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Journal

Applied optics, 54(32)

ISSN

1559-128X

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Publication Date

2015-11-01

DOI

10.1364/ao.54.009573

Peer reviewed

3D Mouse Shape Reconstruction based on Phase Shifting Algorithm for Fluorescence Molecular Tomography Imaging System

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Compiled October 19, 2015

We introduce a fast, low cost, and robust method, based on fringe pattern and phase shifting, to obtain three-dimensional (3D) mouse surface geometry for fluorescence molecular tomography (FMT) imaging. We use two pairs of pico-projector and webcam to project and capture fringe patterns from different views. At first, we calibrate the pico-projectors and the webcams to obtain their system parameters. Each pair of pico-projector and webcam has its own coordinate system. We use a cylindrical calibration bar to calculate the transformation matrix between these two coordinate systems. After that, the pico-projectors project nine fringe patterns with a phase shifting step of $2\pi/9$ onto the surface of a mouse shaped phantom. The deformed fringe patterns are captured by the corresponding webcam respectively, and then are used to construct two phase maps that are converted to two 3D surfaces composed of scattered points. The two 3D point clouds are further merged into one with the transformation matrix. The surface extraction process takes less than 30 seconds. Finally, we apply the Digiwarp method to warp a standard Digimouse into the measured surface. The proposed method can reconstruct the surface of a mouse size object with an accuracy of 0.5 mm, which is sufficient to obtain a finite element mesh for FMT imaging. An FMT experiment of a mouse shaped phantom with one embedded fluorescence capillary target is performed. With the warped finite element mesh, we reconstruct the target successfully, which validates our surface extraction approach. © 2015 Optical Society of America

OCIS codes: (120.3890) Medical optics instrumentation; (120.2650) Fringe analysis; (120.6650) 6650 : Surface measurements, figure.

<http://dx.doi.org/10.1364/ao.XX.XXXXXX>

1. INTRODUCTION

Fluorescent Molecular Tomography (FMT) has emerged for almost two decades and has been used widely in biomedical research labs because of its unique features such as nonionized radiation, low cost and wide availability of molecular probes [1] [2]. The typical applications of FMT include protease activity detection [3], cancer detection [4], bone regeneration imaging [5], and drug delivery [6] etc. In FMT, the fluorophores are injected inside a mouse body intravenously and then excited with lasers to emit fluorescence photons, some of which will propagate to the mouse surface and get measured [7]. Then three-dimensional (3D) distribution of fluorophores inside the mouse body is reconstructed iteratively from the surface measurements [8].

Most FMT imaging systems use a charge-coupled device (CCD) camera to measure fluorescence photon intensity on

the mouse surface with a non-contact mode because the CCD camera can provide more measurements compared with fiber based detectors [2]. The forward modeling and the reconstruction of FMT are based on a finite element mesh, which is used to discretize the mouse body. For FMT imaging system, we have to obtain the geometry of the mouse surface first before we can construct the finite element mesh. So the mouse surface acquisition is critical in FMT imaging.

Different methods have been applied for extracting the mouse surface. In one study, the mouse was hung and rotated to be viewed at different angles by a camera, thus the 3D geometry can be reconstructed [9] [10]. In another study, a photogrammetric camera was employed to acquire the 3D mouse shape [1] [11]. Line lasers have also been used to extract the mouse surface by scanning the surface sequentially. For example, Li *et al* utilized a three-line laser method [7] to extract the mouse profile, while Gaind *et al* employed a single line

laser scanner [12]. Recently, Lee *et al.*, utilized line lasers and David Laser scanner software [13] in their FMT system. All these techniques can extract reasonable 3D mouse geometry. However, they are either expensive, complicated or time consuming. Aside from the above optical methods, CT scan [14] [15] is also known to be able to reconstruct 3D mouse surface accurately but it introduces ionized radiation and is very expensive.

In this paper, we present a phase shifting method to extract the mouse surface. This method is based on fringe pattern projection [16], which has been developed during recent years because of its high resolution, high accuracy and simple system configuration. Various reconstruction algorithms have been developed, such as 3-step phase shifting algorithm [17], Fourier transform profilometry [18], and wavelet transform profilometry [19] etc. In this paper we propose to build a system using a pico-projector and webcam with 9-step phase shifting algorithm because of its high accuracy and simplicity. Particularly, our mouse surface extraction system has extremely low cost due to the affordable prices of pico-projectors and webcams. Only 10 pictures are needed to reconstruct the mouse surface for each pair of pico-projector and webcam. The picture acquisition and the surface reconstruction take less than 30 seconds in total.

It is nontrivial to generate a finite element mesh from the reconstructed mouse surface point cloud. In former studies, we generated a watertight surface mesh at first. Then we use Tetgen [20] to make a 3D mesh from the surface mesh [7]. It is very challenging to create watertight surface mesh considering the complicated mouse geometry. To simplify the finite mesh generation, a Digiwarp algorithm has been proposed to warp an established mesh onto the point cloud and has been proved to be effective [21]. Furthermore, the internal organs of the mouse can be warped to reasonable positions too. In this paper, we apply the Digiwarp algorithm to generate successfully a finite element mesh onto the point cloud we obtained from a mouse shaped phantom. With the warped finite element mesh, we reconstruct a fluorescence target successfully using the measurements in an FMT experiment.

The rest of this paper is organized as follows. In section 2, the steps of the 3D surface reconstruction method are introduced, including the basic principles of phase shifting, selection of phase shifting step number, pico-projector and webcam pairs calibration, phase to coordinate conversion, merge of two point clouds, an introduction of Digiwarp method and a brief description of our FMT imaging system. Section 3 describes the mouse shape extraction results and FMT reconstruction results. Section 4 concludes the paper with discussions.

2. METHODOLOGY

The 3D surface measurement system is shown in Fig. 1. There are two pico-projectors (AAXA p4x, AAXA Technologies Inc., Tustin, CA) and two webcams (C615, Logitech, Apples, Switzerland). Each pair of pico-projector and webcam projects and captures fringe patterns from different views of the object, in order to extract the object geometry from the top and two side views. The pico-projectors project fringe patterns onto the surface of the object. The patterns are deformed due to the modulation of the object surface. The webcams capture the deformed fringe patterns. The minimum focal distance of the webcam is 200 mm. The projected patterns cover an area of 120 mm by 70 mm, which is sufficient for a mouse. The pico-projectors and the webcams

Fig. 1. Schematic of the surface extraction system.

have small sizes and are at low cost. These components with small size can be easily mounted inside the FMT imaging system as described in [7].

A. Phase Shifting Algorithm

In phase shifting method, N fringe patterns with a phase shifting step of $2\pi/N$ are generated by a computer and delivered to the pico-projector for sequential projection onto the object surface. The 1-D sinusoid fringe patterns are described as:

$$F_n(u_p, v_p) = \cos(2\pi f v_p + \frac{(n-1) \cdot 2\pi}{N}), n = 1, 2, \dots, N \quad (1)$$

where (u_p, v_p) are the image coordinates of the projector, and the patterns along v_p direction are the same for each u_p . The phase of each point on the surface is calculated as [22]:

$$\phi(u_c, v_c) = \arctan \frac{\sum_{n=1}^N I_n(u_c, v_c) \cdot \sin(\frac{2\pi n}{N})}{\sum_{n=1}^N I_n(u_c, v_c) \cdot \cos(\frac{2\pi n}{N})} \quad (2)$$

where (u_c, v_c) are the coordinates in the webcam image, and $I_n(u_c, v_c)$ is the n^{th} deformed fringe pattern captured by the webcam. The fringe pattern measurement should be performed in a dark chamber in order to reduce the effects of ambient light. It should be noted that the phase obtained by Eq.2 is from an arctan function, which means $\phi(u_c, v_c)$ is wrapped between $[-\pi, \pi]$. Phase unwrapping method is utilized after the calculation of Eq.2 to obtain continuous phase information. Some phase unwrapping methods have been studied and reported [19] [23] [24]. In order to warrant the reliability of the unwrapping results, we use the multilevel quality guided phase unwrapping method as described in [23]. For this method, the phase map points are divided to several levels according to a quality map, which is generated from the gradient of the phase map. The points with best quality are unwrapped first, and then the points with lower quality, until all points are unwrapped. Points with very low quality are discarded. A fast scan-line algorithm [23] is utilized within each level in order to speed up the phase unwrapping

process. Thus this method can generate good unwrapping phase map quickly. After that an additional centerline image is used to obtain the absolute phase at each pixel [25].

It is worth noting that the spatial frequency of the projected fringe pattern should be set well. If the spatial frequency is too high, phase error appears in patches with complex geometry during phase unwrapping. If the spatial frequency is too low, only a small range of phase values can be used, which results in the measurement errors. In our experiment, the spatial frequency of the projected fringe patterns are chosen empirically. There are 50 pixels per fringe-cycle and the related spatial frequency is about 138 cycles per meter. These values can be adjusted slightly according to different distances between the object surface and the pico-projector.

B. Selection of Phase Shifting Step Number

Theoretically, three fringe patterns are enough to calculate the surface geometry of an object [17]. In reality, however, due to the non-linearity of the commercial projectors, obvious fluctuation shows on the extracted 3D surface if we only use three fringe patterns [26]. Phase error compensation methods have been developed to solve this problem [26] [27] for real-time measurement systems. It has also been reported that the phase error caused by the projectors' non-linearity can be reduced by increasing the phase shifting step number [28], while the drawback is that the measurement time increases accordingly. In order to simplify phase error correction algorithms and meanwhile to maintain the surface accuracy, we increase the fringe pattern number. We use different fringe pattern numbers from 3 to 15 to measure a white plane and analyze the average phase error for each step number. Finally, after analysis, we choose the fringe pattern number N in Eq. 1 and 2 to be 9.

C. Pico-projector and Webcam Pairs Calibration

For one pair of pico-projector and webcam, there are 3 coordinate systems: the webcam coordinate system, the pico-projector coordinate system and the world coordinate system [25]. System calibration is required to obtain the intrinsic parameters of the webcam and the pico-projector and to create relationships among the three coordinate systems. For our FMT imaging systems, there are two pairs of pico-projector and webcam, so the calibration has to be performed for each pair.

Both the webcam and the pico-projector have intrinsic parameter matrices of the following form:

$$A = \begin{bmatrix} \alpha & \gamma & u_0 \\ 0 & \beta & v_0 \\ 0 & 0 & 1 \end{bmatrix} \quad (3)$$

where u_0, v_0 are coordinates of the principle point; α, β are focal lengths along u and v axis of the image plane, and γ is the skewness of u and v axis.

The calibration process is similar to the method described in [25]. The camera calibration is finished by the Matlab Camera Calibration Toolbox [29]. The projector checker board images are generated by pixel to pixel mapping from camera images, where the 9-step phase shifting algorithm is utilized again.

After all the intrinsic parameters are obtained, the extrinsic parameters are calibrated to create relationships among the webcam, the pico-projector, and the world coordinate systems. The extrinsic 3×4 parameter matrix is shown as:

$$M = \begin{bmatrix} R & t \end{bmatrix} \quad (4)$$

where R is a 3×3 rotation matrix and t is a 3×1 translation matrix. The extrinsic calibration is finished by the Matlab Toolbox as well.

D. Phase to Coordinates Conversion

After all the calibration parameter matrices are obtained, the phase map generated in section 2.A can be converted to the 3D coordinates in the world coordinate system. We have the following equations to describe the relations among different coordinate systems:

$$S_c \begin{bmatrix} u_c \\ v_c \\ 1 \end{bmatrix} = A_c [R_c t_c] \begin{bmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{bmatrix} = \begin{bmatrix} m_{11}^c & m_{12}^c & m_{13}^c & m_{14}^c \\ m_{21}^c & m_{22}^c & m_{23}^c & m_{24}^c \\ m_{31}^c & m_{32}^c & m_{33}^c & m_{34}^c \end{bmatrix} \begin{bmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{bmatrix} \quad (5)$$

$$S_p \begin{bmatrix} u_p \\ v_p \\ 1 \end{bmatrix} = A_p [R_p t_p] \begin{bmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{bmatrix} = \begin{bmatrix} m_{11}^p & m_{12}^p & m_{13}^p & m_{14}^p \\ m_{21}^p & m_{22}^p & m_{23}^p & m_{24}^p \\ m_{31}^p & m_{32}^p & m_{33}^p & m_{34}^p \end{bmatrix} \begin{bmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{bmatrix} \quad (6)$$

where the subscripts c and p denote the camera and projector, respectively, S is scale factor, and (u_c, v_c) and (u_p, v_p) are image coordinates of the webcam and pico-projector which have the same phase value. A is the intrinsic parameter matrix. R means rotation matrix, t is translation matrix, and m means the elements of matrix $A[R t]$. The above parameters are known and X_w, Y_w, Z_w are the 3D coordinates in the world coordinate system to be determined. In Eq. 5 and 6 there are 6 equations but only 5 unknowns (S_c, S_p, X_w, Y_w and Z_w), so we can ignore the information about v_p to reduce one equation. S_c and S_p can be solved from Eqs. 5 and 6 as:

$$\begin{aligned} S_c &= m_{31}^c X_w + m_{32}^c Y_w + m_{33}^c Z_w + m_{34}^c \\ S_p &= m_{31}^p X_w + m_{32}^p Y_w + m_{33}^p Z_w + m_{34}^p \end{aligned} \quad (7)$$

We can cancel S_c and S_p by plugging in Eq. 7 into Eq. 5 and 6, and obtain below equations:

$$\begin{aligned} (u_c m_{31}^c - m_{11}^c) X_w + (u_c m_{32}^c - m_{12}^c) Y_w + (u_c m_{33}^c - m_{13}^c) Z_w \\ = m_{14}^c - u_c m_{34}^c \\ (v_c m_{31}^c - m_{21}^c) X_w + (v_c m_{32}^c - m_{22}^c) Y_w + (v_c m_{33}^c - m_{23}^c) Z_w \\ = m_{24}^c - v_c m_{34}^c \\ (u_p m_{31}^p - m_{11}^p) X_w + (u_p m_{32}^p - m_{12}^p) Y_w + (u_p m_{33}^p - m_{13}^p) Z_w \\ = m_{14}^p - u_p m_{34}^p \end{aligned} \quad (8)$$

From Eq. 8 the 3D world coordinates (X_w, Y_w, Z_w) can be calculated.

E. Alignment of Two Point Clouds

As the two pairs of pico-projector and webcam are calibrated independently, they have different world coordinate systems, as shown in Fig. 2a. $\{O_1, x_1, y_1, z_1\}$ is the world coordinate system for the first pair, while $\{O_2, x_2, y_2, z_2\}$ is the world coordinate system for the second pair. So we need to perform

point clouds alignment between the two point clouds in two different coordinate systems to merge them inside one point cloud. We use a calibration bar as shown in Fig. 2b to transform both coordinate systems to the conical mirror coordinate system $\{O_{con}, x_{con}, y_{con}, z_{con}\}$. Because the position of the calibration bar in the conical mirror coordinate system is known, we can obtain the rotation and translation matrices for each coordinate system, and transform them into the conical mirror system, so that the two 3D point clouds can be merged. During our experiments we find that the two 3D point clouds of a mouse shaped phantom cannot be merged precisely after the alignment. There is a slight misalignment about 3° of rotation around the x_{con} axis, and 1 mm of translation along the y_{con} axis. This misalignment may come from the slight position errors of the calibration bar in the conical mirror system. The rotation and translation matrices that work well for the calibration bar result in errors for the mouse shaped phantom. So we have an additional step of 3D registration as described in [30] to make the two point clouds align with each other. In this step, we select several points from point cloud 1, and try to find the rotation and translation matrices that minimize the distance from these points to point cloud 2.

Fig. 2. (a) Three coordinate systems in the FMT imaging system and (b) photograph of the calibration bar.

F. Digiwarp Method

Digiwarp algorithm had been developed by Joshi *et al.* [21] and is used to warp an established finite element mesh onto a measured surface with scattered point cloud so that the tedious steps from point cloud to finite element mesh are avoided. We apply the Digiwarp algorithm to obtain a finite element mesh from our surface measurements. The Digiwarping process has three steps: posture correction, surface fitting and elastic volume warping. Posture correction means to reposition the limbs and the head of the Digimouse in order to match those of the mouse surface point cloud obtained from our method. In this step, 14 corresponding points from the limbs and the head are picked from both the Digimouse and the mouse point cloud. After posture correction, volume warping is implemented to warp the internal anatomy of Digimouse. Then the Digimouse surface is adjusted to fit the subject mouse point cloud by surface fitting. After that, the volume warping is implemented again to warp the internal anatomy to fit the subject mouse point cloud.

G. FMT Reconstruction

To validate FMT reconstruction with the mesh generated from the proposed surface extraction method, we perform an FMT

experiment with a mouse shaped phantom embedded with a capillary tube that is 20 mm long and 1 mm in diameter. The target is filled with $10 \mu\text{m}$ DiD fluorescence dye solution. The FMT imaging system has been described in detail elsewhere [31]. Briefly, the FMT imaging system consists of a conical mirror, a line pattern laser mounted on a rotary stage and a CCD camera, as shown in Fig. 3. After the surface scan, the object is transported into a conical mirror by a linear stage for FMT scan. The conical mirror is used to collect the fluorescence photon information over the whole object surface, as described in [7]. A 643 nm line laser (Stocker Yale Canada Inc.) is used to excite the fluorescence photons. The laser beam scans across the object surface sequentially. A Cambridge (CRI) Nuance camera (Advanced Molecular Vision, Inc.) is used to perform photon measurements, and a motorized filter wheel (Lambda 10-3, Sutter Instrument, Novato, CA) is positioned in front of the camera lens to select fluorescent emission wavelengths. We use 30 line laser source positions and 14,723 detectors. The optical parameters at excitation and emission wavelengths are both $\mu_a = 0.002 \text{ mm}^{-1}$ and $\mu_s = 1.1 \text{ mm}^{-1}$. The propagation of excited and emitted lights are modeled by the diffusion equation that is solved by the finite element method [32]. We follow the reconstruction methods proposed by Zhu *et al.* [8][33] for the reconstruction of distribution of the fluorescence dye.

Fig. 3. Photograph of the FMT imaging system with the two pairs of pico-projector and webcam.

3. EXPERIMENT RESULTS

A. System Calibration

In our system the webcams' resolution is 640×480 and the pico-projectors' resolution is 854×480 . Fig. 4a and Fig. 4b show one example of our camera checker board image and its corresponding projector checker board image generated from 9-step phase shifting method. The checker board images are used for calibrating the webcam and the pico-projector. The squares on the check board have a size of $6.8 \text{ mm} \times 6.8 \text{ mm}$. For each pico-projector and webcam pair, 16 camera pictures are taken and 16 projector images are generated for calibration. The projectors are calibrated with Matlab Calibration Toolbox [29] after all projector checker board images are generated. Our system calibration results are listed as below:

Camera intrinsic parameter matrices:

$$A_{c1} = \begin{bmatrix} 1280.3138 & 0 & 356.8074 \\ 0 & 1246.5246 & 154.2757 \\ 0 & 0 & 1 \end{bmatrix}$$

$$A_{c2} = \begin{bmatrix} 1062.7811 & 0 & 368.5365 \\ 0 & 1058.3372 & 238.1154 \\ 0 & 0 & 1 \end{bmatrix} \quad (9)$$

Projector intrinsic parameter matrices:

$$A_{p1} = \begin{bmatrix} 1735.1733 & 0 & 492.8961 \\ 0 & 1704.1114 & 492.3768 \\ 0 & 0 & 1 \end{bmatrix}$$

$$A_{p2} = \begin{bmatrix} 2123.4733 & 0 & 519.3688 \\ 0 & 2049.8541 & 230.0904 \\ 0 & 0 & 1 \end{bmatrix} \quad (10)$$

Camera extrinsic parameter matrices:

$$M_{c1} = [R_{c1} \quad t_{c1}] = \begin{bmatrix} 0.0312 & 0.9550 & -0.2949 & -34.3981 \\ 0.8756 & -0.1685 & -0.4528 & 19.0146 \\ -0.4821 & -0.2441 & -0.8414 & 220.8508 \end{bmatrix}$$

$$M_{c2} = [R_{c2} \quad t_{c2}] = \begin{bmatrix} 0.0234 & 0.9896 & -0.1419 & -43.2571 \\ 0.8246 & -0.0994 & -0.5568 & -7.8332 \\ -0.5652 & -0.1040 & -0.8184 & 181.9324 \end{bmatrix} \quad (11)$$

Projector extrinsic parameter matrices:

$$M_{p1} = [R_{p1} \quad t_{p1}] = \begin{bmatrix} 0.1734 & 0.9841 & -0.0390 & -41.6328 \\ 0.9805 & -0.1762 & -0.0867 & -38.7379 \\ -0.0922 & -0.0232 & -0.9955 & 236.7787 \end{bmatrix}$$

$$M_{p2} = [R_{p2} \quad t_{p2}] = \begin{bmatrix} 0.1257 & 0.9880 & 0.0896 & -38.8240 \\ 0.9265 & -0.0847 & -0.3667 & -17.6024 \\ -0.3547 & 0.1291 & -0.9260 & 280.7086 \end{bmatrix} \quad (12)$$

B. Selection of Phase Shifting Step Number

The average phase errors for each step number from 3 to 15 are shown in Fig. 5. From this result we can see how the non-linearity of projectors affects the accuracy with increasing step number. Generally, the phase error decreases as the number of steps increases. We see some oscillations in the curve plotted in Fig. 5. But we can still observe that the phase errors caused by the non-linearity of projectors are relatively small when the fringe pattern number is larger than 7. In order to reduce the effects of projectors' non-linearity as much as possible and without adding too much scanning time, we choose the phase shifting step number to be 9.

Fig. 4. (a) A camera checker board image and (b) the corresponding projector checker board image.

Fig. 5. Phase errors caused by non-linearity of projectors with different fringe pattern numbers.

C. Alignment of Two Point Clouds

We use the calibrated 3D shape extracting system to measure the calibration bar as shown in Fig. 2b. The calibration bar has a radius of 22 mm and a length of 57.9mm. We have calculated the optimal rotation and translation matrices for 2 point clouds and merged them as shown in Fig. 6a. We plot a cross section as shown in Fig. 6b, and compare it with the ground truth. We see that the measured calibration bar surface overlaps with the ground truth pretty well.

Fig. 6. (a) Alignment of the two point clouds of the calibration bar and (b) the cross section compared with the ground truth.

D. Mouse Shaped Phantom Surface Extraction

We measure a mouse shaped phantom that is 110 mm long, 33 mm wide and 13 mm high. The mouse phantom is made of 2% agar and 1% intralipid, and its photo is shown in Fig. 7a. Fig. 7b and 7c show the fringe patterns captured by two webcams from two different views. There are in total nine such fringe patterns with a phase shifting step of $2\pi/9$ for each webcam, and an additional centerline picture, which is used to determine the absolute phase. Fig. 8a, 8b and Fig. 8c, Fig. 8d plot the wrapped phase map and the unwrapped phase map of webcam 1 and webcam 2, respectively. Fig. 9 shows the 3D reconstructed results of the mouse geometry after the alignment of two point clouds and 3D registration, from which we can see that the reconstructed size is quite close to the true size.

Fig. 7. (a) Photograph of a mouse shaped agar phantom, (b) one fringe pattern captured by webcam 1 and (c) by webcam 2.

E. Accuracy Evaluation

In order to evaluate our system's accuracy, we have fabricated a step object for which the step height between the two planes is 8.13 mm. Its photo is shown in Fig. 10a and the reconstructed step is shown in Fig. 10b. As it is hard to view this object by the two webcams simultaneously, we only test it using one pair of pico-projector and webcam. We measure the mean height of the points on the two planes, then subtract the mean values to obtain the measured step height as 8.15 mm. We also calculated the standard deviations of the points height on the two planes respectively, as shown in Table 2. From the results we can see the standard deviations are less than 0.2 mm for both planes, and our system can retrieve the result with errors within 0.5 mm, which is good enough for FMT imaging.

Table 1. Measured height of the step object (mm)

	Mean	Standard Deviation
Lower plane	10.11	0.17
Higher plane	18.26	0.13

To further validate our system's accuracy, we compare the surface data of the mouse shaped phantom obtained from the

Fig. 8. (a,b) The wrapped and (c,d) the unwrapped phase map for webcam 1 (a,c) and webcam 2 (b,d).

Fig. 9. The mouse surface point cloud.

Fig. 10. (a) The picture and (b) the reconstructed results of a step object.

proposed method with the surface geometry from a computed tomography (CT) image. For the micoCT scan, 180 projections are obtained (x-ray tube settings: 80 kVp, 0.2 mA) and reconstructed using the vendor supplied filtered backprojection method. The CT image (pixel size 0.095 mm) is used to generate the surface geometry as ground truth for our comparison.

All the data sets are shown in Fig. 11a, from which we can see they overlap very well. We then calculate the distance from each point of the webcam-projector data to its nearest point of the CT data (only the trunk part from $x = 30$ mm to $x = 90$ mm in Fig. 11a is compared), and the mean distance is 0.323 mm, which further validated that our system's accuracy is within 0.5 mm. Fig. 11b shows one cross section in Fig. 11a at $x = 60$ mm. The cross section also proves that the surface data obtained from our method is very close to the CT data.

Fig. 11. Comparison between the surface data obtained from the webcam-projector pair and the CT data of (a) the whole surface and (b) a transverse section at $x = 60$ mm.

F. Digiwarp Results

After the mouse surface point cloud is obtained, we perform Digiwarp to the point cloud and generate the finite element mesh. Fig. 12 plots the 932 corresponding points between the point cloud from the mouse shaped phantom and the Digimouse. Among these 932 corresponding points, 8 points are chosen manually from the nose, arms and legs, and the other 924 points are chosen automatically slice by slice from the trunk along the x axis. To map the 924 points on the trunk, we divide trunk section of the point cloud and the digimouse into 30 slices evenly. The Digiwarp results are shown in Fig. 13a-e. Fig. 13a is the original subject mouse point cloud and Digimouse. Fig. 13b shows the

Fig. 12. 932 corresponding points (red dots) between the (a) extracted mouse surface point cloud and (b) the Digimouse.

corrected posture of Digimouse, in which the limbs and the head match the position of those of the subject mouse point cloud and Fig. 13c plots the first volume warping result. Fig. 13d shows the surface fitting result while Fig. 13e shows the final volume warping result. A finite element mesh of the measured mouse surface is generated from a standard Digimouse, as shown in Fig. 13f, and is ready to be used in FMT reconstruction process.

G. FMT reconstruction Results

With the reconstruction methods as described in [8][33], we are able to obtain a good result in about 30 seconds, as shown in Fig. 14. The L1 regularization parameter is empirically set to be 1% of the maximum of the measurement after back projection for the best result. Fig. 14 plots the transverse, coronal and sagittal views of the overlaid FMT and gray-scale CT images. The red color line plots the mouse phantom boundary from the warped mesh. From these results we can observe that with the finite element mesh generated by the proposed 3d shape extraction method, the FMT reconstruction result is pretty consistent with the CT reconstruction.

4. DISCUSSIONS AND CONCLUSION

Compared with the approach described in [34], our paper is different in following aspects. At first, we use very low cost webcams, not the expensive CCD camera. Secondly, we have two pairs of pico-projector and webcam to cover the surface from two views. Thus we can extract the top and two side views of the surface. Thirdly, we apply the projector calibration method so that we do not need the stepped pyramid-shaped calibration object. Fourthly, we warp a Digimouse mesh into our extracted point cloud to generate the finite element mesh easily and robustly. Fifthly, we validate the surface extraction approach with FMT experiments and with CT scan. Lastly, we have investigated the effects of phase shifting steps on the accuracy of the extracted surface.

Table 2 listed accuracy and time or picture number reported in other mouse surface extraction methods and the proposed approach in this paper. From this table, we know that our approach needs less picture numbers and have the similar accuracy. It is worth noting that our approach can image the concave surface but the approach in reference [9] can only image the convex surface.

In sum, we utilize low cost equipment, including webcams and pico-projectors to extract mouse surface geometry fast and robustly, in order to develop an affordable and optimal 3D FMT imaging system. The proposed surface extracting system is portable and easy to combine with an existing FMT imaging system. With the Digiwarp method, this system can generate

Fig. 13. Digiwarp Results: (a) the original point cloud from the mouse shaped phantom and Digimouse, (b) the corrected posture of Digimouse, (c) the first volume warping result, (d) the surface fitting result, (e) the final volume warping result and (f) the FEM mesh after Digiwarp.

Fig. 14. (a) The tranverse, (b) coronal and (c) sagittal views of the overlaid FMT (rainbow) and CT (grey) images. The color line plots the FMT image boundary. The arrows indicate the plotted section position.

mouse surface mesh for FMT imaging system in a new way. Experimental results indicate that the accuracy of the proposed surface extraction method is within 0.5 mm, which is sufficient for FMT reconstruction as validated with the FMT images. In future, we are going to optimize our FMT imaging system and apply the proposed approach with the optimized FMT system to *in vivo* mice imaging.

Table 2. Comparison Between Different Surface Measuring Methods

	Accuracy	Picture Number or Measuring Time
360° Gemoetry		
Projection [9]	50um	72 pictures
Three Line Lasers [7]	1 mm	50 pictures
Surface Scanner [13]	0.5mm	7-10 s
The Proposed Method	0.5mm	20 pictures

This research is partially supported by Startup Fund from University of California, Merced and graduate student summer fellowship from Biological Engineering and Small-scale Technologies (BEST) program, School of Engineering, UC Merced.

The authors thank Dr. Simon Cherry in UC Davis for lending us the CRI camera and the line laser, thank Michael Lun for the proof reading, and thank Y. Yin for his helpful suggestions.

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