Published in final edited form as:

Opt Lett. 2012 August 1; 37(15): 3126–3128.

Strategy for automatic and complete three-dimensional optical digitization

Xiaoli Liu¹, Xiang Peng^{1,2,*}, Hailong Chen¹, Dong He¹, and Bruce Z. Gao²

¹Key Laboratory of Optoelectronic Devices and Systems of Ministry of Education and Guangdong Province, Shenzhen University, Shenzhen Guangdong 518060, China

²Department of Bioengineering, COMSET, Clemson University, Clemson, South Carolina 29634, USA

Abstract

This Letter proposes a new strategy of a three-dimensional (3D) scanning pipeline to achieve complete 3D digitization of complex objects in a real scene. This strategy consists of a one-dimensional array of optical 3D sensors combined with an automatically controlled turntable. An efficient calibration method for the sensor array is presented to guarantee the accuracy of the 3D measurement. Furthermore, an automatic registration technique is also proposed for aligning multiple range images taken from sensor array. Experiment results are also presented to demonstrate the proposed approach.

Automatic digitization of three-dimensional (3D) complex objects in a real scene has become an important issue in many application areas [1–4]. Online or *in situ* quality inspection and cultural heritage digitization may be good examples in this regard. Most of the existing optical methods, including laser scanning and fringe projection profilometry, can merely obtain a portion of the range image of a 3D object due to the limitation of the field of view (FOV) of a 3D optical sensor. It is a difficult task for a single 3D sensor to digitize the whole object automatically through a single acquisition, especially for objects with complex geometric shape and topology. This issue could be addressed with a strategy of mobile digitization by a single 3D optical sensor moving around the object. However, it will be inflexible and need a large work space. What we are concerned about here is a strategy of automatically controlled digitizing process and a complete digitization of 3D complex objects. For this purpose, we propose a new strategy that utilizes a one-dimensional (1D) array of 3D optical sensors combined with a rotation turntable to get a complete digitization of complex object automatically. The idea behind it is similar to an optical measurement network proposed recently [1]. With this approach, the automatic registration of multiple range images taken from the sensor array is also a challenging task for building up a final digital 3D model of the object. Moreover, it is not trivial to acquire the top and bottom information of objects simultaneously.

Figure 1(a) shows a schematic diagram of proposed strategy for automatic and complete 3D digitization. A 1D sensor array consisting of multiple 3D optical sensors are arranged in a vertical direction (three sensors are used in our experiment), and each node sensor has its own position and orientation in space. The working principle of optical 3D sensors is based on phase-aided active Astereo (PAAS) [5]. A turntable with motorized controls is used for rotating objects in different angles. With the combination of a 1D optical sensor array and

turntable, it is possible to automatically and completely acquire the range images of the object from various viewpoints with proposed strategy.

To enable this strategy to work properly, we must address two important issues. (1) Due to the lack of overlapping among the FOVs of multisensors, it is hard to perform the calibration of multisensors simultaneously. (2) In practice, the rotational axis of the turntable may not be strictly vertical to the working plane. This may be due to the machining error and the error caused by assembly or an unstable environment, leading to a big challenge to achieve accurate and automatic registration of multiple range images. To address these issues, this Letter proposes the corresponding methods for simultaneous calibration of the optical sensor array and for automatic registration of range images that will be free from the error caused by inaccuracy of the rotational axis.

For the first issue, to overcome the lack of overlapping among multiple 3D optical sensors, we construct a special 3D calibration target with plenty of encoded markers that can be seen by all node sensors on the array. The relative positions of encoded markers on the calibration target as a cloud of benchmark points (CBP) can be determined by the bundle adjustment (BA) technique [6,7]. Using the coordinates of the CBP, we are able to calibrate the sensor array simultaneously with a specific calibration procedure that will be described later on. For the second issue, it is impractical to correct the uncertainty of rotational axis through the calibration of rotation axis. However, as the turntable with motorized control has reliable repetitive precision, we arrange several rotation angles of the turntable in advance. These predefined rotation angles correspond to different view angles of each node sensor on the optical sensor array, covering the complete object. In the calibration of an optical sensor array, we present a technique to determine the relationship among these view angles including the rotations and translations of each node sensor. As long as this has been done, it is possible to automatically register the range images taken from these view angles.

In the process of the sensor array calibration, we place the calibration target onto the turntable and control its rotation according to predefined angles. In each angle, all cameras in the optical sensors take the images of the calibration target simultaneously. The single camera calibration model can be built as follows [8,9]:

$$E(\mathbf{k}, \mathbf{K}, \mathbf{R}_c^{(i)}, \mathbf{t}_c^{(i)}) = \sum_{i=1}^N \sum_{j=1}^M \|\mathbf{x}_{ij} - \hat{\mathbf{x}}(\mathbf{k}, \mathbf{K}, \mathbf{R}_c^{(i)}, \mathbf{t}_c^{(i)}, \mathbf{X}_j)\|^2, \quad (1)$$

where $\mathbf{X}_j (j = 1, \dots, M)$ is the j th marker selected centroid from the M markers in 3D space, $\mathbf{x}_{ij} (i = 1, \dots, N)$ is the corresponding two-dimensional image point observed from the i th view angle. $\mathbf{K}$ is the camera matrix including the focal length and the position of principle point as well as a skew parameter, $[\mathbf{R}_c^{(i)} | \mathbf{t}_c^{(i)}]$ is the matrix describing extrinsic parameters such as rotations and translations with respect to the camera position and orientation. $\mathbf{k}$ stands for the radial and tangential distortions of camera lens. $\hat{\mathbf{x}}$ is an estimate of $\mathbf{x}_{ij}$ using the camera model. The minimization of Eq. (1) is a nonlinear optimization problem that can be solved by the Gauss–Newton or the Levenberg–Marquardt method [10].

In this way, all cameras in the optical sensor array can be calibrated simultaneously. As shown in Fig. 2, we construct $2S + 1$ coordinate frames, where S is the number of sensors. The world coordinate frame ($O_W X_W Y_W Z_W$) has been placed on the calibration target, and $2S$ camera coordinate frames ($O_{sL} X_{sL} Y_{sL} Z_{sL}$, $O_{sR} X_{sR} Y_{sR} Z_{sR}$, $s = 1, \dots, S$) located on the camera centers respectively. For an optical 3D sensor array, each sensor coordinate frame is placed on its own left camera center. The transformations between a pair of cameras can be derived in a straightforward way:

$$\mathbf{R}_{sLR}^{(i)} = \mathbf{R}_{sL}^{(i)} \mathbf{R}_{sR}^{(i)^{-1}}, \mathbf{t}_{sLR}^{(i)} = \mathbf{t}_{sL}^{(i)} - \mathbf{R}_{sL}^{(i)} \mathbf{R}_{sR}^{(i)^{-1}} \mathbf{t}_{sR}^{(i)}. \quad (2)$$

Also the transformation between the p th sensor and the q th sensor can be also obtained in a similar way:

$$\mathbf{R}_{pq}^{(i)} = \mathbf{R}_{pL}^{(i)} \mathbf{R}_{qL}^{(i)^{-1}}, \mathbf{t}_{pq}^{(i)} = \mathbf{t}_{pL}^{(i)} - \mathbf{R}_{pL}^{(i)} \mathbf{R}_{qL}^{(i)^{-1}} \mathbf{t}_{qL}^{(i)}. \quad (3)$$

As a result, there are N transformations ($i = 1, \dots, N$) coming from N view angles respectively. In our experiment, we took the average of them as the final evaluated transformations.

Next we compute the transformations among the N view angles of the turntable rotation. Consider the calibrated sensor s , it can reconstruct the 3D coordinates of partial markers that are visible from the i th view angle in its own coordinate frame $O_{sL}X_{sL}Y_{sL}Z_{sL}$. Let

$\mathbf{X}_k^{(i)} (k=1, \dots, L)$ represent these markers and they correspond to those markers $\mathbf{X}_k$ on the calibration target (in the world coordinate system) that can be uniquely determined by the code value. The optimal transformation $\mathbf{R}_{sW}^{(i)} \mathbf{t}_{sW}^{(i)}$ that maps the set $\mathbf{X}_k^{(i)}$ onto $\mathbf{X}_k$ can be solved by minimizing an error criterion in a least-squares sense:

$$E(\mathbf{R}_{sW}^{(i)}, \mathbf{t}_{sW}^{(i)}) = \sum_{k=1}^L \|\mathbf{X}_k - \mathbf{R}_{sW}^{(i)} \mathbf{X}_k^{(i)} - \mathbf{t}_{sW}^{(i)}\|^2. \quad (4)$$

The close-form solution of Eq. (4) can be worked out using Eigen-system computation based on the unit quaternions representation [11]. In this way, all transformations from the N view angles to the world coordinate frames can be determined accurately. There will be S group transformations with S sensors. With these transformations, we can automatically register all range images of the object, taking from the predefined view angles through the turntable rotation. As a result, a complete 3D reconstructed model associated with these range images is created using the integration method proposed by Soucy [12].

To demonstrate the validity of a proposed method, a prototype of a 3D optical digitizer was built up as shown in Fig. 1(b). The turntable was driven by a motorized control. The 3D optical sensor based on the PAAS was composed of two CCD cameras (ImagingSource, 1280×960 pixels) and a LG DLP projector (HX300G, 1024×768 pixels). We arranged the turntable to rotate eight angles ($N=8$) with spacing 45 deg from each other. The calibration target was constructed using a shaped-box attached with 166 markers as shown in Fig. 1(b). The coordinates of markers were determined using BA strategy [7] (the Nikon D200 camera with 3872×2572 pixels was used to capture 23 images of target for computing). With this target, the calibration of 3D optical sensor array was conducted. A flat plate with uncertainty 0.01 mm was used as a criterion to evaluate the accuracy of calibration. Figure 3(a) illustrates the error distributions from measured points to the fitting plane, ranging from -0.05 to $+0.05$ mm.

In order to assess the stability of the transformation $\mathbf{R}_{sW}^{(i)} \mathbf{t}_{sW}^{(i)}$, we computed the relative standard deviation (RSD) of the S group transformations from S sensors. We define the RSD of rotation matrix and translation vector as RSD_R and RSD_t respectively:

$$RSD_R(\%)=100 \cdot \sqrt{\sum_{s=1}^S \|\mathbf{R}_{sW}^{(i)} - \bar{\mathbf{R}}_W^{(i)}\|^2 / (s-1) / \|\bar{\mathbf{R}}_W^{(i)}\|}, \quad RSD_t(\%)=100 \cdot \sqrt{\sum_{s=1}^S \|\mathbf{t}_{sW}^{(i)} - \bar{\mathbf{t}}_W^{(i)}\|^2 / (s-1) / \|\bar{\mathbf{t}}_W^{(i)}\|},$$

where $\|\cdot\|$ represents the 2-norm of the matrix and the vector. $\bar{\mathbf{R}}_W^{(i)}$ is the average of $\mathbf{R}_{sW}^{(i)}$, and $\bar{\mathbf{t}}_W^{(i)}$ is the average of $\mathbf{t}_{sW}^{(i)}$. Figure 3(b) shows the values of RSD_R and RSD_t in eight angle-views, respectively. It can be seen from Fig. 3(b) that the RSD_R and RSD_t are less than 0.08%.

We digitized a Buddha head statue with a height about 40 cm to verify the feasibility of our proposed method. All range images covering the complete views of the statue were captured automatically with the experiment setup shown in Fig. 1(b). Furthermore, the range images were also automatically registered to the unified coordinate frame with proposed method. Figure 4(a) shows the registration results of multiple-range images where different colors represent different range images. Each range image consists of about 1 million triangle patches. Figure 4(b) shows the distribution of registration errors, from which we can see that the registration error is less than 0.1 mm. Figure 5 shows the final digital model of the 3D Buddha head statue with 432,508 triangle patches (after simplification). Table 1 shows the running time of the process taken by three sensors and from eight view angles (CPU i7 and RAM 4G).

Finally, it should be pointed out that we can increase or reduce the number of 3D sensors in the array to adapt complete field digitization according to the complexity of geometric shape and topology of the object.

In conclusion, we have introduced a novel strategy for automatic and complete digitization of 3D objects. The embodiment of this strategy consists of a 1D array of 3D optical sensors combined with a rotation turntable. To guarantee the accuracy of the 3D digitization, we have presented an efficient method for the calibration of optical sensor array. In addition, we have also proposed an automatic registration technique for aligning multiple range images taken from the optical sensor array together with turntable rotation. The experimental results have verified the feasibility of the proposed approach for automatic and complete digitization of a complex 3D object in real scene.

Acknowledgments

The authors thank the National Natural Science Foundation of China (grants 60775021, 61171073) and the Scientific and Technological Project of the Shenzhen government for their financial support.

References

1. Peng X, Liu X, Yin Y, Li A. Opt. Lett. 2011; 36:157. [PubMed: 21263485]
2. Gorthi SS, Rastogi P. Opt. Lasers Eng. 2010; 48:133.
3. Chen X, Su X, Guo L. Appl. Opt. 1991; 30:1274. [PubMed: 20582138]
4. Zhang Z, Ma H, Zhang S, Guo T, Towers CE, Towers DP. Opt. Lett. 2011; 36:627. [PubMed: 21368929]
5. Reich C, Ritter R, Thesing J. Opt. Eng. 2000; 39:224.
6. Yin Y, Peng X, Li A, Liu X, Gao B. Opt. Lett. 2012; 37:542. [PubMed: 22344100]
7. Atkinson, KB. Close Range Photogrammetry and Machine Vision. Whittles; 2003.
8. Yin Y, Peng X, Liu X, Li A, Qu X. Opt. Commun. 2012; 285:2048.

9. Zhang S, Huang PS. Opt. Eng. 2006; 45:083601.
10. Hartley, R.; Zisserman, A. Multiple View Geometry in Computer Vision. 2nd ed.. Cambridge University; 2003.
11. Horn BKP. J. Opt Soc. Am. A. 1987; 4:629.
12. Soucy M, Laurendeau D. IEEE Trans. Pattern Anal. Machine Intell. 1995; 17:344.

(a) **(b)**

Fig. 1.
(Color online) (a) Schematic diagram of the measurement strategy with a 3D sensor array,
and (b) the practical setup in the experiment.

Fig. 2.

(Color online) Schematic diagram of the optical sensor array calibration.

Fig. 3.

(Color online) (a) Error distributions between 3D points and the fitting plate, and (b) the RSD of transformations from optical sensor array in eight angle views.

Fig. 4.
(Color online) (a) Registration of the Buddha head statue, and (b) the distribution registration errors ranging from 0 mm to 0.1 mm.

Fig. 5.
(Color online) 3D reconstruction with proposed strategy.

Table 1

Running Time for Digitizing the Buddha Head Statue

Process	Acquiring the 24 Range Images	Turntable Rotation (eight angles)	Registration and Integration	Total
Time (s)	$4\text{ s} \times 24 = 96\text{ s}$	$3\text{ s} \times 8 = 24\text{ s}$	28 s	148 s