Article

Online Monitoring of Torpedo Car Shells Based on Equal Angle Scanning

Yumei Tang * and Kefu Liu

School of Information Science and Technology, Fudan University, No. 220 Handan Road, Shanghai 200433, China; kfliu@fudan.edu.cn

* Correspondence: 19110720076@fudan.edu.cn

Abstract: Infrared sensors are being applied more and more widely in industrial production applications. Based on the theory of thermal radiation, this paper discusses the system design principle, temperature calibration method, and thermal image analysis method in detail. The system passed the measurement unit certification, showing that the field of view is 180°, the number of scanning points is 2048, the linear velocity is 10–100 Hz, the spatial resolution is 2.5 mrad, and the precision is ± 1 °C. An online monitoring test of torpedo car was carried out in the steelmaking plant of Bao Steel. The results show that the system has strong anti-interference ability, stability, and reliability, and meets the application requirements of online monitoring.

Keywords: infrared sensors; calibration model; online monitoring; torpedo car

Citation: Tang, Y.; Liu, K. Online Monitoring of Torpedo Car Shells Based on Equal Angle Scanning. *Appl. Sci.* **2021**, *11*, 8053. <https://doi.org/10.3390/app11178053>

Academic Editor: Carosena Meola

Received: 17 July 2021

Accepted: 25 August 2021

Published: 30 August 2021

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1. Introduction

The torpedo car is a very important large-scale molten iron transportation equipment in the steel industry. It is a torpedo-type molten iron tank used in a large blast furnace. It is also called a mixed iron car. It has good insulation conditions, small heat loss, and insulation time. Furthermore, it is energy saving and enduring. Because of the large volume of the car, it can also store molten iron to coordinate the temporary imbalance of ironmaking and steelmaking. At the same time, it can replace the steel-making mixer and ordinary molten iron car to complete desulfurization, dephosphorization, and other operations during the transportation of molten iron [1,2].

The lining may crack, bulge, and spall due to chemical erosion, mechanical erosion, and rapid cooling and heating. Due to its high cost of maintenance, repair, and replacement, continuous monitoring and temperature detection are required to assess the lining of the torpedo car. When the refractory material is locally damaged severely but not found, it will cause a serious accident [3,4].

Infrared thermography (IRT) is a science dedicated to the acquisition and processing of thermal information from non-contact measurement devices [5]. It is an effective, fast, and noncontact measurement technology that is especially suitable for measuring the temperature of moving objects [6–8]. To our knowledge, the traditional measurement method is commonly used in the steel industry; that is, the relevant staff carry portable infrared instruments to detect the quantity of torpedo cars on the transportation railway [9]. Not only is this method labor intensive, but also the measurement results are not stable, especially in hot or rainy and snowy weather. In order to improve the efficiency of monitoring and measurement stability, and effectively reduce the labor intensity of related operators, online infrared sensors are wanted for scanning and imaging [10,11].

In this work, based on equal angle scanning, a 3–5 μm infrared scanner is designed. A temperature calibration model is proposed and the panoramic thermal image of the torpedo car is obtained. Furthermore, an online monitoring analysis system for the temperature field of the torpedo car is developed. The inner lining thickness is simulated by thermal

map, and the temperature map is drawn according to the body shell size. Finally, the safety alarm and accurate positioning are realized.

2. Theory and Method

2.1. Infrared Radiation Theory

According to Planck's law of black body radiation [12], as long as the temperature of any object in nature is higher than absolute zero ($-273.15\text{ }^{\circ}\text{C}$), it will emit energy in the form of electromagnetic radiation in a very wide range of wavelengths, generating electromagnetic waves (radiation energy). Different materials, different temperatures, different surface brightness, different colors, etc., emit different infrared radiation intensity. Planck's radiation law gives the specific spectral distribution of blackbody radiation. At a certain temperature, the energy radiated by a blackbody per unit area in unit time, unit solid angle, and unit wavelength interval is:

$$B(\lambda, T) = \frac{2hc^2}{\lambda^5} \cdot \frac{1}{\exp\left(\frac{hc}{\lambda kT}\right) - 1} \quad (1)$$

$B(\lambda, T)$ —Blackbody's spectral radiance ($\text{W} \cdot \text{m}^{-2} \cdot \text{sr}^{-1} \cdot \mu\text{m}^{-1}$)

c —Speed of light ($2.998 \times 10^8 \text{ m} \cdot \text{s}^{-1}$)

T —Absolute temperature of blackbody (K , $T = t + 273$)

h —Planck constant ($6.626 \times 10^{-34} \text{ J} \cdot \text{s}$)

k —Boltzmann constant ($1.380 \times 10^{-23} \text{ J} \cdot \text{K}^{-1}$)

At a certain temperature, the spectral radiance of a black body has an extreme value, and the position of this extreme value is related to the temperature. This is the Wien displacement law (Wien) [13]:

$$\lambda_m \times T = 2898 (\mu\text{m} \cdot \text{K}) \quad (2)$$

λ_m —Wavelength at maximum blackbody spectral radiance

T —Absolute temperature of blackbody (K , $T = t + 273$)

The normal temperature range of the shell of the torpedo car is $100\text{--}500\text{ }^{\circ}\text{C}$, so we choose a medium-wave infrared detector ($3\text{--}5\text{ }\mu\text{m}$), probing to achieve the maximum signal-to-noise ratio.

According to Planck's Formula (1), we put forward the voltage response model of the infrared detector (3):

$$U = \frac{A}{\exp\left(\frac{B}{t+273.2}\right) - 1} - C \quad (3)$$

Here, t is the target radiation temperature, U is the voltage signal output by the detector, and A , B , C are the correlation coefficients.

2.2. System Design

As is shown in Figure 1, we design a high-speed line scan infrared temperature measurement system, which uses synchronous motor scanning and real-time image processing to realize the reconstruction and visualization of the two-dimensional temperature field of the moving target. It is composed of a refrigerated infrared temperature measurement module and a DC brushless motor synchronous scanning module, high-speed signal acquisition and processing module, computer real-time image splicing, and other technical components. The infrared sensor mainly receives the radiant energy emitted by the measured object, focuses it on the detector through the receiving lens, completes the conversion of the optical signal to the electrical signal, and then obtains the voltage value by low noise amplifier, filtering, and analog-to-digital conversion.

Figure 3. (a) Infrared scanner, (b) FPGA-based digital signal processing with inner blackbody compensation.

2.3. Temperature Calibration

As shown in Table 2, we use a standard black body (M315-HT, LumaSense, Tempe, AZ, USA) to calibrate the measurement data of the infrared sensor, and obtain the relationship data between the black body temperature t and the output voltage U of the infrared sensor.

Table 2. Calibration data set by blackbody.

T (°C)	U (V)
80	0.04
95	0.05
100	0.06
130	0.12
150	0.18
200	0.42
230	0.65
250	0.85
260	0.95
270	1.2
280	1.3
290	1.4
300	1.55
310	1.7
320	1.9
330	2.1
340	2.3
350	2.5
380	3.25
400	3.8
450	5.45

According to Formula (3), we can obtain the temperature inversion Formula (5) of the temperature measurement system:

$$t = \frac{B}{\log\left(\frac{A}{U+C} + 1\right)} - 273.2 \quad (5)$$

As is shown in Figure 4, we use the Matlab R2016a curve fitting tool to perform curve fitting on Formula (3), and obtain the correlation coefficients: $A = 631.2$, $B = 3444$, and $C = 0.002758$.

Figure 4. Curve fitting of temperature voltage response model.

The ADC(AD7321, ADI) input range is ± 5 V, the full-scale range is 10 V with 8192 codes, and the LSB size is 1.22 mV.

Here, we define $K(t)$ as $dt/dU = K(t)$. Temperature of resolution is $\Delta T = K(t) * \text{LSB}$. Table 3 is the temperature resolution in different ranges.

Table 3. Temperature resolution in different temperature ranges.

$t/^{\circ}\text{C}$	U/V	dt/dU	Resolution/ $^{\circ}\text{C}$
100	0.06	646.02	0.8
200	0.42	152.38	0.2
300	1.55	61.25	0.07
400	3.8	34.37	0.04

3. Experiments

As is shown in Figure 5, the main equipment at the monitoring site includes two scanners (in the red dashed line ellipse in Figure 5); four RFID antennas (in the yellow dashed line circle in Figure 3); and RFID tags installed on the torpedo car (each torpedo car is equipped with four RFID tags, two tags both on the front and back sides). The system collects, calculates, and transmits temperature data on the shell surface, and transmits it to the central control room through an optical fiber network. The software adopts the B/S(Browser/Server) architecture. The main equipment in the central control room is the temperature data server and the large-screen display platform in the console. The large-screen display platform is used for real-time display, and the temperature data server can be used for offline data analysis.

Figure 5. Online monitoring application.

4. Results and Discussion

4.1. Real Time Analysis of Heat Map

As is shown in Figure 6a, the length of the torpedo car is 14.5 m, the speed of the torpedo car with two tanks is about 8 km/h (normally 6–10 km/h), and scanning time is about 6.6 s. As is shown in Figure 6b, if the line speed is 20 ms, the image resolution is no less than 330 line. If the line speed is set as 10 ms, the image resolution is no less than 660 line.

(a)

(b)

Figure 6. (a) Mechanical diagram of 320 t torpedo car, (b) thermal imaging.

As is shown in Figure 7, we use the pseudo-color to describe the surface temperature field distribution on the two sides of the torpedo car. By comparing the temperature corresponding to the color scale on the left, the temperature and relative height of each surface position can be visually distinguished from the figure. Through the temperature information fed back from the graph, it is analyzed and inferred whether the torpedo tank body lining is damaged, whether there is sediment at the bottom, etc., as well as the specific geometric dimensions and precise physical location on the surface of the torpedo car when the above situation occurs. Based on the heat transfer model and boundary conditions [14], we perform linear mapping, which can simulate the radial temperature distribution of the car shell, providing a basis for the design of refractory linings and the establishment of accurate heat transfer models.

Figure 7. Thermal imaging and axial temperature profile.

4.2. Statistical Analysis of Heat Map

As is shown in Figure 8, image reconstruction and unit segmentation (20×10 elements) are performed based on the axial temperature data and the physical model of the shell.

Figure 8. Image reconstruction of torpedo car.

Each unit is preset to a limit value of $350\text{ }^{\circ}\text{C}$. Whenever a temperature value higher than this preset value is read, the system outputs the high-temperature alarm status, and displays the temperature value table of each unit on the monitor screen, and informs the operator of a “high temperature” alarm by voice.

5. Conclusions

Based on the theory of thermal radiation, this paper discusses the system design principle, temperature calibration method, and thermal image analysis method in detail. The system has passed the measurement unit certification, showing that the field of view is 180°, the number of scanning points is 2048, the linear velocity is 10–100 Hz, the spatial resolution is 2.5 mrad, and the precision is ± 1 °C.

The temperature of the torpedo car shell is 100–500 degrees Celsius. Low-cost area array thermal imaging cameras mainly use uncooled long-wave infrared technology (8–14 microns). There are phenomena such as large temperature measurement errors in high-temperature sections, inaccurate data, and poor environmental adaptability [15,16]. According to Wien's law, to accurately measure the temperature, the mid-wave infrared imaging technology can obtain the best performance.

The cooling medium-wave infrared scanning temperature measurement system can cool the detector thermoelectricity and compensate for the temperature, which can output data steadily day and night; the unique large field of view (0–180 degrees) is especially suitable for online detection of moving objects. In order to adapt to rain, snow, fog, and other weather, the installation distance should not be too far. In addition, it can simulate the lining thickness and locate the fault accurately, to assist in the analysis and infer the damage trend of the inner lining, and then help determine when the torpedo car is repaired, which not only greatly reduces the manpower and material costs, but also reduces the number of spare torpedo cars.

Author Contributions: Conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing—original draft preparation, Y.T.; writing—review and editing, visualization, supervision, project administration, K.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Hefei GoodTech, Co., Ltd.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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