Speckle Based Pose Estimation for 3D Measurement of the Feature-less Environment by Two Cameras

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ABSTRACT

In this research, we propose the 3D measurement system combining structured light and speckle based pose estimation by introducing two different setting cameras. The proposed system consists of two lasers, namely spot laser and line laser, and two cameras, with and without lens, which can obtain both focused and defocused images at once. Local shapes are measured using focused images by structured light method. 3D positions of points projected by laser are calculated by triangulation. Pose changes are estimated from speckle information using defocused images. Displacements of speckle patterns are detected as optical flow by Phase Only Correlation (POC) method. Pose changes are estimated from speckle displacements by solving equations derived from the physical nature of speckle. The target shape as a whole is reconstructed by integrating the local shapes of each image into common coordinates using estimated pose changes. In the experiment, the texture-less flat board was measured with motion. From the experimental results, it is confirmed that the shape of the board was reconstructed correctly by the proposed 3D measurement system.

Keywords: 3D measurement, pose estimation, speckle

1. INTRODUCTION

Laser measurement method enables non-contact and high-precision 3D measurement. In laser measurement, the measurement range is limited to the points where the reflected laser light from the target surface can be observed. Therefore, it is necessary to integrate local measurement results at multiple viewpoints to reconstruct the whole structure of large targets. A well-known approach is to connect local 3D measurement results based on 3D shapes consistency.[1]

However, it is difficult to integrate local results only by shape information in some cases. For example, in the measurement of the inside of long structures surrounded by planar walls such as pipes, railway vehicles, and tunnels, the relative position of longer direction cannot be determined only by shape information because there are few unevenness or corners in the environment. To solve this problem, a method using texture information has been proposed, which integrates local 3D shapes by pose estimation based on images from a camera.[2–5] However, even this method cannot be applicable in the case that the environment has neither 3D features nor texture. Therefore, pose estimation which can be used for a feature-less environment is important to achieve 3D measurement in the feature-less environments.

The use of speckle is considered as a pose estimation method in such a macroscopically feature-less environment. Speckle is a high-contrast pattern generated by the interference of reflected light when a rough surface is irradiated with coherent light such as a laser. If the surface roughness of the irradiated surface is larger than the laser wavelength, speckles are generated. Therefore, motion estimation is possible due to the microscopic structure of the target surface. There are previous research of motion estimation based on speckle.[6–8] The research[6,7] proposed the speckle encoder to estimate translation of sensor using speckle. To estimate the local laser measurement results from multiple viewpoints, it is necessary to estimate not only translation but also

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rotation.[8] developed the 6 DOF pose estimation system including rotation estimation. However, speckle based pose estimation has not been applied to 3D measurements. The problem in combining the pose estimation system with laser measurement is that the previous system needs defocused images against the target surface to observe a clear speckle pattern. Therefore, it is necessary to use a camera in addition to the speckle observation camera to combine with existing laser measurement methods.

In this research, we propose the 3D measurement system by the combination of structured light and speckle based pose estimation by introducing two different setting cameras to obtain both focused and defocused images at once.

2. PROPOSED METHOD

2.1 OVERWIEW OF PROPOSED MEASUREMENT SYSTEM

The proposed system consists of two cameras, with and without lens, and two lasers, namely spot laser and line laser, as shown in Fig. 1. The measurement process is shown in Fig. 2. Firstly, 3D positions of points irradiated by laser are measured. Line and spot patterns by laser are observed clearly by the camera with lens. Therefore, distances of points can be calculated by triangulation from the image with the lens. Secondly, pose changes between sequential images are estimated. Speckle caused by spot laser can be observed clearly by the camera without a lens. Then the optical flow can be obtained by comparing the pattern of small areas of two images. Pose changes can be estimated by solving the equation relating pose changes to speckle displacements. Displacements of speckle patterns are detected as optical flow by Phase Only Correlation (POC) method.[9] Finally, the target shape as a whole is reconstructed by integrating the structured light results in each image into common coordinates using estimated pose changes.

2.2 POSE ESTIMATION BASED ON SPECKLE INFORMATION

In this section, the pose estimation method using speckle information is explained.

Firstly, the relation between speckle displacement and light source movement is introduced. Laser light projected from a laser source is reflected on the target surface. The interference of reflected light determines the amplitude of the speckle pattern. Assuming that the position of the laser source is $\mathbf{l}$ and the irradiated region of target surface $\mathbf{\Omega}$. Speckle amplitude of point $\mathbf{f}$ can be represented by a superposition of complex amplitude of light from each reflected point $\mathbf{s} \in \Omega$. Then, $E(\mathbf{f})$, complex amplitude at point $\mathbf{f}$ is represented as follows:

$$E(\mathbf{f}) = \sum_{\mathbf{s}\in\Omega} \frac{\alpha(\mathbf{s})E(\mathbf{l})}{\Gamma(\mathbf{l},\mathbf{s})\Gamma(\mathbf{s},\mathbf{f})} e^{ik(\Gamma(\mathbf{l},\mathbf{s})+\Gamma(\mathbf{s},\mathbf{f}))}, \qquad (1)$$

where $\alpha(\mathbf{s})$ represents reflectance at $\mathbf{s}$ and $\Gamma(\mathbf{x},\mathbf{y})$ represents the optical path length between $\mathbf{x}$ and $\mathbf{y}$. Let $\mathbf{f}'$ be the point corresponding to $\mathbf{f}$ when the light source slightly moves from $\mathbf{l}$ to $\mathbf{l}'$. Because of $E(\mathbf{l}') = E(\mathbf{l})$, $\mathbf{\Omega}' \approx \mathbf{\Omega}$

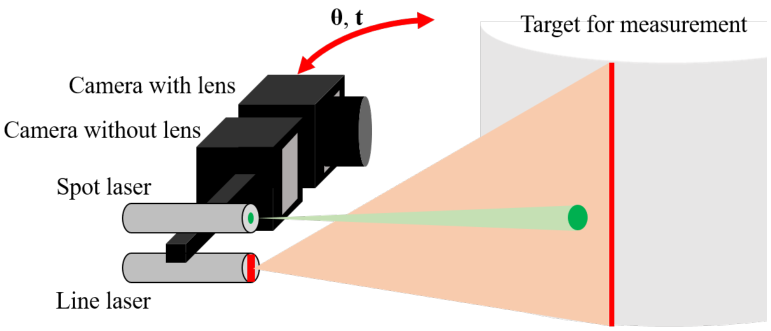

Figure 1. Proposed 3D measurement system.

$E(\mathbf{f}')$ can be written as follows:

$$\begin{aligned} E(\mathbf{f}') &= \sum_{\mathbf{s}\in\Omega'} \frac{\alpha(\mathbf{s})E(\mathbf{l}')}{\Gamma(\mathbf{l}',\mathbf{s})\Gamma(\mathbf{s},\mathbf{f}')} e^{ik(\Gamma(\mathbf{l}',\mathbf{s})+\Gamma(\mathbf{s},\mathbf{f}'))} \\ &\approx \sum_{\mathbf{s}\in\Omega} \frac{\alpha(\mathbf{s})E(\mathbf{l})}{\Gamma(\mathbf{l},\mathbf{s})\Gamma(\mathbf{s},\mathbf{f})} e^{ik(\Gamma(\mathbf{l}',\mathbf{s})+\Gamma(\mathbf{s},\mathbf{f}'))} \\ &= \sum_{\mathbf{s}\in\Omega} \frac{\alpha(\mathbf{s})E(\mathbf{l})}{\Gamma(\mathbf{l},\mathbf{s})\Gamma(\mathbf{s},\mathbf{f})} e^{ik(\Gamma(\mathbf{l}',\mathbf{s})+\Gamma(\mathbf{s},\mathbf{f}'))}. \end{aligned} \tag{2}$$

To satisfy $E(\mathbf{f}) = E(\mathbf{f}')$, following relation must hold:

$$\forall \mathbf{s} \in \Omega, \|\mathbf{l}' - \mathbf{s}\| + \|\mathbf{f}' - \mathbf{s}\| - \|\mathbf{l} - \mathbf{s}\| - \|\mathbf{f} - \mathbf{s}\| = const. \tag{3}$$

By differentiating with respect to $\mathbf{s}$, eq. (3) can be rewritten as follows:

$$\mathbf{e}_{sl'} + \mathbf{e}_{sf'} - \mathbf{e}_{sl} - \mathbf{e}_{sf} = \mathbf{0}, \tag{4}$$

where $\mathbf{e}_{sl'} = \frac{\mathbf{l}'-\mathbf{s}}{\|\mathbf{l}'-\mathbf{s}\|}$, $\mathbf{e}_{sf'} = \frac{\mathbf{f}'-\mathbf{s}}{\|\mathbf{f}'-\mathbf{s}\|}$, $\mathbf{e}_{sl} = \frac{\mathbf{l}-\mathbf{s}}{\|\mathbf{l}-\mathbf{s}\|}$, $\mathbf{e}_{sf} = \frac{\mathbf{f}-\mathbf{s}}{\|\mathbf{f}-\mathbf{s}\|}$. Because the movement of light source is small, eq. (4) can be transformed as follows:

$$\begin{aligned} \mathbf{e}_{sf'} - \mathbf{e}_{sf} + \mathbf{e}_{lf'} - \mathbf{e}_{lf} &= \frac{\partial \mathbf{e}_{sf}}{\partial x_\mathrm{f}}\Delta x_\mathrm{f} + \frac{\partial \mathbf{e}_{sf}}{\partial y_\mathrm{f}}\Delta y_\mathrm{f} + \frac{\partial \mathbf{e}_{sf}}{\partial z_\mathrm{f}}\Delta z_\mathrm{f} + \frac{\partial \mathbf{e}_{sl}}{\partial x_\mathrm{l}}\Delta x_\mathrm{l} + \frac{\partial \mathbf{e}_{sl}}{\partial y_\mathrm{l}}\Delta y_\mathrm{l} + \frac{\partial \mathbf{e}_{sl}}{\partial z_\mathrm{l}}\Delta z_\mathrm{l} \\ &= \frac{1}{\|\mathbf{f}-\mathbf{s}\|}(\mathbf{I} - \mathbf{e}_{sf}\ \mathbf{e}_{sf}^T)\Delta\mathbf{f} + \frac{1}{\|\mathbf{l}-\mathbf{s}\|}(\mathbf{I} - \mathbf{e}_{sl}\ \mathbf{e}_{sl}^T)\Delta\mathbf{l} \\ &= \mathbf{M}\Delta\mathbf{f} + \mathbf{N}\Delta\mathbf{l} = \mathbf{0}, \end{aligned} \tag{5}$$

where $\mathbf{M} = \frac{1}{\|\mathbf{f}-\mathbf{s}\|}(\mathbf{I} - \mathbf{e}_{sf}\ \mathbf{e}_{sf}^T)$, $\mathbf{N} = \frac{1}{\|\mathbf{l}-\mathbf{s}\|}(\mathbf{I} - \mathbf{e}_{sl}\ \mathbf{e}_{sl}^T)$. As a result, the speckle displacement due to the movement of the light source is formulated.

Next, pose change is estimated using the aforementioned formulation. Let σ be the pixel size of the image sensor. Because the camera observing speckles have no lens in the proposed system, the 3D position of speckle $\mathbf{p}_{u,v}$, which is observed at pixel (u, v), is represented as follows:

$$\mathbf{p}_{u,v} = \begin{bmatrix}\sigma u & \sigma v & 0\end{bmatrix}^T. \tag{6}$$

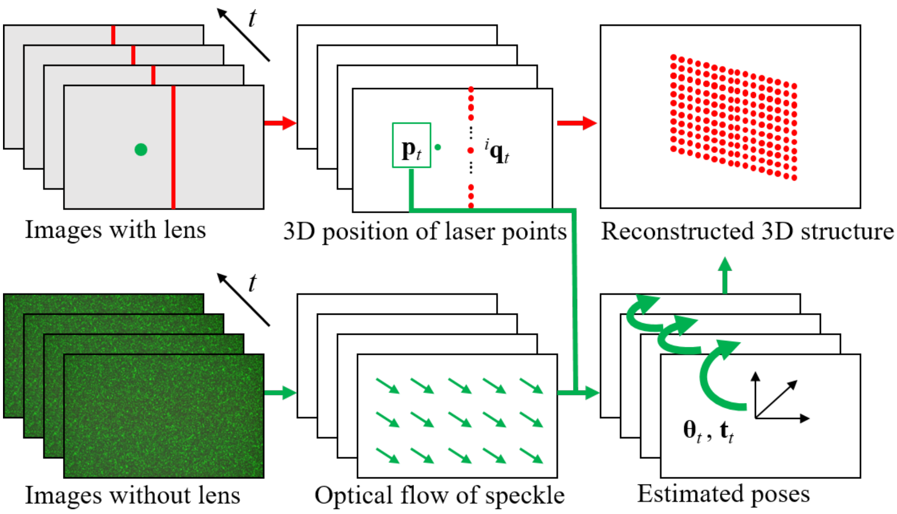

Figure 2. Process of 3D measurement.

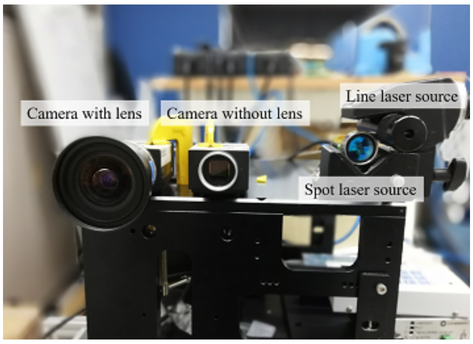

Figure 3. Measurement equipment.

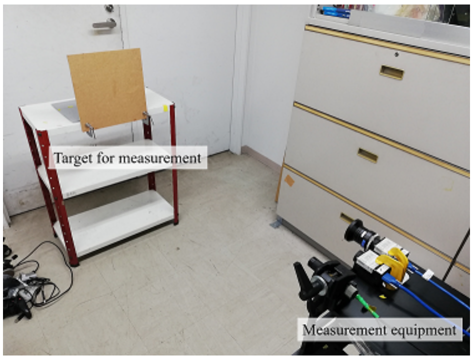

Figure 4. Experimental setting.

Let $\mathbf{R}$ and $\mathbf{t}$ be rotation and translation of the camera observing speckle. If the corresponding speckles before and after movement are detected as (u, v) and (u', v'), respectively, $\Delta\mathbf{f}$ can be written as follows:

$$\Delta\mathbf{f} = \mathbf{R}\mathbf{p}_{u',v'} + \mathbf{t} - \mathbf{p}_{u,v}. \tag{7}$$

Let $\mathbf{l}_o$ be the position of the laser source in the lensless camera coordinates, which can be calibrated in advance because relative position between the camera and laser source are fixed during measurement. $\Delta\mathbf{l}$ can be written using $\mathbf{l}_o$ as follows:

$$\Delta\mathbf{l} = \mathbf{R}\mathbf{l}_o + \mathbf{t} - \mathbf{l}_o. \tag{8}$$

From eq. (5), (7), and (8), following equation can be obtained:

$$(\mathbf{M} + \mathbf{N})\mathbf{t} + \mathbf{M}\mathbf{R}\mathbf{p}_{u',v'} - \mathbf{M}\mathbf{p}_{u,v} = \mathbf{0}. \tag{9}$$

When the amount of rotation is small, the rotation matrix $\mathbf{R}$ can be expressed as a rotation vector $\boldsymbol{\theta}$ as follows:

$$\mathbf{R}\mathbf{x} = \mathbf{x} - [\mathbf{x}]_\times \boldsymbol{\theta}, \tag{10}$$

where

$$[\mathbf{x}]_\times = \begin{bmatrix} 0 & -z_\mathbf{x} & y_\mathbf{x} \\ z_\mathbf{x} & 0 & -x_\mathbf{x} \\ -y_\mathbf{x} & x_\mathbf{x} & 0 \end{bmatrix}. \tag{11}$$

Applying eq. (10) to eq. (9) gives follows:

$$(\mathbf{M} + \mathbf{N})\mathbf{t} - (\mathbf{M}[\mathbf{p}_{u',v'}]_\times + \mathbf{N}[\mathbf{l}_o]_\times)\boldsymbol{\theta} + \mathbf{M}(\mathbf{p}_{u',v'} - \mathbf{p}_{u,v}) = \mathbf{0}. \tag{12}$$

$\mathbf{M}$ and $\mathbf{N}$ are matrices calculated from the 3D position of the laser spot obtained by the structured light. Therefore pose change between sequential images can be estimated by solving (12), which is the linear equation with respect to $\boldsymbol{\theta}$ and $\mathbf{t}$.

2.3 EXPERIMENT

An experiment was conducted to verify the proposed 3D measurement system. The measurement equipment was composed of two cameras, a line laser, and a spot laser as shown in Fig. 3. The camera was a POINTGREY camera GS3-U3-41C6C-C, and the wavelengths of the line laser and the spot laser were 650 nm and 532 nm, respectively. As shown in Fig. 4, a texture-less flat wood board was placed in front of the camera as the target for measurement, and the equipment was moved 100 mm horizontally by an electric linear guide perpendicular to the camera optical axis.

The experimental results are shown in Fig 5 and Fig. 6. Figure 5 shows the estimation results of the horizontal and vertical translations in each frame by the proposed method. The horizontal axis shows the frame, and the

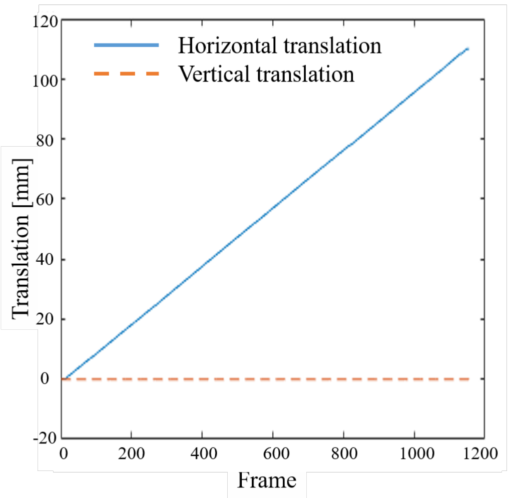

Figure 5. Result of translation estimation.

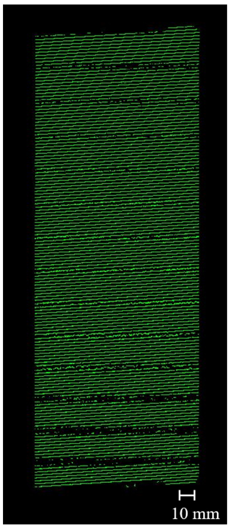

Figure 6. Result of reconstruction.

vertical axis shows the amount of movement from the initial value. In both the horizontal and vertical results, a straight line with almost constant inclination is obtained, which means constant velocity motion was estimated by the proposed method. The estimated value in the final frame was 110 mm for the horizontal and 0.02 mm for the vertical, and the error of the moving distance against the true value was about 10 mm. Figure 6 shows the motion estimation of the area scanned by the line laser on the measurement target board. It can be confirmed that the shape of the flat plate has been successfully restored.

3. CONCLUSION

A speckle-based 3D measurement system using two different settings cameras was proposed. From the experimental results, it was confirmed that translation could be estimated with an error of about 10 mm for a translation of 100 mm. In this paper, we verified the performance of translational motion estimation by the proposed method. The future work is to verify the performance of translation in the depth direction and rotation estimation.

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