3D reconstruction of rotational video microscope based on patches

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ABSTRACT
Due to the small field of view and shallow depth of field, the microscope could only capture 2D images of the object. In order to observe the three-dimensional structure of the micro object, a microscopy images reconstruction algorithm based on an improved patch-based multi-view stereo (PMVS) algorithm is proposed. The new algorithm improves PMVS from two aspects: first, increasing the propagation directions, second, on the basis of the expansion, different expansion radius and times are set by the angle between the normal vector of the seed patch and the direction vector of the line passing through the seed patch center and the camera center. Compared with PMVS, the number of 3D points made by the new algorithm is three times as much as PMVS. And the holes in the vertical side are also eliminated.

Keywords: Microscope, 3D reconstruction, PMVS, Patches

1 INTRODUCTION
Microscope is widely used in biomedicine, industrial observation and measurement. As the image of the microscope is 2D, it is difficult to observe the 3D structure of the object because of the small depth of field and the narrow field of view of the microscope. In order to resolve this problem, microscopic 3D reconstruction is an active research field in the past three decades. The three-dimensional reconstruction methods of optical microscopy is classified into the following classes: confocal or defocus microscopy [1][2], optical coherence tomography [3], optical projection tomography [4], stereo microscopy [5] and monocular rotational video microscopy. Confocal or defocus microscope system reconstructs 3D surface models from confocal image stacks, but this method is not applicable for objects with concave side. OCT and OPT are widely used in the biomedical field, however, they require that the sample is transparent. Stereo microscope has a shallow depth of field and is effective for observation under relatively low magnification only. Monocular rotational microscope reconstructs the 3D micro model from several 2D images of the object taken from different views. This method is convenient and has lower demands for applying environment. By tilting samples using nanobelts to generate localized rotational motions, Kratochvil [6] used structure-from-motion algorithm to reconstruct pollen and mold spores three-dimensional models under a scanning electron microscope. Atsushi [7] employed the shape-from-silhouette (SFS) method to reconstruct a voxel-based 3D model from silhouette images which are captured from an acquisition system consisting of a digital microscope and a computer controlled turntable. In this paper, an improved PMVS is used for micro object reconstruction from images captured by a rotational video microscope. Rotational video microscope, which is assembled with a rotating mirror, could observe the surface of the micro object around 360 degrees without inclining the lens and object and complex adjustment. PMVS (patch-based multi-view stereo) [8] proposed by Furukawa et al. is superior in quality and quantity in the field of the big scene 3D reconstruction. In recent years, PMVS is improved to
adapt to different scenarios and needs. Taipang Wu et al. [9] provided a unified approach based on closed-form solution to tensor voting to implement the match-propagate-filter pipeline, which leads to less accumulation errors and outliers in the propagation results. Limin Shi [10] adjusted the patches based on geometrical information and expands different resolution images, which improved the accuracy and efficiency. When PMVS is applied to microscopy, some holes will appear in the 3D point cloud. In order to fill these holes, our method improves the expansion step of PMVS by setting different seed patches with different extension radius and times.

2 METHODOLOGY

The framework of our method is shown in Figure 1. First, accurately calibrated parametric models of the optical microscope are built [11]. Second, structure-from-motion system [12] [13] is used to produce a 3D reconstruction of the camera and (sparse) scene geometry. Finally, taking image sequences and photography matrixes produced by SFM as input of PMVS, the 3D model of the sample is reconstructed. PMVS algorithm consists of a simple match, expand and filter procedure. Features and corner points are first detected by Harris and difference-of-Gaussians operators, then they are matched across multiple images to yield a sparse set of patches computed based on triangulation measuring method. The detailed feature of the object could not be described completely only with sparse patches, so the neighborhood information is taken account of to recover the neighborhood information of 3D space. The initial sparse patches regarded as seed patches are expanded to nearby position to obtain a set of patches based on that they are in the same plane and have the same normal vectors. To avoid holes in the vertical side of 3D models, the expansion radius and times are calculated depending on the angle between the normal vector of the seed patch and the direction vector of the line passing through the seed patch center and the optical center. After the expansion procedure is completed, visibility consistency is enforced to remove the erroneous patches. Through these above steps, accurate dense 3D model of the micro object is reconstructed.

![Figure 1 Flow chart of improved-PMVS](image)

2.1 Patch expansion

Expansion step is a key step on 3D reconstruction. Expansion step is performed by expanding the seed patches $p$ to nearby position to obtain a set of new patches $p'$ based on that they are in the same plane and have the same normal vectors. Since the expansion directions will affect the density, our method adds directions from six to eight to obtain a more dense result.
When expanding seed patches $p$, every direction will be checked whether it is empty within a certain radius range. It is unnecessary to expand in this direction if a patch $p'$ has already been reconstructed around 22.5 degrees and is a neighbor of $p$.

$p$ and $p'$ are defined to be neighbors if

$$\left| \left( c(p) - c(p') \right) * n(p) \right| + \left| \left( c(p) - c(p') \right) * n(p) \right| < 2 \rho_1$$  \hspace{1cm} (1)$$

$\rho_1$ is the distance corresponding to an image displacement of $\beta_1$ pixels in the reference image $R(p)$ at the depth of the centers of $c(p)$ and $c(p')$.

### 2.2 Expansion radius refinement

Rotational video microscope has a small field of view and observes the object from a certain angle, so the vertical side of the object will be small in the images. If we expand the seed patches with the expansion radius calculated with the fixed width of pixels, there will be some holes in the vertical side of 3D models. The expansion radius $r$ directly affects the density of the reconstruction result. The reconstruction result with larger expansion radius is sparse, and with smaller expansion radius is dense but cost more time to calculate. But if the radius is less than a certain range, the result will be also sparse. The initialization parameter of the new patch $p'$ is defined as

$$c(p') = c(p) + \cos(\alpha) * r * dx + \sin(\alpha) * r * dy$$  \hspace{1cm} (2)$$

$$n(p') = n(p)$$  \hspace{1cm} (3)$$

Figure 2 Schematic of patch expansion directions
The coordinate \( c(p') \) of new patches \( p' \) is initialized as the point where the viewing ray passing through the image intersects the plane containing the seed patch.

The normal vector \( n(p') \) is initialized by the corresponding values of \( p \).

Figure 3 New patch \( p' \) is the point where viewing ray passing through the image intersects the plane containing the seed patch \( p \). 

As it is shown in Figure 4, \( n_1 \) and \( n_2 \) are normal vectors to plane AB and plane EF. Line CB and line CD correspond the same pixel distance-line GH in the image. If the expansion radius depends on the same pixel distance, the expansion radius of the patch \( C \) in the plane EF will be larger than in the plane AB. The 3D point cloud is sparse and even occurs holes when expanding with larger radius. The vertical side of the micro object has a large \( \alpha \) compared with other areas. In order to fill the holes of the vertical side, different extension radius and times are set by the angle \( \alpha \).

Figure 4 \( \alpha_1(\alpha_2) \) is the angle between normal vector \( n_1(n_2) \) and the vector of the line connected by \( c \) and camera center.

Expansion times \( t \) and radius \( r \) are computed according to \( \alpha \), as follows:

\[
t = \left[ \frac{1}{\cos \alpha} \right]
\]

(4)
\[
\text{radius} = \frac{d}{\text{scale}} \cos \alpha \cdot \text{csize} \cdot i (0 < i \leq t)
\]  

(5)

Where \( \text{scale} \) is the scale factor and \( d \) is the distance from \( c(p) \) to the camera center. \( \text{csize} \) is the size of image cell, which is set to 2 in the experiment.

3 EXPERIMENT

In this section, a few experiments are performed to evaluate the quality of our new algorithm. To prove that the holes in the vertical side of the reconstruction result are eliminated obviously, the reconstruction images and the total number of the 3D points are compared with PMVS. In our experiments, LED and button, which are convex objects and concave objects separately and have obvious lateral structures, are chosen as the reconstruction objects. Rotational video microscope produced by Pomeas Optical Technology (Hong Kong) Co., Ltd. is used to photograph the image sequences. The comparison results of the reconstruction result images and the total number of the point cloud are shown in Figure 6 and Table 1.

![Figure 6](image)

(a) LED 3D model of PMVS (b) LED 3D model of our method (c) Button 3D model of PMVS (d) Button 3D model of our method

<table>
<thead>
<tr>
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<th>LED</th>
<th>BUTTON</th>
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<tr>
<td>Our method</td>
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Table 1 Comparison of algorithm for the number of 3D points

4 CONCLUSION

An improved PMVS algorithm is proposed in this paper, which fill the holes appearing in the vertical side of the reconstructed 3D model when applying PMVS to rotational video microscope. First, we add the directions of expansion to increase the density of reconstruction. Second, we calculated the expansion radius and times based on the angle...
between the normal vector of each seed patch and the direction vector of the line passing through the camera center and the seed patch center. In this paper, images of an LED and a button are captured by rotational video microscope and are used to conduct experiments. The result of the experiments shows that the holes are reduced obviously and the total number of points are tripled compared with PMVS. And the improved PMVS has more application areas, especially in rotational video microscope 3D reconstruction.

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REFERENCES