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2007-01-1103

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Reprinted From: IVI Technology and Intelligent Transportation Systems (SP-2099)

ISBN 0-7680-1633-9

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2007 World Congress
Detroit, Michigan
April 16-19, 2007

SAE International™

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ISSN 0148-7191

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Printed in USA

2007-01-1103

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ABSTRACT

The performance of a parking system is dependent on many factors. One is the placement of the sensors. In this paper a system which uses ultrasonic ranging sensors is considered. The mounting of a ultrasonic sensor on a passenger vehicle is restricted by, among other factors, design, assembly process, enclosure cost and reliability. All of which must be considered when choosing optimal mounting locations.

The basis of this work includes a ray-trace based simulation environment which is used to capture the physical properties of sound traveling through air. The simulation environment together with sensor models, is used to evaluate the effect of different mounting positions on the accuracy of the detection of the parking space. The Hough transform is used here, as well as in the real system, in order to extract the confining lines of the parking space from the sensor measurements. The strength of these lines are then used to compare different sensor mounting locations.

The created simulation environment differs from other work in this area since it tries to capture the *physical* properties of the sound waves as opposed to the geometric-only approach. The emitted sound pulse is divided into a large number of rays, each with sound properties tied to them. These rays are then traced through a model of the parking space environment, reflections are calculated and finally the summarized echo into the listening sensor is calculated.

The simulation is implemented in 3D Studio MAX which make it relatively easy to create various realistic parking scenarios. An important factor for choosing 3D Studio MAX as the basis of the simulation environment was that it allowed for a new way of modeling ultrasonics using ray-tracing, and at the same time – using the same ray-tracing technology – excellent visualization capabilities.

Figure 1: Visualization generated from the simulation environment during simulation of a parking maneuver.

BACKGROUND

As described in [7] an automatic parking system has been developed by the Division of Mechanical Engineering, division of Fluid and Mechanical Engineering systems, at Linköping university in cooperation with Volvo Car Corporation. The system developed uses ultrasonic range sensing to estimate the position and size of a parking space in which it can park.

The placement of the sensors on the body of the car is crucial for the performance of the system. The sensors must be able to correctly identify all obstacles to prevent parking related damage and accidents. The sensor placement is further restricted to the design and materials of the body of the car.

To be able to evaluate different sensor mounting locations in terms of the performance of the final system, a simulation environment had to be developed. The presented simulation is based on physical properties of sound traversing through air and is implemented in 3D Studio MAX. The chosen environment has the added ben-

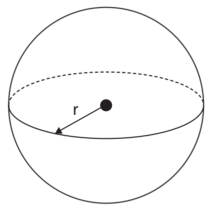

Figure 2: Expansion of a three-dimensional wave.

efit of "free" visualizations, as seen in Figure 1.

THEORETICAL OVERVIEW

The basis of the simulation model that was developed is the *physical* properties of sound traveling through air and reflecting on various surfaces. This section will try to give a brief overview of theses properties.

THE PHYSICS OF SOUND

The definition of a wave, according to [1], is a disturbance within some medium. This disturbance propagates with a medium dependent velocity, is often periodic, and transfers energy from its source to its destination.

There are two basic types of waves, transverse and longitudinal, which are distinguished by the direction of the wave oscillation relative to the direction of the wave propagation. In a transverse wave, each point in the medium moves in a sinusoidal pattern perpendicularly to the direction of the wave, as it propagates through the medium. In a longitudinal wave however, the motion of each point in the medium is in the same direction as the wave propagation.

The power of the an acoustic field is often expressed in terms of intensity. The definition of acoustic intensity is the rate of flow of acoustical energy through a unit area around the point of interest. This imaginary area is always oriented perpendicularly to the direction of wave motion. The intensity is expressed in watts per square meter (Wm^{-2}) and can be written as

$$I = \frac{p_0 u_0}{2} = \frac{u_0^2 \rho c}{2} = \frac{p_0^2}{2\rho c} \tag{1}$$

where p_0 is the acoustic pressure amplitude, and u_0 is the particle velocity amplitude [2].

Many kinds of sound sources produce diverging spherical waves in which the acoustical energy spreads over an increasingly larger area as the sound travels away from the source. This means that the sound intensity, as well as the acoustic pressure amplitude will decrease over distance. For a spherical point source, the acoustic intensity will decrease with the square of the distance from the source as

$$I = \frac{W}{4\pi r^2} \tag{2}$$

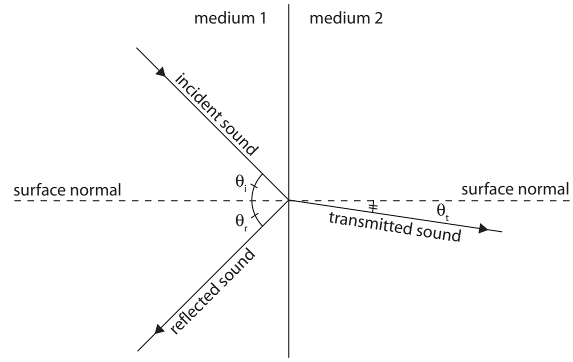

Figure 3: The reflection and refraction of a sound wave incident on a material boundary between medium 1 and medium 2 (Reproduced from [1])

due to the increasing area of the sphere, where W is the acoustic power of the source and r is the radius to the point of interest, [5]. See Figure 2.

When a sound wave traveling in medium 1 encounters a boundary of medium 2, some of the sound is reflected from the boundary back into medium 1, and some is transmitted into medium 2, according to [1] (see figure 3). How this occurs is dependent on the nature of the two medias. Within the scope of this work the case when medium 1 is a gas (air) and medium 2 is a solid (the obstacle we are trying to detect) is the relevant case, and it will be described in the following paragraphs.

According to [1], sound waves are reflected from a surface with the reflection angle equal to the incident angle of the wave, with respect to the surface normal as

$$\theta_r = \theta_i \tag{3}$$

The amount of sound reflected from the surface is dependent of the properties of the two medias [6]. The sound power reflection coefficient, α_r, describes the ratio of sound energy that is reflected to medium 1. If the reflection occurs at the surface of a solid, α_r can be calculated as

$$\alpha_r = \frac{I_r}{I_i} = \frac{\mathbf{z}_n - \rho_1 c_1}{\mathbf{z}_n + \rho_1 c_1} \tag{4}$$

where $\mathbf{z}_n$ is the normal specific acoustic impedance of medium 2 (the solid) [6]. If the solid body is stiff enough not to behave as a membrane and start vibrating when the sound hits the surface, $\mathbf{z}_n$ can be substituted with the characteristic impedance $\rho_2 c_2$ of the solid.

ULTRASONICS RANGE SENSING

An ultrasonic range measurement sensor is a SONAR[1] system, which measures distance by transmitting a sound pulse and listening for the returning echo. By measuring the time from the transmission of the sound pulse until the echo returns, the distance to the object which produced the echo can be calculated if the speed of sound is known

[1] Sound Navigation and Ranging

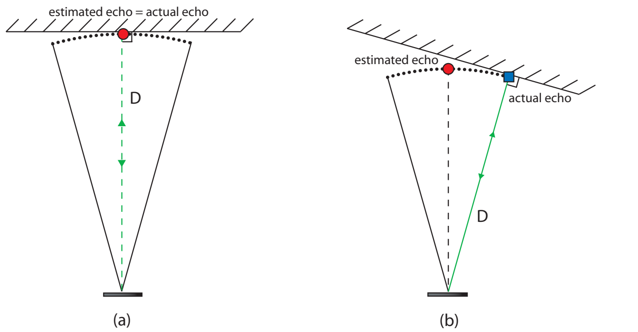

Figure 4: Estimation of sensor echo using a method where the estimated echo is placed perpendicularly in front of the sensor.

in the medium. The time between transmitting and receiving the sound is called the time of flight, or TOF, and the distance to an object is calculated as

$$D = \frac{TOF \cdot c}{2} \tag{5}$$

where c is the speed of sound. The reason for dividing the distance with two, is because the sound travels from the sensor to the object and back again, double the measured distance.

Ultrasonic range measurement gives a very accurate reading of the distance from the sensor to an object. One of the most significant drawbacks of ultrasonic range measurement is that, since the sound diverges in a conical beam from the sensor, the measured distance can lie anywhere on a spherical segment defined by the sensors beam angle and the distance to the echo, as in figure 4. There is no way of deciding exactly from where on this segment the echo actually comes.

The sensor will always measure the distance to the closest object perpendicular to a wavefront in the beam pattern, compare figure 4 (a) and (b). Since the exact position of an echo is not known, an estimation has to be made, and there are some different methods for this that are practiced in different applications. The most straight forward solution is to place the position of the echo perpendicularly in front of the sensor. This method produces an error of estimation as soon as the echo does not come from a wavefront directly in front of the sensor, at $\theta = 0$ in the beam, as in figure 4 (a). As soon as the echo comes from a wavefront at $\theta \neq 0$ in the beam, there will be an error of estimation, as in figure 4 (b).

An ultrasonic sensor emitting a pulse can be seen as a cylindrical piston source where the emitted intensity (or pressure amplitude) varies with the polar angle of the beam. This variation is described in the beam pattern, see Figure 5.

The beam pattern will depend on several characteristics of the sensor. Mainly the radius of the sensor and the emitted frequency. For a constant operating frequency, the beam angle of the sensor will be inversely proportional

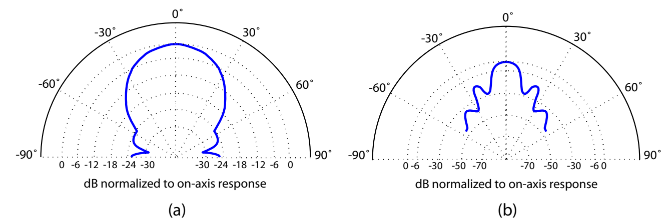

Figure 5: Beam patterns for two different sensors with (a) $a = 6.5\ mm$, $f = 40\ kHz$ and (b) $a = 20\ mm$, $f = 50\ kHz$ is shown.

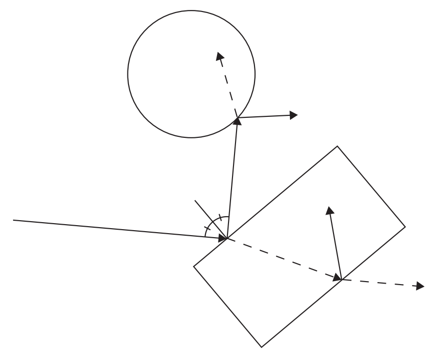

Figure 6: Ray tracing for a ray with both multiple reflections and transmissions. Reflection rays are illustrated as solid lines, and transmission rays as dashed lines.

to the sensor radius [6]. In figure 5 beam patterns for two different sensors with different diameters and operating frequencies is shown.

RAY TRACING

Ray Tracing is a method of creating photo realistic rendered images. It emulates phenomenas as lighting and shadowing, reflection and refraction among others. The basis of ray tracing is to follow rays through a 3D scene and calculating every reflection along its path [3]. The rays can be followed either from the position of the viewer to their source, or by following them from the source to the viewer. The first method is most commonly used since it requires less computations due to the fact that a lot of rays can be eliminated.

Using the rules described in the previous section, Equation 3, reflection can be calculated as the rays travel through the scene and collides with the objects [8]. Transparency is modeled using transmission rays which is passed into the object, the angle of the transmitted rays is dependent on the refraction index of the material. Figure 6 illustrates the reflection and refraction of a ray.

SIMULATION OF ULTRASONICS

When an object is measured using ultrasonic ranging, the end result is highly dependent on the geometry of the object. It is therefore important to be able to create a realistic model of not only the sensors but also the environment. The propagation, in terms of transmission through air and

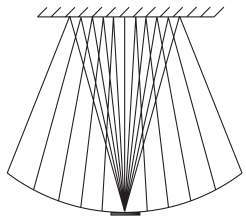

Figure 7: The sound pulse seen as rays.

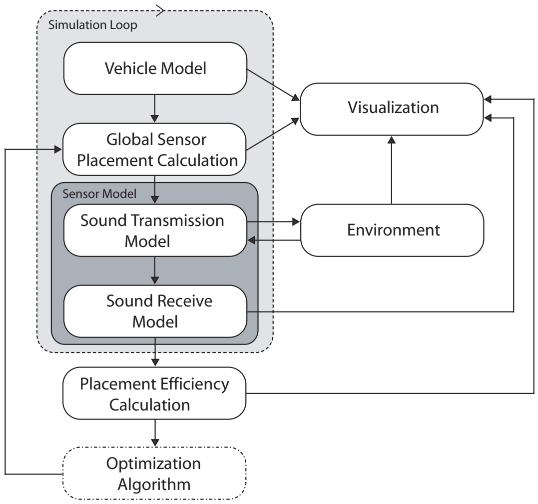

Figure 8: Simulation model overview with the simulation loop marked.

reflection on obstacles, of the sound pulse through the environment is the key element to modeling ultrasonics.

The different 3D modeling software packages that are available each meet that criteria if we can view the sound pulse as rays and using the ray tracing technology incorporated in the software. If each emitted pulse is divided into a large number of rays and spread as in Figure 7, the result should be a realistic model of the ultrasonic ranging. The complete model requires accurate models of the emitting, the transmission and the receiving of the sound pulses.

SIMULATION OVERVIEW

The chosen 3D modeling package is 3D Studio MAX since it contains the programming language MAX Script which makes it easy to implement control loops and an intuitive user interface all in one package. The main drawback of the created simulation is that the computing power required is extremely high. The computation time is dependent on the resolution of the rays. A high resolution requires that each sound pulse is divided into more rays which increases the number of calculations required.

The implemented simulation environment consist of several parts. The main simulation loop, top part in Figure 8, consist of the ultrasonic simulation. After a simulation is completed the result is evaluated using an efficiency algorithm which is based on the hough transform presented in [4]. The optimization can, using this efficiency calculation relocate the sensors on the car and then start another simulation. The environment models the surrounding obstacles, consisting of cars and the curb and the visualization of the scene comes “free” with 3D Studio MAX.

Figure 9: Sensor movement during a receive cycle.

TRANSMIT AND RECEIVE MODEL

The emitted sound pulse is divided into a number of distinct rays as can be seen in Figure 7. Each ray is associated with an intensity measure coming from the beam pattern (see Figure 5) and radiates in a spherical cone from the sensor. The friction against air is neglected so the intensity of *each* ray is constant as it propagates. Also reflection losses are neglected.

As the sensor starts listening for the returned echo the key factor is the accumulated returned intensity. A ray that passes through the sensor is considered to be “heard” by the sensor and the intensity of that ray is added.

Since the sensor in this case is mounted on a *moving* vehicle some care has to be taken when calculating if a ray passes through the sensor. To solve this problem a technique where the starting point (the location of the sensor when the pulse was emitted) and the ending point (the location when a maximum TOF has elapsed) of the sensor is determined. After that a rectangle is drawn between these points, see Figure 9. Any ray passing through this area is considered to be heard by the sensor. This is a simplification and will not produce large errors since the sensor movement during the transmit-receive cycle is small.

ENVIRONMENT MODEL

The environment model of a parking scenario must provide an accurate model of the surfaces of the other parked cars and the curb. The resolution of the parked cars is a significant factor of the computing time for a simulation run. The level of detail must be high enough to provide accurate measurements and at the same time low enough to keep computing power down. Figure 10 shows car models with different polygon counts.

The shape of the vehicles is also an important factor, a large SUV results in a completely different result than a small compact.

Figure 11 shows the two types of cars chosen for the simulation and sensor placement calculation. A larger station wagon in (a) and a smaller sedan vehicle in (b). Both cars have in the vicinity of 1000 polygons. This gives a good

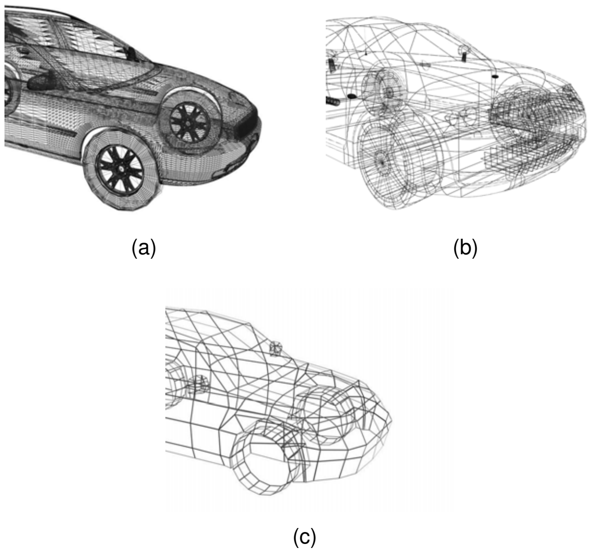

Figure 10: Car models with about (a) 300 000 polygons, (b) 150 000 polygons and (c) 1 000 polygons

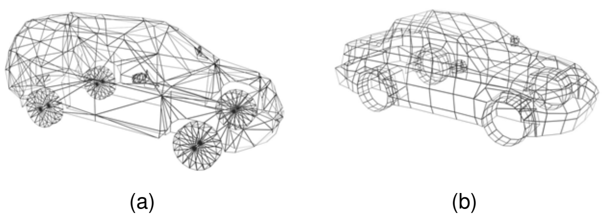

Figure 11: Low polygon car surface models used in simulation in form of (a) a larger station wagon and (b) a smaller sedan.

enough surface approximation for ultrasonic modeling and at the same time keeps simulation time at an acceptable level.

The rest of the surrounding, the curb and the road, is modeled as a box with height 0.1 m and a plane respectively. It would be interesting to create a more realistic, rough model of the road surface since road roughness is the source for a high number of spuriouses when measuring with ultrasonics. This would, however, lead to extremely long calculation times. The algorithm presented in [4] is however proved to be robust against such spuriouses so it can be argued that they are not such an important factor.

MODEL VALIDATION

The validation was conducted using an ultrasonic sensor (SensComp Smart Sensor 600) attached to a angular servo (consisting of a motor, a gearbox and an encoder). The measurements where collected using a dSPACE system. Figure 12 shows the experimental setup.

The most interesting results are viewed Figures 13 through 16, plots that show both the good and the bad behavior of the model. It is observed that the real sensor almost every time gets more hits on its right side, which

Figure 12: Ultrasonic sensor mounted on angle servo with a resolution of 0.5 degrees. With this angle servo connected to the real time system dSPACE accurate measurements can be made.

means that this particular sensor don't have a perfect symmetric beam pattern. The beam pattern varies between different sensors, probably because of differences in the membrane.

In Figure 13 the object is a plane wall (800 mm wide). At 1 m, it is seen how the simulation agrees well with the real measurements. Both the major and secondary lobes looks the same in simulation as in real measurements.

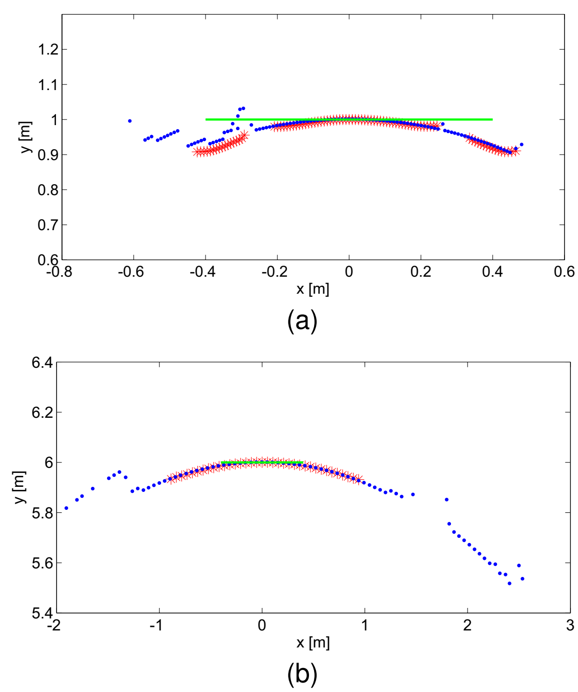

Figure 13: Real (dots) and simulated (asterisks) measurements on a 800 mm wide wall at (a) 1 m and (b) 6 m.

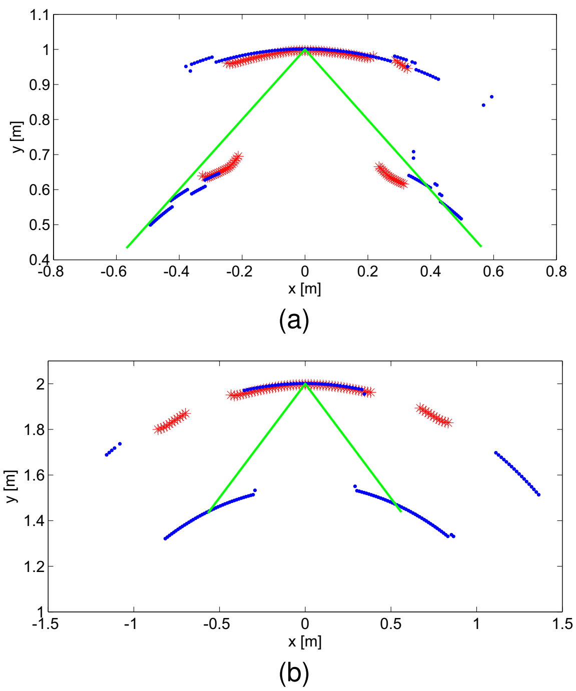

Figure 14: Real (dots) and simulated (asterisks) measurements on a inside corner with 800 mm sides at (a) 1 m and (b) 2 m.

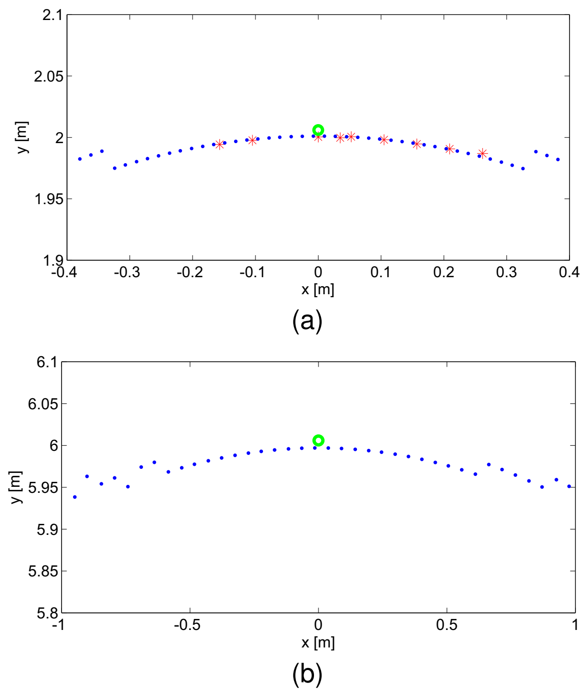

Figure 15: Real (dots) and simulated (asterisks) measurements on a cylinder with 12 mm in diameter at (a) 2 m and (b) 6 m.

Also at 6 m, where only the major lobe is seen, the results agrees. It should be noticed that the model don't have echoes for as wide angles as the real measurement.

In Figure 14 some interesting effects can be seen. In the experimental measurements, echoes occur as direct reflections from the side of the walls creating the inside corner. In the simulations however, the planes have no thickness and therefore no echoes can be detected. The double reflections coming from inside the corner is the same though.

In Figure 15 a small cylinder (12 mm in diameter) shows if the model can cope with smaller object. In these plots the weakness of the model can be seen. It doesn't get as many echoes as the experiments. There are almost no echoes at 2 m and none at all with at 6 m.

With the sensor sweeping almost 360 degrees in a smaller room (1.6 by 1.6 m) the results plotted in Figure16, is obtained. Simulations produce almost the same results as the real measurements. Echoes that occur at the middle of some walls are there because the walls where built up by two planes in the real measurements, which resulted in a small bump that the sensor registered. In reality echoes also occur at a longer distance (down to the right in the figure), because the sound have been reflected more than two times as in the model.

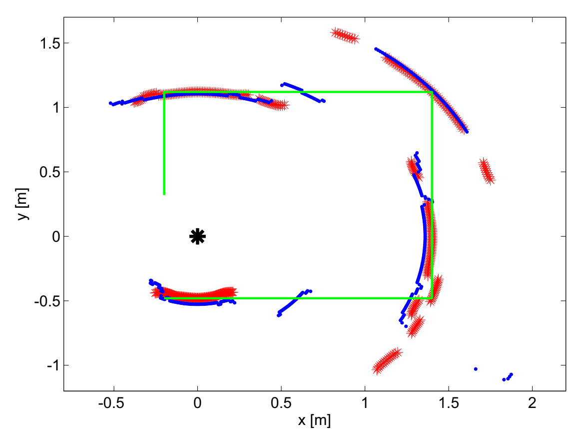

Figure 16: Real (dots) and simulated (asterisks) measurements in a small room ($1.6x1.6\ m$). The large asterisk represent the sensor position.

CONCLUSIONS

The result of this work is a simulation environment created in 3D Studio MAX which can accurately model the physics of ultrasonic ranging in parking system applications. The model have been validated against experimental results using a real sensor and real objects.

Furthermore, initial studies in the placement of the sensors used in a parking system have been conducted. The results show that the simulation environment can correctly produce to evaluate different mounting locations of the sensor. The computing time is however extremely high so initial guesses must be relevant to get fast convergence in the optimization.

Furthermore the work has shown that 3D Studio MAX along with other 3D modeling packages can be used to model ultrasonics in a new way.

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