ROBOTICS AND MECHATRONICS

Design and Implementation of a 3 Layered Obstacle Detection System with Haptic Feedback Notification

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BSc Report

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Summary

An Omni-directional wheel based platform is to be tele-operated from an omega.6 haptic device and the implementation of an obstacle detection system is required to aid the user in navigating through, in most cases, an out of sight environment. The system is required to let the user perceive the robot's location, surroundings and status in ways that are easily comprehended and require little to no hesitation in processing (situational awareness). In this work, the use of a layered ranging system for the platform is the approach for the obstacle detection system. The second range which is implemented in this project creates awareness through detecting and ranging obstacles and sends this data as haptic cues through the haptic device. A user's study response revealed the added value that the haptic feedback offers from providing environmental awareness to the user and enhancing the tele operation experience.

Preface

I would like to thank my supervisor dr.ir. Douwe Dresscher for this opportunity that I have valued and learned from so much and also for his guidance that without it you wouldn't be reading this thesis right now. I hope to have fulfilled the expectations required.

Very special thanks and much appreciation entitled to MSc students Mohamed Abdelhady and Shamel Fahmi for their valuable assistance and mentoring throughout my thesis project. It was my pleasure to know you both on a technical and especially on a personal level. Thank you and good luck in your theses.

Contents

1 Introduction

The project discussed in this thesis is part of a bigger project carried by the I-Botics center. The project entails the development of a telepresence implementation with haptic feedback, audio and visual information using the Leo Universal Cockpit and a platform consisting of a KUKA and a Segway omni directional base. The part of the project that is discussed in this report is designing and implementing an obstacle detection system to facilitate the tele-operation of the platform and enhance the tele-presence experience.

Obstacle detection systems are usually associated with autonomously vehicles. A system to compensate for the missing operator and take complete control of the vehicle and assure a complete collision free travel is vital. This is achieved by the use of different sensor technologies and a variety of sensor input combinations to successfully detect an object, identify it as an obstacle and assure consistency and reliability. In a tele-operated platform as is the case for this project, there is a user to navigate and avoid obstacles, moreover the idea of tele-operation is for the platform to be partially, if not completely as in most cases, out of sight of the user who operates it remotely with the help of a remote camera providing a visual representation of the view from the robot. Usually, ideal camera placements are not possible and an operator is left vulnerable when performing complex maneuvers due to the presence of severe blind-spots [44]. An obstacle detection system henceforth can be adopted that allows a robot to detect constraints in the environment automatically and alert the user of them.

In this work, a three layered approach is presented for obstacle detection and its corresponding user notification method. Each layer will have a different type of sensor operating in its own distinct region and approaching communicating with the user differently. Consequently, decisions have to be made to first set the ranges that each of these 3 layers will be defined by and then on that note, survey sensors based on their suitability of operation in each of the 3 layered regions so as at the end, selected sensors can fulfill the criteria required from their respective layer of ranging.

The thesis layout is as follows; in chapter 2 the analysis is discussed. Then in chapter 3, the design of the system is presented followed by the method of implementation in chapter 4. Evaluation of the system is discussed in chapter 5 followed by the results and their reasonings. Finally the thesis is concluded with a few statements consisting of the final outcome, final thoughts and recommendations for the future.

2 Analysis

The three layers operating in the system are differentiated for the users in two ways. First, through their respective maximum range of detection and secondly, the way of communicating to the user the detection of an obstacle.

No matter the type of ranging sensor a detection system might use or how robust it is considered to be, at instances a detection by the sensor might not be ensured. This could be accredited to either limitations the sensor's method of detection has or the occurrence of some sort of a sensor malfunction. Thus a layer of detection is incorporated acting as a close proximity ring surrounding the platform with a perimeter of a few tens of centimeters, to act as a last line of defense against obstacles. If this layer of detection is triggered then a halt state can be performed to stop the vehicle protecting it from collisions.

A second range of detection is the one that will be referred to as the mid-range. The mid-range will operate in a region of a few meters, a region where obstacles will start possessing collision threats and should be highlighted to the user through haptic cues to offer the user with ample time of reaction. This is a range that is considered by most when implementing an obstacle detection system for relatively slow moving robots. [40] stated the need of a ranging sensor with relatively short ranged detection ranges to provide the mobile platform with sufficient environmental awareness of its surroundings and allow it to maneuver about in a realistic fashion, avoiding objects. This mid-range layer can be considered the core of the obstacle detection system or in other words, it has the potential to operate on its own without the need of the other 2 detection ranges.
For this range, the response sent to the user will be through haptic feedback. Several authors have incorporated haptic feedback for robot control in addition to visual data to improve teleoperation performance and reduce collisions [42], [41] and [36]. The average reaction time to a touch stimulus (haptic feedback) is nearly twice as fast as to visual stimulus (camera) . Thus the haptic feedback allows a user to perceive information about the environment and at higher rates compared to visual display [4].

Both the mid and short range layers would lack in detecting at relatively long ranges (6 m and further) and thus environment mapping and path planing would be limited with just these two layers of detection, hence the inclusion of a 3rd and final layer, the long range layer. This layer is designed to provide the user with a rich visual representation of the entire surrounding environment that might not be visible in tele-operation due to the platform being completely out of sight from the user. This layer will reach ranges further than a few meters so it can be able to extend to the end of an environment specifically a room or a lab as in our testing case and provide the user with its visual map.

A visualization of how each layer will look along with the respective range of each layer can be seen in figure 2.1.

In the following sections the criteria required to be met by each layer of detection is discussed then a classification of sensors in terms of their range is explored to decide in which layer of detection a sensor has the potential to operate in and assessing it against the criteria set to its respective layer of detection.

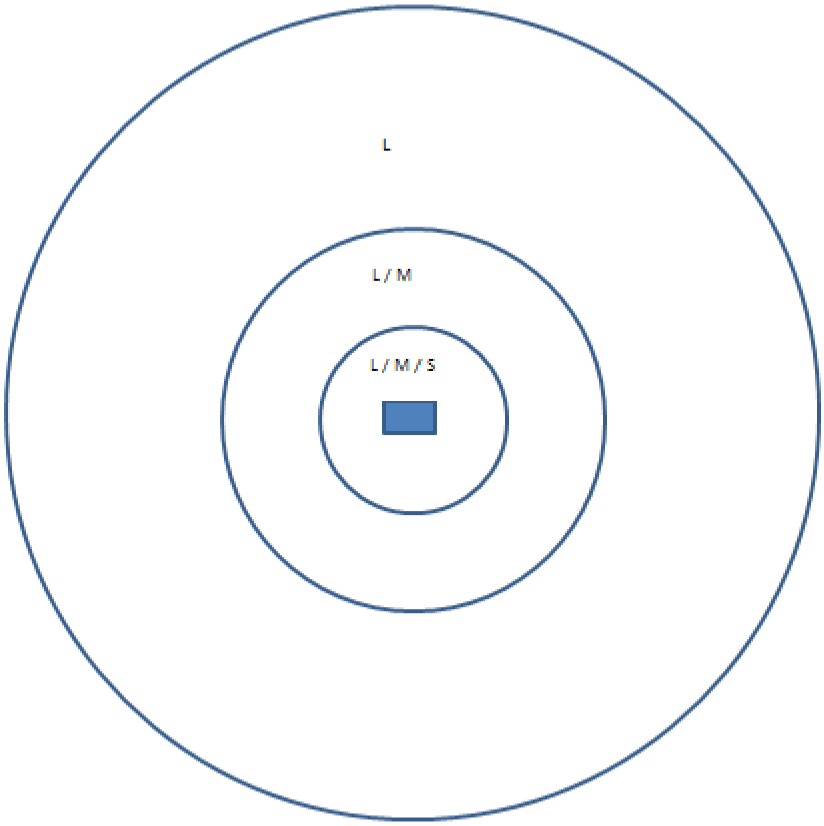


Figure 2.1: A top view of the 3 layers of detection surrounding the platform with their operation ranges (not drawn to scale).
Short range (S) < 20 cm
Mid-range (M) < 650 cm
Long range (L) extends further than 650 cm
(These numbers are just approximates at this moment)

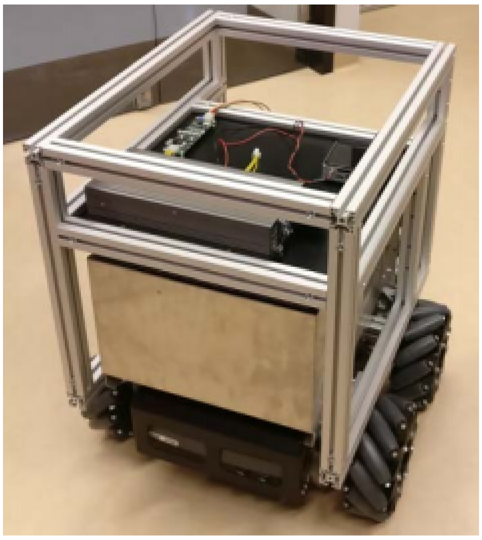


Figure 2.2: A side view of the platform.

2.1 Sensor Requirements

A few sets of criteria were set for each layer of detection to help in selecting the most suitable sensor for each layer along with the importance of these criteria to the system as a whole. But first a few data about the platform is mentioned that will be useful in quantifying the requirements.

The platform is a mecanum-wheel based platform allowing translation movement on the horizontal axes as well as forward and backward movement. The platform has a maximum speed of 0.833 m/s while the average navigation speed in the testing environment is around 0.4 m/s. An image of the platform can be seen in figure 2.2.

Close Range / Proximity Sensor Criteria

Range

Operating range for this layer is from the platform to a further 20-30 cm from the platform. This is set based on that the platform's wheels that protrude outside the body of the platform by a few centimeters as can be seen visible in figure 2.2 and should be included part of the detection range of this range of detection. In addition, any further maximum range would cause frequent halt states to occur when not needed.

Detection of All Types of Obstacles

All obstacle types must be detected and mustn't go unnoticed at this close of a range as a collision would be the result if obstacles go unnoticed.

Protection against Collisions

This criterion is self-explanatory, and it will be emphasized on more when discussing the different sensors that could operate in this region of detection.

Mid-range Sensor Criteria

Range

The operation range is to be from the platform to a further 6.5 meters from the platform.

Accuracy

Accuracy in sensor measurement is an important criterion, haptic feedback is sent to the user with intensities varying with the range of an obstacle. Inaccuracies in sensor measurements could result in the wrong and/or disturbing cues being sent back that might mislead the user's interpretation of the situation.

Reliability

As it can be considered the core of the obstacle detection system or in other words, it has the potential to operate on its own without the need of the other 2 detection ranges, reliability levels should be as high as possible and that specifies that the sensor of choice should be able to detect all types of obstacles.

Response time

Response time is a very important aspect that has to be taken into consideration. As mid-range deals with sensors operating at relatively short distances, at an instant an obstacle could be out of a sensor's range of detection and if the sensor would have a slow refresh rate (slower than the time the platform takes to reach that obstacle) an obstacle might hence go undetected by the sensor and result in a collision.

Taking the maximum velocity of the platform and an approximate maximum detection range of 1 m, a maximum refresh rate of a sensor acceptable (Tmax) is:

$$\begin{aligned} 5/6m/s &= (1-0.3)/Tmax \\ Tmax &= 0.84s \end{aligned} \tag{2.1}$$

Field of View

Considering the platform is Omni directional and obstacle detection sideways is just as important as forwards/ backwards. Hence full 360°coverage across the platform will be required.
The field of view of a sensor is the azimuth angle of detection provided by the sensor and from that the number of sensors required for a full coverage can be determined.

Resolution

The resolution of a sensor determines the accuracy of the azimuth angle of the detected obstacle. The higher the resolution of a sensor the less discretized the azimuth angle values will be.

Long Range Sensor Criteria

Range

The range of operation required will be interchangeable depending on the environment the platform is in. At this moment the environment is taken to be the lab where tests are to be carried out as an example of the current platform environment and taking its length sets a requirement for ranging sensors to have maximum ranges that can extend 7 meters.

3D field of view

The field of view of the sensor is required to be in 3 dimensional orientation with a full 360°in the 2D planar field of view to be able to rebuild the whole surrounding environment.

Resolution

A high resolution is required with in a large field of view for the realization of an accurate 3D map of the environment.

2.2 Sensor Selection for Mid and Long Range

Ultrasonic Sensors

Adopting the technique of time of flight with the use of ultrasonic waves, ultrasonic sensors direct the waves at a target which then reflects the waves back to a receiver and through the time of flight technique, distance to that object is determined. Sonar systems are frequently applied when it comes to detection. [38] state that this can be accredited to their low price and simplicity in operation while [27] highlight the fact that they can recognize most materials and surfaces. Ultrasonic sensors however are prone to some limitations, one of which is that a sensor only gives one distance reading so to obtain a full coverage of the surrounding environment multiple sensors would be needed [38]. A very worthy point to note is a problem that is synonymous with mentioning the use of more than one ultrasonic sensor. Due to the presence of more than one source of ultrasonic transmission, interference of sound waves occurs and is referred to as cross-talk. If a network of sensors is used, the echoed pulses from one sensor might interfere with pulses from another causing destruction of said waves or even have the waves echoed back to a nearby receiver that wasn't the source of the transmission in the first place and doesn't have the reflecting object in its field of view [43].

Range:
Ultrasonic sensors provide remote range measurements from a few centimeters (2 - 3 cm) to (3 - 6 m) depending on the type of sensor.
Accuracy:
Ultrasonic sensors average an error in ranging around 0.5 cm as determined from a few documentations [29], [3] and this error is mostly found true at larger distances rather than at a closer range [29].
Reliability:
As stated, ultrasonic sensors have the attribute of not being affected by the object's color or optical characteristics such as reflectivity, transparency or opacity [5] however the position of the object detected relative to the sensor is very tricky. For an effective range data, the sensor must be perpendicular to the target as much as possible. Errors from detecting round objects are limited since they always show some perpendicular face however for flat objects, care must be taken to ensure that the angle of incidence doesn't exceed a particular range for a detection to occur [28].
Response Time:
Through taking an average of a few ultrasonic sensors' refresh rates [24], [16], [14] and [22], sensors that are famously used for obstacle detection, an average response time is calculated to be around 50 milliseconds.
Field of View:
Sonar sensors are known for their wide field of view ranging up to 45°for some sensors which enables the detection of surrounding obstacles with fewer sensors.

Another advantage is that the detection field of an ultrasonic sensor takes the shape of a cone and thus the field of view is extended to 3 dimensional.
Resolution:
An ultrasonic sensor can detect a single object (the closest) in its field of view and hence ultrasonic sensors have a quite large resolution.

2D LIDARs

With the help of high voltage electricity and with a continuous process of simulated emission and amplification, photons are sent out of the LIDAR along a very narrow beam forming what is known as a laser light. Precise time is recorded for when waves are emitted and sent back from reflecting off targets and hence determining their range. The emitted light waves are in phase with one another and are nearly parallel that they can travel long distances with very minimal divergence (0.1 to 1 milliradian) [12]. Hence LIDARs can be used for long range readings with very high angular resolutions [7]. The angular resolution on an LD-OEM can reach as low as 0.125°[11]. LIDARs contain rotating mirrors that bounce off the light waves to get a wide scan of the environment ahead making a single sensor a viable replacement to an array of other types of sensors. However from their name, their scans are planar and thus an obstacle will go undetected if it's above or below that plane.

Range:
2D LIDARs range is varied form one type to the next. Most have ranges similar to ultrasonic sensors (typically from 5 cm to 4 - 8 m) however, quite a few have maximum ranges that far extend the reachability of ultrasonic sensors by a factor of ten. An example is the LMS5xx that can reach a range of up to 80 m [13].
Accuracy:
LIDARs are famous for their high accuracies that can range objects within a few millimeters according to [7].
Reliability:
Laser scanners in general are prone to not detecting transparent materials due to refractions and specular reflections [37].
Response Time:
As light waves are the source of emission, LIDARs have a very fast response time ranging from 17 ms to 1 s depending on the resolution and the speed that data is being output [38].
Field of View:
The rotating mirrors in LIDARs allow the light waves to do a wide scan when ranging and hence most LIDARs have field windows of 180°and more [1]. However these field windows as mentioned are only limited to a 2D plane.
Resolution:
2D LIDARs offer fractions of a degree (<= 1°) in resolution with some offering more than a 100 times the resolution of ultrasonic sensors.

IR Sensors

The type of IR sensor which will be considered in this section is a long range active type sensor that has an IR transmitter, a position sensitive device and adopts the principle of optical triangulation and through interpreting and processing the signal gives the distance of the obstacle ahead. The range of this type of sensor can reach up to 5 meters [6]. It is common to see infrared sensors used when mid-range distance measurements in navigation systems is required. In [39] infrared sensors were used for their obstacle avoiding robot. [33] adopted IR sensor's distance measurements to explore an environment through detecting obstacles.

Range:
Compared to ultrasonic sensors and 2D LIDAR, this type of sensor is considered to have a relatively short range.
Accuracy:
The IR sensor's measurements show a little instability as they vary with in 2-3 cm of the real measurements [45].
Reliability:
Due to their method of ranging, IR sensors are immune to interference from ambient light and show indifference in measurements to the color of the object being detected as stated by [8] but according to [21], they are usually most effective to a maximum range of 1m.
Response Time:
IR sensors have a fast response time and are usually compared to ultrasonic sensors and labelled as offering faster response rates than what most ultrasounds can [10], [33].
Field of View:
An IR sensor's beam pattern is a reasonably narrow beam pattern, the beam patterns are usually around 5°.
Resolution:
The beam patterns are very narrow that they are labeled by [32] as basically a line offering high resolution detection.

3D LiDaRs

Similar to a 2D LIDAR but with an extra array of laser emitters, 3D LIDARs extend their field of view from a single plane to vertical FOVs that can reach 40°[30]. One famous 3D laser scanner is the Velodyne HDL-64E which was used by five out of six of the finishing teams at the 2007 DARPA challenge [31], a prize competition for autonomous vehicles. Below is a display of a map generated by the Velodyne LIDAR. However 3D LIDARS come with a few limitations, first is their extremely high cost. The aforementioned LIDAR costs nearly 80,000 $. Also response time for this rich map to be generated is relatively lengthy for some.

Range:
3D LIDARs usually extend the ranges of 2D LIDARs and can reach further than a 100 m.
Accuracy:
High accuracies that can range objects within a few millimeters according to [7].
Reliability:
Laser scanners in general are prone to not detecting transparent materials due to refractions and specular reflections [37].
Response Time:
As stated response time for some sensors is relatively lengthy for some. In [38] it is stated that their 3D LIDAR takes 80 seconds for scanning a full 360°scan of the environment consisting of 8000 consecutive scans.
Field of View:
From their name, 3D LIDARs offer 3 dimensional detection range. Up to 360°in azimuth and 45°in elevation.
Resolution:
LIDARs in general offer fractions of a degree (<= 1°) in resolution.

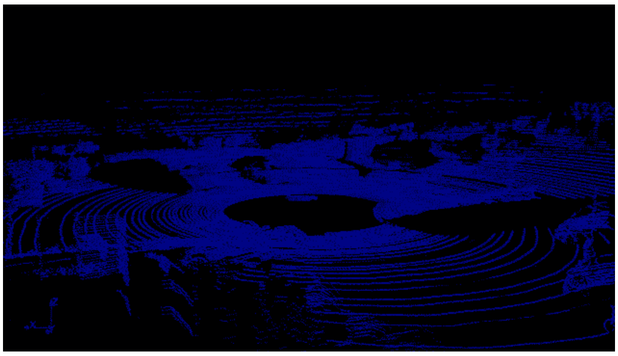
Figure 2.3: A view of the K2Pi radar.

Radar Systems

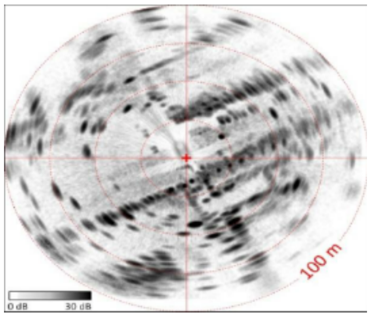
An object detection system that uses a radar wave transmitter and a receiver to give details about an object's location, angle and velocity through the bouncing of waves off the object. Radar systems work along a wide band of transmitted frequencies and can be divided in to two categories, short and long range. The short range transmit radio waves with frequencies of 24GHz and can detect objects till a range of 30 meters [51]. The long range systems operate with a larger frequency of 77GHz with ranges that reach an astonishing 200 km [19]. Radar systems have the capability of rendering precise maps [20] and are especially used in outdoor environments for they are in affected by weather conditions [46]. Many approaches have been considered for interacting between a radar's performance as a detecting sensor and extending its application to environment mapping. Grid based and feature based are amongst the most widely used for radar mapping in robotics [35]. A famous radar scanner that is used for environment mapping is the K2Pi radar [47], [50]. The K2Pi is equipped with a rotating antenna that can attain a full 360°scan around a vehicle in one second with an acquisition every one degree [46].

Range:
Radar systems offer the longest ranging distance of all ranging sensors.
Accuracy:
Depends on the processing algorithm used for mapping.
Reliability:
Radar systems provide robust readings and are in affected by weather conditions.
Response Time:
Depends on the processing algorithm used for mapping.
Field of View:
The K2Pi radar offers a full 360°scan of the environment.
Resolution:
Resolution of the K2Pi radar is a single scan per one degree.

Figure 2.4 shows an example of the visual displays from a Velodyne 3D LIDAR and a K2Pi radar.



(a) A cloud point data generated by a Velodyne HDL 64E LIDAR



(b) Radar image from the K2Pi radar

Figure 2.4: Visual Display from a Velodyne 3D LIDAR (a) and a K2Pi radar (b).

	Range	Accuracy	Reliability	Response Time	Field of View	Resolution
Ultrasonic Sensors	2 - 12 cm to 3 - 6 m	X	X	X	X	
2D LIDARs	5 cm to 4 - 8 m	X			X	X
IR Sensors	3 – 20 cm to 1 m			X		X
3D LIDARs	Up to 80 - 120 m	X			X	X
Radar Systems (K2Pi)	3 m to 100 m	X	X		X	X

Figure 2.5: Comparison of obstacle detection sensors with the mid-range criteria.

The comparisons of each of the pre mentioned sensors with the mid-range and long range criteria are shown in figures 2.5 and 2.6 respectively.

2.3 Sensor Selection for the Close Range / Proximity

This group of sensors doesn't possess the ability of measuring the distance to an object but merely detect its presence. But when looking at them as a last option to avoid inevitable collisions, for them to detect presence is all what is needed in that case. A brief overview of types of proximity sensors is presented in the following section.

Inductive

Theses sensors are designed to detect metallic objects in their nearby vicinity. Inductive sensors create an oscillating magnetic field and when a magnetic material enters this field eddy currents are induced that reduce the oscillation amplitude. A Schmitt trigger is present to respond to these changes and send an output signal [18].

Capacitive

	Range	3D Field of View	Resolution
Ultrasonic Sensors	2 - 12 cm to 3 - 6 m	X	
2D LIDARs	5 cm to 4 - 8 m		X
IR Sensors	3 – 20 cm to 1 m		X
3D LIDARs	Up to 80 - 120 m	X	X
Radar Systems (K2Pi)	3 m to 100 m		X

Figure 2.6: Comparison of obstacle detection sensors with the long range criteria.

Capacitive sensors can detect both metallic and non-metallic materials. Theses sensors consist of two parallel conduction plates just as a capacitor. With no object nearby, there is little capacitance between the plates. As an object enters the sensing zone, the capacitance increases and similarly to an inductive sensor, a Schmitt trigger responds to this amplitude change and outputs a corresponding signal [18].

Other Ranging Techniques (Tactile Sensors)

What makes this category of sensors different is that these sensors do require actual physical contact in order for them to detect presence of an object in contrast to the previously mentioned sensors that are modelled as noncontact sensors. Tactile sensors are able on contact to measure and identify properties of the object such as shape, size, force and temperature. Two very widely used tactile sensors are the piezoelectric and whisker sensors. Piezoelectric sensors are made of piezoelectric materials that upon being stressed can generate an electric charge. These sensors are popular for their high frequency response time and their voltage generation that is directly proportional to the applied force [9]. However, the fact that a force or in our case a collision is required to detect obstacles is destructive to the platform and can't be considered as a defense mechanism.

As their name infers, whisker sensors are based on the actual whiskers of a cat or a rat. A rat relies on its whiskers to gather information about their surrounding environment. Their whiskers have no sensing capability along their length but at their base are mechanoreceptors that detect deformations to the whisker and hence can identify properties of the object in contact. Artificial robotic whiskers operate in a similar way. Many have adopted whisker sensors to their obstacle detection systems such as in [2], [48]. Others have extended on the application their use of whisker sensors to not only presence detection. [49] proposed the use of steel whiskers fitted with strain gauges to extract information about an object. Their lengthy arms that take the brunt of the impact, protect the platform from the collisions unlike the piezoelectric sensors. However, the surface area of the platform is very big and to provide an all-round full protection will require dozens of these sensors to be connected and will not be an attractive design for the platform.

Another option that can be implemented for this range is a simple limit switch. The design would take the shape of a cage, possibly surrounding the wheels, made up of 4 bars (one for each side of the robot) and they will be connected to multiple limit switches so as to extend the area of initiating the limit switch from any point across one of the 4 bars and thus the platform could have a full round protection. This approach can both take the brunt of the collision force and in design won't look as bad as tactile sensors would.

Range

All sensors measured in this section have ranges that don't extend further than the required close range.

Detection of All Types of Obstacles

The different types of proximity sensors all share a common limitation and that is they fall short to either only detecting a specific type of material as the case is for induction sensors and metallic materials or in general lack uniformity in detecting all types of materials [17].
The piezoelectric, whisker and limit switch sensors are all contact sensors and hence detection of all obstacles is inevitable upon contact.

Protection against Collisions

The proximity sensors will protect the platform when they detect the obstacle.
The piezoelectric as mentioned requires force or a collision to occur in order to detect and thus the platform will be vulnerable to collisions that can damage it.
The whisker sensors and the limit switches can take the brunt of the force along their deforming lengths.

2.4 Discussion

Based on the discussions presented in the previous section, these are sensors chosen for each layer of detection.

- 3D LIDAR for long range.
- Ultrasonic sensor for mid-range.
- Limit switch for close range.

Due to time constraints, only the mid-range layer of detection is chosen for implementation and will be discussed for the rest of this thesis.

3 Design

As previously mentioned the mid-range layer of obstacle detection will be the one implemented in this assignment. The system detects the nearest obstacle to each ultrasonic sensor and sends back haptic feedback to inform the user about the obstacles' localization. An overview of the system can be seen in figure 3.1. In this chapter, the components used in the system are introduced. Then the process of developing the haptic force calculation algorithm is presented. Finally further improvements are made to the algorithm deriving the final version of the algorithm.

3.1 System Components

3.1.1 Ultrasonic Ranging Sensors

After narrowing down the choice to what type of sensor to use in our mid-range layer of obstacle detection, we can now focus on a specific type and view the varied products that that type of sensor technology offers. Some ultrasonic sensors have been documented to be prone to anomalies from time to time. [15] have noted that during their testing with an ultrasonic sensor, the sensor would return odd range readings on occasions while [26] introduced filters to check their ultrasonic sensor's range readings for plausibility. An ultrasonic sensor is said to output an anomaly if it displays a range data that is far from the actual range. Example is when a sensor reads 20 cm range while the closest object to it is 1 meter far. Besides that an incorrect range reading would provide the user with misleading information about obstacle proximity, it will also have an effect when considering the method of notifying the user. The sudden change in haptic force resulting from the false sudden change of sensor reading will cause the user to lose control temporary of the vehicle. Thus ultrasonic sensors with anomalies in their readings should be avoided. [40] reviewed four ultrasonic sensors that are most used in robotics for object ranging and detection. The top two candidates were the Devantech and the LV-MaxSonar ultrasonic sensors. [25] did a comparison with 3 ultrasonic sensors and concluded that the MaxSonar sensor among the three tested was the most accurate and provided stable results when it comes to obstacle detection. MaxSonar can be seen to have a good reputation amongst researchers and hobbyists in obstacle detection applications. Focusing on the MaxSonar; considering what is stated by the manufacturers of this sonar device [23] that a key point in manufacturing this sensor is to provide a sensor that is free from anomalies in range readings. Proving that anomalies are absent, tests were carried out by the manufacturers where a MaxSonar EZ1 and a series of Devantech sensors were used to measure the distance to a pendulum. A figure for the results of the experiment can be seen in A.5 where range readings from each sensor are plotted and unlike all other tested sensors, the EZ1 range readings all follow a smooth sinusoidal path with absence of any unexplainable spikes in readings (anomalies).

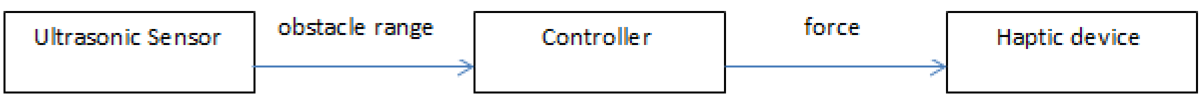


Figure 3.1: Overview of the obstacle detection system.

Therefore for their stable range readings the choice was made for the LV MaxSonar EZ1 to be the ultrasonic sensor of choice operating in the mid-range layer of detection.

3.1.2 Haptic Device

An omega.6 device will be used for controlling the platform while simultaneously providing virtual force feedback impeding the user's control based on the presence of obstacles.
The omega device comes with a haptic SDK interface that offers all basic functions to program desired forces in Cartesian space. The haptic device can feedback up to 12N of force in translation and 8N from its grasper.

3.1.3 Controller

The first function of the controller is to relate the position of the omega to velocity commands to the platform so that the omega could be used as an actuating device to control the platform.

The other purpose of the controller is to calculate the feedback force to be sent to the user through the haptic device. Based on the sensor range readings, the force calculated will be a function of the distance between the platform and an object. One problem with this algorithm is that repulsive forces would always be generated even when the platform is moving away from the obstacle. To counteract that, the algorithm could be extended to include the velocity of the vehicle with respect to an obstacle. The incorporation of the relative velocity prevents force generation when the platform is not moving towards the obstacle.

To calculate the relative velocity of the platform, the velocity of the obstacle detected is required to be known as well as its range from the platform. Ultrasonic sensors don't provide this information unlike for example a radar gun which can through measuring the change in frequency from the echoed transmitted signal. As extra sensors will be needed to measure the velocity of obstacles, an assumption is made for the platform to be operating in a quasi-static environment (obstacles do not move).

Hence the relative velocity will be the absolute velocity of the platform at all times. The velocity of the platform could be measured by one of two ways, either through acquiring the data from the built in encoders on the platform's wheels or integrating the acceleration from an on board IMU. Figure 3.2 show velocity readings taken from the encoders.
Due to the anomalies shown in the encoder measurements which would result in sudden spikes in the force generated, the IMU will be used to measure the velocity of the platform.

Figure 3.3 shows an overview of the updated algorithm.

The haptic force calculated could be presented as such:

$$F = kx + c\frac{\partial x}{\partial t} \tag{3.1}$$

where F is the haptic force, x is the range of the obstacle and k &c are constant values.

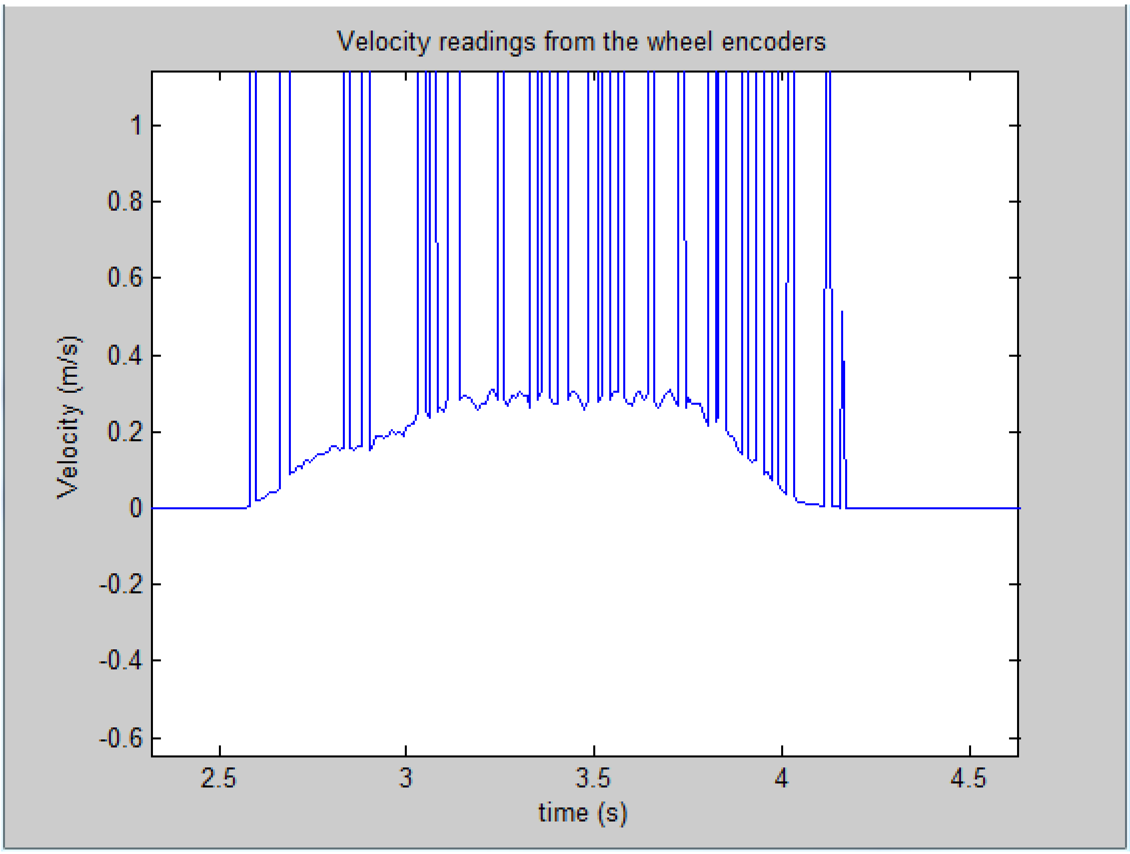


Figure 3.2: Velocity readings from the wheel encoders.

Knowing that the velocity of the platform is equals to the position of the omega device and plugging in to equation 3.1

$$F = \int kx_\omega + cx_\omega \tag{3.2}$$

where x_ω is the x position of the omega device in Cartesian space.

One can see now that the proposed controller acts as a PI controller on the position of the omega, controlling the omega to its neutral position (zero position) in the absence of user input. As previously stated that the position of the omega is equals to the platform velocity, a zero position of the omega results in decelerating the platform to rest.
A visualization of the controlled system could be viewed in figure 3.4:

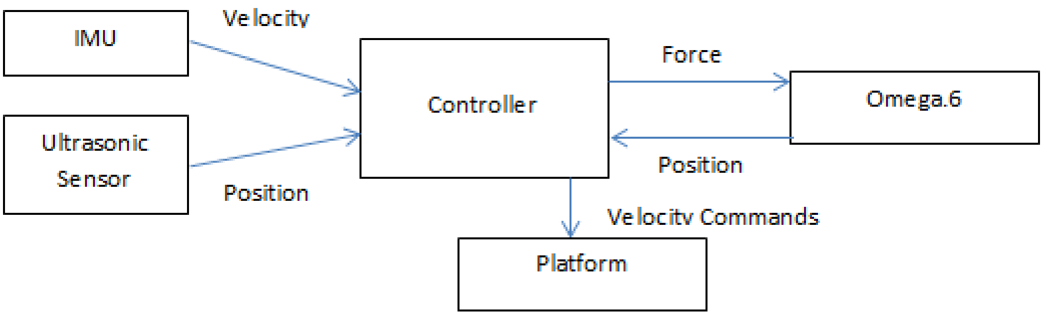


Figure 3.3: Overview of the system with the updated algorithm.

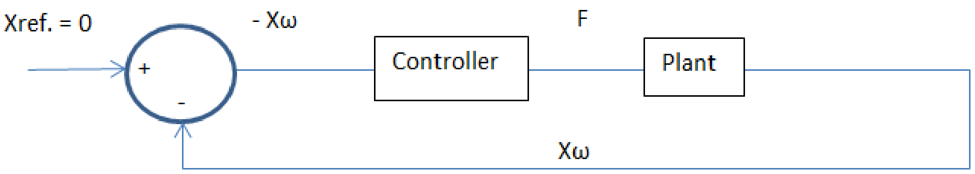


Figure 3.4: PI controller on the omega position.

4 Implementation & System Realization

In this chapter, the implementation method is presented discussing how the different components were realized in the final system.
The two algorithims discussed are the operating of the platform from the haptic device and second sending force feedback to the user, force that varies depending on the sensor data.

Ultrasonic Sensor Mount

To mount the ultrasonic sensor to the frame an ultrasonic sensor holder was designed for 3D printing. The dimensions of the holder are set similar to those of the sensor but with 1 mm clearances to obtain a clearance fit. An M6 hole is included in the design to fasten the holder to an L shaped connector bolted to the platform. Figure 4.1 shows a mounted sensor on the platform.

Middleware (ROS)

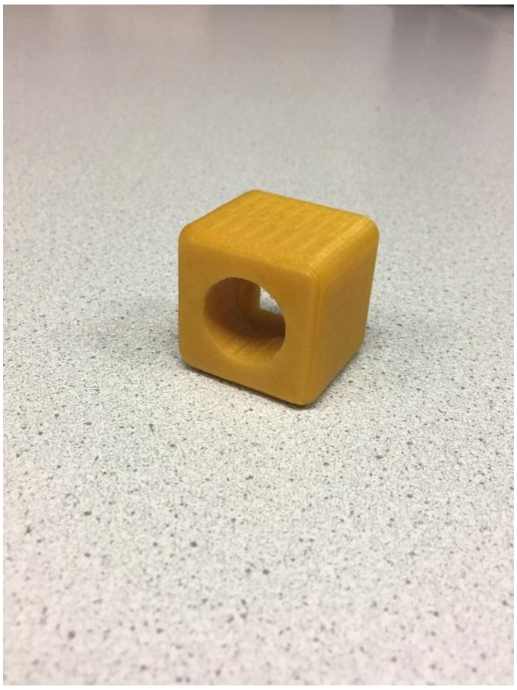
ROS will be the middleware processing all the inputs of the system and outputting the necessary control commands. There are two PCs, a built-in PC which will be referred to as the platform PC. This PC contains the software responsible for the motion of the platform and interfacing the ultrasonic sensors. The second PC is the base PC and on it is the software interfacing the omega. The ROS master will run on the platform PC and the base PC will be connected to this ROS master on the platform PC through a Wi-Fi connection. Delays from the Wi-Fi connection are to be expected and if found to cause problems, connection will be changed to an Ethernet connection.

On the base PC a ROS node will be created to control the motion of the platform with the omega device and to process the sensor readings to calculate the necessary force to be sent to the user through the omega. Sections 4.1 and 4.2 are dedicated to explain the software and algorithms implemented on the ROS node. Figure 4.2 shows the distribution of the different software components between both PCs.

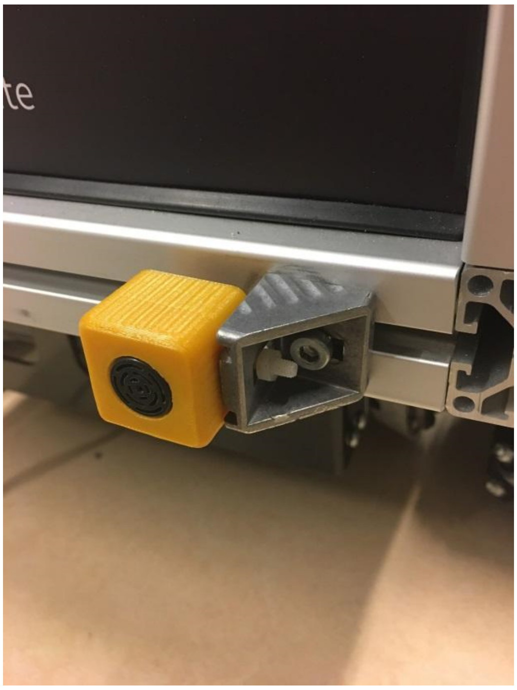
4.1 Controlling the Platform from the omega (Actuation)

The omega's translational workspace is $\phi 160 \times 110$ mm and rotational is $240 \times 140 \times 180°$ in / around the X, Y & Z axes respectively. The omega.6 device will be interfaced through the already available haptic SDK package. To access the inputs the user provides through moving the omega in its workspace, the method *dhdGetPositionAndOrientationRad()* is called which retrieves the position and orientation of the omega in Cartesian coordinates. The omega as an actuation device will be treated as a joystick controller where only the position of the omega in the X and Y directions and rotation in Z are to be considered the inputs for actuation regardless the states of the rest of the inputs.

For the movement of the platform, velocity commands are required to be published to the two nodes responsible for actuating the front and rear axles of the platform. These commands are made up of a twist message which is a 2×3 matrix consisting of linear and angular velocity components in the X, Y & Z directions.



(a) The ultrasonic sensor case.



(b) Sensor inside the case connected to the platform through the connector.

Figure 4.1: Demonstration of the mounting of the ultrasonic sensor.

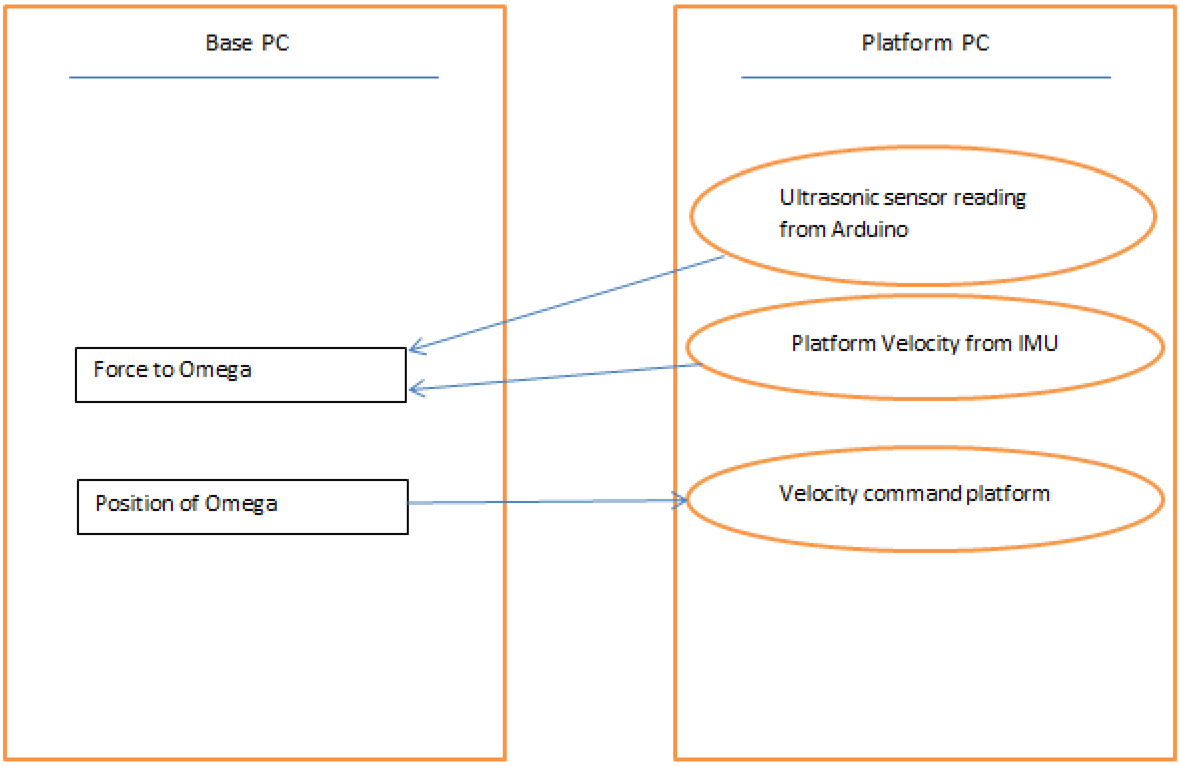


Figure 4.2: Visualization of the different software components in the algorithm.

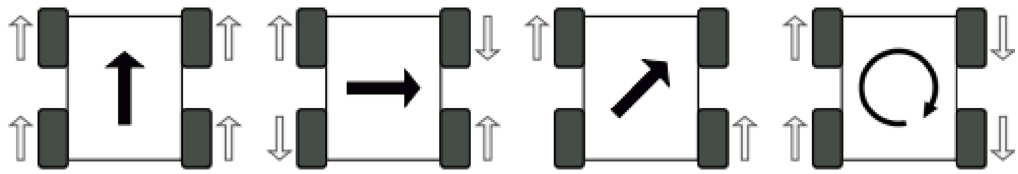


Figure 4.3: Relating different platform motions with wheel rotations.
For a single axle, arrows pointing in the same direction refer to linear command to that axle arrows pointing in the opposite direction to the other refer to an angular command.

As each axle is controlled separately only the linear command in X direction (linear.x) and the angular command in Z direction (angular.z) are used by the platform axles to achieve all types of motion. Figure 4.3 explains how the different motions are achieved.

The node will be used to convert the position of the omega to twist messages and publish them to the two axle nodes to map the position of the omega to velocity commands to the platform. As only forward and sideways motions are considered in the experiment the converting equations will be as follows:

$$\begin{gathered}\text{front.linear.x} = \text{px}\\ \text{front.angular.z} = \text{py}\\ \text{rear.linear.x} = \text{px}\\ \text{rear.angualr.z} = -\ \text{py}\end{gathered}$$

where px and py are the positions of the omega in the X and Y axis respectively.

4.2 Haptic Feedback

Ultrasonic Sensor Interface

The ultrasonic sensors will be interfaced through an Arduino UNO board to process the range data from the sensors. The sensor's interface output formats include pulse width output, analog voltage and RS232 serial output and the PWM method was the method used. The pin responsible for outputting the PWM output outputs the range reading through a pulse width where the distance could be calculated using the scale factor of 147us per inch. A single range reading takes 49ms. Each range cycle starts by the RX pin being either set high or left unconnected, after which the sensor sends the transmit wave and then the pulse width pin is set high and is pulled low once a target is detected.

The Arduino board is connected to the platform PC and publishes each range reading to a topic called ultrasound.

Velocity of the Platform

The platform velocity is calculated on a pre-existing node that subscribes to the data published by the onboard IMU and from it calculates the velocity of the platform and publishes the data to the topic /platform velocity.

Programming the Force to the Omega

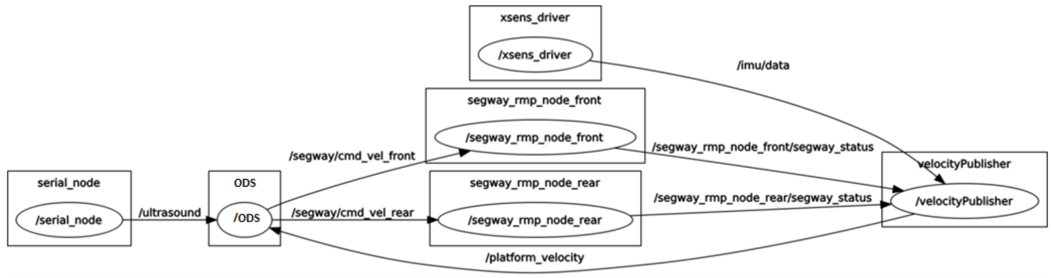


Figure 4.4: ROS rqt graph of the nodes and topics of the final algorithm.

The main base PC node subscribes to the /ultrasound and /platform velocity topics and calculates the Force which is programmed to the omega. To set a force through the arms of the omega the method *dhdsetForce()* is used which sets the desired force vector in Cartesian coordinates.

Figure 4.4 shows the final version of the algorithm implemented on ROS with the help of an rqt graph demonstrating how the different ROS topics communicate with one another.

5 Evaluation & Testing and Results

5.1 Assessing the Range Readings from an Ultrasonic Sensor

A quantitative assessment of the ultrasonic range readings while in motion on the platform was to be designed.

Test Setup

For such an assessment an OptiTrack optical motion capture system is used. This system relies on reflective markers that can be tracked by an array of cameras. The markers could be tracked down to a fraction of millimeter movements with repeatable accuracy [34].

The tracker and the ultrasonic sensor were placed in front of the platform and the platform was driven heading towards an obstacle with the sensor and the tracker facing towards the obstacle.

The data from the OptiTrack and the sensor are recorded to a .bag file for later plotting.

Results

The position from the OptiTrack system is measured with respect to a fixed reference position and to relate it to obstacle ranging data, the reference was changed to the obstacle.

Figure 5.1 show the plots for the range readings from the ultrasonic sensor and the OptiTrack system respectively and their difference throughout the experiment plotted in figure 5.2.

From figure 5.1 it can be seen that the range from the ultrasonic sensor is decrementing in a step wise fashion unlike the more linear decay from the OptiTrack system. This can be accredited to the relatively slow sampling rate of the sensor. From figure 5.2 the difference in range readings throughout the experiment is plotted, the mean range error from the ultrasonic sensor is found to be 0.0051 m. with a maximum error of 0.017 m.

The test carried out proved the accuracy and reliability of the sensor's readings while in motion however the slow sampling rate of the ultrasonic sensor ranging had an influence on the shape of the force but had no felt effect from the real force actually felt during navigation.

5.2 Haptic Force Feedback Evaluation

5.2.1 Design of Experiment 1, Navigating the Platform while Simultaneously Receiving Haptic Feedback

The working of the force calculation algorithm is to be verified during navigation in an environment. Throughout the motion of the platform the algorithm should calculate force values linearly proportional to obstacle proximity and the velocity of the platform.

Test Setup

As an experiment a single sensor was mounted to the platform and the platform velocity commands only limited to values that corresponds to motion towards an obstacle along a path that is perpendicular to the sensor surface. To outline the effect both the proximity and

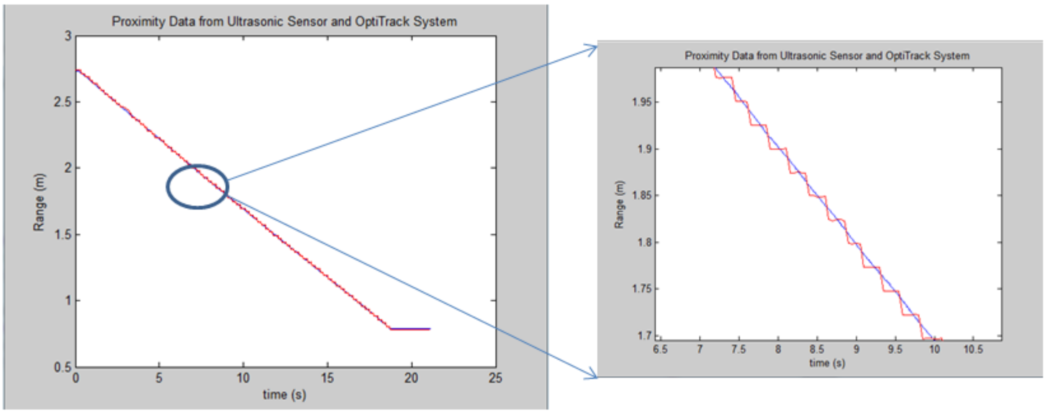


Figure 5.1: Range readings from Ultrasonic Sensor (red) and OptiTrack system (blue).

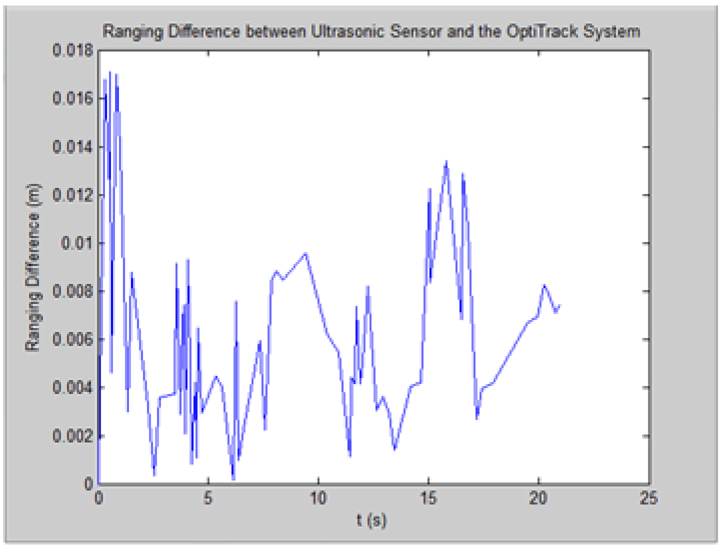


Figure 5.2: Difference in range readings between the ultrasonic sensor (red) and the OptiTrack system (blue).

Figure 5.3: Demonstration of the experiment setup.

velocity separately had on the force feedback, the platform was operated at a constant velocity throughout the experiment and the experiment was conducted twice with two different velocities of 0.1 and 0.7 m/s.

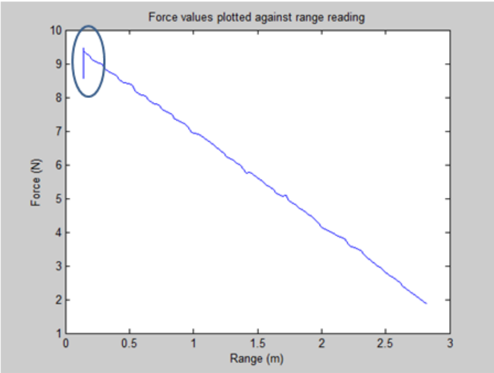
The algorithm was tested by recording the force data throughout the experiment from the running ROS system to a .bag file to be later played back for extraction and plotting by MATLAB. Demonstration of the experiment setup could be seen in figure 5.3.

Figure 5.4 shows the data plots from the experiment discussed. Both force plots show linear rise in value with time. The force plot from the experiment carried out at higher velocity shows a steeper gradient and a higher peak force value than the other experiment with a slower velocity.

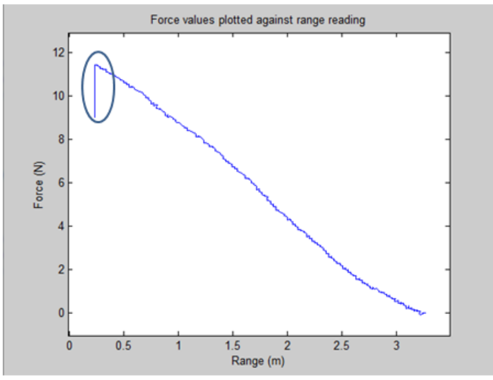
The circle in figures 5.4a and 5.4b show how the force drops as the platform decelerates to zero. Note that the force doesn't drop completely but drops to a lower value than when the platform was in motion. This is especially helpful if the user was to operate the platform in the same direction, the user wouldn't feel a sudden spike in the force sensed.

5.2.2 Design of Experiment 2, Survey

Second the haptic feedback was to be qualitatively assessed as well. The level of intuitiveness and dependency that the addition of the haptic feedback provides along with how the user interprets the feedback signals is to be tested.



(a) Data recorded with platform velocity of 0.1 m/s.



(b) Data recorded with platform velocity of 0.7 m/s.

Figure 5.4: Force values plotted against range readings

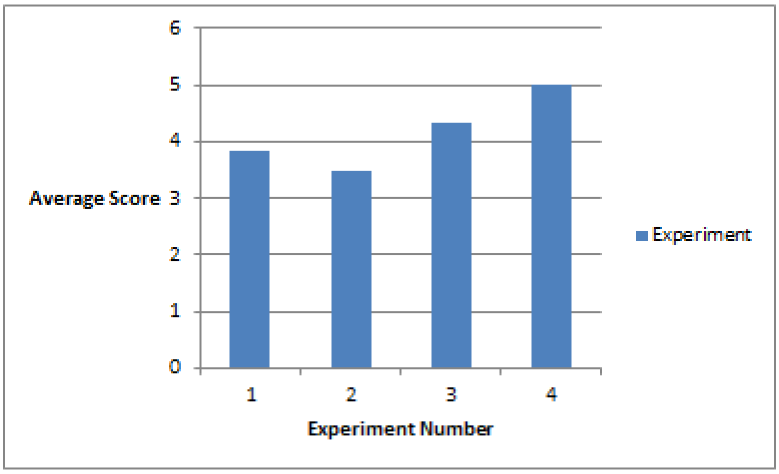


Figure 5.5: Average score for each experiment from the first part of the questionnaire.
Follow up question to experiment 4 score is calculated on the basis of a score of 5 being equivalent to a correct answer from all 6 participants.
Experiment 1: How much does the haptic feedback influence the user to stop? (1-5)
Experiment 2: How much does the speed of operation influence the intensity of the feedback? (1-5)
Experiment 3: How much was the user able to notice differences between the different proximity ranges? (1-5)
Experiment 4: Determining which range the obstacle was in? (1-5)

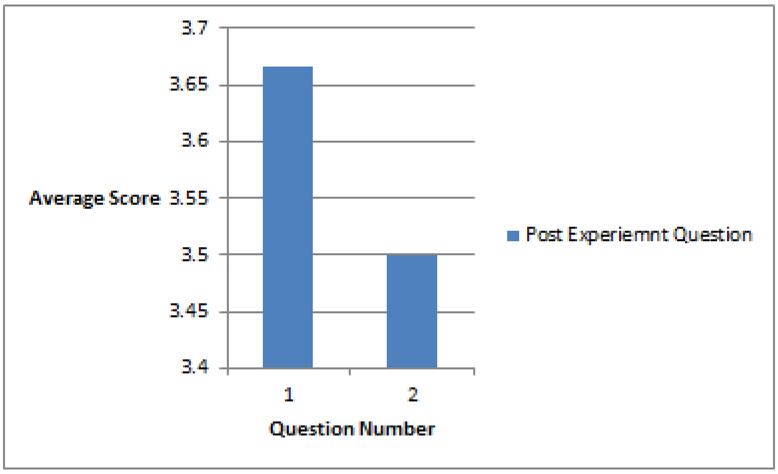


Figure 5.6: Average score for the post experiments questions.
Question 1: How much environment awareness does this system provide? (1-5)
Question 2: If this system is extended to have feedback in a multi-dimensional orientation, how much would this system add to the teleoperation experience? (1-5)

Test Setup

Six test subjects were asked to take part in a series of tests. First they were asked to operate the platform through the omega as a basic familiarity step as it is different on an instinctive level than for example a joystick might be. At the same time the test subjects were operating in the absence of any haptic feedback to set the base line for comparisons with when the haptic feedback is in effect. Then four experiments were carried out with follow up questions as listed below.

Experiment 1: First test subjects were asked to operate the platform in a one dimensional motion heading towards an obstacle, with the platform being out of sight from them to further test the dependency of the haptic feedback. They were asked to stop when they felt it was necessary to from the haptic feedback they felt.
Follow up question: How much does the haptic feedback influence you to stop? (1-5)

Experiment 2: Then they were asked to repeat the earlier experiment but with different speed of operation to grade how much the velocity component affect the feedback.
Follow up question: How much does the speed of operation influence the intensity of the feedback? (1-5)

Experiment 3: An obstacle was placed at 3 equally spaced proximity ranges consecutively from the platform to assess whether the force feedback offers interpretation of the environment to the user.
Follow up question: How much were you able to notice differences between the different proximity ranges? (1-5)

Experiment 4: The obstacle was placed in one of the three aforementioned sub-ranges randomly to further assess the awareness offered from the haptic feedback.
Follow up question: Were you able to tell which range the obstacle is in? (1-5)

Post experiments assessment question were asked to the test subjects.

Question 1) How much environment awareness does this system provide? (1-5)

Question 2) If this system is extended to have feedback in a multi-dimensional orientation, how much would this system add to the teleoperation experience? (1-5)

Result

The results of the first part of the questionnaire are shown in table 1. The average score for the first three experiments are calculated while the score of the fourth question is calculated based on how many answered correctly with 6 correct answers being equivalent to a score of 5. The results are plotted in figure 5.5.

Based on user feedback some observations could be made. Results of the first question show that the basic level of haptic feedback is present that allow the user to interpret an impending collision. The variation in the velocity component didn't influence the haptic force much to be picked up on by some of the test subjects from the second experiment. From experiment 3 it can be seen that range could be approximately interpreted through the intensity of the feedback and hence add to the situational awareness of the user, further backed by the results in experiment 4.

The results of the second part of the questionnaire are plotted in figure 5.6. When asked about how enhanced environment awareness is from the haptic feedback in the first question, an average score of 3.67 was garnered. As for the influence haptic feedback has on tele operation the average score was 3.5 but with half the subjects stating that if a critical region is entered a step or a sudden rise in force would be safer to have when operating rather than the force continuing the ordinary linear growth.

6 Conclusion & Future Recommendations

6.1 Conclusion

Tests with the range readings from the ultrasonic sensor while in motion concluded the accuracy and reliability of the sensor's readings while however the slow sampling rate could result in disturbance in the force if faster platform velocities or faster sampling rates are required to be met.

The setup of a single sensor along with the 1 dimensional movement of the platform was a demonstration for how obstacle proximity and collision threat could be mapped to force feedback.

The user study proved that the haptic feedback had a potential if extended in to multiple sensors covering the entire platform surroundings, to enhance the tele operation experience and create situational awareness for the user.

6.2 Future Recommendations

From the experiments, multiple users stated a drop in the interpretation of the force especially at the closer regions to the obstacle. This can be reasoned to how the force algorithm was calculated as a linear function.
To counteract that, force computation could be based on calculating the time required to decelerate the platform before colliding with the obstacle. The force function then would have an exponential characteristic rather than a linear one. Hence if experiment one is to be tested again with the same conditions, the force output will start with a very small value to a point that it is partially indistinguishable by the user and then after a certain period the force value would elevate exponentially in a very intuitive way that informs the user that the platform has entered a critical region and is very close to an obstacle.

As stated the experiments were done with a single ranging device with the platform operating in a one dimensional orientation. For completion of the obstacle detection system, multiple ultrasonic sensors are required, surrounding the platform to allow full range of motion to the platform (forward, sideways & rotation). For each sensor reading a force will be calculated based on the algorithm discussed. Multiple virtual force values in two dimensions will be the result. A resolution of the multiple forces are to be calculated in to a single vector in the X-Y plane and programmed to the haptic device.

A Appendix 1

A.1 LV-MaxSonar-EZ Datasheet

LV-MaxSonar®-EZ™ Series

High Performance Sonar Range Finder

MB1000, MB1010, MB1020, MB1030, MB1040

With 2.5V - 5.5V power the LV-MaxSonar-EZ provides very short to long-range detection and ranging in a very small package. The LV-MaxSonar-EZ detects objects from 0-inches to 254-inches (6.45-meters) and provides sonar range information from 6-inches out to 254-inches with 1-inch resolution. Objects from 0-inches to 6-inches typically range as 6-inches[1]. The interface output formats included are pulse width output, analog voltage output, and RS232 serial output. Factory calibration and testing is completed with a flat object. [1]***See Close Range Operation***

Features

- Continuously variable gain for control and side lobe suppression
- Object detection to zero range objects
- 2.5V to 5.5V supply with 2mA typical current draw
- Readings can occur up to every 50mS, (20-Hz rate)
- Free run operation can continually measure and output range information
- Triggered operation provides the range reading as desired
- Interfaces are active simultaneously
- Serial, 0 to Vcc, 9600 Baud, 81N
- Analog, (Vcc/512) / inch
- Pulse width, (147uS/inch)
- Learns ringdown pattern when commanded to start ranging
- Designed for protected indoor environments
- Sensor operates at 42KHz
- High output square wave sensor drive (double Vcc)

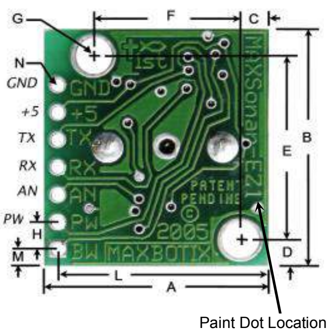
Benefits

- Very low cost ultrasonic rangefinder
- Reliable and stable range data
- Quality beam characteristics
- Mounting holes provided on the circuit board
- Very low power ranger, excellent for multiple sensor or battery-based systems
- Fast measurement cycles
- Sensor reports the range reading directly and frees up user processor
- Choose one of three sensor outputs
- Triggered externally or internally

Applications and Uses

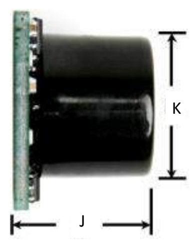
- UAV blimps, micro planes and some helicopters
- Bin level measurement
- Proximity zone detection
- People detection
- Robot ranging sensor
- Autonomous navigation
- Multi-sensor arrays
- Distance measuring
- Long range object detection
- Wide beam sensitivity

LV-MaxSonar-EZ Mechanical Dimensions



A	0.785"	19.9 mm	H	0.100"	2.54 mm
B	0.870"	22.1 mm	J	0.610"	15.5 mm
C	0.100"	2.54 mm	K	0.645"	16.4 mm
D	0.100"	2.54 mm	L	0.735"	18.7 mm
E	0.670"	17.0 mm	M	0.065"	1.7 mm
F	0.510"	12.6 mm	N	0.038" dia.	1.0 mm dia.
G	0.124" dia.	3.1 mm dia.	weight, 4.3 grams		

Part Number	MB1000	MB1010	MB1020	MB1030	MB1040
Paint Dot Color	Black	Brown	Red	Orange	Yellow



Close Range Operation

Applications requiring 100% reading-to-reading reliability should not use MaxSonar sensors at a distance closer than 6 inches. Although most users find MaxSonar sensors to work reliably from 0 to 6 inches for detecting objects in many applications, MaxBotix® Inc. does not guarantee operational reliability for objects closer than the minimum reported distance. Because of ultrasonic physics, these sensors are unable to achieve 100% reliability at close distances.

Warning: Personal Safety Applications

We do not recommend or endorse this product be used as a component in any personal safety applications. This product is not designed, intended or authorized for such use. These sensors and controls do not include the self-checking redundant circuitry needed for such use. Such unauthorized use may create a failure of the MaxBotix® Inc. product which may result in personal injury or death. MaxBotix® Inc. will not be held liable for unauthorized use of this component.

About Ultrasonic Sensors

Our ultrasonic sensors are in air, non-contact object detection and ranging sensors that detect objects within an area. These sensors are not affected by the color or other visual characteristics of the detected object. Ultrasonic sensors use high frequency sound to detect and localize objects in a variety of environments. Ultrasonic sensors measure the time of flight for sound that has been transmitted to and reflected back from nearby objects. Based upon the time of flight, the sensor then outputs a range reading.

Pin Out Description

Pin 1-BW-*Leave open or hold low for serial output on the TX output. When BW pin is held high the TX output sends a pulse (instead of serial data), suitable for low noise chaining.

Pin 2-PW- This pin outputs a pulse width representation of range. The distance can be calculated using the scale factor of 147uS per inch.

Pin 3-AN- Outputs analog voltage with a scaling factor of (Vcc/512) per inch. A supply of 5V yields ~9.8mV/in. and 3.3V yields ~6.4mV/in. The output is buffered and corresponds to the most recent range data.

Pin 4-RX– This pin is internally pulled high. The LV-MaxSonar-EZ will continually measure range and output if RX data is left unconnected or held high. If held low the sensor will stop ranging. Bring high for 20uS or more to command a range reading.

Pin 5-TX- When the *BW is open or held low, the TX output delivers asynchronous serial with an RS232 format, except voltages are 0-Vcc. The output is an ASCII capital "R", followed by three ASCII character digits representing the range in inches up to a maximum of 255, followed by a carriage return (ASCII 13). The baud rate is 9600, 8 bits, no parity, with one stop bit. Although the voltage of 0-Vcc is outside the RS232 standard, most RS232 devices have sufficient margin to read 0-Vcc serial data. If standard voltage level RS232 is desired, invert, and connect an RS232 converter such as a MAX232. When BW pin is held high the TX output sends a single pulse, suitable for low noise chaining. (no serial data)

Pin 6-+5V- Vcc – Operates on 2.5V - 5.5V. Recommended current capability of 3mA for 5V, and 2mA for 3V.

Pin 7-GND- Return for the DC power supply. GND (& Vcc) must be ripple and noise free for best operation.

Range "0" Location

The LV-MaxSonar-EZ reports the range to distant targets starting from the front of the sensor as shown in the diagram below.

Range Zero

The range is measured from the front of the transducer.

In general, the LV-MaxSonar-EZ will report the range to the leading edge of the closest detectable object. Target detection has been characterized in the sensor beam patterns.

Sensor Minimum Distance

The sensor minimum reported distance is 6-inches (15.2 cm). However, the LV-MaxSonar-EZ will range and report targets to the front sensor face. Large targets closer than 6-inches will typically range as 6-inches.

Sensor Operation from 6-inches to 20-inches

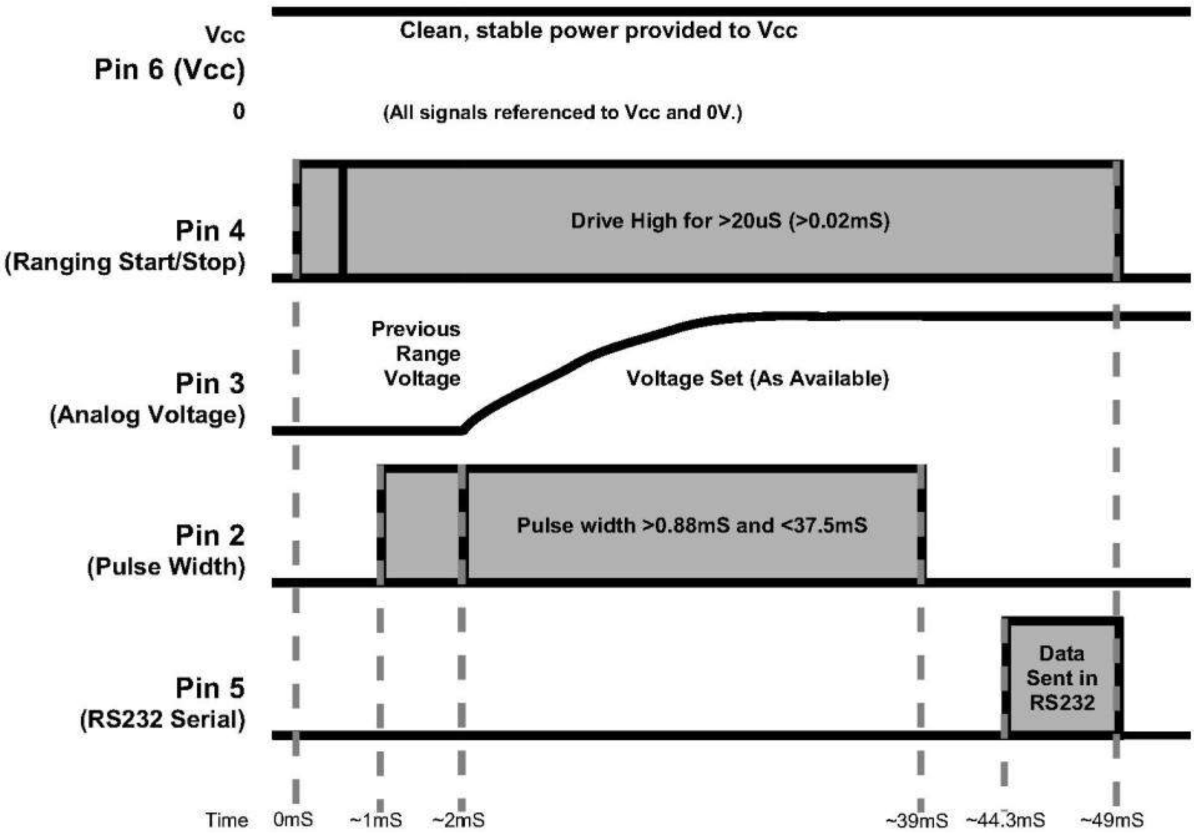
Because of acoustic phase effects in the near field, objects between 6-inches and 20-inches may experience acoustic phase cancellation of the returning waveform resulting in inaccuracies of up to 2-inches. These effects become less prevalent as the target distance increases, and has not been observed past 20-inches.

General Power-Up Instruction

Each time the LV-MaxSonar-EZ is powered up, it will calibrate during its first read cycle. The sensor uses this stored information to range a close object. It is important that objects not be close to the sensor during this calibration cycle. The best sensitivity is obtained when the detection area is clear for fourteen inches, but good results are common when clear for at least seven inches. If an object is too close during the calibration cycle, the sensor may ignore objects at that distance.

The LV-MaxSonar-EZ does not use the calibration data to temperature compensate for range, but instead to compensate for the sensor ringdown pattern. If the temperature, humidity, or applied voltage changes during operation, the sensor may require recalibration to reacquire the ringdown pattern. Unless recalibrated, if the temperature increases, the sensor is more likely to have false close readings. If the temperature decreases, the sensor is more likely to have reduced up close sensitivity. To recalibrate the LV-MaxSonar-EZ, cycle power, then command a read cycle.

Timing Diagram



Timing Description

250mS after power-up, the LV-MaxSonar-EZ is ready to accept the RX command. If the RX pin is left open or held high, the sensor will first run a calibration cycle (49mS), and then it will take a range reading (49mS). After the power up delay, the first reading will take an additional ~100mS. Subsequent readings will take 49mS. The LV-MaxSonar-EZ checks the RX pin at the end of every cycle. Range data can be acquired once every 49mS.

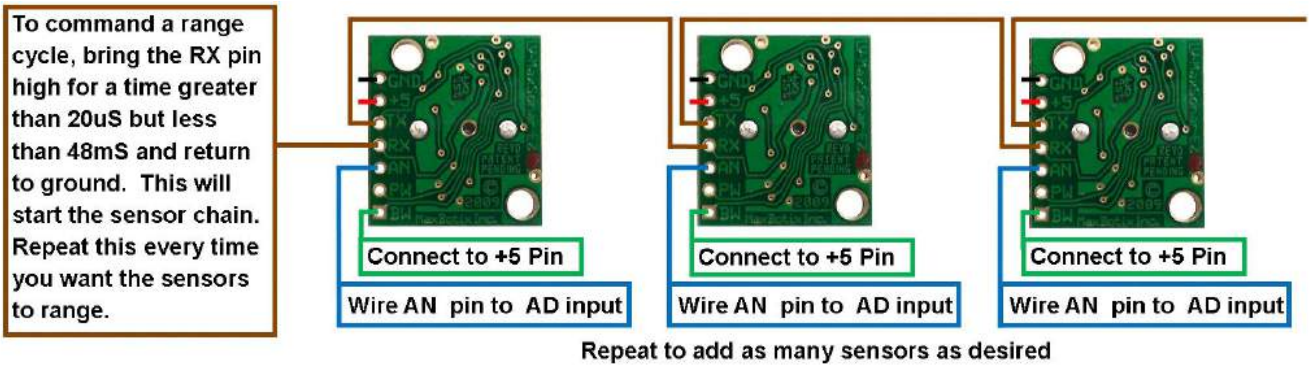
Each 49mS period starts by the RX being high or open, after which the LV-MaxSonar-EZ sends the transmit burst, after which the pulse width pin (PW) is set high. When a target is detected the PW pin is pulled low. The PW pin is high for up to 37.5mS if no target is detected. The remainder of the 49mS time (less 4.7mS) is spent adjusting the analog voltage to the correct level. When a long distance is measured immediately after a short distance reading, the analog voltage may not reach the exact level within one read cycle. During the last 4.7mS, the serial data is sent.

The LV-MaxSonar-EZ timing is factory calibrated to one percent at five volts, and in use is better than two percent. In addition, operation at 3.3V typically causes the objects range, to be reported, one to two percent further than actual.

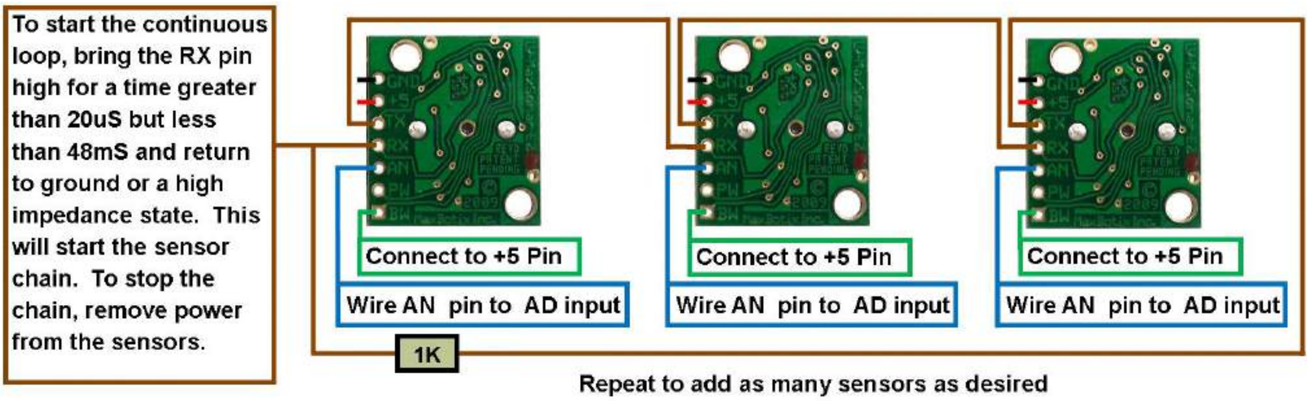
Using Multiple Sensors in a single system

When using multiple ultrasonic sensors in a single system, there can be interference (cross-talk) from the other sensors. MaxBotix Inc., has engineered and supplied a solution to this problem for the LV-MaxSonar-EZ sensors. The solution is referred to as chaining. We have 3 methods of chaining that work well to avoid the issue of cross-talk.

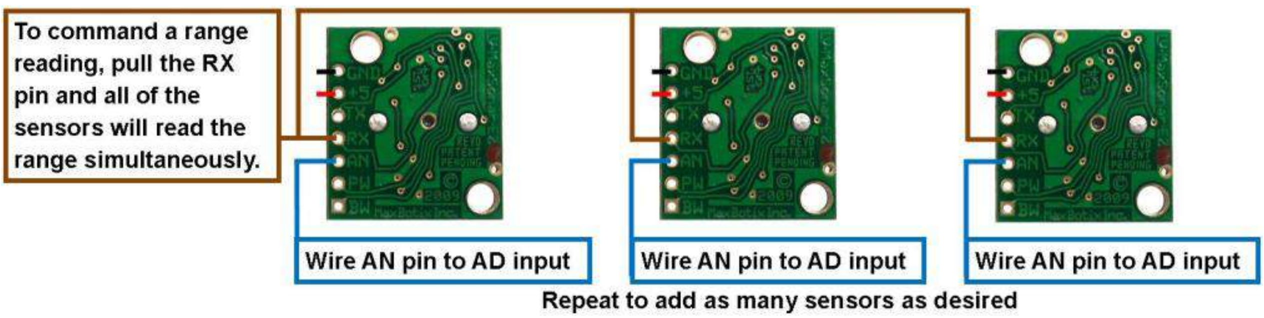
The first method is AN Output Commanded Loop. The first sensor will range, then trigger the next sensor to range and so on for all the sensor in the array. Once the last sensor has ranged, the array stops until the first sensor is triggered to range again. Below is a diagram on how to set this up.



The next method is AN Output Constantly Looping. The first sensor will range, then trigger the next sensor to range and so on for all the sensor in the array. Once the last sensor has ranged, it will trigger the first sensor in the array to range again and will continue this loop indefinitely. Below is a diagram on how to set this up.



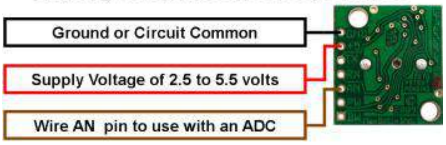
The final method is AN Output Simultaneous Operation. This method does not work in all applications and is sensitive to how the other sensors in the array are positioned in comparison to each other. Testing is recommend to verify this method will work for your application. All the sensors RX pins are conned together and triggered at the same time causing all the sensor to take a range reading at the same time. Once the range reading is complete, the sensors stop ranging until triggered next time. Below is a diagram on how to set this up.



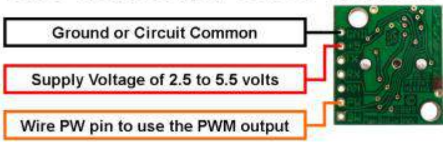
Independent Sensor Operation

The LV-MaxSonar-EZ sensors have the capability to operate independently when the user desires. When using the LV-MaxSonar-EZ sensors in single or independent sensor operation, it is easiest to allow the sensor to free-run. Free-run is the default mode of operation for all of the MaxBotix Inc., sensors. The LV-MaxSonar-EZ sensors have three separate outputs that update the range data simultaneously: Analog Voltage, Pulse Width, and RS232 Serial. Below are diagrams on how to connect the sensor for each of the three outputs when operating in a single or independent sensor operating environment.

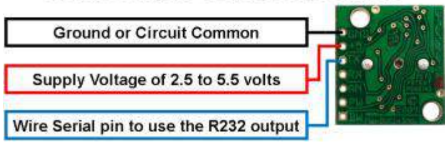
Analog Output Sensor Operation



Pulse Width Output Sensor Operation



Serial Output Sensor Operation



Selecting an LV-MaxSonar-EZ

Different applications require different sensors. The LV-MaxSonar-EZ product line offers varied sensitivity to allow you to select the best sensor to meet your needs.

The LV-MaxSonar-EZ Sensors At a Glance

People Detection Wide Beam High Sensitivity		Best Balance		Large Targets Narrow Beam Noise Tolerance
MB1000	MB1010	MB1020	MB1030	MB1040

The diagram above shows how each product balances sensitivity and noise tolerance. This does not effect the maximum range, pin outputs, or other operations of the sensor. To view how each sensor will function to different sized targets reference the LV-MaxSonar-EZ Beam Patterns.

Background Information Regarding our Beam Patterns

Each LV-MaxSonar-EZ sensor has a calibrated beam pattern. Each sensor is matched to provide the approximate detection pattern shown in this datasheet. This allows end users to select the part number that matches their given sensing application. Each part number has a consistent field of detection so additional units of the same part number will have similar beam patterns. The beam plots are provided to help identify an estimated detection zone for an application based on the acoustic properties of a target versus the plotted beam patterns.

Each beam pattern is a 2D representation of the detection area of the sensor. The beam pattern is actually shaped like a 3D cone (having the same detection pattern both vertically and horizontally). Detection patterns for dowels are used to show the beam pattern of each sensor. Dowels are long cylindered targets of a given diameter. The dowels provide consistent target detection characteristics for a given size target which allows easy comparison of one MaxSonar sensor to another MaxSonar sensor.

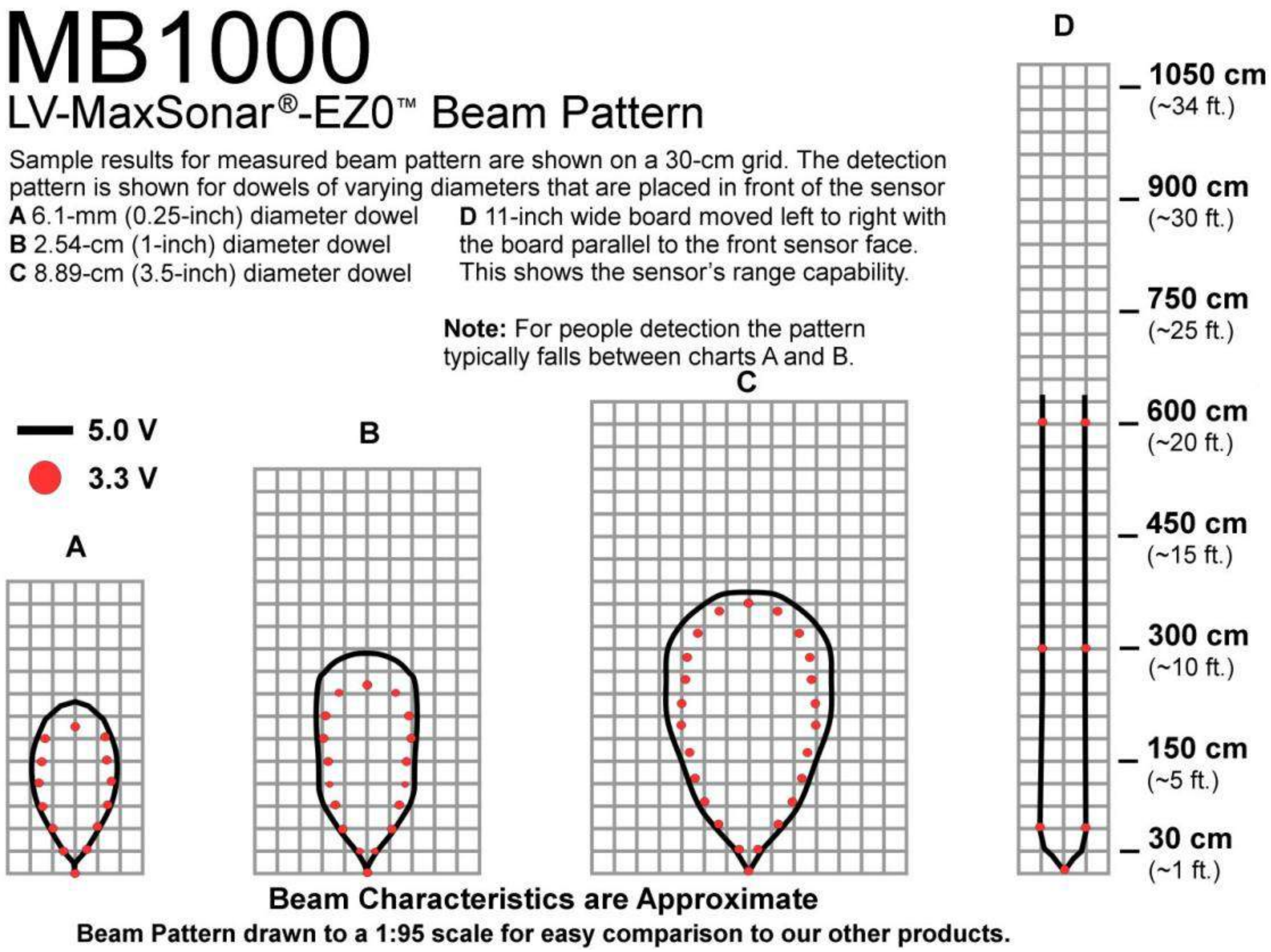
People Sensing: For users that desire to detect people, the detection area to the 1-inch diameter dowel, in general, represents the area that the sensor will reliably detect people.

For each part number, the four patterns (A, B, C, and D) represent the detection zone for a given target size. Each beam pattern shown is determined by the sensor's part number and target size.

The actual beam angle changes over the full range. Use the beam pattern for a specific target at any given distance to calculate the beam angle for that target at the specific distance. Generally, smaller targets are detected over a narrower beam angle and a shorter distance. Larger targets are detected over a wider beam angle and a longer range.

MB1000 LV-MaxSonar-EZ0

The LV-MaxSonar-EZ0 is the highest sensitivity and widest beam sensor of the LV-MaxSonar-EZ sensor series. The wide beam makes this sensor ideal for a variety of applications including people detection, autonomous navigation, and wide beam applications.



MB1000 Features and Benefits

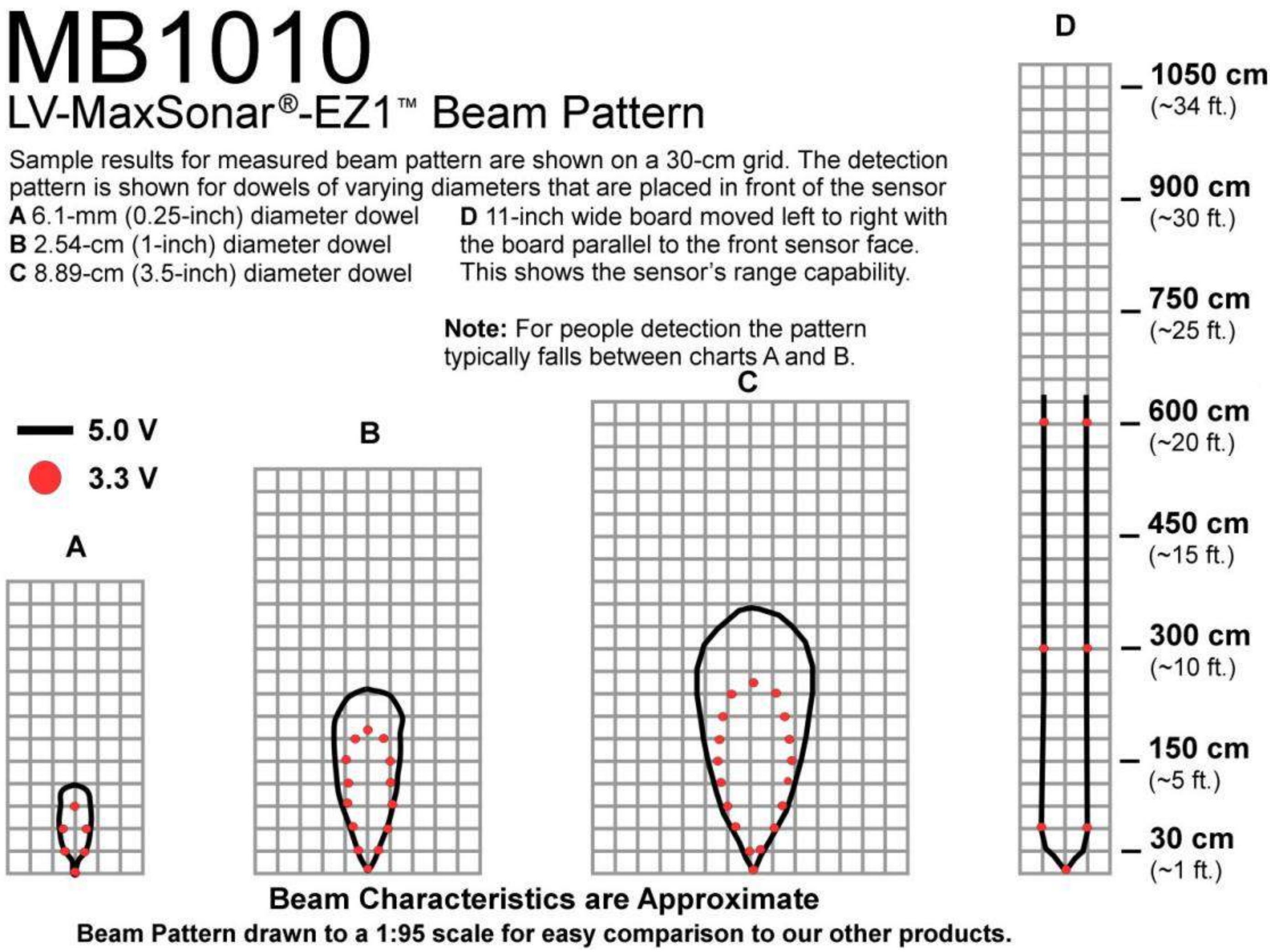
- Widest and most sensitive beam pattern in LV-MaxSonar-EZ line
- Low power consumption
- Easy to use interface
- Will pick up the most noise clutter when compared to other sensors in the LV-MaxSonar-EZ line
- Detects smaller objects
- Best sensor to detect soft object in LV-MaxSonar-EZ line
- Requires use of less sensors to cover a given area
- Can be powered by many different types of power sources
- Can detect people up to approximately 10 feet

MB1000 Applications and Uses

- Great for people detection
- Security
- Motion detection
- Used with battery power
- Autonomous navigation
- Educational and hobby robotics
- Collision avoidance

MB1010 LV-MaxSonar-EZ1

The LV-MaxSonar-EZ1 is the original MaxSonar product. This is our most popular indoor ultrasonic sensor and is a great low-cost general-purpose sensor for a customer not sure of which LV-MaxSonar-EZ sensor to use.



MB1010 Features and Benefits

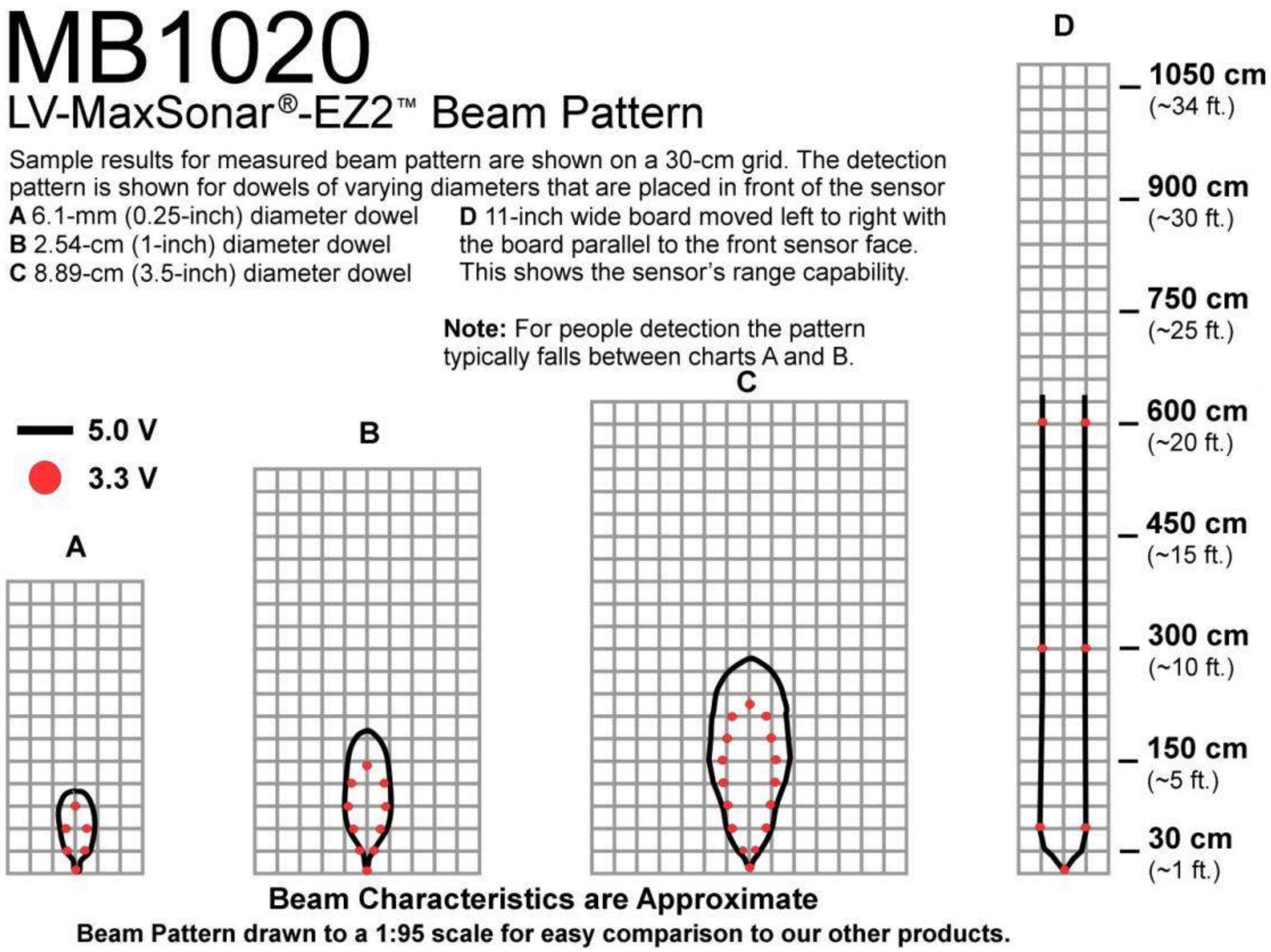
- Most popular ultrasonic sensor
- Low power consumption
- Easy to use interface
- Can detect people to 8 feet
- Great balance between sensitivity and object rejection
- Can be powered by many different types of power sources

MB1010 Applications and Uses

- Great for people detection
- Security
- Motion detection
- Used with battery power
- Autonomous navigation
- Educational and hobby robotics
- Collision avoidance

MB1020 LV-MaxSonar-EZ2

The LV-MaxSonar-EZ2 is a good compromise between sensitivity and side object rejection. The LV-MaxSonar-EZ2 is an excellent choice for applications that require slightly less side object detection and sensitivity than the MB1010 LV-MaxSonar-EZ1.



MB1020 Features and Benefits

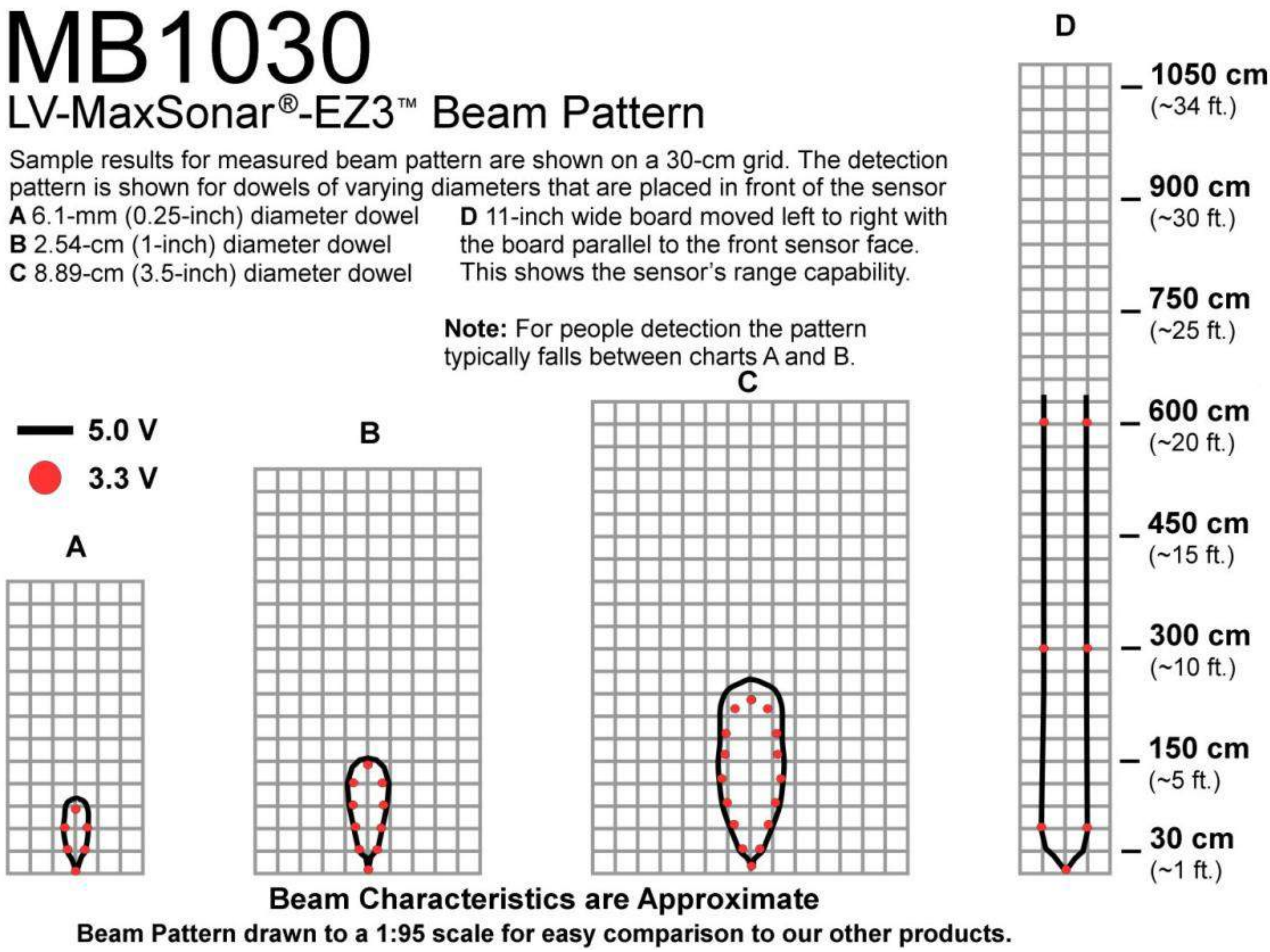
- Great for applications where the MB1010 is too sensitive.
- Excellent side object rejection
- Can be powered by many different types of power sources
- Can detect people up to approximately 6 feet

MB1020 Applications and Uses

- Landing flying objects
- Used with battery power
- Autonomous navigation
- Educational and hobby robotics
- Large object detection

MB1030 LV-MaxSonar-EZ3

The LV-MaxSonar-EZ3 is a narrow beam sensor with good side object rejection. The LV-MaxSonar-EZ3 has slightly wider beam width than theMB1040 LV-MaxSonar-EZ4 which makes it a good choice for when the LV-MaxSonar-EZ4 does not have enough sensitivity for the application.



MB1030 Features and Benefits

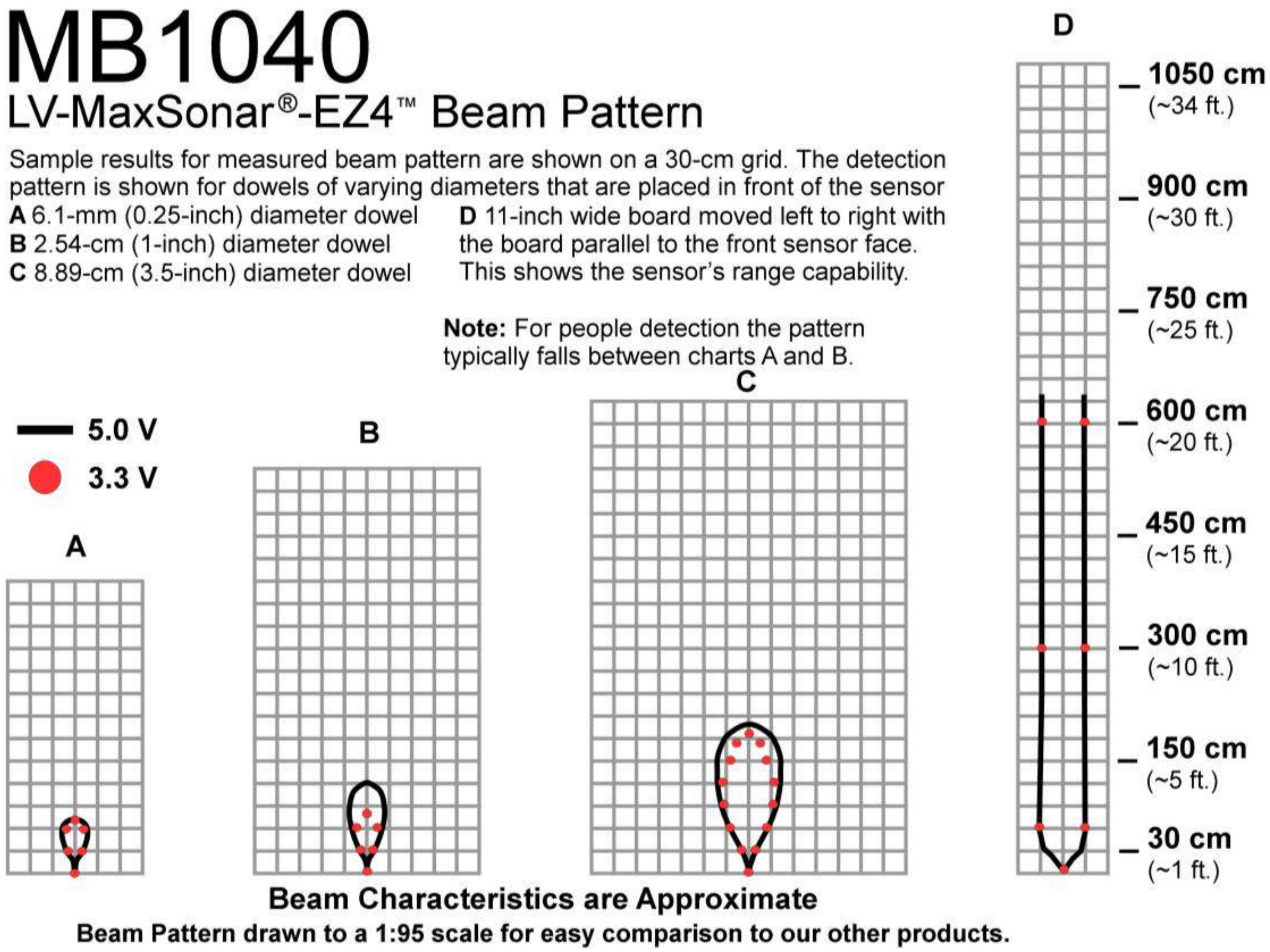
- Excellent side object rejection
- Low power consumption
- Easy to use interface
- Great for when MB1040 is not sensitive enough
- Large object detection
- Can be powered by many different types of power sources
- Can detect people up to approximately 5 feet

MB1030 Applications and Uses

- Landing flying objects
- Used with battery power
- Autonomous navigation
- Educational and hobby robotics

MB1040 LV-MaxSonar-EZ4

The LV-MaxSonar-EZ4 is the narrowest beam width sensor that is also the least sensitive to side objects offered in the LV-MaxSonar-EZ sensor line. The LV-MaxSonar-EZ4 is an excellent choice when only larger objects need to be detected.



MB1040 Features and Benefits

- Best side object rejection in the LV-MaxSonar-EZ sensor line
- Low power consumption
- Easy to use interface
- Best for large object detection
- Can be powered by many different types of power sources
- Can detect people up to approximately 4 feet

MB1040 Applications and Uses

- Landing flying objects
- Used with battery power
- Autonomous navigation
- Educational and hobby robotics
- Collision avoidance

Have the right sensor for your application?
Select from this product list for Protected and Non-Protected Environments.

Protected Environments

1 mm Resolution
HRLV-MaxSonar-EZ

1 in Resolution
LV-MaxSonar-EZ
LV-ProxSonar-EZ

1 cm Resolution
XL-MaxSonar-EZ
XL-MaxSonar-AE
XL-MaxSonar-EZL
XL-MaxSonar-AEL

1 mm Resolution
HRUSB-MaxSonar-EZ

1 in Resolution
USB-ProxSonar-EZ

Non-Protected Environments

1 mm Resolution
HRXL-MaxSonar-WR
HRXL-MaxSonar-WRS
HRXL-MaxSonar-WRT
HRXL-MaxSonar-WRM
HRXL-MaxSonar-WRMT
HRXL-MaxSonar-WRL
HRXL-MaxSonar-WRLT
HRXL-MaxSonar-WRLS
HRXL-MaxSonar-WRLST
SCXL-MaxSonar-WR
SCXL-MaxSonar-WRS
SCXL-MaxSonar-WRT
SCXL-MaxSonar-WRM
SCXL-MaxSonar-WRMT
SCXL-MaxSonar-WRL
SCXL-MaxSonar-WRLT
SCXL-MaxSonar-WRLS
SCXL-MaxSonar-WRLST
4-20HR-MaxSonar-WR

1 cm Resolution
XL-MaxSonar-WR
XL-MaxSonar-WRL
XL-MaxSonar-WRA
XL-MaxSonar-WRLA
I2CXL-MaxSonar-WR

1 mm Resolution
HRXL-MaxSonar-WRC
HRXL-MaxSonar-WRCT

1 cm Resolution
XL-MaxSonar-WRC
XL-MaxSonar-WRCA
I2CXL-MaxSonar-WRC

1 cm Resolution
UCXL-MaxSonar-WR
UCXL-MaxSonar-WRC
I2C-UCXL-MaxSonar-WR

Chemical Shield

F-Option. Available for WR models except UCXL. For additional protection when necessary in hazardous chemical environments.

Accessories — More information is online.

MB7954 — Shielded Cable

The MaxSonar Connection Wire is used to reduce interference caused by electrical noise on the lines. This cable is a great solution to use when running the sensors at a long distance or in an area with a lot of EMI and electrical noise.

MB7950 — XL-MaxSonar-WR Mounting Hardware

The MB7950 Mounting Hardware is selected for use with our outdoor ultrasonic sensors. The mounting hardware includes a steel lock nut and two O-ring (Buna-N and Neoprene) each optimal for different applications.

MB7955 / MB7956 / MB7957 / MB7958 / MB7972 — HR-MaxTemp

The HR-MaxTemp is an optional accessory for the HR-MaxSonar. The HR-MaxTemp connects to the HR-MaxSonar for automatic temperature compensation without self heating.

MB7961 — Power Supply Filter

The power supply filter is recommended for applications with unclean power or electrical noise.

MB7962 / MB7963 / MB7964 / MB7965 — Micro-B USB Connection Cable

The MB7962, MB7963, MB7964 and MB7965 Micro-B USB cables are USB 2.0 compliant and backwards compatible with USB 1.0 standards. Varying lengths.

MB7973 — CE Lightning/Surge Protector

The MB7973 adds protection required to meet the Lightning/Surge IEC61000-4-5 specification.

A.2 Ultrasonic Arduino-ROS Interface

```
/*
   rosserial Ultrasound Example

   This example is for the Maxbotix Ultrasound rangers.
*/

#include <ros.h>
#include <ros/time.h>
#include <geometry_msgs/Twist.h>
//#include <sensor_msgs/Range.h>


#include <stdio.h>
#include <stdlib.h>

//#include <std_msgs/MultiArrayLayout.h>
//#include <std_msgs/MultiArrayDimension.h>

//#include <std_msgs/Float32MultiArray.h>


ros::NodeHandle  nh;

//sensor_msgs::Range range_msg;
//ros::Publisher pub_range( "/ultrasound", &range_msg);

//std_msgs::Float32MultiArray range_msg;
//ros::Publisher pub_range( "/ultrasound", &range_msg);
//std_msgs::Float32MultiArray range_msg;
//ros::Publisher pub_range( "/ultrasound", &range_msg);

geometry_msgs::Twist range_msg;
ros::Publisher pub_range( "/ultrasound", &range_msg);

float pulse1, pulse2, pulse3, pulse4, pulse5, pulse6;
float s1, s2, s3, s4, s5, s6;



void read_sensor() {


  pulse1 = pulseIn(5, HIGH);
  s1 = (pulse1 / 147 ) * 2.54;
  range_msg.linear.x = s1;

 /*
  pulse2 = pulseIn(6, HIGH);
  s2 = (pulse2 / 147 ) * 2.54;
  range_msg.linear.y = s2;


  pulse3 = pulseIn(6, HIGH);
  s3 = (pulse3 / 147 ) * 2.54;

  pulse3 = pulseIn(6, HIGH);
  s3 = (pulse3 / 147 ) * 2.54;
  range_msg.linear.z = s3;

  pulse4 = pulseIn(9, HIGH);
  s4 = (pulse4 / 147 ) * 2.54;
  range_msg.angular.x = s4;

  pulse5 = pulseIn(10, HIGH);
  s5 = (pulse5 / 147 ) * 2.54;
  range_msg.angular.y = s5;

  pulse6 = pulseIn(11, HIGH);
  s6 = (pulse6 / 147 ) * 2.54;
  range_msg.angular.z = s6;*/
}

void setup()
{
  nh.initNode();
  nh.advertise(pub_range);

  pinMode(3, INPUT);
  pinMode(5, INPUT);
  pinMode(6, INPUT);
  pinMode(9, INPUT);
  pinMode(10, INPUT);
void setup()
{
  nh.initNode();
  nh.advertise(pub_range);

  pinMode(3, INPUT);
  pinMode(5, INPUT);
  pinMode(6, INPUT);
  pinMode(9, INPUT);
  pinMode(10, INPUT);
  pinMode(11, INPUT);


}



void loop()
{
  read_sensor();
  pub_range.publish(&range_msg);
  nh.spinOnce();
}


}
```

A.3 Force Algorithm

```cpp
#include "ros/ros.h"
#include <stdlib.h>
#include <stdio.h>
#include <iostream>
#include <string>

#include <geometry_msgs/Twist.h>
#include <geometry_msgs/Vector3.h>
#include <std_msgs/Float64.h>

#include <pthread.h>
#include "drdc.h"
#include "dhdc.h"
#include "CMaths.h"
#include "CMacrosGL.h"



#include "sensor_msgs/Range.h"


#include <math.h>
#include <cmath>
#include <vector>

#include "sensor_msgs/Imu.h"
#include<tf/LinearMath/Matrix3x3.h>
#include<tf/LinearMath/Matrix3x3.h>
#include<tf/LinearMath/Quaternion.h>
#include "segway_rmp/SegwayStatusStamped.h"



sensor_msgs::Range usRange;

geometry_msgs::Twist actualPose;

geometry_msgs::Twist frontOutput;
geometry_msgs::Twist rearOutput;

geometry_msgs::Vector3 setForce;



double sensor1;
//For the addition of extra sensor readings
//double sensor2;
//double sensor3;
//double sensor4;
//double sensor5;
//double sensor6;



double px, py, pz;  // omega position in Cartesian space
double velX, velY; //velY for calculating the velocity sideways when the system is to be extended
bool b;
```

```
bool b;


void sensorCallback1(const geometry_msgs::Twist::ConstPtr& us) {
  //save the received message from sensor 1
  double s1 = us->linear.x;
  sensor1Old = sensor1;
  sensor1 = s1 / 100;

}



void velocityCallBack(const geometry_msgs::Vector3::ConstPtr& msg)
{
  //save the received velocity messages
  velX = msg->x;
  velY = msg->y;


}




int compute_my_forces (double sensor1, double sensor2, double sensor3, double sensor4, double sensor5,double sensor6, double *fx, double *fy)

{

int compute_my_forces (double sensor1, double sensor2, double sensor3, double sensor4, double sensor5,double sensor6, double *fx, double *fy)

{

if(sensor1 < 3.25) {
*fx = ( (3.25 - sensor1) * 3) + ( -velX * 3 );

if(*fx > 12)
*fx = 12;
}
else{
  *fx = 0.0;
}



 return 0;

}



int main(int argc, char **argv){


double fx, fy;//force in the X and Y plane

ros::init(argc, argv, "ods");
  ros::NodeHandle n;


  ros::Publisher frontPlatformCommand =
      n.advertise<geometry_msgs::Twist>("segway/cmd_vel_front", 1);
  ros::Publisher rearPlatformCommand =
      n.advertise<geometry_msgs::Twist>("segway/cmd_vel_rear", 1);




  ros::Subscriber sensorFeedback1 =
     n.subscribe<geometry_msgs::Twist>("/ultrasound", 1, sensorCallback1);

 ros::Subscriber velocityFeedback =
     n.subscribe<geometry_msgs::Vector3>("/platform_velocity", 1, velocityCallBack);






  ros::Rate loop_rate(10);
```

```
ros::Rate loop_rate(10);



dhdEnableExpertMode ();

if (drdOpen () < 0) {
  printf ("error: cannot open device (%s)\n", dhdErrorGetLastStr ());
  dhdSleep (2.0);
  return -1;
}
if (!drdIsSupported())
{
  printf ("unsupported device\n");
  printf ("exiting...\n");
  dhdSleep (2.0);
  drdClose ();
  return -1;
}
if (!drdIsInitialized () && drdAutoInit () < 0) {
  printf ("error: auto-initialization failed (%s)\n", dhdErrorGetLastStr ());
  dhdSleep (2.0);
  return -1;
}
else if (drdStart () < 0) {
  printf ("error: regulation thread failed to start (%s)\n", dhdErrorGetLastStr ());
  dhdSleep (2.0);
  dhdSleep (2.0);
 return -1;
 }



 drdMoveToPos(0.07, 0.0, 0.0);

 drdStop(true);




while (ros::ok()) {



dhdGetPosition (&px, &py, &pz); // read omega position in Cartesian space


if(dhdGetButton(0)) <<only operate the platform if the button (dead-man trigger) is pressed
{


 frontOutput.linear.x = 10* (px - 0.07);
 frontOutput.angular.z = 0.0;
```

```
  rearOutput.linear.x = 10* (px - 0.07);
  rearOutput.angular.z = 0.0;


}
else
{

 frontOutput.linear.x = 0.0 ;
  frontOutput.angular.z = 0.0;

  rearOutput.linear.x = 0.0;
  rearOutput.angular.z = 0.0;


}

//publishing velocity commands
frontPlatformCommand.publish(frontOutput);
rearPlatformCommand.publish(rearOutput);




//programming force to the omega
compute_my_forces (sensor1, sensor2, sensor3, sensor4, sensor5, sensor6, &fx, &fy);
dhdSetForceAndTorqueAndGripperForce (fx,  0.0,  0.0,
                                     0.0, 0.0, 0.0,
                                     0.0);
```

```
                //programming force to the omega
                compute_my_forces (sensor1, sensor2, sensor3, sensor4, sensor5, sensor6, &fx, &fy);
                dhdSetForceAndTorqueAndGripperForce (fx,  0.0,  0.0,
                                                     0.0, 0.0, 0.0,
                                                     0.0);




                ros::spinOnce();
                loop_rate.sleep();

                }


                dhdClose ();
                return 0;







                }
```

A.4 Survey Questionnaire Example

Test name

Name: ______________________________

Date: ______________________________

Survey Purpose

An obstacle detection system has been designed and implemented on a tele operated platform to detect obstacles and notify the operator of obstacles through haptic feedback.

The haptic feedback is designed to be proportional to proximity of the obstacle and the velocity of the platform. (The closer the obstacle and the faster the platform is, the higher the intensity of the force).

This survey is done to scale the level of intuitiveness and dependency of the haptic feedback from the view point of an operator.

Quick Summary of the survey

As the platform is considered to be a tele operated platform, we will have you operate the platform remotely with the platform being out of sight.

You will be guided to operate the platform in a specific direction and heading in a straight line towards an obstacle.
This will be done with different scenarios.

Pay close attention to the haptic force you feel while operating and we will have you answer a few questions based on your experience during navigation.

Basic Familiarity Step

You will navigate the platform in the pre specified direction but without any haptic feedback during the course of navigation.

Experiment 1

Now you will navigate but with the haptic feedback on.
Keep navigating until you feel it is necessary to stop to avoid colliding with the obstacle.

- Question: How much does the haptic feedback influence you to stop?

Poor	Good			Excellent
1	2	3	4	5

Comments ____

Experiment 2

Repeat experiment 1 but with a different speed

- Question: How much does the speed of operation influence the intensity of the feedback?

Poor	Good			Excellent
1	2	3	4	5

Comments ____

Experiment 3

We will place obstacles at 3 equally spaced proximity ranges from the platform

- Question: Were you able to notice differences between the different proximity ranges?

Poor	Good			Excellent
1	2	3	4	5

Comments ____

Experiment 4

We will place an obstacle in one of the three aforementioned sub-ranges.

- Question: Were you able to tell which range the obstacle is in?

Closest		Furthest
1	2	3

Comments ____

Extra Questions

- Question: How much environment awareness does this system provide?

Poor	Good			Excellent
1	2	3	4	5

Comments ____

- Question: If this system is extended to have feedback in a multi-dimensional orientation, how much would this system add to the teleoperation experience?

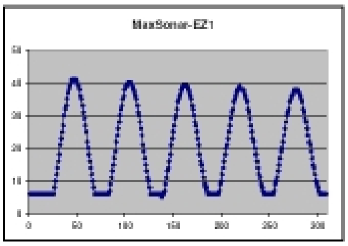
Poor	Good			Excellent
1	2	3	4	5

Comments ____

A.5 Pendulum Test Results

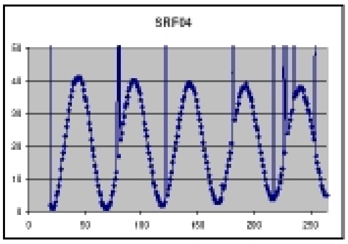
Pendulum Test Results for the LV-MaxSonar®-EZ1™

(and the original MaxSonar-EZ1, and some other selected competing sensors)



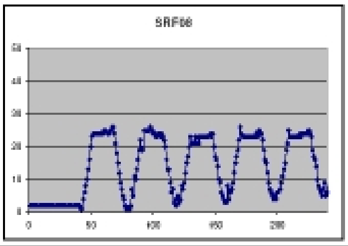
MaxSonar®-EZ1™ (by MaxBotix® Inc.)

- When the ball is pressing against the MaxSonar®-EZ1™, all readings report 6”. (The LV- MaxSonar®-EZ1™ performance is identical.)
- No ranging anomalies occur. (One up close reading correctly reports 5” instead of the nominal 6” minimum distance.)
- This plot is typical. We warrantee this result. In addition, all EZ1™ sensors shipping after 1/1/2007 have this parameter 100% verified.



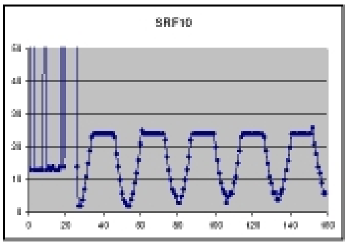
SRF04 (by Devantech Ltd.)

- When the ball is pressing against the SRF04 the sensor does not detect the ball. (Very slight gap allows the ball to be detected.)
- A few random ranging anomalies occur. And some readings appear to not detect the ball, but instead range a more distant object or report maximum range.



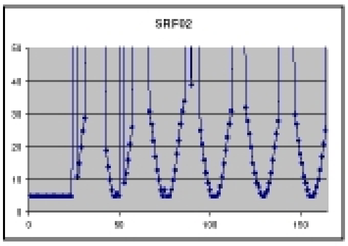
SRF08 (by Devantech Ltd.)

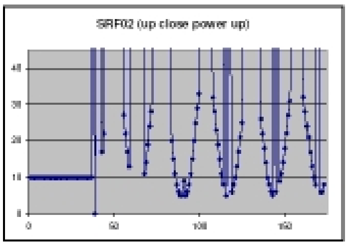
- When the ball is pressing against the SRF08, the sensor reports a continuous low range (3”). (Slight gap allows closer readings.)
- A few random ranging anomalies occur with incorrect estimates of about 2” to 4”.
- Above 24” only the berber carpet on the floor is detected. (The wide beam width of the sensor detects the carpet.)



SRF10 (by Devantech Ltd.)

- When the ball is pressing against the SRF10, the sensor reports 12” (i.e. the distance to the carpet on the *floor) and also has interment maximum range readings. (Slight gap allows closer readings.)
- Ranging anomalies appear to occur up close.
- Above 24” only the berber carpet on the floor is detected. (The wide beam width of the sensor detects the carpet. The SRF10 detects some floors and most walls for over 180°.)





SRF02 (by Devantech Ltd.)

- When the ball is pressing against the SRF02, the sensor reports 5” or 10”. In addition, although not shown here, sometimes the SRF02 reports 0”, but sometimes 0” is reported when the sensor does not detect an object (i.e. when in a large open space).
- Many random ranging anomalies occur. Up close, sometimes the SRF02 does not detect the ball. Past 30”, in general, it does not detect the ball. (but the SRF02 will, in general, detect the ball, if stationary).
- Two plots are shown because of the “AutoTune” feature.
  - The top plot shows the results with the sensor turned on before the ball is pressing against the sensor.
  - The bottom plot shows the results with the sensor turned on with the ball pressing against the sensor.
  - The SRF02 appears to perform better when powered up without an object close to the sensor.
- Not sure what “best in class performance” means or what parameter(s) apply.

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Figure A.1

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