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Integrated in-machine vision system development for on-site monitoring of end mill wear and tool life prediction

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Abstract

Traditionally, the lifespan of cutting tools, particularly end mills, is assessed by measuring flank wear, requiring frequent removal and reinstallation of the tool. This conventional approach is time-consuming and labor-intensive, leading to inefficiencies in machining processes. To address these limitations, this study proposes an integrated in-machine vision system for monitoring of end mill wear and tool life prediction.

The developed vision module is designed to be installed inside machining equipment, eliminating the need for tool removal. It features a USB image sensor, a retractable linear electric stage, and a motorized rotation stage for optical magnification adjustment. The system allows capturing high-resolution images of flank wear with multiple magnification levels and transmits data to an industrial PC via Ethernet-based TCP communication. A dedicated control program enables seamless remote operation, visualization, and image acquisition.

Experimental validation demonstrated that the proposed vision system successfully captured and transmitted flank wear images immediately after machining, significantly reducing inspection time while minimizing errors due to frequent tool handling. Future advancements incorporating AI-based diagnostic software could further enhance predictive maintenance, contributing to the realization of smart manufacturing systems.

In-machine vision module, tool wear monitoring, end mill frank wear, visual inspection, smart manufacturing

1. Introduction

Accurately assessing cutting tool life is crucial in machining processes, as it directly impacts productivity, costs, and product quality. Traditionally, tool lifespan, particularly for end mills, is determined by measuring flank wear width. This requires removing the tool, inspecting it under a microscope, and reinstalling it, making the process time-consuming and labor-intensive[1]. Additionally, frequent tool handling increases the risk of misalignment, wear inconsistencies, and unexpected failures, reducing machining efficiency[2].

To address these challenges, advancements in vision technology have enabled the development of in-machine monitoring solutions for tool wear analysis[3].

This study proposes a novel vision module equipped with a compact image sensor that can be integrated directly into machining equipment. This study introduces a novel vision module with a compact image sensor that seamlessly integrates into machining equipment. Designed with a retractable mechanism and optical magnification adjustment, the module minimizes the effects of cutting fluids while ensuring optimal image scaling based on the tool's size. By capturing high-resolution images of the end mill's flank wear without requiring tool removal, this system aims to significantly enhance tool life prediction accuracy while reducing downtime and labor costs.

2. Methodology

2.1. Vision Module Design and Functionality

The developed vision module is designed for seamless integration within the machining environment, enabling monitoring of tool wear without requiring tool removal. The system incorporates a rotational mechanism capable of adjusting between -10° to +10°, allowing for optimal image capture of the end mill's flank wear from various angles.

To protect the lens and image sensor from contamination by cutting fluids and debris during the machining process, the vision module is designed to operate in a retractable manner. The module extends outward only when an image needs to be captured and retracts into its protective casing when idle. This design enhances durability and prolongs the operational lifespan of the imaging components.

2.2. Imaging Capabilities and Data Transmission

The vision module supports multiple magnification levels—normal, 50x, 100x, and 150x—allowing detailed and scalable observation of tool wear. The selection of different magnification levels provides flexibility in monitoring varying degrees of tool wear, facilitating a more accurate and comprehensive evaluation of cutting tool condition.

Captured images are transmitted to an external control computer via Ethernet-based TCP communication, enabling high-speed data transfer and efficient processing. The external control system is responsible for receiving, storing, and analyzing the image data.

2.3. Control and Integration

To ensure seamless operation, a dedicated control program has been developed for remote management of the vision module. This control software operates through Ethernet communication, allowing users to adjust the capture position while viewing the video in real time. Additionally, it enables capturing desired images and transmitting them as photos. Integrating the vision module into existing machining systems minimizes the impact on standard machining processes while enabling the acquisition of images for more accurate tool life prediction.

This methodology enables a highly efficient, non-intrusive tool wear monitoring approach that eliminates the need for frequent tool removal and reinstallation. Furthermore, the system's adaptability makes it suitable for integration with future artificial intelligence-based diagnostic solutions, paving the way for predictive maintenance and enhanced machining automation.

3. Design and Development of the Vision Module

3.1. Block Diagram of theVision Module

The developed vision module functions as an integrated system for tool wear monitoring in machining environments. Figure 1 presents the system architecture. It consists of a vision module, a base module, a MiniPC, and an industrial PC.

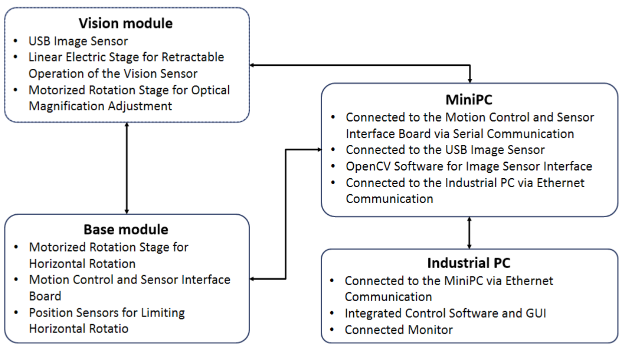

Figure 1. System architecture of the developed vision module

3.1. Vision Module

The vision module includes a USB image sensor, a linear electric stage for retractable operation, and a motorized rotation stage for optical magnification adjustment. During operation, the vision module extends only when capturing an image and retracts afterward to prevent contamination.

3.2. Base Module

The base module enables horizontal rotation through a motorized stage, with position sensors ensuring precise movement limits. The Motion Control and Sensor Interface PCB, developed using an ATmega microprocessor, integrates three motor drivers for motion control and dedicated sensor input ports

3.3. MiniPC

A MiniPC utilizes OpenCV software to process images and transmits the data to an industrial PC via Ethernet communication. Specifically, a Python program integrates the OpenCV library to establish a connection with the image sensor, continuously streaming 640×480 images and converting them into video. Upon receiving an image capture command, the system captures a 1280×1024 high-resolution image and sends it to the industrial PC for further processing.

3.4. Industrial PC

The industrial PC acts as the central control unit, featuring a graphical user interface (GUI) for monitoring and user control. The GUI is organized into three main sections: one for displaying the video stream, another for motion control, and a third for requesting image transmission and viewing received images.

4. Implementation and Testing of the Vision Module in a Machining Enviroment

The left side of Figure 2 shows the developed vision system installed inside the machining equipment. After machining, the vision system is used to capture an image of the end mill, and this image represents the state where the user has completed position alignment through the video feed from the vision system. The right side of Figure 2 is a sample image of the flank wear of the end mill captured at 150x magnification.

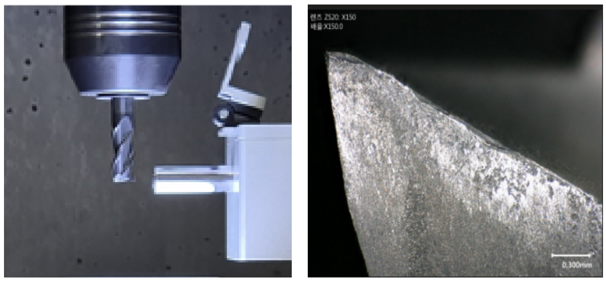

Figure 2. (Left) Vision system installed inside the machining equipment for end mill imaging after machining. (Right) Flank wear of the end mill captured at 150x magnification.

5. Conclusion and Future Work

Through the experiment, it was confirmed that the developed vision system can be installed in the machining equipment to capture flank wear images of the end mill immediately after machining without removing the tool. The captured images were instantly transmitted to the industrial PC via the communication port and could be viewed on the control screen. This proposed process has been confirmed to dramatically reduce the time required for acquiring flank wear images.

In the future, if flank wear images corresponding to different machining processes and cycles are collected using the developed vision system, it could be utilized in applications such as tool life prediction.

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