See Better by Moving: Robust In-Situ Specular Surface Roughness Estimation Using Active Camera Motion

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***Abstract*— This study proposes an in-situ multiviewpoint surface measurement approach for a polishing robot using fringe-pattern illumination. By exploiting the angular dependence of specular reflection, we utilize a weighted average, C_{w_avg}, which quantifies viewpoint reliability using a mask image. This enables robust surface roughness estimation against ambient light fluctuations, even with strictly limited calibration data. Moreover, it demonstrated a separability ($J = 62.61$) approximately 2.1 times higher than the best fixed viewpoint, quantitatively confirming its robustness against lighting variations. This study aims to realize a fully autonomous mirror-polishing system.**

I. INTRODUCTION

Mirror-finished products are widely used in medical and manufacturing fields, driving demand for the robotic automation of the mirror finishing process. While significant progress has been made in contact force-based polishing control, the process generally involves multiple stages from rough to finish polishing [1], [2], [3]. Determining the optimal transition timing between stages significantly impacts final quality. To automate this, acquiring actual surface conditions, like surface roughness, is essential alongside contact force. Although optical interferometers provide high-precision measurements, their high cost and laboratory-focused design hinder integration into manufacturing lines [4]. To address this, vision-based fringe-pattern illumination offers a practical alternative, analyzing luminance contrast without requiring specialized setups [5].

However, strong specular reflections make fixed-viewpoint vision-based measurement highly susceptible to lighting variations. Inspired by humans observing mirrors from various angles, we propose an approach where a robot actively changes the camera viewpoint. We demonstrate that integrating multi-viewpoint images not only outperforms fixed-viewpoint estimation but also reduces contrast variance, thereby enabling robust quantitative evaluation. This active measurement behavior directly corresponds to the “Act to Sense” concept. By applying this in-situ measurement to a polishing robot and assessing surface conditions through active viewpoint changes, we aim to develop a system for autonomous transition decisions, enabling the robot to “Act Better” through automated advanced polishing.

II. METHOD

This section presents the proposed active measurement approach for robust surface roughness estimation. To mitigate the influence of ambient light fluctuations, we actively exploit the angular dependence of specular reflection. The specific system configuration and the mathematical details of the evaluation are described in the following subsections.

A. System Configuration

The proposed system consists of a 6-axis manipulator, a web camera, and a liquid crystal display (LCD) screen. A black-and-white fringe pattern is displayed on the LCD screen and projected onto the surface of the workpiece surface. The image of the fringe pattern specularly reflected on the surface is captured by the web camera, and the surface condition is estimated by analyzing its luminance contrast. The web camera is mounted on the end-effector of the manipulator. As shown in Fig. 1, the measurement is performed while rotating the camera in the *x*-*z* plane from 20° to 50° in 5° increments. During this process, the distance between the camera and the LCD screen is maintained at 30 cm, and both are positioned to maintain the specular reflection geometry.

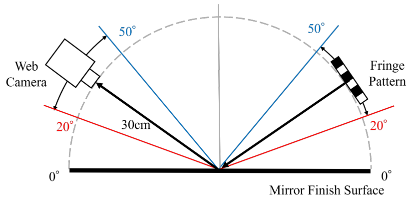

Fig. 1. Schematic illustration of the system

B. Contrast calculation

The luminance contrast C is calculated from the average luminance of the white (AW) and black (AB) fringe regions [5]:

$$C = \frac{AW - AB}{AW + AB} \tag{1}$$

Since mirror surfaces are highly sensitive to lighting changes, single-viewpoint measurements are often insufficient. Thus, we define a weighted average contrast C_{w_avg} from multiple viewpoints as the evaluation metric:

$$C_{w\_avg} = \frac{\sum (w_i \cdot C_i)}{\sum w_i} \tag{2}$$

where C_i and w_i are the contrast and weight at each viewpoint i. The weight w_i is calculated using the white pixel area ratio r_i of a binarized mask image:

$$w_i = 4r_i(1 - r_i) \tag{3}$$

In an ideal pattern, $r_i = 0.5$ ($w_i = 1$). For distorted patterns, r_i approaches 0 or 1, decreasing the weight and thereby suppressing low-reliability images.

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TABLE I

AVERAGE ROUGHNESS CLASSIFICATION ACCURACY

Method	Accuracy [%]
Fixed Viewpoint 20°	73.8
Fixed Viewpoint 25°	96.2
Fixed Viewpoint 30°	99.4
Fixed Viewpoint 35°	99.6
Fixed Viewpoint 40°	**100.0**
Fixed Viewpoint 45°	91.4
Fixed Viewpoint 50°	77.4
Proposed Method (C_{w_avg})	**100.0**

III. EXPERIMENTS

A. Experimental Conditions

To verify the effectiveness of the proposed method, experiments were conducted using three types of aluminum plate samples with different surface roughnesses (grit sizes: #1200, #4000, and #8000). A larger grit size corresponds to a finer polish, with #8000 representing the smoothest mirror finish. The experimental setup is shown in Fig. 2. For each sample, surface images were acquired while rotating the web camera in the x-z plane from 20° to 50° in 5° increments, and the contrast value C_i for each angle was obtained. Furthermore, to investigate the effect of the lighting environment on changes in contrast values, experiments were conducted under the following three lighting conditions, with measurements taken three times for each condition:

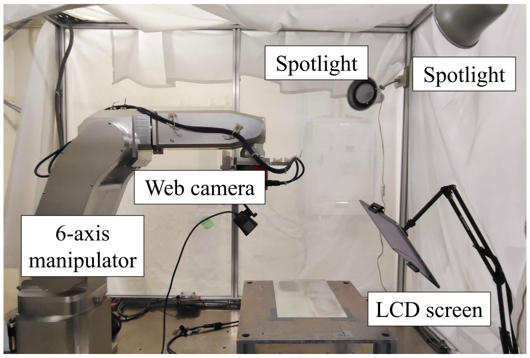

Fig. 2. Experimental setup

- Condition 1 (Spot only): Using only two spotlights
- Condition 2 (Fluor. only): Using only fluorescent lights
- Condition 3 (Spot + Fluor.): Using both fluorescent lights and two spotlights

B. Result

Classification performance was evaluated using a random sub-sampling validation. For each of the 100 iterations, a decision tree (maximum depth of 2) was trained on 9 randomly selected samples (3 per roughness class) and tested on the remaining 18 samples to calculate the average accuracy. Table I shows the accuracy for each viewpoint and the proposed method. Among the fixed viewpoints, only 40° achieved 100% accuracy, while the others degraded (e.g., 99.4% at 30°, 73.8% at 20°). In contrast, the proposed method consistently yielded an accuracy of 100.0%.

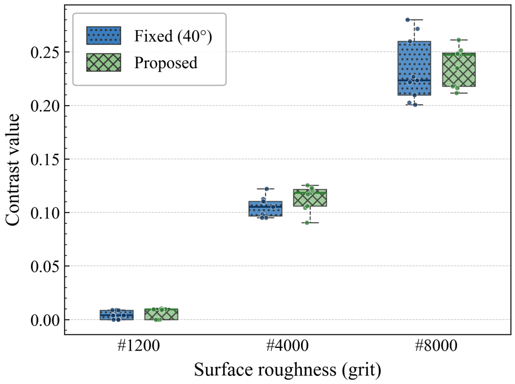

Fig. 3. Comparison of contrast value distributions between the proposed method and the best-performing fixed viewpoint. The separability measures J are 29.39 (40°) and 62.61 (proposed).

Fig. 3 shows the distribution of contrast values for the best-performing fixed viewpoint (40°) and the proposed method. The separability measure is defined as $J = S_\mathrm{B}/S_\mathrm{W}$, where S_B and S_W represent the between-class and within-class variances, respectively. A larger value of this metric indicates smaller within-class variance and larger between-class separation, making it suitable for quantifying classification stability. The proposed method yielded $J = 62.61$, which is approximately 2.1 times higher than that of the optimal fixed viewpoint (40°: $J = 29.39$).

C. Discussion

The fluctuating accuracy of fixed viewpoints (Table I) highlights their vulnerability to lighting variations. Even the optimal 40° viewpoint exhibits a narrow inter-class margin ($J = 29.39$). With such unstable decision boundaries, slight contrast shifts easily cause misclassifications under limited training data, explaining the accuracy drops at other angles. Conversely, the proposed method achieves perfect accuracy with a significantly wider margin ($J = 62.61$). By actively integrating multiple viewpoints, the weight w_i dynamically mitigates localized lighting noise and overexposure, effectively suppressing outliers undetectable from a single angle.

These results demonstrate that the proposed active sensing approach resolves the fundamental limitations of passive methods, enabling highly robust surface roughness estimation independent of lighting environments.

IV. CONCLUSIONS

This study proposed an in-situ multi-viewpoint surface measurement approach for a polishing robot using fringe-pattern illumination. By evaluating viewpoint reliability to calculate a weighted average contrast (C_{w_avg}), our method achieved 100% classification accuracy. Furthermore, it demonstrated a separability ($J = 62.61$) approximately 2.1 times higher than the best fixed viewpoint, quantitatively confirming its robustness against lighting variations. Building on these results, we aim to feed this in-situ data back into the control loop to autonomously determine process transitions. This will lead to a fully autonomous mirror-polishing system, seamlessly bridging “Act to Sense” and “Act Better”.

ACKNOWLEDGMENT

This paper is based on results obtained from a project, JPNP14004, subsidized by the New Energy and Industrial Technology Development Organization (NEDO).

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