Characterization of a Radial Laser Scanner for Mobile Robot Navigation

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Abstract

A Radial Laser Scanner is a device that provides distances to the surrounding objects by scanning the environment in a plane (usually parallel to the ground). This paper is concerned with the calibration of one of such a sensor, called the Explorer. In particular we present a probabilistic sensor model that considers the sensor readings to be affected by gaussian noise as well as truncated by the sensor resolution. We also describe some experiments aimed to characterize the range measurements against the operating time, different target materials, beam incidence angle, etc. A brief analysis of the angular error is also presented.

1. Introduction

A radial laser scanner is a device that measures distances to the objects in the environment intercepted by the laser beam. It is of great interest to mobile robot applications, since the information supplied by this sensor can be used to estimate the robot position [1, 2, 5, 8, 10] and to build or update a map of the environment [4, 10].

In this paper we present a set of experiments aimed to characterize the Explorer radial laser scanner, including deviations in the measures due to noise, discretization, non-linear response, and different object surface properties and orientations.

The Explorer, as many of the laser rangefinder used for mobile robot navigation, is not a standard commercial sensor but it was made to order under specification of our Department. In addition to calibrate the sensor to verify that it fulfill all the specifications, we believe that a more complete characterization is also important for two main reasons:

1. Improvement in robot position estimation and map building can be obtained if the errors (random and systematic) in the measures supplied by the sensor can be quantified. It would allow, for example, to develop a virtual sensor that corrects by software the known deviations in the real sensor measures [9].

2. It can be derived a sensor model which would allow to simulate the sensor behavior and facilitate the development of new laser-based algorithms without physically using the scanner.

We have not found in the literature too much work done concerning the calibration of laser rangefinders. Fortunately, some exceptions are the technical reports of Kweon et al [7] and Krotkov [6], at the Robotics Institute, Carnegie Mellon University. Both deal with 3D laser rangefinders (the ERIM and the Perceptron) and their applications to terrain map building. A closer work is the one developed by Sedas and Gonzalez [3, 9] for the Cyclone laser range scanner, although they do not include an explicit model for the range measurements.

This paper is organized as follows. A description of the Explorer and the experimental setup are presented in sections 2 and 3, respectively. Then, the characterization of the range measurement against different surface properties, target orientations and scanning speed and sample rate is presented in section 4. Section 5 proposes a model for the measuring process which includes a rounding function and an gaussian noise disturbance. Finally a brief analysis of angular errors is presented.

2. The Explorer laser rangefinder

The Explorer is a time-of-fight radial laser range scanner, manufactured by Schwartz Electro-optics Inc. (SEO) under specification of the Department of System Engineering and Automation, University of Malaga. The components of the Explorer are an emitter/receiver pulsed gallium infrared laser, a rotating prism, a driving motor, and an encoder mounted on a steel housing (Figure 1).

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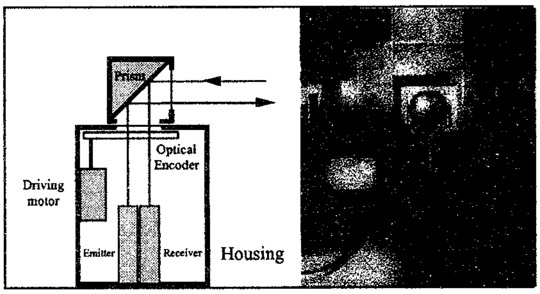

Figure 1. The Explorer laser radial scanner.

In the scanning process a laser beam is sent by the emitter and deflected horizontally by the prism. By rotating the prism, the Explorer is able to scan 360 degree field of view in a plane perpendicular to its axis of rotation (parallel to the ground) providing a two dimensional description of the environment in polar coordinates (ρ,θ).

A scan supplied by the Explorer consists of a one-dimensional array of range indices I_R, which are integer values between 0 and 1023 (ten bits resolution). The angle θ corresponding to each range index is given by its order in the array. According to the specification sheet the Explorer is able to measure distances from 0 to 35 meters and this interval is mapped into the range index interval. Thus, to convert a range index into a real distance (in meters) the manufacturer gives an scale factor of 3.418 cm. per index (35m. divided by 1024). Obviously, this factor also states the resolution of the measurements.

The specification sheet also states the following characteristics: range accuracy of $\pm$10 cm., the angular resolution can be programmed to measure 128, 256, 512, 1024 and 2048 data per revolution, and the rotation speed is programmable between 0.5 and 4 revolutions per second.

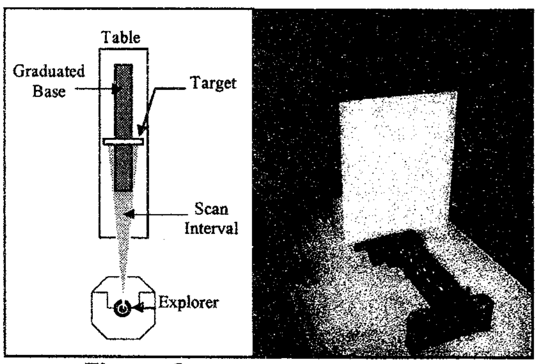

Figure 2. The experimental setup

3. Collecting data

To perform the calibration experiments the setup shown in figure 2 has been used. It consists of a table on which a graduated frame with a sliding support has been mounted. This setup allows to precisely place a target at different distances from the sensor. In most of the experiments the target was a wooden panel of 30x20cm. attached to the sliding support.

The data for the experiments have been collected as follows:

- For each scan supplied by the sensor, only a small interval, corresponding to the central hits on the target are stored for later processing (Figure 2).
- A number of scans (between 100 and 2000 depending on the case) are taken at each target position. This allows to carried out an statistical analysis of the measurements.
- The real distance from the sensor to the target is obtained by measuring the distance up to the table (using a measuring tape fixed on the floor) plus the distance along the graduated sliding base. At every position of the table, the target distance can be varied until 1 meter.

Through this collecting process we obtain a set of readings from which the frequency histogram, the mean and the mode at each target distance are determined. The mean is important since it is the most likely true value, while the mode is the most likely value provided by the sensor.

4. Characterization of the range measurement

In this section we present a set of experiments aimed to characterize the influence of different operating parameters in the range measurements. In particular we analyze the effect of the operation time, surface reflectance properties, sample rate and target orientation.

4.1. Influence of operation time

The objective of this experiment is to illustrate the influence of the time the sensor has been operating over the data it provides.

In this experiment, with the target placed at a fixed distance (2 meters) from the sensor, we turned on the sensor and took 100 scans every five minutes until complete eight samples. Then, 100 scans every half of an hour were taken completing, thus, 2 hours.

Figure 3a shows the measured range indices as a function of time. Figure 3b shows the mean of these range indices. Observe that the data supplied by the sensor are time-dependent, although this dependency disappears later in time. In particular, after 30 minutes the range indices become stable and therefore time-independent. This experiment was repeated with targets at 4 and 8 meters with identical results.

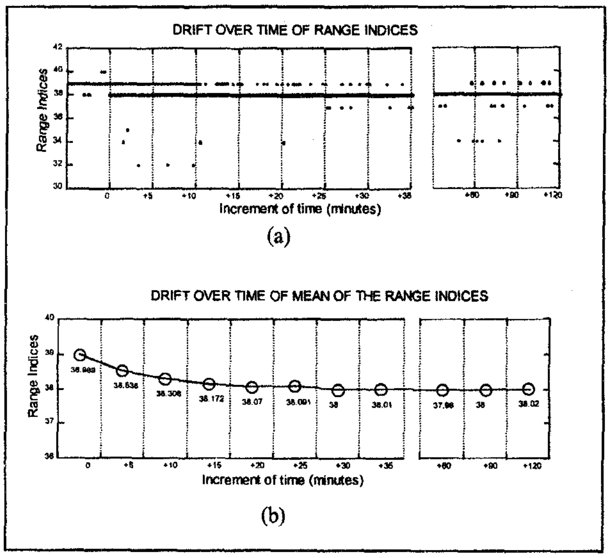

Figure 3. Range drift over time.

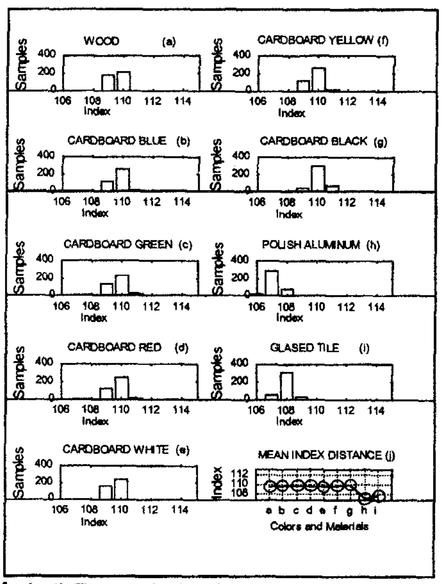

Figure 4. (a-i) Range index histograms for different target materials. (j) Mean of range indices (400 samples).

4.2. Influence of target surfaces

At this point we want to characterize the behavior of the data supplied by the Explorer when the laser beam hits surfaces with different reflectance properties (texture, color and specular behavior).

For this experiment we have used 5 targets. These targets were situated at 1, 2, 4 and 8 meters and 400 samples were taken. The materials were:

- Wood.
- Cardboard of 6 different colors: white, black, cyan, yellow, red and green.
- Polish aluminum.
- Glazed tile.
- Glass.

Figure 4 shows the histograms obtained for each of the different target at a distance of 4 meters. Notice that the range index supplied by the sensor does not vary significantly with the color of target but does with specular behavior of the surface.

This experiment was repeated for two new target positions at 2 and 8 meters with the same results. The glass was not detected for any of the three cases.

4.3. Influence of sample rate and rotation speed

As commented in section 2, the Explorer can be programmed to acquire different number of samples per revolution and to scan at different speeds. In this experiment we analyze the influence of different sensor operating modes (sample rate and scanning speed) in the range measures.

With the target placed at a certain fixed distance we have taken 2000 scans for all the possible combination of rotation speed and sample rate.

Figure 5 shows the result of this experiment. The differences observed for each mode of operation were minimum, and so, the data supplied by the sensor can be considered independent to the rotating speed and sample rate being used.

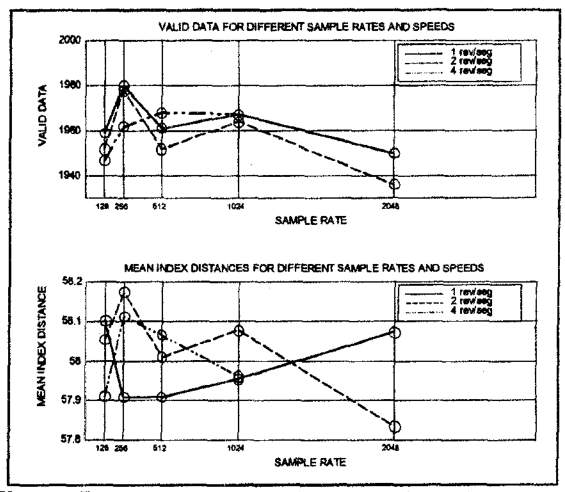

Figure 5. Influence of sample rate and rotation speed.

4.4. Influence to different target orientations

The objective is to determine the influence of the incidence angle between the laser beam and the target. To perform this experiment we have used a manual rotary positioning table on which the target was mounted. Nine different target angles at a distance of 1.6 meters were considered[1]: -60°, -40°, -20°, -10°, 0°, 10°, 20°, 40°, 60°. For each of these angles, 100 samples were taken by selecting only the central reading of each scan.

[1] These angles are measured between the laser beam direction and the vector normal to the surface.

Figure 6 plots the mean and variance computed from the data obtained in this experiment. Observe that the target seems to move away from the sensor as the orientation increases. Surprisingly, the variance is not affected by this circumstance.

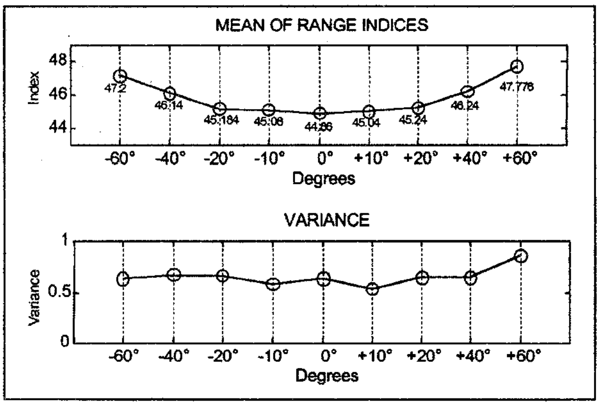

Figure 6. Mean and variance of the range indices for different target orientations.

5. A model for the range measurement

In this section we propose a relationship between the true distance and the range index provided by the scanner.

The Explorer range measuring process can be modeled as a transformation of the true distance d_T affected by an additive Gaussian noise η into the range indices interval [0,1023]:

$$I_R = Round\big(T(d_T + \eta)\big) \qquad \text{(EQ 1)}$$

where I_R is the range index provided by the sensor, $Round(\cdot)$ is the rounding function and $T(\cdot)$ is an unknown scale transformation. We want to characterize the sensor model by computing the standard deviation σ of the noise η and the function $T(\cdot)$.

Considering the above experiments, this model should also account for the orientation and reflactance properties of the object surfaces. For mobile robot navigation purposes, however, it would require to get this information from the environment, which usually is not possible. Thus, for the experiment, we fixed the incidence angle at 0° and used just one surface material (wooden panel).

According to the manufacturer, $T(\cdot)$ is a linear function with slope K given by the resolution of the sensor, which is set to be 3.418 cm/bit, that is:

$$I_R = Round\left(\frac{d_T + \eta}{K}\right) \qquad \text{(EQ 2)}$$

Figure 7 shows, for 400 samples at 70 different target positions between 1 and 8 m., the errors in the measures when using this function. These errors were computed using the equation:

$$e = d_T - I_R \cdot K \qquad \text{(EQ 3)}$$

which includes the errors due the discretization and the noise η.

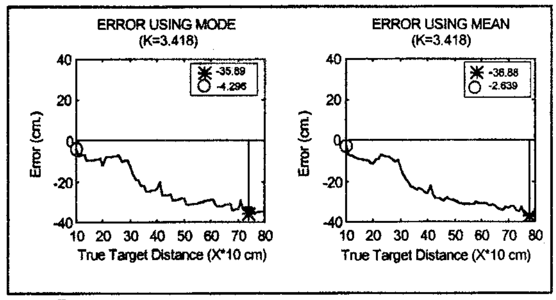

Figure 7. Measure errors when using equation 2 and the resolution given by the manufacturer (3.418).

This nominal resolution (K=3.418) provides increasing errors as the true distance increases, which means that it is not the correct slope for a linear function $T(\cdot)$. In order to compute a more suitable value of K we have tried a set of 100 different resolutions between 3.55 and 3.65 cm. at increments of 0.1mm. For each value within this interval the mean squared error was computed using the data shown in Figure 7. The minimum was reached for a resolution of 3.603 cm. (Figure 8a).

For this range resolution, the errors are within ±10cm. around the real distance, which is in concordance with the manufacturer specification given in section 2 (see Figure 8b). Notice that if the range discretization were other than the rounding function, for example a truncation, the error in Figure 8 would be equal or greater than the mean error K/2.

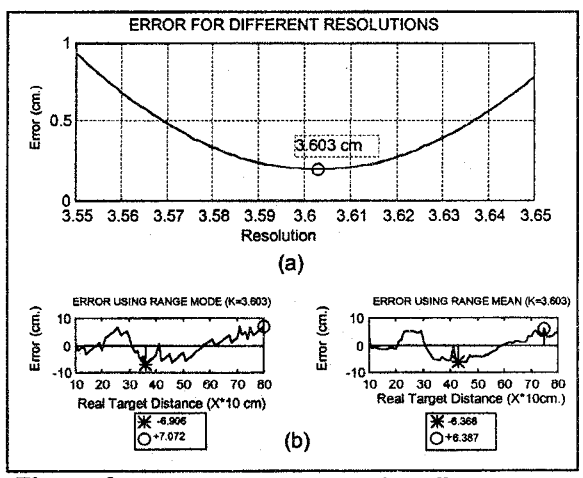

Figure 8. a) Mean squared error for different range resolutions. b) Errors for a resolution of 3.603 cm. (400 samples) .

5.1. Computing the conversion table

Although the above value of K is optimal for the full interval, the error becomes significantly at some distances due to non-linear behavior of the sensor. To reach better results for all the ranges we propose to precopile a conversion table to map a given range index to its corresponding real range distance. This conversion table is computed as follows:

1. For each target position given in Figure 9, the mean range index was computed using 100 samples.
2. A temporary table mapping mean range index with its corresponding real distance was built.
3. From this temporary table and using lineal interpolation, we compute a new conversion table where real distances are indexed by the range indices provided by the sensor (from 0 to 1023).

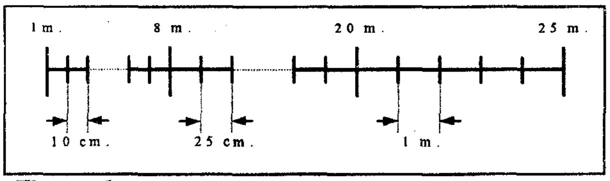

Figure 9. Target positions to compute the conversion table.

Figure 10 shows the accuracy attained using the conversion table for two different range intervals. As expected, the best results are achieved when the true distance is estimated by using the mean of the data[2] (Figure 8b).

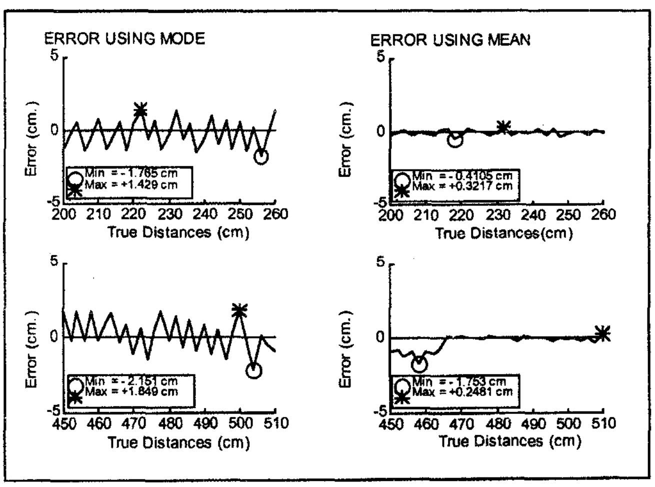

Figure 10. Measure errors using the conversion table (100 samples).

[2] In this case a new linear interpolation is necessary to look for the range distance corresponding to the mean of a set of range indices (a real number).

5.2. Computing the noise function η

We assume that η is a gaussian normal function $N(0,\sigma)$. To complete the sensor model of equation 1, the standard deviation σ must be computed. The process to compute σ was the following:

1. We placed the target from 2.01 to 2.30 cm. at increments of 1cm. At each of the 30 target positions we took 100 scans and 3 readings at the center of the target were selected from which we built a frequency histogram (with 300 samples).
2. The same experiment that above but simulating was performed. The range measurements using the model of equation 1 for a set of σ values between 0.7 and 1.6 centimeters and the look-up table obtained in section 4.1.
3. For each of the σ values the mean squared error between the two histograms was computed using the equation:

$$\frac{1}{30}\sum_{i=1}^{30}\sum_{j=-1}^{1}\left(HS_i(j)-HR_i(j)\right)^2$$

where HS_i and HR_i are the simulated and real histograms at the target position i (i.e. 2 m. and i cm.), respectively. The parameter "j" indexes the three-most frequent range indices of the histograms.

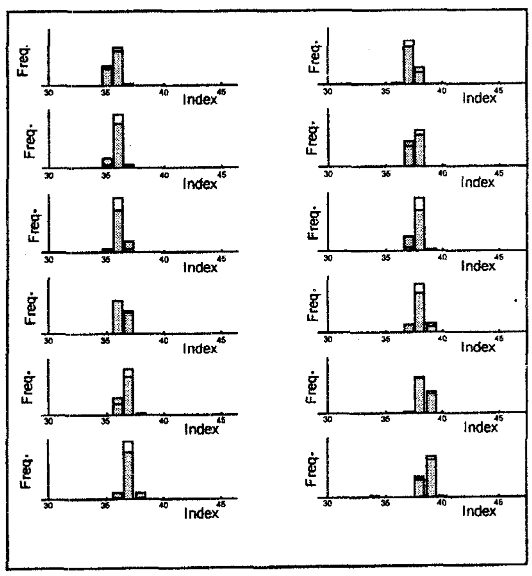

Figure 11. Real and simulated (filled) histograms for σ=1.2 cm. appear overlapped.

The minimum was achieved for σ equals 1.2 centimeters as we can see in figure 12. Although the σ seems to varies from one distance to another we have checked that this variation is tiny enough to be cleared away.

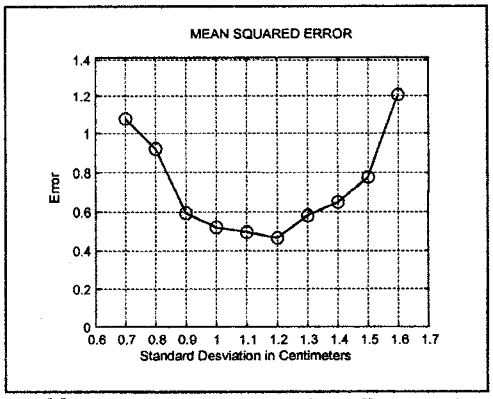

Figure 12. Mean squared error for different σ in eq. 3.

This value was validated with another sets of range distances distributed along the full working interval (up to 35 meters). Additionally, the small error observed in all the cases confirms that the assumption of gaussian noise is adequate.

6. Characterization of Angular Errors

To complete the characterization of a radial laser scanner we need to analyze the angular behavior of the sensor, which has effect in the positioning of laser beam. Two different angular errors may occur: panoramic angular error and deviations from the nominal scanning surface.

A radial laser scanner provides a polar description (ρ, θ) of the surrounding obstacles. Panoramic error refers to deviations of the beam from that provided by the sensor (θ). Basically, it will depend on the optical encoder and electronic used for triggering the laser pulse.

In order to check how precise the panoramic positioning is, we have investigated the angular repeatability with the following experiment. We placed the Explorer in front of a small target at 1.5m. with a uniform background at 2.5m. Figure 12a plots the mean, over 100 scans, of the range indices obtained for 2048 readings per revolution. Figure 12b displays the 100 "images" seen by the sensor. Observe that, at the border of the target appears the so called "mixed points" [6] which refers to measures where the footprint of the laser beam lies on the edge of the objects. In these cases the range value is a combination of the object's distance and of the background.

The second angular error consists of the tilting of the laser beam. If the sensor construction was perfect, the scanned surface will be a plane parallel to the ground at a specific height. However, imprecisions in the sensor construction, originate that the scanned surface to be other than the expected parallel plane.

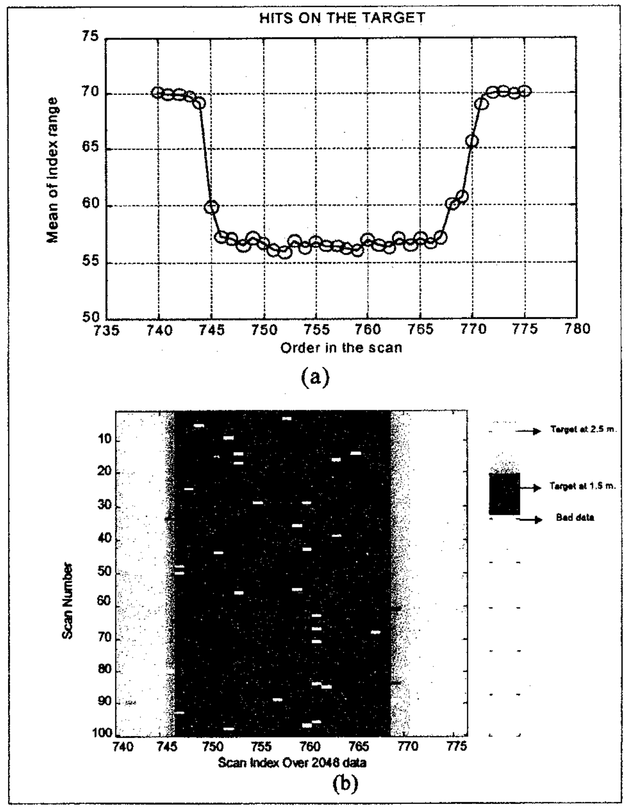

Figure 13. Repeatability experiment of the angular positioning of the laser beam.

To check this we have carried out the set of geometric experiments described in [3], from which we conclude that the Explorer has a very small deviation in the tilt of the prism which causes the scanned surface to be a cone (Chinese hat shape) with a negligible inclination of about 1 degree.

7. Conclusions

In this paper, we have experimentally characterized and modeled the Explorer laser rangefinder. We have tested that the actual Explorer nominal range resolution does not correspond with the manufacturer specifications. A more precise range resolution has been computed and a conversion look-up table has been developed that significantly improves the sensor performance. We have also verified that the ranges supplied by the sensor depend on the specular behavior of the surface but not on the color neither the texture. The incidence angle of the beam also affects the range distances although their dispersion (standard deviation) is not affected.

All these results can be of a great interest in mobile robot navigation. In particular we have taken advantage of them when developing algorithms for position estimation and map building. Currently, the computed sensor model is being used for testing the algorithms in simulation.

8. Acknowledgments

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