Glass Detection Using Polarization Camera and LRF for SLAM in Environment with Glass

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***Abstract*—In this paper, we propose a glass detection method in a wide range for SLAM in environment with glass. Degree of polarization from polarization camera is used to detect glass which cannot be detected by laser range-finders (LRFs). Glass is only detectable with LRFs in small incident angle. The angle of polarization of reflected light on the surface of glass is large in large incident angles. The straight line of glass in LRFs' measurement is calculated, and detected as glass or vacant space by using a degree of polarization. We verified the method experimentally, and the results showed that our method can detect glass in a wide range.**

Keywords—glass detection, polarization, polarization camera, degree of polarization, laser range-finders, SLAM

I. Introduction

There is high potential for the usage of mobile robots in human environments. Simultaneous Localization and Mapping (SLAM) is widely used for a mobile robot in building a map of the surrounding environment and localizing itself in the environment.

Glass is a common material in an office-like environment, mainly for windows or doors (Fig. 1). To make mobile robots work safely in indoor environment, precise SLAM is necessary in environment with glass.

Laser Range-Finders (LRFs) are rangefinders that emit laser beams to determine the distance from an object. LRFs are widely used for SLAM because of its high accuracy. However, SLAM by LRF performs unsatisfactorily in environments with glass. Non-glass objects are detectable with LRF in a wide range, however, glass is only detectable with LRF in a small range (Fig. 2). The incident angle is the angle with a line perpendicular to the surface at the point of incidence. LRF can detect glass when the incident angle is small. This makes SLAM accuracy lower. Glass is not included in map since LRF can detect glass only in small range. The glass detection failure disturbs scan matching schemes, then localization becomes inaccurate.

To solve this SLAM problem, the classification of glass and non-glass has been previously explored by the robotics community. Koch et al. [1] detected glass by a multi-echo LRF. Their method requires this special type of LRF and cannot be applied to more widely used single-echo LRF. Wang et al. [2] detected glass by intensity change of specular reflection of the glass surface. However, their method requires the robot to move in paths that enable LRF to scan objects

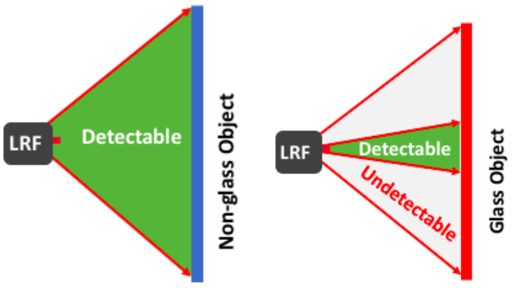
Fig. 1. Glass environment

from the normal direction of the object surface in order to receive the specularly reflected light. Jiang et al. [3] calculated glass confidence by using neural networks, and made a glass confidence map. However, this method cannot work well when glass is very clean and is detectable to LRF in very small range. These methods use limited glass detectable range, thus these do not solve the problem that LRF can detect glass only in small range.

To solve the small detectable range, another sensor has been used to detect glass. Yang et al. [4] detected glass by a sonar sensor. A sonar uses ultrasounds to measure the distance from object, thus it can detect glass in a wide range. However, the sonar has lower spatial resolution than LRF, thus the resulting map of glass is inaccurate.

In this paper, we propose a new method to detect glass in a wide range for SLAM in environment with glass by using polarization.

Polarization is used to detect transparent object and measure the shape of transparent objects. Shashar et al. [5] showed that squid uses polarization to detect transparent pray. Mahendru and Sarkar [6] detected glass from camera image by using the degree of polarization (DOP). DOP is a quantity of the portion of light wave which is polarized. Schechner et al. [7] detected specular reflection by modeling DOP changes according to the incident angle. DOP is measured by a polarization camera which has on-tip polarizers. In this paper, we use LRF and a polarization camera to detect glass in a wide range.



(a) (b)

Fig. 2. (a) Non-glass object detection with LRF.(b) Glass detection with LRF.

II. METHODOLOGY

In this section, firstly, an overview of our proposed method is given. Then the method of calculating DOP, and the method of detecting glass location is given.

A. Approach

We assume the environment has natural light and/or artificial light. Also, existing glass is assumed to have a flat surface, and the glass is surrounded by opaque objects like window flames.

Natural light has random directions of vibration planes of light. The light with biased vibration planes called polarized light (Fig. 3). The light reflected on the smooth surface has a deviation in vibration planes, hence the light becomes polarized. The light reflected on the rough surface does not become polarized.

LRF can detect both glass objects and non-glass objects when the incident angle is large. LRF cannot detect glass objects when the incident angle is large.

Consequently, there are four states in DOP and LRF detection when the incident angle is large.

- Small DOP and no detection with LRF: No object
- Small DOP and detection with LRF: Opaque object
- Large DOP and no detection with LRF: Smooth and transparent object (glass)
- Large DOP and detection with LRF: Smooth and opaque object (mirror)

When DOP is large and LRF cannot detect an object, the object is judged as glass. Therefore, DOP can be used to detect glass.

Glass positions cannot be detected only by DOP. We assume glass position from calculation of LRF, and then determine the assumed position is glass or not by DOP.

The glass detection flow chart is shown in Fig. 4. Image of polarization camera is used to calculated the DOP. Then glass position is detected by data of LRF and DOP.

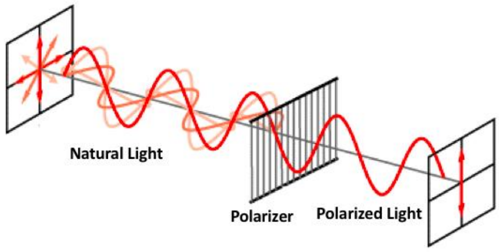


Fig. 3. polarized light

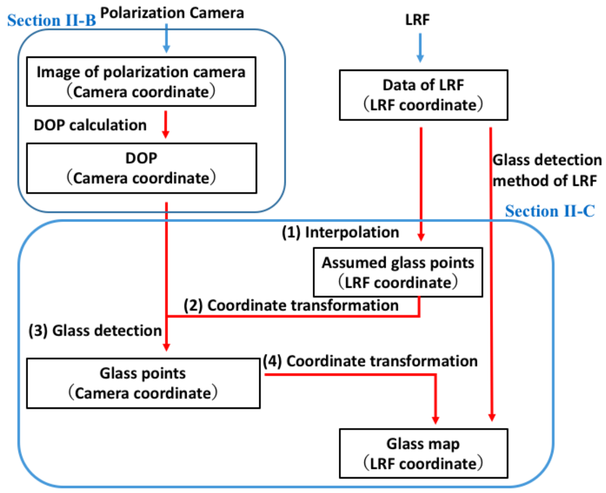


Fig. 4. Glass detection flow chart of our method.

B. DOP Calculation from Polarization Camera

Polarizer is an element that lets light waves with particular polarization pass through while blocking light waves with the other polarizations (Fig. 3). The intensity of light passing a polarizer is large when the angle of the polarizer and the vibration plane of passing light is the same. The distribution of the intensity of light passing polarizer becomes sinusoidal function with respect to the angle of polarizer [8]. DOP D is defined as:

$$D = \frac{I_{MAX} - I_{MIN}}{I_{MAX} + I_{MIN}}, \quad (1)$$

where I_{MAX} is the maximum value of the sinusoidal function, and I_{MIN} is the minimum value of the sinusoidal function.

The incident angle is the angle between the direction of incident light and perpendicular to the surface. The DOP of the light reflected on glass surface changes as the incident angle changes, and reach to maximum when the incident angle is 55 degree to 60 degree (Fig. 5) [8]. Thus, the glass detection becomes highly accurate by using DOP in a large incident angle. LRF can detect glass when incident angle is small. A polarization camera can detect glass when the incident angle is large. Therefore, glass is detectable in a wide range by fusing LRF and polarization camera.

The polarization camera has on-chip polarizers with four directions (0 degree, 45 degree, 90 degree and 135 degree) (Fig. 6). It can get the light intensity passing four directions of polarizers by one image. Each pixel has an intensity of one direction. Sinusoidal function is fitted to these four intensities,

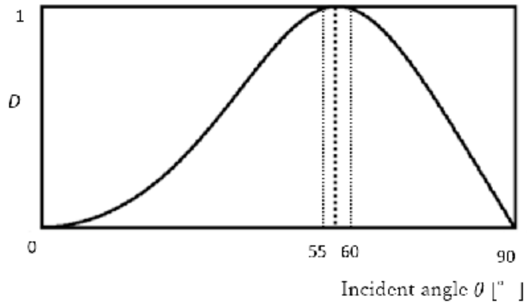


Fig. 5. DOP to incident angle

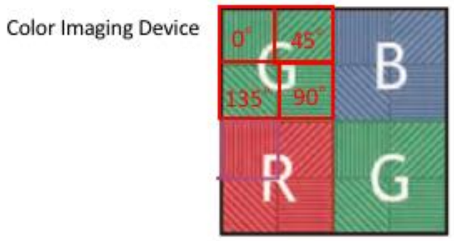


Fig. 6. Polarizer of polarization camera

and calculate DOP D. Light intensity y as a function of the angle of polarizer θ is represented as follows:

$$y(\theta) = A\cos(2\theta) + B\sin(2\theta) + C, \qquad (2)$$

Where A,B,C is constant value.

The angle of polarizer θ that this camera can measure is 0 degree, 45 degree, 90 degree and 135 degree:

$$\begin{bmatrix} y(0) \\ y(45) \\ y(90) \\ y(135) \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1 \\ 0 & 1 & 1 \\ -1 & 0 & 1 \\ 0 & -1 & 1 \end{bmatrix} \begin{bmatrix} A \\ B \\ C \end{bmatrix}. \qquad (3)$$

Equation (3) is calculated by using pseudo-inverse matrix:

$$\begin{bmatrix} A \\ B \\ C \end{bmatrix} = \begin{bmatrix} 0.5 & 0 & -0.5 & 0 \\ 0 & 0.5 & 0 & 0.5 \\ 0.25 & 0.25 & 0.25 & 0.25 \end{bmatrix} \begin{bmatrix} y(0) \\ y(45) \\ y(90) \\ y(135) \end{bmatrix}. \qquad (4)$$

The fitted sinusoidal function is obtained. Amplitude and phase difference $\emptyset$ is calculated by Eq. (2):

$$y = \sqrt{A^2 + B^2}\sin(2\theta + \emptyset) + C, \qquad (5)$$

Thus, DOP D is calculated by substituting maximum value $I_{\mathrm{MAX}} = \sqrt{A^2 + B^2} + C$ and minimum value $I_{\mathrm{MIN}} = -\sqrt{A^2 + B^2} + C$ into Eq. (1):

$$D = \frac{\sqrt{A^2+B^2}}{C}, \qquad (6)$$

This DOP D is used for glass detection.

C. *Glass position detection*

As proposed in section II-*A*, the object with large DOP can be detected as glass when it is not detectable with LRF. Also, we combine distance information from LRF because the glass position cannot be estimated by DOP. We propose the method of detecting glass position.

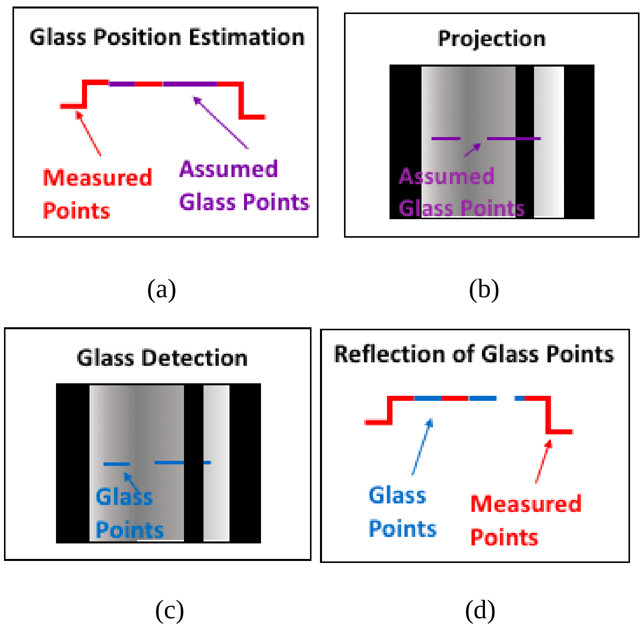


Fig. 7. small{Detection of glass position. (a) Detection of LRF. Points detected by LRF is red, the points assumed to be glass is green. (b) Image of DOP. It is white when DOP is large. Green points are projection of assumed glass points to image. (c) Glass detection to assumed glass points. Blue points are detected as glass points, and red points are detected as non-glass points. (d) Reflection of glass points to detection of LRF. Blue points are glass points.

Glass is detectable with LRF when the incident angle is small. Jiang et al.'s method is used for glass detection [3]. When the incident angle is large, the glass position is detected as follows:

1) Glass points assumption.
From points detected by LRF, glass points are assumed (Fig. 7(a)). In the LRF detection, a line is interpolated. Points on the line are called assumed glass points.

2) Projection to polarization camera.
The assumed glass points are projected to the image of polarization camera (Fig. 7(b)).

3) Determination of glass.
By threshold processing to DOP, assumed glass points on image are detected as glass or non-glass (Fig. 7(c)).

4) Reflection to LRF.
In the assumed glass points, the points detected as glass in (3) is reflected on the map made from LRF detection (Fig. 7(d)).

In (1), glass points are assumed. Glass is detected as a straight line in LRF detection because glass is assumed to be plane. LRF can detect glass in small incident angles and opaque objects like window frames. The detected points are part of straight line of glass. The points are used for line estimation if the neighboring points are under threshold value. In the LRF detection, the line is estimated, and the points on the line are called assumed glass points.

In (2), assumed glass points are projected on the camera image. The positions of assumed glass points in the camera image can be obtained by using extrinsic parameters between LRF and polarization camera and intrinsic parameters of the

Fig. 8. Environment of experiment.

polarization camera. The extrinsic calibration is calculated by Vasconcelos et al.'s method [9].

In (3), glass is detected. The DOP D of assumed glass points is got by method of section II-*B*. When D is larger than the threshold value, the point is detected as glass. When D is smaller than the threshold value, the point is detected as non-glass. The points detected as glass are called glass points.

In (4), glass points are reflected on the data of LRF. A two-dimensional map can be obtained from data of LRF. The position of the glass points in the LRF coordinate is calculated by using the extrinsic parameters between LRF and the polarization camera and the intrinsic parameters of the polarization camera. Then it is reflected to the map from LRF.

III. Experiment

To verify that our proposed method can detect glass in a wide range, we conducted an experiment in environment with glass window. In the experiment, HOKUYO UTM 30LX-EW for LRF and LUCID VP-PHX050S-Q for the polarization camera was used. LRF was mounted on the robot, and the polarization camera was also mounted on the same robot with camera facing to the window. To verify that our glass detection method can detect glass and vacant space, the left glass window was open, and other glass windows were closed (Fig. 8).

IV. Results

The result of DOP and glass detection to assumed glass points are shown in Fig.9. The image shows pixel with image DOP, larger the DOP is, the more white the pixel is. The left vacant space has small DOP and detected as non-glass. For the glass, the left glass windows which are large in the incident angle have large DOP and detected as glass. However, the right glass which is small in the incident angle is small in DOP and detected as non-glass. This is because DOP is low when the incident angle is low.

The result of glass position is shown in Figs. 10 and 11. Figure 10 shows the result from only the glass detection method using the polarization camera. The black object shows the camera position. Red points are data from LRF and the blue points are data detected as glass. Thus, when the incident angle is large, the glass is detected. Figure11 shows the result of the glass positions from both the glass detection method using polarization camera and the glass detection method using LRF. The glass in a wide range is detected by fusing LRF and polarization camera.

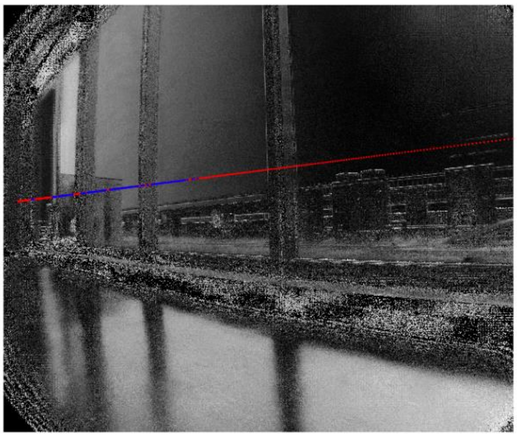


Fig. 9. Result of DOP and glass detection. The image shows the DOP, larger the DOP is, more white the pixcel is. The line in the image is assumed glass points. The blue points are detected as glass, and red points are not detected as glass.

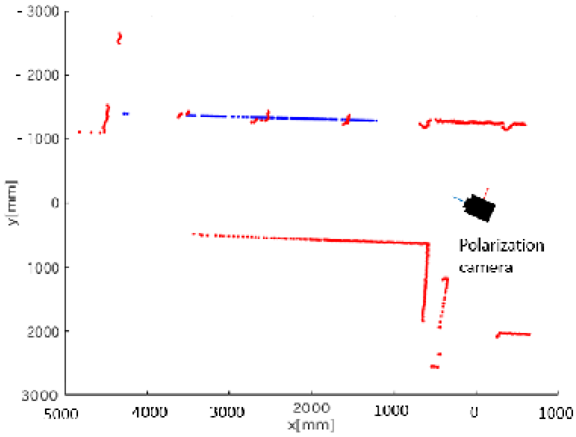


Fig. 10. Result of glass position from polarization camera method.

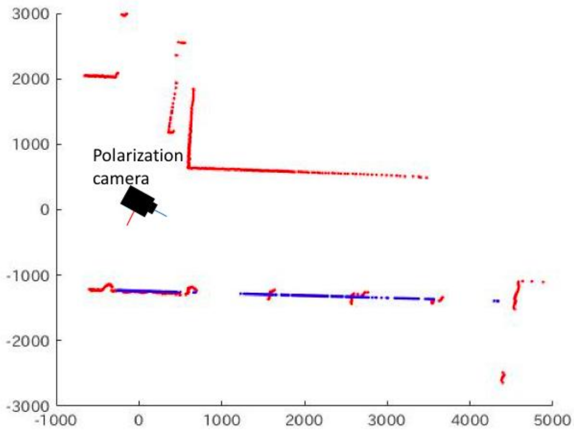


Fig. 11. Result of glass position.

The result of DOP D to the incident angle is shown in Fig. 12. Red points are non-glass points, and blue points are glass points. Threshold value is 0.45 in which balanced error rate is smallest. Glass points are detected as glass when D is larger than threshold value, and non-glass points are detected as non-glass when D is smaller than threshold value. The glass detection works when absolute value of the incident angle is larger than 35 degree. The D of glass points (blue points)

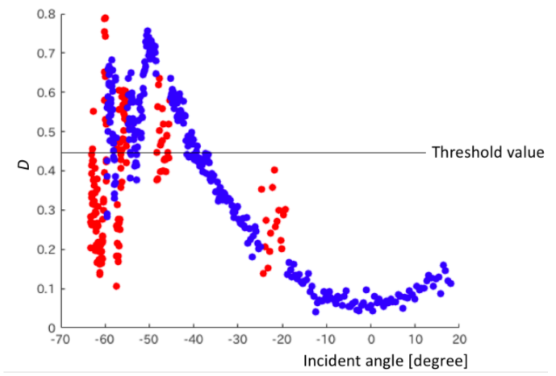


Fig. 12. Glass probability of polarization camera to incident angle. Red points are non-glass points and blue points are glass points.

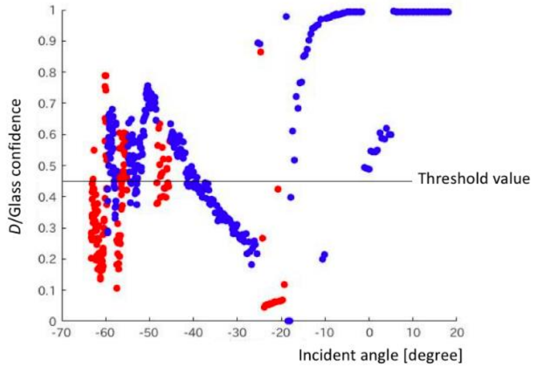


Fig. 13. Glass probability of polarization camera and LRF to incident angle. Red points are non-glass points and blue points are glass points.

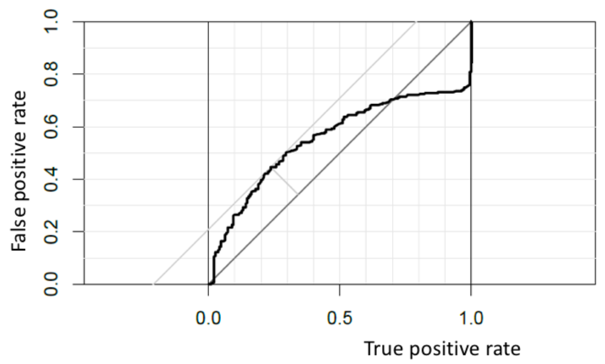


Fig. 14. ROC curve of glass detection with polarization camera.

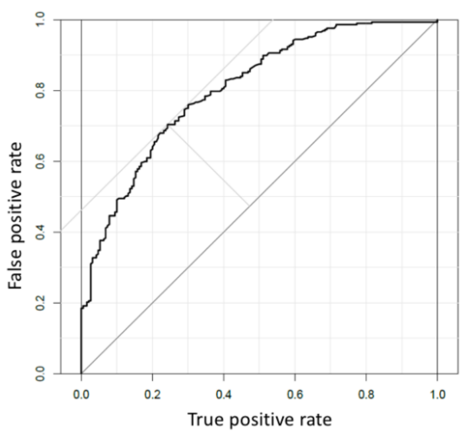


Fig. 15. ROC curve of glass detection.

mainly follows the theoretical *D* to the incident angle curve (Fig. 5).

True positive rate is the proportion of glass points correctly detected as glass. False positive rate is the proportion of non-glass points incorrectly detected as glass.

The ROC curve of glass detection from polarization camera is shown in Fig. 14. ROC curve is a performance measurement for a classification problem at various thresholds settings. Area under the curve (AUC) is the area under the ROC curve, and AUC represents separability degree. Higher the AUC, better the model is at glass detection. AUC of this glass detection is 0.55 and it is not high. This is because the glass detection did not work in the large incident angle (Fig. 12).

The result of DOP *D* and glass confidence to incident angle is shown in Fig. 13. Glass confidence from LRF was used when LRF detected the point. DOP was used when LRF did not detect the point. Glass points were detected as glass from glass confidence when absolute value of the incident angle is smaller than 25 degree. Glass was detected in a wide range except for the range where absolute value of the incident angle is 25 degree to 35 degree. This shows that our method detects glass in a wide range.

The ROC curve of glass detection from polarization camera and LRF is shown in Fig. 15. AUC of this glass detection is 0.81. Glass detection has high accuracy by fusing LRF and polarization camera.

V. Conclusions

In this paper, we proposed a method to detect glass in a wide range by fusing polarization camera and LRF. Glass is detectable with LRF when the incident angle is small. Glass is detected by using DOP from the polarization camera when the incident angle is large. We verified that the method can detect glass in a wide range by the experiment.

In future work, we propose SLAM system using this method and verify our method. Also, DOP may be used for detecting glass in a small incident angle by combining incident angle.

Acknowledgment

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