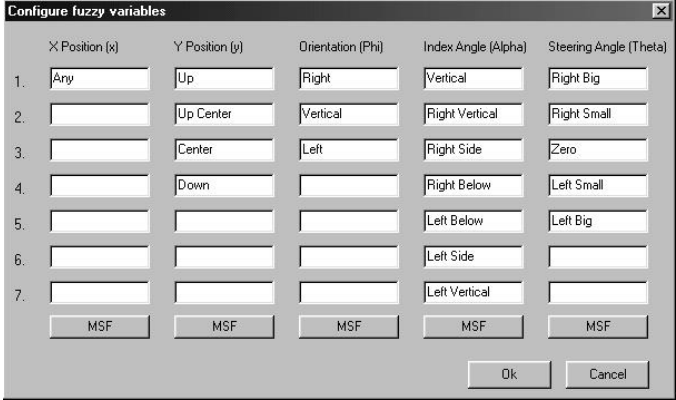


Figure 4.3. Fuzzy variable configuration window of the simulation program

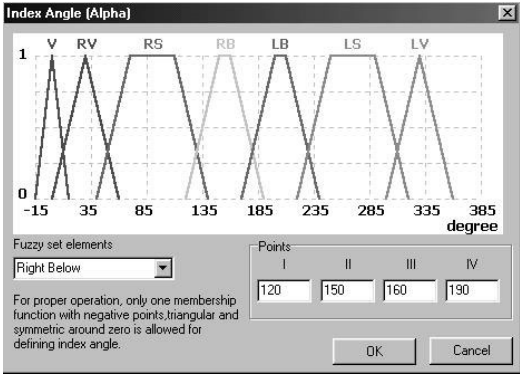


Figure 4.4. Membership function definition window of the simulation program

		α						
		V	RV	RS	RB	LB	LS	LV
R		LS-f	LB-f	RB-b	RB-b	RB-b	LB-b	RB-f
ϕ	V	Z-f	LB-b	RB-b	RB-b	LB-b	LB-b	RB-b
	L	RB-f	LB-f	RB-b	RB-b	LB-b	LB-b	LS-b

Figure 4.5. Rule map export window of the simulation program

4.3 Performance test of the system

Testing of the parking maneuvers of the system is performed in an artificial parking bay. Size of the parking bay is fixed to 2m x 2m and it is generated by closing an area with barriers that are made of cardboard. A signal generator, which is tuned to 38 kHz, is built and two infrared leds are connected to it as the IR light source for marking the parking point. The signal generator is placed at one of the walls. Three different parking points are used during the tests. The first point is 120 cm away from one side, the second one is 137 cm away from one side, the third one is 127 cm away from one side.

The controlling action of the system occurs in a cyclic manner as described before. Position data is collected from the environment and control outputs are generated and maintained for a predefined time. At the end of this time a new cycle begins with position data collection. The system is turned off at each cycle and the exact position is measured and logged. This is continued until the parking action is completed.

A termination criteria for parking maneuver generation is programmed into the controller of the model car. If the distance of the car to the wall that is in front is less than 10 cm and index angle and the orientation of the car is between -15° and 15° then the parking maneuver generation is stopped.

In the first parking scenario the model car system is placed at a point where the x-coordinate is 123 cm and the y-coordinate is 109 cm. The orientation (θ) of the car is 180° . The signal source is placed 120 cm away from the origin. The resulting positions of the simulation program and the real car during the parking maneuver according to the first scenario are presented in Figure 4.6 and in Figure 4.7 respectively. The distance between the grid points in the figures are 20 cm. Among the figures the ones that are marked with 'T' are the combination of the numbered figures and they are given to give an idea about the followed path. The results of the first scenario at the final position are also given in Table 4.1.

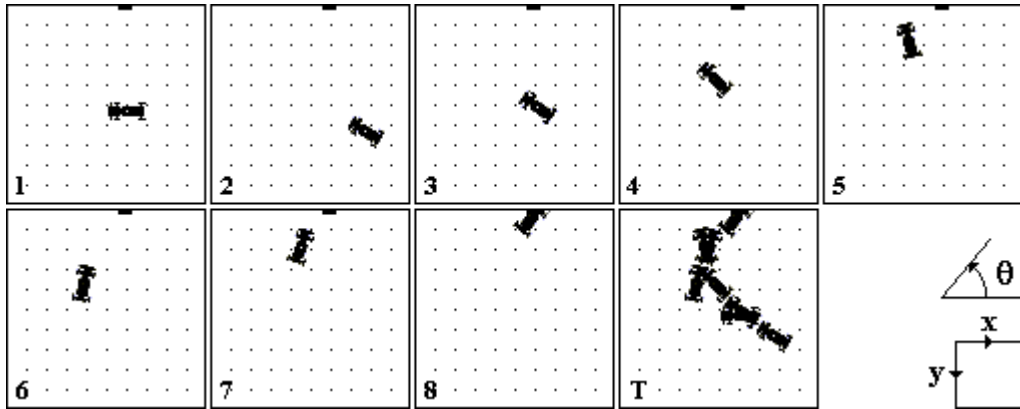


Figure 4.6. Resulting positions of the simulation according to first scenario

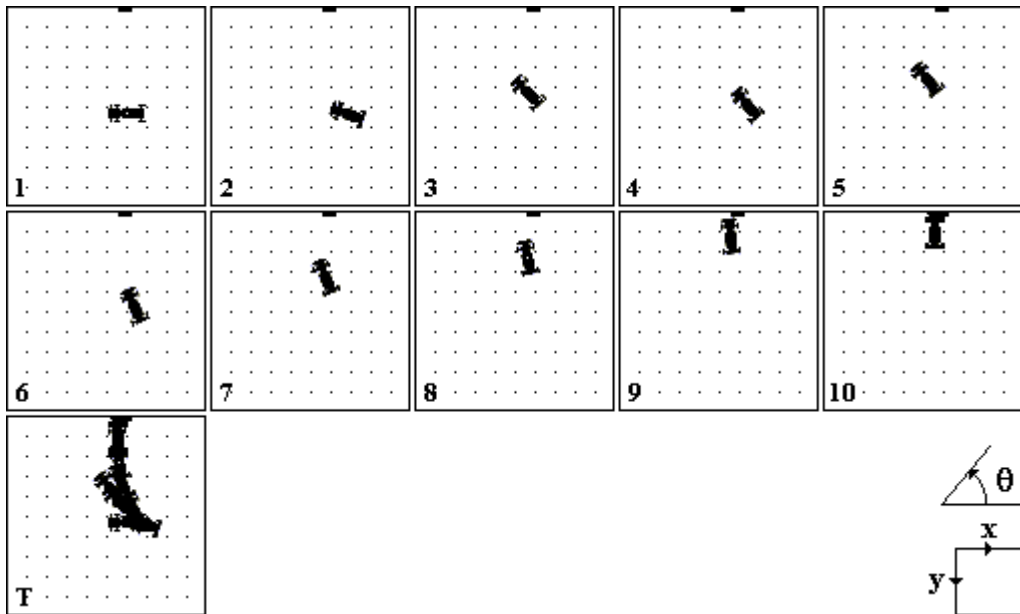


Figure 4.7. Resulting positions of the car according to first scenario

Table 4.1. Results of the first scenario at final position

Scenario 1	x-distance	y-distance	orientation
Simulation	120	10	48°
Real system	114	10	90°

The output leds of the 38 kHz signal generator are directed to different angles to generate IR light to a wide angle in order to be detected by the car at any angle with a cost of a drop in the index angle measurement precision. As previously mentioned, angular variables are in the range of [0..100]. So one full rotation of the rotary table is divided into 100 steps. Index signal detection continues 3 or 4 steps at some points in the parking bay due to the reason that is mentioned above. This also decreases the detection of the absolute position of the parking point. There is some difference between the path of the simulation result and the result of the real car. This is mainly because of the low index angle precision due to the large cone angle of the IR light emission that is mentioned above. In this system once a difference occurs between the paths, the difference increases with the following maneuvers. Paths that are similar to the real system can be obtained by manipulating the position of the parking point a little in the simulation program. These little manipulations are in the order of 10 cm and they are acceptable because of the reason that is explained above.

In the second parking scenario, the model car system is placed at a point where the x-coordinate is 67 cm and the y-coordinate is 99 cm. The orientation (θ) of the car is 234° . The signal source is placed 137 cm away from the origin. The resulting positions of the simulation program and the real car according to the second scenario are presented in Figure 4.8 and in Figure 4.9 respectively and the results at the final position are given in Table 4.2. The simulation results are obtained by placing the parking point at the nearest possible value, 140 cm, at the simulation program. The paths of the simulation and the real system are more similar in this case and both of them can be accepted to be successful.

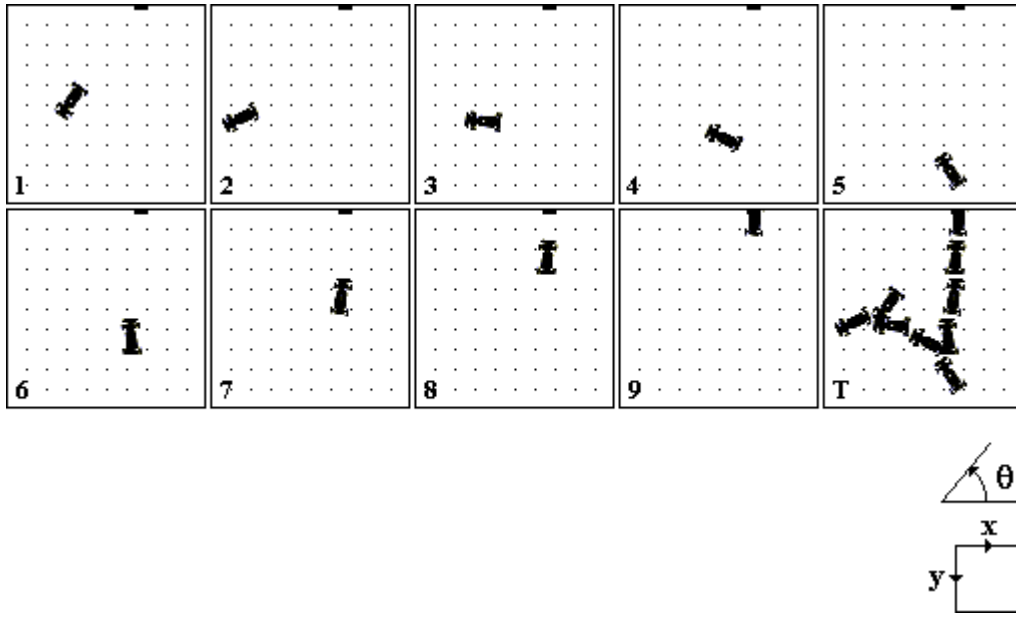


Figure 4.8. Resulting positions of the simulation according to second scenario

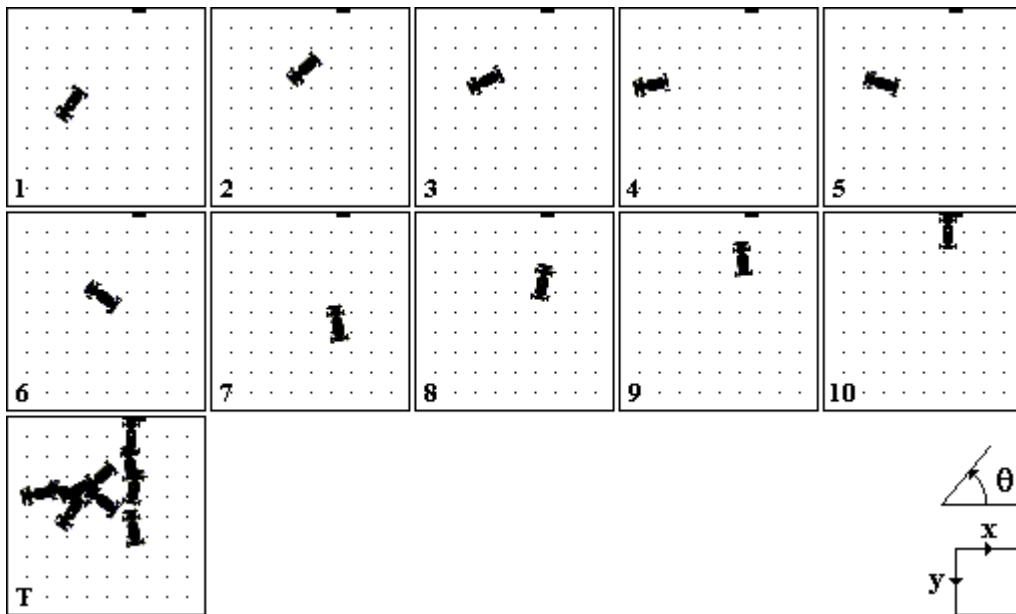


Figure 4.9. Resulting positions of the car according to second scenario

Table 4.2. Results of the second scenario at final position

Scenario 2	x-distance	y-distance	orientation
Simulation	138	10	86°
Real system	127	15	90°

In the third parking scenario the model car system is placed at a point where the x-coordinate is 172 cm and the y-coordinate is 169 cm. The orientation (θ) of the car is 270° . The signal source is placed 127 cm away from the origin. The resulting positions of the simulation program and the real car according to the third scenario are presented in Figure 4.10 and in Figure 4.11 respectively and the results at the final position are given in Table 4.3. The simulation results are obtained by placing the parking point at the nearest possible value, 130 cm, at the simulation program.

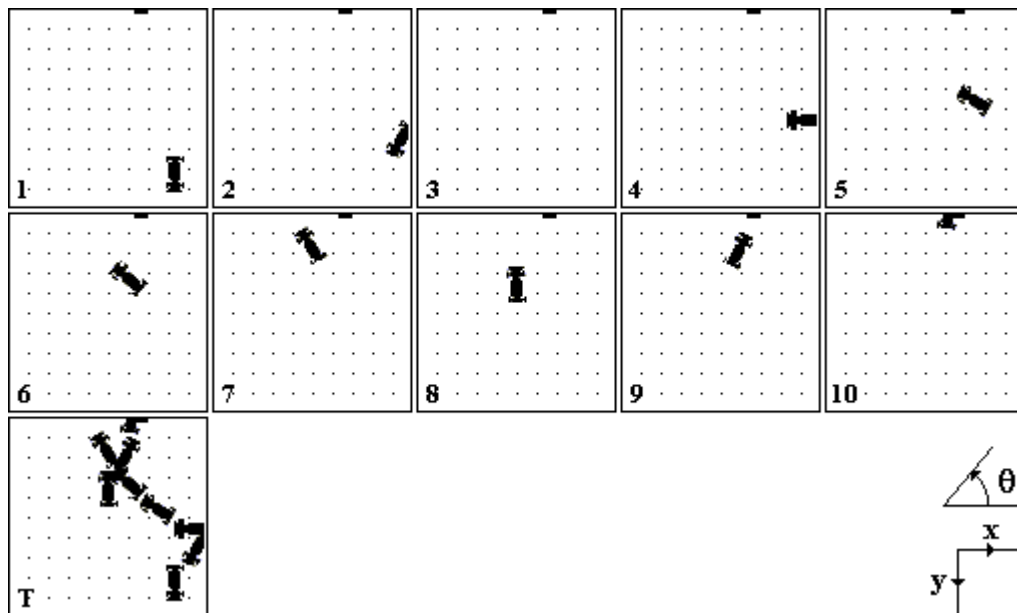


Figure 4.10. Resulting positions of the simulation according to third scenario

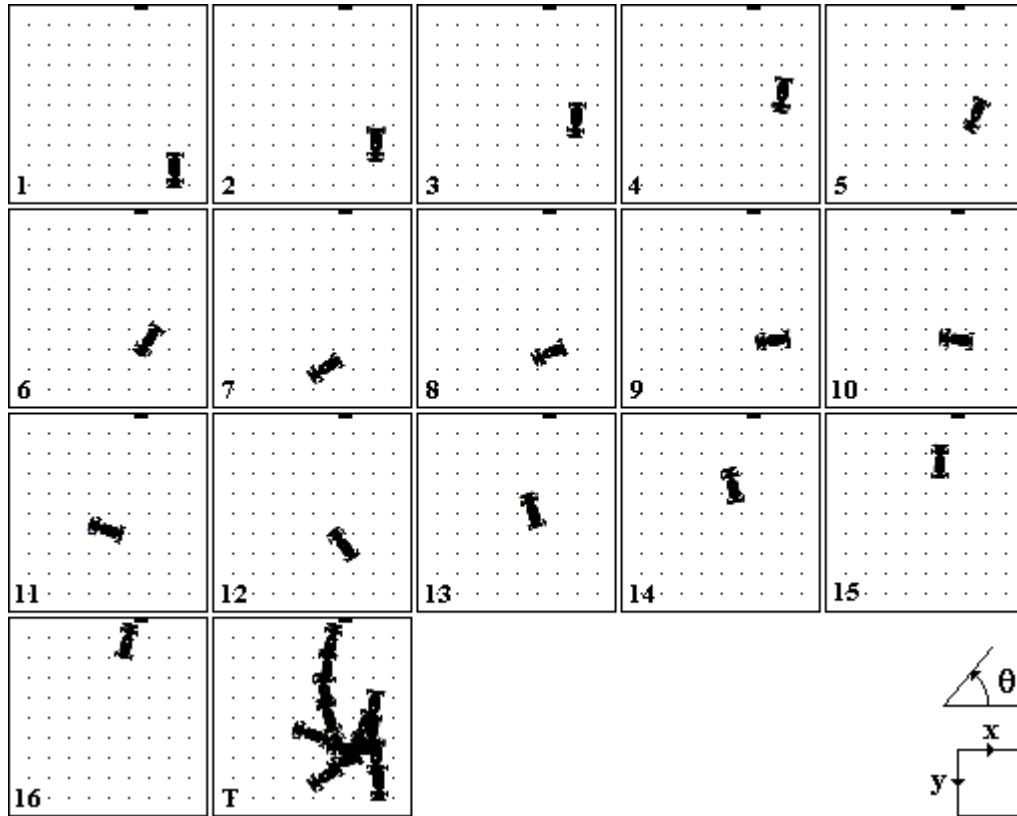


Figure 4.11. Resulting positions of the car according to third scenario

Table 4.3. Results of the third scenario at final position

Scenario 3	x-distance	y-distance	orientation
Simulation	126	0	81°
Real system	121	16	77°

When all the given results and paths are examined, the real system and the simulation program can be considered to be successful in generating the necessary parking maneuvers. The results of the simulation program and the real system are not exactly the same in the examined scenarios but they cannot be considered to be completely distinct. These differences are natural. Index angle measurement of the car is not precise enough to exactly determine the place of the parking point due to

the previously mentioned reasons. The same is also valid for the orientation measurement due to the cone angles of the distance measurement sensors. Beside these factors the position data sampling intervals of the simulation program and the real system are slightly different from each other. During maneuvers, the real system measures the distance at the direction of motion continuously to prevent collisions and may change the data sampling interval due to a sudden stop. Direction of motion variable is a crisp variable and it may have two values. The fuzzy system generates this output by comparing the grade of membership values. The grade of membership values of backward and forward maneuvers may be slightly different from each other at some point and for this point the controller selects the one with a higher grade and removes the ambiguity. But at a neighboring point this selection may change due to the slight difference of the grades. The selection of one of these two points for position data sampling is dependent on the time instant of the stopping action. This selection is important due to the direction of motion difference and affects the rest of the maneuver path. All these factors are the possible reasons of the path variations between the real system and the simulation.

During the studies it is observed that the system performance is not satisfactory for the points that are near to the parking wall but away from the parking point. An example is given in Figure 4.12.

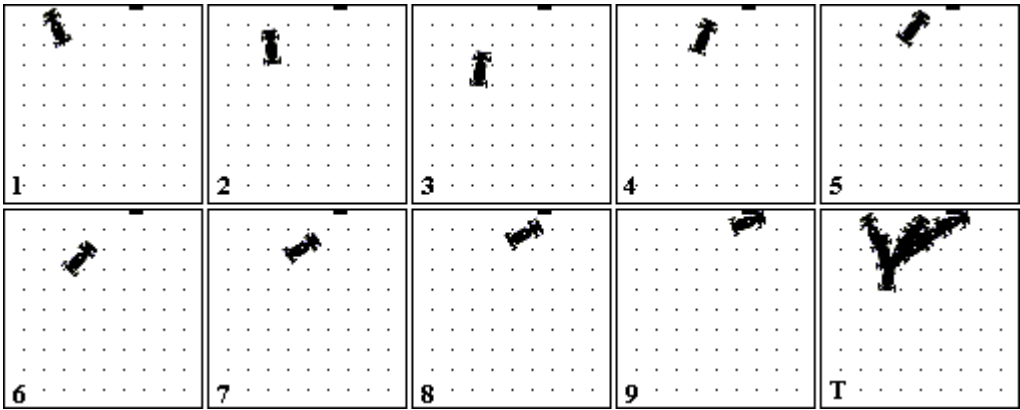


Figure 4.12. Unsatisfactory parking action

When Figure 4.12 is examined it can be said that for a successful parking action the backward maneuver of the first three steps should be continued for a while to obtain a wider maneuver area. This kind of characteristic can be added to the system by adding more backward maneuver rules to the system. Although this addition improves the characteristics at some points, an increase in the number of backward maneuver rules causes oscillatory back and forward motions and results more and more dead points.

The outputs of the system are generated according to the current state of the system with this kind of fuzzy logic type control strategy. In other words the system is not capable of foreseeing the future actions that are necessary or possible like the chess playing computer programs. Its reasoning process takes only the current state into consideration. If a path planning or estimating capability may be inserted into the system by applying other control strategies, this kind of maneuvers may be handled better.

4.4 Analysis of the fuzzy control system

4.4.1 Completeness of the control rules

A fuzzy control system that is able to generate control output for any input state is considered as complete. All the fuzzy controllers studied experimentally should satisfy the condition of completeness. During the design stage if the determined linguistic fuzzy set members cover all the input domain by interfering each other and all the possible rules are defined, the completeness of the system is evident. This is valid for the fuzzy control system of the model car. All the input domain is covered by manipulating the membership functions and all the possible rule combinations are defined without a gap. A menu item is added to the simulation program to export all the output values of the controller to a file with definable increments of the input domain. When the exported file is examined, it is observed that an output value is generated for every input value by the controller. The exported data set is four dimensional and it is composed of input values as y-

position, index angle, orientation and output value as steering angle. It is impossible to visualize this four dimensional data set with a single surface plot so two sample wireframe surface plots are presented in Figure 4.13 and in Figure 4.14 for y-position is fixed to 80 cm and 140 cm respectively.

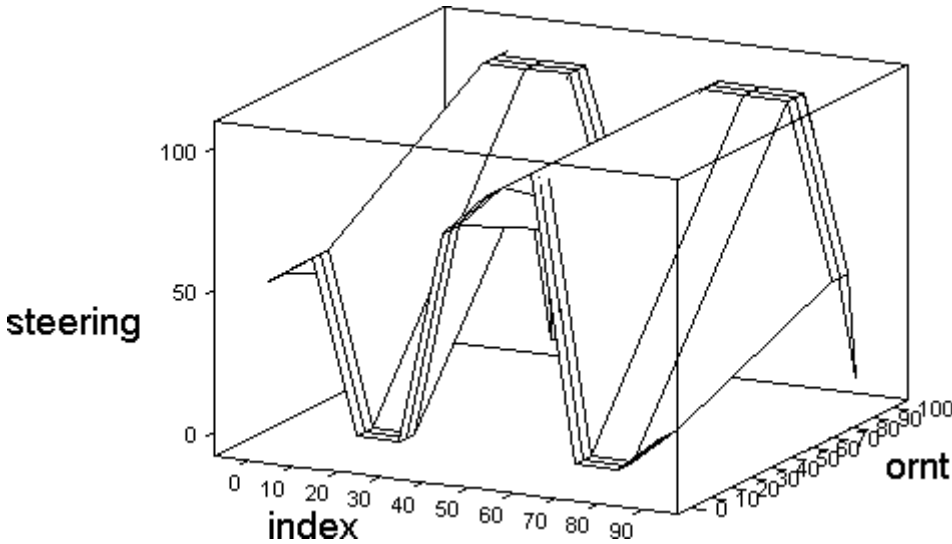


Figure 4.13. Output of the controller for y-position is fixed to 80 cm

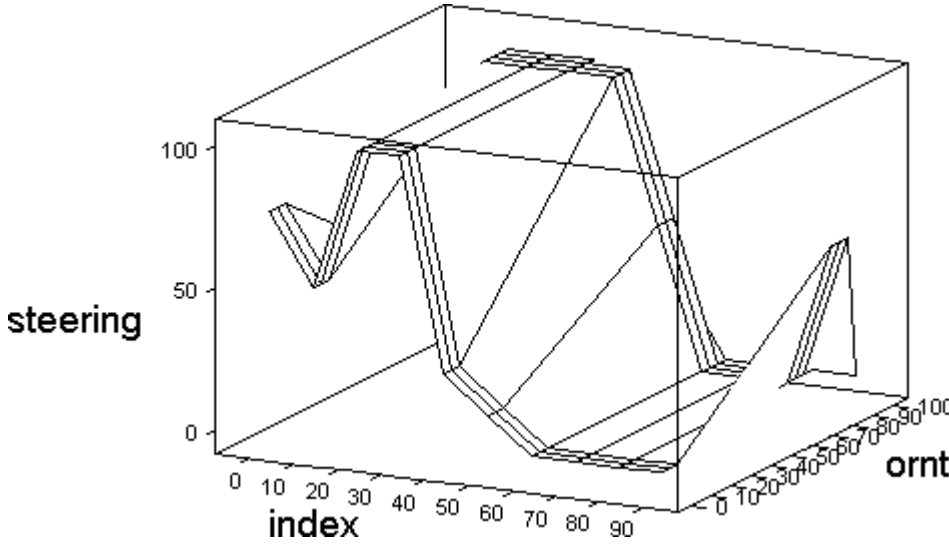


Figure 4.14. Output of the controller for y-position is fixed to 140 cm

4.4.2 Consistency of the control rules

Consistency of the control rules is an important issue in the design of fuzzy controllers. If the derivation of fuzzy control rules is based on the human operator experience, the rules may be subjected to different performance criteria. In practice, it is important to check the consistency of fuzzy control rules in order to minimize the possibility of contradiction [17]. Where a set of control rules is available, inconsistency is evident if, for a given input of the controller, the resulting fuzzy set of control is multimodal. This occurs when there are two control rules with almost the same state (condition part) and diverse actions are suggested [18]. When there is inconsistency between the rules, the control rules should be studied to get a deeper insight into their interrelationships and the main contradictory control rules should be tried to be eliminated or replaced.

Consistency between the control rules is measured by using an incidence index. This is a non-negative number representing the inconsistency level between two rules. In the fuzzy controller of the self-parking model car system there are 84 fuzzy rules as previously mentioned. All of the rules are compared in pairs and incidence index values are obtained. The result is a symmetrical [84 x 84] matrix storing the incidence index values of the rule pairs. This matrix is generated by the simulation program with a dedicated menu item under the file menu. First of all the ranges of the input variables are scaled to the interval [0,1]. Then for all of the rules, the center of gravity of the 3 dimensional truth value matrix for the condition part of the rule is calculated. The center of gravity values of input truth value matrices for all of the rules are stored for future use. Then the range of the output variables are scaled to the interval [0,1] and the center of gravity of the truth value vector for all possible output values are calculated and stored. After these calculations all possible rule pairs are determined and the absolute differences between the input variable center of gravity values and the absolute differences between the corresponding output variable center of gravity values for the rule pairs are found. The absolute difference between the input variable center of gravity values of the rule pair represents the distance between the input states of these rules and the absolute

difference between the output variable center of gravity values of the rule pair represents the distance between the corresponding outputs of these rules. The absolute difference of these two numbers is the incidence index number and it is a measure of inconsistency. The higher the number, the higher the inconsistency between the rule pair. When the 3 dimensional truth value matrices for the condition parts of the rules are examined, it is observed that the longest distance in these matrices can be the diagonal distance which equals to approximately 1.7 for a cubic matrix each side with 1 unit. So, it may be expressed that the maximum value of incidence index value, so the inconsistency, can be 1.7 in this study. The obtained symmetrical incidence matrix is a huge matrix, so to give an idea, in Table 4.4 and in Table 4.5 two portions of the matrix that is presenting the inconsistency levels between the rules of the system is given. The largest inconsistency index in the overall matrix is found to be 1.28 and it is between rule 64 and rule 21. This number can be observed in Table 4.5. When all of the matrix is considered a threshold level around 1 results an almost completely consistent system.

Table 4.4. Portion 1 of the symmetrical incidence matrix

RULE #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0	0,15	0	0,18	0,32	0	0,15	0,06	0,43	0,15	0,28	0,1	0,06	0,7	0,14	0,37
2		0	0,15	0,33	0,47	0,35	0,2	0,18	0,7	0,34	0,45	0,44	0,28	0,85	0,38	0,6
3			0	0,18	0,32	0,5	0,35	0,1	0,66	0,31	0,36	0,56	0,41	0,72	0,34	0,63
4				0	0,14	0,68	0,53	0,02	0,56	0,35	0,3	0,67	0,57	0,55	0,26	0,68
5					0	0,82	0,67	0,14	0,45	0,43	0,33	0,7	0,65	0,44	0,17	0,76
6						0	0,15	0,31	0,72	0,41	0,56	0,36	0,31	0,66	0,97	0,11
7							0	0,45	0,85	0,28	0,44	0,45	0,34	0,7	1,09	0
8								0	0,4	0,25	0,07	0,07	0,25	0,4	0,19	0,18
9									0	0,85	0,67	0,47	0,65	0,2	0,32	0,7
10										0	0,18	0,68	0,5	0,65	0,6	0,34
11											0	0,86	0,68	0,47	0,47	0,45
12												0	0,18	0,67	0,65	0,44
13													0	0,85	0,81	0,28
14														0	0,05	0,85
15															0	0,9
16																0

Table 4.5. Portion 2 of the symmetrical incidence matrix

RULE #	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75
15	0,18	0,33	0,84	0,72	0,67	0,09	0,05	0	1,06	1,19	0,78	0,26	0,25	0,2	0,36	0,93
16	0,25	0,59	0,26	0,13	0,16	0,9	0,92	0,95	0	0,12	0,7	0,26	0,74	0,77	0,3	0,13
17	0,16	0,48	0,38	0	0,2	0,92	0,92	0,92	0,05	0,05	0,62	0,3	0,76	0,76	0,26	0,2
18	0,11	0,39	0,52	0,16	0,25	0,95	0,92	0,89	0,1	0,04	0,51	0,36	0,81	0,77	0,23	0,26
19	0,36	0,64	0,41	0,24	0,82	0,01	0,04	0,1	0,89	0,92	0,45	0,44	0,13	0,19	0,24	0,73
20	0,27	0,59	0,37	0,15	0,94	0,12	0,05	0,05	0,92	0,92	0,42	0,57	0,01	0,09	0,3	0,76
21	0,09	0,25	0,14	0,36	1,28	0,45	0,37	0,25	0,7	0,67	0,65	0,92	0,34	0,24	0,62	0,55
22	0,25	0,08	0,72	1,09	0,5	0,25	0,19	0,1	0,49	0,65	0,78	0,34	0,16	0,11	0,47	0,55
23	0,45	0,77	0,1	0,26	0,24	0,49	0,52	0,59	0,33	0,18	0,44	0,09	0,57	0,6	0,16	0,27
24	0,39	0,69	0,2	0,15	0,19	0,51	0,5	0,52	0,43	0,29	0,31	0,14	0,6	0,59	0,1	0,35
25	0,36	0,62	0,31	0,01	0,08	0,6	0,53	0,48	0,5	0,41	0,17	0,23	0,67	0,61	0,06	0,42
26	0,13	0,39	0,64	0,45	0,5	0,33	0,41	0,5	0,48	0,53	0,1	0,31	0,26	0,34	0,08	0,56
27	0,06	0,36	0,62	0,38	0,65	0,19	0,29	0,43	0,52	0,5	0,01	0,45	0,13	0,23	0,15	0,6
28	0,27	0,05	0,38	0,61	1,03	0,19	0,07	0,08	0,34	0,27	0,24	0,82	0,23	0,12	0,48	0,41
29	0,3	0,16	0,33	0,71	0,33	0,08	0,14	0,21	0,3	0,45	1,07	0,51	0	0,07	0,65	0,24
30	0,23	0,58	0,26	0,12	0,16	0,57	0,6	0,66	0,27	0,13	0,48	0,02	0,49	0,53	0,09	0,33

Rule 64 of the system is modified from Right Small forward to Right Big forward and incidence matrix is recalculated. A part of the new matrix is given in Table 4.6.

Table 4.6. A part of recalculated symmetrical incidence matrix

RULE #	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75
15	0,18	0,33	0,84	0,72	0,92	0,09	0,05	0	1,06	1,19	0,78	0,26	0,25	0,2	0,36	0,93
16	0,25	0,59	0,26	0,13	0,09	0,9	0,92	0,95	0	0,12	0,7	0,26	0,74	0,77	0,3	0,13
17	0,16	0,48	0,38	0	0,05	0,92	0,92	0,92	0,05	0,05	0,62	0,3	0,76	0,76	0,26	0,2
18	0,11	0,39	0,52	0,16	0	0,95	0,92	0,89	0,1	0,04	0,51	0,36	0,81	0,77	0,23	0,26
19	0,36	0,64	0,41	0,24	1,07	0,01	0,04	0,1	0,89	0,92	0,45	0,44	0,13	0,19	0,24	0,73
20	0,27	0,59	0,37	0,15	1,19	0,12	0,05	0,05	0,92	0,92	0,42	0,57	0,01	0,09	0,3	0,76
21	0,09	0,25	0,14	0,36	1,03	0,45	0,37	0,25	0,7	0,67	0,65	0,92	0,34	0,24	0,62	0,55
22	0,25	0,08	0,72	1,09	0,25	0,25	0,19	0,1	0,49	0,65	0,78	0,34	0,16	0,11	0,47	0,55
23	0,45	0,77	0,1	0,26	0,49	0,49	0,52	0,59	0,33	0,18	0,44	0,09	0,57	0,6	0,16	0,27
24	0,39	0,69	0,2	0,15	0,44	0,51	0,5	0,52	0,43	0,29	0,31	0,14	0,6	0,59	0,1	0,35
25	0,36	0,62	0,31	0,01	0,33	0,6	0,53	0,48	0,5	0,41	0,17	0,23	0,67	0,61	0,06	0,42
26	0,13	0,39	0,64	0,45	0,75	0,33	0,41	0,5	0,48	0,53	0,1	0,31	0,26	0,34	0,08	0,56
27	0,06	0,36	0,62	0,38	0,9	0,19	0,29	0,43	0,52	0,5	0,01	0,45	0,13	0,23	0,15	0,6
28	0,27	0,05	0,38	0,61	0,78	0,19	0,07	0,08	0,34	0,27	0,24	0,82	0,23	0,12	0,48	0,41
29	0,3	0,16	0,33	0,71	0,08	0,08	0,14	0,21	0,3	0,45	1,07	0,51	0	0,07	0,65	0,24
30	0,23	0,58	0,26	0,12	0,41	0,57	0,6	0,66	0,27	0,13	0,48	0,02	0,49	0,53	0,09	0,33

In this matrix the largest inconsistency index in the overall matrix is found to be 1.19 and now it is between rule 64 and rule 20. So an improvement is obtained. Actually the change in the rule base of the system results a better performance in the simulation. But further improvement trials to decrease local inconsistencies result local decreases with a cost of increase of inconsistency levels of other rules. Also these attempts generally affect the parking behavior of the simulation inversely. When the acceptable self-parking performance of the model car itself is considered, the control rules of this system should be studied as a different study to get a deeper insight into their interrelationships, for more improvement in the consistency characteristics of the system.

CHAPTER 5

DISCUSSION AND CONCLUSIONS

5.1 Outline and Discussion

The design, construction and performance testing of a vehicle system that has car-like kinematics and an embedded fuzzy controller for this vehicle that will manage self-parking action have been considered within the scope of this thesis study. Vertical parking at a signed point in a parking bay is aimed and performed.

At the beginning of the study, a literature survey is performed and the types of sensors and control methods of similar studies are explored. Employment of a fuzzy controller is decided considering the nature of the problem. The required sensors for interfacing to the environment are selected and the application platform is determined with the selection of the microcontroller. A controller hardware is designed, built and programmed to collect data from the sensors, apply fuzzy control to the system and generate the outputs that are necessary for the parking action. Fuzzy control parameters are separated from the source code of the microcontroller and a fuzzy engine code that has the capability of handling a general fuzzy system with different number of fuzzy sets and members is developed. A flexible system that can be modified easily after the design process is obtained with this strategy.

A visual computer program with a user-friendly interface is developed to simplify the design, modification and simulation of the fuzzy system. The program is designed to be compatible with the fuzzy control hardware by the resolution of the input data and the calculations of fuzzy mathematics. So 8-bit arithmetic is used in the computer program during the fuzzy calculations as the controller hardware.

However the calculations related to the kinematics of the car are performed with floating mathematics during the simulation process. The computer program is designed to be a user-friendly development environment. The system parameters including the number of fuzzy sets and set members, membership functions and the rules are made to be defined and modified easily. All these parameters can be exported by the program for presentation purposes. After an acceptable fuzzy system is obtained in the simulations, all the system characteristics can be exported in a file that is to be downloaded to the EEPROM of the controller hardware. It takes a few seconds to transfer the characteristics of the designed fuzzy control system to the hardware of the real system.

The performance tests of the system are performed in an artificial parking bay which is built with barriers that are made of cardboard. The dimensions of the testing area are 2 m x 2m. Three scenarios for the parking action of the car is tried. The position of the car is determined after each maneuver and the results are logged. The position data that is obtained during these scenarios is visualized by the help of the computer program. All of the scenarios are also tested in the simulation program and a comparison is performed.

5.2 Conclusions

The simulations and the experimental studies in the field show that the system can be accepted to be successful for many cases except some dead points. It is seen that generally the paths of the real system and the simulation are slightly different from each other but there are also similar points between them.

The experimental results show that the parking behavior of the system is sometimes similar to the parking behavior of a human driver. However, when the dead points and the incapability of the sensory system are considered, the system cannot be replaced with the human driver.

The developed vehicle system is a good platform for researches and studies related to this field. Other control strategies should be tried to obtain better performance.

5.3 Future Recommendations

One of the most important developments about the system is modifying the sensory system for more precise angular measurements as the orientation of the car and the index signal. Excluding this one, there are two approaches for the future work about this thesis study. First one is about the car and second one is about the developed fuzzy logic control architecture.

The control type of the system may be changed to handle path planning and estimating processes. A control strategy based on neural networks or artificial intelligence may be tried and performances may be compared with the fuzzy control strategy. Parallel parking between two obstacles may also be tried with this system as another approach. Another alternative study is developing a learning system that is generating the rules by trial and error.

Embedded control systems are everywhere around us in our lives. There is an increasing trend of using fuzzy type control in such devices like fuel injection systems, engine control units, automatic gearbox controllers, washing machines, gas heaters, etc. In all of these devices tiny processors are employed. There are some commercial development tools in the market for developing fuzzy control systems and made them to operate on these tiny processors. The controller hardware and the computer program that is developed in the scope of this thesis study may be converted into a development platform with some modifications and it may be made to be a good and cheap alternative for the expensive products of the market. It may be in the form of a fuzzy add-on unit with two or three interfacing pins with a serial protocol and may be used with the common high level programming language using control hardware of the robotics studies such as Handyboard or Basicstamp.

APPENDIX A

USER'S MANUAL AND MAINTENANCE

The user's manual of the system is composed of two sections. The first section includes the cabling, connections and maintenance of the controller circuit and the second section includes the details about the simulation program which is also used for fuzzy system design purposes.

A. Cabling, connections and maintenance of the circuit

A printed circuit board is designed for the control circuitry of this system and details about this circuit are given in Chapter 2. Although it is aimed to obtain a bug-free design, some errors are determined after the manufacturing process. This may be considered as normal in a prototyping application like this one. Small additional circuits and components are added to the circuit to overcome these errors. These additions can be summarized as ultrasonic sensor interfacing circuit, voltage division resistors of the A/D converter for reference voltage generation, and the low-pass filter at the output stage of the direction sensor which is composed of a resistor and a capacitor. The voltage division resistors are soldered at the back side of the printed circuit board. The components of the low pass filter are placed on the rotary table and signal from the sensor is transferred to the input port of the printed circuit board after passing through the low pass filter components. The ultrasonic sensor interfacing circuit is built separately and the signal from the output of this sensor is transferred to the printed circuit board through this circuit. This circuit can be observed near the input ports of the printed circuit board.

The definitions of the input and output ports of the circuit are given in the layout figures which are presented in Chapter 2. Identification of the ports can also

be performed by the help of the writings on the printed circuit board. All of the components of the system, including the sensors and motors should be connected to the proper ports according to the circuit diagrams which are given in Chapter 2. This must be performed when the system power is in off state. The signal from the ultrasonic sensor is important for the operation of the system. Absence of this pulse type signal inhibits the operation of the system. The termination of this signal is waited by the microcontroller for execution of the rest of the code and for the determination of the distance. If this signal is lost somehow, code execution is inhibited and this can be observed with a stationary state in the motors of the system without a displayed warning message in the LCD. So, extreme attention should be paid in order to preserve the existence of the ultrasonic sensor pulse signal at the input port of the printed circuit board for proper operation. The same is valid for the rotary table index sensor. Absence of this signal results improper operation of the system. According to the state of the input port, which is dedicated for this sensor, the rotary table may not be rotated completely in the data sampling mode that is resulting a continuous trial of data sampling attempts or the rotary table may be rotated quickly to both of the directions in the scanning mode to seek for the index position of the table as usually, but due to the lack of this signal, this action may be continuously performed in an undesired fashion. The malfunction or absence of the rest of the sensors does not cause a directly observable misbehavior in the system, but it results undesired decisions of the fuzzy control system. The proper operation of the short range distance measurement sensor can be checked by observing the measured distance value that is displayed in the LCD. The red led on the circuit may be used for proper operation check of the direction sensor by directing it to the 38 kHz signal source. The correct polarity of the DC traction motor can be checked by comparing the actual direction of movement with the claimed direction of movement which is displayed in the LCD. If an undesired behavior is observed, motor polarity should be switched by switching the cables. The cables of the stepper motor can be identified by checking the resistance between the cables according to the given wiring of the stepper motor coils which is presented in Chapter 2. Data collection is performed by clockwise rotation of the rotary table when observed

from the top. A quick return action is performed by a counter clockwise rotation of the table after a data collection attempt. If operation of the stepper motor is obtained with a reverse direction of rotation behavior, the coil connections should be switched. Steering servo motor should be connected to its dedicated port with a proper polarity. Black and red cables are ground and V_{cc} connections respectively where the white cable is signal input to the motor. The LCD of the system is an optional component. The absence of this component does not affect the operation of the system but it is vital for determination of the current state of the system.

The rotary motion of the table brings some difficulties in cabling. The rotation behavior of the table should be observed and a suitable movement for the cables should be obtained by trials.

The power which is needed to operate the system is delivered from two battery packs. The first one is the original battery of the model car and it is rechargeable. The second one is a battery pack that is composed of four AA type batteries. These packs are connected in serial and two different voltages that are needed for the system are generated. The connections related to the batteries are presented in Chapter 2. The polarity of the header type connector of the second battery pack should be observed carefully. A two-way double switch is employed to switch both of the voltages at the same time. The original battery of the system may be recharged when it is needed. This operation must be performed when the two-way double switch of the system is in its off state and the other battery pack is disconnected by using its header type connector. A power supply with 10V or 12V output may be connected to the terminals of the original battery of the system without any modification of the other cables which are connected to this battery. But extreme attention should be paid to check the off state of the power switch of the system and to disconnect the other battery. Charging time varies with the supplied current but it may be suggested that 1600 mA.h of charge should be supplied for complete charging. This can be obtained by supplying 160 mA of current for 10 hours or 320 mA of current for 5 hours, etc. But the charging current should not be greater than 500 mA. The second battery pack is not rechargeable at

the moment but rechargeable AA type batteries can also be used for this pack. The operating lives of the battery packs need not to be equal. The voltages across their terminals should be observed with a voltmeter in order to decide which one to charge.

38 kHz signal source should be connected to a 12V power supply. Proper operation may be checked by observing the state of the red led on the car when the direction sensor is aligned properly. Signal source may be placed at any place in the parking bay. If the signal source is not operating or the emission is not detected by the car, the microcontroller assumes the direction of the parking place as the front side of the car and moves directly.

B. Usage of simulation program

A visual computer program running in PC environment is developed for this study as it is mentioned before. This program is also used for fuzzy system design purposes. Design of a new fuzzy control system for the self-parking model car system may start with the execution of the program. The first step of the design procedure is the configuration of the fuzzy variables. A second form is designed for this purpose and this window is viewed by clicking the dedicated menu item under edit menu or the dedicated button on the main form. Configuration of fuzzy variables starts with determination of linguistic fuzzy set members for the fuzzy sets of the system. The linguistic terms are written inside the edit boxes. There are MSF buttons for each of the fuzzy sets. These buttons are used for showing another form which is used for defining membership functions for each fuzzy set. This form lists all the defined linguistic variables for the fuzzy set of concern and allows definition of membership functions for each of the linguistic set member of the fuzzy set of concern by using four points which are used for definition of a membership function. The membership functions are drawn during this definition process. The second step of the fuzzy system design comes after the definition process of linguistic fuzzy set members and the corresponding membership functions. This

step is the definition of the rules. This is performed by using the comboboxes at the main form of the program. After the fuzzy variable configuration step, the program lists all the defined fuzzy set members and displays them at the associated comboboxes that will be used for the definition of the rules and evaluates all the rule configuration possibilities with the number of rules that is generated. All the rules can be defined or modified by the user by using these comboboxes. The system can be saved to a file at any instant and can be reloaded anytime with the corresponding menu items under file menu or with the dedicated buttons on the main form. After rule definition step the parking characteristics of the model car can be simulated by clicking the animation button on the form. The second usage of this button pauses the movement of the car. The car can be placed at any place with any orientation by using the dedicated button on the main form and the defined rules can be modified according to the parking characteristics of the car that are obtained with the simulation action in order to obtain a desired behavior. The path followed by the car can be displayed by using a menu item that is placed under file menu. Fuzzy engine of the computer program can be checked for consistency with the fuzzy engine of the controller hardware. Any input state can be defined and output can be obtained. This is performed with a menu item that is placed under edit menu.

The program has many data export capabilities. The most important one is the export of the look-up table. Menu item for this purpose is placed under file menu. All the membership function limits and rules are exported in a hex file including a small look-up table for short range distance measurement sensor. This file can be downloaded to the EEPROM array of the controller hardware through the programming hardware by using a suitable downloader program. All the control characteristics can be transferred to the model car hardware by this action. Other information related to the fuzzy system can also be exported by the program for presentation purposes. Defined membership functions of the system can be exported in the form of bitmap image files and this action is performed with a menu item that is placed under the file menu. Rule maps of the system can be viewed and exported as the membership functions. The menu item for viewing the rule maps is placed

under file menu. All the output values of the system can be exported for continuity check of the controller as a text file. The menu item for this purpose is also placed under file menu. Another data export action is the export of the symmetrical incidence matrix as a text file through the dedicated menu item under file menu. This matrix is used for consistency check of the fuzzy control rules. The current view of the parking bay can be saved as a bitmap image file as the last of the data export actions of the program.

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