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IMPROVED LASER-BASED NAVIGATION FOR MOBILE ROBOTS

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Abstract

An autonomous mobile system can operate as a service robot in various environments. In many man-made environments like buildings, there exist a lot of glass panes, such as windows, doors and glass walls. This can make robotics tasks more complicated, since one of the most popular sensor systems, namely laser range finder, faces problems with measuring correct distances when hitting glass surfaces. In this paper the behavior of a laser scanner with respect to glass surface is modeled using a probabilistic approach. This sensor model is employed to improve mapping and localization of a mobile robot in an office environment. Both of the applications have been tested with a real robot.

Keywords: Laser-based navigation, laser scanner, mobile robots, glass surface, SLAM, Office environment.

1. Introduction

Nowadays, lasers have become most commonly used perceptual sensors. Most of the autonomous mobile robots are equipped with laser scanners [10]. As a service robot, autonomous mobile system could operate in variety of real environments. Mobile robots equipped with laser scanners may face problems in environments having window panes as discussed in [2]. A mobile robot equipped with the laser sensor sends the light beams to sense the environment around it. The sensor produces unexpected and suspicious measurements as it encounters glass panes in office environments [8]. These erroneous measurements make localization process more difficult and delocalize if the system is localized. In an environment with window panes (glasses) around the robot, the glasses will not be detected to a significant extent as obstacles by the robot at the distance of glasses [11], [12], [6], as mostly the light passes (refracted) through the window panes. Aboshosha et al [1] considered the presence of glass doors in the environments as a problem for the laser range finders. Glass surfaces are also not recognized easily by ultrasonic sensors [3].

There are different proposed solutions in order to cope with the existence of glass in the environment around the robot. Muñoz et al [9] pointed out the special behavior of laser light through glass. They considered the measurements obtained from such laser scans are difficult to deal with and suggested the use of Lorentz’s estimator to handle these measurements. They preferred the use of Lorentz’s estimator over least square estimator as big errors show big influence in least square estimator and in Lorentz’s estimator function small errors have more influence than the bigger errors. In the proposed approach, these measurements are directly handled using the characteristics of light. Lai et al [5] proposed to fuse the laser and sonar data. For this purpose they maintained two maps, one built from the laser data and another built from fused data of both the sensors. Sonar data was preferred over laser, in case of glass, especially when the range measurement obtained in front of glass and sonar reported range is less as compared to the laser sensor.

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Yang et al [13] suggested the fusion of laser scanner and sonar sensor to identify mirrors and windows. The sonar sensor was used to detect the window panes, missed by the laser sensor. In this paper an approach to solve the problem of existence of glass in the environment around the robot, using just the laser sensor, is proposed.

2. Glass Sensor Model

Laser range finders are most popular sensors in autonomous robotics. Range finders give the range to the nearby objects in specific range. For a service robot to be useful it is required to operate autonomously in various kinds of environments. If the special behavior of the laser light with respect to glass surface is not taken into account, it could be difficult to get accurate observations with a laser scanner in the environments with many window panes. As laser is a light, therefore when it is incident on the glass surface, two optical phenomena occur, namely reflection and refraction.

Reflection is the change in direction of a wave at an interface between two different mediums so that the wave returns back into the medium from which it originated. Refraction is the change in direction of a wave due to change in speed, as the speed of light is different in different mediums.

When the laser light is reflected from the glass surface directly towards the laser sensor then this reflection is termed as direct reflection as shown in Fig. 1. On the other hand, if the light reflected from the glass surface travels towards nearby objects instead of going directly towards the laser sensor then this reflection is termed as normal reflection as shown in Fig. 1. The developed laser sensor model deals

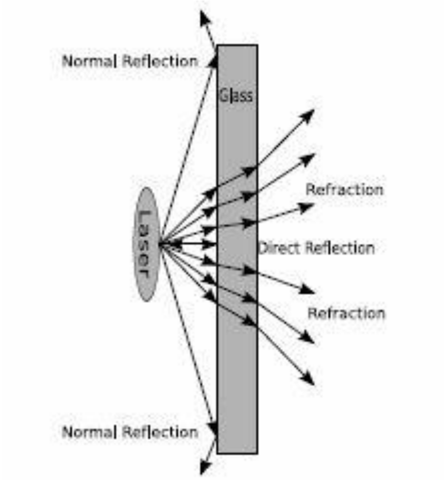


Fig. 1. Direct reflection, refraction and normal reflection

with special behavior of laser scanner due to the presence of glass panes in the vicinity of a laser scanner. This model consists of the combination of three probability density functions. This model incorporates three different types of

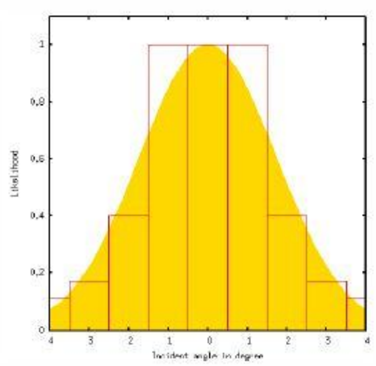


Fig. 2. Likelihood graph of direct reflection

inaccuracies in range measurements, where two of them are of essential importance, as otherwise the measured ranges will be totally different from the expected ranges. The third probability density function is also important as it models the elongation of the laser beam depending upon the thickness of glass. The three measurement inaccuracies comprise direct reflection, normal reflection and refraction. Therefore the desired model is the mixture of three probability density functions.

2.1. Direct reflection

In practice, direct reflection occurs when the laser light incident on the glass surface orthogonally making an incidence angle of zero degree. When laser light incident on the air-glass interface is nearly orthogonal, only 4% of the light is reflected back, exactly in the direction of incidence [4].

Direct reflection due to glass surface causes short range measurements in the laser scan. These reported short range measurements corresponds to d_g, the distance of the laser sensor to the glass. Therefore, it is necessary to model the direct reflection in order to accurately interpret the laser scan, since only the beams that are normal (with zero incident angle) or near normal are reflected orthogonally in the opposite direction [4] and all the other beams do not show this behavior, it could be concluded that as the incidence angle of incident beams deviates from the normal to the glass surface, the capability of laser beams to show direct reflection reduces and vanishes at some certain angle of incidence for certain d_g. Likewise as the incidence angle of incident beam approaches towards normal, it is more likely that the beam will show direct reflection. Experiments were performed in order to analyze the direct reflection at different angles of incidence. The results of the experiments support the statement in [4].

The height of red bars in Fig. 2 represents the frequency of direct reflection at the corresponding incidence angles, calculated from the experimental data. Therefore the likelihood of direct reflection can be modeled using the normal distribution with mean as zero incident angle as shown in Fig. 2. The standard deviation σdr for direct reflection is dependent on d_g.

Experiments were performed in order to obtain variance at different d_g. The analysis of the recorded ranges showed

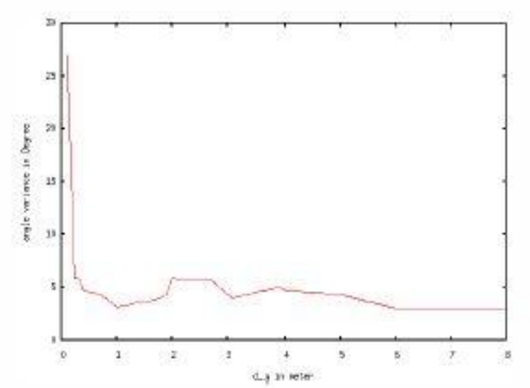


Fig. 3. Relation between the angular variance regarding to Direct reflection versus d_g

that at different d_g, different numbers of beams demonstrated direct reflection. The graph drawn between the angle variance regarding direct reflection and distance is shown in Fig. 3. In normal cases, 3° variance for direct reflection is found to be appropriate, when $d_g \geq 1m$. Therefore $\sigma d_r = \sqrt{3}$ is used. Mathematically the likelihood of direct reflection could be written as

$$P(direct|angle) = e^{\frac{-(\theta_i)^2}{2\sigma^2_{d_r}}},$$

where Θ_i is the incidence angle and $\sigma^2 d_r = 3°$ in normal case. The likelihood of direct reflection is used as weight for the probability of sensor observation z, directly reflected from the glass, which gives the range from the laser sensor to the glass surface. The probability of sensor observation z is also modeled using the normal distribution with mean d_g as the distance of the glass from the laser sensor. The σ_z is the standard deviation of observation z that is taken from the sensor model, discussed in [10]. Mathematically it could be written as

$$P(z, direct|angle) = P(direct|angle) \cdot P(z|direct, angle),$$
$$P(z, direct|angle) = P(direct|angle) \cdot \frac{1}{\sqrt{2\pi}\sigma_z} e^{-\frac{(z-d_g)^2}{2\sigma_z^2}}.$$

2.2. Normal reflection

It is observed that when laser beam incident on the glass surface at an angle of $\Theta_i = 0$, then most part of light is transmitted through the glass surface and small fraction of light is reflected in the same medium. This behavior of transmittance from the glass surface decreases sharply with the increase in the angle of incidence as shown in Fig. 4. Almost, at an incidence angle of 80°, almost half of the light is transmitted through the glass and the other half is reflected back into the same medium. The relationship between the reflection and transmittance depending upon the angle of incidence could be well represented through the graph in Fig. 4. In order to examine this behavior, a scenario was created in which the laser sensor was looking upward to the sky through the glass shown in Fig. 5. This scenario also helps to understand the sensor behavior in situation when the transmitted light beam can not come back to the sensor receiver. The goal was to check until what degree of incident angle the sensor considers the weaker reflected light beam from an object near the glass. It was observed that until an incident angle of 76° the

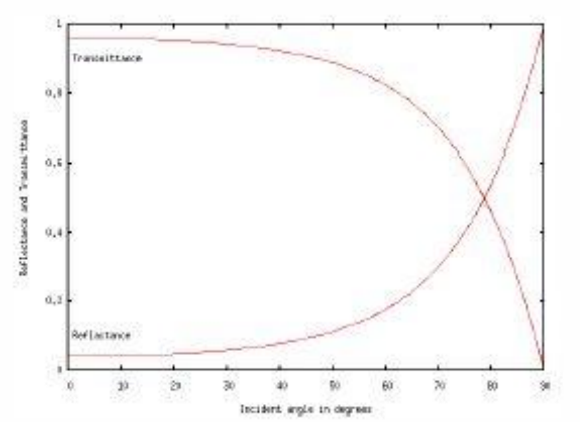


Fig. 4. Reflectance and transmittance versus Θ_i, where

Reflectance $= \left(\frac{n_{air}\cos\theta_i - n_{glass}\cos\theta_{refrac}}{n_{air}\cos\theta_i + n_{glass}\cos\theta_{refrac}}\right)^2$ and

Transmittance= $\left(\frac{2n_{air}\cos\theta_i}{n_{air}\cos\theta_i + n_{glass}\cos\theta_{refrac}}\right)^2 \cdot \frac{n_{glass}\cos\theta_{refrac}}{n_{air}\cos\theta_i}$.

n represents the refractive index of light in a medium and Θ_i is the angle of incidence and Θ_{refrac} is the angle of refraction w.r.t Θ_i.

reflected light beams were considered by the laser sensor receiver when the transmitted light beam could not come back to laser sensor as there was no obstacle in the way of these light beams.

From the energy chart of reflectance and transmittance, it is obvious that the only almost 30% of light is reflected at angle of incidence of 76° and rest of the light is transmitted. It is also essential to model this behavior of light, which is once again dependent on the incident angle of light. The likelihood of this Normal reflection is modeled using the exponential distribution given the angle of incident of the light beam on the glass, shown in Fig. 6. It is obvious from the reflectance and transmittance graph that it is appropriate to model the likelihood function by exponential distribution for the reflection behavior of light beams given the angle of incidence. Mathematically the likelihood function for normal reflection can be written as

$$P(norm|angle) = e^{-\lambda\cdot(90-\theta_i)},$$

where Θ_i is the incidence angle of light on glass surface, λ is the rate parameter, which is used in order to tune the likelihood of reflectance of laser light beams. The value of rate parameter λ is adjusted as 0.09 in order to obtain the likelihood in accordance with the reflectance and transmittance graph.

The probability of sensor observation in this part of the glass sensor model is again modeled using the normal distribution, weighted with the likelihood of normal reflection. Mathematically the probability for the sensor observation could be written as

$$P(z, norm|angle) = P(norm|angle) \cdot P(z|norm, angle),$$

$$P(z, norm|angle) = P(norm|angle) \cdot \frac{1}{\sqrt{2\pi}\sigma_z} e^{-\frac{(z-D)^2}{2\sigma_z^2}},$$

$$D = d_o + d_g$$

Fig. 5. Laser facing upward

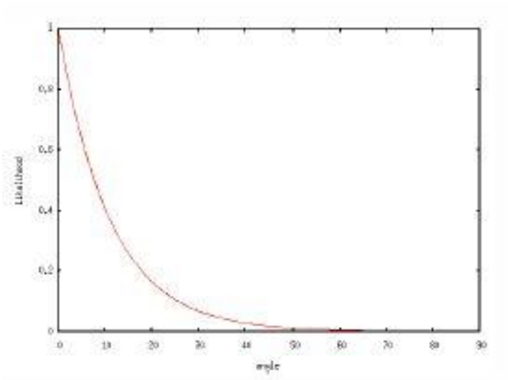


Fig. 6. Likelihood graph of Normal reflection

where the variable d_o represents the distance from the glass to the nearby object as shown in Fig. 5. The σ_z is the standard deviation of observation z that is taken from the sensor model, discussed in [10].

2.3. Refraction

Refraction is the change in the direction of beam due to the change in speed. The velocity of laser light decreases, when the light enters from a medium, having low refractive index (air), to a medium having high refractive index (glass). The laser range finders use the time of flight in order to calculate the range. Therefore whenever the light beams pass through glass the measured ranges are longer than the actual range. The elongation of laser beam depends upon the thickness of glass. In order to check the amount of elongation in the laser beam, ranges were measured with and without the glass of 0.08m thickness, placed in the way of laser beams.

The likelihood of direct reflection and reflection are modeled through normal distribution and exponential distribution. Since at all the other angles where the likelihood of direct reflection and reflection is low, the likelihood of refraction will be high. Therefore the likelihood of refraction is simply calculated by subtracting the likelihood of direct reflection and reflection from 1. Mathematically it could be written as

$$P(ref|angle) = 1 - P(norm|angle) - P(direct|angle)$$

There is one thing to notice that direct reflection and normal reflection are two mutually exclusive events. It is obvious as the direct reflection models only those beams that are incident on the glass surface normally or near normal and normal reflection models those beams that are reflected at an angle of incidence greater than 70°. The probability of sensor observation is modeled through normal distribution weighted with the likelihood of refraction. The probability function could be represented as

$$P(z, refrac|angle) = P(refrac|angle) \cdot P(z|refrac, angle),$$
$$P(z, refrac|angle) = P(refrac|angle) \cdot \frac{1}{\sqrt{2\pi}\sigma_z} e^{-\frac{(z-\phi)^2}{2\sigma_z^2}},$$
$$\phi = (d_{real} + offset)$$

where the offset value is also added to the real distance to the closest obstacle d_{real}. This is due to the fact that when the laser light passes through the glass, the speed of light slows down. This causes the elongation of beam. The z is the sensor observation. The σ_z is the standard deviation of observation z that is taken from the sensor model, discussed in [10].

2.4. Complete glass sensor model

The complete glass sensor model is simply the combination of all the calculated probabilities using De Morgan's law.

$$P(z|x, m) = P(\alpha_1|angle) \vee P(\alpha_2|angle) \vee P(\alpha_3|angle).$$

Expanding the above equation

$$P(z|x, m) = P(\alpha_1|angle) + P(\alpha_2|angle) + P(\alpha_3|angle)$$
$$-P(\alpha_1|angle) \cdot P(\alpha_2|angle) - P(\alpha_1|angle) \cdot P(\alpha_3|angle)$$
$$-P(\alpha_3|angle) \cdot P(\alpha_2|angle).$$
$$\alpha_1 = (z, refrac),\ \alpha_2 = (z, norm),\ \alpha_3 = (z, direct)$$

2.5. Experiments

The glass sensor model can be applied in the environments containing glasses for localization and mapping, in context of autonomous intelligent systems. In different kinds of robotic problems the glass sensor model is used with specific formulation. The experiments were performed on the real data obtained by the autonomous system while traversing the office environment, containing many glass windows.

2.5.1. **Localization**:

For localizing the robot in the office environment with glass windows, the complete glass sensor model is used, given the map of the environment. The map used in localization is shown in the Fig. 7. The red lines represent the glasses in the environment. The robot takes a round trip from its start location *S* to a point in the map and turns from that point back to its starting position and halts at position E. During its round trip it encounters six window glass panes at different angles as obvious from the Fig. 7. When the laser beams incidence on the glass

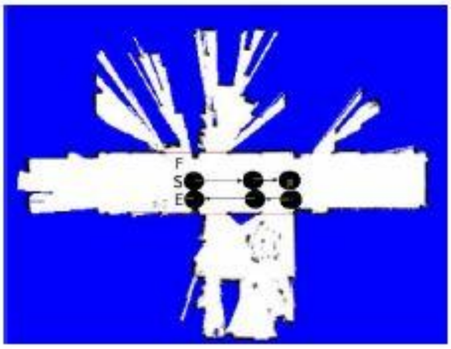
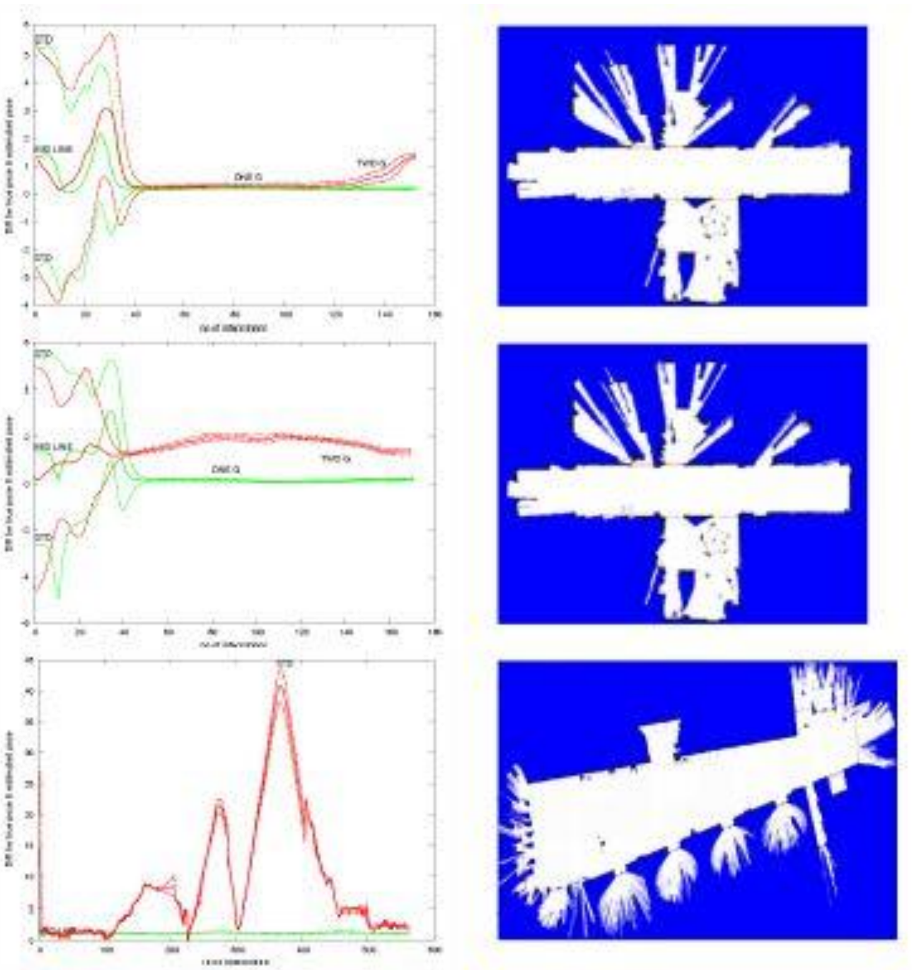


Fig. 7. Localization map

surface, then the glass sensor model is used to calculate the probability of the range measurement obtained by the beam of laser scan. For this purpose the intersection of the beams are calculated using the given map and the estimated robot location. When a beam in the laser scan does not hit the glass, then the probability of the range measurement for that is calculated by the sensor model without the glass [10].

2.5.2. **Evaluation of glass model:**

The middle line represented as MID LINE, drawn in the graphs is calculated by the difference between the sensor model estimated pose and the true pose of the robot as shown in Figs. 8. The more this line nearer to the zero value in the graph the more the sensor model estimated pose is accurate and vice versa. The surrounding dashed lines represented as STD, represent the standard deviation of particles from the mean estimated position of the robot at that time. When the MID LINE and the surrounding lines of STD (representing the standard deviation) are very near to each other, it means the particle cloud is concentrated around the estimated robot pose. More the lines STD get apart from the MID LINE, more the particle cloud increases in volume. The red lines represent the sensor model without glass modeling [10] and green lines represent the sensor model with glass modeling. During the process of localization the robot localize



Figs. 8. Graphs along with the map, from top to bottom represent the localization error graphs, performed with 5, 15 and 100 laser beams. Red lines in the map represent the glasses.

itself using the sensor model (without glass modeling), encounters the glass such a way that the direct reflection occurs then the particle cloud around the robot's estimated position expands. When the robot equipped with laser sees one glass such that direct reflection occurs the particle cloud increases which may be seen by the increase in the standard deviation in the Figs 8. The label *One G* in the Figs 8 represents the standard deviation as the laser sees the one glass such that direct reflection occurs and *Two G* represents when the laser sees glasses on both of its sides such that direct reflection occurs. If the robot encounters glasses on both of its sides such a way that the direct reflection occurs, then the robot cloud is displaced and halts at false position *F* in case of localization performed using the map shown in the Fig. 7. There it never went during the traversal of environment. In the actual traversing of environment, the robot stops at position *E* as shown in the Fig. 7.

2.5.3. Glass mapping using core heuristic:

In heuristic approach, three different cases are taken into account to decide if a cell is occupied, empty or glass cell. A cell can have different labels, including OCC; EMP and GLS*i*, where $i \in$ L. L = {GLS0,GLS5,GLS10,….,GLS180}

For simplicity the angles are discretized to 5° degrees. For each cell it is counted, how many times the cell is hit or missed at all the possible angles from 0° to 180°. The selection of cell's status as empty, occupied or glass is done depending upon the number of hits and misses. Cell hit means that the cell is traversed such that the beam ends in that cell and cell miss means that the cell is traversed without the beam ending in that cell. Using this heuristic approach many false positive glass hypotheses may also be generated. As if a cell is only reached once and the laser beam ended in the cell. Thus that cell may also be considered as the glass cell. The mapping results obtained using the core heuristic, grid-based glass mapping is shown in the Tab. I. The heuristic could be explained through the following Fig. 9.

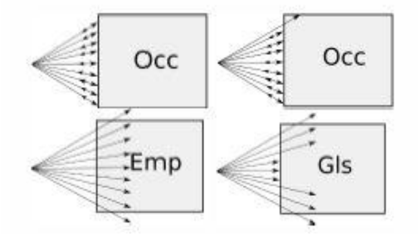


Fig. 9. The arrows represent the laser beams and the boxes represent the Cells.

2.5.4. Glass mapping using direct reflection:

Direct reflection model is the probabilistic formulation of the heuristic used to recognize a cell as potential glass hypothesis. In order to estimate if the cell under analysis is glass or not, the glass hypothesis is given a maximum likelihood by assuming that the angle of incidence of beam with the glass is zero. The probability of the glass hypothesis is strongly related to the fact that if the cell under consideration is occupied or not. This could be easily explained by an example. Let's consider Cell-A to be a glass cell and Cell- B to be simply an occupied cell shown in Fig. 10. In case

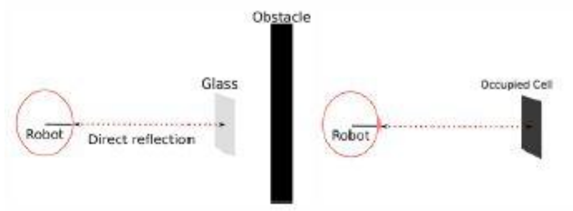


Fig. 10. Cell scenario

of Cell-A, if the beam incidence on the glass orthogonally, making an incidence angle of 0°, then range measurement will be shorter than the actual range measurement, due to the direct reflection, as Cell-A is the glass cell. In case of Cell-B, the range measurement will not be shorter, this time beam simply bounced back from the opaque surface towards the laser sensor, as the cell is occupied. This way all the occupied cells can be differentiated from the glass cells, taking into account the real distance d_{real} and sensor reported range d_{range}. Therefore, the occupancy probability of the cell is introduced that helps to distinguish the occupied cells and glass cells. The occupancy probability is modeled by the sigmoid like function shown in Fig. 11. The sigmoid function is given as under

$$P^t_{occ} = \frac{1}{1 + e^{(d_{real} - d_{range} - 5)}},$$

$$P_{occ}(x, y) = \prod_{t=0}^{T} P^t_{occ}(x, y),$$

As long as the actual range is smaller than or equal to the range given by the range finder, then the cell is considered occupied when the actual range is greater than the range provided by laser range finder, then the cell is considered with high probability as a glass cell. The occupancy probability of the cell is used to weight the probability of cell to be a glass cell as given below

$$P_g^t = P(g) \cdot (1 - P_{occ}^t),$$
$$P_g(x,y) = \prod_{t=0}^{T} P_g^t(x,y),$$

where P(g) is the glass hypothesis and given maximum likelihood value assuming a cell to be a glass cell, because it is handled by $(1\text{-}P^t_{occ})$. The probability for a cell being

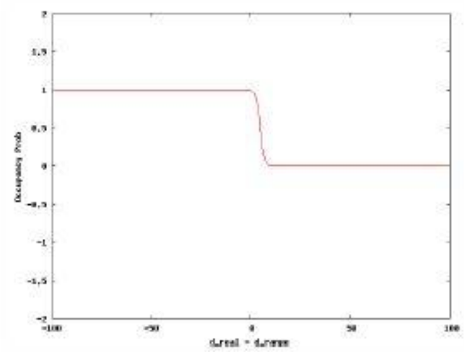


Fig. 11. Sigmoid function

empty is simply obtained as under

$$P_{emp}(x,y) = 1 - (P_g(x,y) + P_{occ}(x,y))$$

The cell is classified as EMP, OCC or GLS by the maximum value. Probabilities for glass, occupied, and empty for each cell in map are obtained as described above.

2.5.5. Map refining using Markov Random Field :

To smooth the result of direct reflection model, Markov Random Field is used [7]. For the glasses in the environment the 2nd order neighborhood is used. The regularity function used to regularize the neighborhood is as under

$$REG(x,y,l) = \sum_{x'=\pm x} \Psi(l, f(x',y)) + \sum_{y'=\pm y} \Psi(l, f(x,y')) + \sum_{(x',y')=\pm(x,y)} \Psi(l, f(x',y'))$$

where the function f(x, y) gives the label of site and function is used to produce a penalty value depending upon the labels of the neighboring cells. The pair site containing cells with different angles are punished using

TABLE I

TEST RESULTS FOR GLASS MAPPING

	Heuristic	without MRF	with MRF
Found	228	409	105
False +ive	910	813	262
Exact Found	18	32	26
Not Found	30	2	4
Found (with Displacement)	8	22	26
Ground Truth	56	56	56
recall	4.0	7.3	1.8
precision	0.3	0.6	0.5
precision (2 cell tolerance)	0.5	0.96	0.92

the Ψ function, by increasing the regularity value. The function Ψ is defined as under

$$\Psi(l_1, l_2) = \begin{cases} 3, & \text{if } l_1 = l_2 = GLS \ and \ \theta_{l_1} \neq \theta_{l_2} \\ 0.6, & \text{if } l_1 = \text{gls } l_2 = \text{emp} \\ 0, & \text{otherwise.} \end{cases}$$

The same kind of discretization, as used in heuristic approach, is also used here.

2.5.6. Evaluation of mapping:

Precision and recall test is performed in order to check how precisely glass cells are detected in the grid map, how many false positive glass cells are obtained and how many glass cells are left undetected using simple heuristic and glass sensor model with/without Markov Random Field. The following Tab. I shows the statistics about glass cells, false positives and false negatives obtained by applying different methods, mentioned above.

The values of precision and recall are calculated as under

$$\text{recall} = \frac{\text{found glass (cells)}}{\text{all the glass (cells)}}, \quad \text{precision} = \frac{\text{correctly found glass (cells)}}{\text{all the glass (cells)}}$$

3. Conclusions and Future Works

3.1. Conclusions

In this paper, a mathematical model for the special behavior of laser sensor in the presence of glass in the environment, is described. The sensor model is applied to cope with the measurement inaccuracies produced in range measurements using laser sensor. The sensor model is used along with the sensor model [10] to localize the autonomous intelligent system in office like environment, having many glasses around, using laser sensor. The error graphs in Fig. 8 show the reduction of localization error whenever the proposed glass sensor model is used along with the sensor model [10] compared to situation when only sensor model [10] is used. The different probabilistic formulation of the direct reflection part of the proposed glass sensor model is used to do the glass mapping in the environment. The efficiency of the glass mapping may be increased by increasing the angle discretization of glass hypothesis in the environment. Glass mapping experiments performed with the probabilistically formulated direct reflection showed good results as shown in Tab .I.

3.2. Future works

The mapping could be improved using the normal reflection part of glass sensor model. Whenever the light is normally reflected from the glass surfaces and is reflected back from the obstacle to the laser sensor through the glass surface as show in the Fig .12. Then the sensor falsely reports an obstacle at straight distance d (dotted line) from the laser sensor as shown in Fig. 12, where the d distance corresponds to the distance traveled by the laser beam (bold line). Using the normal reflection model afterwards the glass cells are detected, these falsely detected obstacles can be removed. Similarly the direct reflection part of glass sensor model can be used along with the refraction model to detect glass surfaces, doing SLAM. The detection can be performed by taking into account a cell of the grid and considering that cell as a glass hypothesis at an angle in context of the incident laser beam. Then checking that cell if the laser beam is passed (refracted) through that cell reporting longer range at different angle (angle of incident laser beam with cell) than the range when the laser beam is considered to be orthogonal to the cell.

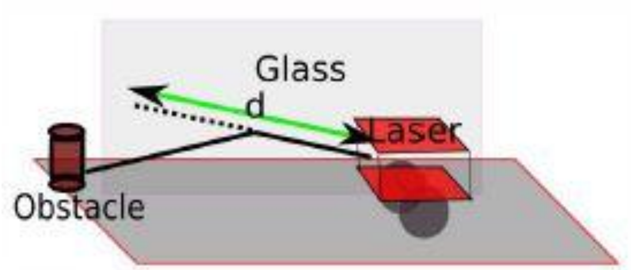


Fig. 12. Falsely detected obstacle due to normal reflection behavior

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