TAMPERE UNIVERSITY OF TECHNOLOGY

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OUTDOOR OBSTACLE DETECTION USING ULTRASONIC SENSORS FOR AN AUTONOMOUS VEHICLE ENSURING SAFE OPERATIONS

Masters of Science thesis

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ABSTRACT

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Ultrasonic or sonar sensors are widely used for range finding for indoor and outdoor applications in robotics. However, for outdoors applications, they pose different environmental challenges. Ultrasonic sensor can be used both in air and underwater. It emits acoustic pulses in a cone shaped form in its surroundings and waits for the echoes from the objects nearby that lie within its working range. Ultrasonic sensors have convincing advantages over other sensors. However, sonar sensors have different practical limitations as well which need to be carefully dealt with while working with these sensors.

Ultrasonic sensors have several applications in electronics and robotics including obstacle detection and avoidance, mapping and navigation, object recognition and identification. Ultrasonic sensors are widely used in automatic car parking systems in modern vehicles, where two to four sensors are mounted in rear bumper for detecting obstacles up to 2.5 meter and assisting the driver about the parallel parking.

The thesis is mainly divided into two parts. In the first part, background studies and literature review is presented which describes sonar sensing principle, applications, advantages, limitations and outdoor sensing challenges. In the second part, a sonar system for obstacle detection for a mobile machine is implemented and its tests and results are discussed.

The study indicates the testing of ultrasonic sensors for obstacles detection for an autonomous mobile vehicle outdoor. The sensors were tested both on static frame and on real machine detecting different obstacles from 60 cm up to five meters. The results are better when the object is in front or moving along the axis of the sensor. The sensors are connected in series and are in ranging mode all the time. The experimental results show that the environmental factors like, air turbulence and temperature change affect the speed of sound in air and measuring range. The ranging value is better indoors than the outdoors for same obstacles. However, the results are better on less windy day and also when the surface is strong reflector. It is noted that the results get improved when a cone made of paper or plastic is wrapped around the transducer. The sensor is protected with a water proof casing made of PVC plastic material and it is noted that the casing made of aluminum does not yield good results as compared with the plastic casing. The two or more sensors attached in line increase the covering area of the system.

TERMS AND DEFINITIONS

Acoustic	The science dealing with the transmission of sound waves.
Beam Pattern	Beam patterns show the relative amplitude of the acoustic pressure (generated or received) as a function of direction relative to the transducer. For reciprocal transducers transmit and receive beam patterns are basically the same. Beam patterns are three-dimensional.
Beam Width	The width of the main beam lobe, in degrees, of the transducer. It is usually defined as the width between the "half power point" or "-3dB" point.
Blanking Distance	Minimum sensing range in an ultrasonic proximity sensor. Blanking distance is a function of the ring down time of the transducer as the transducer must ring down before it can receive the sound reflected from the target.
CAN	CAN bus (Controller area network) is a message based protocol designed to allow microcontroller and devices to communicate each other with in a vehicle without a host computer.
Damping	Materials, design, and mounting techniques used to reduce ringing in the transducer.
Main Lobe	The main acoustic beam in a directional transducer. There are other, smaller lobes called side lobes that are located around the main lobe
Piezo-electric ceramic	A material made of crystalline substance which creates charges of electricity by the application of pressure and vice versa.
Resolution	Minimum change in distance that can be measured by the sensor when the target moves relative to it.
Sonar	Word is derived from "sound navigation and ranging." It describes a devise that transmits frequency sound waves in air or water and registers the vibrations reflected back from an object.
Target Strength	A measure of the percentage of the acoustic energy hitting the target that is reflected back to the transducer.
Time-of-Flight	Technique for calculating the distance to a target by using the timing of the return echo from the target and the speed of sound in the medium between the target and the sensor.

PREFACE

I am thankful to almighty ALLAH for the successful completion of this thesis. Then, I owe my special gratitude to my supervisor Mika Hyvonen and Reza Ghabcheloo. My colleagues, Otso Karhu, Janne Honkakorpi and Jukka-Pekka Hietala were very helpful during the course of my work. I thanks to their guidance and help.

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CONTENTS

1. INTRODUCTION

The word 'sonar' is an acronym for sound navigation and ranging and was initially developed for underwater applications [1]. Sonar, or ultra-sonic sensing, uses the propagation of acoustic energy at much higher frequencies than are audible to humans. The primary purpose of sonar is the extraction of information or characterization of objects in the environment. The estimation of position (or distance to an object), and its velocity and shape can be obtained.

The sonar principle works both in the air and underwater [2]. In the air, sound waves are absorbed quickly, in contrast to radio waves, which travel unhindered. Underwater, sonar works like radar in the air, although it uses sound waves instead of electromagnetic waves. Sound waves travel thousands of miles underwater because of their low absorption and the presence of natural oceanic waveguides, whereas the sea is opaque to most Electromagnetic waves. Ultrasonic sensor employs acoustic pulses and the echoes which return from the objects in order to measure the range of an object. The object’s range is proportional to the echo travel time (to and from the object) as the velocity of the sound is known to be 344 meters per second in the air. Sonar also provides directional information.

Sonar is a widely used sensor in ranging applications and robotics. Ultrasonic sensors have several advantages over other sensors like; they have high directivity which means they offer less diffraction or bending around an object due to high frequency and lower wave length of ultrasound making ultrasonic beam focus and direction towards the target easier. They have a lower speed than light or radio waves. They are independent of material, surface, color, and size. They can work under dust, dirt, fog and bright light. They can detect transparent and shining objects. They have measuring range from few millimeters to more than 5 meter. Other advantages include their low cost, light weight, low power consumption and have low computational efforts. Due to these advantages they become the only choice in certain applications.

There are three main applications for sonar in robotics [3]. The first is obstacle detection and avoidance, where the range to the closest object is measured by detecting the first echo. The robots use this information for path planning to avoid collision with the object. The second is mapping, where a sonar map of the environment is constructed by performing a rotational scan and getting a collection of echoes. The third is object recognition/identification. This involves classifying the sonar map in order to identify one or more physical objects. The information can be useful for robot registration or landmark navigation. Ultrasound phenomenon is quite useful in other applications as well for example, it is widely used in today’s modern automotive for automatic car parking systems [4], it is appropriate for military applications because it is inaudible to humans and therefore undetectable, it is quite useful for detection of hostile fluids passing through vessels because ultrasound can pass through the vessel or pipe when mounted outside the pipe, it can pass through biological tissues which makes it useful in the medical applications.

The resolution and accuracy of an ultrasonic sensor is typically better at higher frequencies [5]. Resolution is affected by wavelength of the sound, the Q (a transducer's quality factor which describes the amount of ringing, ceramic element(s) undergo when power is applied to the transducer) of the transducer, the reflecting characteristics of the target, the operation of the target detection electronics in the sensor, and the uncertainty in the assumed value of the sound [5]. While, typically the maximum value for range can be obtained at lower frequencies. The value of range and resolution measured for a particular distance is also affected by the geometric shape and reflectivity of the target due to varying strength of the target echoes. Ultrasonic sensor with narrow beam pattern is usually used for detecting the required targets. However, a narrow beam pattern requires orientation of the target is accurately known with respect to the sensor's axis. The understanding of the effective beam angle is needed to know targets to be detected or ignored. The factors that affect the affective beam angle are distance to target and the reflections received from the target.

The variation in sound speed between source and target is one of the prominent sources of error in measuring exact distance [3]. The main reason for this variation in speed can be temperature change between source of sound and the target. Therefore, temperature compensation is needed for accuracy of measurement. The other factors such as target movement, air turbulence and humidity also affect the amplitude or strength of echo received by the target.

The objective of this work is to develop a sonar based obstacle detection system for a mobile machine that can properly detect the obstacle which can be or come from back side of the machine. The obstacle is defined as an object that can cause some safety issue or hindrance to smooth motion of the machine. It can be a human, object, fence, blocking or some tree/branch. However, the tests are conducted for human and plastic polls. The obstacle can be either static or dynamic i.e. moving towards or away from the machine. The mobile machine should continue its specific motion without touching or hitting the obstacle towards its destination.

The scope of this document is that it presents only experimental study/work. No simulations or Mathematical modelling of the sensors behaviours is conducted. No sensors fusion is done. The only sensing modality used is ultrasonic sensors. All environmental factors are treated as external error sources. No deep study in analysing one or more to know its affects on the performance of the sensor is done. Range is limited for weak reflective targets and this is taken as a limitation, no operation is done on targets to improve reflections.

The study indicates the use of ultrasonic sensors for obstacles detection in an open environment for an autonomous mobile vehicle just like prevalently used for automatic parking system in modern automobiles now-a-days. The ultrasonic sensors used can detect obstacles from 60 cm up to five meters. Below 60 cm is the blanking zone. The sensors are connected in series and all the sensors are in ranging mode all the time. The sensor works in a continuous loop as: first the ranging request is sent to all the sensors on the bus then wait for 80 ms finally the ranging value is read from all the sensors through CAN bus.

The experimental results show that the performance is affected by the environmental factors because the ranging value is better indoors than the outdoors for the same obstacle that is moving in front of the sensor. However, if the target is strong reflector and there are less disturbances and temperature is usual, we can expect nearly the same results outdoor as well. The results on the machine in real world scenario were showing this fact where results are better for strong reflector and less affected by the environment. It is noted that the results get improved when a cone made of paper or plastic is wrapped around the transmitting part of the transducer. The sensor is protected with a water proof casing made of PVC plastic material and it is noted that the casing made of aluminum does not yield good results as compared with the plastic casing. Two or more sensors increase the covering area of the system.

The obstacle detection system tested for different obstacles on static and real machine are shown which can detect obstacles quite accurately without much affected by the environment, noise and vibrations of the machine and mutual interference of the sensors. The results are quite promising for the system designed.

2. THEORATICAL BACKGROUND

2.1. Overview

Mobile robots are gaining more and more space in both industrial and educational purposes due to their sophistication and multi-tasking. There are different types of mobile robots classified by the environment of their working: land based (legged, and robots having human like shape called anthropomorphic robot, robots with wheels, tracked robots), air-based (plane, helicopter and blimp robot), water-based (boat, submarine) and combination of these.

Like Mobile robots, mobile machines are also gaining popularity. Mobile machine can work on uneven terrains and in winter as well due to four wheel drive. Mobile machines are used for several different purposes which include various load handling tasks, material handling, landscaping, lawn mowing, snow removal, sand spreading and in constructions.

Mobile machines are made more and more intelligent and economical. It is a globally active field of research. For example, an advanced tele-operated mobile machine is constructed serving as a test bench for further research at Tampere University of Technology in Intelligent Hydraulic Automation department (IHA) [6].

Mobile robot navigation is a challenging research problem. The term 'Localization' is used to refer to the process of determining the current position of the mobile robot with respect to its surroundings by using the information of the sensors [7]. The obstacle detection and avoidance is the primary task in this. Our project use SRFWPR485 sensor [8] to accomplish the tasks of detection of obstacle.

Different navigational techniques are employed in mobile robotics [9]. They include LIDAR (Light Detection and Ranging), RADAR (Radio Detection and Ranging), SONAR (Sound Detection and Ranging) , laser scanners, beacon light and Radio Frequency (RF).The working principle of these techniques is different. Based on the system's demand the suitable technique is used. Laser scanners or range finders are most popular for navigation due to their high accuracy and sensing rate. The use of sonar for navigational purposes is almost ceased but still they have some appealing advantages like, cheaper, smaller, lighter and less power consumption which make them easy to put on every robotic platform [7],[9].

The mobile machine in this project uses laser scanner which is mounted at front of the machine for navigational purposes. It is needed to make machine safe from behind from any obstacle that may cause hindrance in smooth motion or some safety issue. To attain this purpose, sonar sensors are chosen.

2.2. Sonar Working Principle

Sonar employs acoustic pulses and the echoes returned from objects to measure the range to an object. The object range is proportional to the echo travel time (to and from the object) as the velocity of sound (c) is known to be 344 meters per second in the air at standard temperature and pressure. The range (r) to the object/target is calculated by the following equation

$$r = ct/2 \qquad (1)$$

The range (r) is equal to multiplication of speed of sound (c) and time taken (t) by the pulse to and from the target. The division with 2 converts the total distance traveled by the pulse to half the distance, which is the range to the object. The factors that limit the range in the air are beam losses due to spreading and acoustic absorption. It means that the expected range is not achieved because air is an open medium and some of the beam is absorbed and diverted to different angles than to the target alone.

Figure, 1 shows a sonar map in a simplified configuration consisting of a transducer which acts as both transmitter and receiver, an object within the range of the sonar beam which reflects back the probing pulse as echo to the transducer. The echo travel time is called the time of flight (TOF) and is measured from the transmission time taken by the probing pulse. The echo is a replica of the probing pulse.

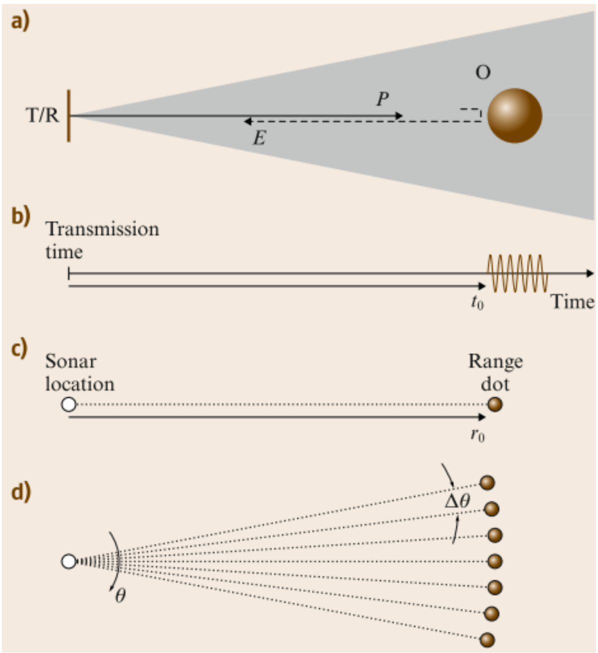

Fig.1. *SONAR ranging principle. (a) Configuration (b) echo waveform (c) range dot placement (d) sonar map [3].*

A sonar map is formed by placing a dot with the orientation of the transducer about the vertical axis by angle theta [3]. A series of dots corresponding to the angles are placed at the distance delta theta, forming a sonar map, which is made up of arcs.

Sonar sensors beam angle is bigger than laser beam angle [9]. This makes sonar difficult to use than laser because of more chances of errors if environment is not carefully considered. The distance reported by the sensor is the distance of the first object in the way of sound wave. In this way, the same distance can be reported for multiple unique objects in the path of sound wave. The solution to this problem is the integration of multiple sonar sensors in a way that can help classify the different objects.

Bats and some other nocturnal creatures don't have ability to visually trace their prey. They use a technique called, echolocation to locate their prey [10] as shown in Figure, 2. The techniques employ complex filtering and correlation techniques. [11] Presents the work inspired by the study of bats using ultrasound for applications in industrial automation. Dolphins, porpoises can also produce ultrasonic sounds as well.

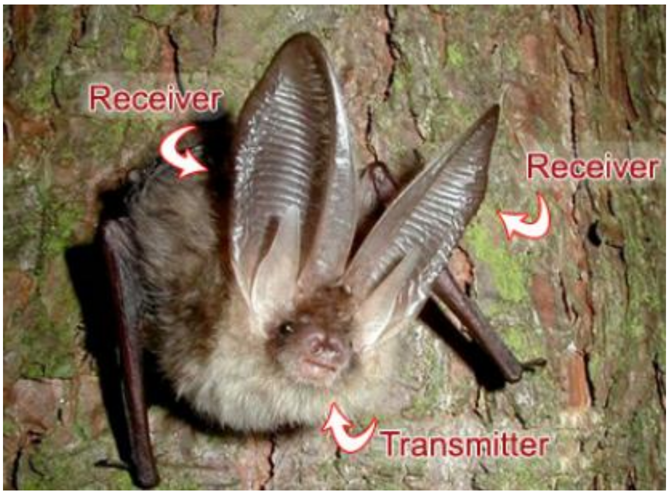

Fig.2. *Bats sonar systems*

2.3. Ultrasonic and sound

Sound is a mechanical vibration of an elastic body [12]. Humans can hear frequencies ranging from 20 Hz to 20,000 Hz where human ear is more sensitive to frequencies around 3,500 Hz. The frequencies above 20,000 Hz are called ultrasound and below 20 Hz are called infrasound. The use of ultrasound for range finding is called sonar.

The wavelength of ultrasound is much larger than the wavelength of light, i.e. usually around 4 mm as compared to 550 nm for visible light.

2.4. Speed of sound

The speed of sound affects the sonar's data acquisition rate because it varies greatly with temperature, pressure, humidity of the environment and therefore it is critical player in determining the accuracy of the sonar data. The speed of sound depends on the medium in which it passes through and generally proportional to the stiffness and density of the medium. The speed of sound in air is 343.2 meters per second at 20 degrees Celsius and in water 1500 m/s and in steel bar 5000 m/s.

2.5. Sound reflection Cases

Sound signal transmitted to target is a longitudinal sound wave and upon its reflection from the target, a flat surface, the distance can be measured provided the dimensions of target are larger than the wave length of sound wave [12]. The conditions for surface of target, distance to target, and size of target and angle of transmission are discussed in Figure, 3.

Ideally, surface should be flat or smooth, hard and at right angle to the sound wave because this surface reflects sound strongly than the soft and rough surface. A small and rough surface reflects weakly (weak echoes) which reduces the distance and is not good for the accuracy of distance measurement.

Ideally, less distance between sensor and target object is required because in this way stronger echo can be obtained. However, object having better reflecting surface at higher distances can ensure sufficiently strong echo.

Big size object has more area for reflection than the small size object. The object recognized as target is the object that is nearest to the sensor.

Angle or inclination of target object affect greatly to the reflection of that object. The part which is right angle to the sensor reflects the sound. If the object is at large angle, the echo is then not detected by the sensor because it is reflected away from the sensor

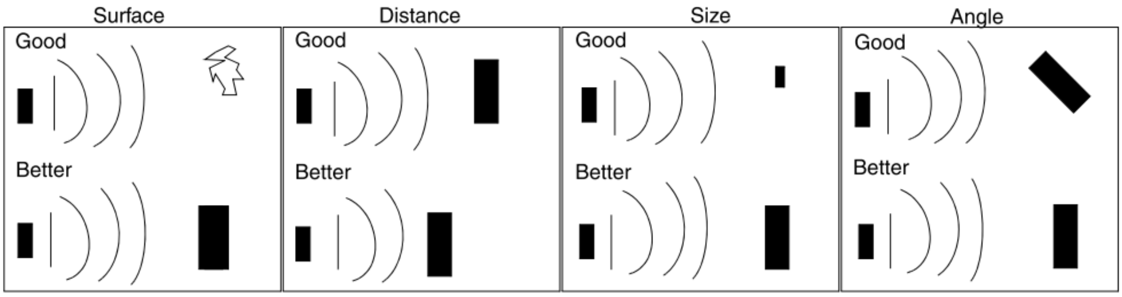

Fig.3. *Sound reflection cases [12].*

2.6. Ultrasonic Artefacts

In simple environments ultrasonic sensors works well but as the complexity of the environment increases, ultrasonic system start producing mysterious results and artefacts making the ultrasonic sensors as noisy, poor quality sensing modality because of their inability to result into a reliable map.

Sonar champions believe that unless and until we can understand the sonar echoes to the level employed by bats and dolphins we can’t expect the more reliable results and if we get successful in doing this we can use sonar for many new applications [13].

There are two categories of artefacts based on how they are treated. First one deals with the artefacts before transmitting data by building robust and intelligent sensors and second one deal with the artefacts that are produced after transmission of the ultrasonic data by doing high level of post processing on the data received by the ultrasonic sensor. However, for the simple environments the post processing on data works quite well but for real world environments this does not work that well and there left only first category to go for other alternatives like camera and/or laser systems.

There are two types of artefacts: axial multiple reflection (MR) and dynamic artefacts [3]. The MR artefacts are due to delayed echoes received after the time set for them is finished and new echo is transmitted. In this way, the echo received shows some close lying object near the sensor and obscuring the actual object that lies at further distance. The treatment to MR artefact is by increasing the waiting time for the probing pulse from 50 ms but reverberant environment can still produce these artefacts [14].

Dynamic artefacts are produced by the moving objects in front of sonar beam like person moving [3]. Although the sensor report the actual values of range for these objects but the appearance of these objects in static environment map is not needed and should not be the part of the map because this makes the stored and actually produced map error prone.

Other commonly seen artefacts are no axial MR artefacts [15] which appears when an object at some angle reflects the beam to some other echo-producing. The range value produced in this way is from the object whose location is different from the location indicated by the sonar map.

The perturbing echo is difficult to determine and process because of the speed fluctuations in the medium and ever present electronic noise. Random fluctuations are even seen in stationary sonar working in static environment [16].

3. LITERATURE REVIEW

Ultrasonic sensors are used in a variety of applications and still sonar systems are under research to produce more near to nature sensors. Following sections highlight the work done in the field of sonar sensing.

3.1. Related work

Ultrasonic sensor with fixed beam-width is commonly used in mobile robotics. [17] Shows the use of multiple ultrasonic sensors employing the different beam-width sensors used simultaneously for mobile robot navigation purposes. The small beam-width sensor is good in resolution but for wider angular region the more number of sensors are required. The use of wide beam-width sensors results in less number of sensors while covering the detection area. However, it results in poor resolution which is solved by fusing (stacking) the different beam width sensors to get better resolution and also larger covering area making navigation powerful in complex environment.

In many cases, ultrasonic sensors are attached to a horn for increasing the intensity of echoes [18]. This makes the directivity of the sensor narrow. A narrow directivity is also desired for knowing the exact direction of the obstacle. However, for an obstacle to be properly detected by narrow directivity, as shown in figure, 4, it should be perpendicular to the line of axis of the sensor. As, it is important for obstacle detection to know whether obstacle at first exist in the sight of the sensor or not and at second how far it is, therefore, a wide directivity is also required for obstacle detection as shown in Figure,4.

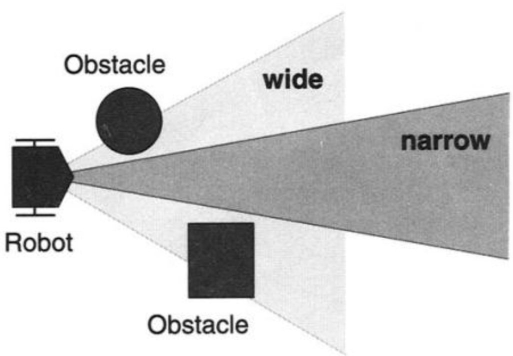

Fig.4. *The directivity of ultrasonic sensor. Narrow directivity misses the obstacles [18].*

Obstacle detectability depends on the individual system used. Directivity of the sensor depends on the directivity of transducer and sensitivity of the sensor and both these affect the resultant sonar map and it makes it necessary to understand the sonar map with care [18].

An intelligent parking system using hybrid approach to combine ultrasonic and magnetic sensors is shown in [19] yielding an accurate, cheap and more practical solution to parking system. The number of vehicle on each floor are counted by magnetometer and the cars going up and cars going down on the entrance of the floor is counted by two ultrasonic sensors one for each purpose. The ultrasonic sensor can also provide additional characteristics of the vehicle making the detection of specific car easier.

A person tracking mobile robot using combination of RF and ultrasonic sensor modalities is developed [20] who is capable to detect moving person and avoid obstacle simultaneously in unstructured or semi-structured environments. An RF/ultrasonic positioning system provide the real time relative position of the target person in term of range and bearings (the way the person is standing or moving). The system gets the target's current state as control input and performs the tracking operation. Mobile robot also utilize the sonar system having 16 sonar ring performing the distance measurement and direction measurement of the target. The information received through this serves also as an input necessary for obstacle avoidance. The two algorithms running are potential field algorithm and the obstacle avoidance algorithm. Potential field algorithm is responsible for converting resultant forces into translational and steering velocity needed for controlling the robot. The obstacle avoidance algorithm is activated when the robot is close to the obstacle.

Another interesting work is shown in [21] employing sonar system on mobile robot capable of distinguishing the trees from poles (smooth and round) by analysing the backscattered echo data. The data is collected by a mobile robot having sonar system as shown in Figure, 5. The sonar system provides 3D scanning of the surroundings. The distinguishing process takes place in four steps. Firstly, the number of scans for one object is done. Secondly, the square root of the backscattered signal energy versus scan angle plot is drawn by a fifth order polynomial fit. Thirdly, asymmetric and deviated features are noted in the plots and finally more feature extraction is done on asymmetry-deviation graph yielding a single point in abstract phase space. Round poles lie near to origin than trees as trees have more irregular scattering patterns due to their roughness. Results are shown for 20 trees and 10 metal poles.

Fig.5. *Mobile robot with sonar scanner [21].*

A similar kind of work was shown by Keith W. Gray in his thesis [9]. An obstacle detection and avoidance system for an autonomous ground vehicle (tractor) for farming purposes was designed and implemented capable of obstacle detection and avoidance in a typical real-world farming environment. A range sensor is used for obstacle detection giving real time updates of the environment. Obstacle avoidance is achieved in two subsystems: global and local avoidance systems. Local one manoeuvres the tractor for unknown obstacles around the tractor and consists of an obstacle filter and an obstacle avoidance algorithm. The global one is a mission-level path planner that pre-plans paths around all unknown obstacles. The obstacle filters tell about the unknown obstacles to path planner and enable the avoidance algorithm if the pre-planned path is blocked. The information about known and unknown obstacles is obtained from the obstacle filter and this knowledge is used by the avoidance algorithm to avoid the obstacle safely. The vehicle after manoeuvring the obstacles returns to its pre-planned path as quickly as possible.

3.2. Sonar transducer Technologies

Two major types of technologies in sonar transducers are Electrostatic and piezoelectric transducers [3]. They can operate in air and can work as both transmitter and receiver at the same time. Electrostatic transducer have high sensitivity and bandwidth but the operating voltage is high i.e. 100 V whereas the piezoelectric transducers operate at lower voltages. The High-Q resonant ceramic crystal in piezoelectric transducer provides narrow frequency response to that of electrostatic transducers response, where "Q" (A Transducer's quality factor) describes the amount of ringing ceramic element(s) undergo when power is applied to the transducer. It defines the sensitivity of the transducer to changes in driving frequency. The following Figure, 6 illustrates the difference between the High-Q and low-Q resonance of an ultrasonic transducer.

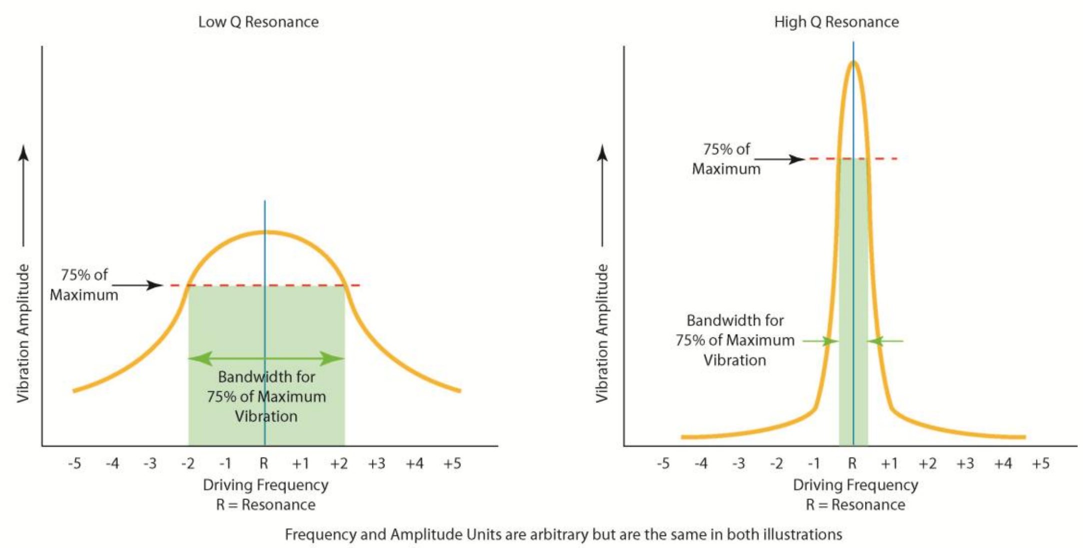

Fig.6. *Illustration of high-Q and low-Q resonance of an ultrasonic transducer [22].*

In Figure, 6 the broadband device on the left side show a wider range of operating frequencies that can produce the set value of 75 % of maximum amplitude (the result can be seen on other target percentage values other than 100%), while the device on right hand side has high-Q value which means that it can produce higher value of amplitude than the broadband device when operated at narrow range of frequencies [22]. In High-Q device, the slight change in driving frequency from its resonant frequencies make a considerable change (reduce) in the vibrations of the transducer while this does not happen in low-Q device which continues to vibrate with its maximum amplitude despite the changes in the driving frequency from its resonant frequency are made.

As piezoelectric transducer can have one ceramic element serving as both transmitter and receiver, however, a separate transmitter and receiver in piezoelectric transducer is preferred [3] because it increases the transmitted power and receiver's sensitivity respectively. Piezoelectric resonant crystal changes its dimensions (a mechanical movement) when voltage is applied across its ends and in reverse operation it produces the voltage upon mechanical vibration. A concave conical horn is also mounted on the crystal sometime to acoustically match the crystal acoustic impedance to that of air [3].

MEMS (Microelectromechanical systems) based ultrasonic transducers do exist. They are fabricated on silicon chip and are mounted with electronics [3]. They offer cost effective solution to standard transducers because a low cost mass production is possible. MEMS transducer acts as an electrostatic capacitive transducer made of thin membrane of nitride. These transducers can operate up to several megahertz's of frequencies offering low signal-to-noise ratio as compared to piezoelectric transducers due to their better matching to air acoustic impedance [23].

An in-depth comparison of electrostatic and piezoelectric electromechanical coupling is presented in [24]. The coupling is required to produce ultrasonic pulses or to generate power. In technical literature, it is known that the electromechanical coupling for electrostatic devices can be nearly 100% while for piezoelectric devices; it is thought to be significantly smaller. In the paper, a model of thin-film piezoelectric is developed which allows a comparison of electrostatic and piezoelectric technologies in electromechanical coupling factor, capacitance, stiffness and actuation force. The comparison shows those capacitance and actuation force coefficients are drastically different for the two technologies, and are controlled by material properties and device geometries.

3.3. Why use sonar

Sensors that receive and respond to stimuli coming from outside their body are called exteroceptive sensors such as laser, sonar or camera. Exteroceptive sensors are successfully used for robot localization. Exteroceptive sensors provide measurements of the environment around the robot. As the robot moves, these measurements change and then the problem of localization can be formulated in terms of the correlation between consecutive sensor readings. Moreover, the exteroceptive sensor readings can also be matched against a priori map of the environment [7]. Among these, laser has good accuracy and sensing rate whereas, sonar due to its low price, smaller size, lighter weight and low power consumption and easy to mount become better choice in some applications.

Cameras offer some benefits too that include low power requirements and less price and small size. However, the advantage of sonar over cameras are (a) sonar readings can easily be processed than the vision algorithms (b) the range value from sonar is suitable for localization process than the image given by the camera.

Sonar sensors have an advantage over light based sensors; they are independent of the target surface as being transparent or black.

Amplitude-based infrared devices are inexpensive but can’t provide accurate range values like laser based systems can provide and that too with high precision [2]. The reason is the dependence of infrared on target surface reflectance properties.

Sonar is much better sensor for position estimation. Bornstein and Koren’s used sonar rings to form ‘sonar bumper’ with rapid sensor firing rates in agreement with the concept of continuous map building [25].

Since, different sensors have different weakness and strong points; therefore, the combination of these is done, and is called sensor fusion, to achieve better results. It is a popular research area [26]. The combination of sonar and infrared sensor results in a multisensory product capable to achieve better performance since sonar is not considered good in finding corners and infrared sensor is not considered good in reporting the range value. [27] shows such research.

3.4. Limitation of sonar sensors

Sonar sensors are not ideal devices and have some limitations. The result of a sonar sensor is limited by its resolution, the size of the object it can detect, range it can measure and actual echoes it can get. The timing circuit of a sensor may result in a false echo and hence the distance computed may not match with the actual distance.

3.4.1. Beam angle

The sound which emerges from the transducer is not in a nice pencil-shaped compact beam form but rather it is cone-shaped as shown in Figure, 7.

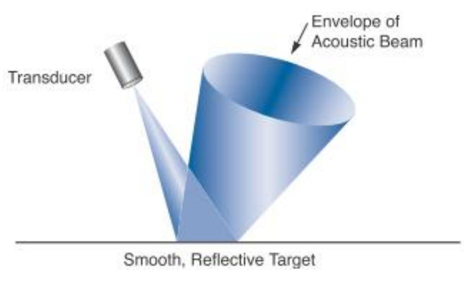

Fig.7. *Sound reflection and cone shaped beam [28].*

Generally, a transducer transmits energy in a beam pattern that has a narrower beam width as shown in Figure, 8. The length of main lobe indicates the maximum range that the transducer can achieve. The use of enough power ensures a greater range so objects which are many meters away can be detected.

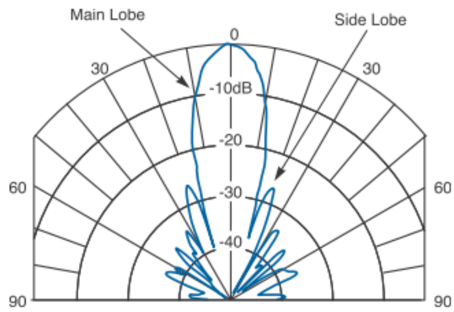

Fig.8. *Typical beam pattern [28].*

The main lobes define the beam width and contain most of the energy. The energy outside the main lobe is concentrated in side-lobes. Side-lobes are not desired because they can disguise the true location of the target by generating false echoes. Side-lobes exist in every transducer but a good transducer reduces the incidence of side-lobes.

The wide beam width causes poor directional resolution. The small beam angle sensor is good in resolution but for wider angular region, the more number of sensors are required. However, the use of wide beam angle sensors results in less number of sensors while covering the detection area but are susceptible to acoustic noise. A transducer sends a lot of energy sideways and this may cause problems if the receiver has the same sensitivity because it may receive the transmitted pulses and not only the echoes. In this way, the sensing range of the transducer is reduced. A transducer with a wide beam angle provides less target object selection than one with a narrow beam angle. A wide beam transmit energy into the environment more widely and over greater volumes and the reflected energy from the target is less than it is with a narrower and more compact beam.

3.4.2. Slow sound speed

A slow sound speed reduces the sonar sensing rate [3] because sensing rate is directly dependent on sound speed. A slow sound speed is caused by the environmental effects. When the echoes from the targets are received from a previous pulse then the next probing pulse should be sent to the target otherwise a false reading will occur. Time-of-Flight (TOF) is measured from the most recent pulse. The delay time of 50ms is applied between the transmitted probing pulses. However, reverberant environments cause false readings because sounds reflect again and again.

3.4.3. Oblique Surfaces

Objects that are at right angles to the axis of the beam yield accurate and reliable distance measurements values. But, if the target or any smooth surface is at an oblique angle then it is difficult to get detectable echoes because it deflects the sonar beams, as shown in Figure, 9. The robot with the obstacle avoidance sonar sensor may collide with the target in this case.

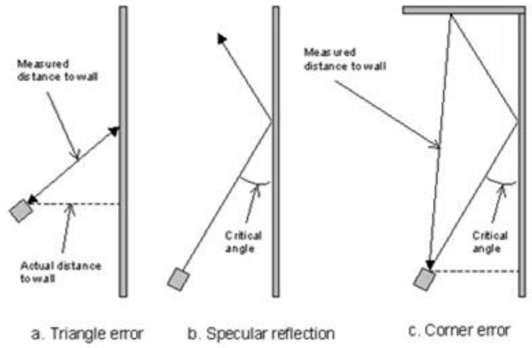

Fig.9. *Sources of errors [29].*

3.4.4. Strength of echo

The geometry and nature of target's reflective surface affect the echo strength from the target and in return it affects the range value and resolution of the range sensing system. [5] explains thoroughly the effects of targets on echoes strength. It is seen that the sound pressure is reduced by the spreading loss by 20 log (R/R_0), where R is a distance of the target from the sensor and R_0 is the reference distance, as the sound travels from the sensor to target. Similar loss is seen in echo from the target making the total loss as 40 log (R/R_0). The term 'Target strength (TS)' [30] is used to measure the reflectivity of the target which is defined as 10 x the logarithm to the base 10 of the intensity of the sound returned by a target at a reference distance from its "acoustic centre," divided by the incident intensity of the transmitted sound pulse. The target strength of simple geometric shapes can be theoretically computed.

The TS values computed in this way serves only as an approximation to real targets as the real targets are composed of multiple reflecting surfaces [5]. Sound reflected from these multiple surfaces produce echoes of different amplitude that sums up to make a complex summation of these multiple pressure waves of different amplitudes and phases. Movement of target or variation in the relative velocity of sound in the path of acoustic also drastically changes the TS. The result can be large variations in the echo level produced by a target from one pulse to another during ultrasonic sensor operations [5].

3.4.5. Noise interference

The transducer emits short bursts of ultrasound at 40 kHz. The transmitter emits only this frequency and the receiver is made insensitive to frequencies other than 40 kHz. In this way, most extraneous noise is avoided. However, sharp mechanical shocks and motor vibrations can produce false readings [28]. This situation can be avoided by mounting the transducer on foam rubber or alternatively, mounting the source of noise on foam rubber.

The level of background noise diminishes with the increase of frequency. The reason of this is that the less noise is produced at higher frequencies in the environment. And, the noise that is produced is greatly attenuated as it travels in the air [5].

3.4.6. Maximum sensing range

The maximum range of an ultrasonic sensor depends on many factors including the transducer design, working conditions, electronics design and signal interpretation [28]. It is seen that the maximum sensing range is longer at lower frequencies of the sensor [5] because low frequency suffers less attenuation due to factors such as humidity, dust and air turbulence. Therefore, low frequency travels more whereas, at higher frequencies, the values of resolution and accuracy of the sensor are better and of course shorter sensing ranges [5].

It is important to consider the characteristics of the application when selecting the ultrasonic sensor with right sensing range. The beam angle is also associated with the sensing range. Increasing the gain of a sensor to get maximum sensing range also widens the beam spread resulting more ultrasonic noise and detecting unwanted targets [31].

Most of the sensors specifications are based on the ideal conditions, like, good reflective surface, calm and clear environment and target lying in front of the sensor’s axis. The real life situation is somewhat different to this. It is, therefore, beneficial to choose a sensor having maximum sensing range than the desired range [31].

3.4.7. Minimum sensing range

A transducer has a minimum sensing range of some distance say, for example, 60cm, then below 60cm the sensor is virtually blind to any resonance, i.e. no echo is received. This region (from the surface of the transducer to the 60cm minimum range) is called the 'blanking zone' and it occurs due to mechanical vibrations, called 'ringing' [28]. The ringing must stop before the signal from the object reflects back to the sensor. There will always be some amount of 'ring time' that ensures the dissipation of the mechanical and electrical energy after excitation ceases [28]. So, if the person is near to the machine (within the 60cm zone) then it will not be able to detect that person it.

3.4.8. Atmospheric Influences

Variation in atmospheric conditions (like temperature, pressure and humidity) cause significant changes in the speed of sound [3]. The accuracy of measurement by a sonar sensor is, therefore, critically dependent on these factors. Air flux or turbulence also affects the accuracy of measurements by disturbing sound waves and reducing the echo from the target [32].

3.5. Sonar applications

As an example, the recent automatic vacuum cleaners rely on sonar technology to perceive the environment and to perform localization [7].

There are three main applications for sonar in robotics [3]. The first is obstacle detection and avoidance, where the range to the closest object is measured by detecting the first echo. The robots use this information for path planning to avoid collision with the object. The second is mapping, where a sonar map of the environment is constructed by performing a rotational scan and getting a collection of echoes. The third is object recognition/identification. This involves classifying the sonar map in order to identify one or more physical objects. The information can be useful for robot registration or landmark navigation.

Ultrasound popularity in electronics applications is due to several reasons [4]. It is compressional vibration of air. It is undetectable by human because it’s inaudible to humans. It has high directivity. It has slower speed than radio waves and light.

Ultrasound is safe for human ears for example, in a car parking sensor over 100dB sound pressure is *generated* which is equivalent to the audible sound pressure near a jet engine [4].

Ultrasound's feature of narrow directivity, due to its high frequency and hence short wavelength, is used in medical [4]. This feature of ultrasound is similar to microwaves. The treatment of kidney stone breakup is done by emitting ultrasounds from outside the body maintaining low energy level to safeguard the human body.

Ultrasound is used to see the characteristics of the matter by detecting and visualizing the changes in reflectance and transmittance of that matter in the medium as an example of organ in human body [4].

Ultrasound ensures low speed signal processing because it travels slower in air than the light and radio wave travel. For example, an ultrasound wave takes 3 ms to travel 10cm whereas light and radio waves take 3.3ns for the same distance. This allows measurement using low speed signal processing [4].

Ultrasonic wind sensor gives horizontal wind speed and direction as manufactured by Vaisala as shown in Figure, 10. Its WINDCAP ultrasonic wind sensor has triangular design assuring the accurate measurements of wind speed from all directions [33]. Its advantages over other mechanical wind sensors due to it’s no moving parts are that they are free from friction, inertia, time constant and over speeding etc.

Fig.10. *Vaisala WINDCAP ultrasonic wind sensor [33].*

Ultrasonic sensors are used in automatic parking systems for detecting obstacle nearby and assisting drivers about the parallel parking by controlling the steering, acceleration and braking systems of the vehicle based on the information from the ultrasonic sensor about the location and space available for parking [4].

In rear bumper of the vehicle, two to four ultrasonic sensors are mounted ensuring the obstacle detection up to 2 to 2.5 meter and communicating the signal via a buzzer to driver. Rear sensor main characteristics are its directivity, sensitivity, ringing time and sound pressure [4].

Directivity of sensor depend the size and shape of the transducer and also to its vibrating frequency [4]. The narrower directivity is achieved at higher frequency keeping the size of the vibrating surface of the sensor constant or at larger size when the frequency is kept constant. Making horizontal directivity wider ensures better coverage with less number of sensors while making the vertical directivity narrower increases the sensor usability. Shorter ringing time means closer detection range.

Ultrasonic sensors in vehicles are driven by high voltage (70 to 100 V) with the use of transformer in order to make them waterproof and less sensitive by making their transmitted ultrasound signal stronger [4].

3.6. Outdoor sonar sensing challenges

Sonar sensors for indoor use have proved quite successful. Outdoor environments, however, adds additional constraints on the type of sensor that can be used for example; it should be robust against moisture, dust particles and noise from the vehicle engine and other sound sources.

Ultrasonic sensors are traditionally restricted for indoor use because of their high-precision in indoor environments. For outdoor use, there are limited uses and mostly it is employed in a similar fashion like indoor use. In applications, like guidance of vehicle and mobile robots, it is used as a unit of multi-sensory system assigned low-precision tasks like close obstacle detections when machine is about to collide with them, or the coarse ranging of large navigation landmarks [34], [35] [36].

"Sonar's reputation as an unreliable sensing technology for outdoor applications is mainly due to the large influence that meteorological parameters have on the propagation of ultrasonic signals, which is a direct consequence of the mechanical nature of these waves. Changes in temperature and humidity, the presence of fog or rain in the atmosphere, and wind-induced refraction can cause strong variations in the attenuation of acoustic waves. As a result, a classical sonar system based on threshold detection of the signal envelope can provide very different results depending on the operating conditions. Furthermore, acoustic noise sources are more likely to be found outdoors. Aircrafts, pneumatic drills, bridge vibrations or even corona effects in high voltage cables are examples of ultrasonic sources which could render sonar in systems completely useless in certain environments" [32].

To overcome the challenges mentioned in last Para, different special signal processing techniques are employed for the use of ultrasonic in outdoor applications, like continuous transmission frequency modulated (CTFM) [37], the use of cross correlation with transmitted patterns for an outdoor sonar [38], the wind compensation method [39].

The different phenomenon of sound waves in air like sound attenuation, reduced sound speed, and turbulence affects significantly the measuring range of ultrasonic sensor in air.

3.6.1 Sound attenuation mechanisms

Sound attenuation in environment occurs due to geometrical spreading, atmospheric absorption and the attenuation caused by the presence of fog or rain.

Geometrical spreading is defined as the amplitude decay of an elastic wave caused by the expansion of its wave-front away from the source [32]. Therefore, it does not depend on the propagation medium but on the features of the transducer used. Besides geometrical spreading a part of acoustic waves energy is dissipated in environment into thermal energy as well that affect the acoustic pressure decaying it exponentially.

Atmospheric absorption of acoustic wave in air is mainly due to two reasons: viscothermal processes and the oxygen and nitrogen molecular relaxation processes. Atmospheric absorption of acoustic wave depends on four parameters: wave frequency, temperature, humidity and pressure. And, it increases rapidly with frequency. An important observation for outdoor sensors design is, the signal absorption in the air for warm summer day can be more than six times greater than the signal absorption on cold winter morning [32].

Besides geometric spreading and atmospheric absorption, which are always present in the air, there are other factors like fog, rain and turbulence etc. which further cause attenuation of these signals. Figure, 11 illustrates the case for intense rain of 80 mm/h and a light rain of 5 mm/h. It is seen that the intense rain can cause in a 50 KHz ultrasonic wave an attenuation similar to that caused by a dense fog (approximately 0.1 dB/m), and this attenuation is even greater for higher frequencies. For, frequencies below 50 kHz or in less intense rains this attenuation is negligible in practice.

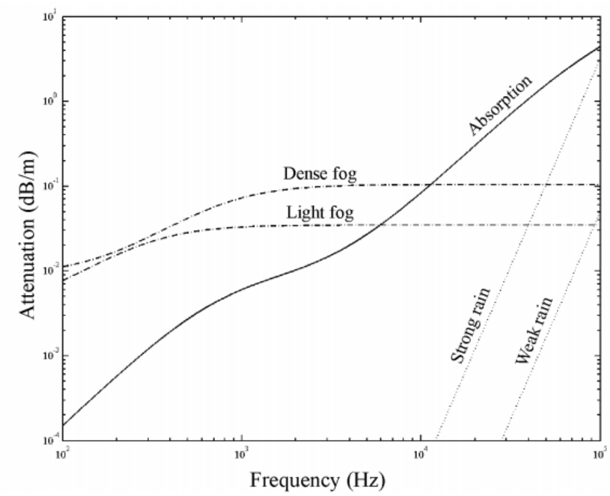

Fig.11. *Attenuation caused by the fog and rain as a function of frequency [32].*

3.6.2 Mechanisms affecting the propagation speed

One of the main reasons for erroneous position measurement in ultrasonic systems is the change of sound speed in the path of transmission between transmitter and target. This is largely caused by the uncertainty in average temperature in the path of transmission. Therefore, temperature compensation factor is employed within the sensor in order to get maximum sensing accuracy. Temperature and wind affect the propagation speed of sound by the following relationship

$$s = vp + c(T).\sqrt{1-(\frac{v_n}{c(T)})^2} \quad (2)$$

Where c(T) is the propagation speed (in m/sec) of the phenomenon which is temperature dependent; and vp and v_n (both in m/sec) are normal and parallel to the direction of propagation components of the wind. The above expression, when normal component is assumed as small compared to the sound speed c, approximates to the following.

$$s = vp + 331.6 \ . \sqrt{1-\frac{T}{273.15}} \quad (3)$$

Where s is the speed of sound (in m/sec) and temperature (T) is in Celsius degree. Since, in outdoor environment, both temperature and wind speed are height dependent, sound speed also shows dependency on height and as a result refraction of ultrasonic wave occurs as shown in Figure, 12.

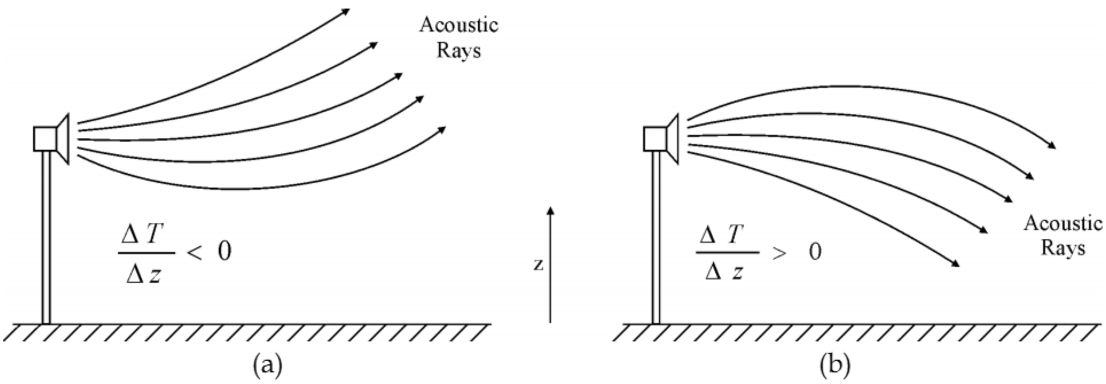

Fig.12. *Temperature-induced Refraction [32].*

Wind-induced refraction due to height also occurs as shown in Figure, 13. Wind shear phenomenon occurs as the wind speed increases from zero at ground to some constant value at hundreds of meter altitude. Sound wave travelling downward bents further downwards because at lower heights sound speed is lower and inverse occurs when it is propagating upwards.

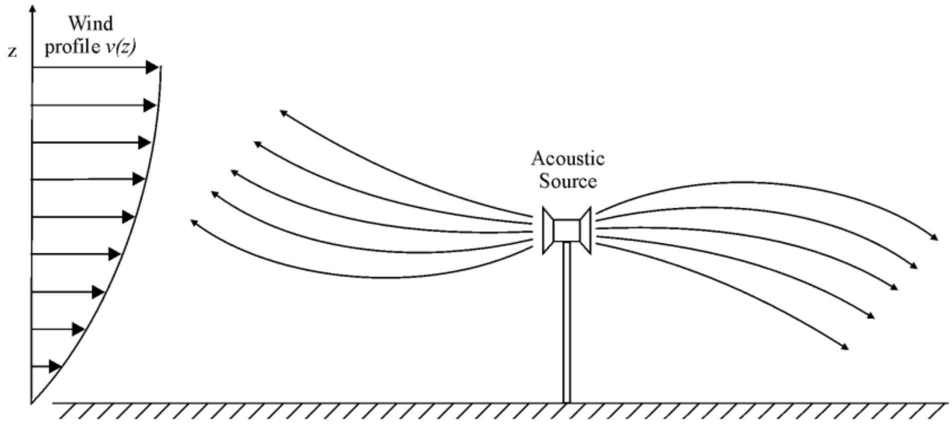

Fig.13. *Wind induced refraction[32].*

3.6.3 Turbulence

It is usual to see that the amplitude of echo pulses change dramatically due to variation in the speed of sound in the transmission path caused by the turbulence and/or target movements.

[40] Present the turbulence effects on sound propagation mechanism and an outdoor sensor prototype using signal coding and pulse compression techniques. The proposed prototype is experimentally tested and it is observed that the coding scheme employed provides high gain process for detecting short emissions whose coherence is unaffected by turbulence and hence making the system robust enough to work under unsuitable environmental conditions.

In lower layer of atmosphere, wind is rarely stationary and almost always random fluctuations in the form of highly rotational fluxes occurs, called turbulent eddies affecting significantly to wind speed and temperature and hence changing propagation velocity of acoustic wave. Turbulent eddies change the refraction index and cause scattering of wave energy and consequently bringing additional attenuation of acoustic wave travelling through this turbulent eddies as shown in Figure, 14.

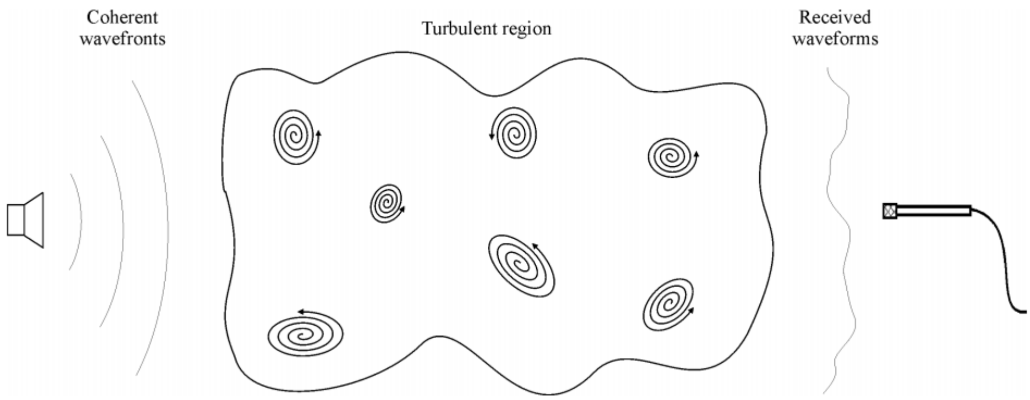

Fig.14. *Propagation of an acoustic wave through a turbulent region [32].*

When acoustic wave passes through a series of turbulent eddies, its initial coherent format which was spherical having identical amplitude get changed because of the change these turbulent medium (having different size, velocity and temperature eddies) cause on the acoustic wave. As a result, a receiver placed at certain distance record random fluctuations in phase and amplitude of the acoustic wave.

Classical sonar systems whose echoes are detected after exceeding certain threshold limit cannot work reliably outdoors [32]. Echoes amplitude from two objects at the same distance changes significantly mainly depending on the weather conditions like, temperature, humidity, rain, fog and windy air. The resulted value of range calculated based on time of flight (TOF) operation is very different than what was expected. Air turbulence further induces variations in amplitude and phase of these echoes.

An alternative to classical sonar systems is signal coding and pulse compression techniques [32]. These techniques proved very successful because of their capability to measure simultaneously TOF of echoes of different emissions with high precisions. In these techniques contrary to ultrasonic pulses, modulated binary codes are sent with good correlation properties, and are detected with matched filtering. Thus, when a code matched with the corresponding filter is received, a correlation peak is obtained whose height is proportional to the length of the code and is independent to the amplitude of the code. The system with these techniques maintains high robustness to noise by emitting the long pulses. Strong variations in amplitude of received echo modify the height of the correlation peak leaving position of peak unchanged. In this way, the results from the systems would be unchanged even when the signal is attenuated. Moreover, several transducers can perform simultaneously under the same operating conditions when adequate selections of codes with low values of cross-correlation are chosen [32].

3.7. CTFM

The conventional pulse-echo ultrasonic sensors are now replaced by continuous transmission frequency modulated (CTFM) ultrasonic sensors which are different from pulse and echo type ultrasonic sensors [3]. The main difference is in the transmission coding and the processing needed to get required information from the echo signal. CTFM continuously transmit a signal of varying frequency usually of saw-tooth pattern as shown in Figure, 15.

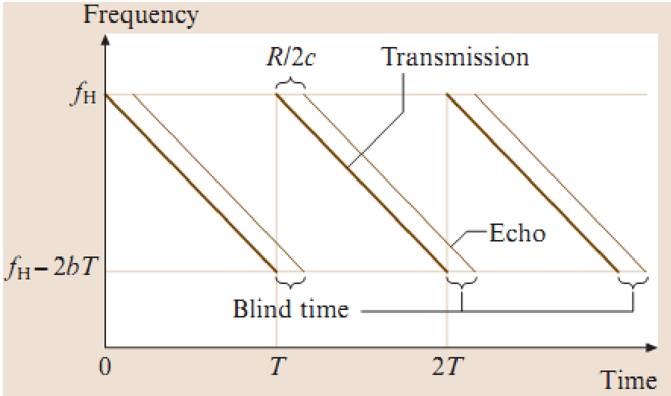

Fig.15. *Frequency versus time for CTFM [3].*

To calculate range for an object by this method, time delay between an echo's transmitted and received frequency is calculated [41]. This deviation provides range value for the object. Later, the data is filtered by transforming it to frequency domain from time domain by fast fourrier transforms. The range value is seen from echo's power spectral density. CTFM offer high signal to noise ratio and are capable to detect minute echoes from the target with not much affect by the environmental noise. They have more sensitivity than pulse-echo type and can give more detailed acoustic data of the object detected. The energy of the transmitted signal is spread evenly over time in CTFM which results in low peak acoustic power emission compared toTOF ultrasonic sensors [41]. They also provide higher average value power and greater sensitivity to weak reflectors. However, CTFM sensors have disadvantages of requiring separate transmitter and receiver and data processing is complex [41].

A mobility aid for blind people has been developed using CTFM ultrasonic sensors [42],[43]. The system is based on a sweep of f_H = 100 kHz down to 50 kHz with a sweep period of T = 102.4ms. After demodulation, ranges are heard as audible tones with frequencies up to 5 kHz corresponding to ranges up to 1.75m. The system uses one transmitter and three receivers as shown in Figure, 16. Users of the system can listen to the demodulated signal in stereo headphones corresponding to left and right receivers, each mixed with the central large oval receiver.

Fig.16 . *Aid for blind people. Oval shaped is transmitter and the other three are receiver [3].*

Another application of CTFM ultrasonic sensor is shown in [44]. The work mimics a blind person using a sonar navigational aid to traverse a path or corridor. A commercially available ultrasonic mobility aid is used to capture echoes from a corridor and correlate these to the geometric features of the corridor. The aim is to develop a perception system, which is capable of interpreting, in real time the echoes to discern the geometric features of the environment, so that this data can be used to navigate a robot through it.

3.8. Multiple ultrasonic sensors

Multiple ultrasonic sensors are generally used to increase the covering area of the sensors, increase the accuracy of obstacles positions and decrease the scan time. Multiple ultrasonic sensors can cause problems if they are all taking measurements at the same time; they may interfere with each other [45]. So, the best way to use is when only one sensor is firing at any time in this way the resulted range value will be correct. The multiple ultrasonic sensors may have their own noise, a phenomenon called, crosstalk. It differs from other environmental noise because it causes repeated error readings. So, the solution to avoid multiple sensors interference is to wait for some time for first sensor ranging to die down before a second sensor starts taking readings. Typically, a delay time of 70ms to 80 ms is sufficient. Two sensors mounted at opposite directions can be fired together at the same time without any problem.

Another way to avoid interference is to group the alternative sensors [8], for example, sensors numbered 1,3 and 5 belong to one group and sensors 2,4,6 belong to other group in this way these two groups sensors will be firing at different times. It is recommended to group the sensors even when these are not close enough because it makes more effective use of the buses bandwidth.

In conditions when a mobile robot having multiple ultrasonic sensors is giving data, it is better to make a decision based on multiple range values rather than a single sensor data because the data put forward by the sensor may have reported erroneous value. In this way, the ‘confidence’ of the algorithm will increase about the presence of the obstacle [46].

When operating the mobile robot at higher speeds it becomes necessary to increase the sampling of data to avoid the collision. This fast sampling of data from multiple sensors also increases the chances of crosstalk [47].

4. SONAR SYSTEM IMPLEMENTATION

This chapter explains the ultrasonic obstacle detection system implementation, both hardware and software. It also shows the specifications of the sensor and how to send communicate with it. Different methods used to improve the results like implementation of cone and water proof casing are also discussed in this chapter.

4.1. Ultrasonic system description

The Sonar system consist of the Microcontroller unit that monitors and controls the whole process of transmitting the probing pulses, running the timer and calculating the distance upon receiving the echo from the target around as shown in Figure, 17. The 'Tx' and 'Rx' are transmit and receive pins of the microcontroller.

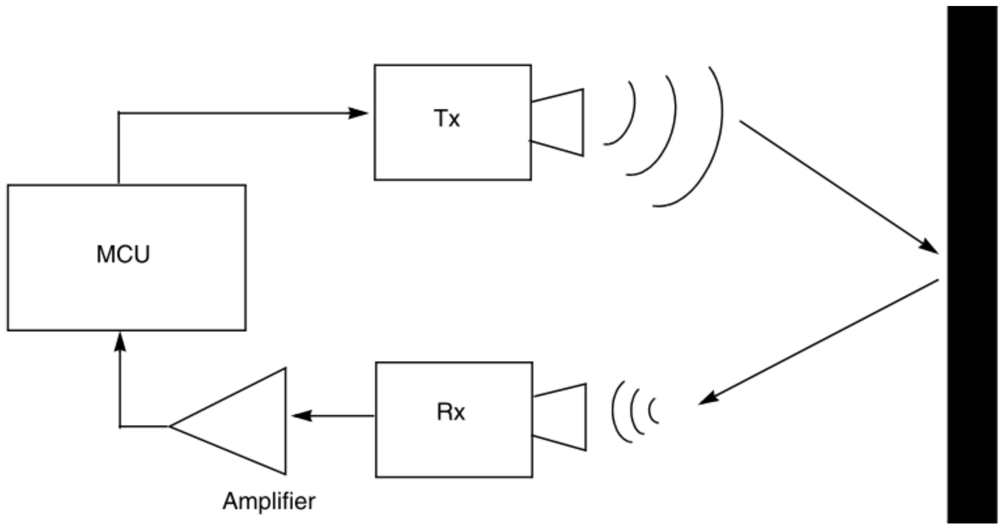

Fig.17. *Ultrasonic system simple description*

The software generates 40 kHz burst signal and 70ms in SRF485WPR the ranging value can be obtained by using some specific commands. In the backend, in microcontroller, a variable that measures the distance is activated which measures the time taken by sound to rebound by the target and hence distance is calculated in this way.

In SRF485WPR, a data frame is sent to the module and then response is listened. The data frame looks like as shown in Figure, 18.

Break	Command	AddressH	AddressM	AddressL	Data	Check Sum

Fig.18. *Data Frame*

The serial data is fixed at 38400 baud 1 start, 2 stop and no parity bits. Each module has a unique 24 bit address which is programmed already in the sensor. Where, Break -

is defined as a continuous low in excess of 22 bit periods, followed by a high of 2 bit periods. Each bit is 26 µsec at 38400 baud, so 22 * 26 µsec = 572 µsec, its ok to be longer. Command is one of a number of commands that the SRF485WPR will respond to. Address H, M, L-is the 24-bit address of the module. Data is the data you wish to send to the module, zero (0x00) if nothing is required by the command. Chksum is the 1's compliment (bitwise negation) of the sum of all the previous bytes (not counting the break).The module respond with a variable number of bytes, 0 to 4 depending on the command, but the transmit frame is always the same, a break followed by 6 bytes.

4.2. Ultrasonic sensor specifications

The sensor used for range finding is SRF485WPR, which is typically designed for car parking applications. Its specifications are shown in the following table 4.1.

Table. 4.1. *Specifications of SRF485WPR ultrasonic range finder*

Range (cm)	60 cm – 500 cm
Output (µsec, cm, inch)	range reported in microsecond, centimeter or inches
Angle (degree)	30^o
Temperature ($^\circ$C)	-30°C ---- 50°C
Water proof standard	water proof transducer
Typical application	Designed for use in a car parking.
Connection protocol	RS485- up to 127 modules can be connected.
Ranging time (ms)	70 ms
Manufacturer	Devantech Ltd (Robot Electronics)
Voltage (v)	12vdc (8vdc-14vdc)
Current (mA)	10mA
Size(mm)	40.5mmx40.5mm (1.6''x1.6'')

The sensor has a beam angle of 30 degree as shown in the table above. The beam pattern of the transducer, taken from the manufacturer's data sheet, is shown below in Figure, 19, where main lobe and side lobes can be seen. The wide side lobes indicate that the majority of the energy is wasted in side lobes. If side lobes can be directed inward then they can reinforce the main lobe and as a result an increased range value can be obtained. This purpose is accomplished be implementing cone around the transducer. Beam widths are taken at the -6dB points where the units on the vertical axis in the beam pattern are in dB. The beam pattern is conical with the width of the beam being a function of the surface area, frequency and type of transducers and is fixed.

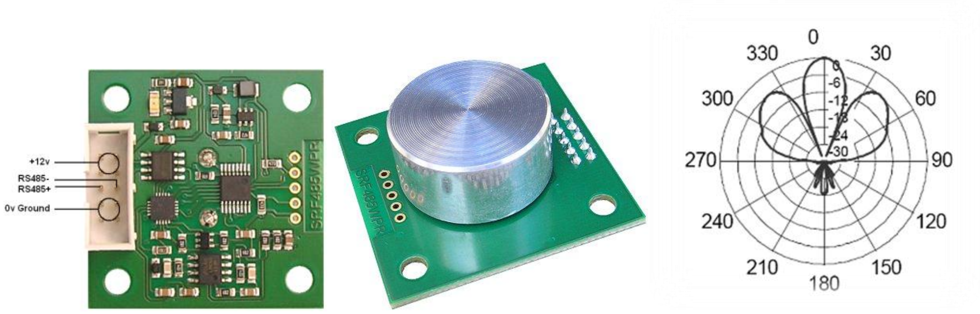

Fig.19. *SRF485WPR and its Beam pattern showing 30° beam angle with side lobes.*

4.3. Reducing side lobes of SRF485WPR sensor

The sensor is very sensitive to the object away from its beam axis or bore sight (which is straight ahead angle in front of the sensor on which the sensor is aimed at). It is recommended by the manufacturer to mount the sensor 12in/300mm above the floor in order to avoid the reflections from the ground or carpet pile or ridges in a concrete floor. However, if it is necessary to mount the sensors lower from this distance then mounting the sensor with its face pointing upwards slightly so to avoid the reflections from the ground. Side lobes of SRF10 are reduced by using different methods as discussed in [48]. The sensitivity of the transducer off bore sight is reduced by wrapping a tube around the transducer. The tubes tested are like paper tube (of two lengths of 0.8” and 0.5”), shrink tube (3/8”ID) and fuzzy velvet ribbon (of two lengths of 0.35” and 0.5”) are experimented. In every case, the sensitivity off bore sight is reduced remarkably. Figure, 20 shows the setup used for reducing the effect of side lobes in SRF10 sensor.

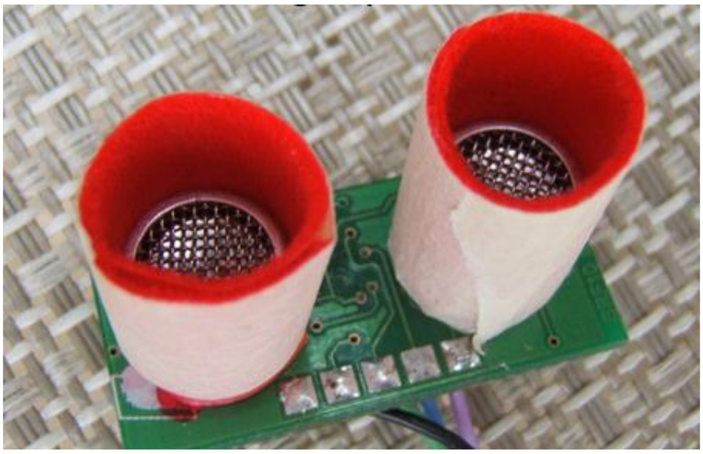

Fig.20. *Long fuzzy velvet tubes of 0.68 inches with masking tape wrapped outside [46].*

4.4. Sensor setup on the machine

The proposed location of the sensor mounting is the rear bumper of the machine as shown in Figure, 21. The length of the rear bumper is 90 cm and it is proposed to place four SRF485WPR sensors on this bumper. The gas exhaust pipe is next to the bumper which may affect the sensor’s performance to some extent. The four sensors are proposed to be mounted on the bar which has holes/mountings at different locations and able to rotate in y-direction freely. The four sensors are proposed to be placed horizontally lying side by side at some specific distance.

Fig.21. *The sensors proposed location.*

The proposed orientation of the sensors is shown in the Figure, 22. It is thought to place the corner sensors facing inwards so that a missed area between the sensors can be covered.

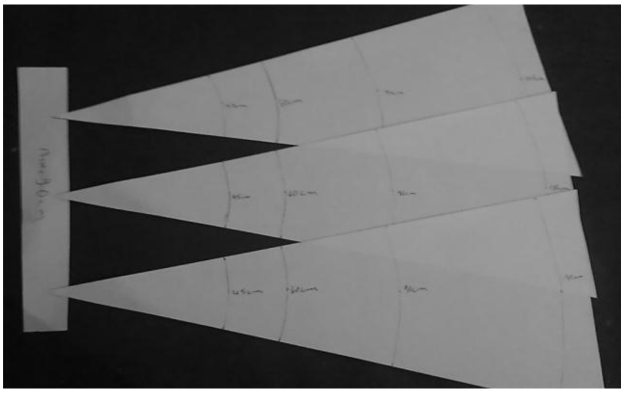

Fig.22. *Orientation of the sensor.*

4.5. Failed setups

The setups that proved less successful in giving the range values indoor for the wooden board which was a target include aluminium plate having sensor attached with and without the cone. When a rubber was put on the surface of the plate so that it can act as a damper to acoustic pulses if they are causing the problems, it was observed that even then the rubber was there the results of range value do not improve. Based on these test, aluminium plate for water proof casing was not chosen because the sensor with aluminium plate and also when a rubber is attached to it, yields no value of range for target. Figure, 23 shows the failed setups for water proof casing. The reason for the failure might be the transmission of ultrasonic waves to the aluminium material because the transmitting part is somehow in touch with it. However, a loosely held transducer in the aluminium plate hole also did not improve the results. It was seen that when the transducer in mounted little away from the aluminium plate, as shown in Figure, 24 (left side), it works fine just like the plastic plate. Therefore, the potential reason in this case is the contact of transmitting surface to aluminium plate.

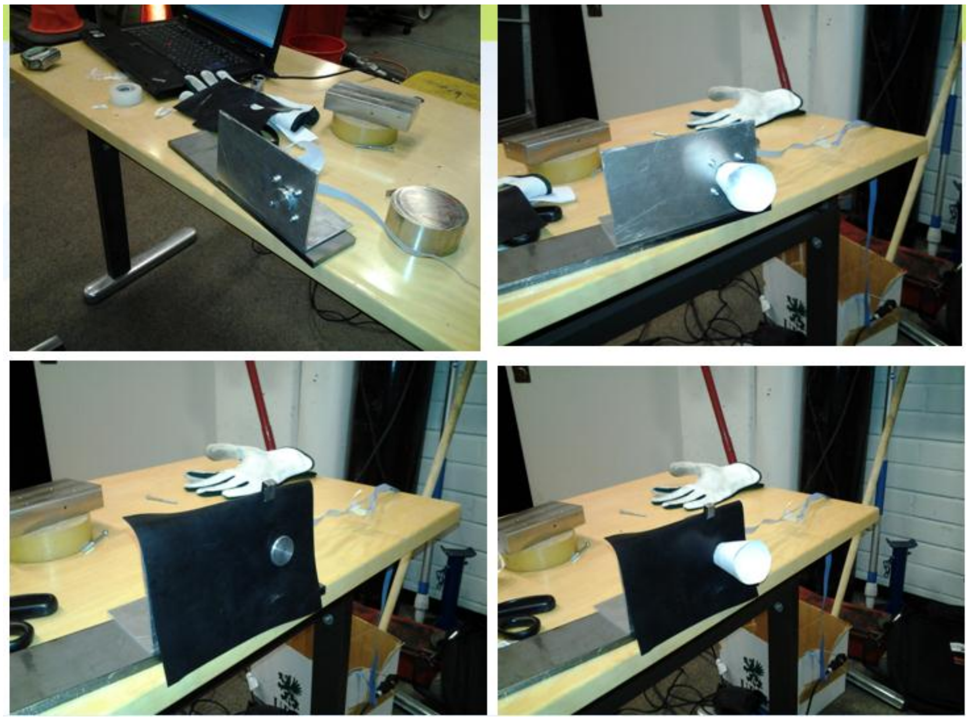

Fig.23. *Failed setups.*

4.6. Cone Implementation and waterproofing of the sensor

It is seen that the placement of cone on the transducer transmitting part greatly improves the result as discussed in 4.3. A tube shaped thing made of paper is also wrapped around the sensor and tested. The results are found quite helpful in reducing the side lobes of ultrasonic beam, however, the cone is found more suitable choice as tube after a certain length was found not working at all. The setup as shown in Figure, 19 revealed good results indoor when tested for a wooden board as a target object. This setup was tested to decide about the material of the waterproof casing for the sensor when mounted on the actual machine. The two different materials tested for waterproof casing for the sensor were aluminium and PVC plastic.

The successful setups for waterproof casing of ultrasonic sensor are shown in Figure, 24. The setups include the sensor attached with the PVC plastic plate and with the aluminium plate where sensor is mounted little away from the aluminium plate; it was done to see what happen when the sensor is not directly in contact with the aluminium plate as was the case in Figure, 23.

The both setups shown in the below figure yielded maximum value of range for the target when tested indoor in the lab corridor. The obvious choice, based on the results was to go for PVC plastic as waterproof casing as it gives good results and also readily available and is cheap as well. The PVC box for the sensor tested, as shown in the results and discussion chapter, were found working fine without affecting the performance of the sensor.

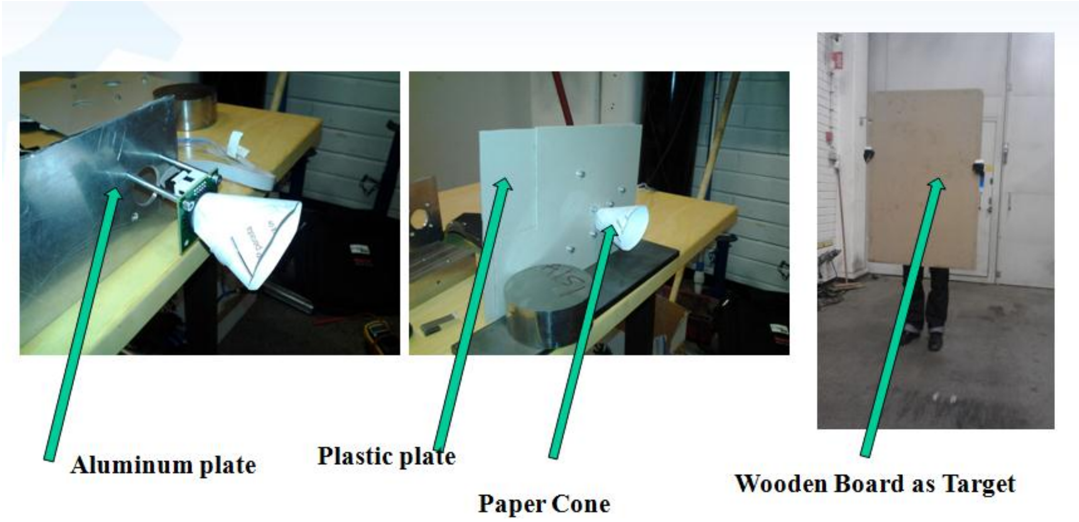

Fig.24. *Sensor setup for indoor for wooden target with paper cone on it.*

4.7. Software Implementation

The software used in this project is *Metrowerks's CodeWarrior (new name of Metrowerks is Freescale electronics). Code warrior's feature named* Process expert is used that employs beans for different modules like serial, timer, CAN etc. The coding is done in C language. The data logging of range values is done in CANOE in the form of ASCII file. The data is also shown in the graphical form in CANOE. The logged file is converted to Excel and range values in decimal are calculated there. The Excel file is converted to comma separated values file and sent to Matlab for plotting.

A data frame, as shown in figure 14, is sent to ultrasonic sensor in order to get a ranging value. First, a break is sent in order to differentiate between two consecutive data frames or signals. Break is defined as a continuous low signal for 22 bit periods, followed by a high signal of 2 bit periods. So, total of 24 bits (3 Bytes) and each bit is 26 µsec at 38400 baud, so 22 * 26 µsec = 572 µsec which is recommended longer can also be used. To achieve desired break is very tricky and it is done on hit and trial basics where a good match between two signals was possible. A technique used to achieve break in our case was to lower the baud rate to 14000 bps and transmit zero for 600 µsec then restore the baud rate to 38400 bps and transmit one for 120 µsec.

In order to get a range value, first an initialization command (80), ranging resulting in inches is sent and then waiting for 75ms after which the range value is available which is read from the command 105 which provide temperature compensated range value. Send frame function, which send data frame to the sensor, takes command, address and data as input. Inside send frame function, firstly break is sent and then command, address and data are all added up and then bitwise negated to yield a value whose lower byte is taken as a checked sum value. The above data frame gives range values for SRF485WPR at 0x002BFB in inches. Although, the values obtained are affected by many factors and accuracy for the values are in doubts. Appendix 1 shows the code for the sensor. A working sensor makes a rapid clicking sound; a sensor that does not click, or is noticeably quieter than the others, is likely to be the cause of a malfunctioning of the sensor.

4.7.1. Problems occurred during software implementation

Ultrasonic sensor was not responding at first to any of the commands sent to it. The problem was the value of delay between two commands was needed which was missing or not known to be right. After hit and trials, a value of break is chosen and its result is seen in oscilloscope which yielding correct graphical shape for two sent frames.

Another problem was to send break before sending commands. It was resolves as discussed previously above. When sensor started working it was producing ticking sound upon working which was vibration sound of it. Outdoor ultrasonic gave different readings due to environmental effects.

When more than one sensor were connected in series and tested indoor, mysteries behaviour of the sensors was observed upon abrupt motion of a person in front of them, they were sensitive enough to catch the quick motion and stopped working. The movement in front of one sensor even caused both of the sensors to stop. Then, the sensors were made less sensitive by increasing the time between initiating the range and reading the value of range. In this way, their speed of working was compromised a bit but the problem of stopping upon quick movements stopped.

4.8. Hardware implementation

The hardware part of the ultrasonic sensor consists of Microcontroller unit having microcontroller and 7805 which is 12 V to 5V converter and all other components, RS 485 driver and power supplies. The hardware block diagram is shown in figure 25.

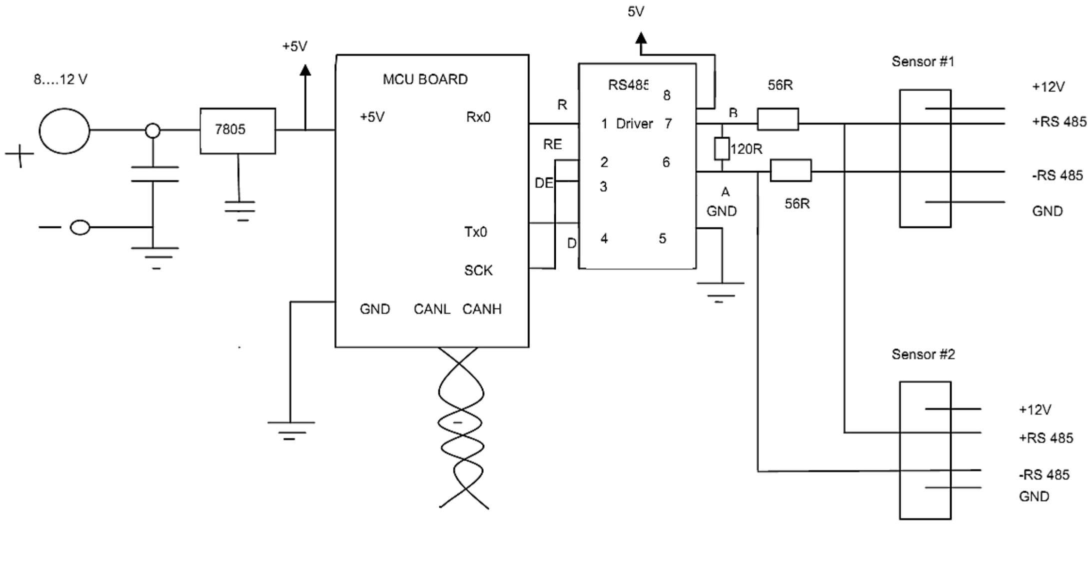

Fig.25. *Hardware System block diagram*

In this figure, microcontroller Rx0 pin is connected to ‘R’ pin of the RS485 driver and Tx0 pin is connected to ‘D’ pin of RS485. A ‘SCK’ pin is selected to control the ‘RE’ and ‘DE’ pins where one of them is active at one time. On the other side of RS485 driver, Pin B is connected to + RS485 pin and Pin A is connected to –RS485 pin of the sensor. The line A and B is connected with a terminal resistor of 120 ohm. The sensor is operating at 12 volts. The resulting values of range reported to microcontroller are also sent via CAN bus to CAN king and CANOE software for further processing. CANOE is used for the data logging and also for graphical output of the sensor. The graphs are seen for the correct response of the sensor.

During testing and working, these sensors don't prove to be of good quality. They don't have very good electronics and failure rate is high. The one unit of the sensor works with one code but the for the same code the other sensor (the new one purchased) doesn't provide ticking sound and giving zero value in CANOE. It was quite annoying to see. They were selected because of their small cone angle and they were suiting the working conditions of the project and also because of the low cost.

5. RESULTS AND DISCUSSION

This chapter will explain the tests carried out on the sensors outdoor with multiply obstacle. The results will be explained with the help of experimental setup and the results of the range values for the obstacles.

First, the sensor was tested indoor (inside a lab corridor) for the wooden board as target as shown in the Figure, 24 and the results are found to be ideal as described in the manufacturer's data sheet as shown in the table 4.1. The lab walls are quite near to the sensor setup but not exactly in the working space of the sensor (i.e. 30 degree cone angle. The sensor is using paper cone wrapped around the transducer transmitting part. The output for the sensor is shown in Figure, 26. A person is carrying a wooden board and is moving away from the sensor from the surface of the sensor to maximum distance away from the sensor. The sensor starts detecting the obstacle from 50 cm to maximum 5 meter. The results are better because of strong reflective surface of wooden board and due to uniform working environment with no influence of weather conditions.

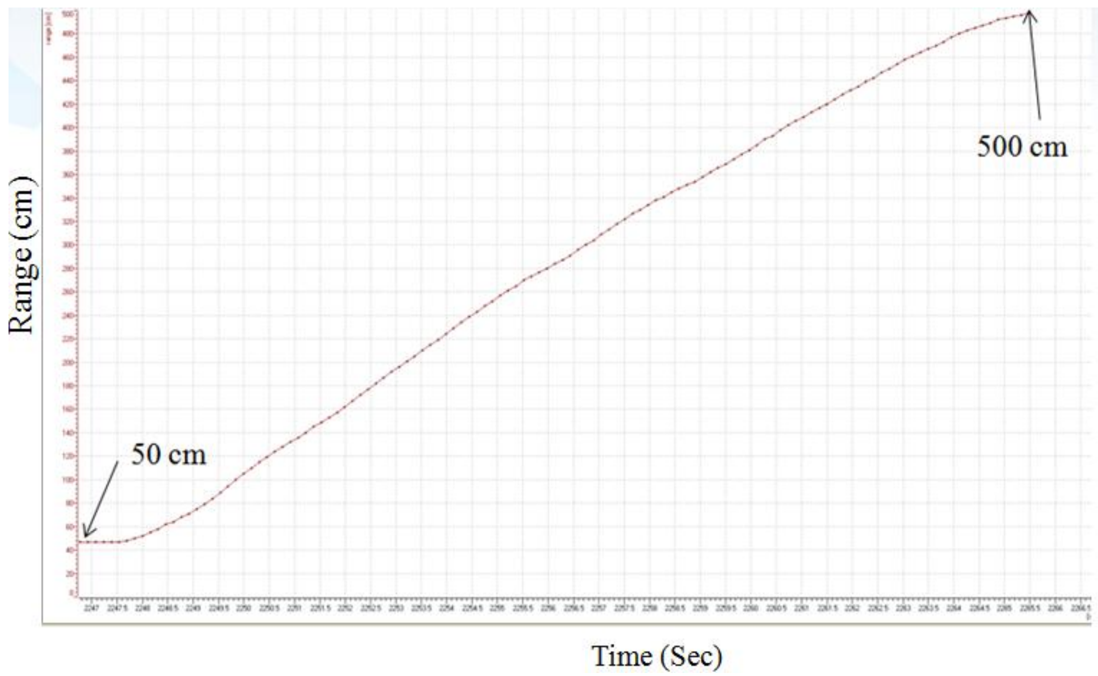

Fig.26. *Indoor test for the sensor for wooden board as a target.*

Previously, a test for the sensor without using cone around its transmitting part was carried out inside the lab room with different machines around but not exactly in the working space of the sensor (i.e. 30 degree cone angle and 60 cm to 5 m range); the setup of the test is shown in Figure, 27. However, there was a wall in front of the sensor at a distance of about 4 m and 20 cm. The temperature was room temperature and uniform. The obstacles were stationary and perpendicular to the surface of the sensor except person moving straight in front of the sensor

Fig.27. *Working environment for the indoor testing*

The results are shown in the Figure, 28, when a repeated movement (coming towards and going away) by a human is made in front of the sensor between two points 180 cm and 360 cm. It is seen that the sensor is showing sinusoidal behavior detecting the change in motion but it is showing 170 cm for 180 cm and 300 cm for 360 cm. The movement between these two points was not precise though.

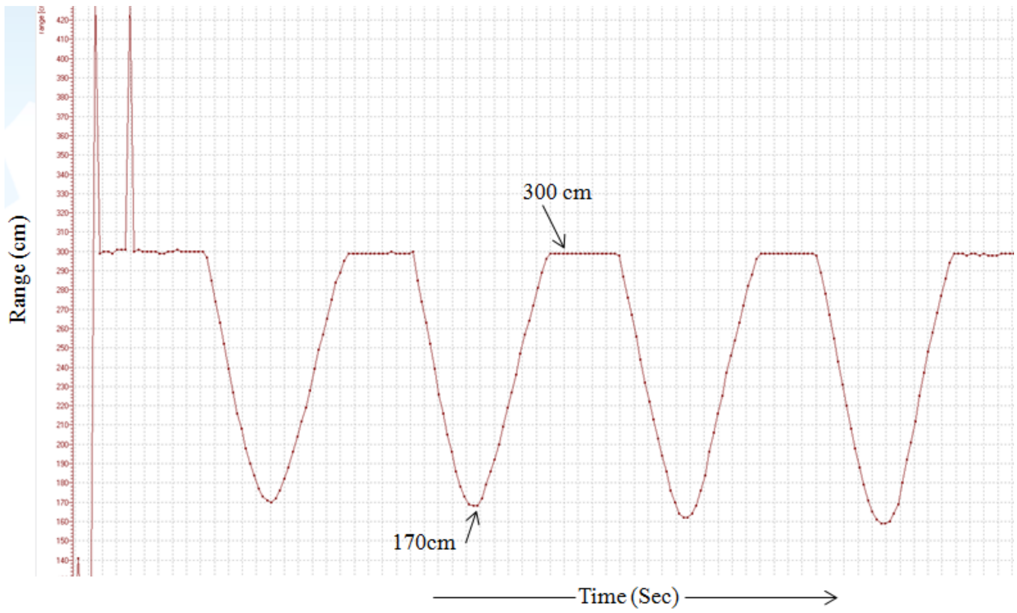

Fig.28. *Indoor testing when a person is moving between two points (180 cm and 360 cm).*

The ultrasonic sensor works quite reliably and accurately (with some exceptions and offset to real distance) in indoor environment. One of the prime reasons for this good results is the uniformity of the factors that affect the range values of the sensor that are temperature, air pressure or turbulence, target movement and orientation and surface, humidity.

5.1. Outdoor testing

The sensor was tested for different obstacle outdoor under different weather conditions. The sensor shown good results when a cone was on it and also there was no turbulence in the environment, and sensor was mounted on stationary frame.

5.1.1. Outdoor testing on bright sunny day

The outdoor testing was carried out on two different days. On first day, it was bright sunny day with temperature 16 degree Celsius. The Figure, 29 shows the working environment of the first day. The target for testing was chosen as plastic poll of 1 m high. The poll was put on distances from the sensor from 1 meter to 3 meter. The sensor was placed on a table with 1 meter height approximately and the sensor does not have any cone attached to it.

Fig.29. *Outdoor testing setup with plastic poll about 1 m high.*

The sensor accurately detected the poll at 1 meter as shown in the Figure, 30. But, it was not showing accurate results for the same plastic poll at 2 m and 3m distances. The reason for this is the weak reflections from the poll at furtherer distances.

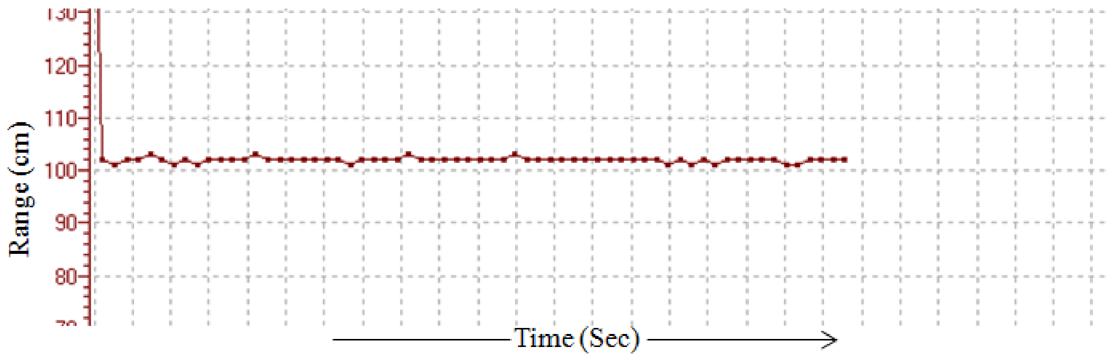

Fig.30. *The result of the sensor for 1 m poll at 1 m distance away from the sensor*

The sensor showed good behavior for thin wooden stick as well when it was moved from 1 to 2 meter distance away from the sensor. Also, the arc motion of the plastic poll within 2 meter was detected accurately by the sensor. The plastic poll was moving within 30 degree cone angle of the sensor.

In Figure, 31, the behavior of the sensor is shown when a person is moving away from the sensor. The sensor can detect the person up to 2.3 meter.

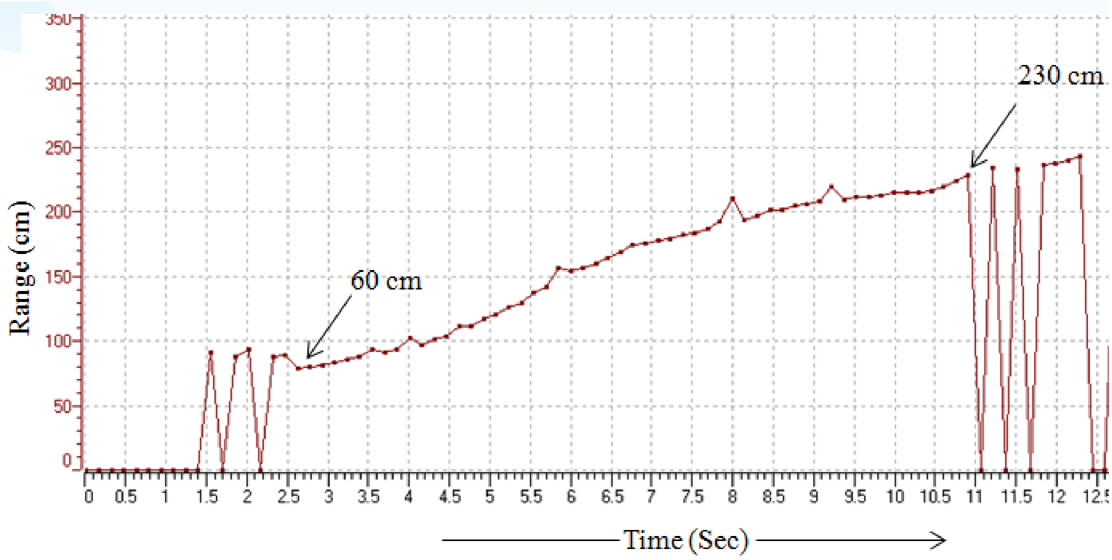

Fig.31. *The sensor behavior when a person is moving away from the sensor.*

The sensor's result gets improved when a person, while holding a metallic plate (of size 32 cm x 40 cm) in his hands, is moving away from the senor. The sensor reported more than 3.5 meter distance as range value. This shows that the value of range is dependent on the nature of target to be detected. The more reflective nature of target ensures stronger echoes from the target while human with cloths sends weak reflections.

The sensors behavior is, however, not constant for the obstacles. Sometimes, it shows un-predictable results for what should be the quite obvious. Later, the code was optimized with more accurate choice of delays between sensor's initializing commands and get ranging command. And, also the use of cone made it possible that the output is consistent all the time.

5.1.2. Outdoor testing on snowy day

The two sensors were tested together outdoor on snowy day when there was no sun and little windy and less visibility and with temperature -6 ºC. The sensors were mounted on a fixed and stationary structure of 110 cm high. The distance between both the sensors was 33 cm. The sensors were mounted in series facing straight towards the targets, and are continuously firing for ranging. The data of range value is seen in real time in CANOE software. First, a rectangular shaped wooden stick which is placed right in front of the sensors, of width 4.5 cm and of height 143 cm, is placed at different distances 60 cm, 1meter, 2, 3, 4 and 5 meter distances. The sensors setup is shown in Figure, 32.

Fig.32. *Sensors setup*

The sensors can detect the obstacle at all the distances with little offset at 5 meter. The results at 60 cm and 5 meter are detected by only one sensor. The results are shown in Figure, 33.

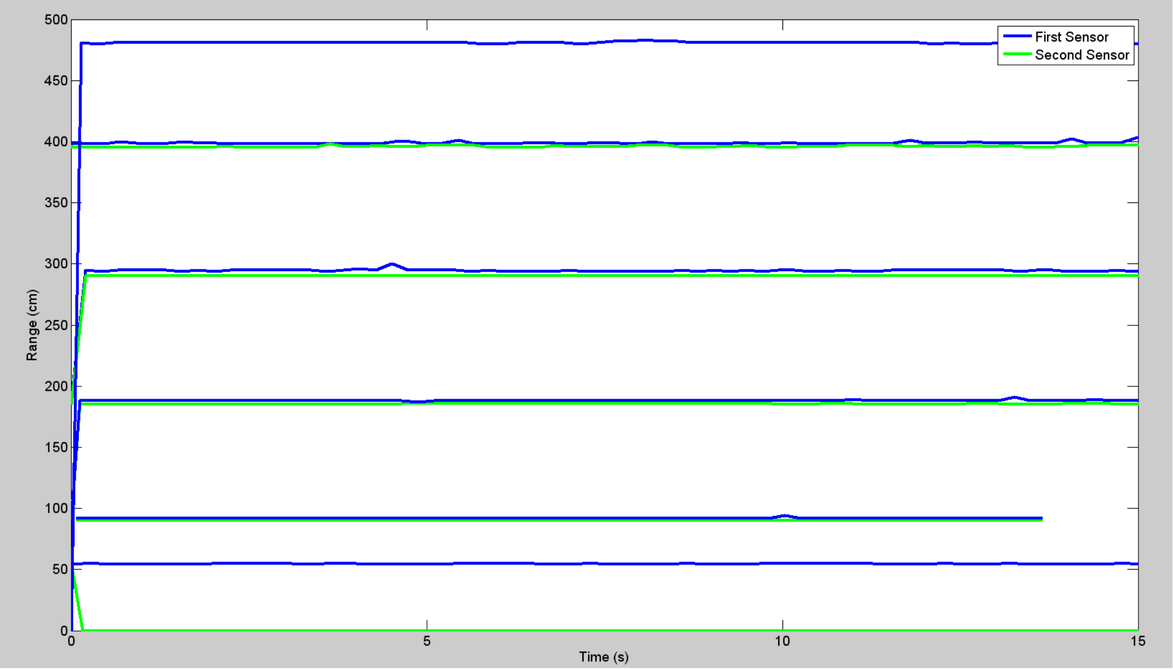

Fig.33. *Sensors result for wooden stick outdoor.*

The sensors are tested for a human as a target as shown in Figure, 34, who is moving towards the sensors. The sensors setup is the same as was in previous setup for wooden stick. The human is moving slowly and the movement of human is detected in real time.

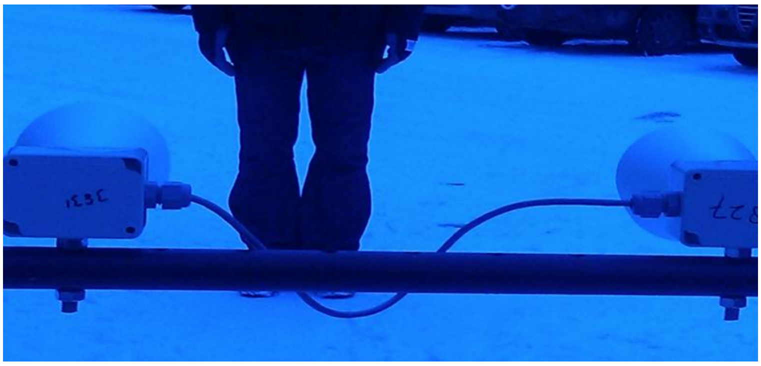

Fig.34. *Sensors setup for the human.*

Both the sensors can detect the human accurately from 370 cm to 50 cm approximately. The results for the human detection are shown in the Figure, 35. The desired area is encircled. However, one of the sensor, the right one, can’t detect the human from 5 meter to 370 cm because of no or poor reflections from the target due to the reason that the human is out of sight from this sensor for this distance. But, once it comes in the region, it is started to be detected by it while the other sensor, the left one, accurately detecting the human, because he is more towards left than right. Still, the detection of the human for 370 cm to 50 cm is quite acceptable. Good thing is that the both the sensor are able to detect the human without interfering each other’s output. This is due to the optimized code and cone implementation. This result of the sensors is quite better than the human detection as was shown in the figure, 35. Since, we were aiming the distance of 2.5 meter for human outside, this result is far better and good thing is that the result is consistent and can be repeated when minor changes are done in testing setup and changes in the environment.

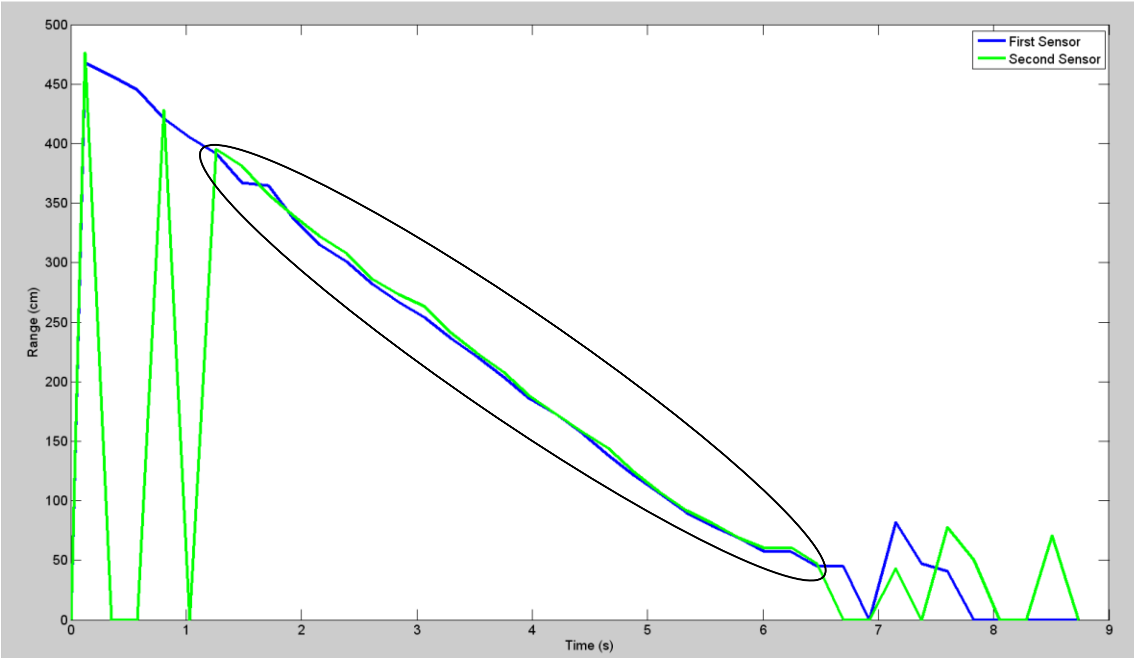

Fig.35. *Sensors result for human moving towards it.*
Further, the sensors are tested for a plastic poll obstacle which was placed right in front of the sensor. The height of the the plastic poll, of conical shape, is 80 cm. The setup for the cone is shown in the Figure, 36.

Fig.36. *Sensors setup for the human.*

Sensors are giving good results for plastic poll placed at 1 meter and 3 meter but for 4 meter and onwards it is not giving good detection because of small height of the poll and also due to conical shape of the poll. The results are shown in the Figure, 37. Still, the results are quite good for the plastic poll and more than desired because plastic is not a good reflector.

The sensors are tested for two objects moving in front of them and found that both the objects are detected. The person near to the sensors report range value first because sensors operate on the principle of reporting ranging for the latest echo they recive. Therefore, one sensor reports one value for both the objects it sees whichever offers first echo. So, two sensors are giving two ranging values for the two objects not four.

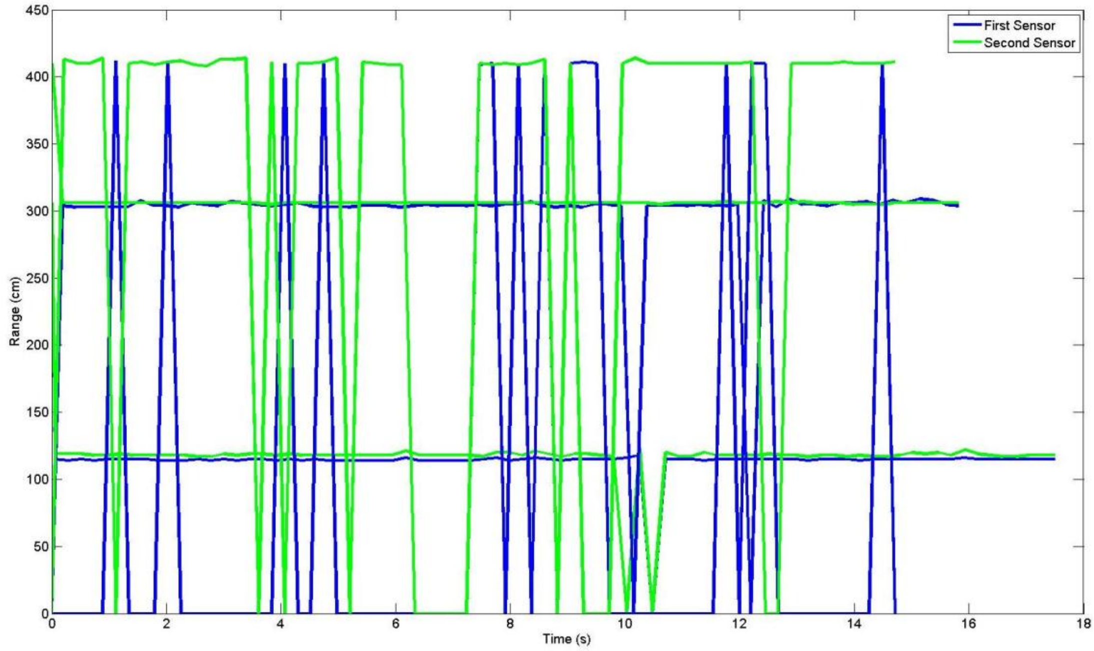

Fig.37. *Sensors result for plastic poll placed at 1, 2 and 4 meter.*

The sensors were tested in another setup to know how the sensors are working independently while connected in series. The sensors were facing at different directions and two person, one before each, are moving in opposite directions. So, one person is moving towards it and other moving away from it. The sensors setup is shown in the Figure,38.

Fig.38. *Sensors setup for detecting two objects.*

The sensors showed good detection for the movement of two objects in front of them. The results are shown in the Figure, 39. The movement was not identical and precise, just a human walk in front of the sensor. The sensor mounted at left showed little less detection, up to 3 meter started from 60 cm while the right sensor showed good detection for the human moving towards it. It detected him from more than 3.5 meter to less than 50cm. The desired area in the figure is encircled by ovals. The sensors response for different objects at different directions ensures the placement of the sensors at different directions where they are allowed to detect different objects without being interfered from other sensor at other direction. The sensors are independent unit just like they are single sensors working independently. In out mobile machine, we can use them at two corners or on each side of the machine.

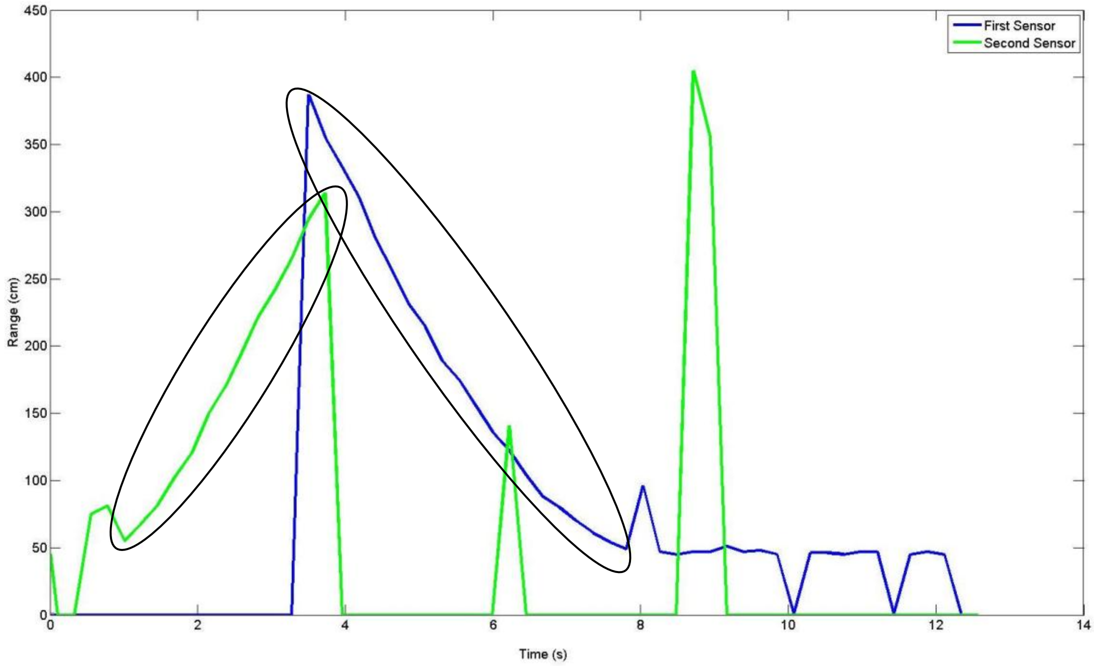

Fig.39. *Sensors result for two different objects at different directions.*

Few other experiments are also conducted on the sensors. First, placing the sensors in series, it was possible to increase their detection area or coverage while the effective detection angle of the two sensors was the same i.e. 30 degree. The behavior of the noise (metal striking) on sensor is seen and it is observed that the noise disturbs the value of range quite much. The operation is full disturbed.

The accurate results from the sensor highly depend on how we place (orientation, mounting height) the sensor and what are the environmental conditions around the sensor and also the target orientation and nature (how reflective or diffuse) affects the range values. So, to get the desired results from the ultrasonic sensor we need complete knowledge of the working environment and the nature of the target we can encounter and also how far we are interested to detect the object and also the mounting of the sensor is very vital. It is seen in almost all cases that the cone implementation on the sensor makes the results consistent and improve them. The sensors are mounted on stationary frame; therefore, we were not able to see the effects of the vibrations on the sensors. It would be seen once the sensors are mounted on the real machine.

5.1.3. Outdoor testing on mobile machine

The sensors were tested on real mobile machine for obstacles like, plastic poll, human and metallic gate (wall) of lab. The environmental conditions are real world scenario. Snow is around and temperature is -1ºC with little wind blowing. There is no such external noise in the environment, only vibrations and noise generated by the machine itself. The sensors are tightened firmly so that they don't move. The cones around the sensors are not that fixed and tight though.

They result are with one sensor because unfortunately, second sensor broke down during testing phase. But, it was good to see the behavior of one sensor on the machine when the machine was in motion making noise and vibrations. The sensors are found not good for weak reflective surface of plastic poll. The sensors setup for the plastic poll is shown in the Figure, 40 while the results are shown in the Figure, 41.

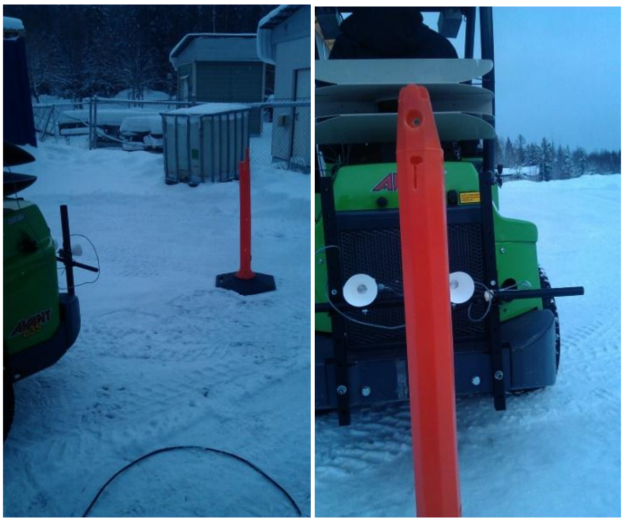

Fig.40. *Sensors setup for detecting plastic poll.*

The vehicle with the sensors is seen in the setup picture. The machine is first standing near the sensors and then starts moving away from it. The results are not that consistent due to less size of the object and also weak reflective nature of the target. The other broken sensor was showing constant value. The result is shown in Figure, 41.

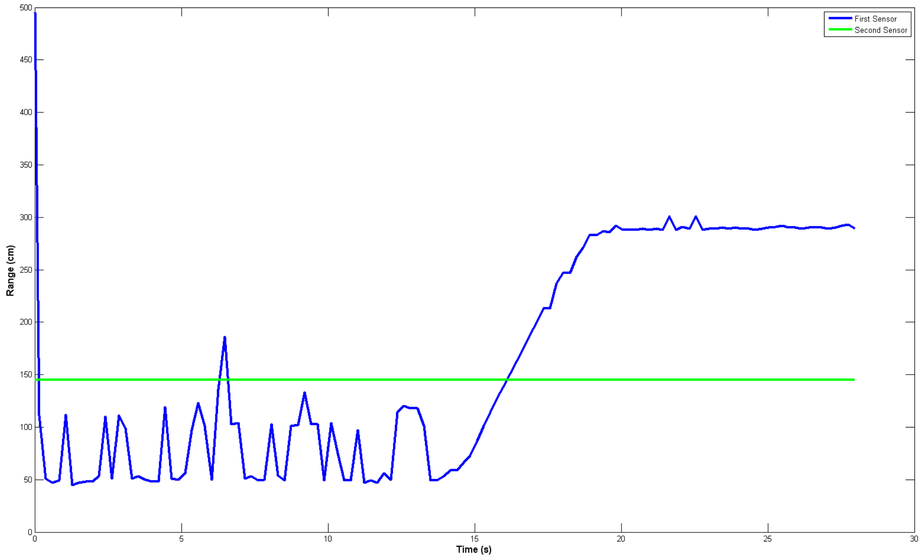

Fig.41. *Sensors result for plastic poll when sensors were mounted on real machine.*

The sensor was tested for human as target object and the results are found very promising as shown in the Figure, 42. The machine is moving towards the human and it started detecting him from 3 meter to around 50cm. The results are quite good keeping in mind the real world scenario. And, the sensors are mounted on the machine which is moving on not flat surface (snow on the floor). The other sensor (green one) is not wrong values because it is broken.

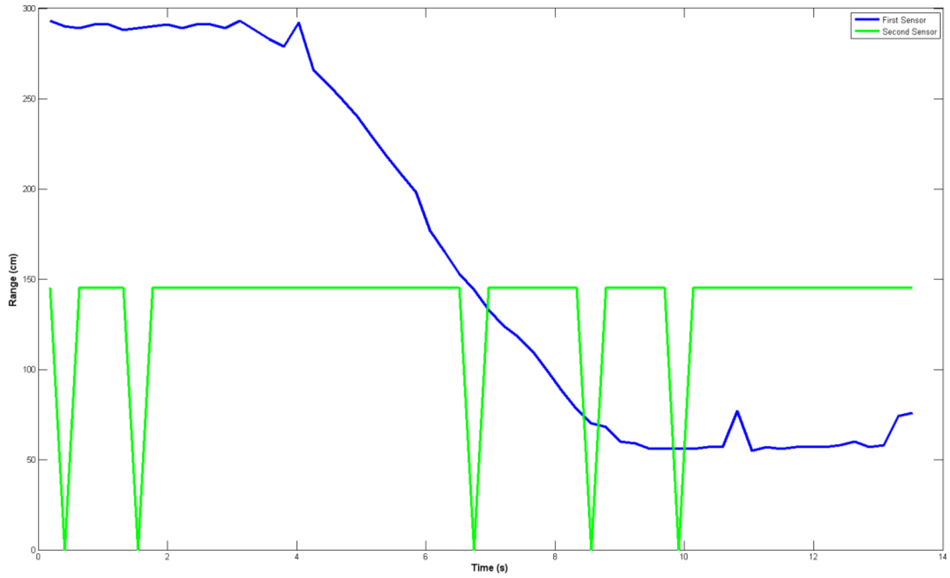

Fig.42. *Sensors result for human when machine is moving toward him.*

Finally, the tests are conducted for the metallic wall of the gate of lab. The results are close to ideal as were reported in the data sheet of the manufacturer. The sensor near the wall is shown in the following Figure, 43.

Fig.43. *Sensor near the metallic wall.*

The results of the sensor are shown in Figure, 44, when the machine is moving towards the wall.

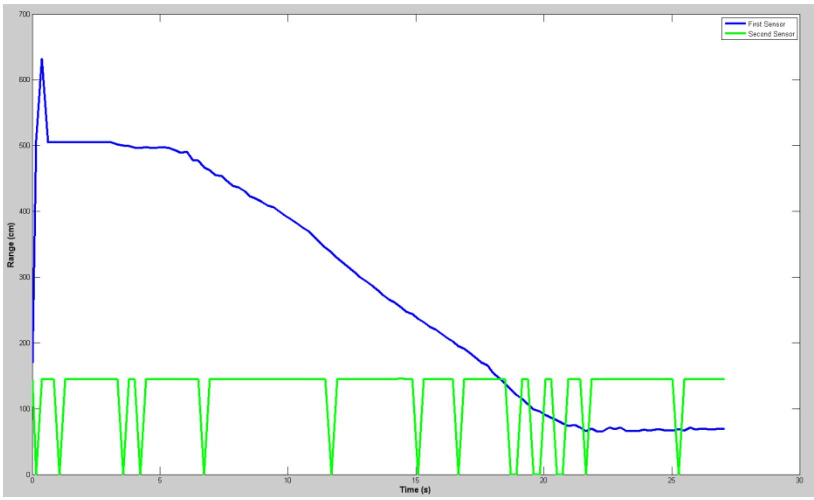

Fig.44. *Sensors result for the metallic wall when machine is moving toward it.*

The results are so good because of the strong reflection from the wall and also due to its greater size. The speed of the mobile machine was not known, but, it was moving quite slowly. The behavior of the increasing the speed of the machine is shown in the Figure, 45. The slope of detection is quite steep. The machine is moving away from the wall.

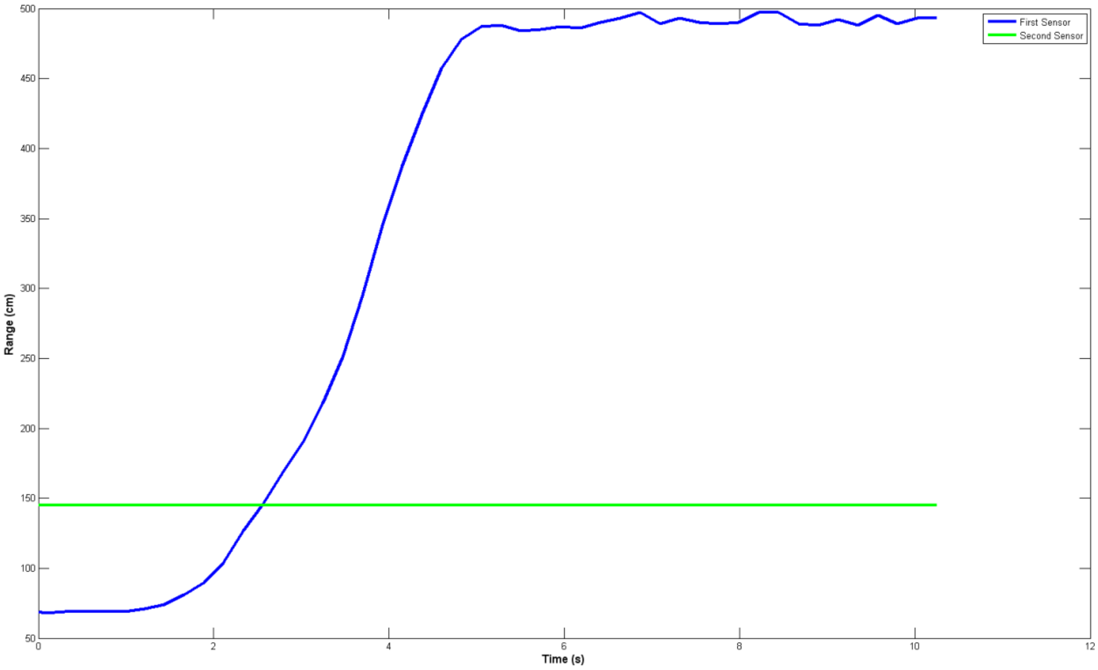

Fig.45. *Sensors result for the metallic wall when machine is moving away from it.*

The results are found less affected by the environmental agents while working outdoors. The vibrations and noise is also found less disturbing, maybe, due to less windy environment and fairly good temperature. Never the less, the results are quite good for obstacle detection in outdoor applications for the weather conditions in which the machine is supposed to work in. The only discouraging thing is the poor quality of sensor's electronics and their higher failure rate during testing phase. But, when they start working, they work fine. The sensors were suiting the working conditions and that was the reason they were selected for this project. Now, the same sensors can be used for the whole system as they qualify for it because of their performance, Or, they may be replaced with finer quality sensors specifically designed for the vehicles obstacle detections.

6. CONCLUSION

An obstacle detection system using ultrasonic sensors designed for an autonomous mobile machine is developed and tested in outdoor under different weather conditions for different obstacle. Two ultrasonic sensors are tested outdoor on static frame for different targets. The sensors are facing targets. The range values obtained for wooden stick, human and plastic poll are quite promising and are more than the desired range value which was set as 2.5 meter. The results are quite reliable even when there are some movements in targets and interception of wind. A wooden stick of 4.5 cm thick as a target object is detected from 60 cm to 5 meter quite accurately which was placed right in front of them. The sensors were detecting a human moving towards them from 370 cm to less than 50cm. A plastic poll of 80 cm high with conical shape is detected at 1m and 3m while the sensors were not giving good results for the same poll at 4 m and onwards. The behaviour of two sensors for two different objects was also tested when the objects were moving in front of each sensor which was facing to it. It was found that the sensors were able to detect them accurately.

The sensors were also tested on real machine and found good choice for the application if their failure rate during testing phase is ignored. The sensor on the mobile machine was tested for plastic poll, human and metallic wall. And, the results were found quite encouraging. The weather conditions and noise and vibrations of the vehicle are found less disturbing. The machine speed was unknown but it was quite slow though.

The results were improved because of the implementation of cone shaped object (of 30-40 degree and 5 cm height) around the sensors transmitting part. It was found that with the cone, the results were much consistent and the pulses transmitted were stronger and also the echoes were stronger. The optimized code for controlling the sensor yielded consistent results all the time. The sensors were made less sensitive to fast moving objects by increasing the time delay between the initializing of ranging and obtaining the range value while little compromising on the speed of sensor. Previously, the fast and abrupt motion of target was stopping the sensors even when it was in front of one sensor. The sensor’s mutual interference was controlled by clearing transmit and receive registers in microcontroller and also giving some delay time in the software between the two ranging commands for the sensors. There was needed to make water proof casing for the sensor so that they can work without getting affected by the weather conditions. For this purpose, different materials like PVC plastic and aluminum plate were tested for water proof casing. It was found that the aluminum plate did not give good results even when a rubber was used on the surface of it while, PVC plate yielded very good results. Sensors have o-ring (rubber sealing) around the transmitting part of them for water proofing and it was found okay i.e. not effecting to the results of the sensor. A mechanical structure for sensors placement on the machine is also designed. The place chosen on the machine is rear part of the machine which is just near to the ground with gas exhaust pump near to it. The place is expected to reveal optimal results.

While working with the sensors, it was found that the sensors have poor electronics, difficult to operate because of difficult choice of certain break (time delay) signal between two commands and unknown behavior of certain units of the sensors while other unit(s) was working fine for the same code. The sensors were also very delicate and could easily stop working. If was learnt that the proper choice of the sensors should be done before starting the project, may that be expensive.

Grouping the multiple sensors between the sensors can be done to avoid interference and increase the bandwidth of the bus. Interfacing the sensors to vehicle electronics and displaying the results and making decisions (how to you the information obtained from the sensors) based on the information are the future steps needed to be done in order to make a complete obstacle detection system.

For potential enhancements, it is recommended that the sensors specifically designed for vehicle obstacle detection in vehicles should be preferred to use like Bosch automotive ultrasonic sensor. A French company, Valeo, supplies ultrasonic sensors to Ford, Rolls Royce and to Ferrari. They claim over 100 million ultrasonic parking sensors are produced since 1991. Murata ultrasonic sensors are also used in automotive for parking assistance. Aimar also have a wide range of ultrasonic sensors with different specifications. CTFM ultrasonic sensors can also be chosen due to their attractive advantages in outdoor applications. Wireless ultrasonic sensors are also available and can be used to avoid cabling issues. It is also possible to do some signal processing for the extraction of the desired results from the sensors data.

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APPENDIX 1: CODE

```
/**
######################################################################
####
**     Filename  : firstproject11.C
**     Project   : firstproject11
**     Processor : 56F8323
**     Version   : Driver 01.06.01
**     Compiler  : Metrowerks DSP C Compiler
**     Date/Time : 2/27/2012, 2:19 PM
**     Abstract  :
**         Main module.
**         Here is to be placed user's code.
**     Settings  :
**     Contents  :
**         No public methods
**
**     (c) Copyright UNIS, spol. s r.o. 1997-2004
**     UNIS, spol. s r.o.
**     Jundrovska 33
**     624 00 Brno
**     Czech Republic
**     http      : www.processorexpert.com
**     mail      : info@processorexpert.com
**
######################################################################
####*/
/* MODULE firstproject11 */

/* Including used modules for compilling procedure */
#include "Cpu.h"
#include "Events.h"
#include "AS1.h"
#include "Bit1.h"
#include "TI1.h"
#include "TI2.h"
#include "Init1.h"
/* Include shared modules, which are used for whole project */
#include "PE_Types.h"
#include "PE_Error.h"
#include "PE_Const.h"
#include "IO_Map.h"

#define TX_MODE 1
#define RX_MODE 0

unsigned char rxData[2] = {0, 0};
unsigned char rxInd;
bool sentOne = FALSE;
```

```
extern volatile unsigned int mS_timer = 0;
extern volatile unsigned int uS10_timer = 0;
extern volatile unsigned char datarecvd = 0;

void SendFrame (unsigned char cmd, long addr, unsigned char data);
void SendBreak(void);
int  CAN_send (unsigned sendID,unsigned length, unsigned data1,unsigned
data2,unsigned data3,unsigned data4);
void DlymS(unsigned char ms);
void Dlym10uS(unsigned char us10);

enum commands

{

  Range_IN=0x50, Range_CM, Range_IN_Tx=0x53, Range_CM_Tx,

  Get_Ver=0x5D,  Get_Range_uncomp=0x5E, Set_Search=0x65,

  Less_than, Set_group, Get_temp, Get_Range_comp

};

void main(void)
{

unsigned int x = 0;
unsigned int range[2] = {0,0};
unsigned char* recv_char = 0;
long SRF485s[2];

SRF485s[0]=0x003827;
SRF485s[1]=0x003831;
//SRF485s[2]=0x002BFB;
//SRF485s[3]=0x00382C;
  /*** Processor Expert internal initialization. DON'T REMOVE THIS CODE!!! ***/
  PE_low_level_init();
  /*** End of Processor Expert internal initialization.                    ***/

  /* Write your code here */


 while(1)
 {


  while (!getRegBit(SCI0_SCISR, TDRE)){};        // /* Is the transmitter empty?

   SendFrame(Range_CM,0,0); // for multiple sensors
```

```
 DlymS(80); //was 100 initially..working at 100..stops at 70 works at 80 and
above

        for(x=0; x<2; x++)

         {


        while(AS1_RecvChar(recv_char) != ERR_RXEMPTY)
                {
                }

                rxInd = 0;


        SendFrame(Get_Range_comp,SRF485s[x],0);

                while(rxInd < 2)
                {
                }

        // range is received MSB first, but for the CAN bus we send LSB
first

                range[x] = ((unsigned)rxData[1] << 8) + rxData[0];

                rxInd = 0;

                if (x==1)
                {
                 CAN_send(0x1EE,4,range[0],range[1],0,0);
                }

                DlymS(70);
         }
 }
}


void SendBreak(void)
{
        // set baudate to 14000
        AS1_SetBaudRateMode(0);

        // send break

        setRegBit(SCI0_SCICR, SBK);

        Dlym10uS(55);           // was 60
```

```
                    clrRegBit(SCI0_SCICR, SBK);

//                  DlymS(1);
                    // set baudate to 38400
                    AS1_SetBaudRateMode(1);
                    Dlym10uS(15);
                                        //send 1
                    //AS1_SendChar(1);

}
void SendFrame (unsigned char cmd, long addr, unsigned char data)

{
                    unsigned char c, chksum_to_send;
                    unsigned char chksum;

                    Bit1_PutVal(TX_MODE);

                    SendBreak();

                    while(!getRegBit(SCI0_SCISR, TDRE)){};

//                  Dlym10uS(10);

                    AS1_SendChar(cmd);

                    chksum = cmd;
                    c = (unsigned char)((addr >> 16) & 0xFF);

                    while(!getRegBit(SCI0_SCISR, TDRE)){};

//      Dlym10uS(10);

                    AS1_SendChar(c);

                    chksum += c;
                    c = (unsigned char)((addr >> 8) & 0xFF);

                    while(!getRegBit(SCI0_SCISR, TDRE)){};

  //    Dlym10uS(10);

                    AS1_SendChar(c);

                    chksum+=c;
                    c = (unsigned char)((addr & 0xFF));

                    while(!getRegBit(SCI0_SCISR, TDRE)){};
```

```
//		Dlym10uS(10);

		AS1_SendChar(c);

		chksum+= c;

		while(!getRegBit(SCI0_SCISR, TDRE)){};

//		Dlym10uS(10);
		AS1_SendChar(data);

		chksum += data;
		chksum = (unsigned char)~chksum;
		chksum_to_send = (unsigned char)(chksum & 0x00FF);	// Try
without

		while(!getRegBit(SCI0_SCISR, TDRE)){};

//		Dlym10uS(10);

		AS1_SendChar (chksum_to_send); // Try with 'chksum' instead of
'chksum_to_send

		while(!getRegBit(SCI0_SCISR, TDRE)){};

		Dlym10uS(29);		// was 28

//		if(cmd != Range_CM)			// Try without if()
//		{
				Bit1_PutVal(RX_MODE);		// ... i.e. only
this...apparently it is working without if()
//		}
}


int CAN_send (unsigned sendID,unsigned length,unsigned data1,unsigned
data2,unsigned data3,unsigned data4)

{
  int retVal = ERR_OK;

  if(sentOne && !(getReg16(FCIFLAG1) & 0x02))  // Wait until last transmission
has succeeded
  {
    retVal = ERR_BUSY;
  }

  if(retVal == ERR_OK)
  {
    sentOne = 1;
```

```
   getReg16(FCIFLAG1);                // Clear interrupt flag

   setReg(FCIFLAG1,0x02);               // for message buffer 1


   setReg(FCMB1_Control,0x0080); // Buffer not ready for transmit, length: don't
care

   setReg(FCMB1_ID_HIGH,sendID << 5);

   setReg(FCMB1_ID_LOW,0);

   setReg(FCMB1_DATA0,data1);

   setReg(FCMB1_DATA1,data2);

   setReg(FCMB1_DATA2,data3);

   setReg(FCMB1_DATA3,data4);

   setReg(FCMB1_Control,0x00C0 + length);// Transmit once, unconditionally,
set length
  }

  return retVal;
}


void DlymS(unsigned char ms)
{
		mS_timer = 0;
		while(mS_timer < ms)
		{
		}
}

void Dlym10uS(unsigned char us10)
{

		uS10_timer = 0;
		while(uS10_timer < us10)
		{
		}
}
/* END firstproject11 */
/*
**
######################################################################
####
```

```
**
**     This file was created by UNIS Processor Expert 03.47 for
**     the Motorola 56800 series of microcontrollers.
**
**
################################################################
####
*/
```