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Shape measurement system of foot sole surface from flatbed scanner image

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Abstract

We present a system to measure 3D shape of sole surface of human foot using flatbed scanner. Our goal is to build a low cost system for reconstructing sole surface of human foot using flatbed scanner for making tailored shoes. There are two main phases in our system: a photometric parameter estimation and a reconstruction phase. The photometric parameter estimation calculates the position of the light source in the scanner. The reconstruction phase uses iterative algorithm to calculate normal vector and the depth information. First, we implement photometric parameter estimation by scanning some white paper in several slant and rotation angles. We conducted some experiments to obtain the best slant and rotation angle combination for calculating light source position of the scanner. We also propose a new method for estimating light source position of the scanner using foot model. Next, we conduct reconstruction phase by scanning user's foot. We then apply median filter with 5×5 mask sizes to remove the noise in scanned image. By using the calculated light source position from the previous step and pixel intensity of scanned image, depth and normal vector are calculated iteratively. We acquire more accurate light source position by comparing albedo ratio and finally we acquire the 3D shape which average error compared with ground truth data is up to 0.97mm.

1 Introduction

Foot shape reconstruction is required for capturing customer's foot shape at shoes shops. This should be low-cost for making all shoes shops can have such system.

Laser scanning system [1] is a one practical system, but it is expensive, and even some customers are afraid of laser illumination. Kouchi et al.[1] and Lee at al.[2] have applied Free Form Deformation (FFD) to the basic shape acquired from database. By using deformation they produce shoes model as captured from customer's foot. Such system is good for the average shape of the foot. However, we still need a suitable shape for each of user's foot without depending on model database.

Amstutz et al.[3] and Lee et al.[2] have proposed system using multiple cameras and database to create average model and to produce foot model by calculating major foot parameters. Particularly, sole shape is very important for foot reconstruction, while these systems can not reconstruct it.

Flatbed scanner is normally used for various purpose in recent years such as digitization of documents and photography. Optical Character Recognition (OCR) as one of technology using flatbed scanner made it is easier to find digital content of many books and literatures. Now we will use flatbed scanner for digitizing part of human body such as reconstruction of sole shape. Particularly we can come up with an application that can be used in general purpose scanner. It can easily be distributed into every shoes shop.

Takahashi et al.[4] have proposed a measurement of hand 2D shape using scanner image. This system measures shape of human hand using silhouette information and database to create personal information.

Reconstruction system have been proposed to reconstruct unfolded book shape using image scanner [5]. Unfolded book has specific shape which can be modeled as polynomial surface. Scanner itself has light sources which can be categorized as proximal light (where light is located close to the object surface). Using scanner properties and approximation based on polynomial model, their method can also recover the shape of book surface. However, this system only covers shape of object which can be modeled as polynomial surface.

This paper proposes a new system to reconstruct 3D shape of foot sole surface using flatbed scanner based on implementation of 3D shape reconstruction using three light sources in image scanner[6]. Human sole surface skin is assumed to be uniform in albedo and lambertian surface which ideally fulfill this method requirement.

The differences of our system with the other system are our proposed method only takes into account scanner parameters and intensity information of sole surface of human foot. Moreover, flatbed scanner uses lamps as light source for scanning. Hence it assures the user's safety of its effect.

2 Proposed Method

We implement a reconstruction method using flatbed scanner [6] to reconstruct sole surface of the foot. Foot sole skin has the same color over the surface (constant albedo) and it has no reflection over the surface (lambertian surface). It has specific patterns (friction ridges) which make reconstruction of sole shape needs more effort. We assumed the light from the environment has no effect on scanning process and no inter reflection from the sole surface nor the environment are taken into account. Our method is divided into two phases: photometric parameter estimation and reconstruction (Figure 1).

To evaluate our system, we calculate the difference

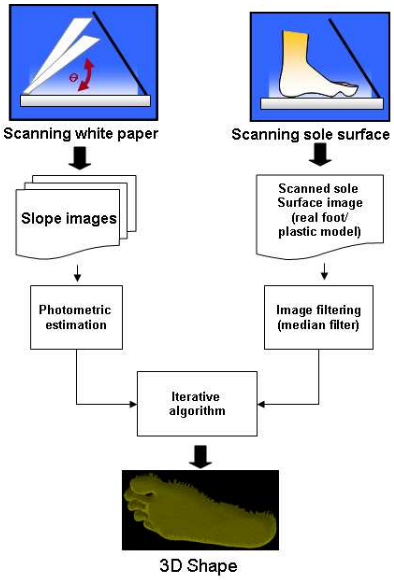


Figure 1: Reconstruction Flow

between measured 3D points with ground truth model file.

2.1 Photometric Parameter Estimation

Scanner has several fixed properties for reconstruction such as camera position, gain, bias, and light position. Photometric estimation is done to calculate the light position in the scanner. Using a method in [6], we conducted several experiments to estimate scanner's light source position. First we calculate many scanner parameters by scanning white paper in some slant angles (θ) and rotation angles (ψ) position (Figure 2).

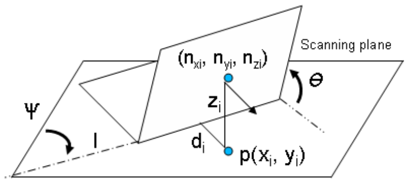


Figure 2: Position of white paper (slope)

We selected many intensity samples of the scanned white paper. Let $p_i(x_i, y_i)$ be a point in the slope of the scanned image, d_i is the distance between p_i and line l, we can compute height z_i and normal vector (n_{xi}, n_{yi}, n_{zi}) using the relation in the Eq. 1.

$$\begin{aligned} z_i &= d_i \cdot \tan\theta, \\ n_{xi} &= \sin\psi \cdot \sin\theta, \\ n_{yi} &= \cos\psi \cdot \sin\theta, \\ n_{zi} &= -\cos\theta \end{aligned} \qquad (1)$$

We can model foot sole skin as lambertian surface using Eq. 2. Here we model the intensity for color element red (P_r) as follows:

$$P_r(x_i, y_i) = a_r \cdot \rho_r \cdot Is_r(x_i, y_j) \cdot \cos(\phi_r(x_i, y_j)) + \Delta_r \quad (2)$$

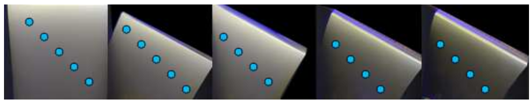


Figure 3: Clicking points over white papers slope

where a_r and δ_r denote the gain and the bias of the photo-electric transformation in the image scanner respectively. ρ_r is the albedo on the surface for the red light source. Intensity of green element (P_g) and blue element (P_b) are computed in the same way.

By using the light source model we model the illuminant intensity of the light source of each component color as:

$$Is_r(x_i, y_i) = \frac{\alpha_r}{\sqrt{(d_{yr}^2 + (z(x_i, y_i) - d_{zr})^2}} + Ie_r \quad (3)$$

where $z(x_i, y_i)$ is the height from scanning plane to the object surface, (d_{yr},d_{zr}) is the position of the light source of scanner (lamp) relative to edge of scanning plane.

$\phi_r(x_i, y_i)$ is the angle between normal vector (n_{xi},n_{yi},n_{zi}) and the direction from the surface to the red light source declared as:

$$\cos(\phi_r(x_i, y_j)) = \frac{d_{yr} \cdot n_y(x_i, y_j) - n_z(x_i, y_j) \cdot (z(x_i, y_j) - d_{zr})}{\sqrt{d_{yr}^2 + (z(x_i, y_j) - d_{zr})^2}} \quad (4)$$

The red intensity of selected points from the slope image is inputted to the Eq. 2, Eq. 3, and Eq. 4 to calculate d_{zr}, d_{yr} ,Δ_r,a_r, α_r, and ρ_r. The equation is solved by using linear least squares. This process is repeated for the green and blue component to calculate d_{zg}, d_{yg}, Δ_g, a_g, α_g, ρ_g, d_{zb}, d_{yb}, a_b, Δ_b, α_b, and ρ_b. We then use optimization algorithm to get optimal parameters.

However, photometric parameter estimation using white paper depends on slant and rotation angles. Here, we propose new method by replacing white paper with white foot model and its known depth and normal vectors. By using this model we assumed we will acquire more accurate approximation of scanner parameters.

First, we scan white foot model using the same scanner. We then adjust the coordinate system of 3D model and the scanned image. Then we project every vertex in the sole part of associated model file into the scanned image. Here we acquired the intensity of every vertex (Figure 4). By inputting the pixel intensity, normal vectors and depth from foot model into Eq. 4 we can calculate the scanner parameters using the same method as white paper slope.

2.2 Shape Reconstruction

To reconstruct sole part of the foot, first we scanned user's foot. Then the scanned image is inputted to the system. Sole skin has a ridge pattern which will be a noise in the shape reconstruction system. This noise can be removed by applying median filter (5x5 masks) to the input image.

Next step is determining the albedo of the sole surface. We can not compute the albedo of the sole

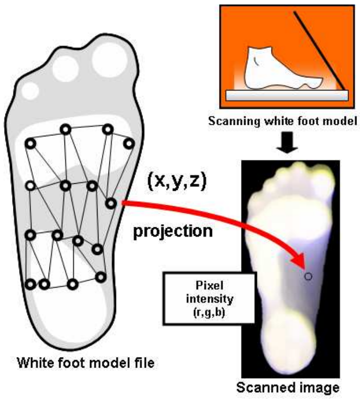


Figure 4: Photometric Parameter Estimation using foot model slope

directly, therefore we compute the albedo ratio with white surface object albedo in the photometric parameter estimation process (Eq. 5). To calculate the albedo ratio (ρ'), we select a pixel (P_{r0}) in the scanned image which seems touches the scanning plane. Then we calculate the albedo ratio using Eq. 6.

$$\rho'_r = \frac{\rho_r}{\rho_{wr}} \tag{5}$$

$$\rho'_r = \frac{P'_{r0} - \delta_r}{Is_{r0} \cdot \cos(\psi_{r0})} \tag{6}$$

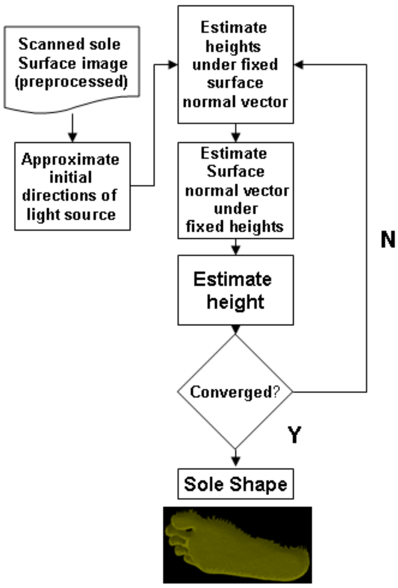


Figure 5: Reconstruction phase

$$P_r(x_i, y_i) = \rho'_r \cdot \alpha_r \cdot \rho_r \cdot Is_r(x_i, y_j) \cdot \cos(\phi_r(x_i, y_j)) + \Delta_r \tag{7}$$

We then input the intensity information of red, d_{zr}, d_{yr}, Δ_r, a_r, α_r, ρ_r, and ρ'_r into Eq. 7. Here we iteratively calculate the $n_y(x_i, y_j)$, $n_z(x_i, y_j)$ and $z(x_i, y_j)$ until the height converged (Figure 5). Since there are three intensity components (red, green and blue), the produced height is average of $z_r(x_i, y_j)$, $z_g(x_i, y_j)$, and $z_b(x_i, y_j)$. We iterate this process for every pixel in the image.

Table 1: Albedo Ratio

slant and rotation angle	ρ'_r	ρ'_g	ρ'_b
10°-0°	0.89	0.76	0.6
10°-0°,30°-30°	1.25	1.21	0.92
30°-30°	1.4	1.24	0.87
45°-30°,30°-20°	-6569.93	1.48	2151.64
40°-60°	-12.74	1.44	0.74
30°-20°,40°-60°,10°-60°	1.21	1.21	0.69

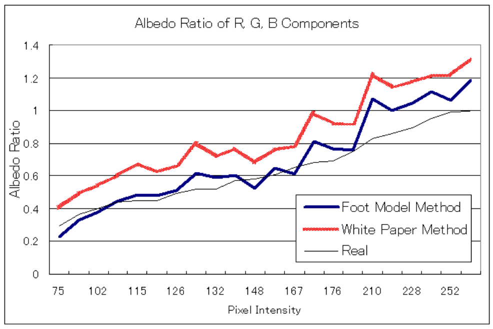
3 Experiments and Result

We use Epson GT-8700F flatbed scanner for experiments. The image resolution used for the input image is 99×257 pixels. The scanning process is done without interference of light from environment.

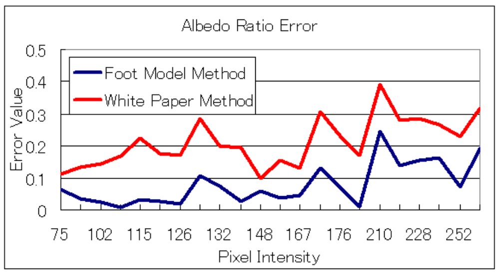
We selected one pixel (red = 175, green = 149, blue = 106) which seems to touch scanning plane. We analyzed between the calculated albedo ratio (Table 1) and the reconstruction result.

Through set of experiments we obtained photometric parameters such as d_z, d_y, δ, and ρ'. We choose albedo ratio (ρ') which lays close to range from 0 to 1 which means the color intensity is around 0 to 255 (see Table 1) for reconstruction phase.

We also did experiments using foot model for estimating photometric parameters. We choose some pixel intensities in the image and compare the calculated albedo ratio using white paper in 10°-0° angles, foot model, and the real albedo ratio as shown in Figure 6(a). The benefit of using foot model are this method doesn't depend on the slant and rotation angles and the albedo ratio is more accurate. The accuracy compared with real albedo ratio is shown in Figure 6(b).



(a) Albedo Ratio Average



(b) Albedo Ratio Error

Figure 6: Albedo Ratio

In the reconstruction phase, we scanned user's foot

Table 2: Evaluation

Sampling	Median Filter	average distance using white paper (mm)	average distance using foot model(mm)
1	1	1.911	0.973
2	1	1.949	1.014
3	1	1.995	1.058
4	1	2.046	1.128
5	1	2.135	1.170
1	3	1.916	0.968
2	3	1.948	1.007

(Figure 7(a)). We then applied sampling and median filter with 5×5 mask size (Figure 7(b)) to remove noise due to friction ridges. We calculate the depth and normal vector to produce 3D shape. Sampling from one pixel to five pixels is depicted in the Figure 8 and the result of using median filter as shown in Figure 9.

(a) Scanned Image (b) Median filter is applied

Figure 7: Input Images

4 Evaluation

We use a foot model and its ground truth file to measure reconstruction accuracy. This foot model was scanned and we reconstructed 3D shape by using our system. We reconstruct 3D shape using two ways of photometric parameter estimation: using white paper method and foot model method.

For comparing two meshes, we implemented registration onto 3D shape from our system and ground truth file. We created many sole shapes under different conditions. We set sampling from one pixel to five pixels. And the median filter was applied one to five times for preprocessing.

The average distance is calculated between every point in both 3D shapes using Attribute Deviation Metric method [7]. The minimum mean error is reached in conditions: no sampling, the median filter is applied three times (Table 2).

5 Conclusion

We have presented a system for reconstructing 3D shape of sole surface of human foot using flatbed scanner. Even using a flatbed scanner we can estimate 3D

Figure 8: Reconstruction with sampling (1 to 5 pixels)

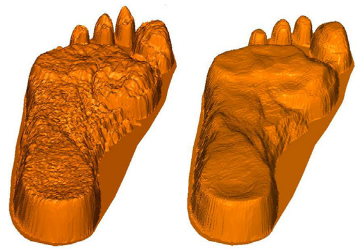


Figure 9: Reconstruction with median filter

shape of the sole surface of the human foot with a minimal error up to 0.97mm. Hence, we can make flatbed scanner as a simple and low cost 3D shape reconstruction device for human body. There are some issues of sole shape reconstruction using scanner. Scanning position of user will lead to a problem since the intensity of the sole skin changes due to the pressure to the scanning plane. Moreover, some pattern of the foot due to injury, friction, or damage on the sole skin will make reconstruction process more difficult. In the future, the ergonomic aspect of the human should be considered for reconstructing sole shape to make application for shoes designers.

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