DEVELOPMENT OF AN AUTONOMOUS VACUUM CLEANER ROBOT

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ABSTRACT

This paper presented an autonomous vacuum cleaning robot with capability for obstacle avoidance. The system design involved augmenting s number of mechanical and electronic components ranging from voltage regulators, motors, sensors, driver circuits, vacuum pump, microcontrollers amongst others). The system was designed for low power consumption. HC-SR04 ultrasonic sensors were employed to detect obstacles, and a PIC16F877 Microcontroller for processing by automatically generating control signals based on these sensors' information transmitted which are thereafter forwarded to appropriate motor drivers. The microcontroller was interfaced with a Radio Frequency module for wireless transmission and reception of information between the transmitter and the receiver while displaying related information on an LCD. The designed system was tested in a real-life scenario having various cleaning complexities achieving an average efficiency of 97.99%.

1. INTRODUCTION

Robots are nowadays utilized for performing various human tasks especially those that are monotonous and repetitive. These tasks for example include sewage cleaning, assembly, pick and place operations, spray finishing operations, spot and electric arc welding among others. Integrating sensors, intelligence, actuators and power supply into a small autonomous unit is a vital issue for developing innovative and sophisticated micro-system [1]. Hence, remotely controlled sensor technologies have been developed by a number of researchers for these kind of market segments achieving an optimum balance of functionality in terms of performance, ease of use, and cost [2,3]. Robots for performing manual domestic activities are now becoming more and more popular especially for the ageing population and these machines could actually be developed for both residential and industrial scale [4]. It is therefore necessary to design and develop machines for performing activities such as sweeping and cleaning. Using robotic machines for floor cleaning can therefore assist tremendously in cleaning wastes and garbage in our environments. This paper therefore aims to present an effective robot for clean dust and waste in typical cleaning areas as manual cleaning by human is costly and ineffective while also being unsafe for human life. The modelling and construction of this autonomous vacuum cleaning robot are presented.

2. MATERIALS AND METHODS

In this section, the materials used as well as a detailed design procedures and methodologies adopted in developing this system are presented. The Vacuum Cleaning Robot was implemented using existing components ranging from Hall sensor for the back tyre, three (3) ultrasonic sensors for obstacle detection, two (2) mechanical micro limit switches for auxiliary obstacle detection, battery voltage indication LCD, Two (2) front tyres, BLDC [7] motors with BLDC controllers, lithium battery, vacuuming motor with fan, vacuum motor driver, PIC16F887 microcontroller [5], 5V regulator, radio frequency transmitter and receiver, Battery charger. The entire system block diagram is shown in Figure (1).

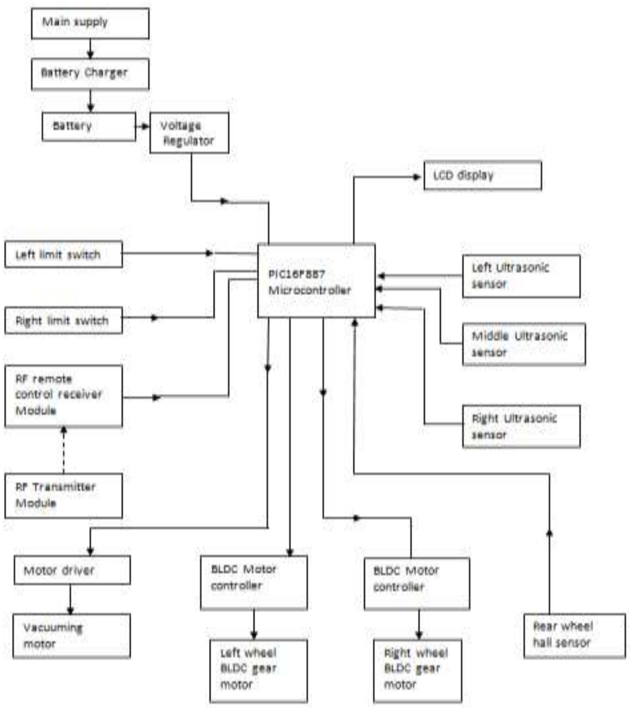


Figure 1: Complete Block Diagram of the Developed Robot System

2.1 Hardware Design

The detailed design of the electronics and mechanical parts that form the entire vacuum cleaning robot is presented. This ranges from the power supply section, the sensing units, the control units, etc

2.1.1 Power Supply

The vacuum cleaning robot is powered by means of a Lithium-ion12V 20,000mAh DC battery. This constitutes the primary power supply to the robot from which other components such as the ultrasonic sensors, microcontroller as well as the motors also tap.

2.1.2 *Ultrasonic Sensors*

The obstacle avoidance capability was achieved using ultrasonic sensors as it is the efficient sensor for detecting the obstacles. Ultrasonic sounds go beyond the human ability of 20HZ to 20KH and works based on a simple principle presented in equation (1).

$$d = v \times t \quad (1)$$

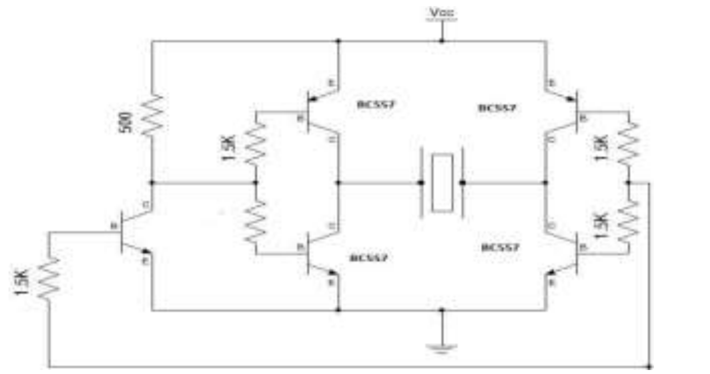


Figure 2: Internal Structure of Transmitter Circuit of the Ultrasonic Sensor

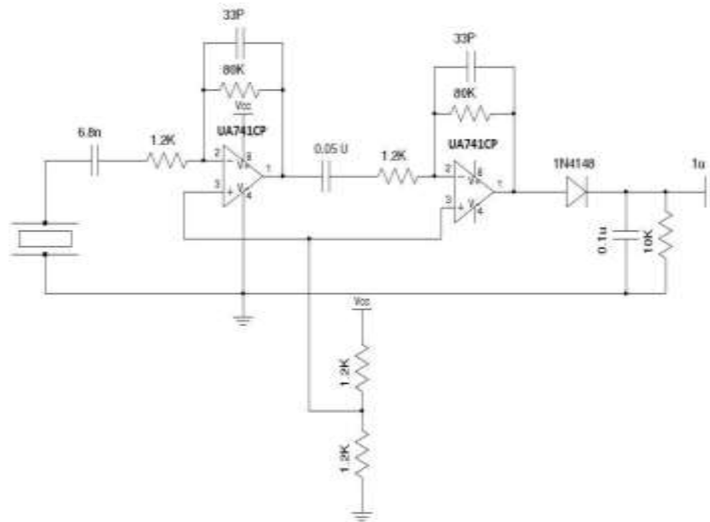


Figure 3: Internal Structure of Receiver Circuit of the HC-SR04 Ultrasonic Sensor

It is the receiver circuit that provides input signal to the Robot for all control of the entire cleaning Robot and comprised of an array of Left, Middle and Right ultrasonic sensors together with Micro switches (left limit and right limit) as well as a magnetic hall effect sensor (for rear wheel).

2.1.3 PIC16f877 Microcontroller

The specifications for the microcontroller were selected as per the data electrical characteristics of PIC16f887 from the manufacturer. The connection of the various components of the robot to the microcontroller are as shown in Figure 4.

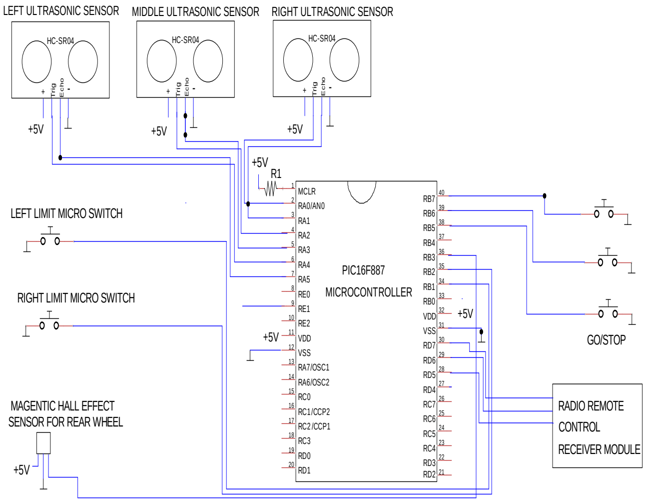


Figure 4: System Inputs and PIC16F877 Microcontroller

The HC-SR04 ultrasonic sensors in Figure 4 were selected to provide an easy method for distance measurement. These sensors are perfect for any number of applications that require performing measurements between moving or stationary objects. As soon as an impulse triggers an ultrasonic burst (well above human hearing), a corresponding "listen" for the echo return pulse is obtained where the sensor measures the time required for the echo return, and returns this value to the microcontroller as a variable-width pulse. The choice of the ultrasonic sensors was due to a number of reasons; it provides a precise and a non-contact distance measurement, and their pin header makes them easy to be connected to any development board, directly or with an extension cable without need for soldering.

2.1.4 BLDC Motor Driver

The motor driver circuitry is an intermediate interface that enables the microcontroller to run the motor directly because of its requirement for higher current rating which can be maintained by driver circuit. In this work, the L293D IC was used as the motor driver circuit. It has four (4) input pins which are pins 15 and10 on the right while pins 2 and7 on the left. The left input pins are responsible for regulating the rotation of the motor connected across left side while the right input for motor on the right hand side. The motors rotate on the basis of the inputs provided depending on the logic level across the input pins (low or high), cross the input pins.

2.1.5 Magnet Hall Sensor

This work used an A1302 which is a radiometric, continuous-time, linear Hall-effect sensor IC which was optimized to provide an accurate voltage output proportional to an applied magnetic field. The magnet hall sensor is depicted in Figure 3.4 and has a quiescent output voltage that is 50% of the supply voltage. Two output sensitivity options are provided which are 2.5 mV/G and 1.3 mV/G. The Hall-effect integrated circuit included in each device includes a Hall sensing element, a linear amplifier, and a CMOS Class A output structure. The Hall sensing element was integrated with the amplifier on a single chip in order to minimize many of the problems associated with low voltage level analog signals.

2.1.6 RF Remote Transmitter and Receiver Module

The radio frequency (RF) transmitter and receiver module was used to manually control the vacuum cleaner robot when desired. The receiver and transmitter module Specifications used are presented in Tables 1 and 2:

Table 1: Receiver Operation Parameters

Parameter	Value
Operating Voltage	5V dc
Quiescent Current	4Ma
Receiving Frequency	315MHz
Receiver sensitivity	-105Db
Antenna	32cm solid core spiral wound
Launch distance	20 – 200 meters

Table 2: Transmitter Operation Parameters

Parameter	Value
Operating voltage	3.3V - 12V
Operating mode	AM
Transfer rate	4Kbps
Transmitting power	10Mw
Transmitting frequency	315MHz
Antenna	25cm solid core spiral wound

The RF transmitter module was adapted for use in this work because of its ability to send and receive signal over 100 meters wirelessly with low power consumption and cost effectiveness. Transmission and reception is based on the use of unique codes in binary format to carry out different functions

2.1.7 Indicator Circuit

This circuit is responsible for indicating the status of the system on the 16x2 LCD and the buzzer sounds an alarm for any action taken while the LED1 indicate that the microcontroller PIC16F887 is powered when ON. Figure 5 shows the indicator circuit.

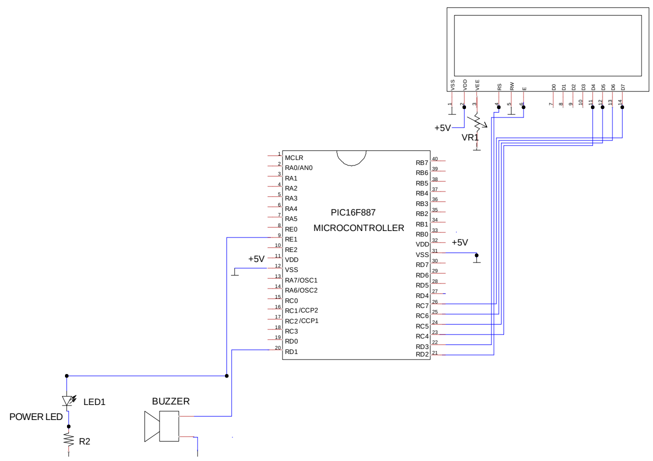


Figure 5: Indicator Circuit

2.1.8 Vacuum Motor Switching Circuit

This circuit switches the vacuuming motor on and off depending on the signal received by the microcontroller from the sensors. Figure 6 shows the vacuum motor switching circuit.

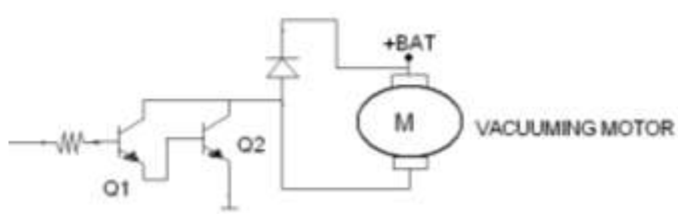


Figure 6: Vacuum Motor Switching Circuit

2.2 Design of the Power Supply Unit

The primary power source which is utilized by the each and every component of this work is a Lithium-ion12V 20,000mAh DC battery which is super rechargeable and portable. This choice was largely because the cleaner is expected to be portable and free to operate at any place. Other features are as presented in Table 3.

Table 3: DC Power Specification

Feature	Type/Value
Size	155x75x40mm
Color	Black
Capacity	20000mAh
Input Voltage	12.6V
Output Voltage	10.8-12.6V

2.3 Design of the Sensing Units

Three HC-SR04 sensors were utilized, which is an off-the-shelf ultrasonic sensor of 40 kHz frequency specification that requires a power supply of 5 volt and a current specification as 15 mA. Hence, a 7805 regulator was used to obtain the desired Vcc voltage from the primary power supply as shown in Figure 7.

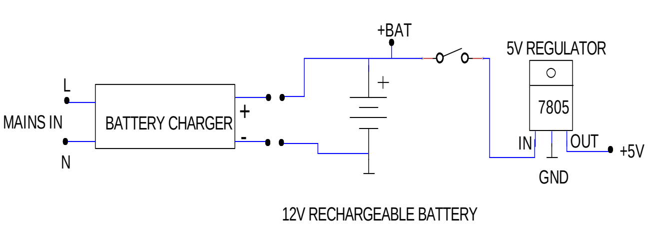


Figure 7: Voltage Regulator Circuit

The sensor detects obstacles at a distance of about 10ft and has four terminals; Vcc, GND, trig, and echo pins.

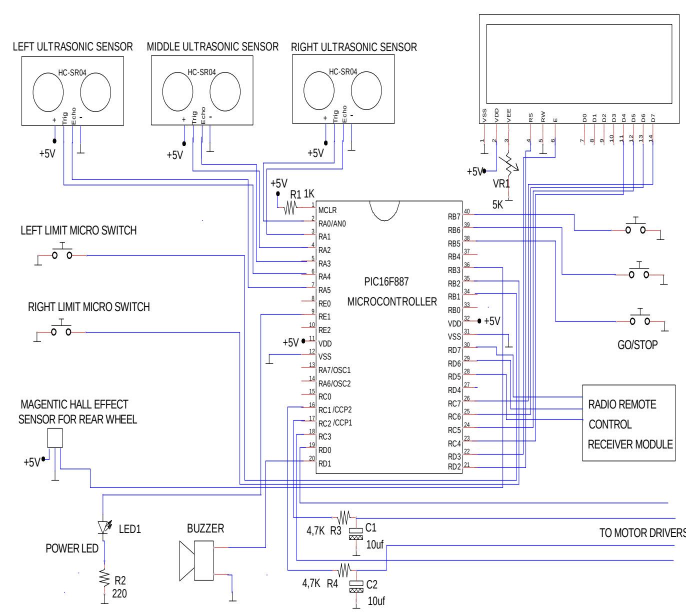
Table 4: Sensors Pin Interfacing with PIC16f877

Sensor	Trig	Echo
1	Pin 6 (RA4)	Pin 7 (RA5)
2	Pin 4 (RA2)	Pin 5 (RA3)
3	Pin 2 (RA0)	Pin 3 (RA1)

Hence, the Vcc terminals are set as 5v and GND connected to the negative terminal

2.4 PIC Microcontroller Circuit and Interfacing

When the power is turned on, the microcontroller gets powered via a 5v regulator (7805), the microcontroller program begins action according to the instructions set. As this constitutes the brain behind the entire robot's operation, the various auxiliary components were interfaced to the PIC16f877 microcontroller via various input/output pins. The details can be seen in Figure 8.



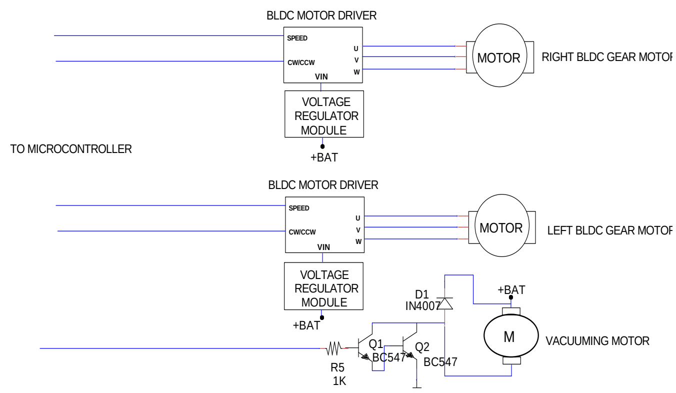


Figure 8: Connection of various components to the Microcontroller

2.5 Operation of the Robot

One design feature of this Robot is its ability to operate in both manual and automatic modes. The manual operation involves manually controlling the navigation of the Robot by means of RF modules used for wireless communication between remote control module and the robot when an obstacle is about to be encountered [6]. On the contrary, the automatic approach involves operating the vacuum cleaning robot without human intervention.

Therefore, in order to achieve a better cleaning efficiency in a reasonably good period of time, a simple algorithm which strictly depends on the nature of the cleaning area is developed. A comprehensive description of its operation flowchart is shown in Figure 9.

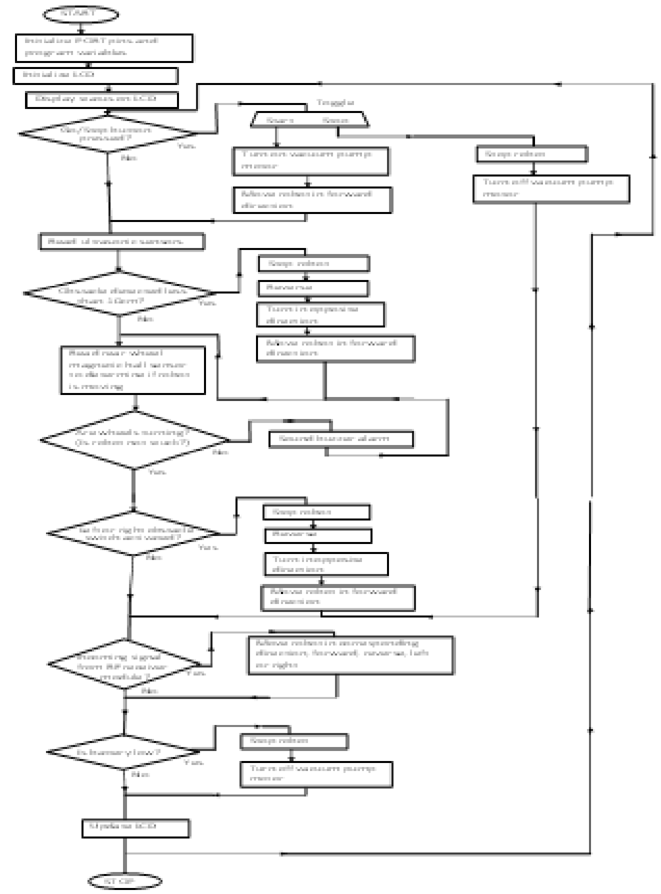


Figure 9: Complete Operational Flowchart of the Autonomous Vacuum Cleaning Robot

As can be seen from figure 9, the navigation of the autonomous robot strictly depends on the presence or otherwise of an obstacle within the confined cleaning area. This means, the algorithm moves left, right, forward or backward depending on the presence of an obstacle within the stated range and does not assume an a priori knowledge of the cleaning paths. With a good choice of initial cleaning position, the developed method performs competitively well.

3. RESULTS AND DISCUSSION

The results of the various experiments conducted are presented and discussed in this section. The results of the obstacle sensing was first presented where an analysis of the actual and measured instances from the ultrasonic sensor where carried out to establish and justify the use of such sensor for obstacle avoidance. The performances of the vacuum cleaning robot under various cleaning complexities were then presented. Results for Manual and automatic cleaning were also presented in terms of task to completion. In each case, the results are first presented in Tables and/or Figures and the related discussions then immediately follow. All result analysis of the acquired data was plotted in MATLAB environment.

3.1 Results for Obstacle Sensing

An analysis of the actual and measured distances from the ultrasonic sensor where carried out and outcome of the investigation is as shown in Table 5. The measured distances were evaluated by utilizing the mathematical equation; Distance = 2x Speed of sound x Time via a simple experimental setup where the speed of sound was assumed to be 340 m/s.

Table 5: Results for Variation in Obstacle Sensing

Actual Distance (cm)	Measured Distance (cm)	Recorded Error (cm)	Percentage Error (%)
10	11	1	10%
20	24	4	20%
30	33	3	10%
40	43	3	7.5%
50	51	1	2%
60	64	4	6.7%
70	73	3	4.3%
80	82	2	2.5%
90	93	3	3.3%
100	100	0	0%

From the results presented in table 5, it can be seen that the actual distance only slightly varies with the measured distance of the obstacle being placed and hence the Ultrasonic sensor is a good choice for obstacle avoidance task in the developed autonomous vacuum cleaning robot. A pictorial comparison of these measurements is as presented in Figure 10.

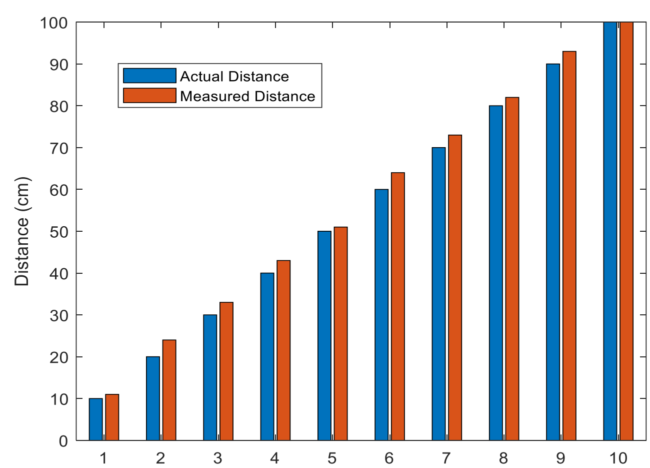


Figure 10: Pictorial Comparison of Actual and Measured Distances

3.2 Results for Cleaning Efficiency Assessment

The cleaning efficiency of the vacuum cleaning Robot was assessed in an environment whose area was measured to be 20.4 square meters under various cleaning complexities. The results of the investigations are presented in Table 6.

Table 6: Automatic Cleaning Efficiency in Varying Environments

Environment	Total area (m2)	Cleaned Area (m2)	Ignored Area (m2)	Cleaning Time (Sec)	Efficiency (%)
Very Simple	20.4	17.67	2.73	106	86.62
Simple	20.4	18.23	2.17	112	89.36
Moderate	20.4	18.87	1.53	119	92.5
Semi Complex	20.4	19.24	1.16	132	94.31
Very Complex	20.4	19.99	0.41	144	97.99

As can be seen in Table 6, the cleaning area ignored by the robot tends to decrease as the cleaning arena gets more complex . Furthermore, the cleaning efficiency increases as the environment gets more complex. This also shows that the developed vacuum cleaning robot can be robust to different cleaning terrains it is subjected to. It was however observed that the time to task completion gets slightly increased as the cleaning complexity gets higher. A graphical presentation of these results is presented in Figures 11 and 12.

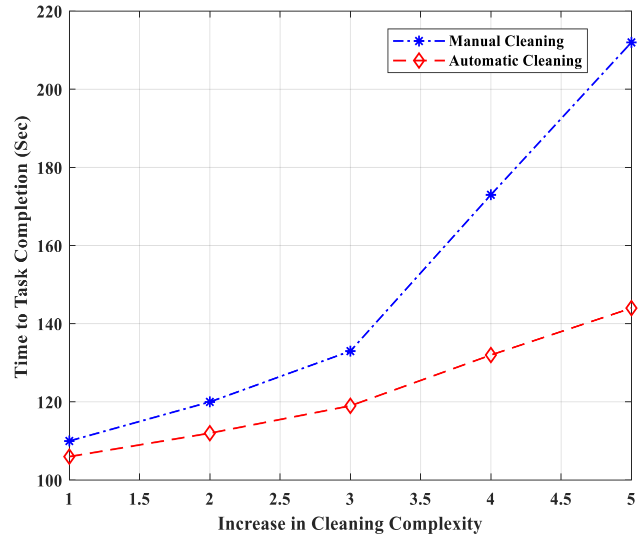


Figure 11: Comparing Manual and Automatic Cleaning

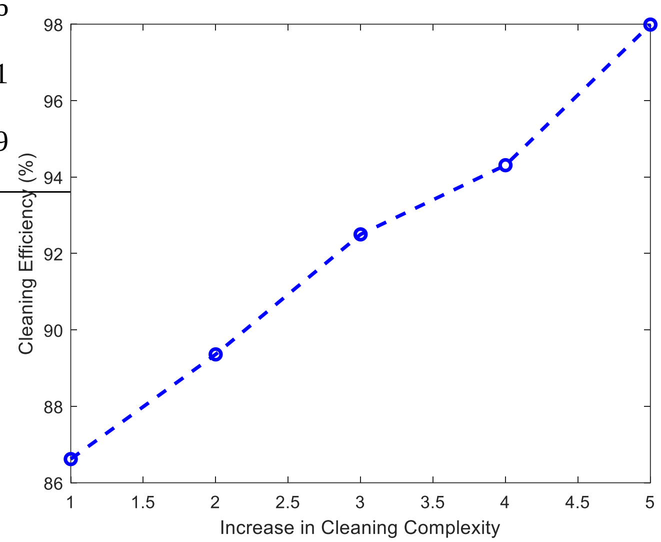


Figure 12: Effect of Cleaning Complexity on Cleaning Efficiency

In order to have a balanced comparison with respect to time to task completion, the performance of the robot was assessed when operated in manual and automatic modes and the results of the comparison is presented in Table 7.

Table 7: Average Time to Task Completion Auto versus Manual

Environment	Manual	Automatic	Improvement (%)
Very Simple	110 sec	106 sec	3.64%
Simple	120 sec	112 sec	6.67%
Moderate	133 sec	119 sec	10.53%
Semi Complex	173 sec	132 sec	23.70%
Very Complex	212 sec	144 sec	32.08%

From Table 7, it is evident that under the same cleaning conditions, the robot when operated in the Automatic mode has a faster completion time. This can be attributed to a number of reasons such as time lag due to operator decision making, task repetition amongst others. The average time to completion difference is calculated as shown:

$$t = \frac{(110-106)+(120-112)+(133+119)+(173-132)+(212-144)}{5} \quad (2)$$

t= 27 sconds. (3)

4. CONCLUSIONS

This paper has presented the design and development of an autonomous vacuum cleaning robot with obstacle avoidance capability. The hardware augmented electronics and mechanical components which operate at low power. Ultrasonic sensors detect the presence of an obstacle while a PIC16F877 microcontroller does the necessary processing. The system is powered by a 12V, 20,000mAh lead acid battery and the sensors generate control signals which are processed before being transmitted to the motor drivers. The prototype when operated in manual mode used an RF module as a platform for wirelessly transmitting and receiving information between a remote control and the robot while displaying related information on an LCD. A developed algorithm for autonomous path navigation incorporated in the robot and tested under various cleaning complexities gave an an average efficiency of 97.99%.

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