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Structured Light 3D Body Scanner for Back Surface Analysis

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Abstract

In this paper we present our 3D scanning system for the surface reconstruction of the entire human body. Scanner is based on the structured light fringe profilometry approach and is assembled from only few basic components – three projectors and six cameras. These components are grouped in three scanning units which can simultaneously illuminate person from all sides and create a full 3D body model. On the application side, we propose the analysis of the human torso (back surface) with a goal to assist the detection and assessment of possible spinal deformities or other muscular changes present on the back surface. We proposed a method for the automatic detection of the symmetry curve based on the analysis of local deviations of surface curvatures. Presented results demonstrate that proposed method is comparable with commercial 3D systems.

1. Introduction

Structured light (SL) profilometry is one popular approach to the 3D surface reconstruction. The object's surface is illuminated using a pattern with a coded structure and then captured by one or more cameras. The decoding between projected and captured pattern structure enables the reconstruction of the scanned object. In order to reconstruct the entire surface of the human body, different body-regions can be either illuminated sequentially (by employing projectors in turns) [1][2] or simultaneously [3]–[5] where multiple projectors illuminate the subject at the same time from different positions. Downside of the sequential multi-projector SL reconstruction is extended scanning time (that grows linearly with the number of projectors used) meaning that subject must remain still for longer time which may be uncomfortable. On the other hand, simultaneous multi-projector SL reconstruction approaches must efficiently solve the problem of the inter-projector interference, which usually requires projecting specifically designed patterns and consequently using some nonconventional decoding methods [3][4]. Fringe projection profilometry is very popular SL approach for 3D surface reconstruction, because it's robustness – it is insensitive to ambient illumination, limitations on the colour of the scanned object are practically negligible, it can produce high-resolution scans and, depending on the decoding method, the relative positioning of the camera and the projector is not strictly conditioned (having in mind that they must retain a common FOV). In order to preserve the robustness property of the aforementioned fringe projection profilometry, in our opinion the method of choice for the surface reconstruction is temporal multiplexing approach proposed in our previous work [5]. This approach does not impose a limit on the number of projectors used nor on theirs placement and thus enables construction of complex scanners with no blind spots. The only prerequisite for previously mentioned simultaneous projection approach is the synchronization of projectors and cameras.

The second part of the paper describes our analysis of the reconstructed human body. Proposed analysis is focused on the human torso, i.e. the analysis of the human back surface topography and geometry in order to detect and assess the possible deformities of the human spine or other muscular bulges that change the symmetry in patient's posture and consequently the surface of the back. Bearing in mind that, in healthy subjects, the spine is one of the main indicators of the back surface symmetry, the first step in most of analysis methods is the estimation of the spinal curve on the back surface. The easiest approach is using reflective adhesive markers and marking a certain number of the vertebrae and then interpolate the spine curve, but more recent methods propose using a (semi-) automatic detection of the asymmetry curve. There are many different approaches to this problem – analysing the depth of the surface profiles, finding maxima in the computed surface curvature [6], or defining an asymmetry function as a left-right differences of the surface curvature [7] or surface normals [8] distribution over the horizontal profiles of the human back. Our work extends the idea of [7], using multi-scaling of the asymmetry function which effectively filters minor asymmetries inconsistent over multiple scales.

2. Multi-Projector 3D Scanning System

Our 3D scanning system is based on multi-projector multi-camera temporal multiplexing fringe projection profilometry. Fringes used for each projector are carefully designed – temporal phase shifts of each fringe set are selected to form an orthogonal basis of the discrete Fourier transform (DFT). That means that for each of P projectors we generate a set of $N \geq 2P+1$ pattern images:

$$I_{\mathrm{PRJ},k}\left(x_{\mathrm{PRJ}},y_{\mathrm{PRJ}}\right)=\frac{1}{2}I_0\left(1+\cos\left(\omega_k x_{\mathrm{PRJ},k}+\varphi_k\left[n\right]\right)\right), \quad (1)$$

$\varphi_k[n] = 2\pi kn/N$, $n = 0, \dots, N-1$ and $k = 0, \dots, P-1$.

Using a multi-projector configuration, each camera captures N frames where each frame includes ambient illumination along with the contribution of each projector:

$$I_{\mathrm{CAM}}\left(x_{\mathrm{CAM}},y_{\mathrm{CAM}}\right)=I_{AMB}+\frac{1}{2}\sum_{k=0}^{P-1}h_k I_k\left(1+\cos\left(\omega_k x_{\mathrm{PRJ},k}+\varphi_k\left[n\right]\right)\right). \quad (2)$$

For each camera we decode a set of N images in a following manner. Firstly, we decompose each set using the Fast Fourier transform as explained in [5]. By comparing the magnitude of the k-th spectral component to some preselected threshold, we determine the area illuminated by the k-th projector and afterwards the wrapped phase ϕ_k of k-th projector can be retrieved as the negative phase of the k-th spectral component. Here, we omit details regarding wrapped phase definition but it can be found in our previous paper [5]. Unwrapping of the wrapped phase can be done using any of the unwrapping algorithms [9], and the final 3D reconstruction is obtained with the triangulation using corresponding camera projector coordinate pairs. Additionally, our post-processing includes some filtering and creating a mesh for the better visual representation of results.

An important part of this reconstruction approach is the adequate synchronization between cameras and projectors. Based on our previous work [10], we chose the software synchronization (opposed to the more expensive hardware synchronization) which relies on the precise timing of projection and acquisition steps.

3. Back Surface Analysis

Although our 3D scanning system can produce a 3D reconstruction of the entire human body we focused our 3D analysis only on the back surface. As stated in the introduction, an important part of the assessment of possible spinal deformities is the estimation of the spinal curve or some other correlated curve on the surface of the back.

Our proposed method is based on the analysis of distributions of surface curvatures and on redefining an asymmetry function. The input to the procedure is a point cloud with associated surface normals representing the back side of the subject's torso. This can be achieved using some 3D body segmentation method or manually by selecting the region of interest. Using precomputed surface normals and the reconstructed dense point cloud, surface curvatures (principal curvatures and principal directions) can be estimated [11].

Hierholzer [7] defined the surface asymmetry function as a sum of local deviations of the surface curvature in some predefined neighbourhood of the chosen point. We adopted this definition, and for each horizontal slice of the 3D back surface, we computed the symmetry function in every point interpolated over that slice. The result is two-dimensional symmetry function map. A valid theoretical assumption is that the symmetry function will achieve maximal values at points which represent the *symmetry curve*. However, the symmetry map produces many local maxima which need to be filtered in order to achieve automatic detection of the symmetry curve. Therefore, we propose *multi-scaling* of the symmetry function – accumulation of multiple symmetry functions computed over different neighbourhoods, which effectively filter minor symmetries which are inconsistent over multiple scales.

4. Results and Discussion

Our 3D scanning system is comprised of three units – each equipped with one projector and two cameras. One projector is Canon LV-WX310ST and two are Acer S1383WHne. All cameras are PointGreys' Grasshopper3 GS3-U3-23S6C. Four cameras are equipped with Fujinon HF12.5SA-1 lenses and two are equipped with Kowa LM8JCM lenses. With the maximal speed of 20 FPS one recording takes about 0.7s, but for more robust and higher quality reconstructions we propose using three frequencies (ω) with seven shifts (φ) per frequency (N = 42) for each projector coordinate which results in acquisition time of 2.1s. The 3D scanning system setup is shown in Figure 1. We used a double-sided calibration board with circular hexagonal grid pattern

Fig. 1. Our 3D scanning system. Note the inter-projector interference pattern on the mannequin and on the floor

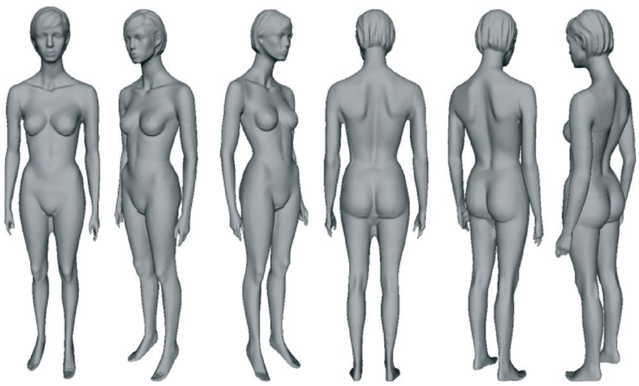


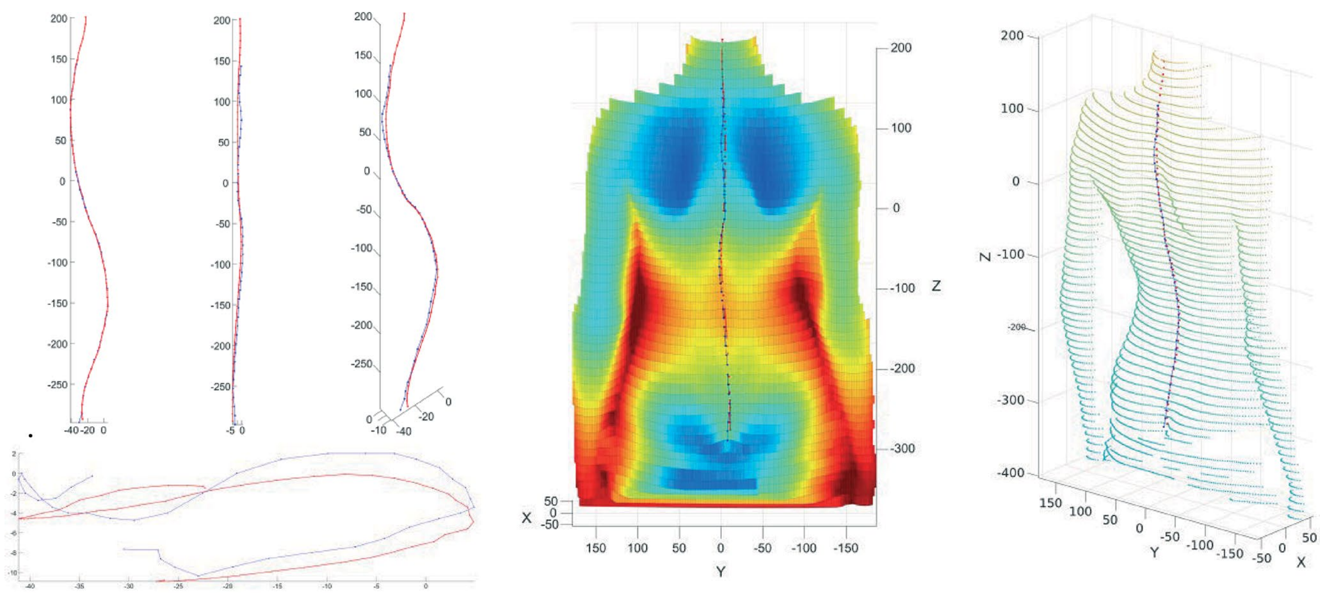
Fig. 2. Resulting 3D mesh of a mannequin after final post-processing.

and coded markings in order to achieve simple and fast geometric calibration of all three scanning units. An example of the final surface reconstruction for the scanned mannequin is shown in Figure 2. The 3D mannequin model is pictured as a mesh surface for better visual representation.

We compared the proposed method for the back surface analysis with a commercial system for the 3D spine and posture analysis – Diers Formetric [12]. We used point clouds reconstructed using a Diers system as our input and applied the proposed method for the detection of the symmetry curve. The comparison with the output of the Diers system (so-called *cls* curve) showed that methods are comparable within limits of physicians' palpation error (5mm) as shown in Figure 3. The contribution of our proposed multi-scaling of symmetry functions is presented in Figure 4. Using this approach we are able to compute the symmetry curve without using any predefined models for the curvature of the human spine.

5. Conclusion

We have proposed a 3D human body scanning system which can be used for the analysis of the human torso, specifically for the back surface analysis. The experi-



(a) (b) (c)

Fig. 3. Comparison of the proposed method (blue line, *symmetry curve*) and Diers Formetric resuts (red line, *csl curve*) in the back shape analysis. (a) Comparison of detected curves in different views (axial, sagittal, coronal, and from side). (b) Detected lines plotted on the depth map of the back surface. (c) Detected lines plotted over the input point cloud obtained with Diers Formetric system.

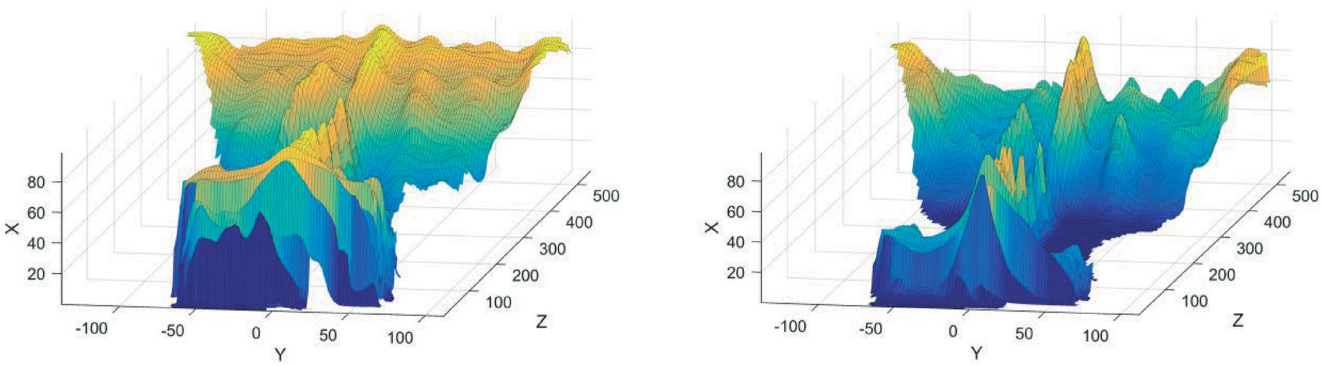


Fig. 4. Symmetry map generated using one scale (left) and using the proposed *multi-scaling* approach (right). Note how local maxima representing the "true" symmetry curve are much more prominent.

ments show that our scanner is very robust and can collect data for a dense 3D reconstruction of the entire human body in only two seconds. The reconstructed surface of the human back can then be analysed using proposed method for the detection of the symmetry curve which does not require any predefined models thanks to the proposed multi-scaling approach. The results are very promising for further extensions of the method because current results are already comparable with the commercial 3D systems.

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