Development of an Angle Measurement System Using Monocular Camera and Moiré Patterns

Junya Tsunoda∗a) Non-member, Sho Sakaino∗∗ Senior Member
Toshiaki Tsuji Senior Member

(Manuscript received April 27, 2018, revised Sep. 14, 2018)

This paper describes the development of an angle measurement system using a monocular camera. In recent years, the measurement of the angle of a human joint has played an important role in various fields. Particularly, in the area of rehabilitation, measurement results are applied to make a diagnosis based on the condition of the patient; therefore, high accuracy is required. However, the use of such results is limited because systems with sufficient accuracy are expensive and bulky. In the proposed method, we introduce a Moiré pattern that magnifies small angular displacements to compensate for the poor resolution of the camera. We experimentally verified the robustness of the measurement results’ assuming practical use.

Keywords: human motion tracking, Moiré fringe, joint angle

1. Introduction

In recent years, measurements of the angle of a human joint have played an important role in various fields (e.g., rehabilitation (4), sports engineering (5), and input interfaces (6)). Particularly, in the area of rehabilitation, we can evaluate the activities of daily living (AODL) from the measurement results. As an index to evaluate the AODL, the range of motion (ROM) plays a key role in characterizing the condition of a patient. In clinical settings, goniometers are generally used to assess the ROM. However, problems with such tools have been reported: an insufficient accuracy in the reliability of the intrarater and interrater (4), which is caused by errors in the visual observation of the therapist. For a quantitative evaluation, various measurement methods have been proposed, which are classified into two main streams: visual tracking and non-visual tracking (7).

In the former stream, one or more cameras are used to capture the human body and extract their joint angles. Three-dimensional motion capture systems are sufficiently accurate for an evaluation. However, they are expensive and bulky, and therefore their use is limited (8). To solve this problem, some low-cost methods have been proposed as a substitute (9). With these methods, monocular RGB or RGB-D cameras are used. These methods have basic motion capture capabilities and are convenient for use clinically. Unfortunately, however, their accuracy is insufficient for a clinical assessment (10).

In the latter stream, sensors placed on the human body are used to directly collect angular information. Inertial sensors, in particular, have been put into practical use. However, such sensors suffer from a drift problem arising from sensor noise (11). Therefore, in spite of certain methods used to deal with this problem, their accuracy is inferior for use in a visual tracking method (10,11). They also require a long time to install and are thus unsuitable for routine measurements.

All systems have their particular advantages and disadvantages, and thus we need to select a measurement method depending on its specific purpose. In our study, a visual tracking system was introduced considering the level of convenience required at the clinical site. We propose an angle measurement system using a monocular camera and a Moiré pattern. A Moiré pattern provides a function for magnifying small angular displacements to compensate for a poor resolution of the camera. This function is a well-known phenomenon and has been utilized in many areas. Takaki developed a strain visualization sticker to evaluate the stress in concrete (10,11). They used fringes printed either on opaque paper or a transparency. They verified that the developed sticker can conduct measurements with an accuracy of less than 1 micrometer. However, problems in practical use, such as the effect of distance and illumination intensity, were not considered. Tanaka developed LentiMark (12), which improves the accuracy of fiducial markers through the use of a Moiré pattern. They applied their method to the measurement of the angle of a human joint, and realized an error of approximately 2 deg. experimentally when assuming practical use. This method uses a combination of a lenticular lenses and fringes instead of two fringe layers. Therefore, the design of the marker, e.g., the axis to measure and the magnification ratio, is limited based on the specifications of the lenticular lenses. In contrast, our method implements a robust measurement with fringes printed either on opaque paper or a transparency. The merits of our method are as follows:

• In principle, there is no error accumulation in long-term...
measured.
• The device mounted on the body is simple, lightweight, and easy to install.
• It can be widely applied because no external power supply is required.

Therefore, we can design the proposed marker specifically for the measurement target and purpose.

The remainder of this paper is organized as follows. In section 2, the principle of a Moiré fringe is described. In section 3, the proposed marker using this principle and its design method are described. In section 4, the verifications of the proposed method are described. In section 5, the conclusions are presented.

2. Principle

2.1 Principle of Moiré Fringe A Moiré fringe is a striped pattern that appears when superimposing two transparent parallel layers. As an example of a simple Moiré fringe, we consider a case of superimposing two linear patterns. We denote the cycle of linear patterns 1 and 2 as \( p_1 \) and \( p_2 \), respectively. Here, \( p_1 \) is slightly larger than \( p_2 \). These patterns are printed either on opaque paper or a transparency. Pattern 2 is superposed on pattern 1.

As shown in Fig. 1, if we superimpose two striped patterns, a Moiré fringe appears. Here, the cycle of a Moiré fringe is denoted as \( p_m \). The relationship between these parameters is represented as follows:

\[
p_m = \frac{p_1 \cdot p_2}{p_1 - p_2} \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cd \[201\]
As shown in these equations, $M$ and $n_m$ are designed independently.

3. Proposed Marker

The marker used in this study is shown in Fig. 4. It consists of multi-ring periodic circular Moiré patterns. Circular patterns are used to measure the relative rotation between sheets. To measure the motion of the rotational joint using the proposed marker, we consider the following issues.

- Distinction between relative rotation between sheets and absolute rotation of the markers.
- Relationship between fringe magnification and cycle.

3.1 Distinction between Relative Rotation between Sheets and Absolute Rotation of Markers

When measuring the angle of a human joint, distinction between relative rotation between sheets and absolute rotation of markers is needed. Otherwise, measurement of the relative rotation of the joint is interfered with absolute rotation of the markers as illustrated in Fig. 5. Such a problem occurs because the reference point of the marker is not defined. Previous studies define a reference point such as a black dot to determine the bounding box of the Moiré pattern. However, this incurs a problem in that the detection error of the reference point deteriorates the level of accuracy. To solve this problem, we propose a method for measuring the relative rotation without being affected by absolute rotation of the markers. In this study, multi-ring Moiré fringe with three-stage is used.

We denote the relative angle between patterns 1 and 2 as $\theta_{rel12}$. The relative angle means the angle between each pattern. We also denote the rotation of both patterns as $\theta_{abs}$. As shown in (4), $\theta_{rel}$ is measured accurately using the Moiré pattern, but the error in $\theta_{abs}$ is not reduced. Therefore, with our method, two fringe patterns with different magnifications, shown in Fig. 6, are used. If the magnification of patterns 1 and 2 is denoted as $M_1$ and $M_2$ ($M_2 > M_1$), the phases of fringes $\theta_1$ and $\theta_2$ are represented as follows:

$$\theta_1 = M_1 \theta_{rel12} + \theta_{abs} + \epsilon_1 \quad \cdots \cdots \cdots \cdots \quad (13)$$

$$\theta_2 = M_2 \theta_{rel12} + \theta_{abs} + \epsilon_2 \quad \cdots \cdots \cdots \cdots \quad (14)$$

Here, their detection errors are $\epsilon_1$ and $\epsilon_2$. Then, $\theta_{rel12}$ is derived from the phase difference between these fringes $\theta_{diff12}$ as follows:

$$\theta_{diff12} = \theta_2 - \theta_1 = (M_2 - M_1) \cdot \theta_{rel12} + \epsilon$$

$$\theta_{rel12} = \frac{\theta_{diff12} - \epsilon}{M_2 - M_1} \quad \cdots \cdots \cdots \cdots \quad (15)$$

$$\epsilon = \epsilon_1 + \epsilon_2 \quad \cdots \cdots \cdots \cdots \quad (16)$$

As shown in (16), $\theta_{rel12}$ is measured without being affected by the error in $\theta_{abs}$. In this case, a pair of patterns can be regarded as a single pattern with magnification $M_{12}$.

3.2 Relationship between Fringe Magnification and Cycle

The pattern shown in Fig. 6 has periodicity, as shown in Fig. 7. Therefore, the same pattern prior to rotation appears when rotating by a certain angle. The relationship among the periodicity $P_{12}$, magnification $M_{12}$, and the number of Moiré lines $i_{12}$ is determined as follows:

$$P_{12} = \frac{2\pi}{M_{12} i_{12}} \quad \cdots \cdots \cdots \cdots \quad (18)$$

As shown in (18), with a pair of patterns, a high magnification and wide cycle are not realized concurrently. To solve this problem, two pairs of patterns with different cycles are used. This process is described in a later section.

3.3 Process to Measure Angular Displacement through Image Processing

To calculate the relative angle from the proposed marker, the process shown in Fig. 8 is used. We use the function of OpenCV 3.4.1 through the following process:
Angle Measurement Using Monocular Camera and Moiré Patterns  (Junya Tsunoda et al.)

In Fig. 4, the marker has three patterns with different magnification ratios to cover the movable range of the joint, in other words, low magnification. In this case, we regarded patterns 1 and 2 as a single pattern with magnification \( M_{12} = M_2 - M_1 \). This pair of patterns is used to derive the rough relative angle and the number of laps between patterns 2 and 3. The other is designed for high magnification sufficient for an accurate measurement. In this case, we regarded patterns 2 and 3 as a single pattern with magnification \( M_{23} = M_3 - M_2 \). This pair of patterns is used to derive the precise relative angle. The process for such determination is as follows:

1. Derive the rough relative angle from the phase difference of patterns 1 and 2.
2. Derive a number of laps between patterns 2 and 3 from a rough relative angle.
3. Derive the precise relative angle from the phase difference of patterns 2 and 3.

The pair of patterns 2 and 3 is designed for high magnification and is insufficient to cover the movable range of the joint. In this case, the same pattern prior to rotation appears when rotating by a certain angle, as shown in Fig. 7. Therefore, we need to derive how many laps the pattern rotates. If the number of laps between patterns 2 and 3 is denoted as \( n_{23} \), the relative angle derived from patterns 2 and 3 \( \theta_{rel23} \) is represented as (19). in the formula represents an estimated value.

\[
\theta_{rel23} = \frac{\theta_{dif23} + 2\pi \cdot n_{23}}{M_{23}} \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdOTS
Angle Measurement Using Monocular Camera and Moiré Patterns (Junya Tsunoda et al.)

3.5 Remove the Effects of Shadows and Reflections

In an actual measurement, the measurement data are affected by shadows and reflections. To remove these effects and improve the accuracy, measurement data should be preprocessed. In this section, as a denoising technique, a preprocessing method utilizing the rule of the Moiré pattern is proposed.

The process is represented as Fig. 9. The measured data are represented as 8 bit (0 - 255) data. To separate the change in luminance by the pattern from that by shadows and reflections, the differential value of luminance is derived, as shown in Fig. 9(b). These values are normalized. As shown in Fig. 9(b), the pattern changes when the luminance changes steeply. In addition, the peak point is regarded as a candidate of the switching point of the pattern. These data are applied in threshold processing based on the assumption that a change in luminance by the pattern is steeper than that by the shadows and reflections. We denote the normalized differential value as $L$, and threshold value as $L_{th}$. Here, $L$ is classified as follows:

1. $|L| < L_{th}$: Noise from shadows and reflections.
2. $L > L_{th}$: The area where the pattern switches from black to white. The peak value is equivalent to the switching point from black to white.
3. $L < -L_{th}$: The area where the pattern switches from white to black. The peak value is equivalent to the switching point from white to black.

The differential value after thresholding according to such classification is shown in Fig. 9(c). The points in this figure indicate the switching points. The luminance derived based on the switching point is shown in Fig. 9(d). Through a comparison between Fig. 9(a) and Fig. 9(d), the influence of the shadows is removed.

3.6 Attachment Method for Proposed Marker

To measure the rotational motion, the marker is placed across the rotational joint. The structure when measuring the rotational joint (e.g., a human elbow joint of human) is as shown in Fig. 10. The marker consists of two layers. Circular patterns are printed on a transparent sheet (OHP sheet) and opaque paper, and pasted to each layer. Each layer is attached to a rotational method, as shown in Fig. 11.

4. Experiment

4.1 Setup

In this section, the accuracy of the proposed method is verified. The equipment used for verification is shown in Fig. 12. To evaluate the accuracy at the time of actual use, experiments were conducted in a lighting environment close to that of actual application. The diameter of the marker was 46 mm. The magnification of each fringe is $M_1 = 8$, $M_2 = 10$, $M_3 = 20$. The magnification of a pair of patterns is $M_{12} = 2$, $M_{23} = 10$. The periodicity of a pair of patterns is $P_{12} = 180$, $P_{23} = 36$ [deg]. The marker was set in the rotating plate. The plate was rotated using a servo motor.
motor (VS-SV1150, Vstone Co., Ltd.). The marker was captured with a digital camera (EX-F1, Casio, Ltd., resolution is 2916 [pixel] × 2178 [pixel]). The camera was positioned directly facing the marker, at a distance of approximately 1.0 m. The true angle was measured using an optical encoder attached to the motor (TA-200, Technohands Co., Ltd., resolution is 0.01 [deg]). Measurements were conducted three times for each angle, and the results compared with the true value. A desktop personal computer (CPU 64 bit 2.93 GHz, RAM 8GB) was used to execute the program. The processing program is written in Python.

4.2 Result  To evaluate the ability to remove the effects of a disturbance, we compared the results with and without the denoising technique described in 3.5. The rotation angle measured by the proposed method is shown in Fig. 13. The measurement error is shown in Fig. 14. As shown in Fig. 14, sinusoidal errors occur. The error seems to be generated in the deviation process of the two circular patterns. Since it is quite difficult to exclude the cause, we created an error model using the least-squares method and introduced an error model. The model is denoted as the dotted line in the left figure of Fig. 14. The result of the error compensation is shown in Fig. 15. From the result, under any conditions, the error is reduced by the error model. With the denoising technique, the maximum error was roughly ±0.4 deg. Without the denoising technique, the maximum error was roughly ±1.0 deg.

These results confirm that the denoising technique improves the accuracy of the measurement in a practical environment.

We compare the accuracy between the proposed method and previous methods in Table 1. The proposed method shows higher accuracy than when applying the Microsoft Kinect (7), the inertial sensors (9), and the Lentimark (13).

4.3 Robustness to Picture Size  In this section, we verified the processing time and the accuracy under several conditions of picture size.

4.3.1 Processing Time  If the picture size is large, the processing time becomes huge and real-time processing becomes difficult. Therefore, to measure the angle in real time, it is necessary to reduce the picture size. We compare the processing time for each image size in Table 2. In this table, only processes requiring much processing time are described. Therefore, the total processing time for each process does not correspond to the total processing time. When the picture size was reduced 4 times, the whole processing time was 16 [ms]. The results show the feasibility of real-time processing.

4.3.2 Accuracy  The RMSE of the measurement error is shown in Fig. 16. Here, the sinusoidal error mentioned in 4.2 was eliminated using the error model. From the result,
under any conditions, the denoising technique improves the accuracy of the measurement.

5. Conclusion

This paper described an angle measurement system using a monocular camera. To compensate for the poor resolution of the camera, a Moiré pattern magnifying the small angular displacement was introduced. The experimental results indicate that the proposed method enables an angle measurement with comparatively good accuracy. Our future work will focus on an improvement of the measurement accuracy and robustness to disturbances, such as the distance and rotation in the pitch and yaw directions.

References


Fig. 16. RMSE of measurement error (sinusoidal error is compensated)