AUTONOMOUS ROBOTIC SYSTEM: POINT-TO-POINT MOBILE ROBOT

By

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DISSERTATION

Submitted to the Electrical & Electronics Engineering Programme
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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Electrical & Electronics Engineering Programme
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BACHELOR OF ENGINEERING (Hons)
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Approved by,

04.06.09

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Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

June 2009

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Mohd Ashraf Bin Mohd Azmi

ABSTRACT

Autonomous robots are defined as robots which can perform desired tasks in unstructured environments on their own without continuous human guidance. Different robots can be autonomous in different ways. The main difference between these robots is the task they have been programmed to do. This project is initiated for educational purpose in order to increase awareness and enthusiasm among students regarding the autonomous robotic system. The first task to ensure this project meet its objective is by doing extensive literature reviews on the subject (autonomous robotic system). Based on the reviews, the general structure and design block (consists of main system and sub-systems) can be constructed. This is referred as the foundation for the project to start with. The scope of study for this project is to focus on theoretical aspects of the system. It divided into several scopes, which are electronics circuitry (for sensors and motors), Programmable Logic Controller (PLC) programming, and some mechanical aspects regard to the physical parts of the robot. These areas are vital in order to develop and implement the theoretical aspects into a working prototype of autonomous robotic system. The project is planned to develop based on the process flowchart approach where every detail of tasks from starting to the end is shown in sequential order. The results on this project mainly present the selection and implementation of prototype sub-systems like locomotion, navigation and control system. The discussions are focus on process and problems occurred during the prototype development. Finally, this project is about fulfilling its objective which primarily is to deliver a working prototype of an autonomous robotic system with the ability to move from one point to another in precise manner.

ACKNOWLEDGEMENT

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

The autonomous robotic system is defined as the system that provide algorithms and programmable instructions for the robot so it can trigger and process its functionality without requiring the help of human or external force. The autonomous system generally has several sub-systems consist of self-maintenance, self navigation, task performance and most importantly the adaptability to its surrounding environment. [7]

The learning and understanding of the robotic system is divided into three major scopes that are the electronics, programming, and mechanical parts. To begin the design of the system, a building block is constructed to show the general inputs, outputs and their connection with the main system of the robot. For the electronics part, revision, comparison and simulation should be done in order to get the suitable electronics circuits and components. The programming part is crucial as it provides the instructions and algorithms needed for the system to get the robot function as desired. In this project, Programmable Logic Controller (PLC) is used as the control system. Thus high understanding and skills regarding PLC are required in order to efficiently use the programming software to produce the desired programming code.

There is need for some mechanical aspects of the system to be covered. It mainly involved around physical aspect of the robot construction such as locomotion system. Finally, it is important to understand and study the behavior of the system when the fabrication of prototype is completed. It is crucial as there is need to get feedbacks on how the system actually behaves in the real-time. The expected output of this project is a robotic prototype that can function autonomously and accurately as desired.

1.2 Problem Statement

In this project, we look into the autonomous robotic system that has been playing such vital role in wide range of areas, either the smallest or the largest robotic structure provide functionality that help human kind in achieving their needs and help them progress forward. But the current situation shows that not many people including engineering student know how the system actually works. In contrary, it is important for the student (especially electrical and electronics engineering students) to know at least the basic understanding of the autonomous robotic system and its mechanism. In working environment, there are possibilities that they are required to encounter tasks involving the autonomous robotic system thus it will be a massive advantage if they have learned the system beforehand. There are some problems that might hinder students from understanding how autonomous robotic system actually works such as:-

- Lack of detail information such as circuit design, system flowchart, mechanical concept and the programming code for the system.
- The complexity of the circuit design, programming source code and mechanical system might lead the student to consume a lot of time to comprehend.
- The complexity of the practical process of modeling an autonomous robotic system which commonly involves circuit implementation and software programming.

By developing a simpler model (compared to industrial and marketable model) of the autonomous robotic system, students might be able to understand on what is required to build such system. Nevertheless, having a specialized purpose or function implemented in this robotic system will further lead them to appreciate and realize what autonomous robots are capable of doing.

1.3 Objectives

The objective of this project is to develop an autonomous robotic system with the function to autonomously operate and move accurately from one point to another. There are several parts of objectives to be achieved in this project, which are:-

- Identify and study the Robotic Process Control System in order to create a system that able to meet the project's requirement.
- Study and construct suitable electronics circuits design to be implemented for the system.
- Study and understand the mechanical aspects of the robotic system.
- Study and use of software to program the Programmable Logic Controller (PLC) to perform the required movements or activities.
- Examine and understand the behavior of the prototype when it is operating in real time after the completion of fabrication.

1.4 Scope of Study

The scope of study in this project is covering several areas such as electronic circuits design, mechanical design, and programming method. The electronics part is required in order to design appropriate electronics circuit for the system. The mechanical part cover mostly the physical part of the system and the programming part is needed to provide instructions and algorithms for the control system (PLC). These three areas are vital in order to achieve the objectives. Revision on previous projects and other references related to this project is necessary to achieve better understanding on the autonomous robotic system.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

. There are a lot of autonomous robots that already exist and implemented in various areas. For the autonomous robotic system, the robot is categorized into two sub-categories, either mobile or stationary.

2.2 Stationary Robotic System

Stationary robots are designed to remain stationary on its place only to have arm like contraptions equipped with grippers or special tools to provide various functions in various areas. These types of robot are popular in industrial places; as the operation involved high accuracy, precision and simultaneous action. These robots are designed to provide the attributes as required. These systems are categorized in the way the joints (attached to arm or gripper) move. [3] The categories of stationary system are as below:-

- ***Cartesian/Gantry robot*:** Used for 'pick and place' work, application of sealant, assembly operations, handling machine tools and arc welding. It's a robot whose arm has three prismatic joints, whose axes are coincident with a Cartesian coordinator. [6]

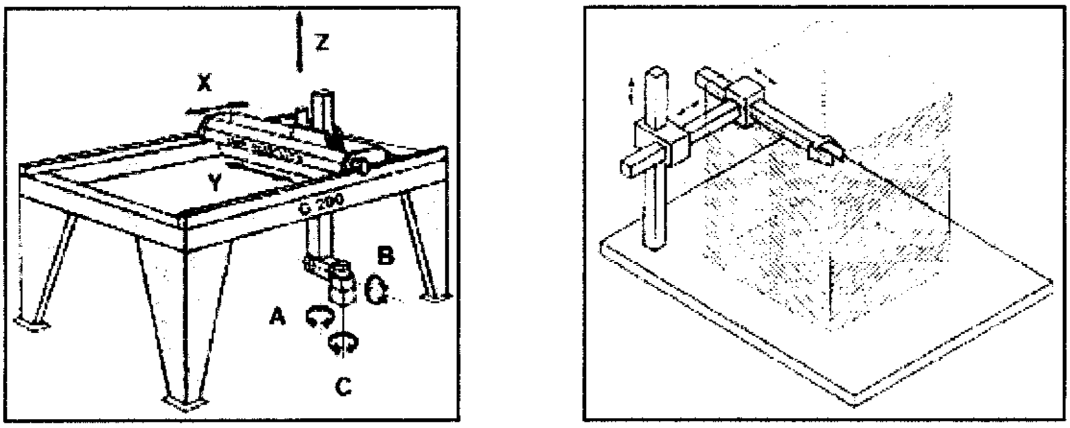


Figure 1 - Cartesian/Gantry Robot Arm

- ***Cylindrical robot:*** Used for assembly operations, handling at machine tools, spot welding, and handling at diecasting machines. It's a robot whose axes form a cylindrical coordinate system. [6]

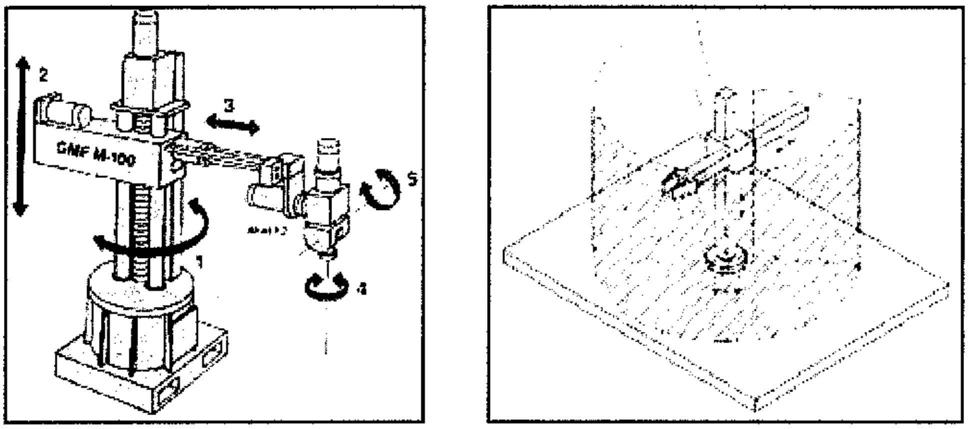


Figure 2 - Cylindrical Robot Arm

- ***Spherical/Polar robot:*** Used for handling at machine tools, spot welding, diecasting, fettling machines, gas welding and arc welding. It's a robot whose axes form a polar coordinate system. [6]

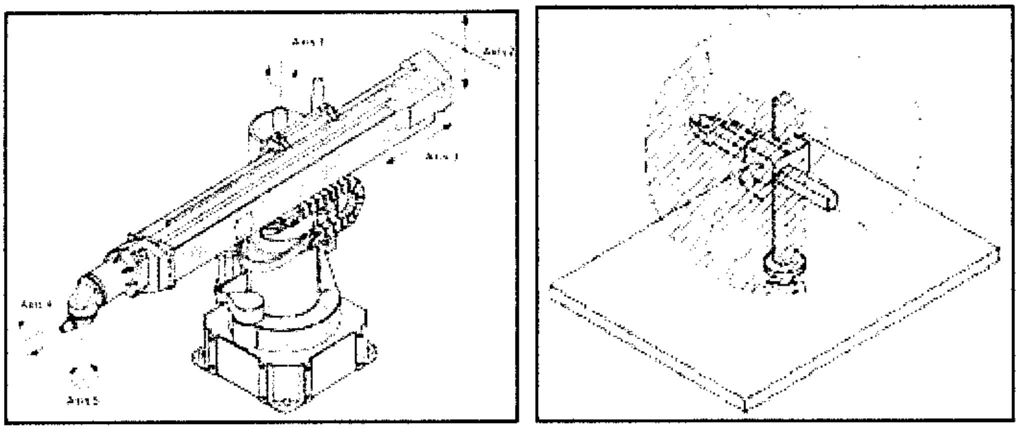


Figure 3 – Spherical/Polar Robot Arm

- ***SCARA robot:*** Used for pick and place work, application of sealant, assembly operations and handling machine tools. It's a robot which has two parallel rotary joints to provide compliance in a plane. [6]

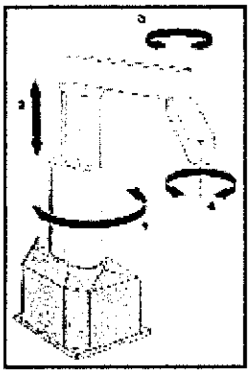


Figure 4 – SCARA Robot Arm

- ***Articulated robot:*** Used for assembly operations, die casting, fettling machines, gas welding, arc welding and spray painting. It's a robot whose arm has at least three rotary joints. [6]

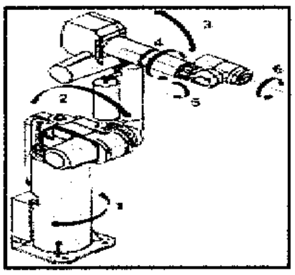


Figure 5 – Articulated Robot Arm

2.3 Mobile Robotic System

Mobile robot is designed to move from one place to another. Wheels, tracks or legs allow the robot to traverse a terrain. [1] The robot relies on its navigation and locomotion system to navigate its surrounding and travel through its path. Such ability allows the robots to be used in various fields. Mobile robots are the focus of a great deal of current research and almost every major university has one or more labs that focus on mobile robot research. Mobile robots can be found in industry, military and security environments. They also appear as consumer products, for entertainment or to perform certain tasks like vacuum. [8] For example, Roomba, an iRobot product has the ability to vacuum the floor for indoor purpose. While LawnBott, an autonomous robotic lawn mower marketed in the U.S. and Canada by Kyodo America Home Robotics, programmed to criss-cross a lawn (from edge to edge) at random angles and will spiral randomly usually in the middle of the lawn.

Figure 6 - Roomba, the iRobot Autonomous Vacuum Cleaner Robot

Figure 7 - LawnBott, the Autonomous Lawn Mower Robot

2.4 Navigation System for Autonomous Mobile Robot

The role play by navigation system in autonomous robotic system is to provide 'vision' for the robot. Mostly using sensors, the robot scan its surrounding and detect for obstacles that might block its movement. If there are any obstacles detected ahead, the robot will act accordingly using programmed instructions in order not to potentially hit the obstacles that might causes damages to the robot. There are variety of sensors available that use different theories and concepts to provide detection and proper navigation for the robot. The type of sensors that commonly used in autonomous robotic system are 'collision detection' and 'collision avoidance' concept.

2.4.1 Collision Detection Concept

A sure way to detect objects is to make physical contact with them. This concept is a form of passive detection, where the robot will only respond and change direction accordingly only after it have already hit any obstacles that come across its path. The physical contact bumper switch, spring whiskers and pressure pad are among the type of collision detection techniques that being used. [1][3]

2.4.2 Collision Avoidance Concept

Avoiding a collision is better than detecting it after it has happened. This concept is a form of active detection, where the robot will detect obstacles from a pre-defined distance (depending on sensor's sensitivity), and changes direction to avoid collision. There are two most common techniques that use this concept which are the infrared light sensor and the ultrasonic sound sensor. [1][3]

2.4.3 Infrared Light Sensor

Light may always travel in a straight line, but it bounces off nearly everything. Infrared light sensor uses an infrared LED and infrared phototransistor. The infrared phototransistor is use to detect the bounced light.

2.4.4 Ultrasonic Sound Sensor

Sound can be used to detect the proximity of objects in much the same as for infrared light. Ultrasonic sound is transmitted from a transducer, reflected by a nearby object, and then received by another transducer. The advantage of using sound is that it is not sensitive to objects of different color and light reflective properties. However, there are materials reflect sound better than others, and some even absorb sound completely. In comparison, proximity detection with sound is more fool proof. The ultrasonic transmitter circuit work as follows; a stream of 40 kHz pulses are produced by a 555 timer wired up as an astable multivibrator. The receiving transducer is positioned two or more inches away from the transmitter transducer. [1]

For best results, a piece of foam can be placed between the two transducers to eliminate direct interference. The signal from the receiving transducer needs to be amplified; an op amp (such as an LM741) is more than sufficient for the job. The amplified output of the receiver transducer is directly connected to another 741 op amp wired as a comparator. The ultrasonic receiver is sensitive only to sounds in about the 40 kHz range. The closer the ultrasonic sensor is to an object, the stronger the reflected sound will be. The output of the comparator will change between low to high as the sensor is moved closer to or farther away from an object. The potentiometer, which can be found on the op amp on the receiver circuit, can be adjusted to vary the sensitivity of the circuit. [1]

Below are the schematic off an example of ultrasonic sound sensor that is found in a website. [10] The circuit behaves slightly different compared to the basic ultrasonic sensor circuit as explained above.

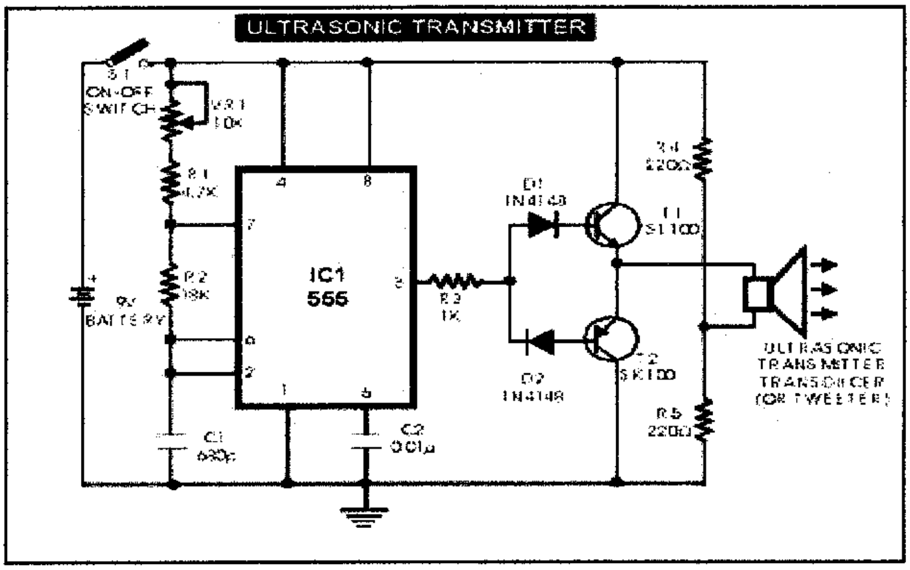


Figure 8 – Schematic Diagram for an Improvised Ultrasonic Transmitter

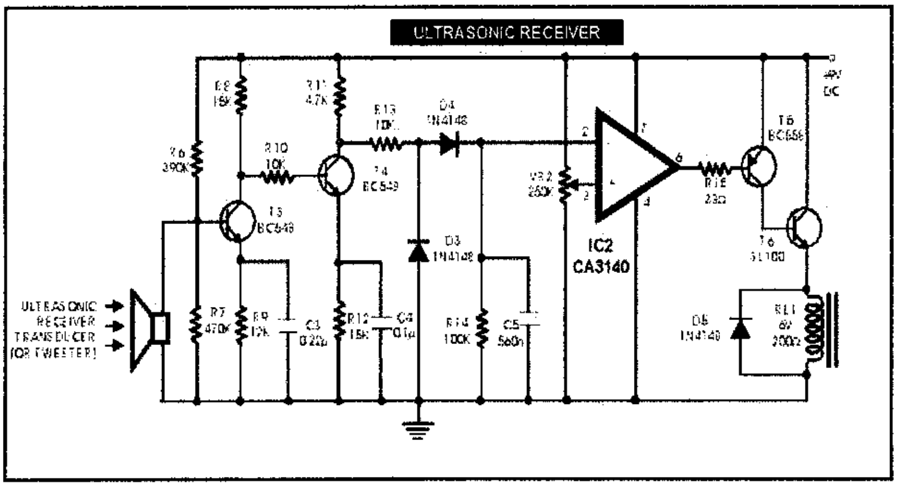


Figure 9 – Schematic Diagram for an Improvised Ultrasonic Receiver

The ultrasonic transmitter uses a 555 based astable multivibrator. It oscillates at a frequency of 40-50 kHz. An ultrasonic transmitter transducer is used here to transmit ultrasonic sound very effectively. The transmitter is powered from a 9-volt PP3 single cell. The ultrasonic receiver circuit uses an ultrasonic receiver transducer to sense ultrasonic signals. It also uses a two-stage amplifier, a rectifier stage, and an operational amplifier in inverting mode. Output of op-amp is connected to a relay through a complimentary relay driver stage. A 9-volt battery eliminator can be used for receiver circuit, if required. When switch S1 of transmitter is pressed, it generates ultrasonic sound. The sound is received by ultrasonic receiver transducer. It converts it to electrical variations of the same frequency. These signals are amplified by transistors T3 and T4. The amplified signals are then rectified and filtered. The filtered DC voltage is given to inverting pin of op-amp IC2. The non- inverting pin of IC2 is connected to a variable DC voltage via preset VR2 which determines the threshold value of ultrasonic signal received by receiver for operation of relay RL1. The inverted output of IC2 is used to bias transistor T5. When transistor T5 conducts, it supplies base bias to transistor T6. When transistor T6 conducts, it actuates the relay. The relay can be used to control any electrical or electronic equipment. [10]

2.5 Locomotion System

The way the robot move from point A to point B is called locomotion. Robot locomotion takes many forms, but wheels and tracks are the most common. [1]

- ***Wheels***: Wheels are the most popular method for providing robots with mobility. Robot wheels can be just about any size, limited only by the dimensions of the robot and one's outlandish imagination. Turtle robots usually have small wheels, less than 2 or 3 inches in diameter. Medium-sized rover-type robots use wheels with diameters up to 7 or 8 inches. The advantages of wheels are they are simple to construct, provide great maneuvering ability and do not require powerful motors as tracks does. They are preferable especially indoor where space is tight and packed with a lot of obstacles. [1]

- ***Tracks***: The tracks usually replace common wheels on each side of the robot, act as giant wheels. The track turn, like wheels, and the robot lurches forward and backward. For maximum traction, each track is about as long as the robot itself. Track drive is preferable for many reasons, including the fact that it makes it possible to mow through all sorts of obstacles, like rocks, ditches and potholes. The track drive provides excellent traction and greater stability. But the drawback is that powerful motors are required to drive the track. [1]

- ***Legs***: Legged robots are a challenge to design and build, but they provide an extra level of mobility that sometimes wheeled and tracked robots do not offer. Due to difficulties and complicated manner of designing legged robot, there are seldom legged robots being made compared to wheeled and tracked robots. [1]

2.5.1 Steering System

Steering system is the system that provides direction to the robot. Basically, it pre-determined its path based on pre-determined instructions or sudden detection of obstacles. There are few types of steering method like differential drive, car-type and tricycle. Each has their own advantages and disadvantages.

- ***Differential***: For wheeled and tracked robots, differential steering is the most common method to getting the machine to go in a different direction. The technique is that one side of wheels or treads stops or reverses direction while other side keeps going. The result is that the robot turns in the direction of the stopped or reversed wheel or tread. Because friction effects, differential steering is most practical with two-wheel-drive systems. Additional set of wheels however can increase friction during steering. [1]

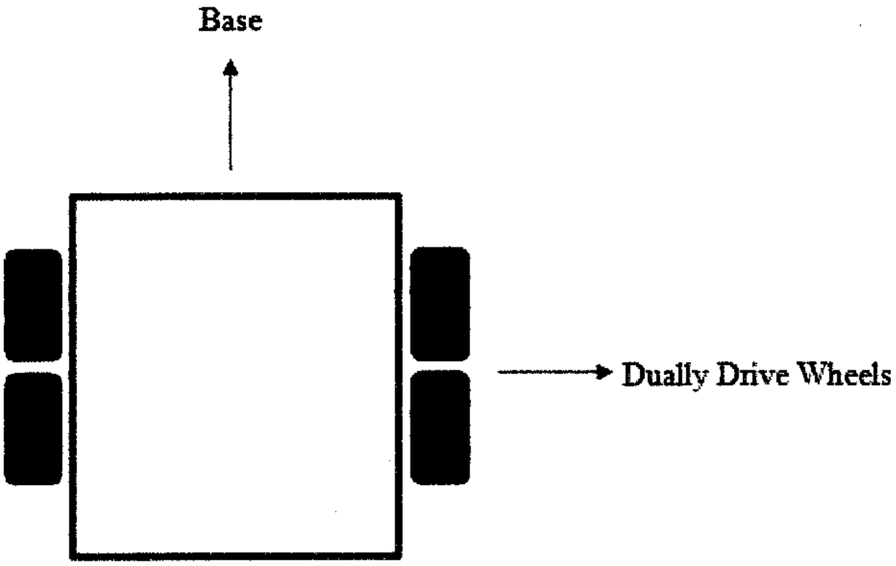


Figure 10 – Dually Drive Wheels Using Differential Drive Method

- ***Car-Type***: Pivoting the wheels in the front is yet another method for steering a robot. Robots with car-type steering are not as maneuverable as differentially steered robots, but they are better suited for outdoor uses, especially over rough terrain. However, better traction and steering accuracy can be obtained if the wheel on the inside of the turn pivots more than the wheel on the outside. [1]

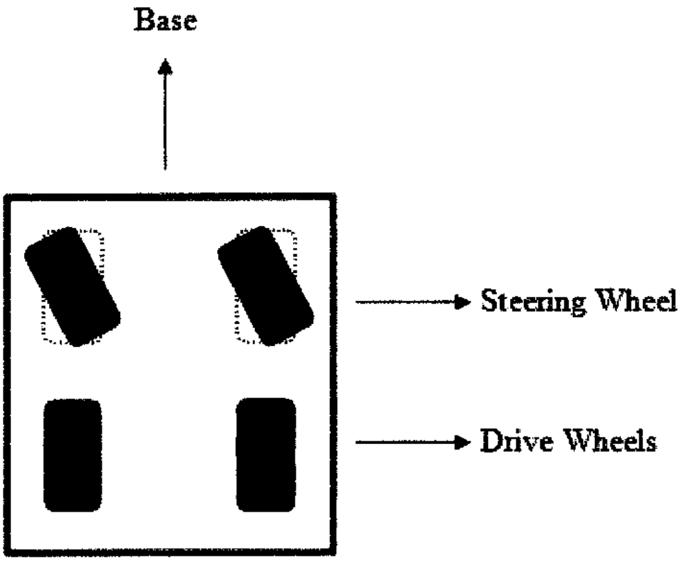


Figure 11 – Car-type Steering Method

- ***Tricycle***: One of the biggest drawbacks of the differentially steered robot is that the robot will veer off course if one motor is even a bit slow. Car-type steering, is one method for avoiding the problem as a result that the robot is driven by just one motor. But car-type steering makes for fairly cumbersome indoor mobile robots. A better approach is to use a single drive motor powering two rear wheels and a single steering wheel in the front. This arrangement is called tricycle. The robot can be steered in a circle just slightly larger than the width of the machine. Distance from the back wheels to the front wheel should be measured carefully as short base will cause instability in turns, causing the robot to tip over opposite direction when making turns. But for tricycle method, the front wheel should be steered with high accuracy in order to be able to travel a straight line. Most often, the steering wheel is controlled by a servo or stepper motor. These two motors provide a high degree of positional accuracy that is required. [1]

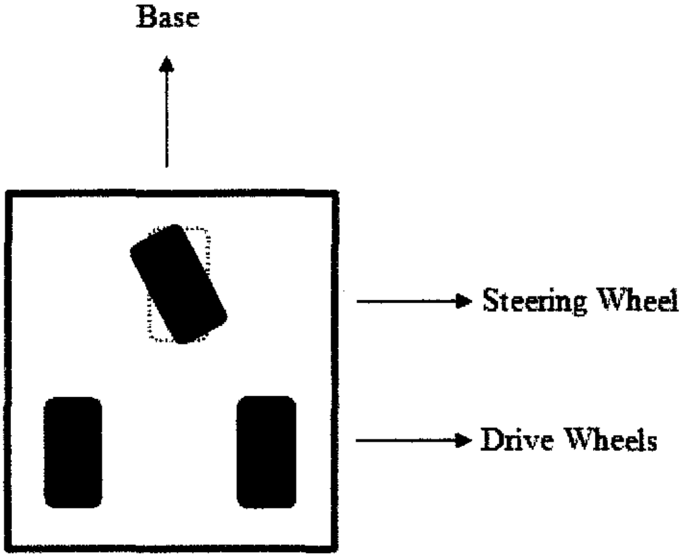
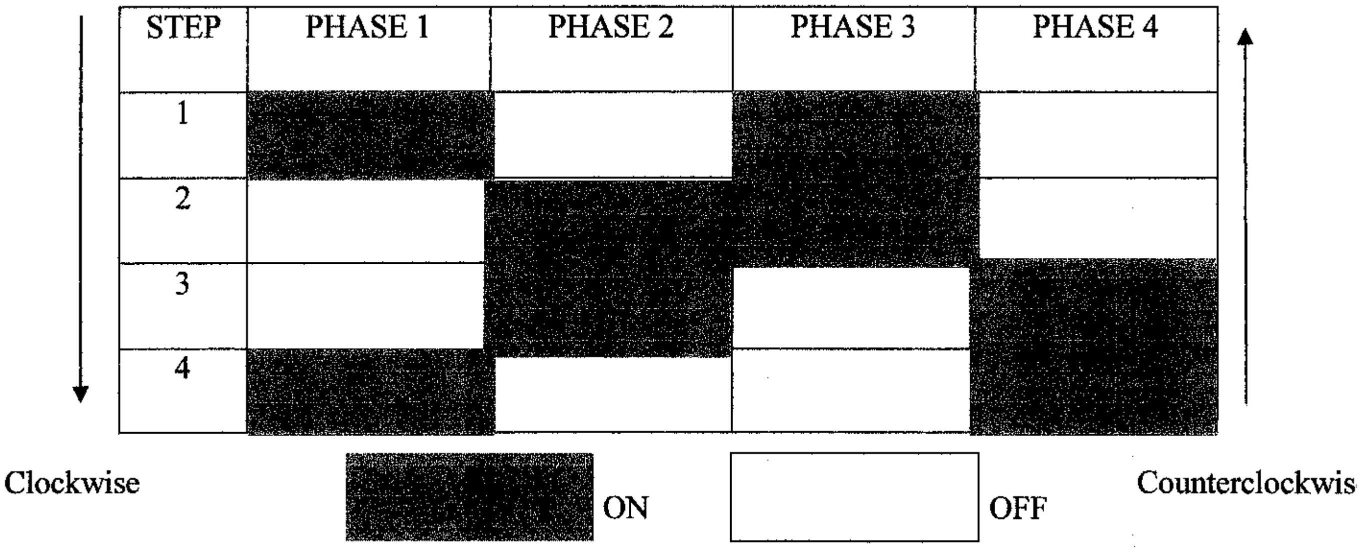


Figure 12 – Tricycle Steering Method

2.5.2 Stepper Motor

Stepper motors are, in effect, DC motors with a twist. Instead of being powered by a continuous flow of current, as with regular DC motors, they are driven by pulses of electricity. Each pulse drives the shaft of the motor a little bit. The more pulses that are fed to the motor; the more the shaft turns. There are several designs of stepper motors. The most popular is the four-phase unipolar stepper. A unipolar stepper motor is really two motors sandwiched together. Each motor is composed of two windings. In operation, the common wires of a unipolar stepper are attached to the positive side of power supply. Each winding is then energized in turn by grounding it to the power supply for a short time. The motor shaft turns a fraction of a revolution each time a winding is energized. For the shaft to turn properly, the windings must be energized in sequence. For example, energize wires 1, 2, 3 and 4 in sequence and the motor turns clockwise. Reverse the sequence and the motor turns opposite way. [1]



STEP	PHASE 1	PHASE 2	PHASE 3	PHASE 4
1	■	□	■	□
2	□	■	■	□
3	□	■	□	■
4	■	□	□	■

Clockwise ■ ON □ OFF Counterclockwis

Figure 13 – The enhanced on-on/off-off four-step sequence of a unipolar stepper motor

The figure above provides a technique of on-on/off-off four-step sequence. It approach by actuates two windings at once. This enhanced actuation sequence increase the driving power of the motor and provides greater shaft rotation precision. Stepping motor differ in their design compared to continuous DC motors. Below are the most important design specifications for stepper motors:-

- ***Stepper Phasing***: By their nature, all stepper motors are at least two-phase. Usually, but not always, the more phases in a motor, the more accurate it is. [1]

- ***Step Angle***: Stepper motors vary in the amount of rotation of the shaft each time a winding is energized. The amount of rotation is called the step angle and can vary from as small as 0.9° to 90°. The step angle determines the number of steps per revolution. The higher the degree of step angle, the less pulse required for the shaft to turn to complete one revolution. [1]

- ***Pulse Rate***: Obviously, the smaller the step angle is, the more accurate the motor. But the number of pulses stepper motors can accept per second has an upper limit. Heavy-duty steppers usually have a maximum pulse rate of 200 or 300 steps per second, so they have an effective top speed of 1 to 3 r/s. Some smaller steppers can accept a thousand or more pulses per second, but they don't usually provide very much torque and are not suitable as driving or steering motors. [1]

- ***Running Torque***: Steppers cannot deliver as much running torque as standard DC motors. However, steppers are at their best when they are turning slowly. With typical stepper, the slower the motor revolves, the higher the torque. [1]

- ***Braking Effect***: Actuating one of the winding in a stepper advances the shaft. If current is continued to be applied to the winding, the motor won't turn anymore. In fact, the shaft will be locked, as if you have applied brakes. This is the reason why a stepper motor is considered having its own brakes built in. The amount of braking power a stepper motor has is expressed as holding torque. Small stepper motor has small holding torque while larger stepper motor has larger holding torque. [1]

- ***Voltage, Current Ratings***: Like DC motors, steppers vary in their voltage and current ratings. Steppers for 5-, 6-, and 12-V operation are not uncommon. The current rating of a stepper is expressed in amps per phase. The power supply driving the motor needs to deliver at least as much as the per-phase specification, preferably more if the motor is driving a heavy load. If, for example, the current per phase is 0.25 A, the power requirement at any one time is 0.50 A. [1]

2.5.3 Driving System

Drive system is the system that mobilizes the robot. Typically, two wheels are moved by a torque supplied by a single DC motor. There are two type of drive motor mount that are the centerline and front-drive. For the centerline, the weight is more evenly distributed across the platform. It also considered having no 'front' or 'back', at least as far as the drive system is concerned. For the front-drive motor mount, the weight is now concentrated more on the motor side of the platform. One advantage of front-drive mounting is that it simplifies the construction of the robot. Its steering circle, the diameter of the circle in which the robot can be steered, is still the same diameter as the centerline drive robot. However, any given front-drive robot may be smaller than centerline drive robot. [1]

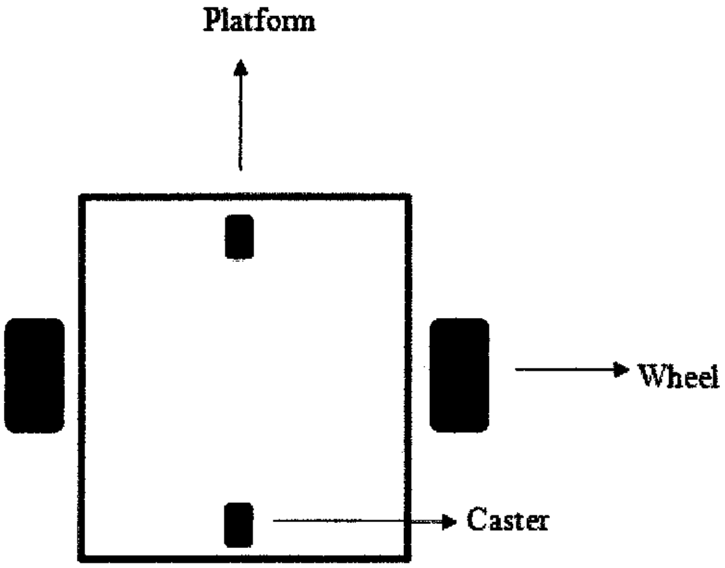


Figure 14 – Centerline Drive Motor Mount with Two End to End Balancing Casters

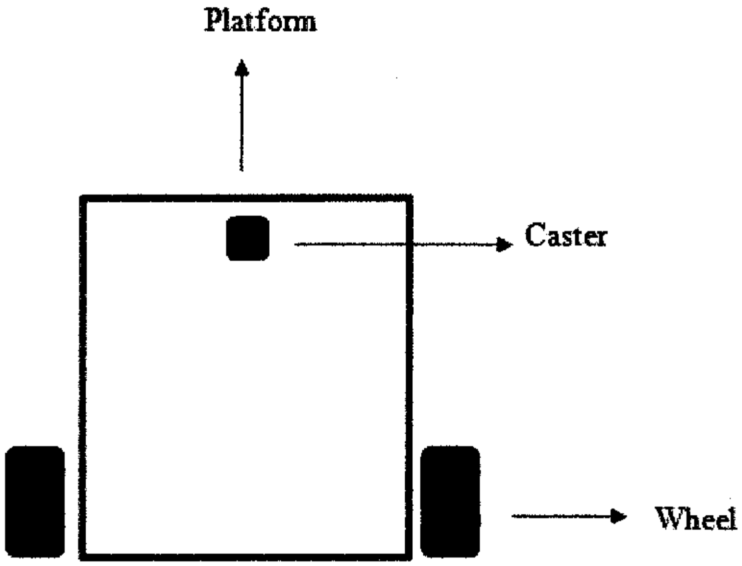


Figure 15 – Front-Drive Motor Mount with Single Opposing Balancing Caster

2.5.4 DC Motor

Powered by continuous direct current, DC motor produces angular force by spinning according to its speed rating. Gears can be used in order to reduce the motor speed if it is too much for the robot to handle. There are two main controls for DC motor; the direction control and speed control. The direction control provides forward and reverse control. Direction control techniques such as relay and power mosfet control are among famously used techniques.

The speed control is important in order to control the speed of the motor. Without this speed control, the robot might not be able to slow down when required. The best way to control the speed of DC motor is to chop the power being passed to it into different sized chunks. The most common way of doing this is to set up a recurring signal; the time for power to be passed to the motor should be a set fraction of this period which known as 'pulse width modulation' or PWM. [1]

There are some things to be considered when choosing a DC motor for the robot:-

- DC motors can be often be effectively operated at voltages above and below their specified rating.If the motor is rated for 12 V, and it it run at 6 V, the odds are the motor will still turn but at reduced speed and torque. Conversely, if the motor is run at 18 to 24 V, the motor will turn faster and will have increased torque. Significantly overdriving a motor may cause it to wear out much faster than normal. However, it is usually fairly safe to run a 10 V motor at 12 V or a 6 V motor at 5 V. [1]

- DC motors draw the most current when they are stalled. Stalling occurs if the motor is supplied current, but the shaft does not rotate. If there is no stall detection circuitry built into the motor driver, the battery, control electronics, and drive circuitry used with the motor must be able to deliver the current at stall, or they could burn out. [1]

- DC motors vary greatly in efficiency. Many of the least expensive motors are meant to be used in applications where brute strength, rather than conservation of electricity, is the most important factor. It is best to stay away from automotive starter, windshield wiper, power window, and power seat motors since these are notoriously inefficient. [1]

- The rotational speed of a DC motor is usually too fast to be directly applied in a robot. Gear reduction of some type is necessary to slow down the speed of the motor shaft. Gearing down the output speed has the positive side effect of increasing torque. [1]

2.6 Control System

Basically, a control system is developed using combinations of hardware (for processing purpose) and software (for programming purpose). Generally, the system requires input in order to produce output in relation to instructions stored in its core memory. An efficient measure of a control system is the ability to relate input and output exactly with the pre-programmed instructions. For autonomous robotic system, the controller is the robot's brain and controls the robot's movements. It's usually a computer of some type which is used to store information about the robot and the work environment and to store and execute programs which operate the robot. The control system contains programs, data algorithms, logic analysis and various other processing activities which enable the robot to perform. [13]

2.6.1 Programmable Logic Controller (PLC) Overview

A programmable logic controller (PLC) is a special form of microprocessor-based controller that uses a programmable memory to store instructions and to implement functions such as logic, sequencing, timing, counting and arithmetic in order to control machines and processes. The term *logic* is used because programming is primarily concerned with implementing logic and switching operations. Input devices such as sensors or switches, and output devices in the system being controlled such as motors or valves are connected to the PLC. The controller then monitors the input and outputs according to this program and carries out the control rules for which it has been programmed. [4]

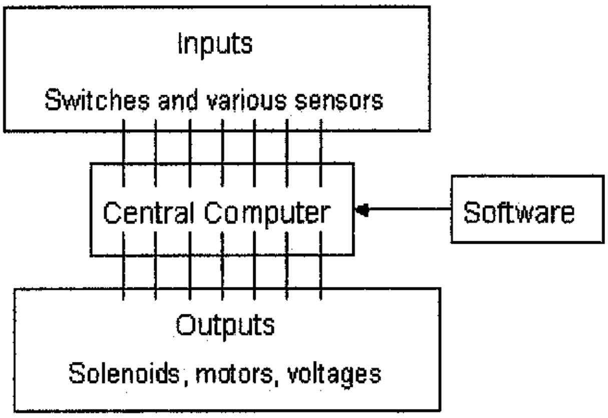


Figure 16 – Basic Programmable Logic Controller System

PLCs have the great advantage that the same basic controller can be used with a wide range of control systems. To modify a control system and the rules that are to be used, all that is necessary is for an operator to key in a different set of instructions. There is no need to rewire. The result is a flexible, cost effective system which can be used with control systems which vary quite widely in their nature and complexity. PLCs are similar to computers but whereas computers are optimized for calculation and display tasks, PLCs are optimized for control tasks and the industrial environment. There are other advantages of PLCs and listed as below [4]:

- Rugged and designed to withstand vibrations, temperature, humidity and noise.
- Have interfacing for inputs and outputs already inside the controllers.

- Easily programmed and have an easily understood programming language which is primarily concerned with logic and switching operations.

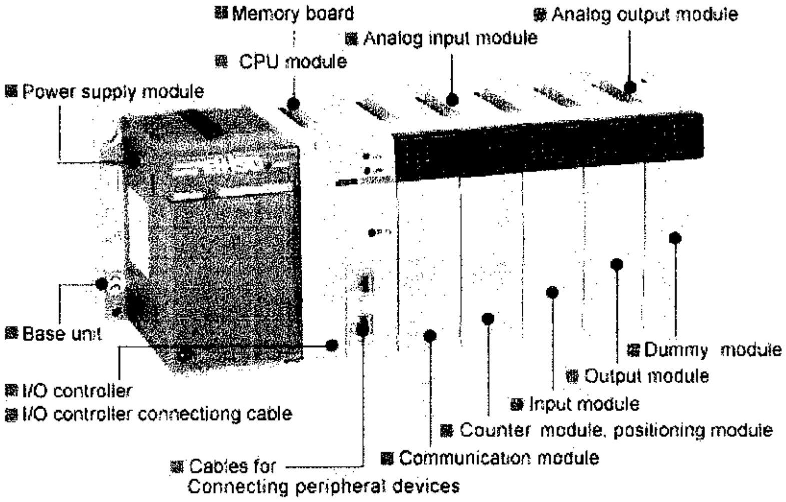


Figure 17 – An example of PLC controller with detail reference

2.6.2 Programmable Logic Controller (PLC) Architecture

Typically, a PLC system has the basic functional components of processor unit, memory, power supply unit, input/output interface section, communications interface and the programming device.

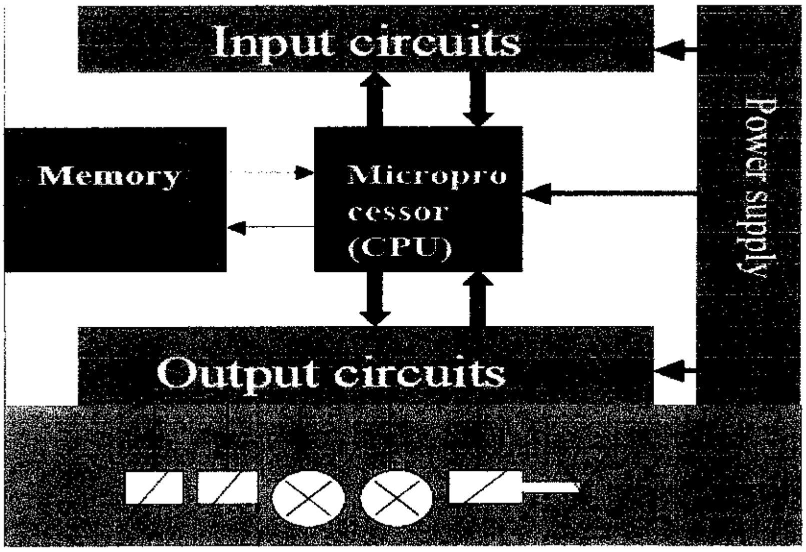


Figure 18 – The PLC internal system

- ***Microprocessor (CPU)***: The unit that interprets the input signals and carries out the control actions, according to the program stored in its memory, communicating the decisions as action singles to the outputs.
- ***Power Supply Unit***: The unit needed to convert the main AC voltage to the low DC voltage (5V) necessary for the processor and the circuits in the input and output interface modules.
- ***Memory***: The unit where the program is stored that is to be used for the control actions to be exercised by the microprocessor and data stored from the input for processing and for the output for outputting.
- ***Input and Output Circuits***: Where the processor receives information from the external devices and communicates information to external devices. The input might thus be from switches or sensors. The output might be the motor starter coils or solenoid valves. [4]

2.6.3 Programmable Logic Controller (PLC) Programming

PLC programming is unique in the sense of the way to program the desired instructions. The system has been designed so not only computer programmers can set up or change the program, but it also can be operated by engineers with perhaps a limited knowledge of computers and computing languages as well. There are five types of languages which can be use to program the PLC that meets the IEC 1161-3 Standard:

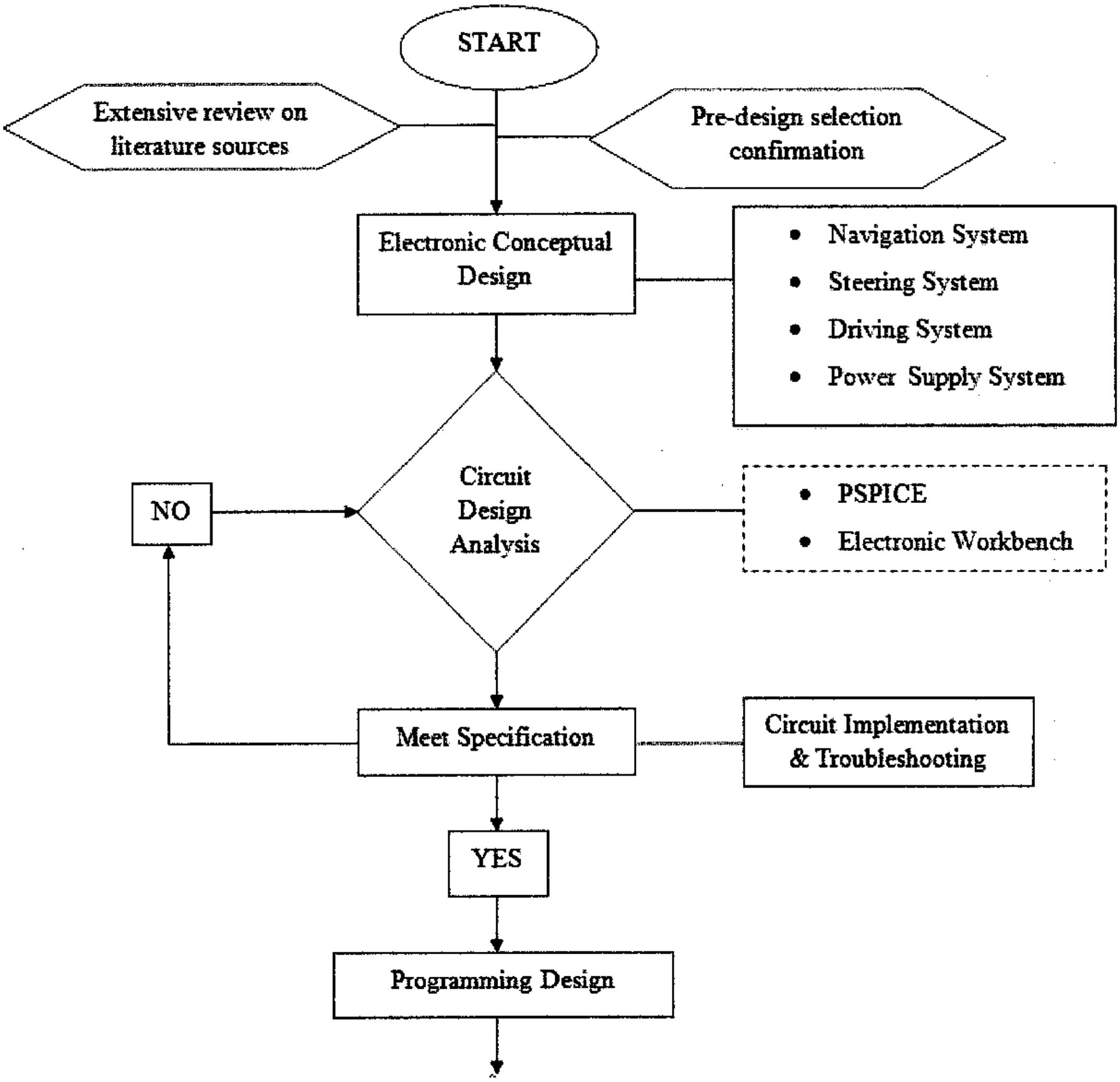
- ***Structured Text Programming***: A high level language that has some similarities to Pascal. Statements can be used to assign values to variables.
- ***Logic Diagram***: A graphical language, and most widely used. Use Boolean Mnemonics to represent the process, before converting to ladder diagram.

- ***Functional Block Diagram Programming***: A graphical language. Use in application involving the flow of signals between control blocks.
- ***Instruction List***: A low level programming language, much like the assembly language programming.
- ***Sequential Function Chart***: A graphical programming method. Very useful for describing sequential type processes.

CHAPTER 3

METHODOLOGY

3.1 Procedure Identification



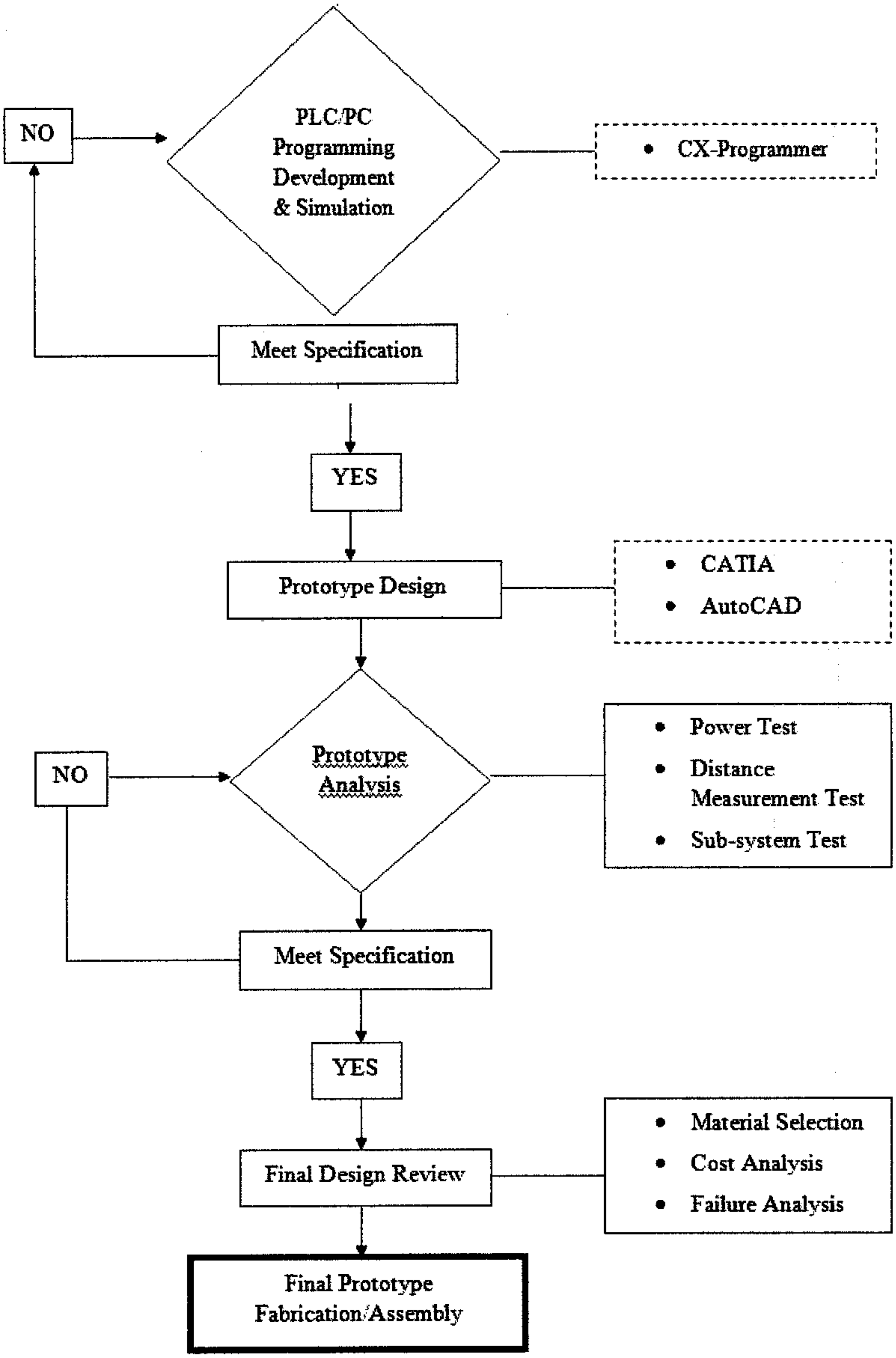


Figure 19 – The process flow chart for autonomous robotic system

3.2 Tools Required

Table 1 – Selection of Hardware & Software

SUBJECT	HARDWARE	SOFTWARE
Electronics Circuits Simulation and Analysis	• Personal Computer	• PSPICE • Electronic Workbench Multisim
Programmable Logic Controller (PLC) Programming and Analysis	• Workstation computer connected with PLC simulation hardware	• CX-Programmer
Prototype Construction	• 2 Ultrasonic Sensors • 2 12V DC Motors • 4 DPDT 24V Relays • PLC Controller • 2 Small Tires • Acrylic Glass, Veroboards • Bolts, Screws, Nuts • 1k Ohm Resistors • 4 Diodes • 2 Power Transistors • 12V Buzzer	

3.3 Building Block Diagram

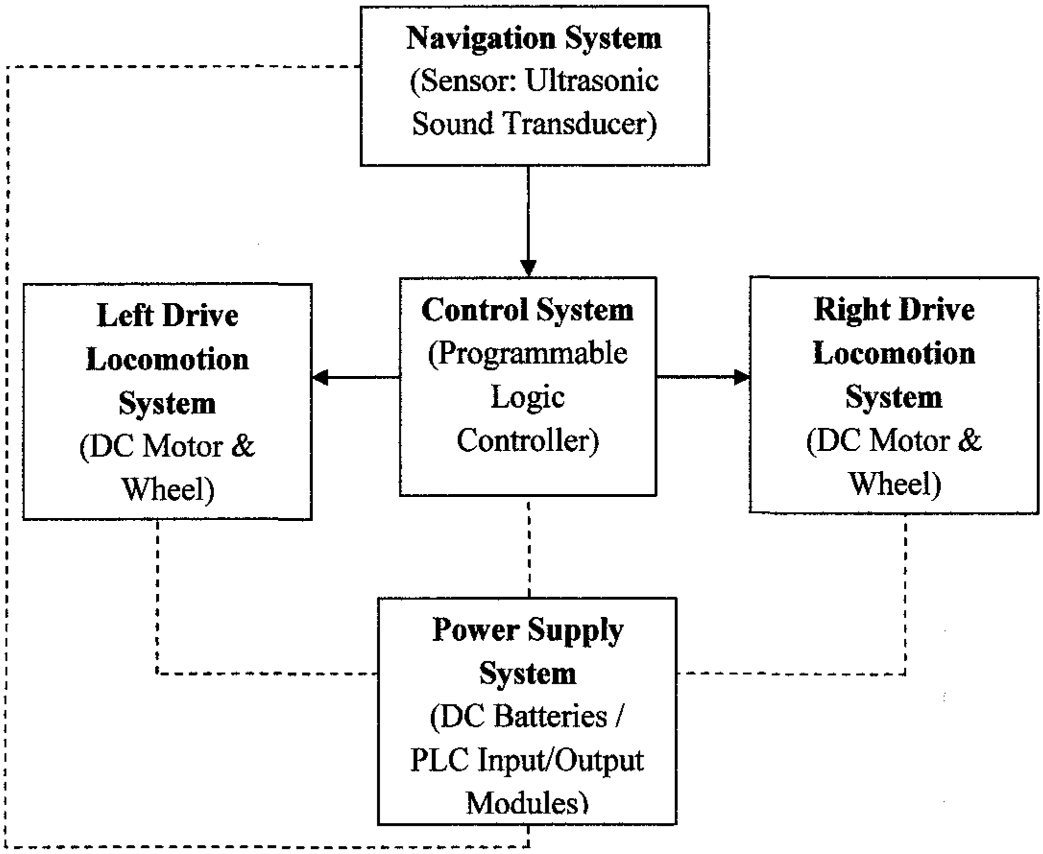
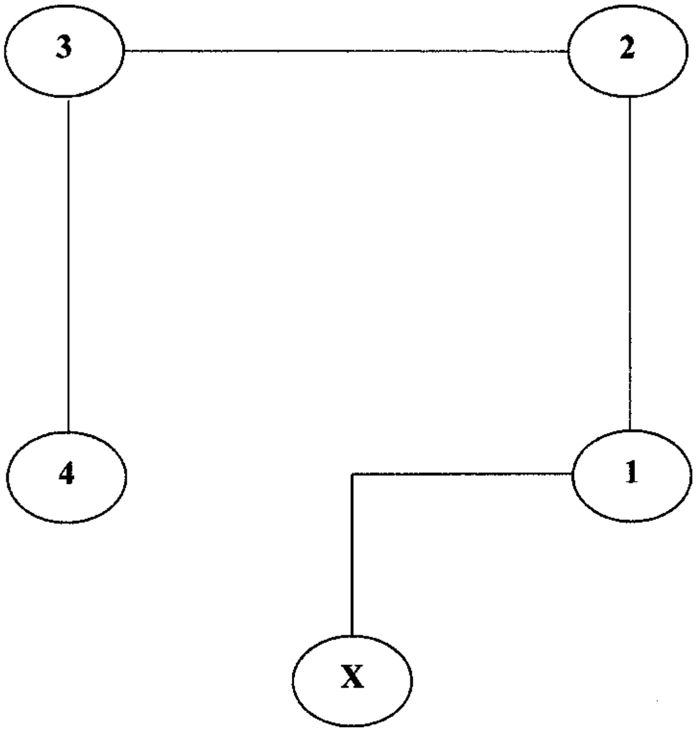


Figure 20 - Main Building Block (Main System Design)

3.4 Prototype Path Planning Diagram



Legend:

X – Origin
1 – Destination Point Mode 1
2 – Destination Point Mode 2
3 – Destination Point Mode 3
4 – Destination Point Mode 4

——— 1 meter distance
——— 2 meter distance

Figure 21 – Prototype Path Planning

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Results

4.1.1 Navigation System

For this project, collision avoidance concept is chosen due to its minimal risks and effects of collision compared to collision detection concept. A table of comparison (between ultrasonic sensor and infrared sensor) has been constructed as below in order to determine the type of sensor that is going to be used in this project.

Table 2: Comparison between Ultrasonic sensor and Infrared sensor

Criteria	**Ultrasonic Sensor (Sound)**	**Infrared Sensor (Light)**
Range Detection	7.5cm – 304.8cm (3.048m)	10cm – 75cm
Current Usage	30mA	30mA
Surrounding Influence(s)	Absorption of sound by materials	Ambient lighting and brightness
Radiation Path	Radiation cone (15° – 35°)	Straight line radiation light

*General attributes comparison; the criteria can differ based on manufacturers

From the table above, ultrasonic sensor is chosen because it has wider range of detection, which enables the system to have wider range of navigation if desired. It is also less influenced by its surrounding compared to infrared sensor. This enable the returning signal bounced from any obstacles to be measured precisely.

4.1.2 Ultrasonic Sensor

The figure below shows the ultrasonic transmitter circuit taken from a website [10]. Then the circuit was reconstructed in Multisim software to be analyzed. An oscilloscope is connected in place of the ultrasonic transducer in order to analyze the voltage across the transducer.

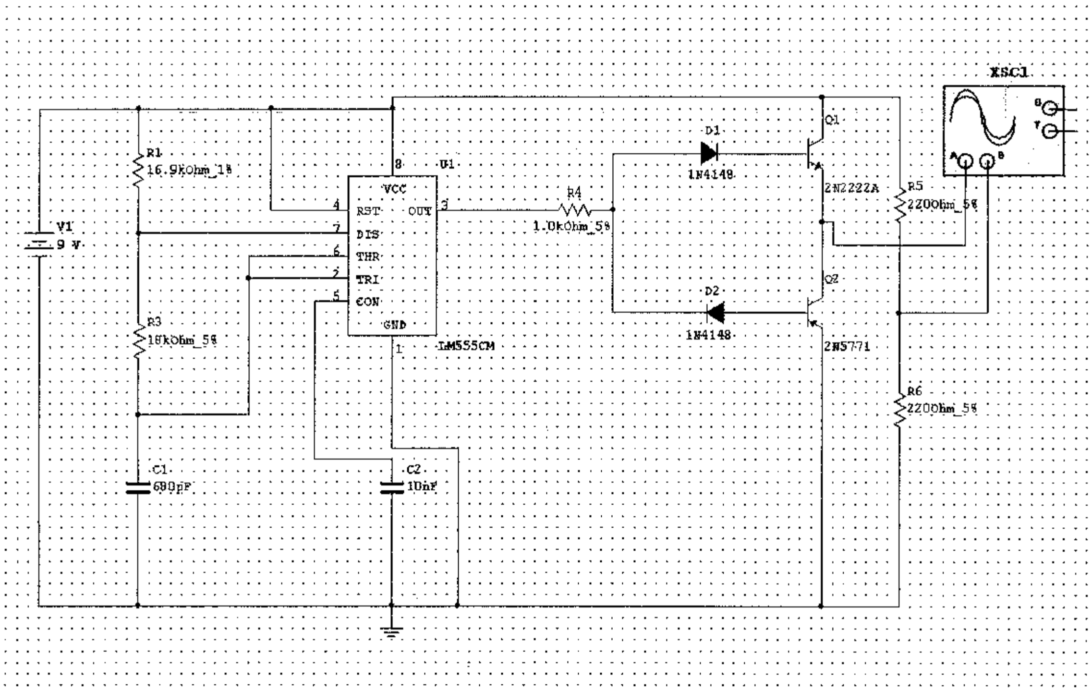
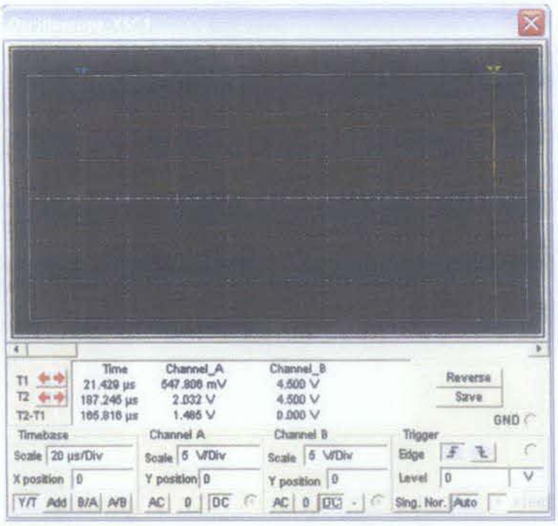


Figure 22 – Ultrasonic Transmitter Circuit Simulation Using Electronic Workbench Multisim

The circuit is desired to be able to produce 40 kHz of sound frequency. By checking with the formula below, theoretically the circuit will be able to produce such frequency.

$$\text{Frequency, } F = \frac{1.44}{(R1 + 2R3) * C1}$$

From the circuit above, R1 = 16.9k Ohm, R3 = 18k Ohm, and C1 = 680p Farad. Thus resulting from the formula, F = 40,031 Hz @ 40k Hz.



	Time	Channel_A	Channel_B
T1	21.429 µs	647.808 mV	4.500 V
T2	187.245 µs	2.032 V	4.500 V
T2-T1	165.816 µs	1.485 V	0.000 V

Timebase
Scale 20 µs/Div
X position 0

Channel A
Scale 5 V/Div
Y position 0

Channel B
Scale 5 V/Div
Y position 0

Trigger
Level 0 V

Figure 23 – Graph Plotting Voltage from Oscilloscope for Ultrasonic Transmitter Circuit

Figure above shows the voltage plot taken from the oscilloscope. The voltage signal (red colored) in square wave pulses is the pulses produced by the 555 timer acting as clock.

F = 40k Hz → T = 1/F = 1/40k = <u>25 microseconds</u>

From the equation above, 25 microseconds (T) is required to complete a frequency cycle of 40k Hz. Thus theoretically, every pulse can only be produce if the period has a minimum of 25 microseconds.

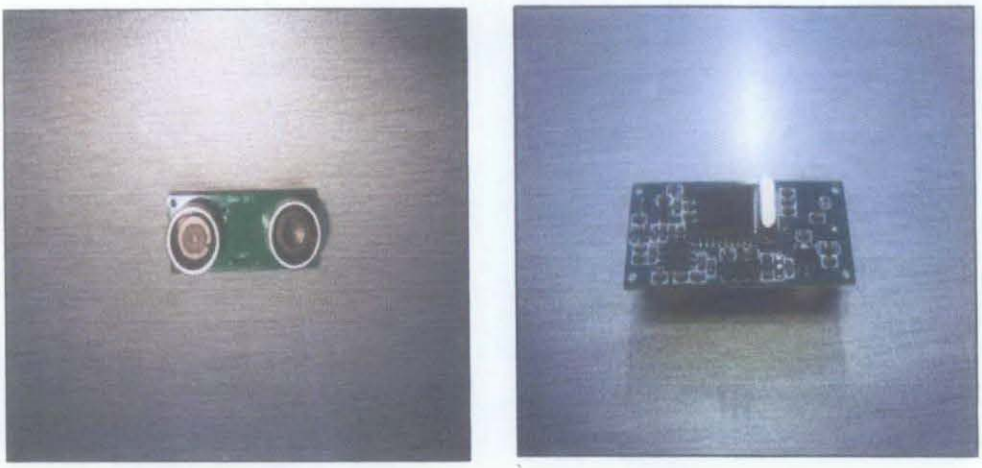


Figure 24 – Ultrasonic sensor

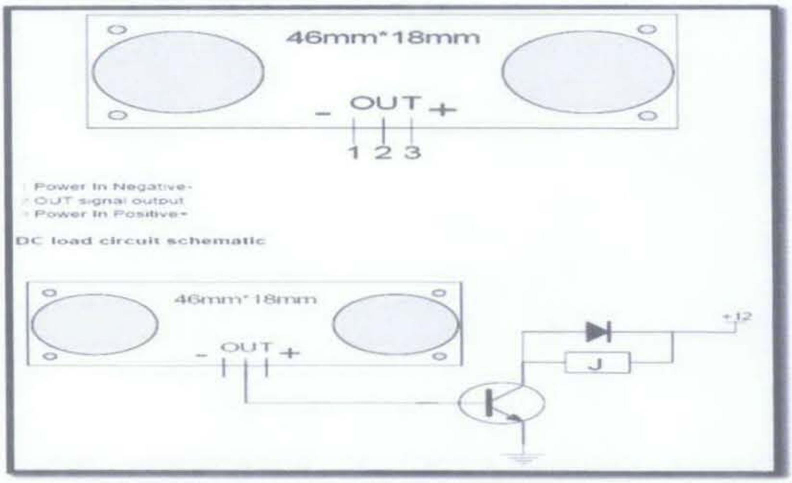


Figure 25 – DC load circuit schematic

Table 3 – Part list for ultrasonic sensor external circuit

PART LIST	DESCRIPTION
Ultrasonic Sensor (Transducer)	Produce and receive pulses of ultrasonic sound to detect obstacles within parameter defined. Default range (21mm – 3m).
TIP41A NPN Power Transistor	Act as switching power transistor to enable 5V of sensor's output to be detected by 24V PLC input module.

When there is obstacle detected, the sensor will produce a 5V pulse through the transistor thus complete the circuit which also connected to a 24V PLC input.

4.1.3 Locomotion System

Table 4 – Comparison between Wheel, Track and Leg

CRITERIA	WHEEL	TRACK	LEG
Size	Varied. Does not necessarily depend on the robot size	As similar to the length of the robot for optimize mobility	Does not have variation. Does not relies on the robot size as well
Advantages	- Simple to construct - Provide great maneuvering ability especially when used indoor - Does not require powerful motors	- Able to mow through all sorts of obstacles - Excellent traction and greater stability	- Extra level of mobility compared to wheels and tracks
Disadvantages	- Unable to drive through difficult terrain - With improper design, the robot can easily tip over during turns	- Requires powerful motors - Large friction area between track and terrain surface	- Difficult to design, thus become least favored compared to wheels and tracks
Recommendation	Comparing the advantages, disadvantages and relevancy to the project, wheel is recommended to be used as part of driving system	X	X

4.1.4 Driving System

The driving system consists of a two DC motors for each two drive wheels. The motor is mounted according to 'Front-Drive Motor Mount' method because it simplifies the construction of the robot. The caster wheel is attached at the front to support the prototype movement. The speed of the driving system is determined by equation below:-

$$\underset{\substack{\uparrow\\ \text{(Drive motor speed)}}}{\frac{(72\text{RPM})}{60\text{s}}} \times \underset{\substack{\uparrow\\ \text{(Wheel diameter)}}}{(5\,(\text{cm}))(3.142)} = 18.82\quad \underset{\substack{\uparrow\\ \text{(Linear speed of system)}}}{\frac{\text{(linear revolution)}}{\text{cm.second}}}$$

*The α (linear speed of system) will be determined at latter stage

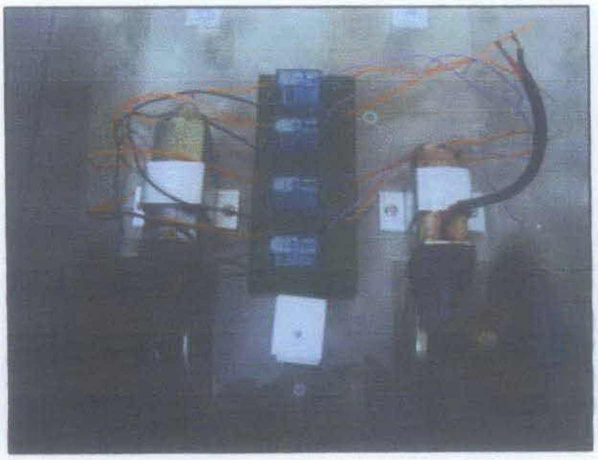


Figure 26 – 12V DC Motors for each Drive Tires

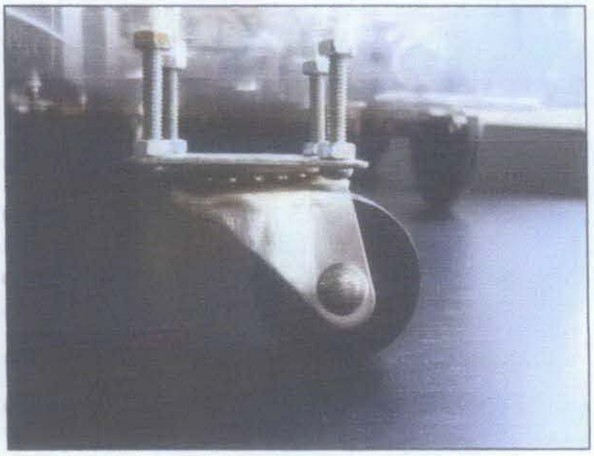


Figure 27 – Caster wheel with bearings

4.1.5 Steering System

The steering system chosen for this project is differential drive system. It manipulates the forward and reverse movement of both left and right DC motors in order to maneuver as desired. For example, if the prototype needs to turn right, the right DC motor can be switch off or spin on reverse motion while the left DC motor move in the forward motion. The opposite movement will create an arc-like turn and the process will end when the angle of turn has been met. The figure of the differential drive system is shown as below:-

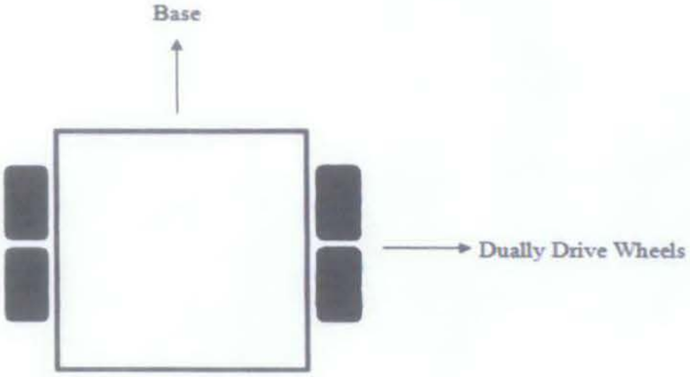


Figure 28 – Differential drive system for autonomous mobile robot

4.1.6 DC Motor Control

The circuit below operates for both ON/OFF state and FORWARD/REVERSE control. In this project, 24V double pole double throw (DPDT) relays are used for both switching and direction control. 24V relay was chosen as it compatible to PLC output modules voltage rating which is 24V. From the figure below, when the first relay contact is on normally open position, the motor is OFF. When the relay is powered and the contact is on normally close position, the motor is then turn ON. The same concept goes for direction control relay. On normally open position, the motor is connected in reverse with the power supply thus create a reverse movement while on normally close position, the motor will move in forward direction.

- When input is HIGH (relay is powered):-
    - switching relay switch ON the DC motor.
    - direction relay turn DC motor in REVERSE direction

- When input is LOW (relay is not powered):-
    - switching relay switch OFF the DC motor.
    - direction relay turn DC motor in FORWARD direction.

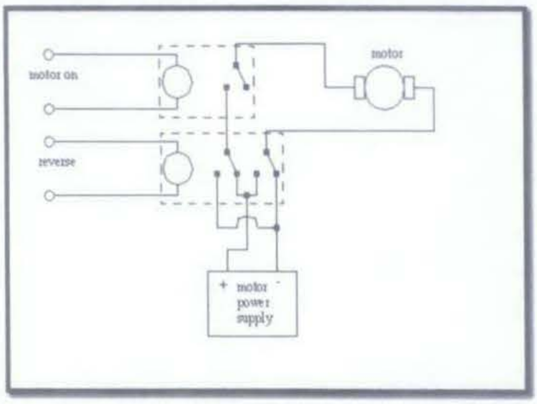


Figure 29 –Relay Based Circuit for DC Motor Control

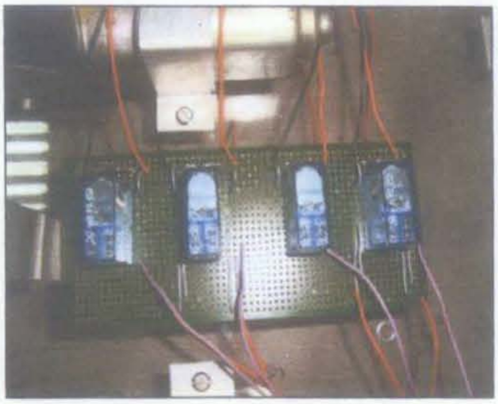


Figure 30 – DC Motor Control Circuit

4.1.7 Prototype Constructions

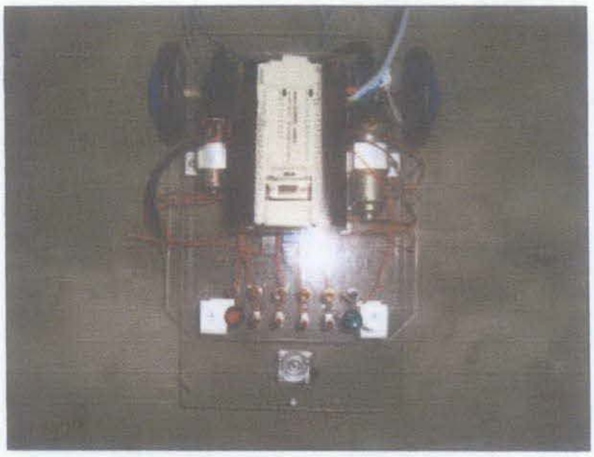


Figure 31 – Upper view of prototype

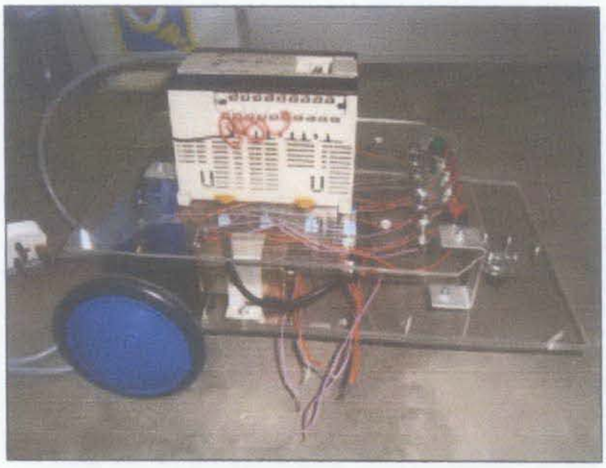


Figure 32 – Side view of prototype

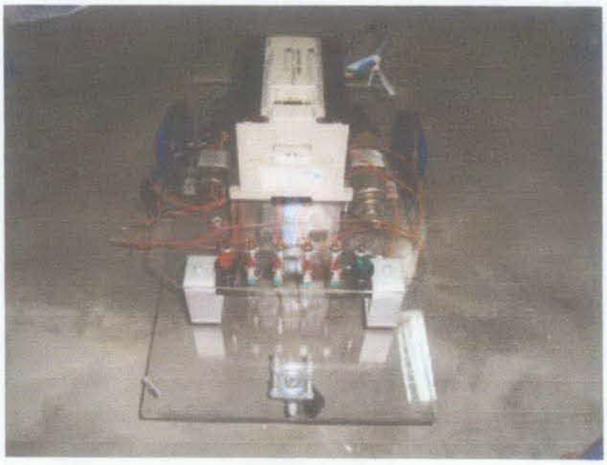


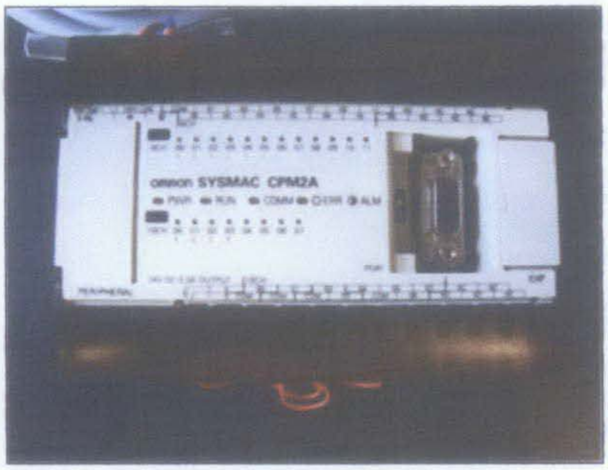
Figure 33 – Front view of prototype

4.1.8 Control System

The control system for this prototype is the OMRON SYSMAC CPM2A Programmable Logic Controller (PLC). It has 12 input modules and 8 output modules. Both modules have their own voltage supply of 24V with 0.3A of current. The input and output connected to the PLC are listed in the table below. The prototype also has a control panel with switches to provide initial input for the PLC. The 24V pilot LED lamp is attached to every switch to indicate its current state.

Table 5 – Input and Output list for the Control System (PLC)

INPUT	OUTPUT
Ultrasonic sensors: • Front left position • Front right position	24V Relays connected to DC Motor: • Left and Right DC Motor: - ON/OFF relays - Direction relays
Push buttons: • Green button – Start button • Red button – Stop/Reset button	Buzzer: • Activate whenever the sensors detect obstacle ahead.
Toggle Switches: • Toggle switch 1 – Activate Mode 1 • Toggle switch 2 – Activate Mode 2 • Toggle switch 3 – Activate Mode 3 • Toggle switch 4 – Activate Mode 4	Voltage supply: • DC Motors (both left and right) • Ultrasonic sensors (both left and right)



- OMRON SYSMAC CPM2A Programmable Logic Controller with 12 Input and 8 Output modules.

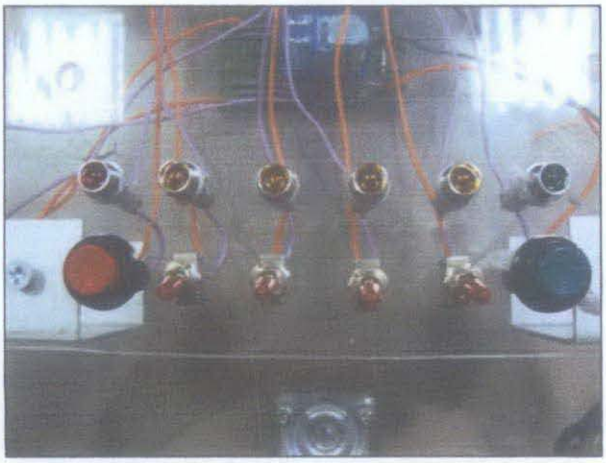
- The modules able to supply 24V of voltage and 0.3A of current.

Figure 34 – Upper view of Programmable Logic Controller (PLC)

- 12V buzzer is used to indicate the existence of obstacle when detected by the ultrasonic sensors.

- The buzzer will stop buzzing when the obstacle is removed.

Figure 35 – 12V Buzzer



- Prototype control panel.
- The pushbuttons are used for start and stop operation.
- The toggle switches are used for mode select.
- The 24V pilot lamps are used to indicate the current state of control panel.

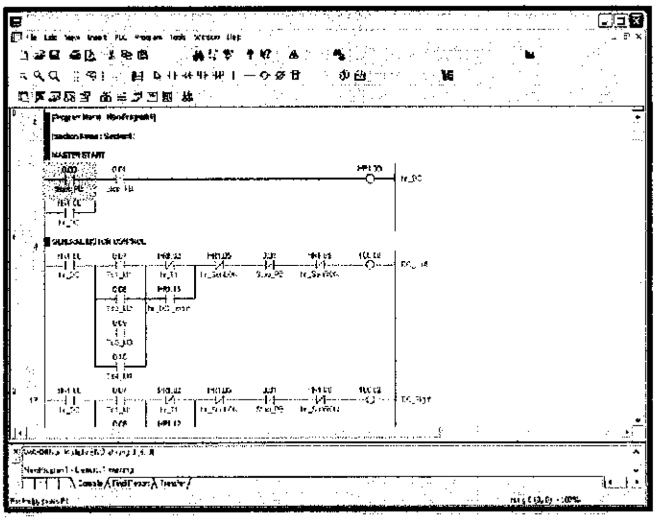
Figure 36 – Prototype Control Panel

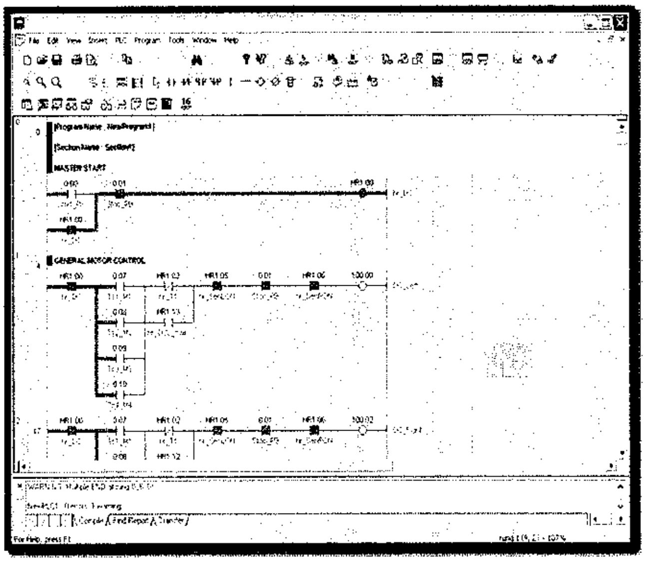
4.1.9 PLC Programming & Simulation

The Programmable Logic Controller (PLC) is programmed using CX-Programmer software and simulated using OMRON PLC Training Kit. The programming method used is ladder diagram method. This method is chosen due its simplicity to construct and troubleshoot. According to the prototype path planning (refer to page 29), there are four destination points the prototype can move to.

There are four toggle switches where each represents the four destination points. For example, in order for the prototype to be able to move to destination point 4, the fourth toggle switch should be switched on and the rest of the switches should be turned off. During this operation, the prototype will move from its original position and move through the path across the point 1, 2, and 3 to reach the destination point 4. Once reached, the prototype will reverse and move across the same path but in the opposite way to reach its original position.

The prototype is programmed to operate in timer base. Thus the PLC is programmed heavily with collection of timers. The main timer used to provide the distance measurement is the Totalizing Timer. The value for the timer represents the distance which converted in time-base domain. Thus, if the timer done with its counting, it indicates the prototype had travelled the required distance and the control system (PLC) will instruct the DC motors to stop.





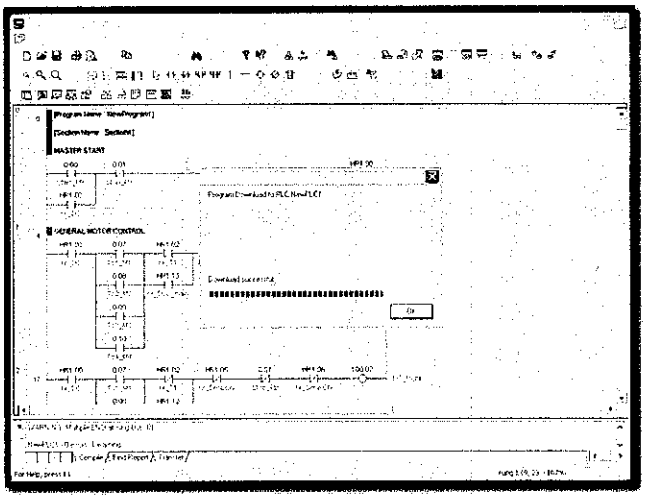


Figure 37 – Examples of ladder diagram programming using CX-Programmer software

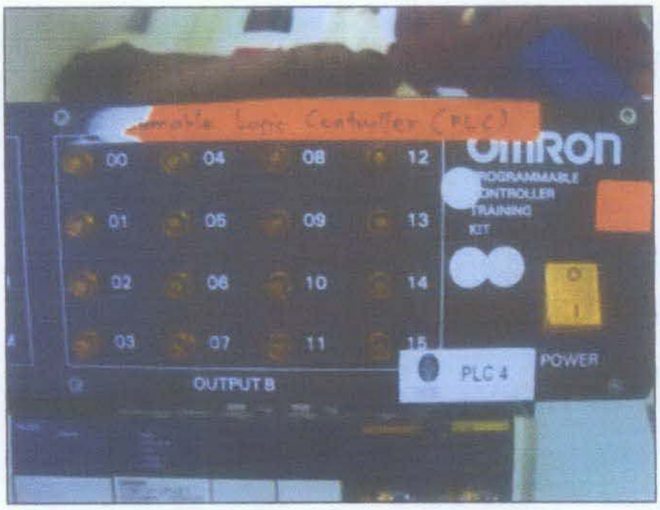


Figure 38 – Omron PLC Training Kit with Output Display.

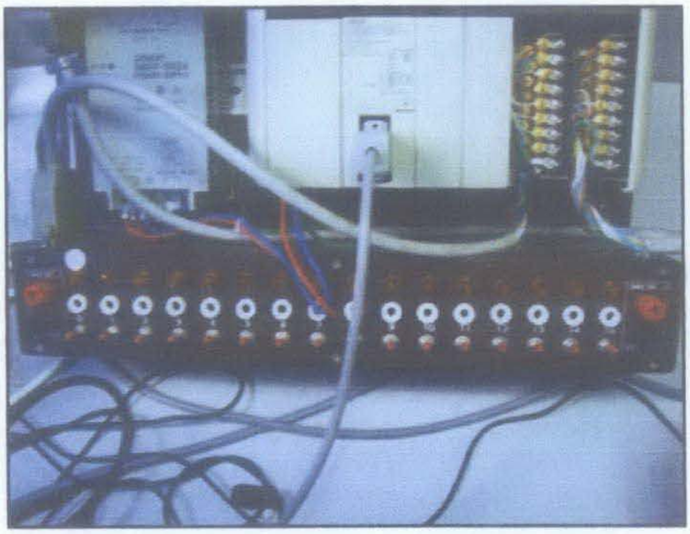


Figure 39 – Omron PLC Training Kit with Input Switches

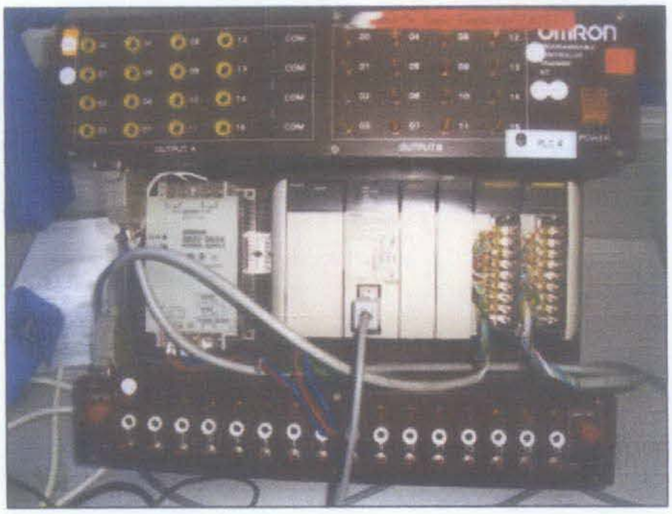


Figure 40 – Omron PLC Training Kit used for Input/output Simulation

4.2 Discussions

4.2.1 Electronics Circuitries

- The initial development of ultrasonic sensor did not produce the desired output pulses. This lead to the use of commercial ultrasonic sensor in order to reduce time consumption in this section. There are several implementation issues as the sensor only needs 6-12V of voltage supply and also producing a discrete HIGH output of 5V and LOW output of 0V. The 5V output signal could not be detected directly by the 24V PLC input modules. Thus, an external circuit using a transistor is implemented to produce an output readable by the PLC input modules.

- Voltage divider concept is applied to step down the 24V voltage supplied by PLC input/output modules to supply the sensors (6-12V) and DC motors (12V).

- 12V Buzzer is used to indicate the existence of obstacle if there is any detected by ultrasonic sensors. When obstacle detected, the control system (PLC) will stop the DC motors and the buzzer will buzz until the obstacle is removed. After the removal, the buzzer will stop buzzing and the DC motor will continue to run depending on the control system (PLC).

4.2.2 PLC Programming & Simulation

- The PLC programming is developed in CX-Programmer software and then simulated using OMRON PLC Controller Kit. This enable easier troubleshooting on the programming developed (ladder diagram) as the training kit provide the indicators function as input and output simulation.

- Since physical distance measurement such as shaft encoder is not used, the distance measurement is implemented through PLC programming where the linear speed of the prototype is converted (interpolated) into time-base. The values then implemented using programmed timers.

4.2.3 Prototype Construction

- The prototype is designed in two layers of perspex in order to separate the control layer with the circuitries layer for safety precaution.
- During the alignment test, the alignment of the tires needed to be adjusted in order to obtain accurate straight line movement.
- Throughout the development of the prototype, various changes has been made to simplify the overall design and reduce cost. For example, initial design used stepper motor as the steering system but due to its complexity, the differential drive steering system is chosen instead by using the DC motors.

CHAPTER 5

CONCLUSIONS

5.1 Conclusions

This project has been developed thoroughly and able to meet the objectives required. Intense reviews on literature works has been done to gain insight knowledge on the autonomous robotic system. The scope of study for this project which are the electronics, mechanical and programming have contributed to the development of the prototype that currently possessing the similar system to autonomous robotic system. The methodology implemented also important in providing the guideline for this project. After several months of research and development, the prototype finally possesses the ability as an autonomous robotic system as well as the function to move from one point to another precisely. Even though the prototype still yet to be fully working, the tests conducted for each sub-system had produced the desired results thus lead to believe that given few more tests, the prototype can fully achieve its objectives.

5.2 Recommendations

- The electronics parts can be revised and simplified if possible to minimize the power usage.
- The AC-powered OMRON PLC can be changed using the 24V DC-voltage controller in order to gain maximum mobility. Using the current controller (AC supplied) requires the cable to be plugged in order to gain voltage source thus limits the movement of the prototype.
- The ladder diagram can be revised and simplified if possible to minimize the complexity as well as increase the efficiency of the programming.
- The wires can be tagged for easier identification for future troubleshooting.
- Since the prototype has not fully working yet, more tests and troubleshooting must be done in order for the prototype to achieve its objectives.
- The prototype should be continuously examined during operating mode in order to detect real-time problems the prototype potentially having.

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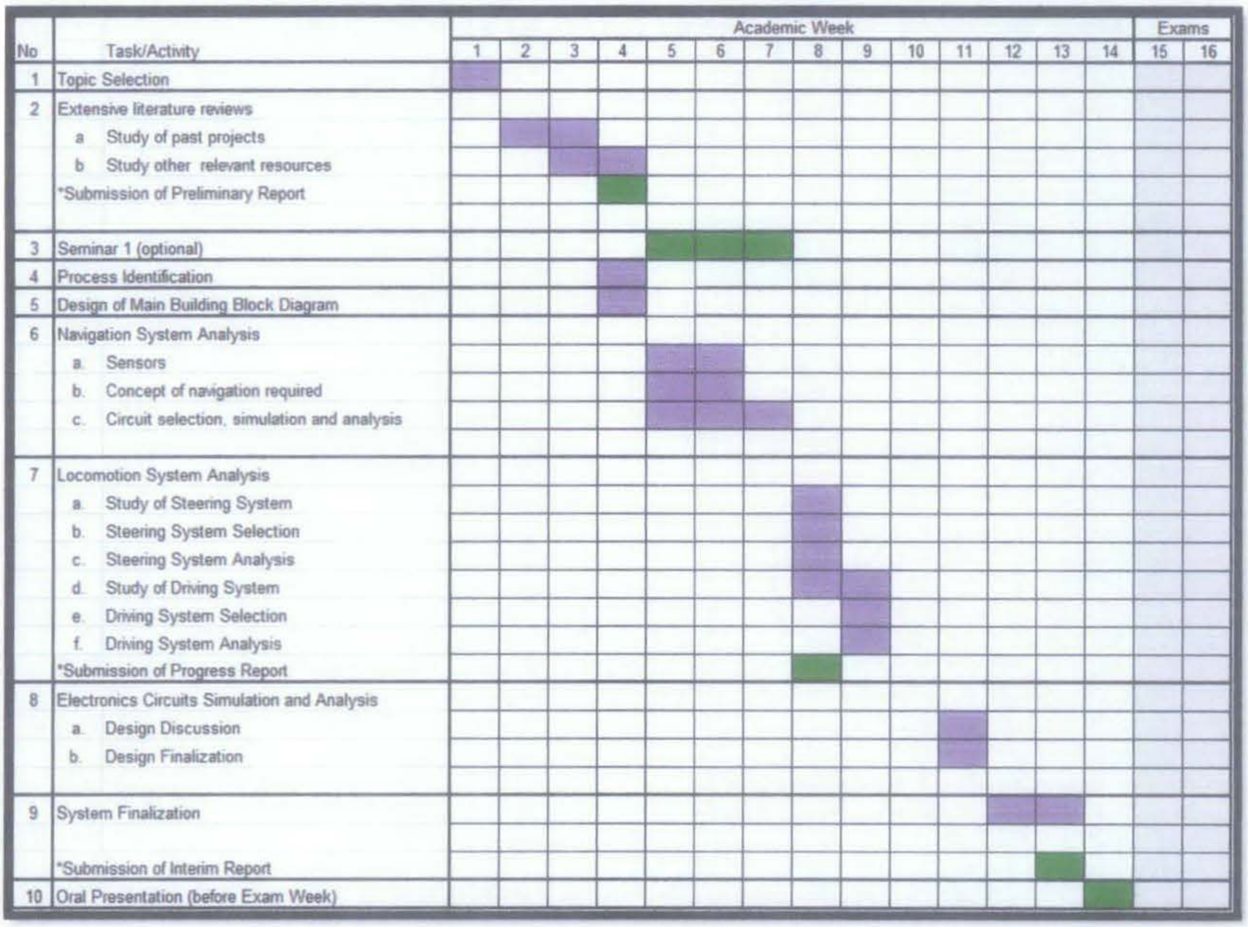
APPENDICES

Appendix A Gantt Chart for FYP I & II

Appendix B Flow Chart for PLC Programming

Appendix C PLC Programming using Ladder Diagram Method

APPENDIX A – GANTT CHART FOR FYP I

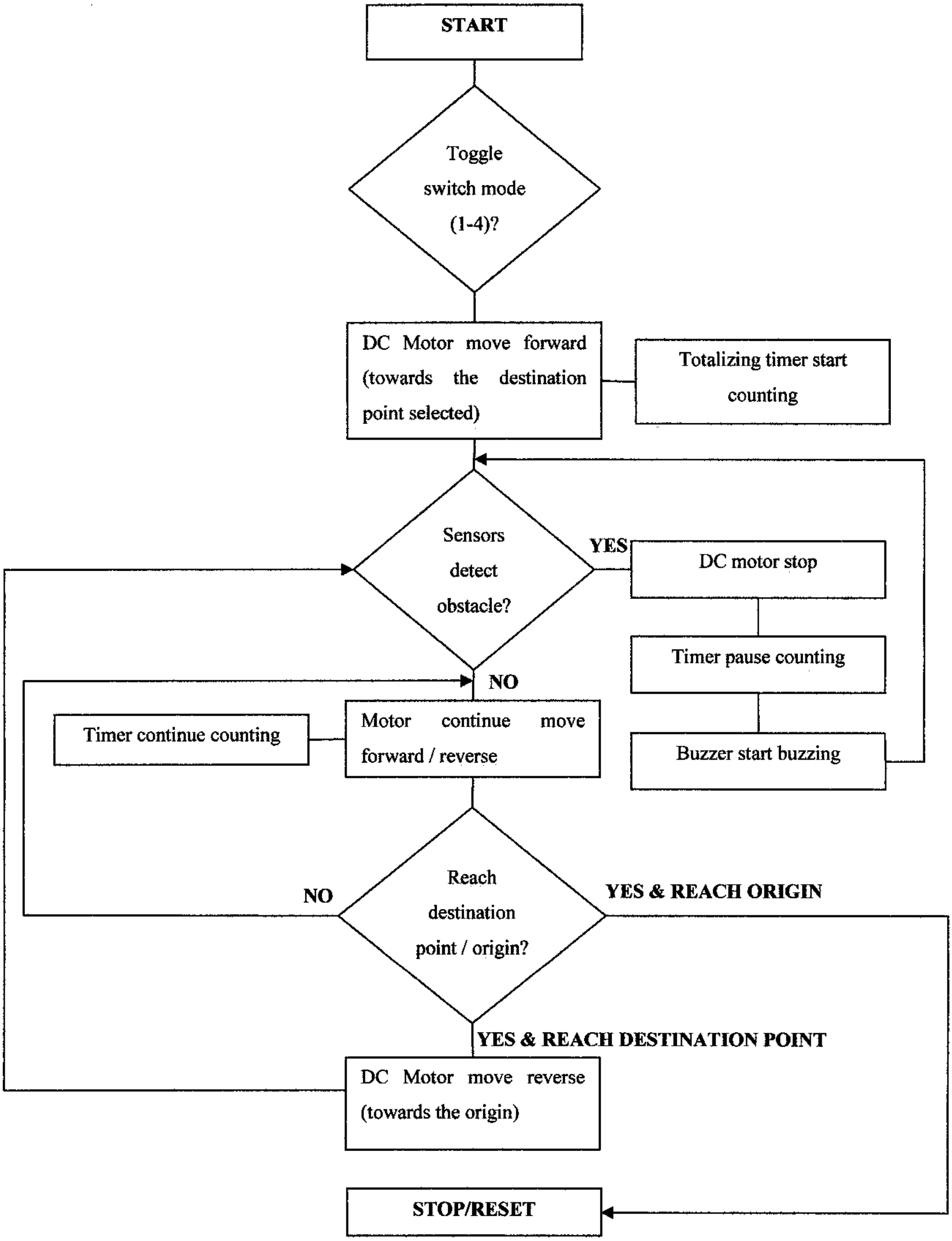


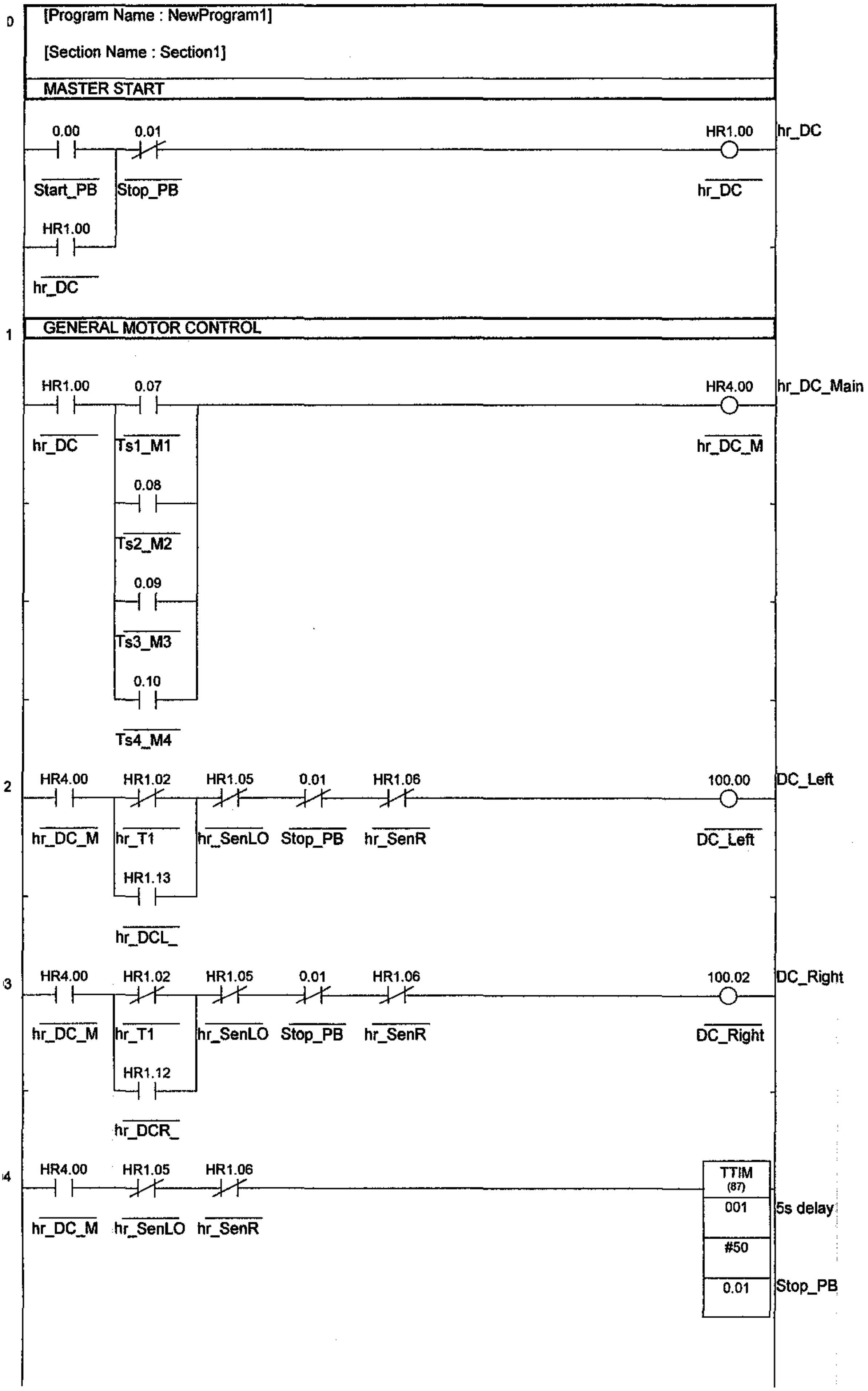
		Academic Week														Exams	
No	Task/Activity	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	Topic Selection	🟪															
2	Extensive literature reviews																
	a Study of past projects		🟪	🟪													
	b Study other relevant resources			🟪	🟪												
	*Submission of Preliminary Report				🟩												
3	Seminar 1 (optional)					🟩	🟩	🟩									
4	Process Identification				🟪												
5	Design of Main Building Block Diagram				🟪												
6	Navigation System Analysis																
	a. Sensors					🟪	🟪										
	b. Concept of navigation required					🟪	🟪										
	c. Circuit selection, simulation and analysis					🟪	🟪	🟪									
7	Locomotion System Analysis																
	a. Study of Steering System								🟪								
	b. Steering System Selection								🟪								
	c. Steering System Analysis								🟪								
	d. Study of Driving System								🟪	🟪							
	e. Driving System Selection									🟪							
	f. Driving System Analysis									🟪							
	*Submission of Progress Report								🟩								
8	Electronics Circuits Simulation and Analysis																
	a. Design Discussion											🟪					
	b. Design Finalization											🟪					
9	System Finalization												🟪	🟪			
	*Submission of Interim Report													🟩			
10	Oral Presentation (before Exam Week)														🟩		

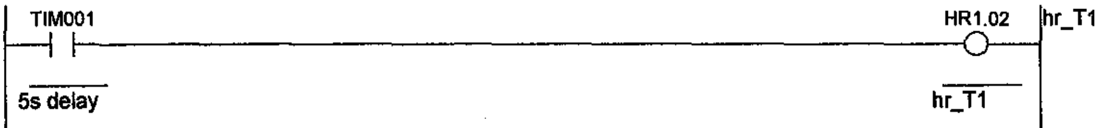
1	PLC Programming & Simulation	🟦	🟦	🟦	🟦													
	*Submission of Progress Report 1				🟥													
2	PLC Programming & Simulation (if unfinished)				🟦	🟦												
3	Construction of Prototype					🟦	🟦	🟦	🟦									
	*Submission of Progress Report 2								🟥									
4	Construction of Prototype (if unfinished)									🟦	🟦	🟦	🟦					
	*Submission of Draft Report												🟥					
5	Prototype Testing & Troubleshooting												🟦	🟦				
	*Submission of Final Report (Soft Cover) & Technical Report													🟥				
6	Prototype Finalization													🟦	🟦			
7	Oral Presentation (after Exam Weeks)																	🟥
7	*Submission of Final Report (Hard Cover)																	🟥

APPENDIX A - GANTT CHART FOR FYP II

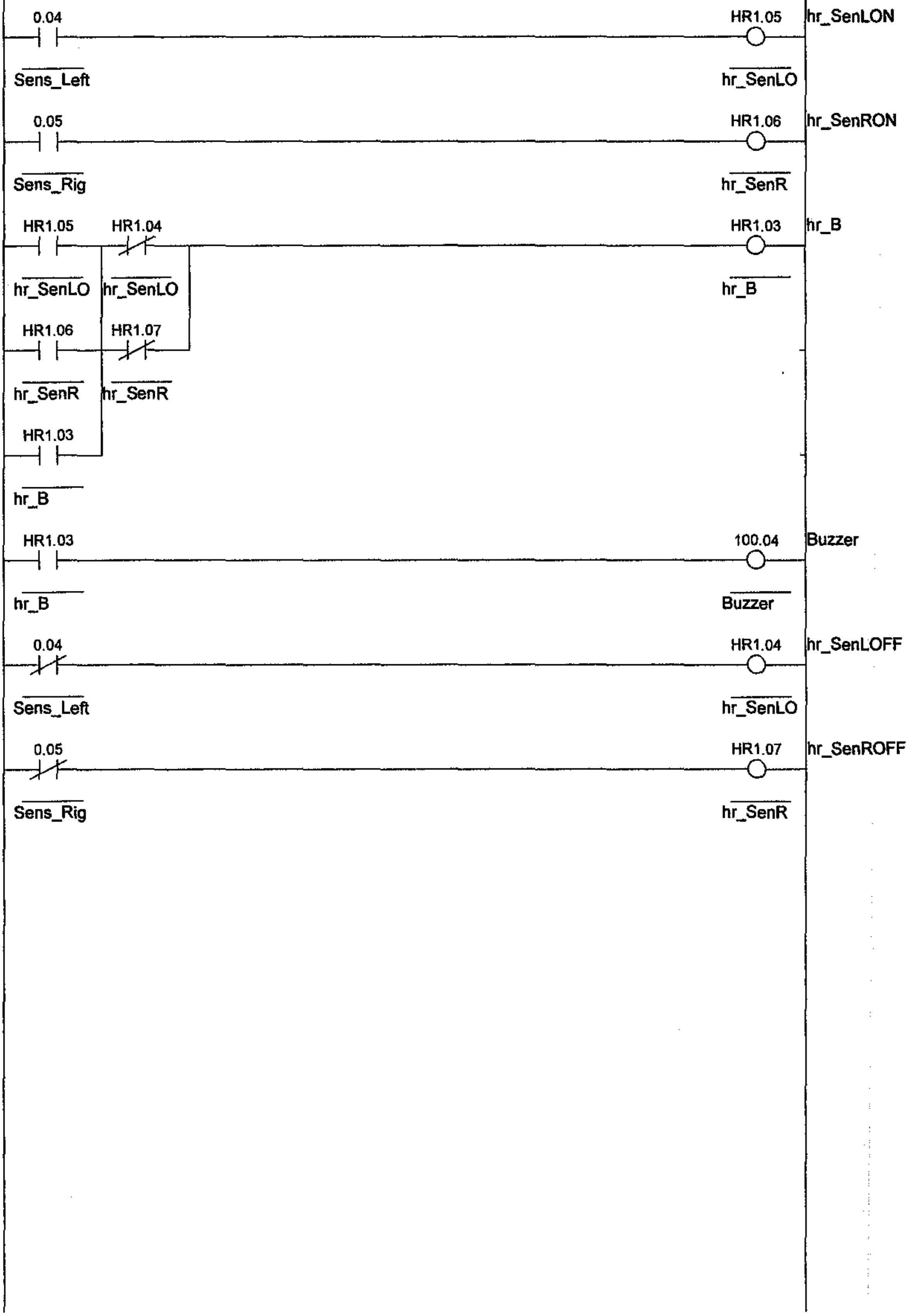
APPENDIX B – FLOW CHART FOR PLC PROGRAMMING

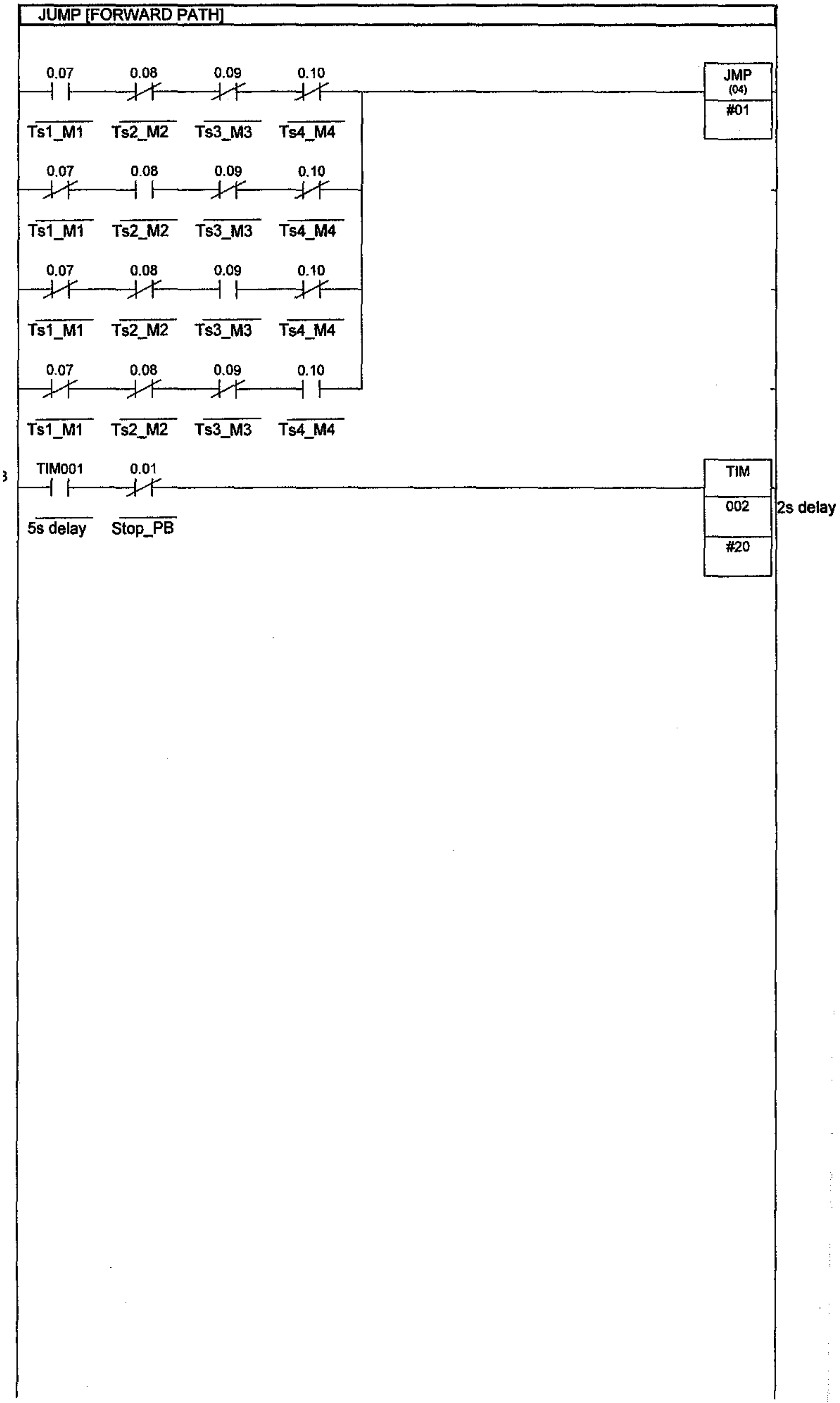


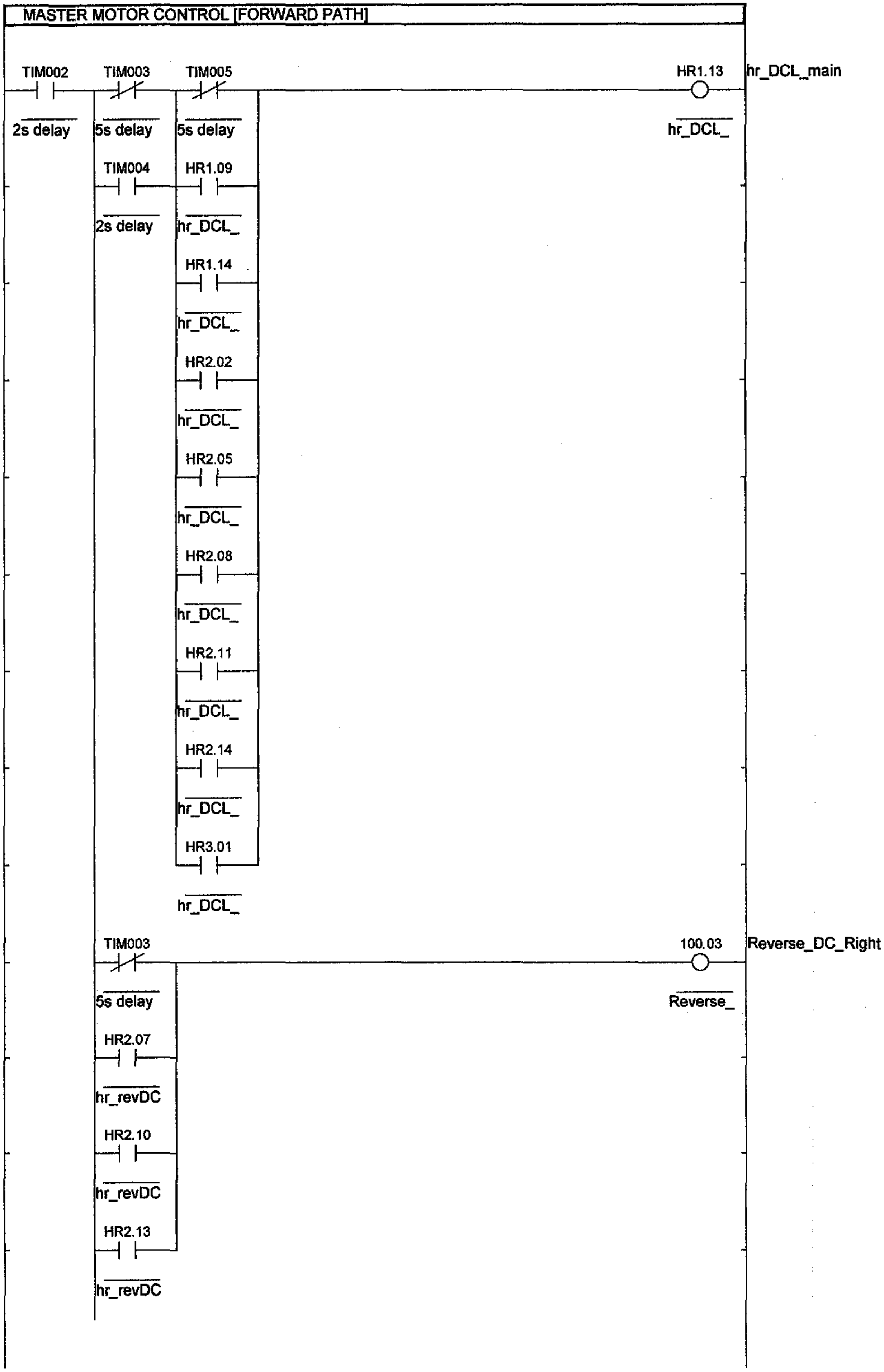

0
[Program Name : NewProgram1]
[Section Name : Section1]
MASTER START
0.00
Start_PB
0.01
Stop_PB
HR1.00
hr_DC
HR1.00
hr_DC
HR1.00
hr_DC
1
GENERAL MOTOR CONTROL
HR1.00
hr_DC
0.07
Ts1_M1
0.08
Ts2_M2
0.09
Ts3_M3
0.10
Ts4_M4
HR4.00
hr_DC_M
hr_DC_Main
2
HR4.00
hr_DC_M
HR1.02
hr_T1
HR1.13
hr_DCL_
HR1.05
hr_SenLO
0.01
Stop_PB
HR1.06
hr_SenR
100.00
DC_Left
DC_Left
3
HR4.00
hr_DC_M
HR1.02
hr_T1
HR1.12
hr_DCR_
HR1.05
hr_SenLO
0.01
Stop_PB
HR1.06
hr_SenR
100.02
DC_Right
DC_Right
4
HR4.00
hr_DC_M
HR1.05
hr_SenLO
HR1.06
hr_SenR
TTIM
(87)
001
5s delay
#50
0.01
Stop_PB

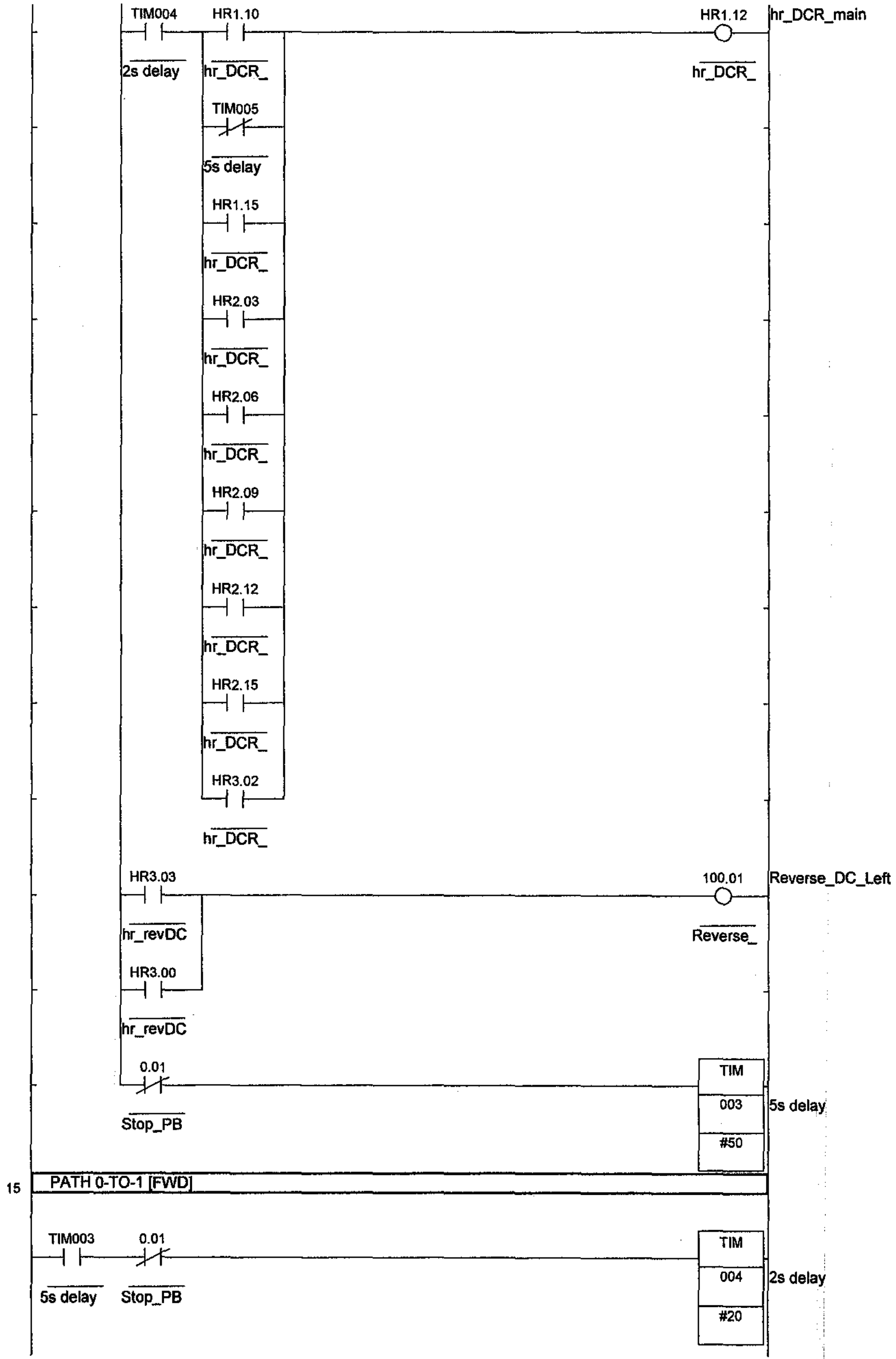


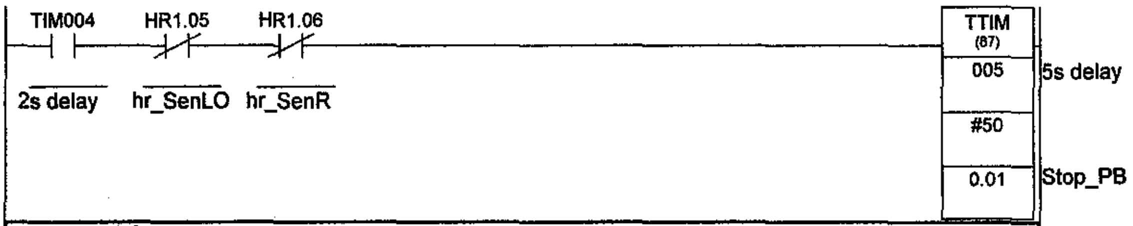
MASTER SENSOR CONTROL



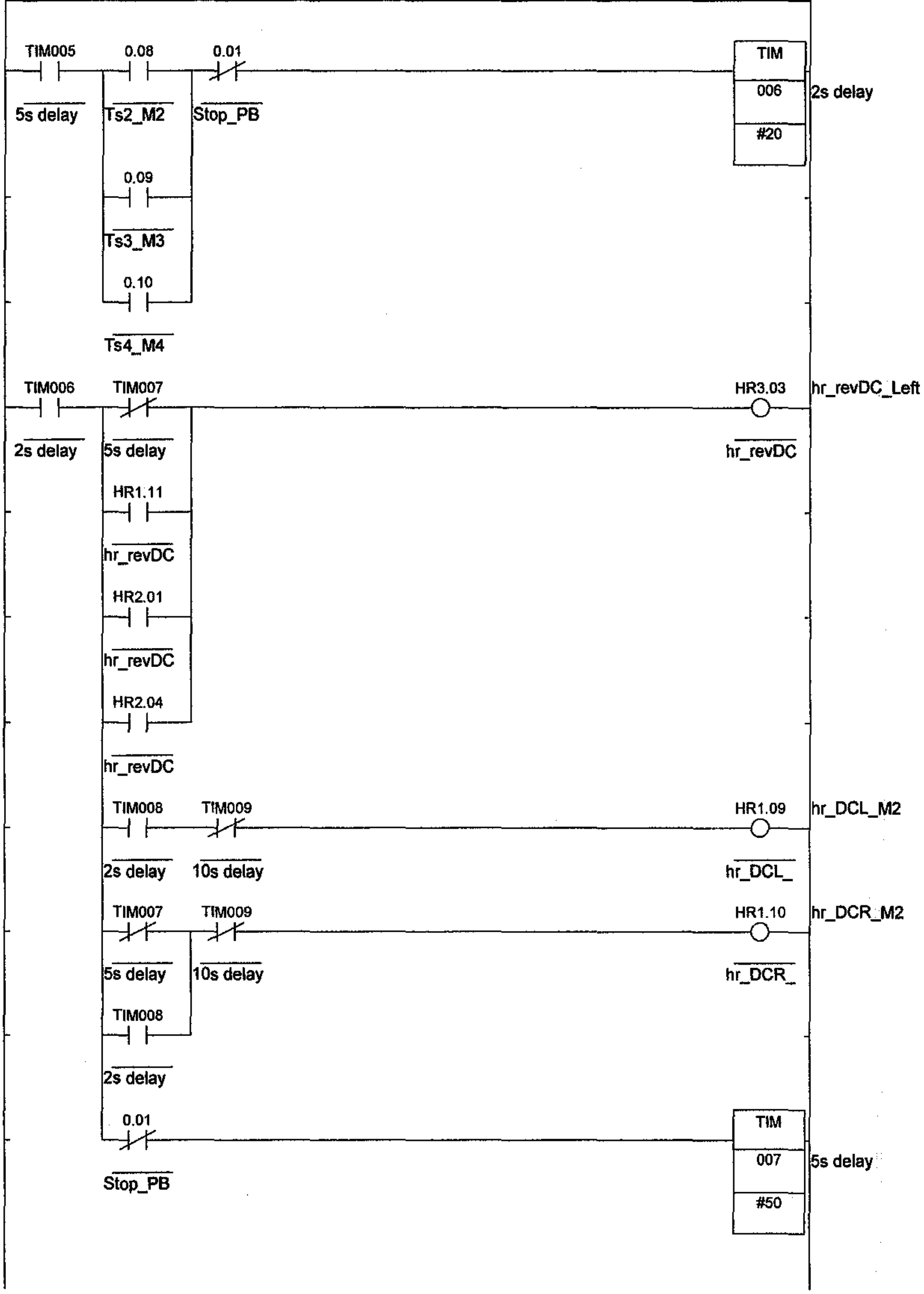

JUMP [FORWARD PATH]
0.07
0.08
0.09
0.10
Ts1_M1
Ts2_M2
Ts3_M3
Ts4_M4
0.07
0.08
0.09
0.10
Ts1_M1
Ts2_M2
Ts3_M3
Ts4_M4
0.07
0.08
0.09
0.10
Ts1_M1
Ts2_M2
Ts3_M3
Ts4_M4
0.07
0.08
0.09
0.10
Ts1_M1
Ts2_M2
Ts3_M3
Ts4_M4
JMP
(04)
#01
3
TIM001
0.01
5s delay
Stop_PB
TIM
002
#20
2s delay

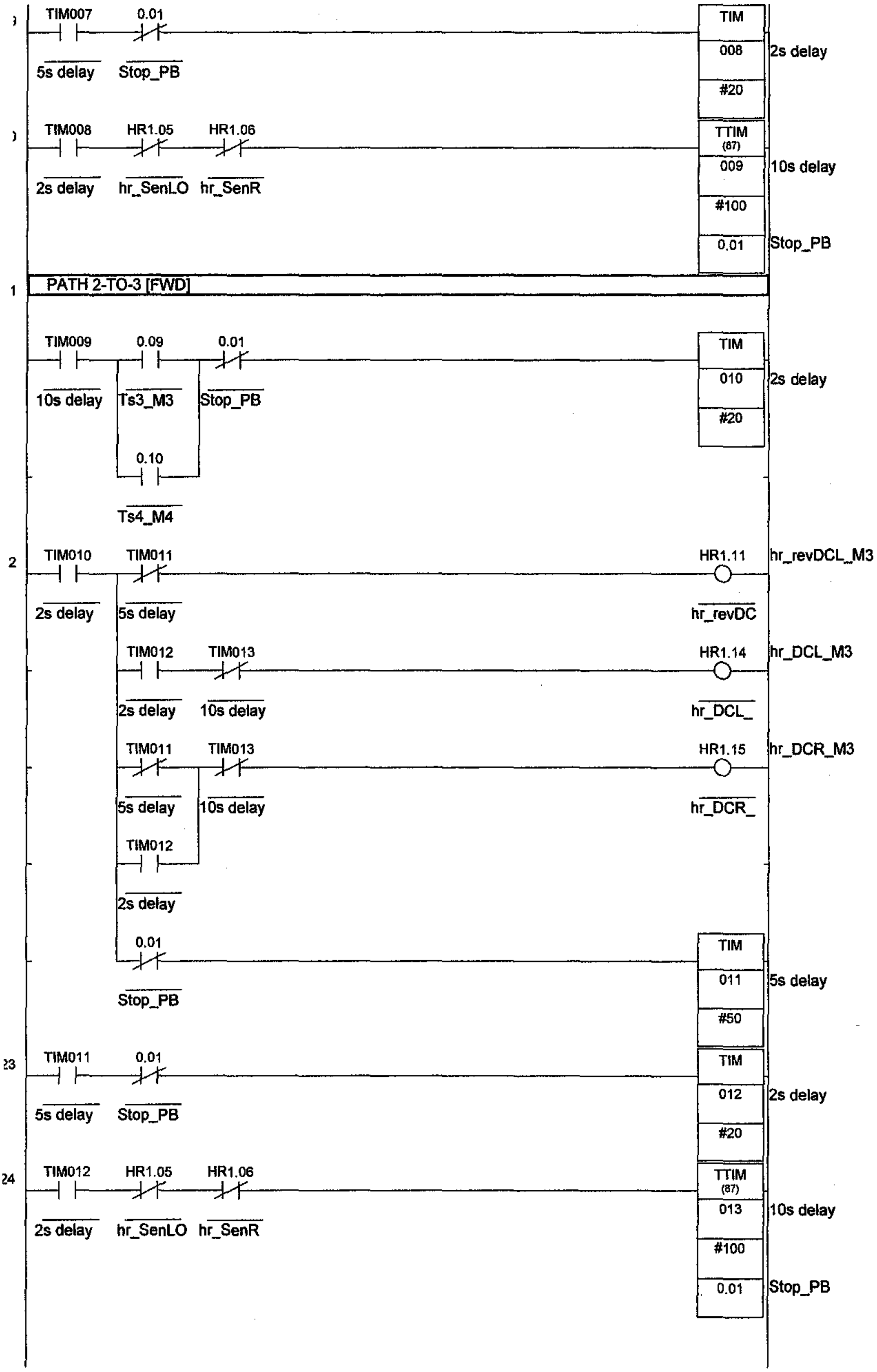

MASTER MOTOR CONTROL [FORWARD PATH]
TIM002
2s delay
TIM003
5s delay
TIM005
5s delay
HR1.13
hr_DCL_
hr_DCL_main
TIM004
2s delay
HR1.09
hr_DCL_
HR1.14
hr_DCL_
HR2.02
hr_DCL_
HR2.05
hr_DCL_
HR2.08
hr_DCL_
HR2.11
hr_DCL_
HR2.14
hr_DCL_
HR3.01
hr_DCL_
TIM003
5s delay
100.03
Reverse_
Reverse_DC_Right
HR2.07
hr_revDC
HR2.10
hr_revDC
HR2.13
hr_revDC

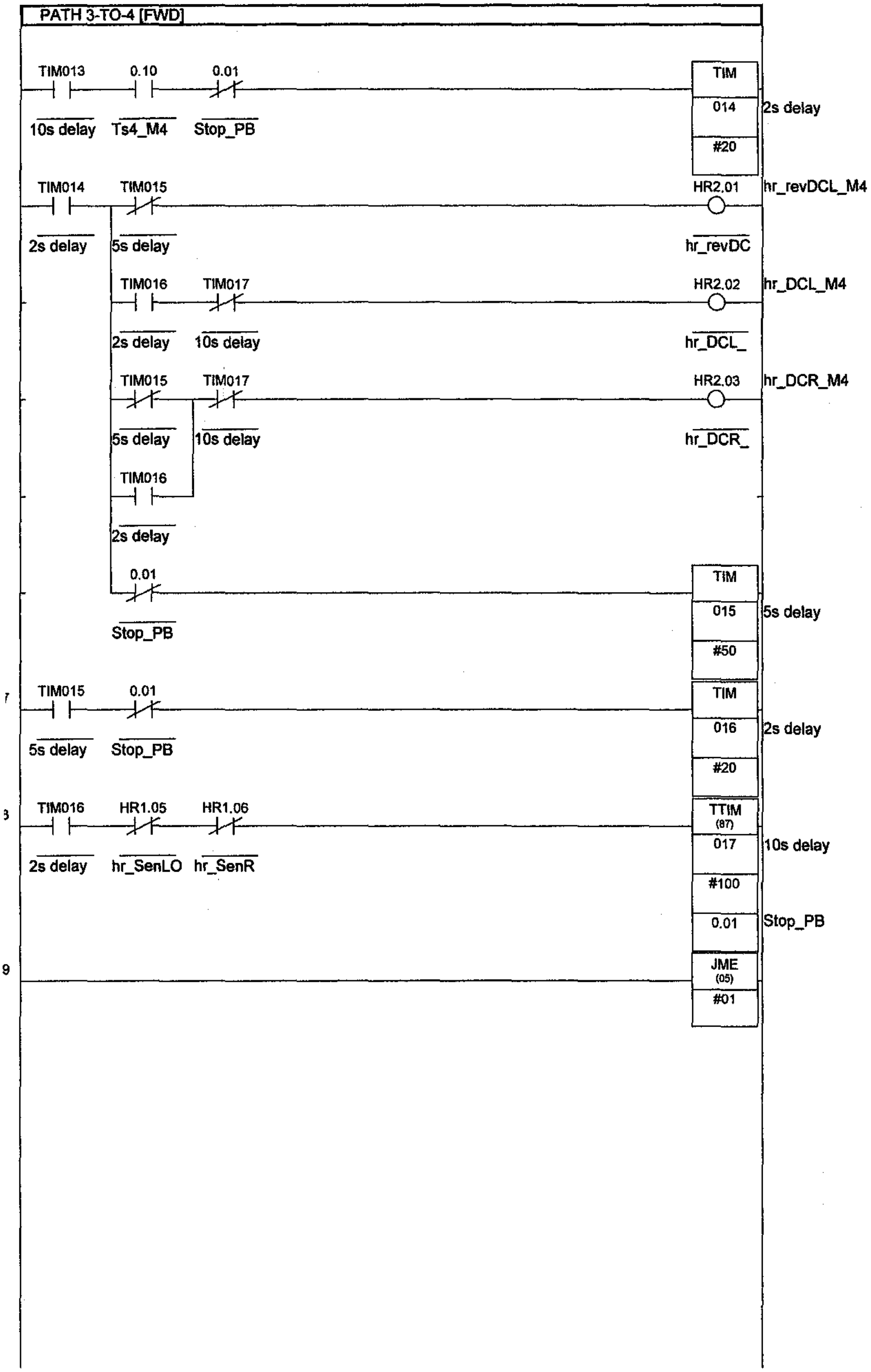

TIM004
2s delay
HR1.10
hr_DCR_
TIM005
5s delay
HR1.15
hr_DCR_
HR2.03
hr_DCR_
HR2.06
hr_DCR_
HR2.09
hr_DCR_
HR2.12
hr_DCR_
HR2.15
hr_DCR_
HR3.02
hr_DCR_
HR1.12
hr_DCR_
hr_DCR_main
HR3.03
hr_revDC
HR3.00
hr_revDC
100.01
Reverse_
Reverse_DC_Left
0.01
Stop_PB
TIM
003
#50
5s delay
15
PATH 0-TO-1 [FWD]
TIM003
5s delay
0.01
Stop_PB
TIM
004
#20
2s delay

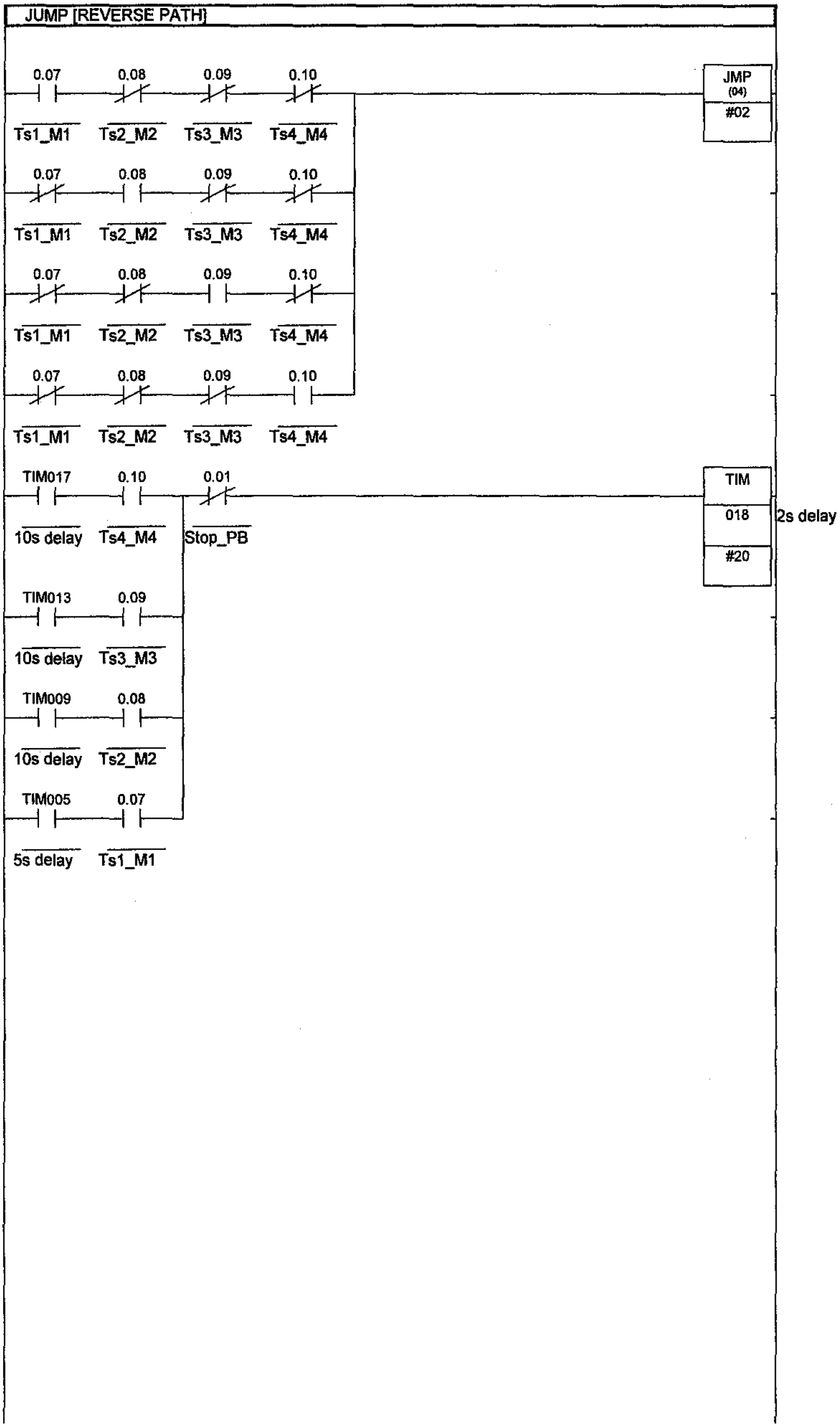


PATH 1-TO-2 [FWD]

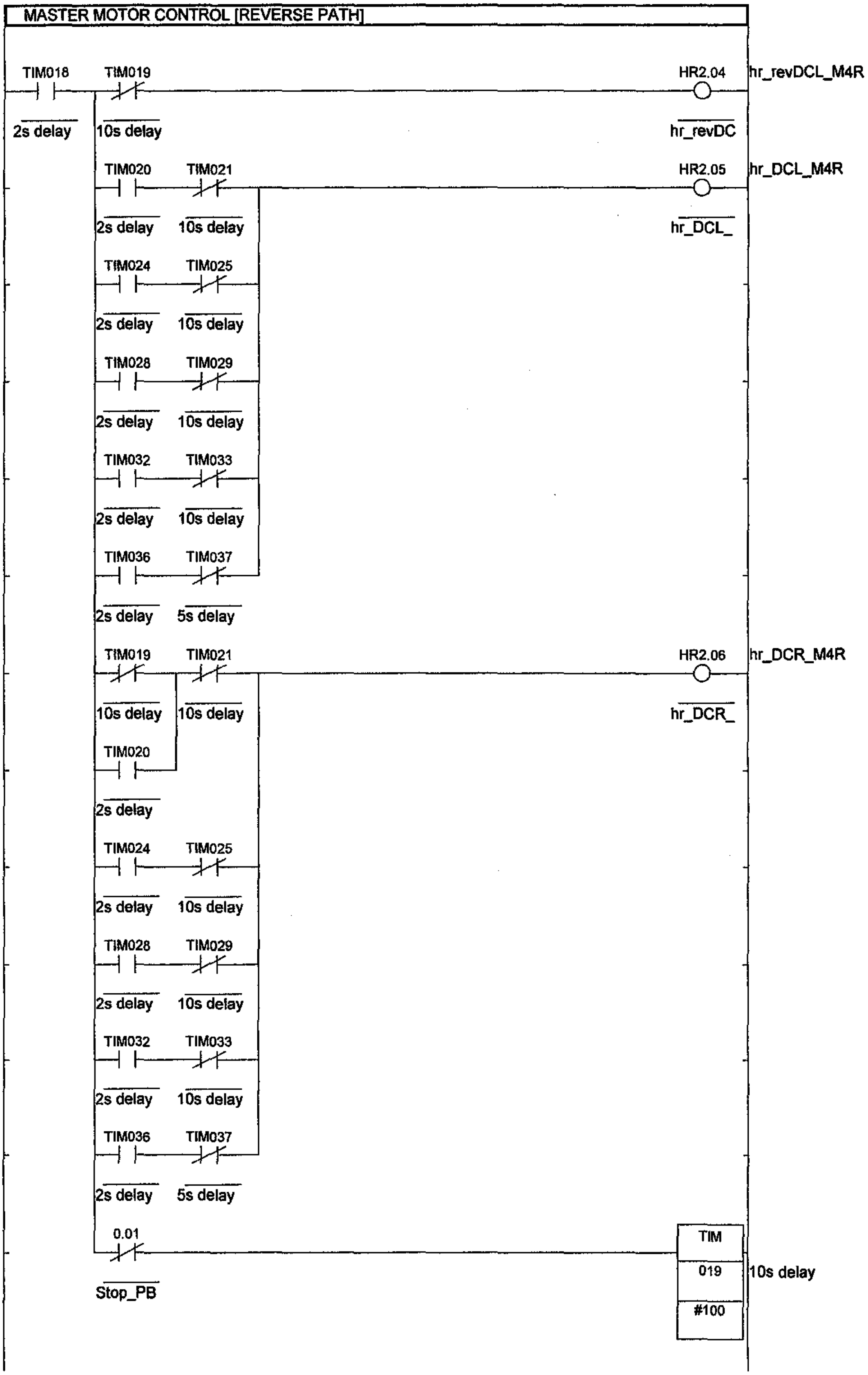


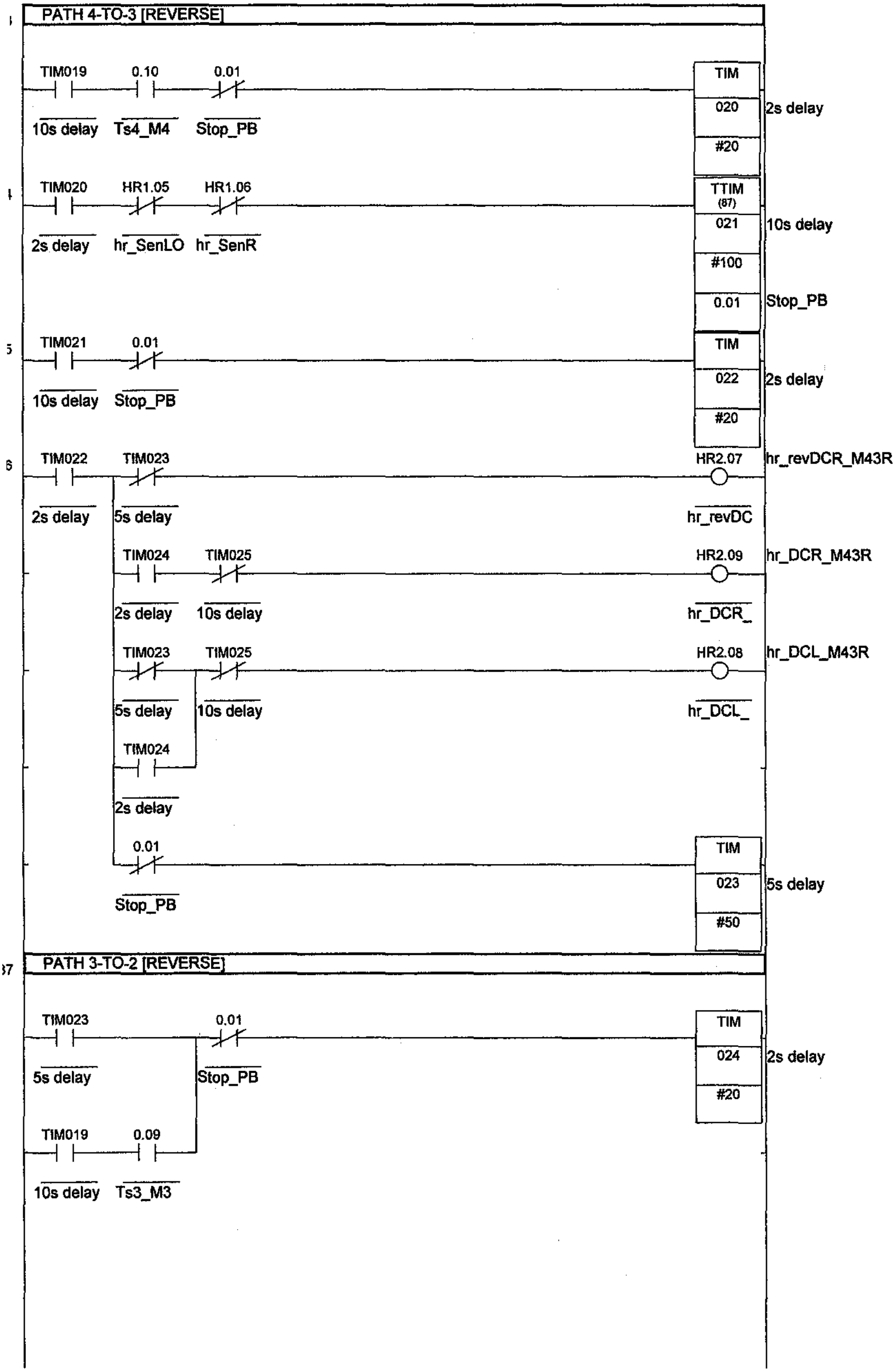

TIM007
0.01
5s delay
Stop_PB
TIM
008
#20
2s delay
TIM008
HR1.05
HR1.06
2s delay
hr_SenLO
hr_SenR
TTIM
(87)
009
#100
0.01
10s delay
Stop_PB
1
PATH 2-TO-3 [FWD]
TIM009
0.09
0.01
10s delay
Ts3_M3
Stop_PB
0.10
Ts4_M4
TIM
010
#20
2s delay
2
TIM010
TIM011
2s delay
5s delay
HR1.11
hr_revDC
hr_revDCL_M3
TIM012
TIM013
2s delay
10s delay
HR1.14
hr_DCL_
hr_DCL_M3
TIM011
TIM013
5s delay
10s delay
HR1.15
hr_DCR_
hr_DCR_M3
TIM012
2s delay
0.01
Stop_PB
TIM
011
#50
5s delay
23
TIM011
0.01
5s delay
Stop_PB
TIM
012
#20
2s delay
24
TIM012
HR1.05
HR1.06
2s delay
hr_SenLO
hr_SenR
TTIM
(87)
013
#100
0.01
10s delay
Stop_PB

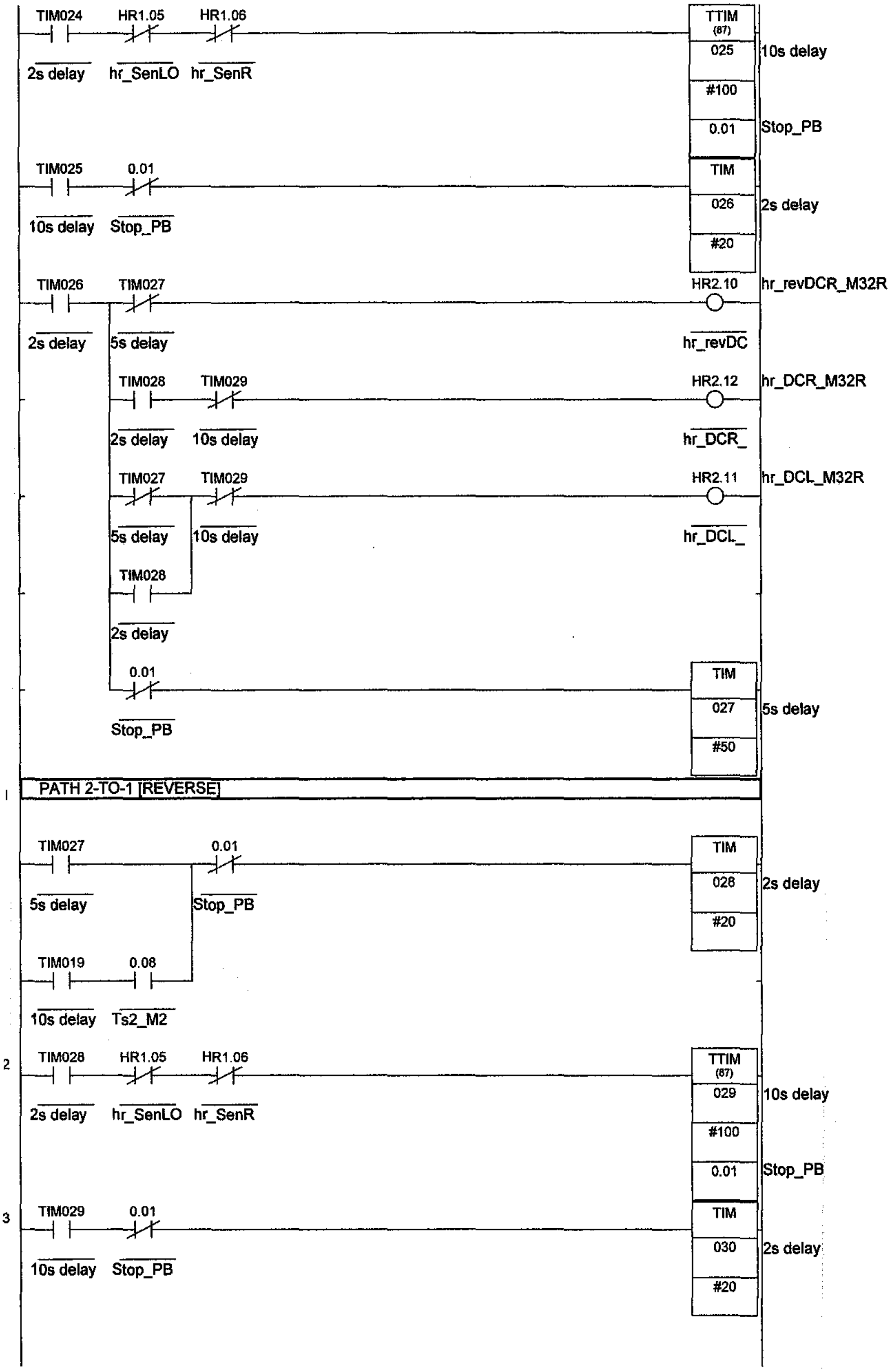

PATH 3-TO-4 [FWD]
TIM013
10s delay
0.10
Ts4_M4
0.01
Stop_PB
TIM
014
#20
2s delay
TIM014
2s delay
TIM015
5s delay
HR2.01
hr_revDC
hr_revDCL_M4
TIM016
2s delay
TIM017
10s delay
HR2.02
hr_DCL_
hr_DCL_M4
TIM015
5s delay
TIM017
10s delay
HR2.03
hr_DCR_
hr_DCR_M4
TIM016
2s delay
0.01
Stop_PB
TIM
015
#50
5s delay
TIM015
5s delay
0.01
Stop_PB
TIM
016
#20
2s delay
TIM016
2s delay
HR1.05
hr_SenLO
HR1.06
hr_SenR
TTIM
(87)
017
#100
0.01
10s delay
Stop_PB
9
JME
(05)
#01

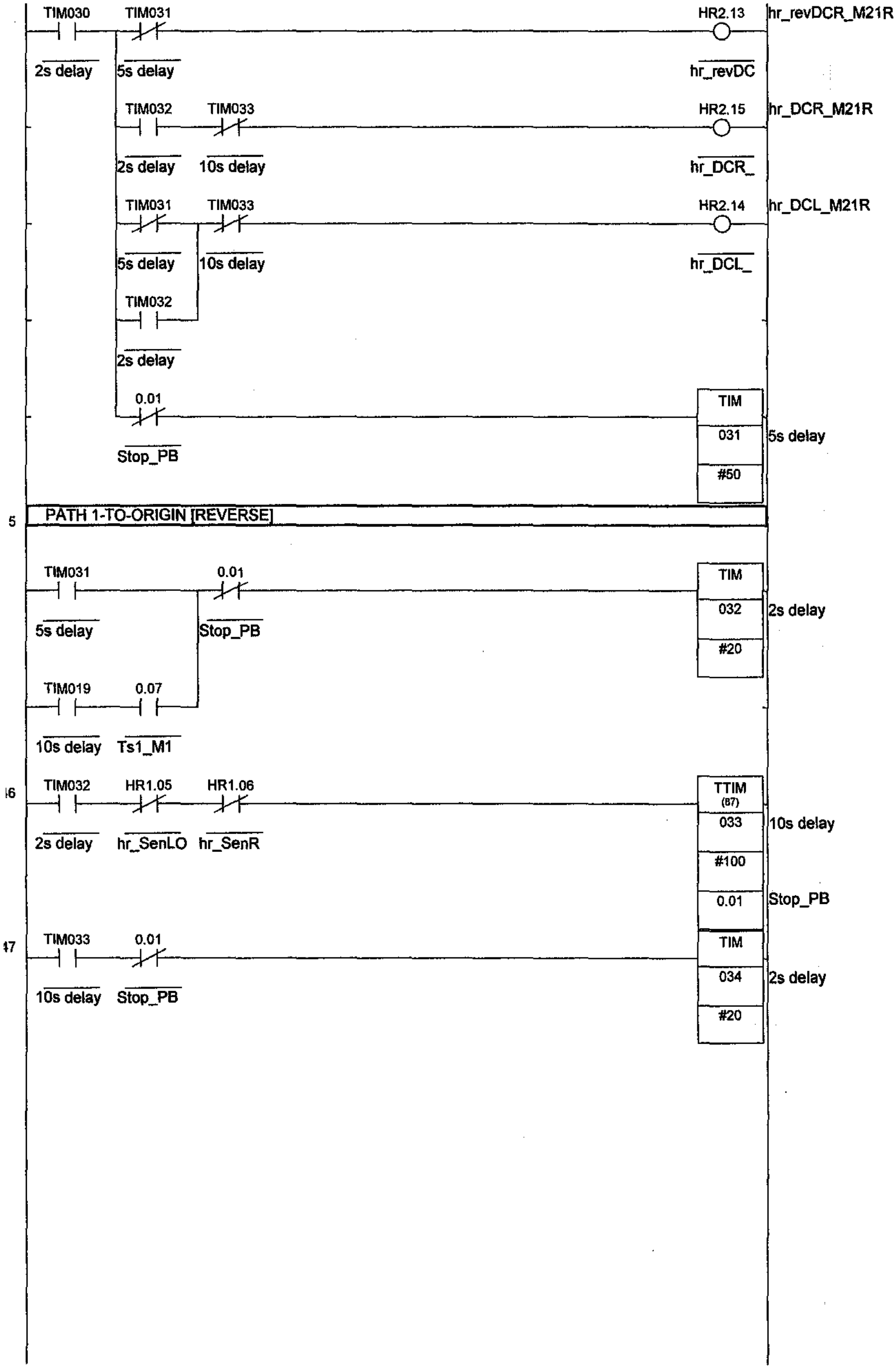

JUMP [REVERSE PATH]
0.07
0.08
0.09
0.10
Ts1_M1
Ts2_M2
Ts3_M3
Ts4_M4
JMP
(04)
#02
0.07
0.08
0.09
0.10
Ts1_M1
Ts2_M2
Ts3_M3
Ts4_M4
0.07
0.08
0.09
0.10
Ts1_M1
Ts2_M2
Ts3_M3
Ts4_M4
0.07
0.08
0.09
0.10
Ts1_M1
Ts2_M2
Ts3_M3
Ts4_M4
TIM017
0.10
0.01
TIM
10s delay
Ts4_M4
Stop_PB
018
2s delay
#20
TIM013
0.09
10s delay
Ts3_M3
TIM009
0.08
10s delay
Ts2_M2
TIM005
0.07
5s delay
Ts1_M1

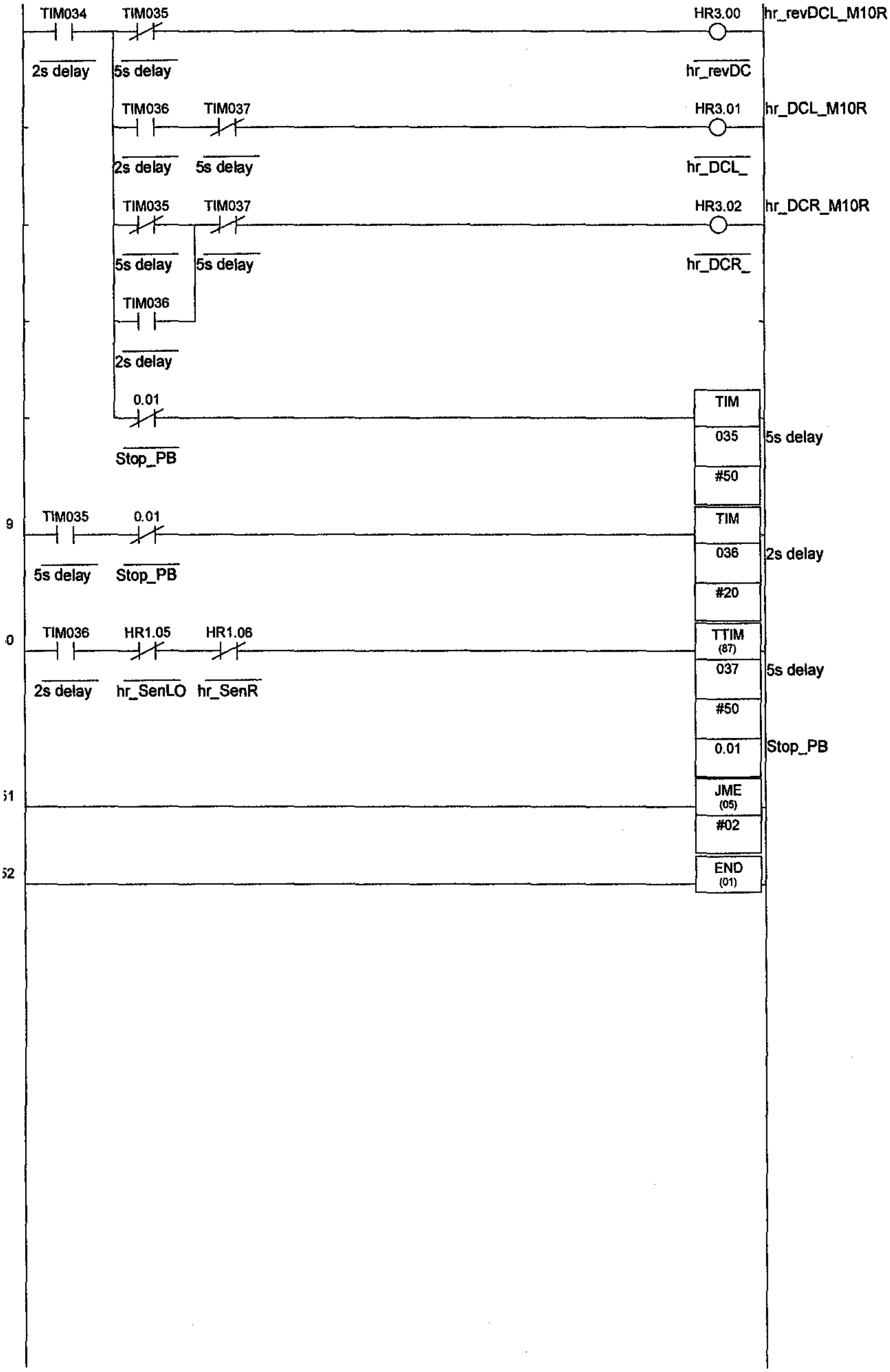
MASTER MOTOR CONTROL [REVERSE PATH]




PATH 4-TO-3 [REVERSE]
TIM019
10s delay
0.10
Ts4_M4
0.01
Stop_PB
TIM
020
#20
2s delay
TIM020
2s delay
HR1.05
hr_SenLO
HR1.06
hr_SenR
TTIM
(87)
021
#100
0.01
10s delay
Stop_PB
5
TIM021
10s delay
0.01
Stop_PB
TIM
022
#20
2s delay
6
TIM022
2s delay
TIM023
5s delay
HR2.07
hr_revDC
hr_revDCR_M43R
TIM024
2s delay
TIM025
10s delay
HR2.09
hr_DCR_
hr_DCR_M43R
TIM023
5s delay
TIM025
10s delay
HR2.08
hr_DCL_
hr_DCL_M43R
TIM024
2s delay
0.01
Stop_PB
TIM
023
#50
5s delay
37
PATH 3-TO-2 [REVERSE]
TIM023
5s delay
0.01
Stop_PB
TIM
024
#20
2s delay
TIM019
10s delay
0.09
Ts3_M3


TIM024
HR1.05
HR1.06
2s delay
hr_SenLO
hr_SenR
TTIM
(67)
025
10s delay
#100
0.01
Stop_PB
TIM025
0.01
10s delay
Stop_PB
TIM
026
2s delay
#20
TIM026
TIM027
2s delay
5s delay
HR2.10
hr_revDCR_M32R
hr_revDC
TIM028
TIM029
2s delay
10s delay
HR2.12
hr_DCR_M32R
hr_DCR_
TIM027
TIM029
5s delay
10s delay
HR2.11
hr_DCL_M32R
hr_DCL_
TIM028
2s delay
0.01
Stop_PB
TIM
027
5s delay
#50
1
PATH 2-TO-1 [REVERSE]
TIM027
0.01
5s delay
Stop_PB
TIM
028
2s delay
#20
TIM019
0.08
10s delay
Ts2_M2
2
TIM028
HR1.05
HR1.06
2s delay
hr_SenLO
hr_SenR
TTIM
(67)
029
10s delay
#100
0.01
Stop_PB
3
TIM029
0.01
10s delay
Stop_PB
TIM
030
2s delay
#20


TIM030
2s delay
TIM031
5s delay
HR2.13
hr_revDC
hr_revDCR_M21R
TIM032
2s delay
TIM033
10s delay
HR2.15
hr_DCR_
hr_DCR_M21R
TIM031
5s delay
TIM033
10s delay
HR2.14
hr_DCL_
hr_DCL_M21R
TIM032
2s delay
0.01
Stop_PB
TIM
031
#50
5s delay
5
PATH 1-TO-ORIGIN [REVERSE]
TIM031
5s delay
0.01
Stop_PB
TIM
032
#20
2s delay
TIM019
10s delay
0.07
Ts1_M1
6
TIM032
2s delay
HR1.05
hr_SenLO
HR1.06
hr_SenR
TTIM
(87)
033
#100
0.01
10s delay
Stop_PB
7
TIM033
10s delay
0.01
Stop_PB
TIM
034
#20
2s delay


TIM034
TIM035
HR3.00
hr_revDCL_M10R
2s delay
5s delay
hr_revDC
TIM036
TIM037
HR3.01
hr_DCL_M10R
2s delay
5s delay
hr_DCL_
TIM035
TIM037
HR3.02
hr_DCR_M10R
5s delay
5s delay
hr_DCR_
TIM036
2s delay
0.01
TIM
035
#50
5s delay
Stop_PB
9
TIM035
0.01
TIM
036
#20
2s delay
5s delay
Stop_PB
0
TIM036
HR1.05
HR1.06
TTIM
(87)
037
#50
5s delay
2s delay
hr_SenLO
hr_SenR
0.01
Stop_PB
1
JME
(05)
#02
2
END
(01)