3D Shape Reconstruction of Sole Surface of Human Foot using Flatbed Scanner

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Abstract We present a system to reconstruct 3D shape of sole surface of human foot using flatbed scanner. Our system consists of two parts: photometric parameter estimation and reconstruction. Photometric parameter estimation calculates the position of the light source in the scanner. The reconstruction phase iteratively calculates normal vector and the depth to produce 3D shape. Due to ridge pattern in foot sole, reconstruction result can not produce smooth shape. We apply median filter to remove noises to make smooth sole shape. Hence, reconstruction result from our system has an average distance compared to ground truth model up to 1 mm.

1 Introduction

A measurement is necessary to obtain the precise foot shape. Many systems have already been developed using various techniques and devices. A good system produces accurate result but has drawbacks in size or complexity. We should consider ergonomics and comfortability aspects to build such a system.

Reconstruction system using laser had already been proposed [1]. Disadvantage of this system are the system is expensive, it needs special device, big in size and makes the user afraid of the laser illumination.

[2] has proposed a system which uses stereo vision to reconstruct all part of the foot. Disadvantages of this system are it needs multiple cameras and their positions should be configured before using the system. However, this research only cover the upper part of the foot. Sole part (lower part of foot) has not been considered yet.

[3] has proposed a reconstruction system of human internal organ using single medical image by applying shape from shading method. However they have to roughly estimate light source position from single the medical image using human eyes. Therefore fixed light source position estimation is important to improve accuracy of reconstruction result.

Another approach based on Deformation has been proposed [4]. By using average shape in database of foot shape, they deform initial shape in some important part of the foot to create last (upper part of shoes) design for shoes, while sole part is not considered.

Another reconstruction system has 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, [5] can also recover the shape of book surface. However, foot sole is not easily modeled as polynomial surface and it this shape varies from person to person. Therefore this method is difficult to apply to human foot.

This paper proposes a system to reconstruct sole surface of human foot using flatbed scanner. Sole part is the lowest part of the foot and is very important part to design shoes. We implement 3D shape reconstruction using flatbed scanner presented in [6]. Human sole surface skin is assumed to be uniform in albedo. Therefore [6] is assumed worked for sole surface reconstruction.

2 Proposed Method

We implement [6] for measuring 3D shape from sole of human foot. Suitable condition for this method is foot skin has constant albedo and it has no reflection over the surface (Lambertian surface). We assume light from the environment has no effect to scanning process and there is no inter reflection from the sole surface nor from the environment . For reconstruction step (Figure 1), first we scan user's foot above the flatbed scanner plane. We segment the sole area manually. We then apply median filter to remove noise which appears due to friction ridges/fingerprint of the sole skin. To evaluate our system, we calculate the difference between measured 3D points with a ground truth model file.

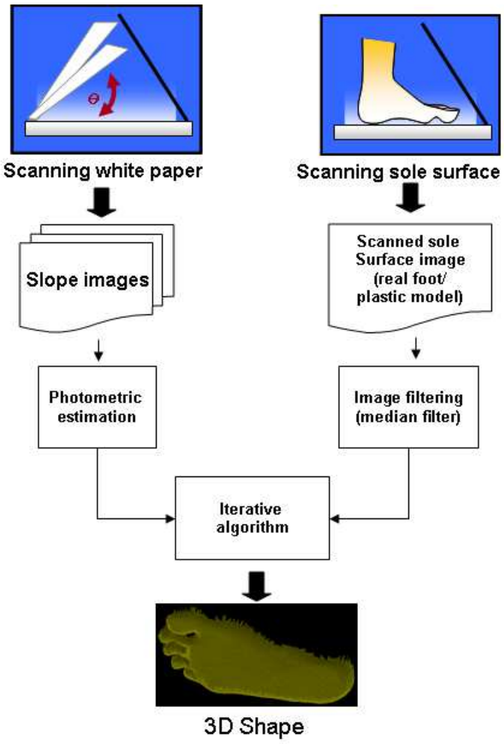


Figure 1: Reconstruction Flow

2.1 Photometric Parameters Estimation

Scanner has several fixed properties for reconstruction such as camera position, light position, gain, and bias. Using the [6] method, we conducted several experiment to estimate the light position of the scanner. First we calculate many scanner parameters by scanning white paper in some slant angles (θ) and rotation angles (ψ) position (Figure 2). This step can be done off-line before the reconstruction step. For applicable system in the shoes shop, this parameters is saved to be configuration file of the system.

We selected many intensity samples of the scanned white paper (Figure 3). In Figure 2, 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

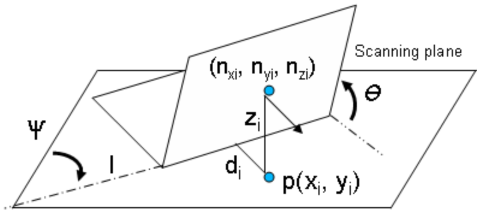


Figure 2: Slope white papers configuration

compute height z_i and normal vector (n_{xi},n_{yi},n_{zi}) using the relation in the Eq. 1.

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

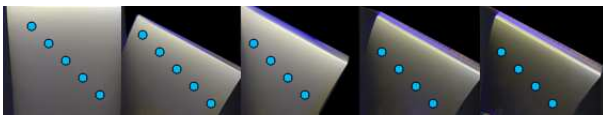


Figure 3: Clicking points over slope white papers

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:

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

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 calculate 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.

2.2 Image Filtering

Sole and palm skin has specific patterns which are called friction ridge or fingerprint for palm. These patterns will produce noise when we scan the sole surface using flatbed scanner. Since we consider pixel intensity for reconstruction process, the difference color in intensity of this pattern will produce zig-zag result in the produced model.

To remove such noises, we apply median filter and sample the image in reconstruction process. We apply median filter 5x5 mask to input image several times.

2.3 Shape Reconstruction

After the scanning and the filtering step, next step is determining the albedo of the sole surface. We can not compute the albedo of the sole 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.

$$\rho'_r = \frac{\rho_r}{\rho_{wr}} \quad (5)$$

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

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

We then input the intensity information of red ($Is_r(x_i, y_j)$), 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 4). 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.

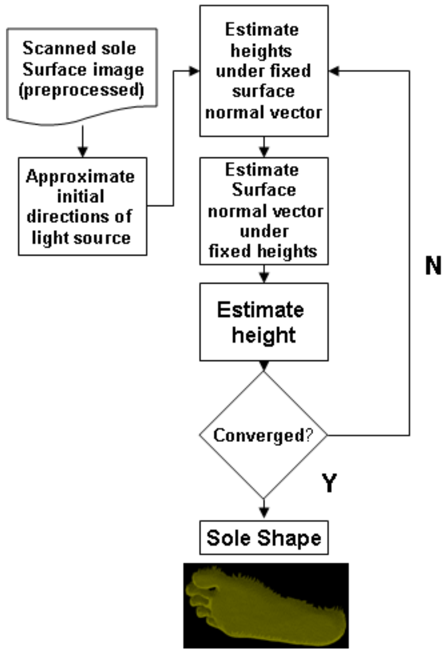


Figure 4: Reconstruction phase

3 3D Data Representation

Reconstruction phase iterates/scan pixels from the input image. We obtain 3D points from every pixel in input image. Therefore, we choose vertex-edge-face representation for representing 3D shape of reconstruction result. Since ground truth file also uses Vertex-edge-face representation, comparison between two model is easy to implement.

4 Experiments

We use Epson GT-8700F flatbed scanner for experiments. Scanner parameters (light source position and illumination properties) are calculated using photometric parameter estimation. First, we scan some white paper in some positions (slant and rotation angle). We obtain best slant and rotation angle 10° and 0° and 30° and 30° for parameter estimation.

We conduct some experiments to get good combination of slant and rotation angle of the slope paper in the photometric parameter estimation. In reconstruction we choose many combinations of the angles to produce minimal error with the ground truth.

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

Table 1: Albedo Ratio

slant & 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

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. Albedo ratio value which isn't close to 0 to 1 range will fail to produce good shape in reconstruction process (Figure 5(d) and Figure 5(e)).

5 Result

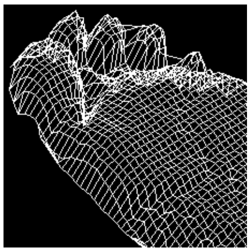
In the reconstruction phase, we scan user's foot. We then applied sampling and median filter with 5×5 mask size to remove noise due to friction ridges (Figure 6(a)). We calculate the depth and normal vector to produce 3D shape (Figure 6(b)). Sampling from one pixel to five pixels is depicted in the Figure 8 and the result of using median filter is depicted in Figure 9.

Computation time of reconstruction process depends on scanned image dimension and pixel sampling. If we use big input image dimension and we take into account every pixel, computation time will be slower.

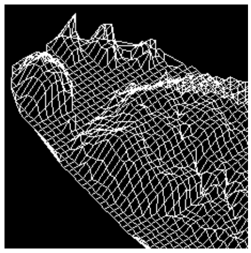
6 Evaluation

We use a ground truth file of human foot to measure reconstruction accuracy. We use a foot model (Figure 7(b)) and ground truth file (Figure 7(a)) acquired by laser system. This foot model was scanned and we reconstructed 3D shape by using our system (Figure 10(b)).

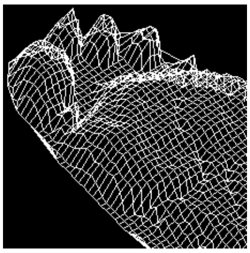
The ground truth file has dimension 257.089×102.148×110.089 units (Figure 7(a)) with 138,484 vertices and 276,783 faces. For registration, we manually cut the sole part of the model so it has dimension of 257.089×102.148×32.068 units (Figure 10(a)) with 59,381 vertices and 117,569 faces.



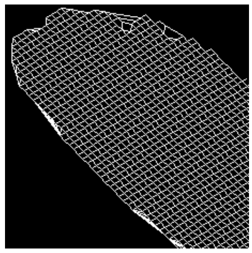
(a) 10°-0°



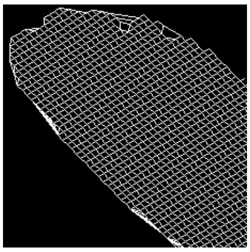
(b) 10°-0°,30°-30°



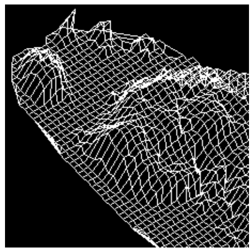
(c) 30°-30°



(d) 45°-30°,30°-20°



(e) 40°-60°



(f) 30°-20°,40°-60°,10°-60°

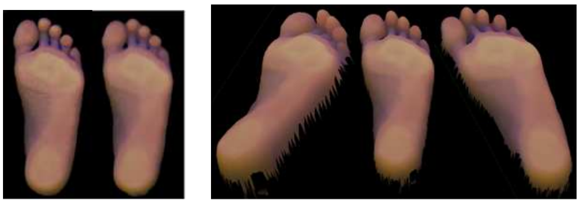
Figure 5: Reconstruction result

For comparing two meshes, we have 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. The median filter was then 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 these conditions: no sampling, the median filter is applied three times (Table 2) or without applying median filter. These condition are true only for foot model since foot model has different surface (smooth surface) with human foot. Big differences mainly occured in the side part of the sole (Fig 12). Biggest differences are displayed as red region in deviation map and smallest differences are displayed as blue region.

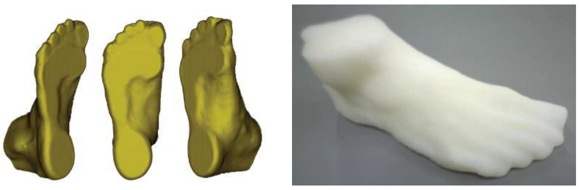
7 Conclusion

We have proposed a system to reconstruct 3D shape of sole surface of human foot. Our system con-



(a) Input image (b) Result with texture

Figure 6: Result



(a) 3D shape (b) Foot Model

Figure 7: Ground truth

sists of two parts: photometric parameter estimation and reconstruction. Through experiments we calculated best slant and rotation angle for photometric parameter estimation. We applied median filter to remove noise due to friction ridge in sole surface.

Even we use a flatbed scanner and one single scanned image we can correctly reconstruct 3D shape of the sole surface of the human foot. Hence, we can utilize flatbed scanner as a simple 3D shape reconstruction device for human body.

Shoemaker can easily use our proposed system in their shops. It doesn't need any difficult configuration and reconstruction process is also fast depending on scanning resolution.

However, we still have to consider the client's needs for shoes comfortability. Our system depends on the albedo of the skin surface. Difference of albedo in sole surface will affect the method and the result of the reconstruction phase. Problem will also appear if shape of the shoes should adjust to pain cause by blister (small fluid pocket due to friction) which mostly happen to many athletes. Therefore special treatment in the sole design need to be added.

8 Future Works

One possibility of a improvement of our system is using double scanning and using two images input with different position of the scanner. The method may be assumed to work using photometric stereo method. By knowing the position of the light source

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

Figure 9: Reconstruction with median filter(1 to 5 times)

using the photometric parameter estimation, the photometric stereo can be applied. The several position of the light source can be obtained using several scanning process of the foot sole surface. However, scanning quality will be reduced when object is located far from scanning plane and make reconstruction phase difficult.

User position in reconstruction process still leaves a problem to solve. When user sits on a chair, reconstructed shape will be different if user stands on the scanning plane. Foot sole shape is deformed due to pressure. Sole surface becomes flat and reconstruction result is not appropriate for designing shoes. Even tough flat sole may still conform user's comfort. However it still needs further elaborate study.

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(a) 3D shape of ground truth (b) 3D shape of our system

Figure 10: Comparison

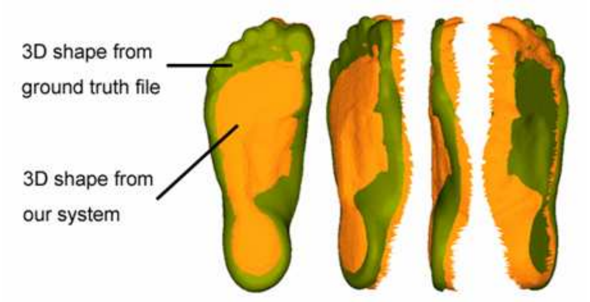

Figure 11: Registration

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Table 2: Evaluation

Pixel Sampling	Median Filter	Vertices	average distance (mm)
1	1	18444	1.077306
2	1	4606	1.172964
3	1	2024	1.329711
4	1	1134	1.465041
5	1	724	1.503186
1	3	18496	1.088442
2	3	4617	1.177509

Figure 12: Deviation Map