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Investigations of Infrared Thermography and Image Processing for Detecting Tool Conditions of Turning Processes

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Abstract

Tool wear in machining could have a considerable effect on the quality of the machined features in relation to dimensional accuracy and surface roughness. Condition monitoring systems could provide the solution to monitor conditions of the process and also, provide diagnostic and prognostic decisions regarding process faults. Because of the small-scale dimensions of the tool, one-dimensional sensors such as force signals might not be sufficiently sensitive to measure changes in tool conditions. Image processing could provide a solution in the application of a condition monitoring system if implemented in a suitable way. In this study, novel evaluation techniques are proposed to predict tool health in a turning process. Four types of image processing algorithms, namely temperature profile analysis; threshold, Canny detector, and gradient techniques are used in order to evaluate their capabilities when used to process infrared image data to detect tool conditions. The results indicate that the infrared images, when integrated with appropriate image processing algorithms can provide a powerful monitoring system for the prediction tool conditions of turning operations.

Keywords - Condition Monitoring, Infrared Images, and Image Processing.

I. INTRODUCTION

Machining operations for instance turning, grinding, milling and drilling have been widely used in industry. Tool wear in machining could have a substantial effect on the quality of the machined features in relation to dimensional accuracy and surface roughness. Therefore; in order to minimize maintenance price, improve quality, increase productivity and prevent damage to the machine or work-piece it is important to observe the cutting tool during the machining process. Production will be controlled independently and dynamically, with a high degree of automation [1]. However, monitoring machining processes become the key trend in the majority of manufacturing industries due to the high competition in the market and corresponding lowering of the production costs, minimal worker presence, or even unmanned machining [2]. Monitoring the cutting tool is one of the concerns in machining processes. Condition Monitoring Systems (CMS) of manufacturing processes are important strategies that handle a flexible, real and cost-effective tool to develop the perfect performance of industrial systems. It is capable of handling and analyzing essential data that helps to predict tool failure. Also, CMS should be capable of taking necessary action to avoid the consequences of failure, before the failure occurs and avoid destruction to the machine or work-piece. In addition to that monitoring matching processes transformed into intelligent factory systems [3]. For example, automatic identification of tool wear based on infrared thermography and a convolutional neural network during the turning process is presented in [4]. The paper has used an IR camera, which can capture nine images per second. However, when images are transformed into the computer, a time delay and loss occur, so the number of captured images per second was halved (4.5 image/s, or 1 image on every 0.222 s). In reference [5] image processing for end milling and drilling processes was investigated in order to quantify the tool wear state. In the first step, a Convolutional Neural Network (CNN) is trained for cutting tool type classification. The results showed 95.6% of success for the tested dataset. An infrared vision system used for monitoring milling processes based on infrared data combined with image processing techniques is reported in [6]. The paper investigated the use of the infrared system for sensing the temperature at the end of an end milling tool during machining. In reference [7] a comparison between four image processing techniques to detect tool conditions is

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presented. It investigated the capability of infrared thermography data, temperature profile, and image processing techniques, to detect tool conditions at the end milling process. The results of four different tool conditions have shown different success. A comparative study for comparing the power of the spindle and the infrared images of the cutting tool for designing CMS for the milling process is presented in [8]. It outlined the implementation of image gradient and wavelet analyses for processing infrared images. The results have shown that the image gradient and wavelet transform are great image processing techniques for detecting tool conditions. In reference [9] tracking of the cutting tool and classification based on machine vision system and image processing algorithms has been described. It compared between principal component analysis approach and an artificial neural network in order to design a real-time and reliable CMS for tool tracking and classification in a milling process. An infrared system for monitoring processes using a novel detection technique has been reported in [10]. It describes the application of an infrared imager combined with a detection algorithm for a process monitoring system. It outlined instances of the capability of the infrared image data to detect faults in the sealing process.

II. RELATED WORKS

Limited studies have been found in the literature for predating tool conditions of turning processes based on infrared image data and image processing techniques. For example in reference [11] tool condition monitoring of the cutting tool of turning process based on thermography is presented. The aim of the paper was to prove that the system can determine whether the cutting tool is suitable for further machining or not. The system was based on the thermography image of the cutting tool after the cut has been finished. Images were taken immediately after the end of the cut. However, the used methodology is not suitable for online monitoring, since the images were captured 60 seconds after the cut has been finished. A machine vision system based on digital image processing is reported in [12]. The paper aimed to develop CMS for the measurement of tool wear in the turning process. Tool images were captured and flank wear was measured using gray-scale analysis of that image. However, images were captured after a one-hour machining interval using the visual camera. Moreover, the approach is time-wasting since images were captured after the insert has been removed. In addition, images were captured after a one-hour machining interval. So during the one-hour intervals, the cutting tool could be completely worn or could lead to machining failure. Thus, the used approach is either not suitable for online monitoring. A CMS which, is used to recognize tool wear automatically during turning is described in [13]. The paper has used an infrared camera and convolutional neural networks for developing a model for tool wear and tool damage prediction. It determined the state of a cutting tool automatically (none, low, medium, high wear level), based on thermo-graphic data. Reference [14] presents a deep learning approach, based on image processing which, is applied to turning chips for indirectly identifying tool wear levels. The procedure extracts different indicators from the RGB and HSV image channels and instructs a neural network for classifying the chips, based on tool state conditions. Images were collected with a high-resolution digital camera during an experimental cutting operation involving tool wear analysis with direct microscope imaging. The feasibility of the deep learning approach for indirectly understanding the tool wear from the chip color characterization is confirmed. However, due to the big effects on chip colors of variables such as the work-piece material and cutting process parameters, the applicability is limited to stable production. From above discussion it can be seen that there are limited studies have been found in the literature for predating tool conditions of turning processes based on infrared image data and image processing. In addition to that, the majority of studies have used off-line approaches for monitoring process control. Furthermore; image processing techniques such as Canny detector, threshold, or gradient have not yet been used in the designing of a CMS for turning processes. Hence, this study is addressing this area by proposing a novel methodology of infrared thermography combined with image processing algorithms for the development a CMS for turning processes. The suggested methodology differs from existing studies because it uses four types of image processing techniques including; the Canny detector, threshold, gradient, and temperature profile. The application of image processing techniques in the CMS could lead to fast training and fast testing in the decision-making stage consequently, lead to earlier tool wear detection. In addition, infrared images in this study will be acquired online during the machining process using a high-speed and high-resolution infrared camera. The used camera in this research can capture 25 images per second, which is enough for quick tool wear detection. Finally, the proposed methodology is an effective and reliable system for designing a real-time CMS for turning processes.

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III. AIM OF THE STUDY

The aim of this study is to prove that infrared images of the cutting tool during the turning process and image processing techniques are suitable for designing a reliable and effective CMS for tool wear detection of turning processes. The paper also, aims to find out where is the best location that can be used to place the infrared camera for acquiring thermography images of the cutting tool during the turning process.

IV. RESEARCH METHODOLOGY

The aim of this paper is to investigate the capability of infrared thermography and image processing techniques, to detect tool conditions of turning processes. A block diagram of the suggested methodology is shown in Figure 1. The methodology contains four main stages as follows:

1. The infrared image is captured using a high-resolution infrared camera and saved in a computer in BMP format for further analysis.
2. Pre-processing is used in order to convert the acquired image into a grey scale level. Also, the Region Of Interest (ROI) is selected in this stage.
3. Feature extraction, in this stage four image processing techniques namely temperature profile analysis; threshold, Canny detector, and gradient are applied in order to extract image features. These techniques are used to process infrared image data in order to evaluate their capabilities to detect tool wear and breakage. Section 6 includes further details regarding each methodology and the related image processing algorithm.
4. Finally stage is to evaluate the used image processing techniques.

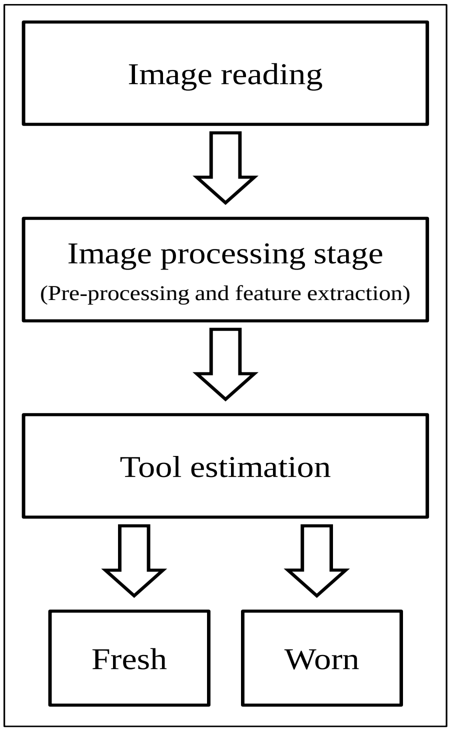

Figure 1: Research Methodology

V. INFRARED MONITORING SYSTEM

The main purpose of the vision monitoring system is to monitor and control the machine and the processes to detect faults. Figure 2 illustrates the basic principle of using the infrared system for monitoring process faults and machine

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conditions in turning processes. An infrared camera is used in this study in order to acquire infrared images during machining process. An infrared camera is an imaging technology that senses infrared radiation and can convert it into a visual image using suitable software that depicts thermal variations across an object or scene as shown in Figure 3. The captured data by the infrared camera are saved on a computer and then analyzed using suitable image processing techniques in order to extract the necessary features for the decision-making process. The decision-making process could use intelligence techniques such as artificial neural networks or fuzzy logic.

VI. Image Processing Stage

The research has utilized a significant number of images of fresh and worn tools. These images are processed using appropriate image processing techniques in order to examine their capabilities to detect tool wear and breakage. The image processing stage is divided into 1) pre-processing, 2) feature extraction stages, and 3) temperature profile of the image of the cutting tool. These stages are described in sections *6.A*, *6.B*, and *6.d* respectively.

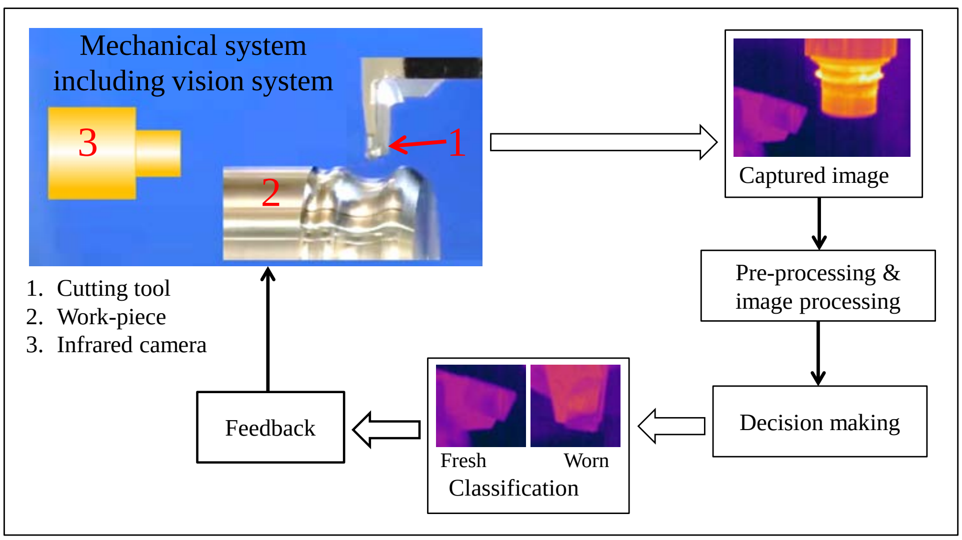

Figure 2: An Infrared Monitoring System

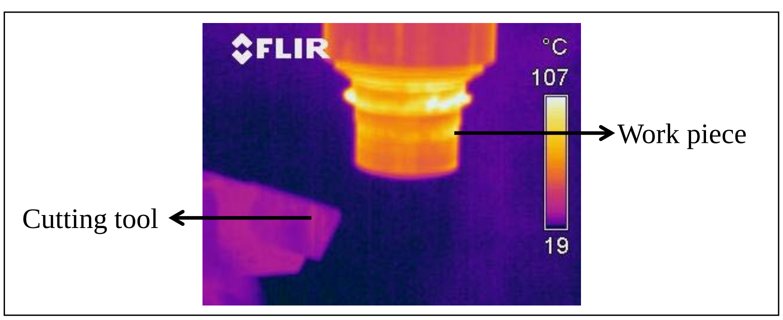

Figure 3: An Example of Infrared Image of Cutting Tool of Turning Processes.

A. Pre-processing

Region Of Interest (ROI) is selected in this stage in order to avoid unnecessary information as shown in Figure 4B. Next is to convert the ROI into a greyscale image for obtaining one numerical value for each pixel, instead of three identical values in the case of RGB true-color images (see Figure 4C).

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B. Feature Extraction Stage

Three image processing techniques namely threshold, Canny detector, and gradient are used in this study in order to extract the main features of the infrared image of the cutting tool. The used image processing techniques in this study are described in the next sub-sections:

a) Thresholding

Thresholding is a technique that is used to isolate the region of interest of the image, that matches the objects the users are interested in [6]. It converts the gray-scale or color image into a binary image. The resulting image replaces all pixels in the input image with luminance greater than a specific level (threshold) with the value 1 (white) and replaces all other pixels with the value 0 (black) [6]. It works by comparing each pixel in the image with the threshold value, if the intensity value is higher than the threshold value, the pixel is set to white in the output, otherwise, it is set to black [6]. Figure 4D illustrates the use of threshold in an infrared image of the turning process.

b) Canny Detector

The canny edge detector is an algorithm that is widely used in image processing and vision systems. It is utilized in order to find image edges by seeking local maxima of the gradient of the image. It is used to detect strong and weak edges and includes the weak edges in the output only if they are connected to strong edges. Figure 4E presents the use of the Canny detector in an infrared image of the turning process.

c) The use of Gradient into Infrared Image

Theorem: Based on [6], If $f(x, y)$ is differentiable, then f has a directional derivative in the direction of every unit $u = \langle a, b \rangle$, and $D_u = f_x(x, y)\, a + f_y(x, y)\, b$. The pattern of the above equation for calculating the directional derivative can be viewed as the dot product of the unit direction vector $u = \langle a, b \rangle$ with the vector $\langle f_x(x, y), f_y(x, y) \rangle$. This vector is called the gradient of f [6]. Figure 4F shows the use of gradient in an infrared image of the turning process.

d) The use of Temperature Characteristic

Because infrared images contain a temperature profile of the cutting tool; therefore it is essential to examine the temperature characteristic to detect tool conditions. The temperature characteristic is presented in Figure 5.

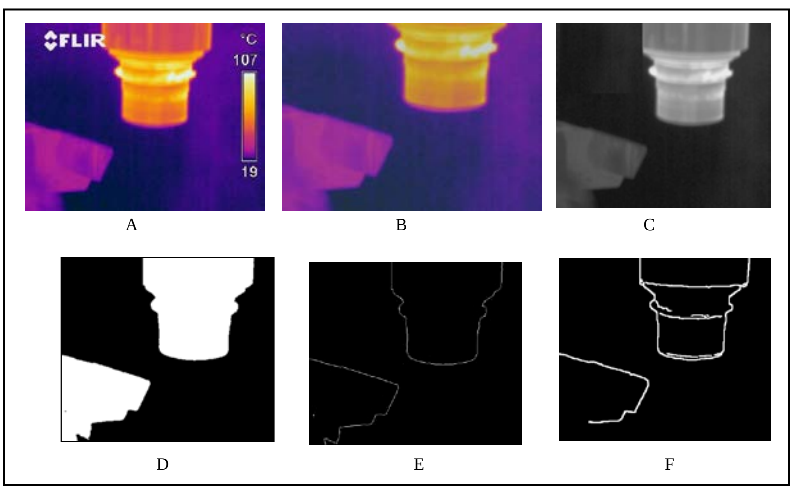

Figure 4: The Use of Threshold (A), Canny Detector (B) and Gradient (C) Techniques.

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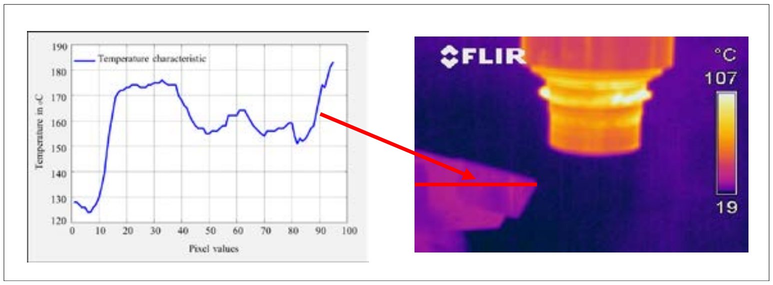

Figure 5: Temperature Profile for Cross Section in an Infrared Image.

VII. Result and Discussion

The above-described four image processing techniques have been applied to infrared images representing different scenarios in order to investigate their capabilities to differentiate between tool conditions. Evaluation of the used image processing can be discussed as follows:

A. Thresholding

Figure 6 shows condition 1, condition 2, and condition3 of fresh, semi-worn, and totally worn tools respectively. Column A, B, C, and D in Figure 6, presents the region of interest of the original, binary image, Canny edge detector image, and gradient image respectively. From Figure 6 column B it can clearly be seen that the threshold has been effectively used and it can correctly differentiate between tool conditions and level of wear or damage. Moreover, condition 3 of Figure 6 clearly indicates the damage to the work-piece. This is because the temperatures of condition 3 have increased due to excessive friction between the cutting tool and the work-piece as a result of the tool becoming increasingly worn.

B. Canny edge detector

The canny detector is used in this paper in order to extract the image features of the cutting tool for estimating the condition of the cutting tool. Column C of Figure 6 illustrates images of conditions 1, 2, and 3 of fresh, semi-worn, and completely damaged tools. From Figure clearly can be seen the capability of the Canny detector to determine the edges of different tool conditions. The Canny detector has successfully detected tool wear and clearly has differentiated between different tool conditions, fresh, semi-worn, and totally damaged tools.

C. Gradient image technique

In this research gradient function is used to analyze the infrared image of the cutting tool in order to evaluate the state of the cutting tool as shown in Figure 6 column D. The column D of Figure 6, presents images of three conditions: fresh, semi-worn, and damaged tools. From Figure 6 column D, it clearly can be observed that the gradient technique has clearly improved the visualization of the image. Moreover, column D of condition 2 clearly indicates the point of the semi-worn tool which has been marked with a circle on the Figure.

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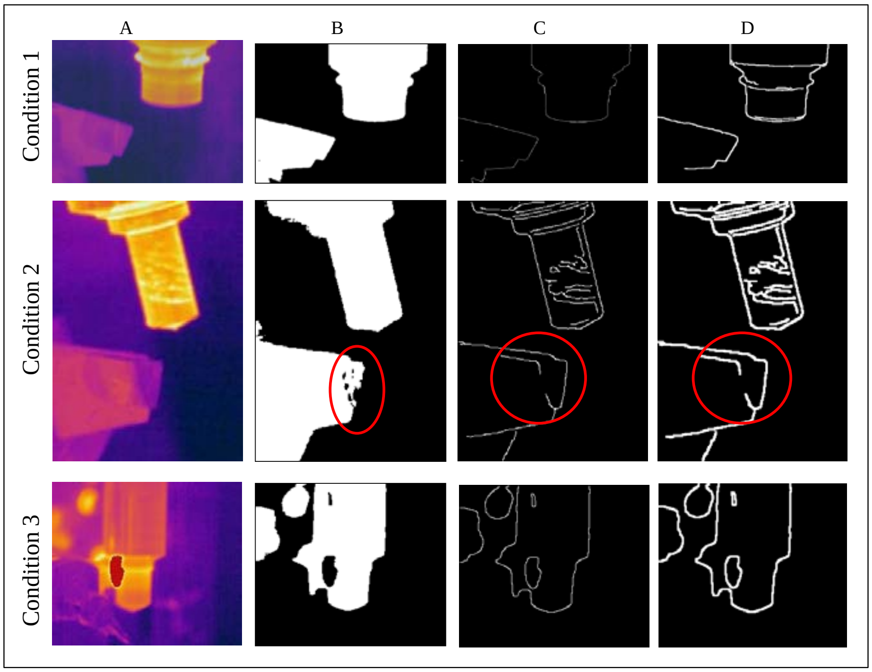

Figure 6: Images of the Three Conditions of the Cutting Tool.

D. Temperature characteristics

Figure 7 presents the temperature profile of two conditions of the cutting tool, condition 1 (Fresh tool) and condition 2 (Semi-worn). The condition 1 in Figure 7 is represented by the solid blue line, indicating that the temperature of the cutting tool is less than 45^{o}C. However, it clearly can be seen that the maximum temperature of condition 2 (red line with circular), is higher than 50^{o}C. It indicates that the temperature characteristic of the semi-worn tool is about 6^{o}C higher than the fresh one.

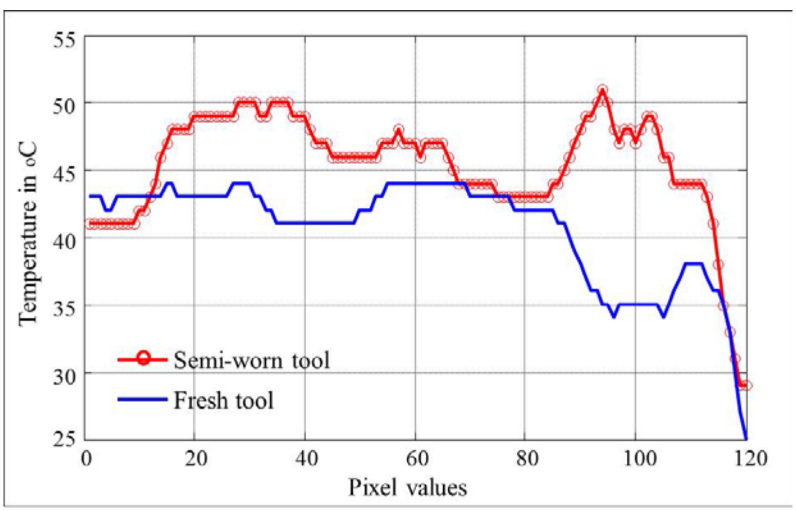

Figure 7: A Comparison between the Temperature Profiles of Two Conditions of Turning Tools.

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VIII. Conclusion

In this paper four image processing techniques have been applied to infrared images representing different scenarios in order to investigate their capabilities to differentiate between tool conditions. The results can be summarized as follows:

1. Canny detector and threshold have successfully detected tool wear, and clearly differentiated between different tool conditions, fresh, semi-worn, and damaged tools.
2. Gradient technique has been used in this research work in order to estimate the tool conditions. The results demonstrate that the gradient technique has been effectively applied and it correctly estimated the different tool conditions. Furthermore; the visualization of the images has been enhanced using the image gradient technique.
3. Temperature profile has proved that the dramatic change in temperature can be an indicator that the tool is begin gradually eroded. It successfully has been differentiated between tool conditions.

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