

# Microcontroller-based mobile robot positioning and obstacle avoidance

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## Abstract

The use of mobile robots is growing in manufacturing facilities, hazardous materials handling, etc. Usually, several sensor systems are used in combination. The task of combining the information into a usable form, suitable for making navigation decisions, is known as sensor fusion. In this paper, the navigation system built on a mobile robot operating in a warehouse is presented focusing on the sensory system used. Hybrid navigation system that combines the perception and dead reckoning is used and gives satisfactory operation. A microcontroller system is designed to control the navigation of a mobile robot while avoiding obstacles. A system of 24 ultrasonic sensors was designed and the operation algorithms were described. The encoder and the ultrasonic sensors used are presented in detail together with the navigation system designed based on their operation.

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**Keywords:** Mobile robot; Navigation control; Odometry; Ultrasonic sensors; Microcontroller

## 1. Introduction

Robot navigation means the ability to wonder in the environment without colliding with obstacles, the ability to determine one's own position, and the ability to reach certain goal locations. So, navigation system may imply the following components: robot positioning system, path planning and map building. These are four popular positioning systems:

1. Odometry (dead reckoning)-based navigation.
2. Active beacons-based navigation system.
3. Landmark-based navigation system.
4. Map-based navigation system.

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Most autonomous robotic systems will have multiple sensors (Brooks, 1986; Mogensen, 2006). Usually several sensor systems are used in combination. These are sometimes complementary, sometimes redundant. In almost all robot systems, multiple sensors from the same type or different types are used to give complete coverage, for example a ring of 24 ultrasonic sensors in  $15^\circ$  increments around a vehicle, mobile robot CARMEL (Computer-Aided Robot for Maintenance, Emergency and Life support) (Borenstein and Koren, 1991). Another example is the Nomad Supper Scout II which carries 16 ultrasonic sensors separated by  $22.5^\circ$  around the vehicle (Yi, 2001). The task of combining the information into a usable form, suitable for making navigation decisions, is known as sensor fusion.

Mobile robots generally carry dead reckoning sensors such as wheel encoders and inertial sensors and also landmark and obstacle detecting and map making sensors such as time of flight (TOF) ultrasonic sensors. Sensors measurements in this case are to be fused to estimate the robot's position.

Vision sensors are used in many applications to build an image of the space confronting the mobile robot in order to detect any obstacle and avoid collisions. Vision systems are usually computationally expensive as image formation is too complicated for many applications.

In this paper, the navigation system built on a mobile robot operating in a warehouse is presented. Hybrid navigation system that combines the perception and dead reckoning was found to be complementary and gives a satisfactory operation of the mobile robot. If environment contains confusing information or few perceptually distinguishable landmarks, the performance of these systems decline. The perceptual aliasing problem can be solved by including the odometry data to discriminate between the similar places. The use of ultrasonic sensors in most applications is easier, cheaper and computationally simpler. Ultrasonic transducers are preferably used to obtain three-dimensional information of the environment (Bak, 2002; Everett, 1995; Borenstein and Koren, 1988; Benitz-Read and Rojas-Ramirez, 2010). They measure and detect distances to moving objects, are impervious to target materials, surface and color, solid-state units have virtually unlimited maintenance-free lifespan. Ultrasonic sensors are not affected by dust, dirt or high-moisture environment.

In Section 2 of this work, the odometry and the odometry errors were presented. Section 3 presents ultrasonic systems, the source of errors that could be encountered and the sensors type specially the sensor used in this work. Section 4 presents the robot description and the sensors, decoders and encoders built on the robot while Section 5 describes the robot controller designed for robot operation with the ultrasonic sensors used clustering and the controller hardware and software. Section 6 details the proposed robot navigation inside and outside the warehouse while Section 7 presents the experimental testing together with the interface board used. Sections 8 and 9 give the results discussion and conclusions.

## 2. Odometry and odometry errors

Odometry is the most widely used navigation method for mobile robot positioning. It is well known that odometry provides good short term accuracy, is inexpensive and allows very high sampling rates. However, the fundamental idea of odometry is the integration of incremental motion information over time, which leads inevitably to the accumulation of errors. Odometry is used in almost all mobile robots for various reasons: Odometry data can be fused with absolute position measurements to provide better and more reliable position estimation (Chenavier and Crowley, in press; Evans, 1994). Odometry can be used in between absolute position updates with landmarks.

Odometry is based on simple equations that are easily implemented and that utilize data from inexpensive incremental wheel encoders. However, odometry is also based on the assumption that wheel revolutions can be translated into linear displacement relative to the floor. This assumption is of limited validity. One extreme example is wheel slippage: – if one wheel was to slip on, say an oil spill, then the associated encoder would register wheel revolutions even though these revolutions would not correspond to a linear displacement of the wheel. There are also, several other subtle reasons for inaccuracies in the translation of wheel encoder readings into linear motion.

To correct the errors in positioning resulting from the odometry system and for safe navigation and obstacle avoidance, ultrasonic sensors are frequently used as they can provide good range information based on the time of flight (TOF) principle. They have been widely used in mobile robot applications (Elfes, 1987; Leonard and Durrant-Whyte, 1992; Borthwick and Durrant-Whyte, 1994).

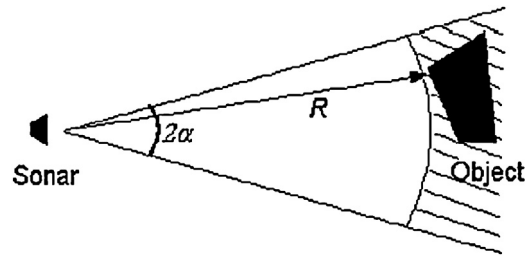


Fig. 1. Angular error of an ultrasonic sensor  $\alpha$  is the half opening angle of sonar cone,  $R$  is a sonar response.

### 3. Ultrasonic systems

Ultrasonic TOF ranging is today the most common technique employed on indoor mobile robotic systems, primarily due to the ready availability of low-cost systems and their ease of interface.

#### 3.1. Ultrasonic sensors

Ultrasonic transducers are preferably used to obtain three-dimensional information of the environment. But some problems appear in sonar response. Ultrasonic sensors suffer from unreliable sonar responses from the environment. For sonar-based mobile robot in confined space, special attention should be paid to these problems. The space is normally a closed environment.

Two major problems are discussed in the following (Kumari, 2012).

##### 3.1.1. Angular uncertainty

When an ultrasonic sensor gets a range response of  $R$  meters, the response simply represents a cone within which the object may be present. There is no way to pin-point exactly where the position of the object is. Fig. 1 conveys the idea. The opening angle of the ultrasonic sensor is  $2\alpha$  and the object can be anywhere in the shaded region for the response  $R$ .

##### 3.1.2. Specular reflection

Specular reflection refers to the sonar response that is not reflected back directly from the target object. In specular reflection, the ultrasound is reflected away from the reflecting surface, which results in longer range reporting or missing the detection of object all together, Fig. 2 (Drumheller, 1987; Lim and Cho, 1994).

#### 3.2. Types of ultrasonic sensor

Before we select or install an ultrasonic sensor, we should be familiar with these terms:

1. Dead zone.
2. Beam angle.
3. Beam cone diameter.
4. Maximum sensing range.
5. Background suppression.
6. Switching frequency.
7. Inclination of target.
8. Environmental considerations.

After studying some types of ultrasonic sensors, we selected the (Devantech SRF04 Ranger Compact High Performance Ultrasonic Ranger (Polaroid, 1987)) for use in this work. Fig. 3 represents the SRF04 ultrasonic sensor.

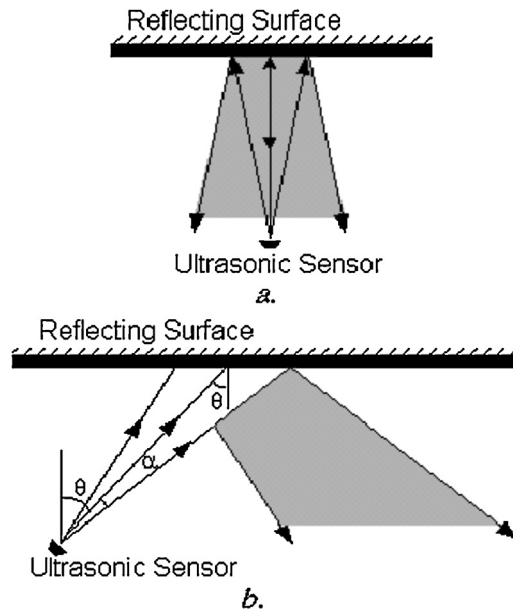


Fig. 2. Specular reflections.

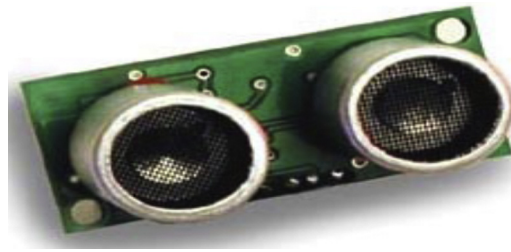


Fig. 3. Devantech SRF04 range.

### 3.2.1. Specifications

The specifications of SRF04 Ultrasonic Ranger are shown in the [Appendix](#). The beam pattern of the SRF04 is conical with the width of the beam being a function of the surface area of the transducers and is fixed. The beam pattern of the transducers used on the SRF04, taken from the manufacturer's data sheet, is shown in [Fig. 4](#).

The ranger works by transmitting a pulse of sound outside the range of human hearing. This pulse travels at the speed of sound (roughly 0.9 ft/m s) away from the ranger in a cone shape and the sound reflects back to the ranger from any object in the path of this sonic wave, [Fig. 5](#).

## 4. Robot description

The mechanical design for the robot plays a critical role in the success of the robot facility. The following specifications should be met:

1. Moving forward and backward without rotation.
2. Moving aside (right and left) without rotation.
3. Have the facility to rotate in a complete circle.
4. The robot will use a battery assembly with total volt 48 V.
5. The control unit and battery charger should be on the robot itself.

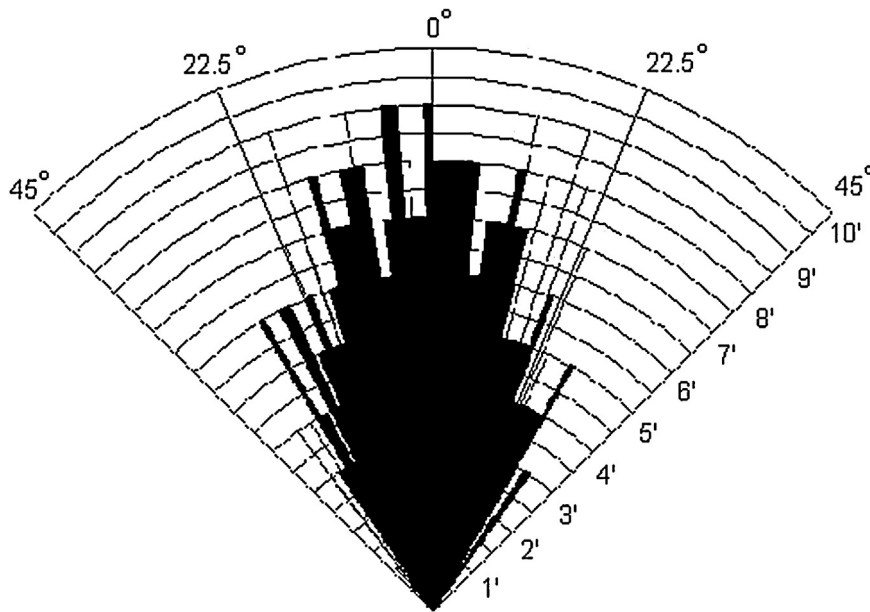


Fig. 4. Beam pattern.

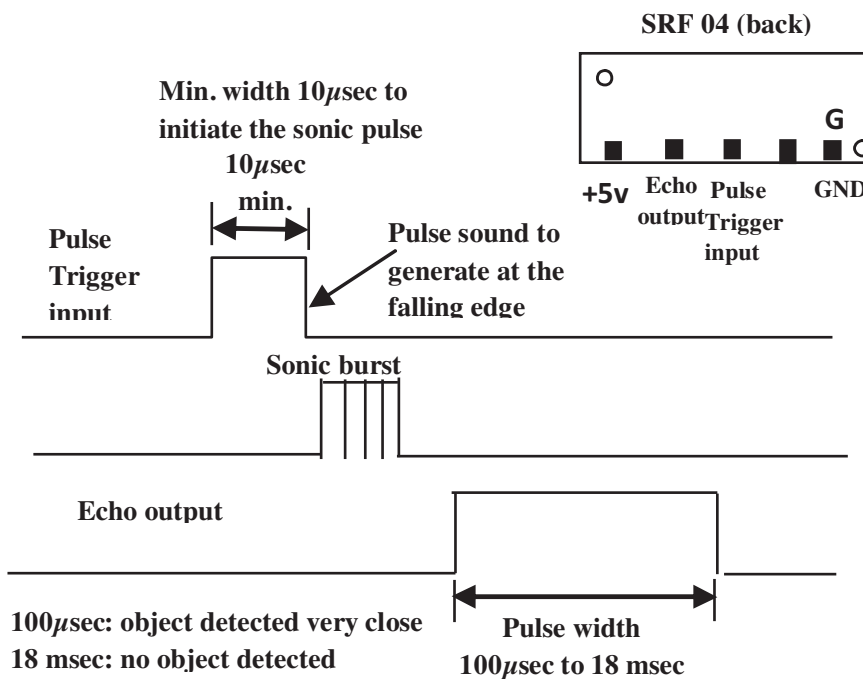


Fig. 5. SRF04 typical waveforms and connections.

The driving system of the robot is composed of 4 wheels each of them equipped with a separate electric motor. A front and rear steering system were added to give flexibility in the motion planning for smooth navigation. The mobile robot configuration is shown in Fig. 6. The robot is equipped with a simple arm used during loading and unloading the components.

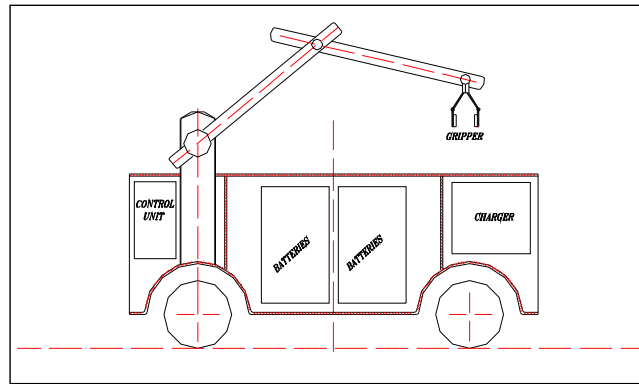


Fig. 6. Mobile robot configuration.

#### 4.1. Robot positioning

Methods for robot positioning can be roughly categorized into two groups: relative and absolute position measurements. Because of the lack of a single good method, developers of mobile robots usually combine two methods, one from each category.

In this work, the relative method used is odometry. This method uses encoders to measure wheel rotation and/or steering orientation. Odometry is totally self-contained and it is always capable of providing the vehicle with an estimate of its position, but the position error grows without bound unless an independent reference is used periodically to reduce the error. Natural landmark recognition was used as an absolute positioning measurement system to correct periodically the right position of the robot.

#### 4.2. Encoder, decoder controller and motion control used

Optical incremental encoders are a mean for capturing speed and traveled distance on a motor. Rotation velocity can be determined from the time interval between pulses, or by the number of pulses within a given time period. Because they are digital devices, incremental encoders will measure distance and speed with perfect accuracy. Quadrature encoders have dual channels, A and B, which are electrically phased  $90^\circ$  apart. Thus, direction of rotation can be determined by monitoring the phase relationship between the two channels. In addition, with a dual-channel encoder, a four times multiplication of resolution can be achieved by counting the rising and falling edges of each channel (A&B).

In this work, the HEDS5540, 3 channels high performance optical incremental encoders are used. This IC consists of multiple sets of photo detectors and the signal processing necessary to produce the digital waveforms. The digital output of channel A is in quadrature with that of channel B ( $90^\circ$  out of phase). The encoder standard resolution is 1024 counts per revolution.

The general purpose motion control IC, HCTL-1100, is employed. It frees the host processor for other tasks by performing all the time intensive functions of digital motion control. The HCTL-1100 provides position and velocity control for DC, DC brushless and stepper motors.

### 5. The proposed controller

At designing a motion controller for an autonomous mobile robot, a main problem must be handled which is the obstacle avoidance problem.

In the case considered, the robot is moving to transport electronic components from a warehouse to one of three production lines. The mission of the robot in the inner warehouse is to pick up components from the target point. So, it will be always moving next to one of the walls as the shelves in this warehouse are located next to the walls. Outside the warehouse, the path will be prescribed according to the target production line. The sensors should be arranged so as to achieve safe navigation inside and outside the warehouse. We use a system of 24 ultrasonic sensors arranged around the vehicle as shown in Fig. 7.

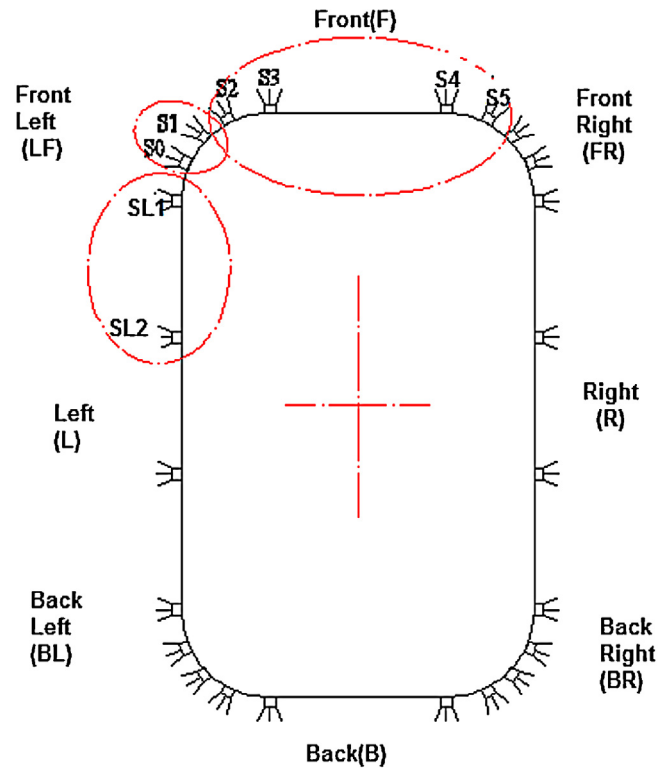


Fig. 7. Sensors clustering.

### 5.1. Sensors clustering

Grouping the sensors is made to facilitate decision making. The sensors in a certain group act as one sensor (grouped sensor). So the sensors in each group must be selected carefully.

The clustering procedures are as follows:

1. Scan the readings of the sensors of the group.
2. The minimum reading is the dominant one and the others are neglected.

The clustering shown in Fig. 7 is the suggested one for our controller. Front Left (FT): Sensors (S0, S1) and Front (F): Sensors (S2, S3, S4 and S5). The robot senses the obstacles using its sonar sensors. In this work, we consider only the static obstacles. The shape and material do not have great impact in our case. The sonar sensors cannot detect obstacles that have height smaller than certain value (indicated in the data sheet), so we consider only obstacles that can be detected by the sonar sensors.

The readings of the grouped sensors are assigned one of two labels which are far and dangerous. Each group has different interpretation to the meaning of far and dangerous. For example for the front sensors group, the reading of the group ranging from 1 m to 3 m is far, while the reading 3 cm to 1 m is dangerous ranging from 1 m to 3 m is far, while the reading 3 cm–1 m is dangerous.

The selection of the range affects on the sensitivity of the sensors or in other meaning the evaluation to the distance between the robot and the obstacle from the point of view if it is dangerous or not. We need the front sensors to be more sensitive than the Front-Right (FR-RT) and Front-Left (FR-LT) to protect the robot from collision with the walls or obstacles during turning at the walls corner or turning around the obstacle to avoid it. These three groups help the robot to avoid the front obstacles and to turn in the corners and start to align again to a new wall. During backward navigation, Back (B), Back Left (BL) and Back Right (BR) are the sensor groups used.

## 5.2. Software development

ATMEL AVR microcontrollers is easily programmed using the ATMEL integrated development environment AVR studio 4, where assembly programs can be edited, simulated, debugged and downloaded to the microcontroller.

In our case to make our programs easy-developed efficient, portable and readable, we decided to program in C. We have used IAR imbedded workbench for ATMEL which is an integrated development environment (IDE) provided by IAR corporation for C-programming of ATMEL microcontrollers. By IDE is meant the full software development cycle including source code editing, debugging, compiling and linking supported in one user friendly operator interface.

Although dead reckoning navigation is easy to implement, it suffers from the drift problem which is serious in some navigation tasks.

So navigation to be reliable should not depend on one mechanism only. Hybrid navigation system that combines the perception and dead reckoning is better. Information from different sources can be fused to help the robot to take the decision of what is the next step. The position estimate provided by dead reckoning is corrected by matching the perception against a stored world map. Landmark-based navigation depends mainly on the agent's perception to its environment. If the environment contains confusing information or few perceptually distinguishable landmarks, the performance of these systems decline. The perceptual aliasing problem can be solved by including the odometry data to discriminate between the similar places.

## 6. Proposed robot navigation

### 6.1. Robot's motion trajectory

The vehicle will move inside and outside the war warehouse. Navigation of the vehicle is divided into three main parts:

1. Inside warehouse.
2. Outside warehouse.
3. Maneuvering at the warehouse door.

Robot can figure out from the odometer system if it inside or outside warehouse. There are several rule bases according to sensors readings and odometer that make the robot switch from one controller to the other.

### 6.2. Robots motion types

The robot vehicle is designed to perform only two distinct kinds of motion in the warehouse:

- (1) Straight-line motion, where both motors are running at the same speed and in the same direction.
- (2) Rotation about the vehicle's center-point, where both motors are running at the same speed but in opposite directions.

This approach is advantageous for several reasons:

1. Wheel slippage is minimized because of the simultaneous action or rest of both wheels and because of the "on-the-spot" rotation action for turns.
2. A relatively simple control system may be used, since in either case the only task of the controller is to maintain equal angular velocities.
3. The vehicle path is always predictable, unlike other motion strategies which smooth sharp corners by an unpredictably curved path. A predictable path is advantageous when global path planning, to avoid obstacles, is employed.
4. The vehicle always travels through the shortest possible distance (straight-line or "on-the spot" rotation).



Table 1  
Expert system's rule base.

#	$\Delta L$	FR	FR-LT	Left wheel	Right wheel
1	0	Far	x	Forward	Forward
2	+ve	Far	x	Back	Forward
3	–ve	Far	x	Forward	Backward
4	X	Dang	x	Forward	Backward
5	X	Dang	Dang	Forward	Backward

### 6.3. The proposed controller

At designing a motion controller for an autonomous mobile robot there is a main problem that must be handled which is the obstacle avoidance problem. The robot senses the obstacles using its sonar sensors.

#### 6.3.1. Controller inside the warehouse

In this location of the warehouse, it is required from the robot to go to certain shelf to pick up some components and then move toward the door as a first step to drive these components to the required assembly lines.

As the mission of the robot in the inner warehouse is to pick up components, so the target point will be always next to one of the walls. So we suggest that the robot will move parallel to the walls until arriving to the target point to pick up the required components.

The readings of the grouped sensors are assigned one of two labels which are *far* and *dangerous*. Each group has different interpretation to the meaning of far and dangerous. For example for the front sensors group the reading of the group ranging from 1 m to 3 m is far while the reading from 3 cm to 1 m is dangerous. The expert system rule base is presented in Table 1.

#### 6.3.2. Motion inside the warehouse

The difference between the readings of the two side sensors  $\Delta L = SL1 - SL2$  are used to help the robot to align to the left wall. We want the robot to keep certain distance to the wall which is estimated in our work to be 50 cm. The selection of this value is targeted to help the robot to turn smoothly at the corners without getting stuck with the walls. While the other grouped sensors allow the robot to detect the obstacles in his way and avoid collision by rotating around it. The used algorithm is shown in Fig. 8. This algorithm is called once entrance to the warehouse is acknowledged and repeated during navigation inside the warehouse.

## 7. Experimental testing

### 7.1. Testing of SRF04 sensor operation

In Fig. 9, the photograph shows the URF board, a single SRF04 sensor, the testing board and a power supply. They were connected together in a successful testing trial. Line 1 is used to display the ranging result and line 2 is used to display the sensor ID whose ranging results is displayed in line 1. Line 1 is used to display the ranging result and line 2 is used to display the sensor ID whose ranging results is displayed in line 1. The sensor connection was made with each of the 24 channels and all these channels give satisfactory result.

### 7.2. The interface board

Since ultrasonic ranging depends on measuring the time duration taken by the ultrasonic wave to travel go and back between the transceiver and the nearest object, it is essential to have a precise means of time measuring which should meet the following requirements:

1. To put a minimum loading on the master microcontroller of the robot to preserve its processing power for the navigation and objects handling tasks.

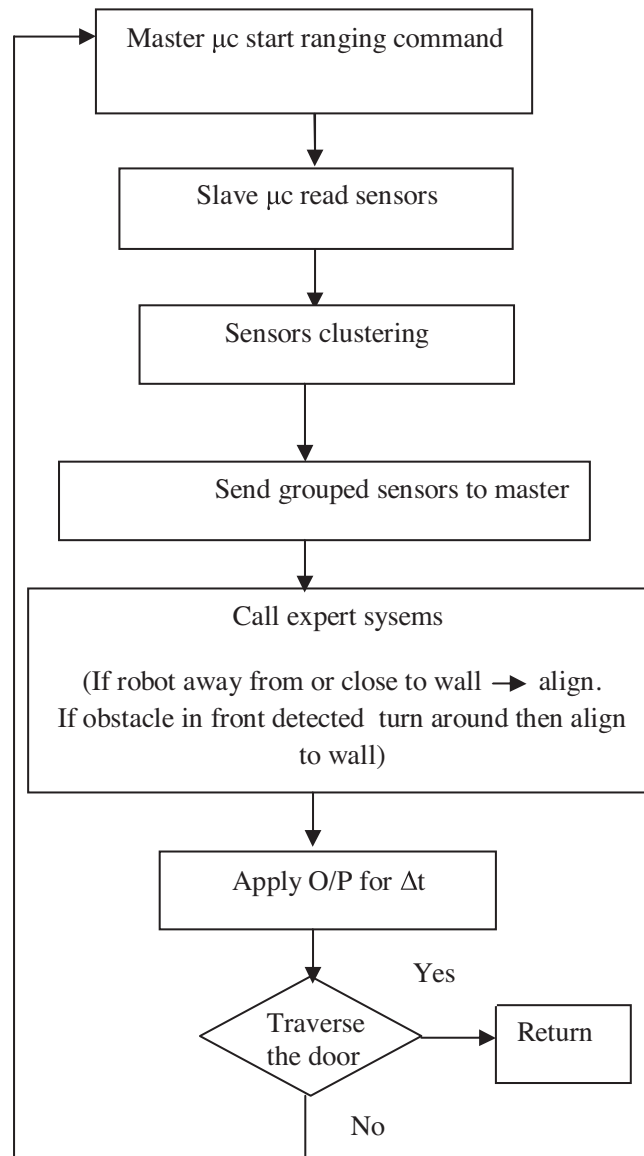


Fig. 8. Algorithm for inner navigation.

2. To provide sufficient number of independent time measuring devices that can serve simultaneously as many transceivers as needed by the mobile robot vehicle.
3. Ranging is to be initiated by the master. The ranging subsystem should acknowledge the master upon completion of each individual ranging task.

The first requirement is met by offering a separate microcontroller that can collect the ranging results from the available time measuring devices and convert them from time units to suitable distance units (centimeters, meters or feet), then store them in an array form. The master microcontroller can acquire these data as needed through a master/slave serial communication link.

The second requirement is met by providing sufficient number of independent counters that can individually and simultaneously count the pulses of a high frequency clock shared by all counters. The planned number of channels in this stage is 24 channels.

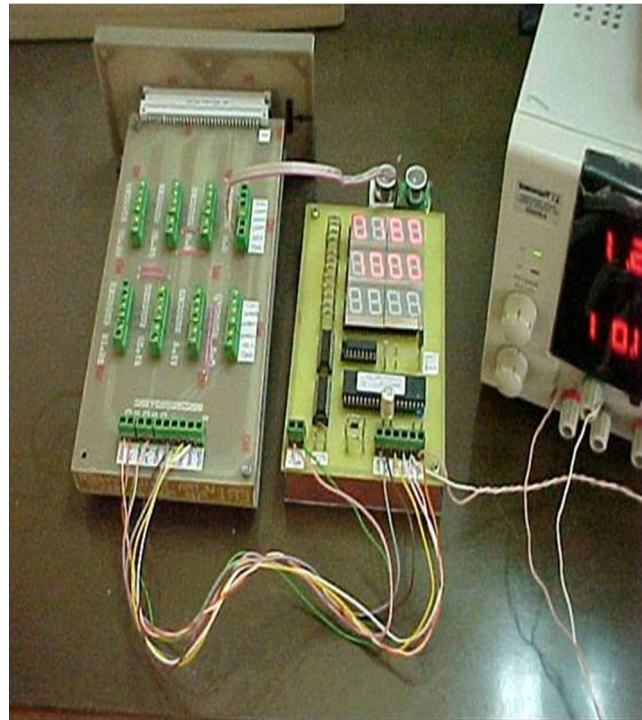


Fig. 9. Ranger testing board, SRF04 sensor and URF board during test.

The third requirement is met by establishing a handshaking link between the master controller and the ranging controller. Through this link a start ranging command is issued by the master and a ranging completed signal is issued by the slave when the latest echo signal of the 24 transceivers is captured.

The main building block beside the Atmel AVR90S8515 microcontroller is a programmable TTL counter chip 8254 which has 3 independent counters.

This main building block is repeated eight times to provide a total of 24 timing channels.

ATMEL AVR microcontrollers are easily programmed using the ATMEL integrated development environment AVR studio 4.

### 7.3. Control architecture overview

The mobile robot control system is a multi-input multi-output large and complex one that may require a dedicated controller for each of its multiple subsystems. For example the robot's wheels need a dedicated motion control system which can receive and execute the following high level motion commands and report execution errors in case of fault incidence:

- Set forward speed.
- Set backward speed.
- Move forward  $X$  centimeters.
- Move backward  $X$  centimeters.
- Stop immediately.
- Turn right  $Y$  degrees.
- Turn left  $Y$  degrees.
- Reset odometer.
- Get odometer.

This motion control task is accomplished in parallel to the requirements of obstacle avoidance task. So, the controller system should be able to accomplish simultaneously the right operation of the robot while taking care of the safety of the system.

The ultrasonic ranging subsystem requires a dedicated controller which can accurately report the distances to the nearest objects for all the installed ultrasonic sensors in response to a high level “Range Find” command issued by the robot master.

#### 7.4. Motion outside the warehouse

Over the outer-warehouse, the robot will move in one of three predetermined paths to arrive to one of the three assembly lines. Each line is assigned a name or a number. These paths were saved in the robot memory, example: – Assembly Line: point Bo then point B1. Each path is saved as a consequence number of  $(x, y)$  points starting from just the warehouse door. So, a look-up table is established to match between the assembly line’s number and the sequence of points representing it. In order that the robot can follow a certain path, it has to trace its points in order until reaching its target. The composite behavior will be divided into four primitive behaviors which are:

Path 1:

1. Move forward 1.5 m.
2. Turn right  $90^\circ$ .
3. Move forward 6 m.
4. Stop.

Path 2:

1. Move forward 1.5 m.
2. Turn left  $90^\circ$ .
3. Move forward 17 m.
4. Stop.

Path 3:

1. Move forward 1.5 m.
2. Turn left  $90^\circ$ .
3. Move forward 4 m.
4. Turn left  $90^\circ$ .
5. Move forward 8 m.
6. Turn right  $90^\circ$ .
7. Move forward 17 m.
8. Stop

The area of the place was divided as a map of  $x, y$  points. Point  $(0, 0)$  is just at the midpoint of the warehouse door. The step was set to be 0.5 m.

When the robot terminates the required job at any of the assembly lines, it will take the reverse direction to his path returning back to the door of the warehouse (point  $(0, 0)$ ). During its navigation, the robot reads continuously the sensors readings. If the robot detects an obstacle in front of him, it will stop and store its position to avoid the collision and at the same time not to lose its path.

Look-up table representing the 3 paths will be as follows:

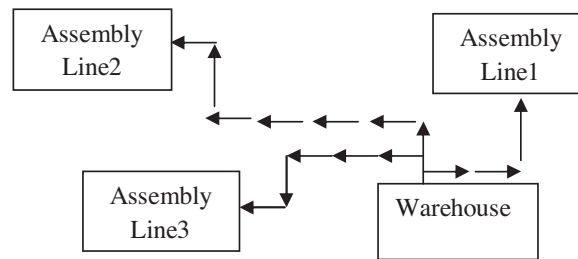


Fig. 10. Schematic diagram of the working area.

Path 1x, y	Path 2x, y	Path 3x, y
0, 0	0, 0	0, 0
0, 3	0, 3	0, 3
12, 3	–34, 3	–8, 3
Stop	Stop	–8, –13
		–42, –13
		Stop

A schematic diagram of the working area is shown in Fig. 10.

#### 7.5. Maneuvering at the warehouse door

The robot system ability to detect obstacles during navigation was tested during maneuvering at the warehouse door while getting in or out the warehouse.

The readings of the ultrasonic sensors indicate if it is in the right position to enter, for example, or not. If the robot detects a part of the wall in the left or right, depending on the set of sensors that detects an obstacle, he has to maneuver to put itself in the right position in front of the door before getting in:

First, he has to go backward for about 50 cm.

Then moving right or left depending on the position detected by the sensors until aligning to the center of the door.

During its route to the production line, in many places the aisles are very narrow, so the robot will stop when he detects an obstacle and gives an alarm, so the obstacle could be removed.

This process was tested successfully during testing the robot operation.

## 8. Results and discussion

During testing of the robot operation, the robot had to go to one of the assembly lines and get back to the warehouse, it maneuvers to put itself in the right position at the door, go to the target Assembly Line and get back to the warehouse entering safely from the door. Some problems were encountered concerning the maneuvering at the door and the errors were adjusted. These paths were traveled successfully at the end.

## 9. Conclusions

The paper presents the control system of a mobile robot operating to transport components from a warehouse to production lines according to prescribed paths avoiding collision to any obstacle during its navigation. The robot has to follow the designed algorithm during moving inside the warehouse to get the required items. Then transporting these items to the prescribed assembly line, it has to follow another algorithm.

A microcontroller system was designed to accomplish this task. An ultrasonic ranger slave microcontroller system was designed and programmed to accomplish this task. The ultrasonic sensor used specifications was presented and

Table 2  
SRF04 specifications.

Beam pattern	See graph Fig. 2
Voltage	5 V
Current	30 mA typ. 50 mA Max
Frequency	40KHz
Maximum range	3 m
Minimum range	3 cm
Sensitivity	Detect a 3 cm diameter stick at >2 m
Input trigger	10 uS Min. TTL level pulse
Echo pulse	Positive TTL level signal, width proportional to range
Weight	0.4 oz.
Size	4.4 cm × 1.6 cm × 1.27 cm

the number of sensors and their positioning around the robot was designed and illustrated. The system was tested in each step. The ultrasonic sensors was tested first to be sure of the consisting of the readings and the corresponding sensors. Also the paths to the three assembly lines were programmed and stored to be followed by the robot. Obstacle detection was examined. The robot stops when detecting an obstacle and gives an alarm in order to remove it.

In this paper, the navigation of a mobile robot in a warehouse was presented. The robot has to navigate inside the warehouse to pick the components needed for the industrial operation. Over the outer path, the robot will move in one of three predetermined paths to reach one of the three assembly lines in operation. These paths were saved in the robot memory. The sensory system used is composed of wheel encoders and ultrasonic sensors to correct the position of the robot resulting from odometry system and to avoid any obstacles during navigation.

The navigation system was described and the sensory system description, positioning and operation was presented. The control of the navigation system was also detailed.

## Appendix.

See Table 2.

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