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Two Illustrative Examples to Show the Potential of Thermography for Process Monitoring and Control in Hot Rolling

Florian Schausberger * **Katrin Speicher** *
Andreas Steinboeck * **Martin Jochum** ** **Andreas Kugi** *

* *Automation and Control Institute, Vienna University of Technology, Vienna, Austria (e-mail: {schausberger,speicher,steinboeck,kugi}@acin.tuwien.ac.at)*
** *AG der Dillinger Hüttenwerke, Dillingen, Germany (e-mail: martin.jochum@dillinger.biz)*

Abstract: This paper deals with the systematic analysis of thermographic images recorded during the hot rolling process of steel plates. In the first part, local disturbances are detected and different approaches for disturbance rejection are proposed. From the processed images, reliable mean temperature profiles in longitudinal and lateral direction are calculated. In the second part of the paper, an optimization problem is formulated and solved to calculate the plate velocity from the thermographic images. The approach proves to be a robust estimation method for the plate velocity. As the thermographic camera is already installed for temperature measurements, no additional measurement devices are needed so that investment and maintenance costs are saved.

Keywords: Thermography, hot rolling, temperature measurement, rolling speed, image processing, unconstrained optimization

1. INTRODUCTION

Thermographic cameras are widely used in very different fields ranging from medicine to building inspection, process monitoring, and non-destructive testing. Numerous application examples can be found in literature, which is reviewed for instance by Usamentiaga et al. (2014). There also a general introduction to infrared thermography is given.

Thermography has two major advantages in comparison with other temperature measurement methods: First, it is a non-contact and non-invasive technique, i.e., it can be used to measure the temperature of very hot or moving objects from a safe distance, which also simplifies maintenance. Second, the provided temperature measurements are two-dimensional and contain far more information than, e.g., single-point pyrometer or thermocouple measurements. These advantages render thermography also a promising measurement technique in the steel industry. There, it is used in laboratory experiments but also on-line during the production. For example, Vidoni et al. (2014) use thermocameras in their experimental strip caster in addition to pyrometers because they provide information about the temperature distribution across the width. The two-dimensional character of the measurement is also exploited by He et al. (2011), who employ thermography to experimentally characterize the scale formed on steel surfaces. In a work presented by Koch and Schroeder (2012), hot spots are detected in real-time thermographic images of hot-rolled steel billets for quality assessment. Their time evolution is analyzed to identify material flaws and to prevent false indications. Viale et al. (2007) also use infrared cameras for on-line detection of hot spots on ladles. Furthermore, the slag is automatically detected during tapping operation.

Summarizing, most of those applications use thermographic cameras for one single measurement purpose and thus exploit only a small part of the information contained in the two-dimensional images. However, different applications of thermography are simultaneously possible using the same image. This includes, e.g., the estimation of the velocity of moving objects or tracking of hot plates during their production. If images captured by several cameras, which cover the whole production line, are utilized, even more possibilities are opened up.

This paper aims at extending the scope of thermography in hot rolling. Since the large number of possible applications cannot be discussed in a single paper, this paper focuses on two different possible applications of thermographic imaging in hot rolling of heavy plates. Section 2 deals with the most obvious possibility, namely the temperature measurement. Using standard image processing techniques, local disturbances are removed from the image so that reliable mean lateral and longitudinal surface temperature profiles can be calculated. Furthermore, characteristic striped patterns can be extracted. Section 3 presents a fast and robust optimization-based estimation strategy for the plate velocity. The proposed method utilizes the non-uniformities of the plate surface temperature in the longitudinal direction. Note that both applications rate the same information, i.e., temperature inhomogeneities,

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in a different way: While they are removed prior to the calculation of representative temperature profiles, they are vital for the estimation of the plate velocity.

2. CHARACTERIZATION OF THE PLATE SURFACE TEMPERATURE

In steel industry, the temperature evolution of the steel product during its production significantly influences its final quality. Therefore, it is crucial that the temperature is monitored and controlled. To this end, temperature sensors are installed at many different positions in the production process, cf. Peacock (1999). In hot rolling, pyrometers are used in most cases, see, e.g., Zheng and Li (2011), Speicher et al. (2014), and the references given therein. However, pyrometers normally measure only on the centerline of the product and do not provide information about the lateral temperature profile, which, for instance, is an important quantity for the adjustment of the water distribution in the cooling section. This drawback can be overcome by using thermographic cameras instead of pyrometers. From the two-dimensional temperature measurements, a mean lateral temperature profile can be calculated. Additionally, the mean longitudinal temperature profile is more reliable than the pyrometer recordings, which are obtained while the product moves through the measuring ray of a pyrometer, because it is less affected by local disturbances, e.g., scale spots.

2.1 Identification of local disturbances

Before averaging the rows and columns of the thermographic image, local disturbances, which may arise from production inhomogeneities, reflection, or obstacles in the field of view of the camera, should be eliminated first. Since all production steps affect the plate temperature either in lateral or in longitudinal direction, it can be assumed that the disturbances are the only part in the measured temperature distribution, which depends on both coordinates. Hence, the measured surface temperature $T(x, z)$ is assumed to be composed of four parts, i.e.,

$$T(x, z) = T_m + T_x(x) + T_z(z) + T_d(x, z). \quad (1)$$

Thus, the local disturbances $T_d(x, z)$ are separated from the mean temperature T_m, and the longitudinal and lateral striped pattern T_z and T_x, which depend only on the lateral coordinate z or the longitudinal coordinate x, respectively. Images with raster size $M \times N$ contain only temperature values at $x_j = j\delta, j = 1, \ldots, M$, and $z_i = i\delta, i = 1, \ldots, N$ with the pixel size δ. The spatially discretized temperature field $T(x_j, z_i)$ can be expressed by the inverse two-dimensional cosine transform (cf. Jain (1989))

$$T(x_j, z_i) = \sum_{n=1}^{N} \sum_{m=1}^{M} C_{nm} \alpha_n \cos\left(\frac{\pi(2i-1)(n-1)}{2N}\right) \cdot \beta_m \cos\left(\frac{\pi(2j-1)(m-1)}{2M}\right), \quad (2)$$

which is a standard tool in image processing and compression. The amplitude of the individual cosine functions depends on the coefficients C_{nm} and the parameters

$$\alpha_1 = \frac{1}{\sqrt{N}}, \quad \alpha_n = \frac{2}{\sqrt{N}}, \quad n = 2, \ldots, N$$
$$\beta_1 = \frac{1}{\sqrt{M}}, \quad \beta_m = \frac{2}{\sqrt{M}}, \quad m = 2, \ldots, M. \quad (3)$$

Hence, the size of the image determines the frequency resolution of (2) as well as the values (3).

The double sum in (2) is rearranged in the form

$$\begin{aligned} T(x_j, z_i) = {} & C_{11}\alpha_1\beta_1 \\ & + \sum_{n=2}^{N} C_{n1}\alpha_n\beta_1 \cos\left(\frac{\pi(2i-1)(n-1)}{2N}\right) \\ & + \sum_{m=2}^{M} C_{1m}\alpha_1\beta_m \cos\left(\frac{\pi(2j-1)(m-1)}{2M}\right) \\ & + \sum_{n=2}^{N}\sum_{m=2}^{M} C_{nm}\alpha_n \cos\left(\frac{\pi(2i-1)(n-1)}{2N}\right) \\ & \cdot \beta_m \cos\left(\frac{\pi(2j-1)(m-1)}{2M}\right). \end{aligned} \quad (4)$$

By comparison with (1), it can be seen that the information about the local disturbances is contained in the coefficients $C_{nm}, n = 2, \ldots, N, m = 2, \ldots, M$. Using this assumption, reliable mean temperature profiles are calculated in the next section. Furthermore, striped lateral and longitudinal patterns can be calculated by evaluating only the second or the third term in (4).

2.2 Calculation of a mean lateral temperature profile

In the following, the thermographic image shown in Fig. 1 is considered to demonstrate the proposed algorithms. In this figure as well as in the following ones, the plate temperature is normalized to the maximum temperature $T_{\max}$. Since the cosine transform (4) requires a rectangular

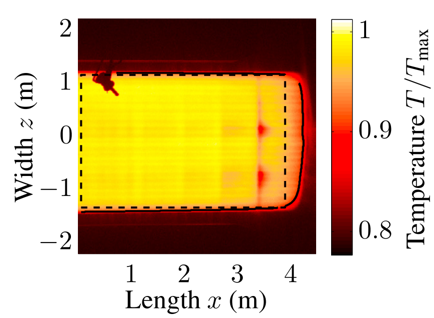

Fig. 1. Original thermographic image with detected edges (solid black line) and selected section for image processing (dashed black line).

section of the plate, the edges of the plate are first detected by an extension of the Canny algorithm (cf. Canny (1986)) and the largest rectangular section inside the identified edges is then selected for the presented analyses. The selected section is shown in Fig. 2(a) and contains two disturbances: two colder spots at the head end of the plate and a pyrometer in the upper left corner. The cold spots may result from water pools on the non-flat surface. In contrast to the cold spots, the pyrometer is a systematic disturbance and is always inside the field of view of the camera. Both disturbances can be extracted