Multifunctional Diagnostics and Process Control Systems Based on Infrared Thermography Methods and Machine Vision Algorithms

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ABSTRACT

In this paper, the applying of infrared thermography methods and machine vision algorithms are considered in the field of metallurgy manufacturing. Necessity of using such combination of methods is caused by such specific parameters, as low picture quality in visible spectrum; low distinction between the objects in visible spectrum; difficulty and instability of contact methods of measuring. In this paper, all the advantages of such approach are considered in the practical solution of "Multifunctional diagnostics and process control system for continuous casting machine". By using infrared thermal video analysis and machine vision algorithms this system provides the following functionality in a real time mode: speed control; ingot geometry control; temperature control and alarm prevention.

1 INTRODUCTION

Infrared (IR) - is electromagnetic radiation, which has longer length of wave than the visible spectrum of light. This part of spectrum cannot be seen by human eye; therefore, it cannot be caught by usual optical devices. Devices can be parted by the wavenumber parameters. Lower cm-1 value, means higher temperature. The whole IR spectrum can be parted on Near-IR (12500 cm-1 - 4000 cm-1), Mid-IR (4000 cm-1 – 400 cm-1) and Far-IR (400 cm-1 – 5 cm-1), see Figure 1. [1]

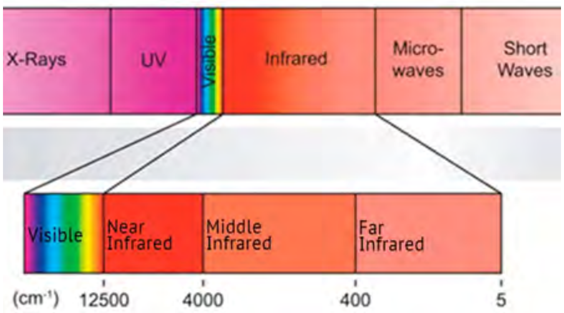

Fig. 1 The Infrared spectrum illustration.

All objects, with temperature higher than absolute zero (-273.16 Co) emit IR radiation. Infrared energy is generated by the vibration and rotation of atoms and molecules. Therefore, the higher the temperature of an object, the more IR energy it emits. In this way, using of devices, which can recognize the IR radiation, provides a bunch of solution for engineering and manufacturing. There are several fields, where it can be applied: night vision, meteorology, astronomy, thermography, etc. Thermography is the technique, which combines the set of algorithms, producing a visible picture of emitted invisible IR radiation. That kind of images, called thermograms, exampled in Figure 2. [2]

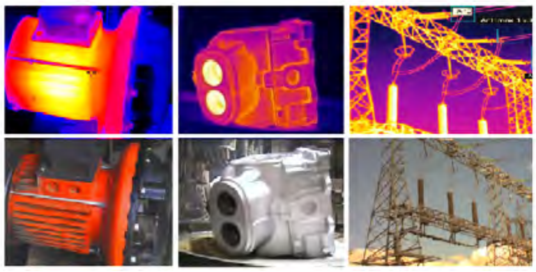

Fig. 2 Examples of IR thermograms and pictures in visible spectrum

Based on the aforesaid, it is considered, that applying of thermography gives many advantages in many fields of science. One of the main advantages of thermograms - warm objects stand out well against cooler backgrounds, which makes it easier to detect them in, for example, region with unstable illumination or with polluted atmosphere. Another advantage is the lack of the contact with the surface. It provides easier ways of measuring in many fields, for example, manufacturing. Therefore, all this positive sides, allows us to create a huge set of applications for many goals. This set of applications is illustrated in Figure 3.

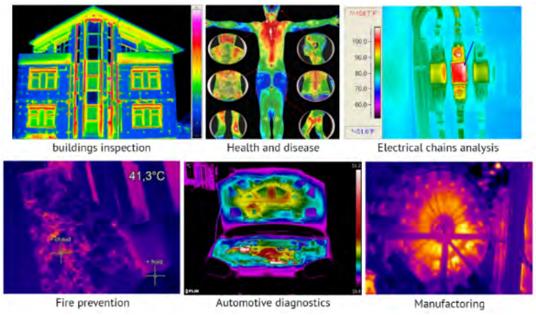

Fig. 3 The set of thermography applications

As mentioned, all the thermography advantages can be applied to the manufacturing field. In many situations, the human analysis of thermograms is not enough due to slowness and inaccuracy. Therefore, for automatization of this process the machine vision algorithms can be applied. Machine vision is the complex of methods, applied to video stream or picture to analyze it, and get the necessary data.

Mostly, the machine vision algorithms applied to the visible cameras content. These cameras use typical analytics, such as pattern matching, image enhancement, presence sensing, gauging, and part identification. Applying this methods to IR thermograms provides a huge amount of new possibilities in fields, previously marked in this work.

2 IR APPLICATIONS APPLIED TO CONTINUOUS CASTING MACHINE

To describe all advantages of combining the IR thermography and machine vision algorithms, the diagnostics and process control system for continuous casting machine was chosen. It covers the stage of secondary cooling process and performs a number of tasks, such as temperature, speed and shape deformations control.

2.1 SPEED MEASURING

The requirement in such method of speed measuring is justified by insolvency of the contact methods. The difference in accuracy in these two methods does not have much influence, because it lays in the acceptable average, which is 1.5% for both of them.

It is important to note that system, based on machine vision method of speed measurement is more robust then contact method. The majority of existing speed measuring systems in continuous casting machine are based on rolling device, under the metal flow. The shortcoming is that sometimes it slips, what gives the wrong value of the speed. Especially, while applying the IR thermography instead of simple video stream makes it even more robust, because this system is more stable to interference caused by steam pollution and illumination instability.

On the other hand, the contact method of measuring needs more time for its service and tuning. Finally, the measuring with the camera reduces the problems with slips, provides non-stop working process during the setting of the system and replacing many mechanisms with one measuring device.

One of the principles of speed measurement based on the template-matching algorithm. This algorithm simply sliding across the picture, looking for the bigger matching value with the template. Mathematically the algorithm of matching, used in this application can be described by term (1), where R(x, y) is the result matrix of metrics.

$$\boldsymbol{R}(\boldsymbol{x},\boldsymbol{y}) = \frac{\sum_{x',y'}(T(x',y') * I(x+x',y+y'))}{\sqrt{\sum_{x',y'} T(x',y')^2 * \sum_{x',y'} I(x+x',y+y')^2}} \qquad (1)$$

System takes the sample from the certain point on the billet and track it all the way down. Then, after loosing the pattern, it loops this operation. To provide the better accuracy more patterns in the different points can be taken and than averaged. Very important not to take to much matching templets, because it can affect on the system performance. The algorithm of simple two-samples tracking is shown in Figure 4.

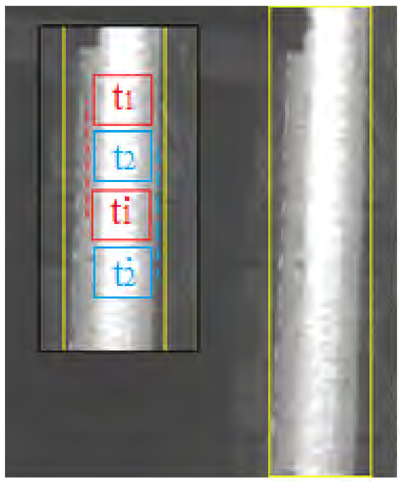

Fig. 4 Two-samples tracking algorithm

On the other hand, for some situations this algorithm would not be necessary, because of uniformity of the object. That is why there is another solution for speed measuring, based on simple cross-correlation function usage (2).

$$K(n) = \frac{1}{(I_2 - I_0)} \sum_{i=I_0}^{i=I_2} (x_i - \overline{x}) * (y_{i+n} - \overline{y}) \qquad (2)$$

x_i and y_i – the array of pixels amplitudes for the first and the next frame, $\bar{y}$ – expected values, I_2 and I_0 – interval borders, n – offset.

The idea is to chose the supervision interval and to count the value of correlation in it between frames in different moments of time. Depending from correlation and time, the speed can be calculated. [3]

This algorithm has some weighty limitations. It needs more time for adjustment and can work only in one detention speed measuring (otherwise, it should be unreasonably more complex). Concluding, the usage of these methods is optional according to the specific of the object and manufacturing.

It is important to mark, that accuracy of a single speed measurement is limited by the accuracy of pattern location definition. In its turn, accuracy of pattern location definition depends from single pixel size from the object face: $1pix = \delta x$. On the Figure 5 an example of pixel size evaluation for the camera with $N_x \times N_y = 382 \times 288$pix matrix and lens $\alpha \times \beta = 13^o \times 10^o$ FOV / f = 41mm with $L = 5m$, is shown.

$$\Delta X = 2L * tan(\alpha 2), \Delta Y = 2L * tan(\beta 2) \qquad (3)$$

$$\delta x = \Delta X / N_x, \delta y = \Delta Y / N_y \qquad (4)$$

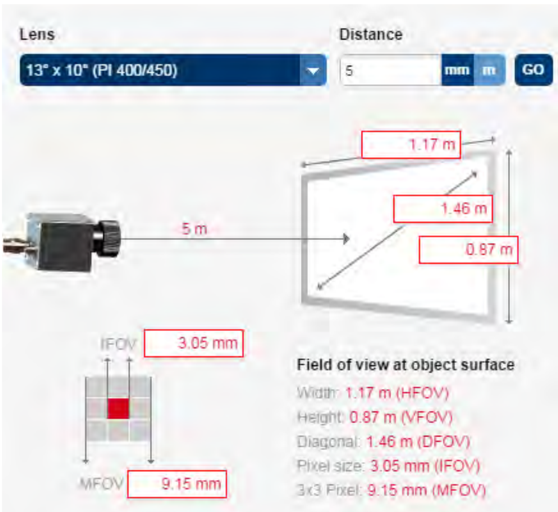

Fig. 5 Example of pixel size evaluation

It this example, the minimum limit of accuracy equals $\delta x \approx \delta y \approx 3mm$. It provides a set of restrictions on time interval in which we want to evaluate the speed with specified accuracy.

Therefore, to get the $\delta t = 0.001$ (mistake equals 1% in 1 time per second interval), the object have to move with 33 mm/sec speed, what is equal to 2m/min. If the real speed of casting ingot lays between 0.5 and 1.5 m/min, the averaging interval has to be increased up to 2-4 sec. Another ways to increase the accuracy is to choose lens with another parameters or the camera with bigger resolution.

It should be noted, that in this method the synchronous processing of a bunch of picture areas with averaging is realized. It allows us to eliminate the statistical mistake.

2.2 <u>TEMPERATURE MEASURING</u>

Temperature control, implemented by IR camera has many advantages unlike other methods. It givers us the whole picture of the area, represented in temperature matrix, when simple methods, give us information about some specific point of the object. Therefore, IR thermography gives us more complex solution for temperature measurement.

Applying of the machine vision provides us a possibility not just to choose the point or the area on thermogram manually, but also to do it automatically. The threshold, banalization and counter recognizing algorithms allow us to find the object of measuring. For example, in the Figure 5, the yellow area is automatically chosen, green and red – manually marked by user and the middle temperature of each one of them is written.

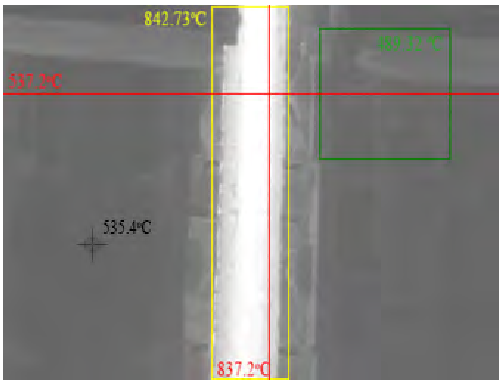

Fig. 6 Example of temperature measurement in different areas

Evaluating the vertical profile is very important for speed measurement. As it was said before, the method of continuous billet speed measuring with IR camera is more robust then other common methods. However, sometimes camera drops the samples due to a high level of homogeneity of the billet.

This problem can be easily solved by adding extra samples to be tracked, but it will take much more time for evaluation and lower system performance. By using vertical trend, we can reduce interferences connected with cooling of the billet.

In Figure 6 the vertical profile is illustrated

Fig. 6 Vertical Trend

Green line is the temperature trend in some specific moment of time, the red one – is the averaged by 3 seconds. As we see, the process of cooling is close to linear and have change of the temperature close to 40 ^{o}C.

So now, there is two ways to reduce the cooling effect. To add values to temperature in matrix, or to apply the gradient to the picture, according to linear function.

2.3 SLAB LENGTH CONTROL

Besides the speed control, this method allows us to measure the length of the way, passed by the ingot. This data uses to provide the control sequences for the cutting machine. Wherein, the accuracy of length measurement will not be higher than (5):

$$\delta L_{max} = 2\frac{L}{\Delta X} * \delta x, \textbf{where L} - \textbf{input ingot lenght} \quad (5)$$

At the same time the minimum value of measurement accuracy will be still depended from pixel size.

$$\delta L_{min} = 2 * \delta x$$

So in example, shown on Figure 5, for $L = 12m$ diapason of deviations from ingot length will be:

$$\pm 6mm \approx \delta L_{min} \le \delta L \le \delta L_{max} \approx \pm 60mm$$

To reach the diapason of measured length deviations from defined value decreasing, we need to increase quantity of patterns in the algorithm and average results.

2.4 SHAPE DEFORMATIONS CONTROL

Profile deformations of continuous casting ingot – sort of defects, connected with deviation of the profile geometry from specified one. It is usually caused by the increasing of metal temperature, filling speed or by inhomogeneity of cooling. Most common deformations is veining on the top surface of the billet, rhombic deformations, edges bulging and edges concavity. The example of such defects is illustrated in the Figure 7.

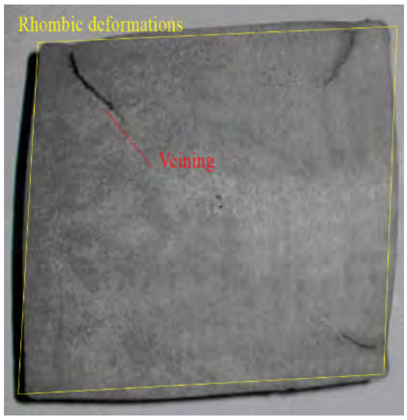

Fig. 7 Example of veining and rhombic deformations

To avoid such defects, machine vision algorithms are used. The goal is to find the contour of the heated object or its cut view and to calculate the difference between perimeter, area, and the specified sample. Due to this needs, the better and more simple way to do it is to use the contour detection algorithm and a chain code idea of storing the data about the contour. Applying of these methods on billet top surface is illustrated in Figure 8.

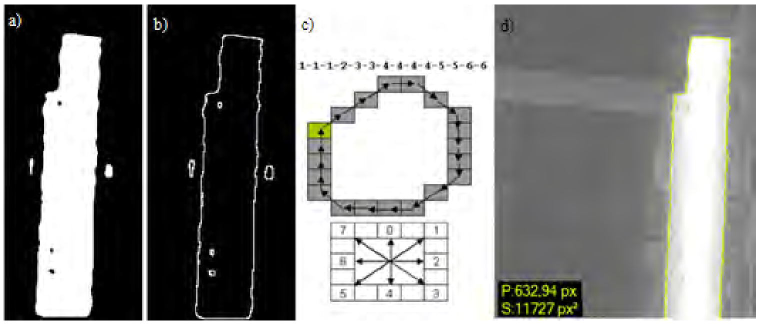

Fig. 8 Contour detection algorithm and chain code

On picture a), the thermogram is subjected by binarization, which is simple conversion of gray-shaded picture to bicolor one, separated by some threshold.

On picture b), the result of the contour detection algorithm is shown. It finds the pointes, where one color changes to another, and than store this points, using chain code. The Freeman chain code [4] is represented in picture c).

In figure d), the result, is shown. Small contours near of the sought-for one, was reduced by smoothing the initial picture. According to information, stored in chain code, perimeter and area can be easily evaluated. Therefore, it is easy to detect any deviation from the shape of the object. However, it is important to consider parameters, evaluated by expressions 3 and 4 to count the accuracy for any specific configuration.

3 SYSTEM REALIZATION

In this section, we consider an example of implementation of this technology developed in cooperation with “ASU Lab” Company for continuous steel casting process control.

3.1 SYSTEM STRUCTURE

Let us look on composition of the system more circumstantially. System can have a bunch of configurations due to specifics of concrete manufacturing. The multipurpose realization contains the Optris® PI camera, laser rangefinder (for system calibration), USB Server, IO-Box, Protection cover, operator station devices and PCS cabinet devices. The structure of the system is illustrated in Figure 9.

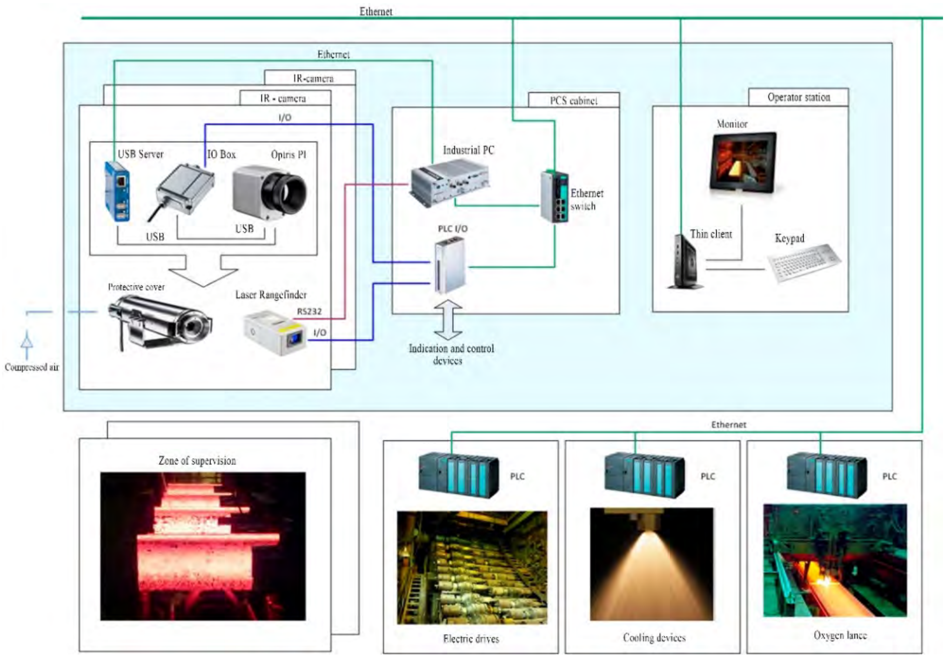

Fig. 9 The structure of the system

Laser rangefinder is needed for real time calibration of the distance between the camera and an object. It is only necessary in that configuration, where there is only one IR camera. Otherwise, the stereo camera effect can be used [5].

As mentioned, designed applications easily integrates in any process control system. It uses modern technologies and hardware of PI series. PI NetBox (IO-Box) is a miniature PC for the IR cameras. It upgrades it to stand-alone solutions or acts as USB to Ethernet adapter. This permits to implement longer distances between PI camera and the process monitoring system (PC).

3.2 RESULTS

Described system was designed for real manufacturing casting process, and shown itself as high available.

The Optris® PI 400 was chosen, so the temperature measuring lays between –20 °C and 900 °C, what is acceptable for specific manufacturing.

For speed measuring the three-sample algorithm was implemented. It provides accuracy for current speed value better than 1.0% in the speed range from 0.5 up to 1.5 meters per minute.

Slab length measuring with three-sample distance-measuring algorithm implementation has provided accuracy better than 0.1%. This result goes ahead with [3].

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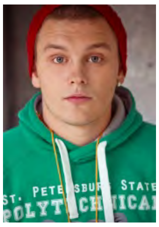

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