ISSN 2076-2429 (print)
ISSN 2223-3814 (online)
Proceedings of Odessa Polytechnic University, Issue 2(70), 2024

METROLOGY, STANDARDIZATION AND CERTIFICATION

МЕТРОЛОГІЯ, СТАНДАРТИЗАЦІЯ І СЕРТИФІКАЦІЯ

UDC 681.2.083

G. Oborsky, DSc., Prof.,
V. Goloborodko,
L. Perperi, PhD, Assoc. Prof.
Odessa Polytechnic National University, Shevchenko Ave. 1, Odesa, Ukraine, 65044; e-mail: plm.mvms@gmail.com

IMPLEMENTATION OF THE HYBRID BINARISATION METHOD FOR THERMOGRAM ANALYSIS

Г. Оборський, В. Голобордько, Л. Перпері. **Застосування методу гібридної бінаризації для аналізу термограм.** Об'єктом цього дослідження є термограми отримані в результаті здійснення тепловізійного контролю процесу механічної обробки на операції зовнішнього точіння. Застосування тепловізійного контролю дає можливість отримання швидкої візуалізації теплового стану зовнішніх поверхонь інструменту, заготовки та стружки в зоні різання шляхом отримання термограм У статті представлено напрацювання з розробки гібридного методу бінаризації для термограм з метою подальшої обробки за допомогою нейромереж. Для реалізації цього проекту було проведено аналіз вже існуючих технологій та алгоритмів, обрано ті які на думку авторів мають найбільший коефіцієнт корисної дії та реалізовано робочий прототип з використанням мови програмування Python 3.6 та фреймворку OpenCV для роботи з растровими зображеннями. Через специфіку формату термограм першим етапом було виконання перетворення кольорових зображень у монохромні, після чого, другим етапом було проведення бінаризації фіксованим методом з метою виділення найбільш гарячих зон, які відповідають зоні різання (зона контакта інструменту із заготовкою). Третій етап включає адаптивну бінаризацію, яка обробляє виокремлену зону кадру за допомогою гаусового розподілу, в результаті чого відбувається виділення саме необхідних об’єктів на кадрі які відповідають різцю, заготовці та подекуди гарячій стружці. Отриманий алгоритм вийшов простим та швидким, не дивлячись на виконання двох послідовних алгоритмів бінаризації, з адекватним рівнем точності перетворення кадру, що дає змогу використовувати їх в подальшому при навчанні нейронними мережами на отриманій вибірці.
Ключові слова: обробка зображень, інфрачервона камера, алгоритм бінаризації, цифрові технології

G. Oborsky, V. Goloborodko, L. Perperi. **Implementation of the hybrid binarisation method for thermogram analysis.** The object of this study is thermograms obtained as a result of thermal imaging control of the machining process during the external turning operation. The implementation of thermal imaging control enables rapid visualisation of the thermal state of the external surfaces of the tool, workpiece, and chips in the cutting zone by obtaining thermograms. The article presents developments in creating a hybrid binarisation method for thermograms to enable further processing using neural networks. To realisation this project, an analysis of existing technologies and algorithms was conducted, selecting those that, in the authors' opinion, have the highest efficiency. A working prototype was developed using the Python 3.13 and the OpenCV framework for processing raster images. Due to the specific format of thermograms, the first step involved converting colour images into monochrome. The second step then applied a fixed binarisation method to highlight the hottest areas corresponding to the cutting zone (the contact area between the tool and the workpiece). The third step involves adaptive binarisation, which processes the highlighted frame area using Gaussian distribution, as a result, the necessary objects in the frame-corresponding to the cutting tool, workpiece, and occasionally hot chips-are accurately highlighted. The resulting algorithm turned out to be simple and fast, despite the execution of two sequential binarization algorithms, while maintaining an adequate level of frame conversion accuracy. This allows its further use in training neural networks on the obtained dataset.
Keywords: image processing, infrared camera, binarization algorithm, digital technologies

Introduction

In the current industrial landscape, non-destructive testing methods are increasingly utilized to assess the thermal state of cutting processes in machining. This is particularly crucial given the continuously rising standards for precision and quality in the manufacturing of components across various industries. An essential role in this process is taken by control and monitoring methods utilising infrared thermography [1, 2]. Nowadays many researchers are focused on the utilisation of infrared technology to enable rapid visualisation of the thermal state of the external surfaces of the tool, workpiece, and chips in the cutting zone through the obtained thermograms. Thermal infrared images (thermograms) obtained using thermal imaging cameras serve as the basis for analysing the thermal state of the research object and conducting assessments based on measurement results [3 – 6]. Today, with the

DOI: 10.15276/opu.2.70.2024.14

ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

development of digital technologies in the context of Industry 4.0, visualisation processes are evolving through computer processing and are widely applied across various industrial sectors and scientific research fields [7, 8].

Thermal image processing refers to the process of converting an image captured by a thermal imager into a digital format and preparing the data for transmission to a computing device for further visual analysis. All images stored on computing devices, whether on a phone, personal computer, or other platforms, despite being saved in digital format, still contain analogue information that can only be recognised and interpreted by the human brain. For a computer, an image remains essentially a massive table where each cell corresponds to a pixel, and its content is represented in colour storage formats such as RGB, HEX, or any other encoding method and when it's processed by the device's graphics processor, this data transforms into how each pixel will emit the corresponding spectrum of light. But how to make a computer to understand what is shown in the picture? This is where the concept of binarisation comes to help us. Binarisation is the process of converting an image into a two-colour representation, where each pixel has only two possible values: black ("0") or white ("1"). The purpose of binarisation is to focus on important information and discard secondary or not essentially important information. There are a few main types of methods of binarisation, such as Fixed binarisation method, Global binarisation methods, Local (adaptive) methods, Histogram- and clustering-based methods, Hybrid methods and Deep learning-based methods. The choice of a particular method for the analysis of images depends on its ability to adapt to specific tasks, such as highlighting important areas on thermograms or preparing images for further machine learning. Accordingly, the use of digital technologies in the metalworking industry necessitates the development of new and the improvement of existing methods for processing thermal imaging data. These methods should be aimed at detecting areas with distinctive spatiotemporal temperature distribution patterns, enabling the collection and analysis of comprehensive information about the condition of the studied objects. Therefore, the examination of issues related to the utilisation of digital processing methods for thermograms by using binarisation algorithms for the analysis of thermal imaging data is important.

Analysis of recent research and publications

One of the goals of Industry 4.0 is to enhance the digitalisation of manufacturing to reduce human involvement and minimise the impact of operator qualification levels on the assessment of technological system conditions during the production process. As noted in the paper [7], Industry 4.0 is driving the growth of intelligent manufacturing processes that integrate cyber and physical systems through a range of technologies, such as the Internet of Things, Big Data, and Cloud Computing.

It is expected that this will trigger significant structural changes and lead to increased productivity and competitiveness in the manufacturing industry worldwide. This is also highlighted in [1], where the authors attempted to minimise the influence of the machine tool operator on the assessment of the cutting tool's performance by evaluating the wear condition of the cutting edge through the use of thermal imaging control.

Such tool wear monitoring eliminates subjective human assessment and contributes to improving the quality of the machined surface, reducing costs through timely tool replacement. In turn, this also helps to prevent defects in the final product.

In the article [9], the authors established a correlation between temperature distribution and the wear of an end mill. The heat distribution was determined using numerical analysis and the finite element method. Tool wear was determined using various image processing methods of the worn tool in the following sequence: RGB format conversion, threshold detection, and binarisation.

In the case study [10], a modified infrared temperature measurement method for orthogonal cutting was proposed to measure the temperature in the contact zone of the rake face with the chip. The article also presents a comparison of the cutting temperature occurring on the rake and flank surfaces of the cutting tool's edge. The authors also apply modelling to explain the observed trends, although they note the imperfections of the model due to the overestimation of temperature gradients on the rake face, possibly caused by the friction law used.

The study [11] states that image processing methods include noise filtering and dynamic distortion correction, binarisation, and morphological operations on extracted contours and objects. After analysing the main methods, the authors concluded that for thermal imaging data of various research objects, the most suitable approaches are Otsu's method segmentation, k-means segmentation, and texture-based segmentation.

The purpose of research

The aim of this study is to develop and improve existing methods of digital processing for thermal imaging data (thermograms) by combining different types of binarisation algorithms. These algorithms are designed to isolate regions with significant temperatures, enabling the acquisition and refinement of information about the condition of the technological system.

Consequently, to accomplish the stated objective, it is necessary to undertake the following tasks:

– conduct a comprehensive analysis of existing binarisation methods;
– identify the most effective binarisation method(s) for processing thermograms;
– develop a methodological framework for implementing the selected binarisation approach;
– carry out an empirical validation of the proposed method.

Research materials and methods

This case study is dedicated to the investigation of the application of the adaptive binarisation method for the analysis of thermal imaging thermograms, followed by its practical implementation. To achieve the stated objectives, theoretical methods were employed, based on mathematical and computational modelling theories, algorithm theory, and the fundamental principles of binarisation methods. The implementation was carried out using the Python 3 programming language and the OpenCV framework.

Results and discussion

The analysis of existing methods for processing graphical images has shown that numerous binarisation algorithms have been developed to address a wide range of various tasks.

The colour intensity of the research object and the background surrounding could play a significant role in processing images and its final result. To solve the problem of separating the research object from the background in a frame, the fixed threshold method is employed as a primary approach. As a result of threshold processing, a binarised image is obtained. However, it is important to note that the main challenge in obtaining a high-quality binarised image from thermograms is their colour palette, which must be converted into a monochrome format, specifically grayscale. To apply binarisation methods to such images, they must first be converted into a monochrome format, meaning the colour palette should be transformed into grayscale. After this conversion, existing binarisation methods [12] can be applied, as presented in Fig. 1.

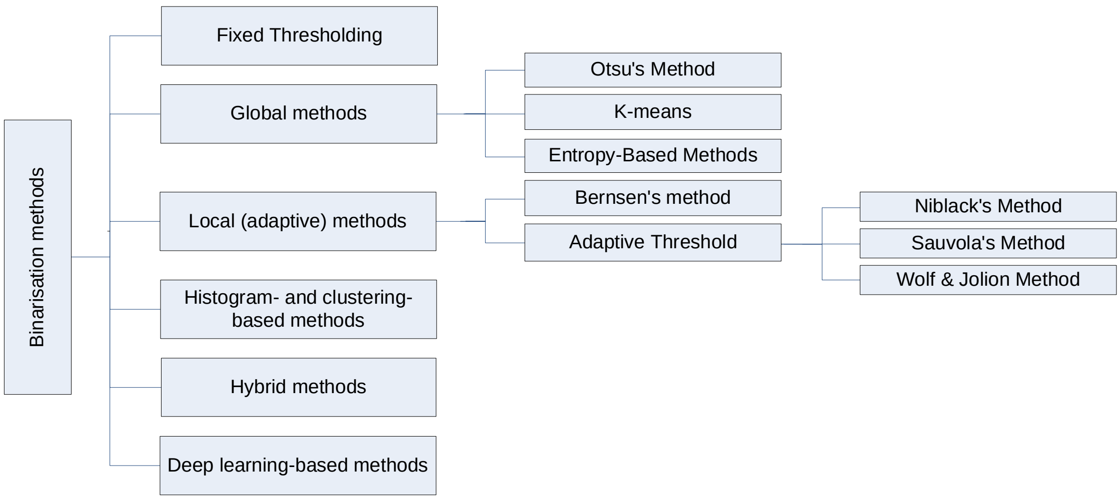


Fig. 1. Binarization Methods

To convert a thermal imaging image into a two-colour (black-and-white) binarised format, it is necessary to analyse existing methods, considering the complexity of the image and its colour intensity. A comparative analysis of existing binarisation methods is presented below in Table 1.

For the development of the project, a combination of the Fixed Threshold Method and the Adaptive Method was chosen to develop a Hybrid Binarisation Algorithm. The Fixed Threshold Method is a technique that applies a single threshold value T (set manually) and compares it with the intensity of each pixel. All pixels that meet this threshold are assigned a value of “1” as True, while all others are assigned “0” as False. This approach isolates the cutting zone with the highest temperature in the

 ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

frame while eliminating any extraneous objects that appear in the image. Formula that describes Fixed Threshold Method is shown below:

$$B(x,y)=\begin{cases}1, \ if \ I(x,y)\geq T; \\ 0, \ if \ I(x,y)<T, \end{cases}, \qquad (1)$$

where $I(x,y)$ – pixel intensity;

T – threshold temperature value, °C.

Table 1

Comparison of Binarisation Methods

Method	Complexity of implementa-tion	Speed	Quality for Complex Scenes	Advantages	Disadvantages	Best Use Case
Fixed Thresholding	High	High	Low	Simple and fast	Fails under uneven lighting conditions	Uniformly lit images
Otsu's Method	Medium	High	Medium	Automatic threshold selection	Assumes bimodal distribution	Images with distinct foreground and background
Local Method	Medium	Medium	High	Effective for images with local illumination variations	Could be sensitive to noise, and require tuning	Images with high detail or local contrasts
Adaptive Methods	Low	Medium	High	Handles varying illumination	Sensitive to parameter selection	Low-quality or unevenly lit documents
Clustering (K-Means)	Medium	Medium	High	Handles complex intensity distributions	Computationally expensive	Images with overlapping intensity classes
Entropy-Based Methods	Medium	Medium	Medium	Maximises information preservation	High computational cost	Images with varying contrast
Deep Learning	Low	Low	Very high	High accuracy and generalisation	Requires training and significant resources	Complex or highly degraded datasets
Hybrid methods	High	High	Very High	Could combine all benefits from a different method	Need a high level of qualification to combine several methods.	Suitable for solving complex and unique tasks

Next, by using Adaptive Binarisation Method the hottest zones become highlighted. Adaptive binarisation determines the threshold value for each pixel individually based on the analysis of its neighbour's pixels values. The OpenCV framework [13] provides the capability to apply Adaptive

Binarisation Method using Gaussian distribution, which enhances its effectiveness and reduces false pixel interpretations. This method uses the weighted average of intensities in the local neighbourhood of each pixel, where the weights are determined by a Gaussian kernel. The Gaussian kernel assigns greater weight to pixels closer to the central one, while distant pixels have less influence at main one:

$$g(x,y)=\begin{cases}1, \ if \ I(x,y)\geq T(x,y); \\ 0, \ if \ I(x,y)<T(x,y),\end{cases} \tag{2}$$

where $T(x,y)$ – the local threshold value for the pixel at (x, y).

Threshold value is described by the formula:

$$T(x,y)=\frac{1}{W}\sum_{i,\,j\in S(x,y)} G(i,j)\times I(i,j)-C, \tag{3}$$

where $S(x,y)$ – the local window around the pixel (x, y);

$G(i,j)$ – the value of the Gaussian kernel at point (i, j);

$I(i,j)$ – the intensity of the pixel (i, j);

W – the sum of all kernel values $G(i,j)$ in the window $S(x,y)$;

C – constant that adjusts the threshold.

Gaussian kernel $G(i,j)$ is defined by the two-dimensional Gaussian distribution:

$$G(i,j)=\frac{1}{2\pi\sigma^2}\exp\left(-\frac{(i-\mu_x)^2+(j-\mu_y)^2}{2\sigma^2}\right), \tag{4}$$

where i, j – pixel coordinates in the local window;

μ_x, μ_y – coordinates of the window center;

σ – the standard deviation parameter, which controls the spread of the weights.

This method provides reliable results for images with uneven lighting, as it accounts for local variations in brightness.

The combination of these two methods provides sufficient tools for detecting and emphasis the cutting zone in a thermogram frame and in the same time do not take a lot of computational resources.

Implementation of the Binarisation algorithm. Before processing the thermogram, it is essential to consider that the frames have not compatible colour palette which has a colour dependence to the temperature range, which poses a significant challenge for applying the foregoing algorithms. To save computational resources of the device the image would be converted to monochrome palette. that means the colours should be transformed into grayscale. The human eye has several unique characteristics in colour perception. Specifically, the human eye is more sensitive to green, less to red, and the least to blue. Therefore, when converting a colour image (RGB) to grayscale, different coefficients should be applied for characteristics of each colour. Therefore, the first step is converting the image to grayscale. To simplify the algorithm operation:

$$I_{\text{grey}}(x,y)=0.299\,\mathrm{R}+0.587\,\mathrm{G}+0.114\,\mathrm{B}, \tag{5}$$

where RGB – the intensities of the red, green, and blue channels, respectively;

$I_{\text{grey}}(x,y)$ – the intensities of the pixel in grayscale.

OpenCV allows this process to be implemented with the following command:

```
gray = cv2.cvtColor(image, cv2.COLOR_BGR2GRAY).
```

The obtained monochrome image is then subjected to the first stage of binarisation using a fixed threshold:

```
_, binary_fixed = cv2.threshold(gray, 200, 255, cv2.THRESH_BINARY).
```

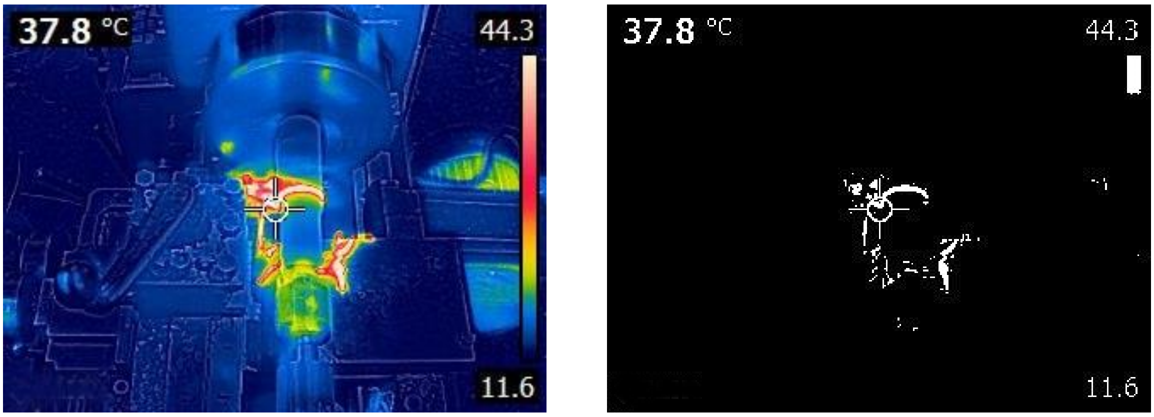
Then the transformed frame could be binarised with Adaptive binarisation with Gaussian distribution:

```
binary_adaptive = cv2.adaptiveThreshold(
  gray, 255, cv2.ADAPTIVE_THRESH_GAUSSIAN_C, cv2.THRESH_BINARY, 11, 2
).
```

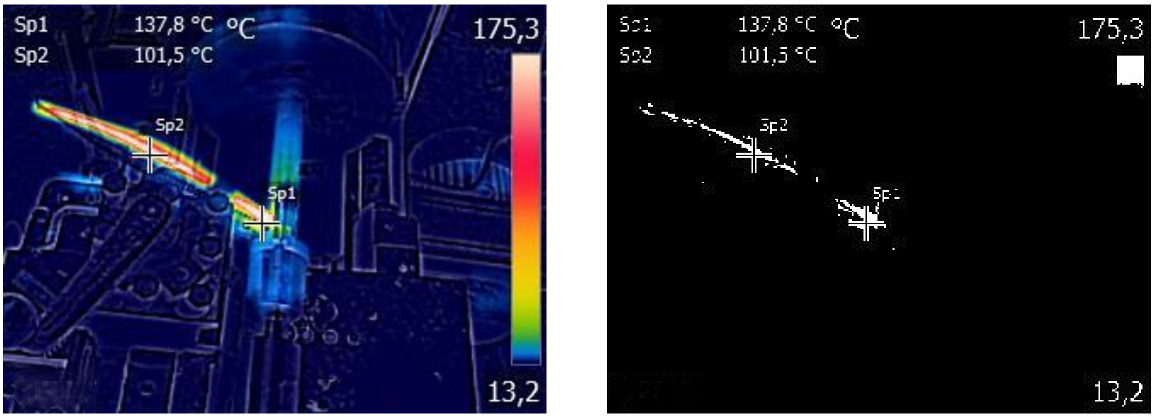
ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

As a result of applying the algorithm to the thermogram (Fig. 2, *a*), a binarised image is obtained, as shown in Fig. 2, *b*.

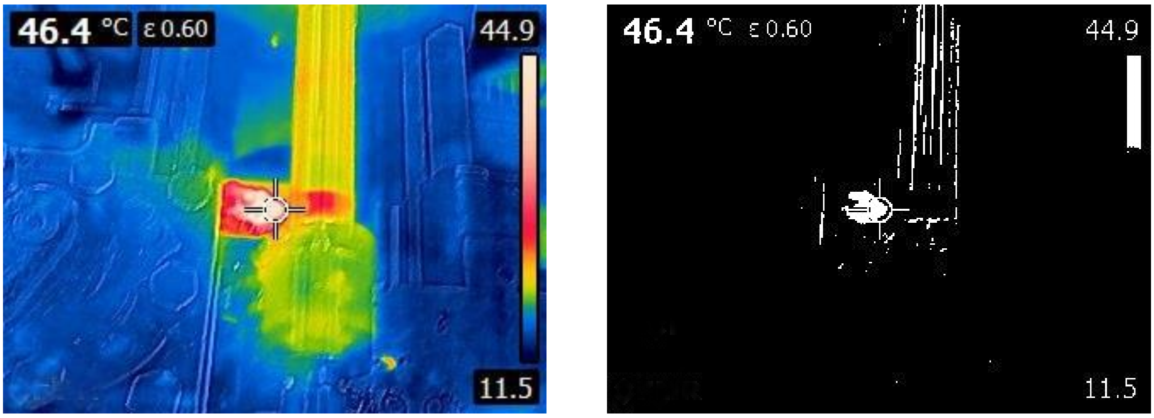
As seen above, the algorithm successfully performed binarisation and isolated the region with the highest temperature, which corresponds to the cutting zone. The execution time for processing a single frame ranges from 0.004 to 0.006 seconds (Fig. 3), while processing a batch of five frames takes up to 0.031 seconds (Fig. 4).



Processing of the material TECAST T (Caprolon)



Processing steel 41Cr4



The steel workpiece and the cutting tool after machining (with the lathe machine stopped)

a *b*

Fig. 2. Thermograms – before (*a*) and after binarization (*b*)

```
Frame processing time: 0.005 seconds
Results saved to files:
Fixed binarization: C:\temp\binary_fixed.jpg
Adaptive binarization: C:\temp\binary_adaptive.jpg
Cutting zone: C:\temp\cutting_area.jpg
Frame processing time: 0.004 seconds
Results saved to files:
Fixed binarization: C:\temp\binary_fixed2.jpg
Adaptive binarization: C:\temp\binary_adaptive2.jpg
Cutting zone: C:\temp\cutting_area2.jpg
Frame processing time: 0.005 seconds
Results saved to files:
Fixed binarization: C:\temp\binary_fixed3.jpg
```

```
Adaptive binarization: C:\temp\binary_adaptive3.jpg
Cutting zone: C:\temp\cutting_area3.jpg
Frame processing time: 0.006 seconds
Results saved to files:
Fixed binarization: C:\temp\binary_fixed4.jpg
Adaptive binarization: C:\temp\binary_adaptive4.jpg
Cutting zone: C:\temp\cutting_area4.jpg
Frame processing time: 0.004 seconds
Results saved to files:
Fixed binarization: C:\temp\binary_fixed5.jpg
Adaptive binarization: C:\temp\binary_adaptive5.jpg
Cutting zone: C:\temp\cutting_area5.jpg
Processing time: 0.031 seconds
```

Fig. 3. Recording of logs during binarization of simple frame

The obtained results indicate that the developed algorithm can be further optimised for processing a thermal camera video stream at a frame rate of 60 frames per second without quality loss. After completing binarisation, the thermogram can be prepared for further processing by machine learning algorithms, such as those implemented with TensorFlow.

```
Adaptive binarization: C:\temp\binary_adaptive5.jpg
Cutting zone: C:\temp\cutting_area5.jpg
Processing time: 0.031 seconds
```

Fig. 4. Recording of logs during binarization of pocket from five frames

As main toolbar for realisation of the project were chosen Python 3.13 and OpenCV framework for processing frames in raster format.

Conclusions

In the result of research the main binarisation algorithms were analysed and a few were selected for combination to develop a hybrid binarisation method. After analysing and comparing several of the most widely used methods, the fixed threshold method and adaptive binarisation were selected. The Fixed Threshold Method allows filtering out all values that do not fall within the target range, while the Adaptive Binarisation Method focuses on and enhances the cutting zone.

As a result, The Hybrid Binarisation Algorithm was developed, based on the Fixed Threshold and Adaptive Binarisation Methods. This approach provided a fast and accurate outcome, with the potential for application in video stream processing. As it seems in the figures 3, the algorithm accurately detects and focuses on the workpiece and cutting tool, while factors such as positioning, angle, and exposure in the frame do not affect the quality of the binarisation process.

Література

1. Brili N., Ficko M., Klančnik S. Tool Condition Monitoring of the Cutting Capability of a Turning Tool Based on Thermography. *Sensors*. 2021. 21(19), 6687. DOI: https://doi.org/10.3390/s21196687.
2. De Maddis M., Lunetto V., Razza V., Russo Spena P. Infrared Thermography for Investigation of Surface Quality in Dry Finish Turning of Ti6Al4V. *Metals*. 2022. 12(1). 154. DOI: https://doi.org/10.3390/met12010154.
3. Zgórniak P., Stachurski W., Ostrowski D. Application of Thermographic Measurements for the Determination of the Impact of Selected Cutting Parameters on the Temperature in the Workpiece During Milling Process. *Strojniški vestnik - Journal of Mechanical Engineering*. 2016. 62(11). 657–664. DOI: http://dx.doi.org/10.5545/sv-jme.2015.3259.
4. Inţă M., Muntean A. Researches regarding introducing temperature as a factor in cutting tool wear monitoring. *MATEC Web Conf.* 2018. DOI: https://doi.org/0.1051/matecconf/201817801013.
5. Голобородько В.В., Оборський Г.О., Перпері Л.М. Застосування тепловізора для вимірювання температури в зоні різання при токарній обробці. *Нові та нетрадиційні технології в ресурсо- та енергозбереженні* : Матеріали міжнародної науково-технічної конференції, 11–12 грудня 2024 р., м. Одеса. Одеса, 2024. С. 188–190.
6. Recent Advances in Thermal Imaging and its Applications Using Machine Learning: A Review / Wilson A. N., Gupta K. A., Koduru B. H., Kumar A., Jha A. Cenkeramaddi L. R. *IEEE Sensors Journal*. 2023. 23 (4), P. 3395–3407. DOI: https://doi.org/10.1109/JSEN.2023.3234335.
7. Sarı T., Gules H.K., Yiğitol B. Awareness and Readiness of Industry 4.0: The Case of Turkish Manufacturing Industry. *Adv. Prod. Eng. Manag.* 2020. 15. P. 57–68. DOI: https://doi.org/10.14743/apem2020.1.349.
8. Gade R., Moeslund T. B. Thermal cameras and applications: a survey. *Machine Vision and Applications*. 2013. 25(1), P. 245–262. DOI: https://doi.org/10.1007/s00138-013-0570-5.

9. Case study in thermal and wear analyses for cutting tools / Cerci Y., Demircioglu P., Bogrekci I., Deniz C., Durakbasa M.N. *In Proceedings of the 11th International Symposium on Measurement and Quality Control*, Osaka University. 2013. (p. 4) URL: https://www.imeko.org/publications/tc14-2013/IMEKO-TC14-2013-34.pdf.
10. Arrazola P.-J., Aristimuno P., Soler D., Childs T. Metal cutting experiments and modelling for improved determination of chip/tool contact temperature by infrared thermography. *CIRP Annals.* 2015. 64(1), P. 57–60. DOI:10.1016/j.cirp.2015.04.061.
11. Подчашинський Ю. О., Лугових О. О., Чепюк Л. О. Аналіз методів обробки відеозображень з вимірювальною інформацією, отриманих від тепловізора / спектральної камери. *Технічна інженерія*. 2023. 1(91). С. 214–221. DOI: https://doi.org/10.26642/ten-2023-1(91)-214-221.
12. Sezgin M., Sankur B. Survey over image thresholding techniques and quantitative performance evaluation. *J. Electron. Imag.* 2004. 13(1). DOI: https://doi.org/10.1117/1.1631315.
13. OpenCV (Open Source Computer Vision Library) URL: https://docs.opencv.org/3.4/d7/d1b/group__imgproc__misc.html#ggaa42a3e6ef26247da787bf34030ed772caf262a01e7a3f112bbab4e8d8e28182dd.

References

1. Brili, N., Ficko, M., & Klančnik, S. (2021). Tool Condition Monitoring of the Cutting Capability of a Turning Tool Based on Thermography. *Sensors*, 21(19), 6687. DOI: https://doi.org/10.3390/s21196687.
2. De Maddis, M., Lunetto, V., Razza, V., & Russo Spena, P. (2022). Infrared Thermography for Investigation of Surface Quality in Dry Finish Turning of Ti6Al4V. *Metals*, 12(1), 154. DOI: https://doi.org/10.3390/met12010154.
3. Zgórniak, P., Stachurski, W., & Ostrowski, D. (2016). Application of Thermographic Measurements for the Determination of the Impact of Selected Cutting Parameters on the Temperature in the Workpiece During Milling Process. *Strojniški vestnik* - *Journal of Mechanical Engineering*, 62(11), 657–664. DOI: http://dx.doi.org/10.5545/sv-jme.2015.3259.
4. Inţă, M. & Muntean, A. (2018). Researches regarding introducing temperature as a factor in cutting tool wear monitoringю. *MATEC Web Conf.* DOI: https://doi.org/0.1051/matecconf/201817801013.
5. Goloborodko, V.V., Oborskyi, G.O., & Perperi, L.M. (2024). Application of a thermal imager to measure the temperature in the cutting zone during turning. New and unconventional technologies in resource and energy saving: *Proceedings of the International Scientific and Technical Conference*, (December 11–12, 2024, Odesa. Odesa, 188–190.
6. Wilson, A. N., Gupta, K. A., Koduru, B. H., Kumar, A., Jha A. & Cenkeramaddi, L. R. (2023). Recent Advances in Thermal Imaging and its Applications Using Machine Learning: A Review. *IEEE Sensors Journal*, 23 (4), 3395–3407. DOI: https://doi.org/10.1109/JSEN.2023.3234335.
7. Sarı, T., Gules, H.K., Yiğitol, B. (2020). Awareness and Readiness of Industry 4.0: The Case of Turkish Manufacturing Industry. *Adv. Prod. Eng. Manag.*, 15, 57–68. DOI: https://doi.org/10.14743/apem2020.1.349.
8. Gade, R., & Moeslund, T. B. (2013). Thermal cameras and applications: a survey. *Machine Vision and Applications*, 25(1), 245–262. DOI: https://doi.org/10.1007/s00138-013-0570-5.
9. Cerci, Y., Demircioglu, P., Bogrekci, I., Deniz, C., & Durakbasa, M. N. (2013). Case study in thermal and wear analyses for cutting tools. *In Proceedings of the 11th International Symposium on Measurement and Quality Control* (p. 4). Osaka University. Retrieved from: https://www.imeko.org/publications/tc14-2013/IMEKO-TC14-2013-34.pdf.
10. Arrazola, P.-J., Aristimuno, P., Soler, D., & Childs, T. (2015). Metal cutting experiments and modelling for improved determination of chip/tool contact temperature by infrared thermography. *CIRP Annals*, 64(1), 57–60. DOI:10.1016/j.cirp.2015.04.061.
11. Podchashynskyi, Y., Luhovykh, O., & Chepiuk, L. (2023). Analysis of methods for processing video images with measurement information from a thermal imager / spectral camera. *Technical Engineering*, 1(91), 214–221. DOI: https://doi.org/10.26642/ten-2023-1(91)-214-221.
12. Sezgin, M., & Sankur, B. (2004). Survey over image thresholding techniques and quantitative performance evaluation. *J. Electron. Imag.* 13(1). DOI: https://doi.org/10.1117/1.1631315.
13. OpenCV (Open Source Computer Vision Library) Retrieved from: https://docs.opencv.org/3.4/d7/d1b/group__imgproc__misc.html#ggaa42a3e6ef26247da787bf34030ed772caf262a01e7a3f112bbab4e8d8e28182dd.

Оборський Геннадій Олександрович; Gennady Oborsky, ORCID: https://orcid.org/0000-0002-5682-4768
Голобородько Володимир Володимирович; Volodymyr Goloborodko, ORCID: https://orcid.org/0000-0001-8614-6606
Перпері Людмила Михайлівна; Liudmyla Perperi, ORCID: https://orcid.org/0000-0002-6840-0241

Received November 02, 2024

Accepted December 10, 2024