# Shape Reconstruction Using a Mirror with a Range Image Sensor – Detection of Mirror in a Range Image

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**Abstract.** In this paper, a method to reconstruct the whole shape of an object using a mirror with a range image sensor is examined. A method to obtain the pose of the mirror from the floor plane reflected in the mirror in range image is proposed. The mirror pose is estimated from the floor plane in the range image and the floor plane reflected in the mirror. The shape of the back of the object is measured from the reflected range image. Coordinate transformation is applied to the reflected back shape using the estimated mirror pose, and the whole shape of the object is obtained by registration of front and back range images. Most previous methods to obtain whole shape of an object use multiple range image sensors or use one range image sensor and moves the sensor or uses a turntable to acquire multiple range images. Compared to these methods, the proposed method does not require exact calibration in advance or precise registration method and thus is easy to use. The effectiveness of the methods is verified by experiments to estimate the mirror pose and reconstruct shape of an object using the estimated mirror plane.

**Keywords:** Range image measurement · Mirror · Three-dimensional shape reconstruction

## 1 Introduction

Range image measurement is widely used when measuring the shape of an object for the purpose of product inspection, 3D modelling, etc. It is difficult to obtain the entire shape of the target object by one shot in these measurements. So methods of measuring from multiple viewpoints and integrating those measurement results, or methods of loading the target object on the turntable and obtaining the whole shape with rotation of the table from one viewpoint are widely used.

However, in the former method, exact calibration for the viewpoint of the range image sensors is necessary in advance, which is time consuming. The latter method has problems such as difficulty in measurement depending on the size of the target object. Therefore, it has been proposed to use a mirror and obtain the whole shape of the object



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more simply by acquiring the shapes from multiple viewpoints simultaneously by one shot [1, 2].

In the method using a mirror and a range image sensor, it is necessary to estimate the pose of the mirror and perform coordinate transformation of the range image based on the pose. Akay and Akgul [2] proposed a method for acquiring a range image of whole shape with high resolution texture by combining a Kinect with a color camera and a mirror. However, with this method, calibration is required in advance for the poses of the Kinect, the color camera, and the mirror, which is difficult and time-consuming. Fasano et al. [3] proposed a method to estimate the position of a mirror from a color image using a mirror with markers at the four corners. However, in this method, multiple markers need to be observed in the measurement range, and it cannot be used depending on the size of the measurement environment.

In this research, we examine the method to reconstruct the shape of the front and back of the object by measurement from one viewpoint without using calibration and markers in advance. For this purpose, we propose a method to obtain the pose of the mirror from the floor plane reflected in the mirror (hereafter, reflected floor plane) in a range image. The proposed method is verified by experiments to detect a mirror and reconstruct whole shape of an object.

## 2 Method to Measure Range Images Using a Range Image Sensor and a Mirror

Figure 1 shows the conceptual diagram of the method. By arranging a mirror at an appropriate angle behind the measurement object, it is possible to simultaneously acquire range images of the front and back of the object. The front and back shapes of the object are obtained by measuring the range image directly and the range image reflected by the mirror, respectively.

As sensors for measuring range images, ToF (time of flight) range image sensors and stereo cameras, including active stereo cameras, are often used. ToF sensors are inappropriate for the use with a mirror because of the following reasons. When range images are acquired through a mirror, incorrect distance values can be obtained as follows. A ToF sensor projects a modulated light to the object, receives the reflected light from the object, and calculates distance from the phase difference between the projected and reflected lights. When a reflected image of an object is measured, the light path should be sensor, mirror, object, mirror and sensor as shown in the red arrow in Fig. 2. However, the light with the path: sensor, object, mirror and sensor as shown in the blue arrow in Fig. 2 is also obtained and produces a wrong distance value. On the contrary, a stereo camera does not have this problem, because the direct image and reflected image are reversed with different size and thus are not wrongly matched. Therefore, we use a stereo camera to acquire range images in this study.

The flow of the method is as follows. First, a mirror is placed behind the object and a range image is measured. At this time, the mirror should be placed at an appropriate angle so that the back of the measurement object reflected from the mirror can be measured by the range image sensor. Next, the pose of the mirror is estimated from the obtained range image. The method to estimate the mirror pose automatically is described in Sect. 3. Finally, coordinate transformation of the range image reflected from the mirror is performed based on the estimated mirror pose. The range image of the back of the measurement object obtained through the mirror is measured at a different position from that in real space. Coordinate transformation of those range images based on the position of the mirror makes it possible to generate a range image of the measurement target with information on the front and back. In addition, since the range image of the back of the measurement object acquired through the mirror is measured to the back of the position of the mirror, range images at positions away from the mirror plane are considered to be the reflected images in the mirror and coordinate transformation is applied to the images.

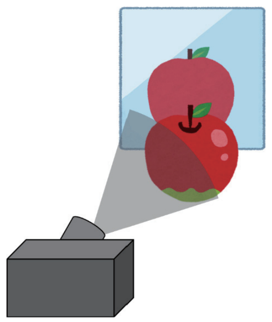

**Fig. 1.** Conceptual diagram of the method

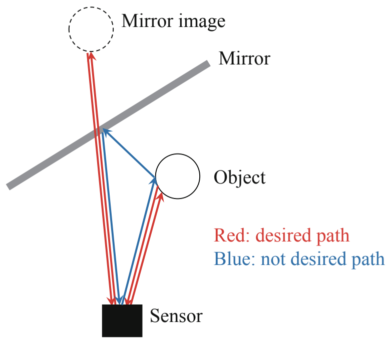


**Fig. 2.** Combination of a ToF sensor and a mirror

## 3 Detection of Mirror in a Range Image

When a scene in which a mirror is placed on the floor as shown in Fig. 3 is measured using a range image sensor, the floor reflected on the mirror is acquired as a flat plane with an inclination different from that of the normal floor as shown in Fig. 4. When these two planes are detected from the range image, the line of intersection of the two planes is the bottom of the mirror, and the angle of the mirror can be determined from the angle of the two planes. Consequently, pose of the mirror can be estimated automatically. This is possible even when a measurement target is placed in front of the mirror, provided that the mirror has a sufficient size for the measurement target and a floor plane in the mirror can be detected from the range image.

RANSAC (random sample consensus) is used to detect the floor plane and the reflected floor plane. Point clouds of the two planes can be extracted by roughly specifying the normal direction of the floor plane in advance, detecting multiple planes with normals close to the specified normal, and removing point clouds that do not belong to those planes. The floor plane and the reflected floor plane can be determined as the largest and the second largest planes, respectively.

The floor plane $P_f$ and the reflected floor plane $P_{f'}$ are expressed by the following equations.

$$a_1x + b_1y + c_1z + d_1 = 0 \tag{1}$$

$$a_2x + b_2y + c_2z + d_2 = 0 \tag{2}$$

Normal of the floor plane $\boldsymbol{n}_f$ and normal of the reflected floor plane $\boldsymbol{n}_{f'}$ are given by

$$\boldsymbol{n}_f = (a_1, b_1, c_1) \tag{3}$$

$$\boldsymbol{n}_{f'} = (a_2, b_2, c_2) \tag{4}$$

A point that lies in the line of intersection of the two planes $\boldsymbol{p}$ can be given as

$$\boldsymbol{p} = \left( \frac{d_1b_2 - d_2b_1}{a_1b_2 - a_2b_1}, \frac{d_1a_2 - d_2a_1}{a_2b_1 - a_1b_2}, 0 \right) \tag{5}$$

As the floor plane and the reflected floor plane are symmetrical with respect to the plane of the mirror, the normal vector of the plane of the mirror $\boldsymbol{n}_m$ can be represented by the difference between the normal vectors of $P_f$ and $P_{f'}$. Consequently, the plane of the mirror $P_m$ has normal vector $\boldsymbol{n}_f = (a_1,\ b_1,\ c_1)$ and passes through the point $\boldsymbol{p}$, and thus can be expressed as follows.

$$(a_1 - a_2)x + (b_1 - b_2)y + (c_1 - c_2)z + d_m = 0, \tag{6}$$

$$d_m = \frac{(a_2 - a_1)(d_1b_2 - d_2b_1)}{a_1b_2 - a_2b_1} + \frac{(b_2 - b_1)(d_1a_2 - d_2a_1)}{a_2b_1 - a_1b_2}. \tag{7}$$

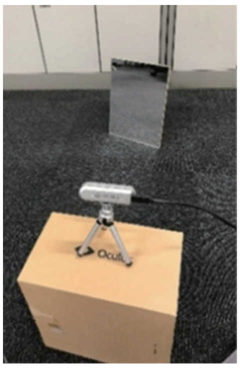

**Fig. 3.** Measurement scene with a mirror.

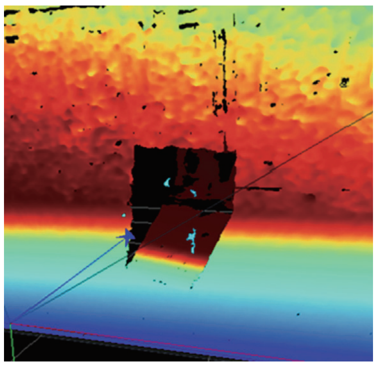

**Fig. 4.** Acquired range image for Fig. 3.

## 4 Experiments

We made experiments to detect a mirror in a range image and estimate its pose. We used the scene in Fig. 3. We used Intel RealSense D435 as the range image sensor. RealSense D435 is a stereo camera with IR pattern projection. The height and the width of the mirror are 330 mm and 220 mm respectively.

Figure 5 left shows the range image acquired in the measurement scene of Fig. 3 displayed as a point cloud. Then, we detected a plane for the point cloud in Fig. 5 left. Figure 5 center and right show the detected floor plane $P_f$ and the reflected floor plane $P_{f'}$. The parameters of the equations of the two planes, the mirror plane $P_m$ estimated from these planes, and the ground truth of the mirror plane $P_M$ are given in Table 1. $P_M$ was obtained by attaching a paper on the mirror and obtaining its range image. Figure 6 shows the range image (point cloud) with a paper on the mirror and the estimated mirror plane.

Table 1 shows that the parameters of the mirror plane are estimated accurately, and Fig. 6 shows that the estimated mirror plane fits the mirror well. In total, it can be said that the mirror plane is successfully estimated.

Figure 7 shows an example of shape reconstruction using the estimated mirror plane. It is shown that the point cloud that is directly measured and the point cloud measured using the mirror overlap seamlessly and the shape of the object is reconstructed well.

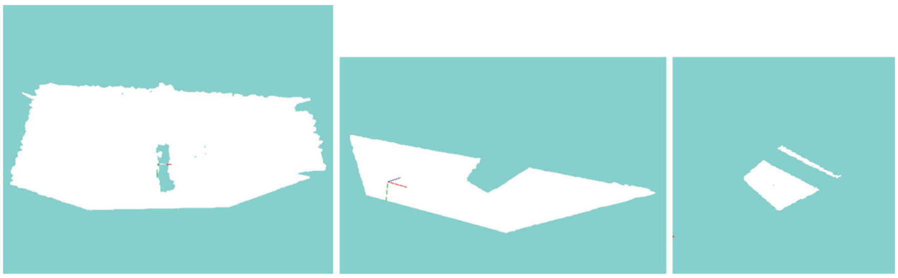

**Fig. 5.** Detection of mirror. Left: point cloud of Fig. 4, center: detected floor plane, right: detected floor plane reflected in the mirror.

**Table 1.** Parameters of each plane.

| Plane | $a$ | $b$ | $c$ | $d$ |
|---|---|---|---|---|
| $P_f$ | 0.1082 | 0.9575 | 0.2673 | −0.3814 |
| $P_{f'}$ | −0.04706 | 0.9988 | −0.01398 | −0.1638 |
| $P_m$ | 0.1553 | −0.04128 | 0.2813 | −0.2176 |
| $P_M$ | 0.1587 | −0.04599 | 0.2895 | −0.2223 |

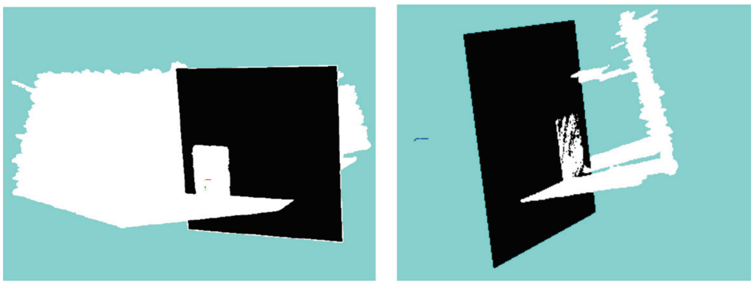

**Fig. 6.** Point cloud of Fig. 4 with a paper sheet on the mirror, and estimated mirror plane. Left: front view, right: right-side view

**Fig. 7.** An example of shape reconstruction: a stuffed toy. Left: measurement scene, center: top view, right: right-side view

## 5 Conclusions

In this paper, we proposed a method to measure the front and back of the measurement object simultaneously by using a mirror and acquiring range images from multiple viewpoints by one measurement. In addition, we proposed a method to detect a mirror and estimate its pose from the floor plane in the range image and the reflected floor plane without prior calibration and markers. The effectiveness of the methods was verified by experiments to estimate the mirror pose and reconstruct shape of an object using the estimated mirror plane.

In the future, we will conduct experiments in a measurement environment where an object is placed in front of a mirror and investigate whether the mirror can be estimated correctly.

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