Design of a Low-cost Autonomous Mobile Robot

Kasun K. Jinasena   kasun@sjp.ac.lk
Faculty of Applied Science
University of Sri Jayewardenepura
Gangodawila, Nugegoda, Sri Lanka

Ravinda G.N. Meegama   rgn@dscs.sjp.ac.lk
Department of Statistics & Computer Science
Faculty of Applied Science
University of Sri Jayewardenepura
Gangodawila, Nugegoda, Sri Lanka

Abstract

Detection of obstacles during navigation of a mobile robot is considered difficult due to varying nature in terms of size, shape and location of the obstacle as well as ambient light that interferes with infra-red (IR) signals of the robot. In this paper, we propose a novel low-cost method that successfully guides a robot along a path using image processing and IR sensor circuits. A high continuous IR signal is converted into a low continuous IR signal by means of a demodulation circuit that enables a peripheral interface controller to receive this low continuous IR signal and take relevant decisions based on the signal. The images taken from a web camera are preprocessed to remove noise and detect edges. Subsequently, an image processing routine effectively calculates the angle to be rotated of the front wheels using a scan line algorithm. A minimum mean distance error of 2.45 was observed in tracking the path at a signal-to-nose ratio of 26.50. The accuracy of speech recognition was 92% for two voice training sessions.

Keywords: Mobile Robot, Infra-red Signals, Voice Recognition, Robot Navigation, Infra-red Communication

1. INTRODUCTION

Current research challenges on intelligent autonomous robots include navigation, task planning and coordination, learning and adaptation, cooperation between robots and humans [1]. Each model incorporates its own perceptual, modeling, and planning requirements.

Recent studies indicate a growing trend towards tracking of paths using mobile robots. A four wheel robot powered by a single motor was developed in the University of Aveiro [2] that uses complex mechanical techniques for both front and rear wheels. By using high-end firewire cameras and a built-in laptop computer, it managed to navigate along a path interpreting traffic lights. A unique two-body mobility platform with a hybrid electric power system was introduced in [3] resulting in an intelligent robotic vehicle with a sensor suite. In subsequent years, a three-wheeled, differential driven vehicle that uses two brushless smart DC servo motors and a hybrid system that provides sufficient power for the vehicle to run continuously at a length of more than 10 hours was developed [4]. The four sensors, (digital camera, scanning laser range finder, digital compass, and differential global positioning system (GPS)), were integrated into a streamlined system architecture with a laptop serving as the computational core of the system.

All these research finding over the years have contributed immensely to the advancements in robotics applications. More recent studies in mobile navigation techniques include autonomous flying vehicle [5], mine detecting vehicles to be used in military applications [6], wall climbing robots where robotics vehicles have been able to walk along a vertical plane using electromagnetism, electrostatic adhesion or air suction [7], medical surgery where the motion of

the heart is tracked in three-dimension [13] and micro robots used in biomedical applications to remove plaque in arteries [14].

Although we are able to come across many applications in robotics that addresses a specific area of research, one important fact that must be considered when navigating an autonomous robotic vehicle outdoors is interferences caused by sunlight [15]. Especially when the robot is guided by IR sensors, there must be a mechanism to distinguish between the sun's IR rays and the rays reflected back from an obstacle located at a particular distance away from the moving vehicle.
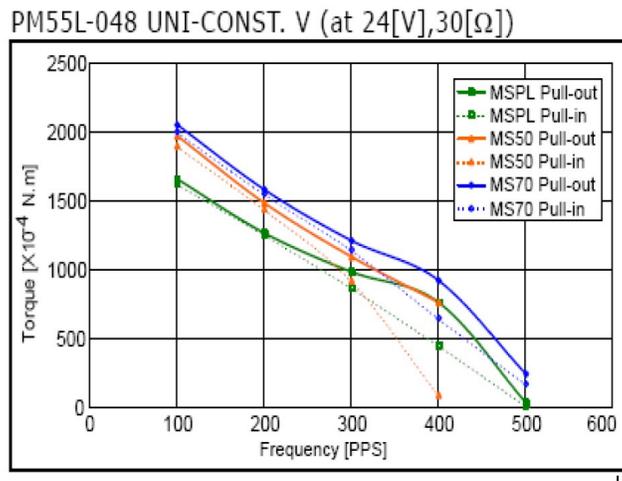
FIGURE 1: Torque charactisircs of stepper motors

2. METHODOLOGY

This research has its own hypothesis such as the track is on a plane surface with different color to its background, there are no junctions, the environment is static or dynamic, and the track with locations of obstacles are not known at the beginning of its navigation. A mechanical structure was designed for the problem involved with electronic solutions for the speed controllers and motor drivers. Image processing, speech recognition and text to speech software were used for the guidance algorithms.

The following sections describe the methodology we have used in designing and implementing the autonomous mobile robot.

2.1 Chassis Design

The chassis provides a solid support for the electronic boards, camera and sensors. Although aluminum pipes are the preferred material to build the robot, iron pipes were selected due to their availability and rigidness. The vehicle moves on three wheels. The two front wheels are each powered by a stepper motor while the rear wheel, hinged freely to the chassis, turns automatically.

The platform is made up of iron and was designed with modularity in mind, i.e., the chassis should provide a solid support for electronic boards, camera and any other items to be mounted in future.

The two main points of concern in selecting a material for the chassis are rigidness and lightness of the material as lightness of the chassis helps save power and enhances transmission. On the other hand, rigidness assists the vehicle to be stronger and carry more weight.
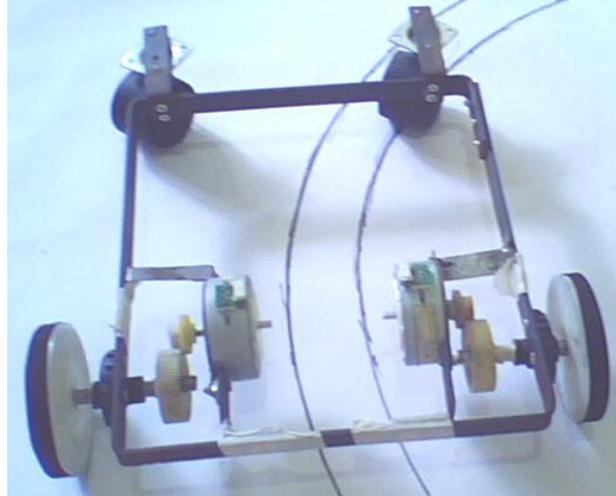
FIGURE 2: Wheel setup of the vehicle

2.2   Wheel Design

Unipolar 24 V, 800 mA per winding (30 Ω) stepper motors are used to power the front wheels. Each step motor will rotate 7.5 degrees as there are 48 steps for a single rotation. Each motor has maximally 0.2 Nm pull-out torque and 0.16 Nm pull-in torque with 100 steps per second with a maximum of 500 steps per second. A gear system is also used to increase the torque by 3 times. It consist of two wheels having teeth at a ratio of one to three to increased the torque by three times while reducing the speed by three times.

Fig. 1 illustrates the torque characteristics of the stepper motors while Fig. 2 indicates the setting up of wheels of the robot vehicle where the front two are steering wheels each powered by a stepper motor and the rear are free wheels. The vehicle turns by changing speed of its front wheels while rear wheels turn automatically. This will allow the robot to maintain more stability than a three wheel vehicle.

The vehicle transmission consists of two stepper motors responsible for steering the vehicle along the surface. Although rear driven wheels are suitable for heavy vehicles such as buses and lorries, front drive is used mainly for lighter vehicles so that they can be easilly manoeuvreable.

As such, a front driven mechanism is chosen for our robotic vehicle. Two motors are connected to the front wheels of robot to make turning easier.

2.3   Obstacle Detection

The vehicle is able to detect certain obstacles along its path and take relevant decisions based on the type of the obstacle. Ultrasound and Infra Red (IR) are the two most widely used obstacle detection methodologies in Robotics [8,9]. By using Ultrasound, the velocity and the direction of a moving obstacle can be identified easily through the Doppler effect. Because ultrasound waves are susceptible to temperature and humidity, IR, whose speed is constant over a particular media, is used in most mobile digital electronics [12].

Our vehicle employs IR to detect obstacles. The main challenge in using IR for this purpose is to distinguish between the robot's and nature's IR at the receiving end. Under strong sunlight, it is possible that a high amount of IR signals may incident on the sensor. As such, we need to overcome the natural IR exerted by the ambient light. One of the solutions to overcome this issue is to investigate the intensity of the two IR signals as natural IR signals has a lower intensity compared to the robot's. Natural IR, however, is not constant over a given period. As such, a

modulated (pulsed) IR signal, obtained with frequency generators, is used to overcome this problem. This modulated pulse signal is shown in Fig. 3.
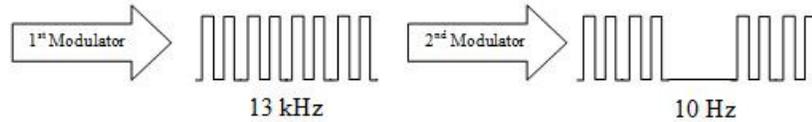
FIGURE 3: IR signal modulation

As depicted in Fig. 4, the 1st modulator converts the continuos signal into a 13 kHz square wave and then the 2nd modulator encloses that 13 kHz signal in a 10 Hz signal.
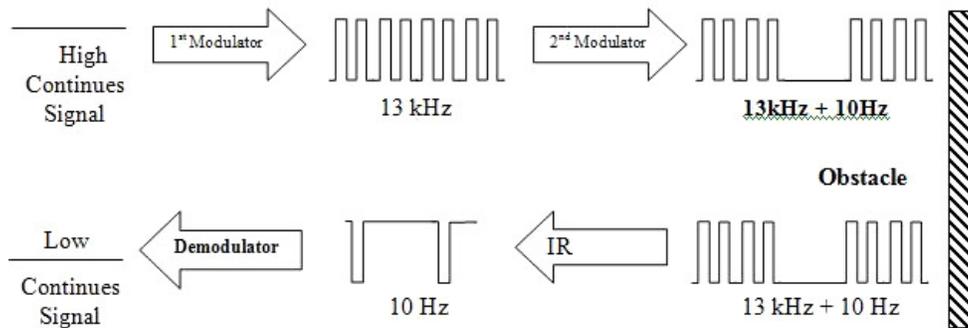
FIGURE 4: Demodulating a reflected signal

Finally, the transmiter emits this signal as IR rays. IR is heat radiation which is absorbed readilly by black rough surfaces while reflected by white shiny surfaces. Therefore, in order to make the robot sensitive to all obstacles equally, once the IR module receive signals reflected by an obstacle with an output of 10kHz (square signal), it is converted to a continuos signal by the demodulator. The result is then sent to a PIC microcontroller to make necessary decisions.

2.4 IR Signal Demodulation
The task of the Demodulator is to demodulate the signal originating from the IR module and regenerate a continuos signal. This is achieved by using a capacitor and properly biased transistors. This transistor circuit causes the signal to be invert but programmatically corrected. Fig. 5 shows the circuit diagram of the demodulator.
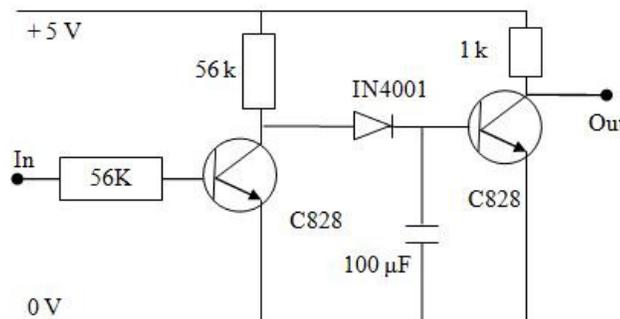
FIGURE 5: IR Signal demodulation circuit

2.5 Stepper Motor Driving Circuit

Fig. 6 shows only a single channel of the stepper motor driver circuit. The actual circuit carries eight of these circuits for eight windings of two motors. We have integrated a mechanism to protect the IN 4001. A photo coupler makes the isolation between high voltage and the low voltage sections. IN4001 protects the D313 from back electro motive force (EMF) of the motor.
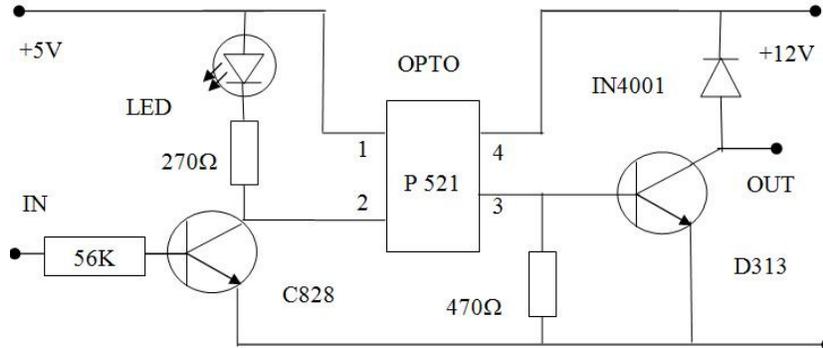
FIGURE 6: Stepper motor driving circuit

2.6 Image Processing & Vision

The input video stream is captured via web camera of 1.3 mega pixels resolution and the frames are extracted as images. These images are then pre-processed to remove Gaussian noise and detect edges.

As in Fig. 7, two lines scan the acquired image to detect the edges of the path. The angle θ of the inner and outer covertures is separately calculated. At each scan line, the curvature is calculated based on the intersection of lines and the edges. Based on the value of the angle θ, the left and right wheels are stopped to make the turns to left and right, respectively.
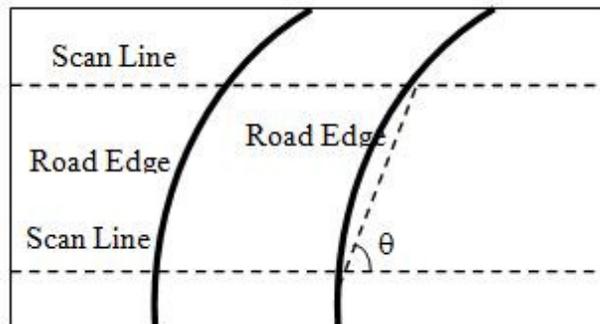
FIGURE 7: Detection of path using curvature

At this research, we carried out experiments to determine the vehicle's ability to track a path that consists of two edges. These edges have been drawn in black color on a white background. More complex tracks with multiples edges will obviously require much advanced image processing routines and fast computing power.

Fig. 8 depicts the main information flow of tracking the edges of a path using image processing technques. It can be seen that the vechile makes a decision to turn the wheels based on the location of detected edges.

2.7 Speech Recognition

We know that every speech recognition system consists of an engine that translates sound waves into text and a list of speech commands. In this research, we used the SAP15 engine that is integrated into Windows XP operating system. This engine was trained using windows voice training wizard in which a profound usage of grammar increases the probability of misinterpretations.
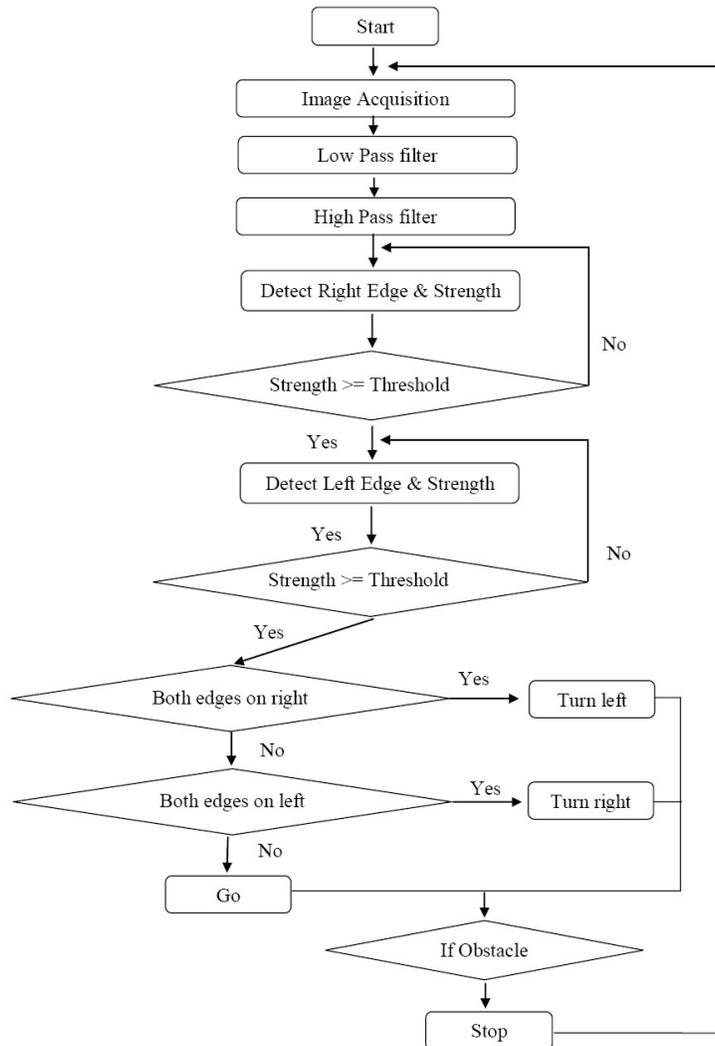
FIGURE 8: Flow chart of path tracking procedure

As such, we tried to keep the set of grammar as small as possible without lose of information. Grammar, which contains the commands "Go", "Left", "Right" and "Stop", is then fed into an XML file.

2.8 Main Board

A photographic illustration of the main circuit board is given in Fig. 9 showing the IR sensor and associated circuitry. The main circuit board constist of **16F877A** PIC as shown in Fig. 10. The pins 37- 40 are being used for the four voice commands given to the vehicle while pins 27 – 30 are reserved for the right stepper motor driver. The left stepper motor is driven by pins 19 – 22.
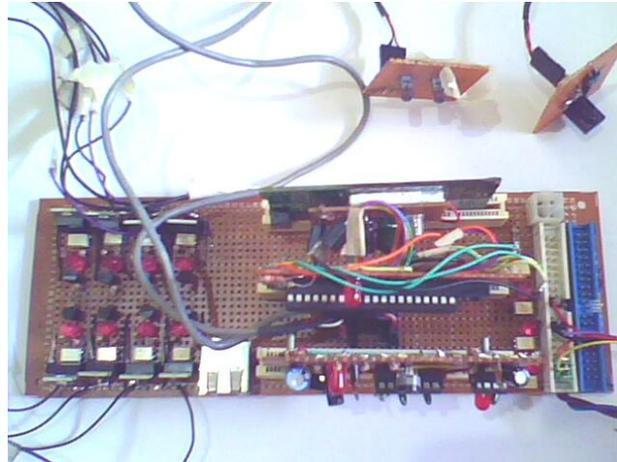
FIGURE 9: Circuit board of the vehicle.
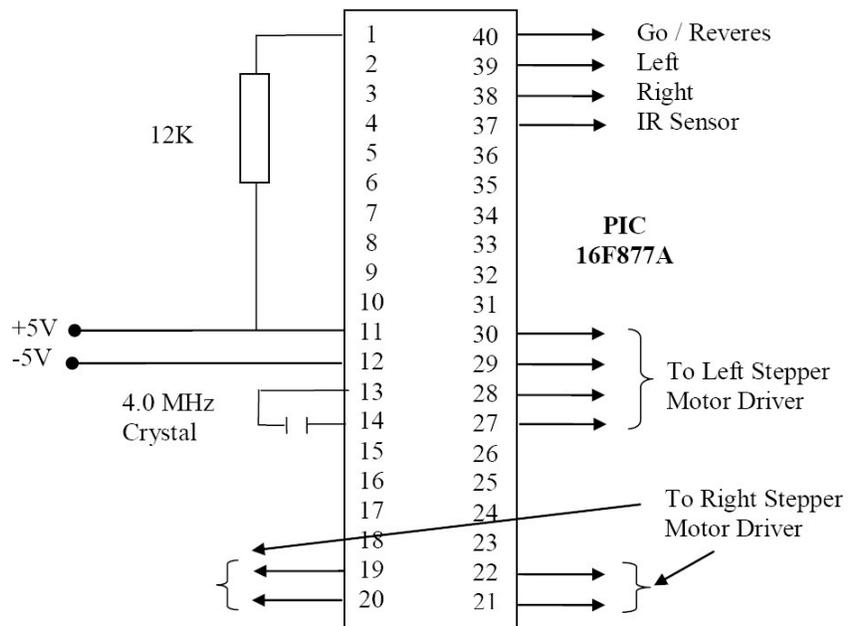
FIGURE 10: Main circuit board

2.9 PCB Design
Fig. 11 illustrates the printed circuit board (PCB) of the vehicle.

2.10 Mechanicla Structure
Fig. 12 shows the dimensions of the robotc vehile. The net weight of the vehicle was found to be 1.2 Kg that includes all the circuitry, wheels, web cam and IR sensor.

The selected dimensions of the robotic vehicle makes it easier to manipulate along a path with sharp edges. Also, the compact size of the structures requires less power to drive forward or backwards.
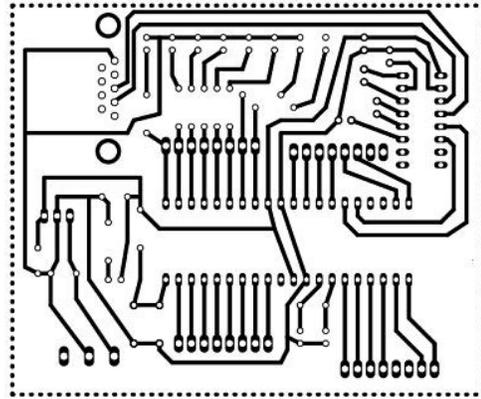
FIGURE 11: PCB of the robotic vehicle.
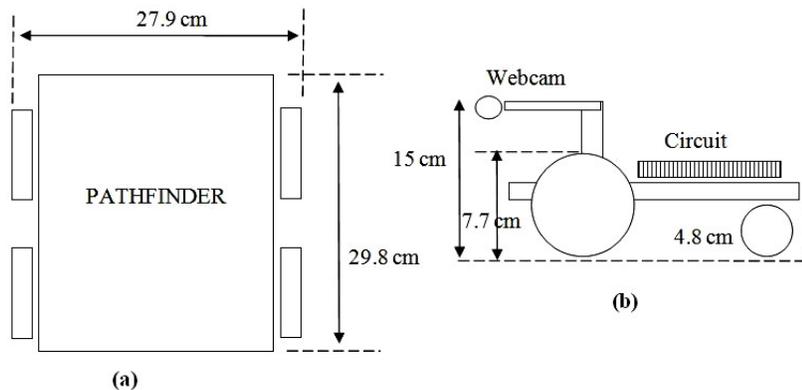
FIGURE 12: Dimensions of the robot: as seen from (a) above and (b) right hand side.

3. RESULTS AND DISCUSSION

3.1 Hardware and Software Requirements
A Personal Computer with a Pentium IV (or above) class Processor, 3.0 GHz, 512 MB or above RAM capacity and 10 GB hard disk space are preferred. All USB ports should be enabled and a microphone, speakers/head phone and web camera are the other accessories that are required. We used Microsoft Windows XP operating system with Microsoft's speech engine 5.1 and DirectX 9 with .NET framework 2.0 and a device driver for the web cam and Useport.sys for port access are required.

3.2 Transmission

As shown in Table 1, the vehicle is able to travel forward or backward with 3.95 inches per second on a flat surface while it turns 360 degrees around any of its front wheels, clockwise in 17.35 seconds and anti clock wise in 17.02 seconds. It travels in a straight line with an accuracy of more than 98.64 %. Speed can be increased by decreasing the period of delay while power decreases.

Characteristics	Result
Forward travel	3.95 inches per second
Forward travel deviation	1.36%
Clockwise rotation	17.36 seconds per 360°
Anti-clockwise rotation	17.02 seconds per 360°

TABLE 1: Transmission characteristics of the robotic vehicle.

3.3 IR Sensitivity

At the beginning of the research, an IR sensor typically found in a computer mouse was used to detect obstacles. It managed to detect obstacles at a distance of more than one foot with a single IR light emitting diode (LED). The major problem, however, was sun light. Since this IR sensor does not have a filter, we found a malfunctioning system even under minor sun light at dawn. The IR modules that are used in televisions, resulted filtering a pre define frequency from sun's IR rays. It was seen that IR modules band pass filter was highly sensitive to 13 kHz IR. Therefore, a modulator and demodulator circuits were designed to support this frequency.

It was also observed that high sun rise still can affect obstacle detection system because the frequency of mixed signal is dominated by the frequency of the signal that has the highest amplitude. This is easily solved by using more IR LEDs that causes the system to be over sensitive under minor sun light. In a practical situation, such as a remote control system for toys, the user is allowed to select the sensitivity level manually.

The distance between the IR transmitter and the IR receiver affects the sensitivity as shown in Fig. 14. Increasing the distance between the IR transmitter and the IR receiver decreases the sensitivity whereas decreasing the distance between the IR transmitter and the receiver increases the sensitivity. Results in Table 2 were obtained by changing the distance between the transmitter and the receiver for a white color, landscaped, A4 size obstacle.

Distance between transmitted & receiver (cm)	Straight detection distance (cm)	Width of detection region (cm)
3	24	22
4	20	20
5	17	17
6	16	14

TABLE 2: Distance vs width of sensitivity

3.4 Color Sensitivity

It was evident that the color of the object was a major factor that determines the correct detection of objects. Fig. 15 shows the sensitivity region of a landscape, A4 size obstacle for the 8 colors. As shown in Table 3, black had a significant deviation while other colors had minor deviations.

3.5 Voice Recognition

It was witnessed that all voice commands did not have an equal accuracy of recognition. The accuracy was highly dependent on the speech pattern of the user.

Color	Distance (cm)
White	24
Yellow	22
Red	20
Orange	19
Green	21
Blue	18
Brown	19
black	3

TABLE 3: Color vs distance of sensitivity

The voice of the speaker needs to be trained first and then, the accuracy can be increased by having more voice training sessions with the system. Fast speech causes less accuracy or even unrecognized commands while long phrases resulted in a higher accuracy than shorter phrases.

The accuracy also tends to get low with increasing number of commands. When two or more commands have similar sound characteristics, the accuracy of those commands decreases. Due to disturbances from ambient noise, a good, high quality microphone was used. Table 4 gives the results of accuracy of the system after one voice training session. Each command was tested ten times with different tones. However, we observed an increase in the accuracy when the number of training sessions was increased. Table 5 provides the average accuracy when the number of voice training sessions is two. More training sessions will be required if the vehicle is to recognize voice commands selected from a large vocabulary.

The speech engine was able to recognize voice of different persons for the same set of voice commands.

Command	Average accuracy (%)
Go	72
Turn left	67
Turn right	68
Reverse	67
Stop	45
Start CV	62
Close CV	66
Who are you	82
Exit	76

TABLE 4: Average accuracy for one voice training session.

Command	Average accuracy (%)
Go	72
Turn left	87
Turn right	88
Reverse	87
Stop	65
Start CV	82
Close CV	86
Who are you	92
Exit	66

TABLE 5: Average accuracy for two voice training sessions.

3.6. Path tracking

Direct application of a high pass filter to the captured image resulted in noise at the output that was highly affected by the path detection module. A significant enhancement was gained by applying a low pass filter to the captured image prior to applying the high pass filter.

The results obtained from image processing were obviously dependent on the resolution of the camera used. In order to keep the cost of the vehicle at a minimum, we used a widely used web camera that can be purchased from any computer store. Also, scanning horizontally on an edge at the middle of the image resulted in several issues especially when there was an object on its side. It was avoided by changing the scan order from the middle to up to the edge. A slight discontinuity or non-uniformity of the road did not make a significant effect to the vision process.

Table 6 provides measured mean distance errors when the vehicle tracks a path under different signal to noise ratios (SNR). The mean distance error e was calculated as

$$e(\mathbf{v}, \overline{\mathbf{v}}) = \frac{1}{l} \int_s \min_{s' \in \overline{\mathbf{v}}} \left| \mathbf{v}(s) - \overline{\mathbf{v}}(s') \right| ds$$

where $\mathbf{v}$ is the path of the robot's movement, $\overline{\mathbf{v}}$ is the actual path of the track and l is the length of v [10].

SNR	Mean distance error
26.50	2.45
22.60	3.35
20.15	4.42
18.75	5.66
17.85	6.57
17.30	13.11
16.50	15.63

TABLE 6: Effect of SNR on mean distance error.

3.7 Safety of PIC Microcontrollers
Unlike other electronic equipments, PIC microcontrollers are vulnerable to high voltages. It was observed that both hardware and software errors resulted in a damaged PIC. It must be noted that the PIC 16F877A microcontroller is able to provide an output of a maximum current of 200 mA while any of its pins provides an output of a maximum current of 25 mA. Exceeding any of these limits causes a burnt microcontroller. Interferences from other electrical signals also affect the inputs to the microcontroller. Most of such problems, however, can be solved by grounding the pins with a higher resistor, such as 10 K.

3.8 Communication
Currently, the robot does all the communication over wired media. Wireless technologies, such as Bluetooth or Wi-Fi, can be introduced so that communication can be done from anywhere even over the Internet. Bluetooth uses the 2.4 GHz radio frequency band to communicate with other Bluetooth devices [11]. However, the issue that needs to be addressed in this scenario is that a majority of popular Bluetooth USB dongles are slave devices without any inbuilt firmware. When it connects to a computer, the computer provides the necessary protocol stack. On the other hand, if it connects to PIC microcontroller, both the USB protocol stack and the Bluetooth protocol stack should be implemented inside the PIC. Since a PIC executes only a single program at a time, a dedicated PIC is needed for this purpose. Although this research uses a PIC16F877A microcontroller, a PIC 18F series also provides the USB interface. IR sensors

IR Sensors tend to get saturated when the distance between the obstacle and the sensor fall below 40 cm. Therefore, it is difficult to use it to measure distances less than 40 cm. When measuring distances that vary between 50 to 70mm, the accuracy of IR sensor ranges from 92 to 95 percent whereas the accuracy of Ultrasound sensor was 90 to 97 percent.

The proposed research show that modulated IR still can be used to detect obstacle even when they are located close to as much as 3 cm. The speed of Ultrasound waves varies with temperature and the humidity] and as such needs correction to obtain correct distances. Since IR is electromagnetic, it neither depends on temperature nor humidity.

4. CONCLUSION
This research presents the design, implementation and results of a low cost minatory model of an autonomous land vehicle based on computer vision, speech recognition and IR transmission.

The main feature developed by this project was its ability to track a path avoiding disturbances from sun light using IR, image processing and computer vision. Moreover, the robot can make voice response to its user. Both the path and location of obstacles were not known in advance. Results indicate that the robot is able to recognize speech at higher accuracy when the number of training sessions is increased. We checked the performance of the robot by adding Gaussian noise along the path to be tracked. With the current setup, it successfully tracked the path when the signal to noise ratio of the image is higher than 17.30.

Extending the research for the vehicle to transmit data using wireless or Bluetooth technology is straightforward.

5. REFERENCES
[1] P. Alfonso, J. Azevedo, C. Cardeira, B. Cunha, P. Lima and V. Santos, "Challenges and solutions in an autonomous driving mobile robot competition", In Proceedings of the Controlo Portugese Conference in Automatic Control, Lisbon, 2006.

[2] T. Fong, I. Nourbakhsh, and K. Dautenhahn, "A Survey of Socially Interactive Robots", Robotics and Autonomous Systems, 42(3-4):143- 166, 2003.

[3]   [online] http://www.avt.me.vt.edu/index.htm.

[4]   C.F. Reiholtz, "Virginia Tech Autonomous Vehicle: Jhonny-5", Department of Mechanical Engineering, Virginia Tech, USA.

[5]   L.O. Mejias, S. Saripallai, P. Cervera and S. Sukhatme, "Visual Surveying of an Autonomous Helicopter in Urban Areas Using Feature Tracking", Journal of Field Robotics, 23(3): 185-199, 2006.

[6]   E. Cepolina and M. Zoppi, "Cost-effective Robots for Mine Detection in Thick Vegetation", In Proceedings of the 6th International Conference on Climbing and Walking Robots, Catania, Italy, 2003.

[7]   B. Aksak, M.P. Murphy and M. Sitti, "Gecko Inspired Micro-Fibrillar Adhesives for Wall Climbing Robots on Micro/Nanoscale Rough Surfaces", In Proceedings of the IEEE International Conference on Robotics and Automation, 2008.

[8]   G. Benet, F. Blanes, J.E. Simo and P. Perez, "Using infrared sensors for distance measurement in mobile robots", Robotics and Autonomous Systems, 40(4): 255-266, 2002.

[9]   V.K. Sehgal, R. Sharma, N. Nitin, D.S. Chauhan, A. Srivastava, A. Kumar, Y. Agerwal and A.M. Khan, "Obstacle Sensing and Anti-falling Sensor Robot Using Embedded Processor", In Proceeding of the 11th International Conference on Computer Modelling and Simulation, 2009.

[10]   L.H. Staib and J.S. Duncan," Model-based deformable surface finding for medical images", IEEE Transactions in Medical Imaging, 15(6): 859-870, 1996.

[11]   Y.C.F. Amin, S.H.M. Fisal, N.Bakar, "Bluetooth enabled Mobile Robot", In Proceedings of the IEEE International Conference on Industrial Technology, 2002.

[12]   W. Fehlman and M.K. Hinders, "Mobile Robot Navigation with Intelligent Infrared Image Interpretation", Springer, 2010.

[13]   R. Richa, P. Poignet and C. Liu, "Three dimensional Motion Tracking for Beating Heart Surgery Using a Thin-plate Spline Deformable Model", International Journal of Robotics Research, 29(2-3): 218-230, 2009.

[14]   J.J. Abbot, K.E. Peyer, M.C. Lagomarsino, L. Zhang, L. Dong, I.K Kaliakaktos and B.J. Nelson, "How Should Microbots Swim?", International Journal of Robotics Research, 28(11-12): 1434-1447, 2009.

[15]   G.Anderson, C. Sheesley , J. Tolson, E. Wilson and E. Tunstel, A Mobile Robot System for Remote Measurements of Ammonia Vapor in the Atmosphere, In Proceedings of the IEEE International Conference on Systems, Man and Cybernetics, 2006.