https://doi.org/10.20965/ijat.2016.p0172

Paper:

Digital Shape Reconstruction of a Micro-Sized Machining Tool Using Light-Field Microscopy

Shin Usuki*,†, Masaru Uno, and Kenjiro T. Miura****

*Research Institute of Electronics, Shizuoka University
3-5-1 Johoku, Naka-ku, Hamamatsu 432-8561, Japan
†Corresponding author, E-mail: dsusuki@ipc.shizuoka.ac.jp
**Graduate School of Engineering, Shizuoka University
3-5-1 Johoku, Naka-ku, Hamamatsu 432-8561, Japan

[Received September 30, 2015; accepted November 24, 2015]

In this paper, we propose a digital shape reconstruction method for micro-sized 3D (three-dimensional) objects based on the shape from silhouette (SFS) method that reconstructs the shape of a 3D model from silhouette images taken from multiple viewpoints. In the proposed method, images used in the SFS method are depth images acquired with a light-field microscope by digital refocusing (DR) of a stacked image along the axial direction. The DR can generate refocused images from an acquired image by an inverse ray tracing technique using a microlens array. Therefore, this technique provides fast image stacking with different focal planes. Our proposed method can reconstruct micro-sized object models including edges, convex shapes, and concave shapes on the surface of an object such as micro-sized defects so that damaged structures in the objects can be visualized. Firstly, we introduce the SFS method and the light-field microscope for 3D shape reconstruction that is required in the field of micro-sized manufacturing. Secondly, we show the developed experimental equipment for microscopic image acquisition. Depth calibration using a USAF1951 test target is carried out to convert relative value into actual length. Then 3D modeling techniques including image processing are implemented for digital shape reconstruction. Finally, 3D shape reconstruction results of micro-sized machining tools are shown and discussed.

Keywords: shape reconstruction, light-field microscope, digital refocusing, shape from silhouette, 3D measurement

1. Introduction

Inspection of microscale industrial components requires high throughput, non-destructibility, and three-dimensional (3D) measurement capability. However, these properties are difficult to achieve simultaneously with conventional 3D measurement techniques such as laser scanning confocal microscopy [1], scanning electron microscopy [2], and scanning probe methods with styli [3]. Therefore, we focus on optical microscopy [4] that provides parallel imaging with an area image sensor for high-speed micro-scale measurement. In general, the reconstruction of 3D geometric information using an optical microscope is problematic because the depth of field is very shallow. Therefore, an image-stacking technique using focal plane scanning is typically used to obtain depth information of the object to be measured [5]. However, these methods are not suitable for industrial applications, because they require a long processing time to take a large number of images. Hence, we propose a high-speed image stacking method based on digital refocusing (DR) [6] with an expanded depth of field.

Geometric modeling techniques including shape reconstruction are required for numerical simulations in computer-aided engineering. Recent progress in 3D printing and ultra-precision machining technologies has increased the demand for analysis and evaluation of micro-sized industrial components. As mentioned, laser scanning confocal microscopy can deliver 3D measurement capability with high spatial resolution, but this measurement is limited to one scanning direction, hence, shape reconstruction of whole components is impossible. A method for 3D reconstruction of micro-objects from multiple photographic images has been proposed [7], however, the depth of field of imaging limits the axial resolution to the order of hundreds of micrometers. Furthermore, the shape from silhouette (SFS) and the shape from focus (SFF) methods have been employed to reconstruct the geometric model of whole components [8], but these techniques are too time consuming in manufacturing.

To overcome these limitations, we propose a SFS-based shape reconstruction method for micro-sized 3D objects using a previously developed light-field microscope [9]. The light-field microscope can provide fast image stacking with high resolution, therefore, the proposed shape reconstruction method is useful for inspection, analysis, and evaluation of micro-sized industrial components.

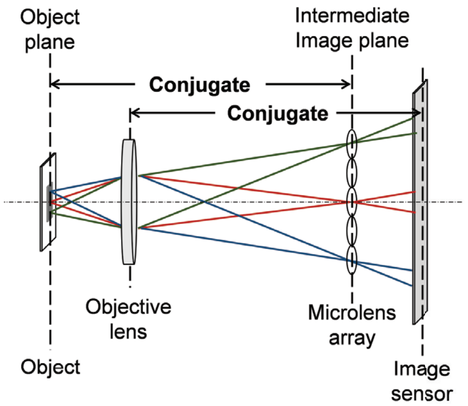


Fig. 1. Light-field microscope optical system.

2. Methodology

2.1. 3D Measurement Using Light-Field Microscopy

In recent years, the computer graphics and image-stacking method, DR, based on the light field has been applied to fluorescent microscopic imaging for expanding the depth of field [10]. **Fig. 1** shows the configuration of a light-field microscopy optical system. In the system, the object plane and microlens array, and the objective lens and image sensor, are conjugate. Therefore, a ray from each microlens corresponds to a ray on a section of the object. Furthermore, each pixel of the image sensor corresponds to a position on the main lens. Hence, by use of a certain microlens and a certain image sensor pixel, it is possible to define a ray from the object as a function that includes two-dimensional (2D) positional coordinates of the microlens and the image sensor pixel. The DR carries out inverse ray tracing from the image plane to the intermediate image plane by using the light field recorded by an image sensor with a microlens.

Figure 2 shows schematics of inverse ray tracing using DR to obtain depth information. A ray from an object is defined and refocusing is done by tracking ray trajectories. A refocus image on an in-focus position is obtained by summing all pixels of the image sensor under each microlens (**Fig. 2(a)**). Similarly, a refocus image on an out-of-focus position is acquired by summing all pixels, considering ray trajectories calculated from a microlens position and a pixel position on the image sensor (**Fig. 2(b)**). Consequently, in this system, it is possible to create refocused images by inverse ray tracing.

2.2. 3D Shape Reconstruction Based on the SFS Method

In this study, microscopic depth images calculated from the stacked images obtained by DR are combined with the SFS method for 3D reconstruction of a measured object with micro-scale structure. The SFS technique is widely used in the reconstruction of 3D geometric models represented as a set of voxels from different viewpoints in computer vision [11] and it is well-suited for edge structure

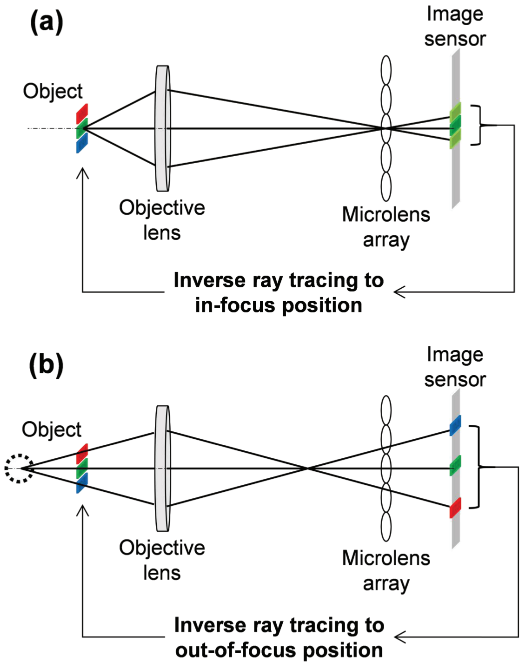


Fig. 2. Inverse ray tracing using DR.

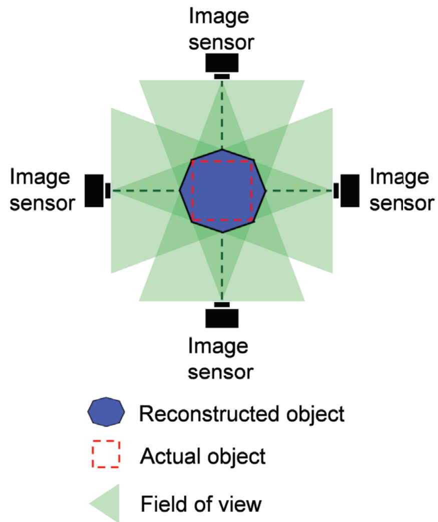


Fig. 3. Conceptual diagram of 3D shape reconstruction by the SFS method.

detection. **Fig. 3** shows a concept of 3D reconstruction by the SFS method. The commonly-used SFS technique requires mask images or binary images obtained from the acquired images to determine if a voxel is in, on silhouette (usually, this is called ambiguous), or out. When the voxel is in or on silhouette, it is retained. However, if the voxel is out, it is removed. Hence, retained voxels represent a 3D geometric model of an object. However, the SFS method cannot retrieve information on the surface asperity of an object. To solve this problem, we adapt depth information using the stacked images obtained by DR, to the geometric model constructed by the SFS method, to include the surface information of the object.

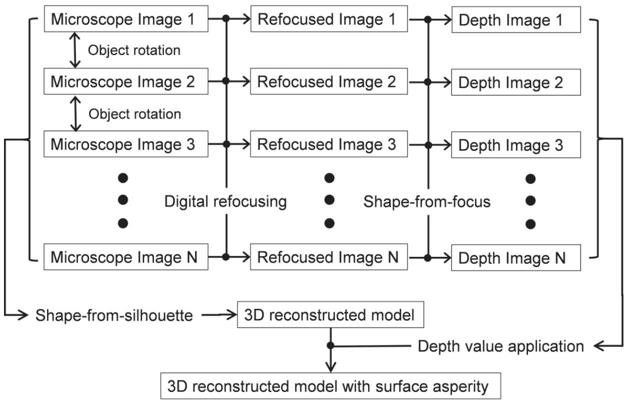


Fig. 4. Processing flow chart of the 3D shape reconstruction based on the DR, SFF, and SFS methods.

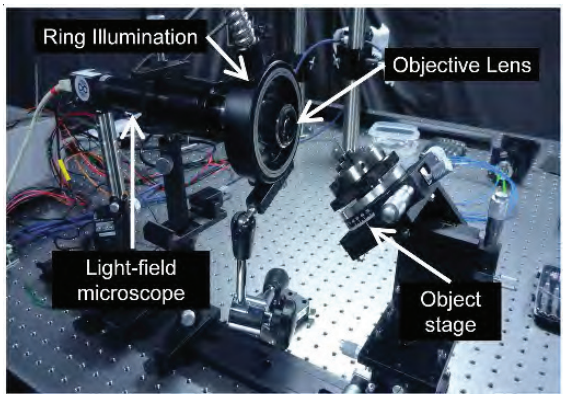


Fig. 5. Prototype of the light-field microscope for 3D shape reconstruction.

3. Development

3.1. Shape Reconstruction System for Micro-Sized Objects Using Light-Field Microscopy

In order to reconstruct a micro-sized object and generate a 3D geometric model of it, the SFS method is employed for edge structure detection and the depth information acquired by the light-field microscope is used to add the surface asperity information of the object. **Fig. 4** shows a processing flow chart of the 3D shape reconstruction. In addition, we developed a prototype of the light-field microscope shown in **Fig. 5**. This microscope consists of a computer for DR and the SFF method, a light-field optical system for depth information acquisition, and a rotating stage for the SFS method. The rotating stage is equipped with a mounted object stage and, for fine rotation adjustment, we used an *x*-*y* motion stage. Additionally, for the uniform illumination on an object, we used light-emitting diode (LED) ring illumination. The experimental conditions are shown in **Table 1**.

3.2. Calibration of Depth

Depth information from the SFS and DR methods is obtained as an arbitrary value. Therefore, it is necessary to measure the actual depth value. We calibrated the depth using a test target inclined at 45° toward the optical axis shown in **Fig. 6**. **Figs. 7** and **8** show the acquired depth images and the results of the calibration, respectively. The color bar in **Fig. 7** indicates distance from the objective lens. When the color is red and blue, it means the position is close to the objective lens and the depth value is large, and, that the position is quite far from the objective lens and the depth value is small, respectively. We measured the distance by comparing the depth value from the acquired color images and line thickness of the test tar-

Table 1. Experimental conditions for 3D shape reconstruction.

Parameter	Value
Microscope magnification	2x
Numerical aperture	0.055
Pixel size of camera	5.5 μm
Frame rate of depth image acquisition	14.1 fps
Pitch of microlens	126.5 μm
Number of images for SFS	18

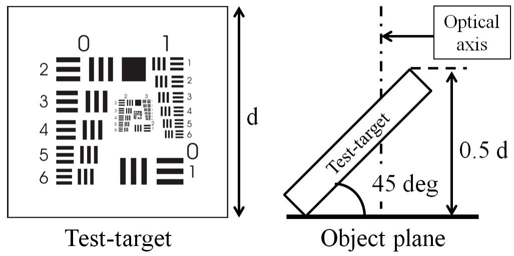


Fig. 6. Calibration target.

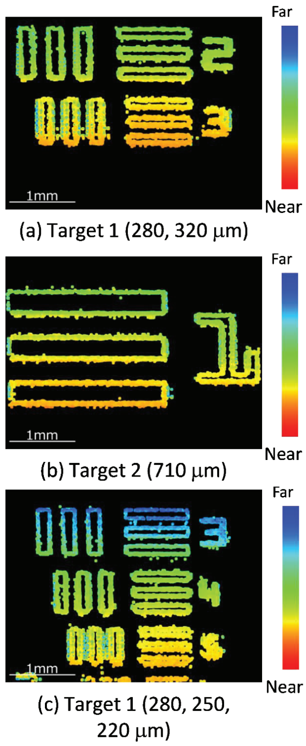


Fig. 7. Depth images of the calibration target.

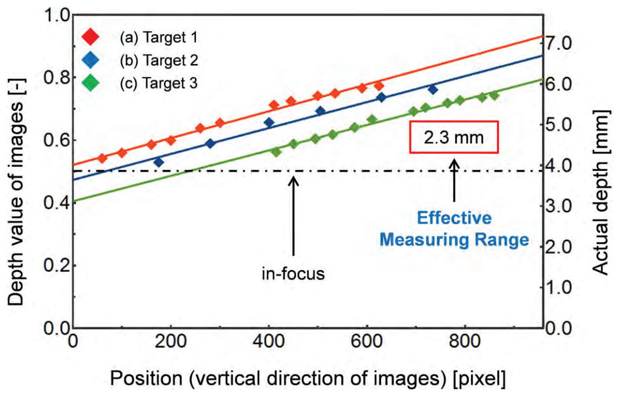


Fig. 8. Actual depth evaluated by the depth images of the calibration target.

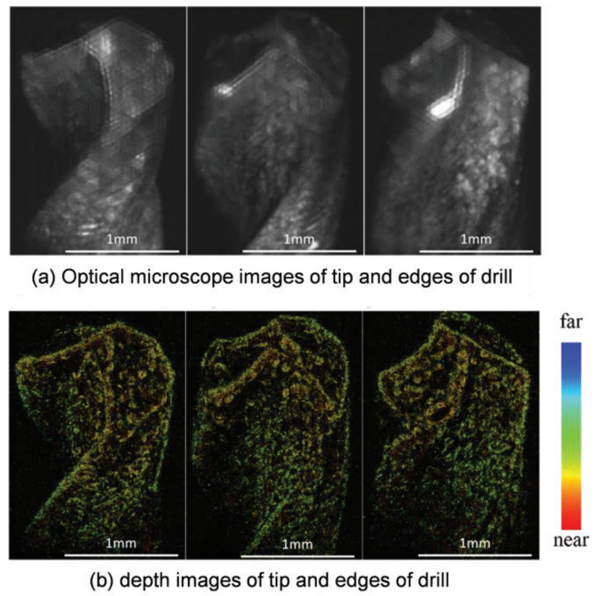


Fig. 9. Actual depth evaluated by the depth images of the calibration target.

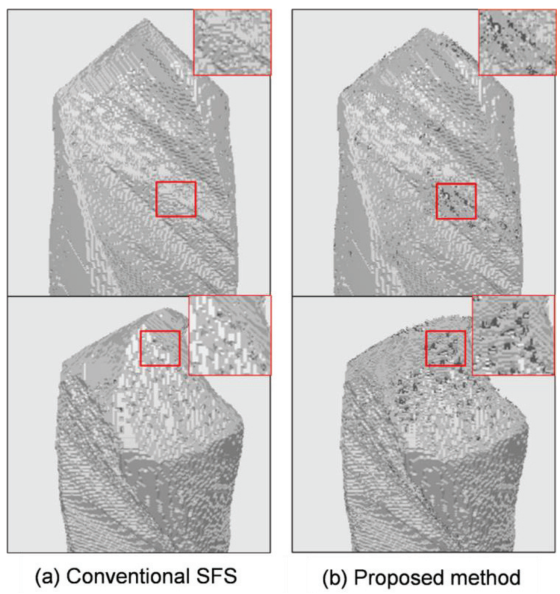


Fig. 10. 3D geometric voxel model of the tip and edges of the micro-scale drill reconstructed by (a) the conventional SFS and (b) the proposed method.

get. Then, we evaluated an effective measuring range. In **Fig. 8**, when the depth value is 0.5, it corresponds to the in-focus position. There is a difference in accuracy between above and below the in-focus position. We only employed upper data from the in-focus position because almost all of the depth images had a depth value of higher than 0.5. We performed the least squares method and measured the gradient of these lines for the calibration. All of these gradients were similar and close to 45° of the test target. Then, we derived the relationship between depth values and actual depth, with the depth value 0.1 corresponding to an actual depth of 0.77 mm. Therefore, the effective depth range of the developed system was 2.3 mm.

4. Experiment

4.1. Reconstruction of a Micro-Sized Machining Tool

Recently, micro-sized tools such as micro-drills and micro-endmills have been employed for ultra-precision machining. They can form 3D shapes with flexible finishing, but pose many problems in mass production. Abrasion and deficit of the tool edge are the critical issues in the repeatability of the machining process. Although the tools are made from extremely hard materials, the tools have quite sharp edges, so they are damaged and unusable immediately after use. The damage mechanism is complicated and has not been clarified in detail. Condition analysis, performance evaluation, and quality control of the tools are required. A digital geometric model of a micro-sized machining tool can be built by the proposed shape reconstruction method and can be analyzed and evaluated by numerical simulations.

4.2. Results and Discussion

Reconstruction of a micro-sized machining tool was carried out by using the developed and calibrated light-field microscope and resulting depth images. Firstly, images of a 1.3 mm diameter drill were obtained and the microstructure of its tip and edges were reconstructed. Then, eighteen images for the SFS method were acquired from different viewpoints, including both the microscope images and the depth images shown in **Fig. 9**. An orthogonal projection of voxels for inside/outside judgment was used because the optical microscopic image is orthographic, which is a different methodology to that utilized in the conventional SFS method. This makes it easy to configure the experimental condition in the SFS process. **Fig. 10** shows the 3D geometric voxel model of the tip and edges of the drill reconstructed by both the conventional SFS method and the proposed method. 300 × 300

$\times$ 300 voxels were used in the SFS technique, and the marching cube method [12] was used to refine the resulting voxel models. The depth images taken by the light-field microscope prototype were applied to add surface asperity to the reconstructed 3D model. In the conventional SFS method (**Fig. 10(a)**), the reconstructed object does not contain information on the surface asperity, although it includes edge information. On the other hand (**Fig. 10(b)**), the proposed method can reconstruct the tip and edges, as well as the surface asperity. Therefore, the proposed method can be applied to reconstruct the microstructure of the object accurately. In the case of smaller diameter tools with sharper edges such as micro-endmills, however, complete shape reconstruction would be more difficult. This is because of the measurement resolution of $\sim 63\ \mu$m, assumed from the specific properties of the optical system in the 3D imaging range of 5.0 mm $\times$ 5.0 mm $\times$ 2.3 mm determined by the field of view of imaging and evaluated through the calibration.

5. Improvement

5.1. Improved Equipment and Calibration

In order to reconstruct a machining tool shape with a diameter of less than one millimeter and sharper edges, we employed a higher magnification 5x objective lens with higher numerical aperture 0.255 in the developed light-field microscope. Accordingly, another calibration experiment was carried out. The calibration target was the same as former one (see **Fig. 6**). **Fig. 11** shows the resulting microscopic images and depth images of different focused areas of the target. Line 3-3 (a), line 3-4 (b), line 3-5 (c), and line 3-6 (d) correspond to line pitch 99.0 mm, 88.5 mm, 78.7 mm, and 69.9 mm, respectively. The relationship between arbitrary depth value and actual depth value determined by the target is shown in **Fig. 12**. There are some errors and deviations in the calibration result, but enough linearity was confirmed for depth measurement. The arbitrary depth value of 0.1 corresponds to an actual depth of 0.17 mm. Therefore, the effective measuring range of the improved equipment was approximately 0.5 mm.

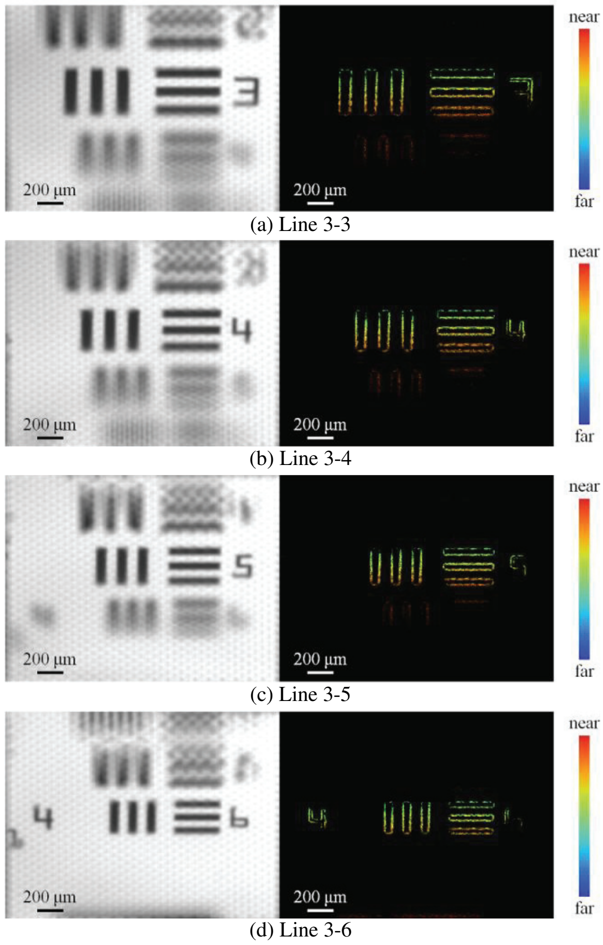


Fig. 11. Microscopic images and depth images of different focused areas of the calibration target.

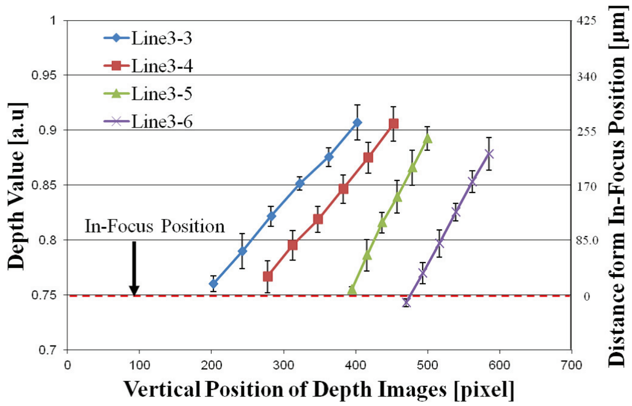
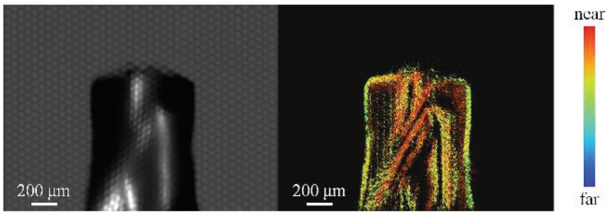


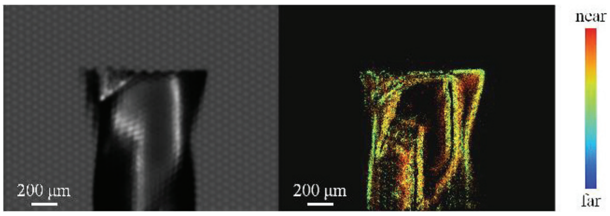
Fig. 12. Relationship between arbitrary depth value and actual depth value.

5.2. Results and Discussion

Reconstruction of a micro-endmill with a diameter of 0.8 mm and blade length of 0.5 mm was attempted using the improved equipment. Moreover, for further time saving of image acquisition, the number of images for the SFS method was decreased to six in this reconstruction so that rotation angle of the tool was 60° for each camera shot. **Fig. 13** shows the resulting microscopic images and depth images by DR. The depth image of the micro-endmill was noisy and caused some shape error in the reconstruction result. Hence, the filtering based on the moving least squares (MLS) [13] was applied for better reconstruction. A comparison of the raw depth image and filtered depth image is shown in **Fig. 14**. The noise in the depth image was reduced without losing the edge and blade structure information of the endmill. **Figs. 15(a)** and **(b)** show the filtered depth images with the conventional SFS technique and a geometric voxel model of the endmill reconstructed by the SFS method, respectively. The reconstruction procedure is the same one as mentioned in the previous section. By using the proposed method, cutting blade structure as well as convex and con-

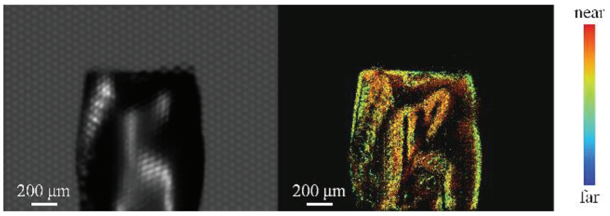


(a) 0°



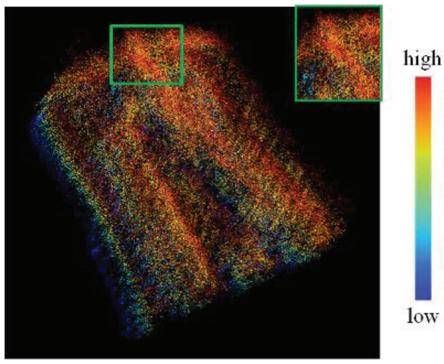
(b) 60°

⋮

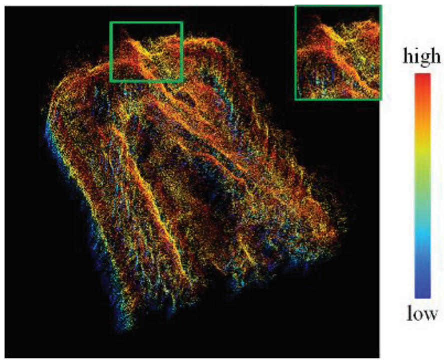


(c) 300°

Fig. 13. Microscopic images and depth images acquired with respect to the rotation angle of the tool.



(a) Before filtering



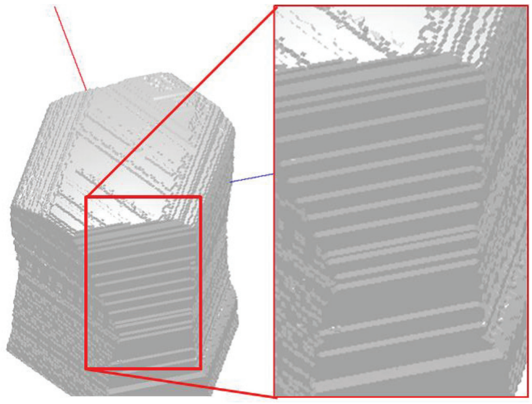
(b) After filtering

Fig. 14. Comparison of (a) raw depth image and (b) filtered depth image by the MLS.

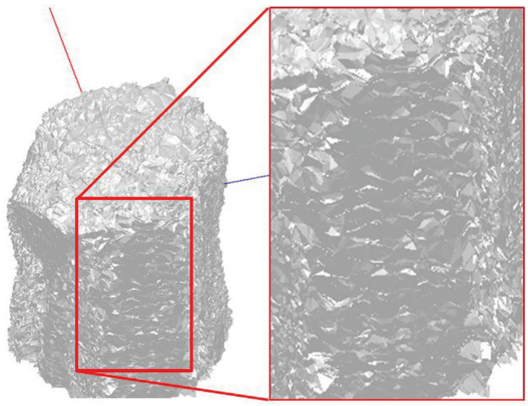
cave structure on the surface were reconstructed in the resulting voxel model. This was achieved with an improved measurement resolution of ~ 25 μm by using the higher magnification objective lens. Although the 3D imaging range was reduced to 2.0 mm $\times$ 2.0 mm $\times$ 0.25 mm, the depth range was expanded by the SFS method to cope with the smaller diameter of the endmill. The processing time of reconstruction was approximately 0.5 s in the case of the octree voxel level 8 and total processing time was less than 1 s by a PC with general specifications.

6. Conclusion

In this study, we propose a 3D measurement and digital shape reconstruction method using the SFS technique and microscopic depth images of a micro-sized object by light-field microscopy. The equipment development, calibration, and improvements are carried out for a series of experiments. The proposed method was applied to build geometric models of micro-sized machining tools. In contrast to the conventional SFS technique, the proposed method can reconstruct convex and concave structures. However, the light-field microscope used has poorer spatial resolution than a conventional optical microscope because the microlens array limits incident light to the CCD sensor. Therefore, it is difficult to obtain high accuracy in the reconstruction. In future work, super resolution techniques based on imaging path control [14] will be employed for further improvement of the developed system.



(a) SFS result



(b) Our method result

Fig. 15. (a) Filtered depth images by the conventional SFS technique and (b) geometric voxel model, reconstructed by the proposed SFS method, of the endmill.

Acknowledgements

This work was supported by JSPS KAKENHI Grant-in-Aid for Scientific Research(C), Grant Number 24520050.

References:

[1] N. S. Claxton, T. J. Fellers, and M. W. Davidson, "Laser scanning confocal microscopy," Department of Optical Microscopy and Digital Imaging, National High Magnetic Field Laboratory, Florida State University, p. 37, Unpublished, 2005. http://www.aptechnologies.co.uk/images/Data/Vertilon/PP6207.pdf [Accessed February 22, 2016]

[2] J. Pawley, "The development of field-emission scanning electron microscopy for imaging biological surfaces," Scanning, Vol.19, No.5, pp. 324-336, 1997.

[3] R. Howland and L. Benatar, "A Practical Guide to Scanning Probe Microscopy," Park Scientific Instruments, 1993.

[4] J. McDonald, "Optical Microscopy Microelectronics Failure Analysis," Desk Reference Fifth Edition EDFAS, 2004.

[5] S. K. Nayar and Y. Nakagawa, "Shape from Focus," IEEE Trans. on Pattern Analysis and Machine Intelligence, pp. 824-831, 1994.

[6] Y. Bando and T. Nishita, "Towards Digital Refocusing from a Single Photograph," Pacific Graphics, pp. 363-372, 2007.

[7] K. Atsushi, H. Sueyasu, Y. Funayama, and T. Maekawa, "System for reconstruction of three-dimensional micro objects from multiple photographic images," Computer-Aided Degign, Vol.43, No.8, pp. 1045-1055, 2011.

[8] H. Sueyasu and T. Maekawa, "3D shape evaluation of micro products using computer vision techniques," IPSJ SIG Technical Report, Vol.146, No.8, 2012.

[9] S. Usuki, M. Uno, and K. T. Miura, "Resolution-improved digital refocusing microscope for microstructure measurement," Proc. of the 12th euspen Int. Conf., Vol.280, No.3, 2012.

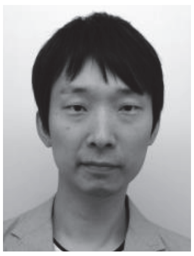
[10] M. Levoy, R. Ng, A. Adams, M. Footer, and M. Horowitz, "Light Field Microscopy," ACM Trans. on Graphics, Vol.25, No.3, pp. 924-934, 2006.

[11] R. Szeliski, "Rapid Octree Construction from Image Sequences," CVGIP: Image Understanding, Vol.58, No.1, pp. 23-32, 1993.

[12] W. E. Lorensen and H. E. Cline, "A High-Resolution 3D Surface Construction Algorithm," ACM Computer Graphics, Vol.21, No.4, pp. 163-169, 1987.

[13] D. Levin, "Mesh-Independent Surface Interpolation," Geometric Modeling for Scien-tific Visualization, Vol.3, 2003.

[14] S. Usuki and K. T. Miura, "High-Resolution Tolerance against Noise Imaging Technique Based on Active Shift of Optical Axis," Int. J. Automation Technology, Vol.5, No.2, 2011.



Name:
Shin Usuki

Affiliation:
Research Institute of Electronics, Shizuoka University

Address:
3-5-1 Johoku, Naka-Ku, Hamamatsu 432-8561, Japan

Brief Biographical History:

2002/2004/2008 Received B.Eng., M.Eng., and D.Eng. from Department of Precision Engineering, The University of Tokyo

2008-2013 Assistant Professor, Division of Global Research Leaders, Shizuoka University

2013- Associate Professor, Research Institute of Electronics, Department of Mechanical Engineering, Faculty of Engineering, Shizuoka University

Main Works:

• "Optical Microscopy with Improved Resolution Using Two-beam Interference of Low-coherence Light," Measurement, Vol.78, pp. 373-380, 2016.

Membership in Academic Societies:

• Japan Society for Precision Engineering (JSPE)
• Japan Society of Mechanical Engineers (JSME)

Name:
Masaru Uno

Affiliation:
Department of Mechanical Engineering, Shizuoka University

Address:
3-5-1 Johoku, Naka-Ku, Hamamatsu 432-8561, Japan

Brief Biographical History:

2012 Received B.Eng. from Department of Mechanical Engineering, Shizuoka University

2014 Received M.Eng. from Department of Mechanical Engineering, Shizuoka University

Main Works:

• "3D measurement and reconstruction using microscopic depth images," Proc. of the 5th Int. Conf. of Asian Society for Precision Engineering and Nanotechnology, 2013.

Name:
Kenjiro T. Miura

Affiliation:
Department of Information and Technology, Graduate School of Science and Technology, Shizuoka University

Address:
3-5-1 Johoku, Naka-Ku, Hamamatsu 432-8561, Japan

Brief Biographical History:

1982/1984 Obtained B.Eng. and M.Eng. from The University of Tokyo

1991 Obtained Ph.D. from Cornell University

2003- Full Professor, Department of Mechanical Engineering, Faculty of Engineering and Department of Information Science and Technology, Graduate School of Science and Technology (joint appointment), Shizuoka University

Main Works:

• T. Kenjiro and R. Miura, and U. Gobithaasan, "Aesthetic Curves and Surfaces in Computer Aided Geometric Design," Int. J. of Automation Technology, Vol.8, No.3, pp. 304-316, 2014.

Membership in Academic Societies:

• Japan Society for Precision Engineering (JSPE)
• Japan Society of Mechanical Engineers (JSME)
• Information Processing Society of Japan (IPSJ)