Calibration of Two 3D Sensors with Perpendicular Scanning Directions by using a Piece of Paper

Ju-Hwan Lee and Soon-Yong Park
School of Computer Science & Engineering, Kyungpook National University, Daegu, South Korea

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Abstract: It is difficult to find the 3D transformation relationship between two 3D sensors when the scanning directions of the two sensors has very large angle, for example 90 degrees or more. In this paper, we propose a very simple and efficient calibration method to get 3D transformation between two 3D sensors using a piece of white-colored paper. A piece of white-colored paper is folded in a quadrangular pyramid shape. The paper calibration object is placed on the transparent acryl board to get the shape of the object from two 3D sensors whose scanning direction is about 90 degree. The performance of the proposed calibration method is verified through 3D model reconstruction experiments. The calibration error between two sensors is less than 0.5 mm.

1 INTRODUCTION

In the shoe industry in the past, customized products were only offered to people with special needs, such as medical treatment and athletic players, but many companies are doing researches to improve customer satisfaction with the recent trend. An example of customized products are customized shoes, insole and so on. To make customized shoes or insole, it is necessary to know accurate 3D shape information of customer's foot.

In the past, the foot measurements were made using callipers, tape measure and special tools such as the Foot-Measuring Instrument of Charles F. Brannock (The Brannock Device Company, 1927). Alternatively, there is also a measurement method of foot shape using clay. The above two method is called contact measurement method. However, contact measurement results in foot deformity when it is measured by a person, thus accurate results cannot always be obtained. In addition, there is a disadvantage that an accurate measurement is a time-consuming task.

In order to overcome this problem, many researches have been done to acquire 3D shape of human foot using non-contact measurement methods (Kouchi & Mochimaru, 2001), (Wibowo et al., 2017). The non-contact method measures the 3D foot shape through a 3D sensing device composed of laser, white light or pressure device. It has the advantage of

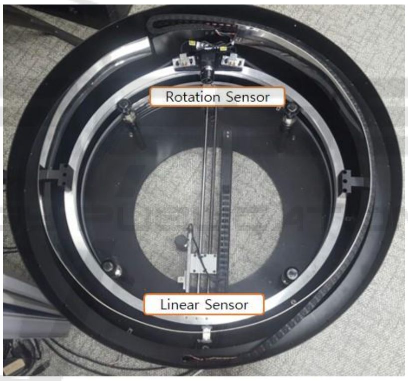

Figure 1: A circular-type 3D foot scanner using structured light sensing method.

measuring accurate shape information without deformation of foot shape and measuring faster than the contact measurement method.

Several commercial 3D foot scanners are available already. Examples are LSF-350 foot 3D scanner of 3DOE solutions (3DOE Solution, 2013), HP Fitstation's 3D foot scanner (FitStation, 2018) and Podia scanner of STT systems (STT Systems, 2018).

In general, the 3D foot scanner is equipped with two or more 3D sensing devices to acquire shape information of the entire foot. The sensor of the foot scanner normally uses structured light for precise measurement. And the scanning system consists of a lower 3D sensor which scans the sole of the foot and

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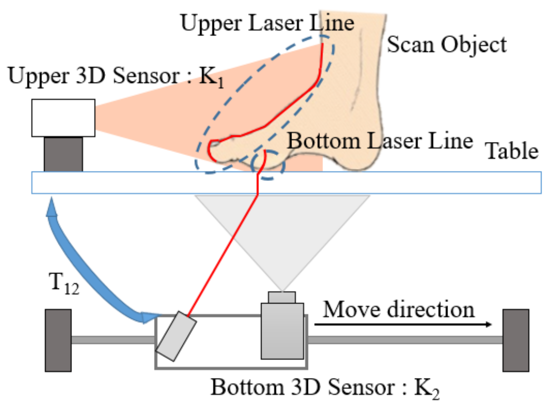


Figure 2: The circular foot scanner consists of an upper 3D scan sensor and a lower 3D scan sensor.

an upper sensor scans the upper part of the foot. The two scan results are then combined to obtain the entire 3D shape of the foot.

In a previous paper of this study (Lee et al., 2017), we developed a three-dimensional circular foot scanner with upper and lower 3D sensors to obtain the whole shape of the foot, as shown in Figure 1. For scanning the whole shape of the foot, the upper sensor moves along a circular stage and the lower sensor moves along a linear stage. To obtain the correct shape of the whole foot, it is necessary to represent the data acquired from each view point as a single view point. In order to represent the data obtained from different viewpoints as a single view point, it is necessary to know a 3D transformation relation between the two sensors.

In Figure 2, K_1 and K_2 represent the upper and the lower 3D scanning sensor coordinate systems. The 3D transformation relationship between the two sensor systems is expressed as T_{12}. T_{12} is represented by a 3x3 rotation matrix R and a translation vector t. In general, for two different cameras, the transformation matrix between two viewpoints can be obtained by the Zhang algorithm (Zhang, 2000) which uses a checkerboard. In our previous research, we also used a checkerboard pattern to find the transformation relationship between the upper and lower 3D sensors.

However, the Zhang algorithm is difficult to use for calibration between two sensors when the angle between two sensors's viewing direction is large. Unfortunately, because most foot scanners use multiple 3D sensors to obtain soles and foot shapes, the viewing angles between the sensors are often more than 90 degrees. In this reason, some researches have been done to calibrate 3D sensors with large between large viewing angle by using special calibration objects.

(Barone et. al., 2013) calibrates two sensors by placing printed markers on an object. Using markers has an advantage of being able to know the direction of the object and clearly identify the feature points for correction, but placing printed markers on the object is an inconvenient method. (Mitchelson and Hilton, 2003) use a specially designed LED pattern to calibrate two sensors. Another calibration method is using three or more checkerboard pattern attached perpendicular each other on a cube box. But it is not easy to make two or more sensors see the three checkerboard pattern simultaneously.

When a 3D scanning system consists of multiple 3D sensors with large viewing directions, it is difficult to calibrate the sensor coordinate systems. In the previous researches, only specially designed calibration objects and algorithm are used. In addition, because the 3D scanning systems of the previous researches have different structure than our scanning system, it is not easy to employ the previous methods.

In this paper, we propose a very simple and easy calibration method for the calibration of two 3D sensor systems. Especially the proposed method is applied for the calibration of our 3D foot scanning system. We evaluate the performance of the proposed method by obtaining the 3D model of the human foot using the transformation between the two 3D sensors.

2 CALIBRATION METHOD USING A PAPER OBJECT

The authors of this paper have reflected on how to calibrate between two sensors that are more than 90 degree easily and simply. And making of the calibration object was also focused on using materials that are readily available from around, so that anyone can calibrate easily the two sensors. Therefore, the criteria of the proposed calibration object are as follows:

1. The material of the calibration object should be readily available from around.
2. The making of the calibration object should be easy enough for everyone.
3. Algorithms for calibrating between the two sensors using a calibration object should also be simple.

2.1 Calibration Object using One Piece of Paper

As described in the introduction, specially designed calibration objects can be used for our foot scanner. However, it is not easy to make a special calibration object, such an exact square-shape board, attaching LED patterns, and attaching printed markers on an object.

In this paper, we try to find a simple and efficient method for calibration of two 3D sensors which have orthogonal scanning directions. We propose a very simple solution by using an easily available piece of A4 paper. First we make a quadrangular pyramid object using a piece of A4 paper and use both sensors to scan the inside and outside shapes of the object. And then we calibrate between the two sensors by matching the 3D shapes. The background of making the calibration object using an A4 paper is as follows:

- The thickness of one piece of A4 paper is less than 0.1mm.
- After making a quadrangular pyramid object with a single piece of A4 paper, the inner and the outer of the object are scanned. Then the two scan data can be matched with only 0.1 mm error, which is negligible.
- A piece of A4 paper can be easily obtained from around.

Figure 3 shows how to scan a calibration object made with a piece of paper from two 3D sensors. As shown in the figure, if the scanning of the calibration object consisting of 3D data from an upper sensor and a lower sensor, each sensor can acquired 3D surface data of the inside and outside of the calibration object. The shape of the calibration object does not matter, while the shape of the calibration object used in this paper is a pyramid shape that is easy to make, and one edge of the pyramid is cut out to find the direction of the object.

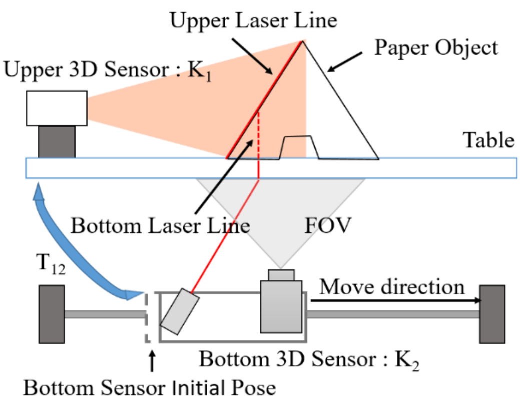


Figure 3: How to scan a calibration object made from one paper with two sensors. We can obtain 3D scanning data of the inner and outer surfaces of calibration objects from two sensors.

Any other shape or material can be used for calibration object, but it should be very thin. The thinner the portion corresponding to the side of the calibration object, the less the calibration error between the two sensors. In this paper, we make a calibration object with the shape of a pyramid that is easiest to make with a piece of paper.

2.2 Calibration Method

In order to represent the data acquired at different viewpoints as a single coordinate system, we should find 3D transformation relationship between two sensors by using the calibration object. The transformation matrix T_{12} between the two sensors can be expressed as Eq. 1.

$$T_{12} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

When the calibration object is scanned by the two 3D sensors, the acquired scan data of the calibration object is represented by the coordinate system of each sensor.

If there are 3D surface information of the same object at different viewpoints, the 3D transformation matrix between two sensors can be simply found using the well-known ICP (Iterative Closest Point) algorithm (Besl and McKay, 1992). Since the scan resolution of each sensor is different, the 3D transformation matrix T_{12} between the two sensors can be obtained using the point-to-plane ICP algorithm (Low, 2004).

Figure 4 illustrates how to use the point-to-plane algorithm to find the 3D relationship between two sensors. In the figure, two 3D surfaces of the scanned object by sensors K_1 and K_2, are 'K_1 surface' and 'K_2

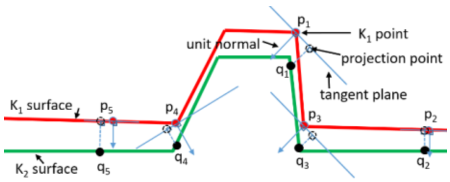


Figure 4: How to use the point-to-plane algorithm to find the transformation matrix between two points.

surface', respectively. And the points on the surface are expressed as p_i and q_j. Ideally speaking, two 3D shapes of the calibration object scanned by both sensors must be the same.

First, the unit normal for all points p_i on the 'K_1 surface' is calculated by using neighbour points of p_i. Then, the 3D point q_i on the 'K_2 surface' which is closest to p_i on the 'K_1 surface' is projected onto the tangent plane of p_i. Therefore we can find p'_i on the tangent plane of p_i, as the correspondence of q_i as shown in Eq. 2. By minimizing the error ε, we can find 3D transformation matrix T_{12} in which the sum of the distances of p'_i and q_i is minimized by using LSM (Least Square Minimization).

$$\varepsilon = \sum_i \| (\mathrm{T}_{12} q_i - p'_i) \bullet \mathrm{n} \| \tag{2}$$

The above point-to-plane ICP can be expressed as follows pseudocode code.

```
-----------------------------------------------------------------
T_12 = InitializeMatrix
n_i  = UnitNormal(nearThreepoints q_i)
While(ε > T_ε)
   // Find the corresponding point q_i where the
distance between p_i and q_j is minimum…
  q_i = MinDistancePoint(q_j)
  // Find the T matrix that minimizes the error...
  Tε = Σ_i ‖ (T q_i − p'_i) • n_i ‖
  T_12 = T_12 T
  // Convert q_j to global coordinate system
  q_j = T_12 q_j
-----------------------------------------------------------------
```

Theoretically, when a calibration object made using a piece of paper is scanned with two sensors, the 3D transformation relationship between the two sensors is obtained perfect. However, because the paper thickness, there is a 0.1mm translation error between the two sensors. In this paper, we consider that this small error is negligible in the application of our 3D foot scanner.

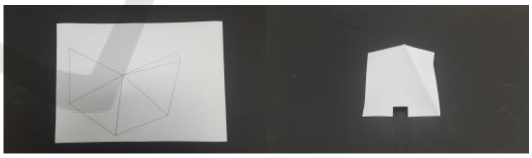
3 EXPERIMENTS

To verify the performance of the proposed method, we used a circular 3D foot scanner as shown in Fig 5. As shown in the figure, the upper 3D sensor of the circular scanner is designed to rotate along the center axis of the turntable and scans the instep of the foot. The upper 3D sensor consists of one vision camera and two line lasers.

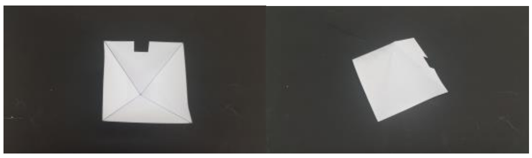
The depth of the scanned object surface is calculated by detecting two line lasers projected on the instep of the foot from the image of the camera. Therefore, the rotation sensor scans partial surface of the foot. The lower 3D sensor of the circular foot scanner consists of one laser and one camera. The sensor is mounted on a linear stage, so it scans the bottom part of the foot. The angle of the upper and lower sensors is almost 90 degree, but not exactly.

Figure 5: A circular 3D foot scanner for experiments.

To calibrate 3D relationship between the two sensors, a piece of A4 paper is used. By folding the paper, we make a pyramid-shaped calibration object as shown in Figure 6. Any other shape of object can be use if the object's outer and inner surface has enough geometry for ICP matching. The size of the object is very appropriate for 3D scanning with our foot scanner. At the one side of the pyramid, there is a cut-out to distinguish the direction of the object as shown in the figure.



(a) (b)



(c) (d)

Figure 6: Photographs of the calibration object (a) shows the schematic of the calibration object drawn on a piece of A4 paper, (b) shows outer surface of the object which is scanned by the upper sensor, (c) shows inner surface of the object which is scanned by lower sensors, (d) shows a side view of the calibration object.

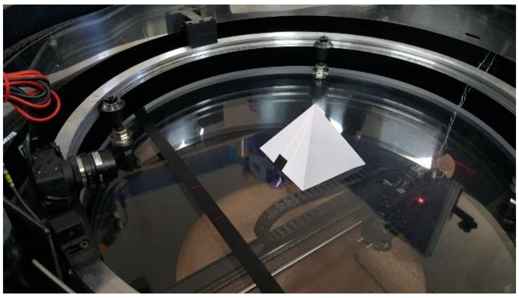


Figure 7: A pyramid object placed at a position visible from both 3D sensors.

As shown in Figure 7, the calibration object is placed at the center of the circular scanner, and the calibration object is scanned using both the upper and lower sensors of the scanner. Figure 8 shows images of the calibration object captured from the two cameras. Figure 9 shows the 3D scanning results from the two sensors. Since the scanned information of the object is expressed based on the coordinate system of each sensor, the surface information of the object scanned by the two sensors in the single coordinate system can be expressed as shown in Fig 9 (e).

Using the point-to-plane ICP algorithm described in Section 2.2, we can calculate the three-dimensional transformation relation between two sensors with the 3D surface information of the calibration object scanned by each sensor. Figure 10 shows the results

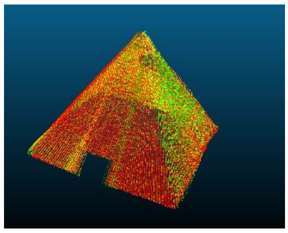


Figure 10: ICP matching result of the two scanned shapes.

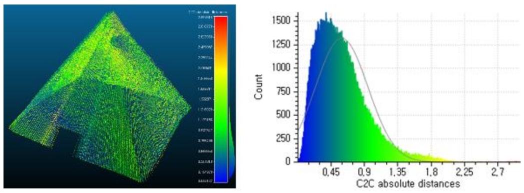


Figure 11: Matching error between the two 3D shapes after ICP transformation.

of the point-to-plane ICP algorithm between the two sensors. It looks that two shapes are matched exactly since the color of the two shapes are overlapped. Therefore, we can confirm that the surface information of the calibration object expressed in different coordinate systems is transformed to one coordinate system.

To analyse the transformation error, the ICP matching error is shown in Figure 11. From 3D points on the 'K_1 surface', we find the closest points on the

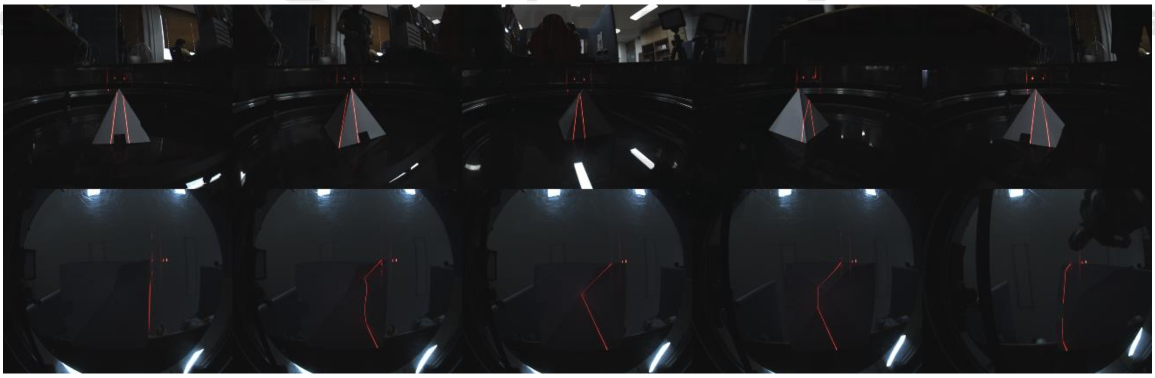


Figure 8: Images obtained from the upper and lower sensors of the foot scanner.

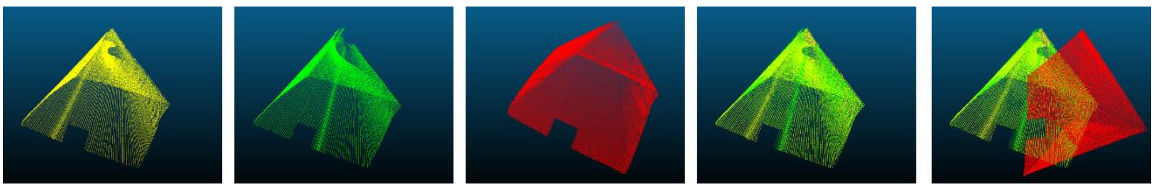


Figure 9: (a) and (b) shows the scanned 3D points of the calibration object using the left and right lasers of the upper 3D sensor, (c) shows the scanned 3D points using lower sensor, (d) shows 3D points that combine (a) and (b), (e) shows two scanned shapes by the upper and lower sensors in the upper sensor's coordinate system.

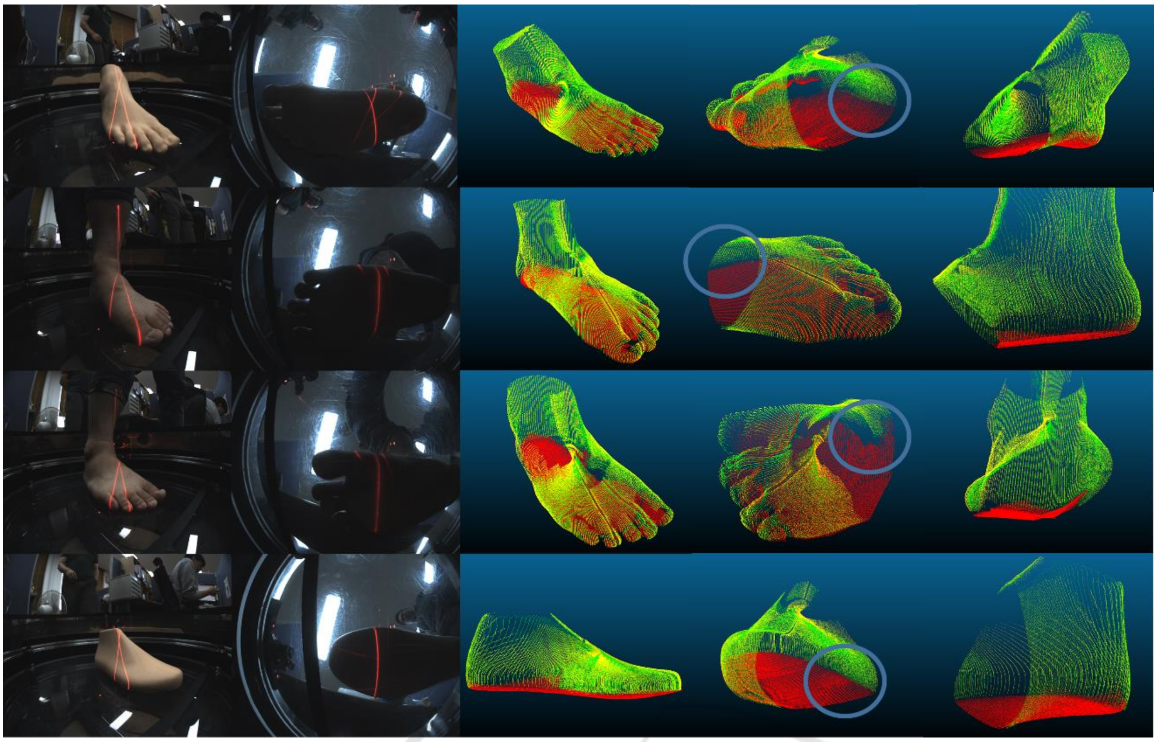


Figure 12: Results of 3D foot models by using the transformation relation between two sensors. From the top, 3D models of a plastic foot model, human left and right foot, and a plastic raster of shoes.

'K_2 surface'. The distance between the closest matching points is measured and displayed in Figure 11. The overall trans-formation error is less than 0.5 mm on average. Theoretically, the 3D reconstruction error of the foot scanner is 0.1mm, because it is the thickness of the paper object. However, in real experiments, the 3D foot reconstruction error is more than 0.1 mm. The 3D reconstruction error mainly due to two reasons. The first is the thickness of the paper and the second is the reconstruction error of each 3D sensor.

After the calibration, we know the 3D transformation between two sensors. Using the calibration data, the foot scanner can be used to reconstruction various models after scanning the object using two sensors. Figure 12 shows results of modelling after scanning various objects on the foot scanner. The results show that the 3D model of human foot obtained from the scanner. The upper and the lower 3D shapes are matched very exactly. In the enlarged part of the 3D model, we know that 3D shapes of two different sensors are aligned very exactly.

4 CONCLUSIONS

It is difficult to find the 3D transformation relationship between two sensors when the angle between the two sensors is perpendicular or 90 degrees or more, such as a foot scanner. Therefore, in this paper, we propose a simple method to find the 3D relationship between two sensors with a paper calibration object. The calibration object proposed in this paper has advantages that it can be easily made by anyone and it is easy to obtain an A4 paper. The transformation relationship between the two sensors was obtained by using the calibration object, and the performance of this paper was verified by reconstructing 3D models of human foot.

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