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Video Telemetric Control of Industrial Products

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Abstract. The principles of creating a system of contactless measurement of the physical quantities and parameters characterizing impact of external factors on industrial products are considered. Introduced are the concepts and definitions concerning remote contactless measurement of parameters. The article describes a variant of the system with a temperature measurement unit, a contactless method of temperature measurement by means of video cameras based on pyrometric methods and the theory of thermal radiation taking into account the integral coefficient of thermal radiation of a gray body. The temperature dependences of the integral coefficient of thermal radiation for some metals are given. After processing video information by the spectral method, the calculation of the integral value of temperature in the controlled zones under examination by a color spectrum or brightness is carried out. Provided is the analysis of the existing algorithms of compression of video information. Application requirements and the principles of creating a system with a wide-range temperature measurement unit and its distinctive features are formulated.

Keywords: video telemetry, thermo-video telemetry, telemetry, power-loaded areas, temperature, external influencing factors, measurement, video image

Definitions and concepts

Telemetry (telemeasurement) — a set of technologies for carrying out remote contactless measurements and collecting information to be later passed on to the operator or users; a constituent part of telemechanics. The term comes from the Greek roots *tele* — "remote" and *metron* —"measurement". Even though the term, in most cases, is used in reference to methods of remote data transmission (for example, via radio or infrared radiation), it also characterizes the process of transmitting data with the help of other means of mass communication, such as telephone and computer networks, fiber-optic or other wired communications [1].

Either telemetry sensors with a special embedded communication module or a remote terminal unit (telemetry system) to which ordinary sensors are connected are generally used for gathering information. Yet, for industrial products there are areas or objects the average temperature in standard operating mode of which exceeds 1200-1500 K, as well as areas with increased radiation, humidity and mechanical loading. Such areas are referred to as "power-loaded areas".

Power-loaded areas in industrial products – areas (determined by an a priori estimate) with a heightened probability of damage (product component failure) caused by radiation and/or thermal radiation.

A contact method of temperature measurement by using temperature sensors is not applicable due to the substantial radiation and thermal radiation emissions and to the impact of mechanical overloads (large energy release in an enclosed space as a whole). The aforementioned power-loaded areas are prone to contingencies and emergencies.

For this reason, a remote contactless method using video cameras for measuring the impact of external factors on industrial products – video telemetry– is proposed.

Video telemetry – a remote contactless method of measuring parameter values (levels of external factor impact on industrial products) with the help of video cameras that consists in converging video images into measurement signals with the subsequent imaging of value information for the parameters of interest.

Design concept of video telemetry systems

Let us consider the video telemetry system functional diagram. Parameters subject to telemetry are measured by processing video images of the object and by measuring the physical quantities that characterize the impact of external factors on industrial products. Figure 1 gives the generalized functional diagram of the video telemetry system inclusive of measurement and display equipment.

The video image in the form of electric signals or digital stream (video stream) from video cameras is sent to the video information processing unit where parameters being telemetered are calculated (only variant (a)); further processing and compression of information as well as preparation for targeted information transmission (in this case, video stream) through a radio link is carried out. The signal is transmitted through the link to the receiver station and afterwards – to the video information display equipment, where physical quantities that characterize factors affecting industrial products (only variant (b)) are also calculated.

The received information flow is demodulated and processed in the video information reception unit. Processed information is transferred to the parameter calculation and display unit with a polling rate of approximately 1…3 fps.

The video control system design is suggested to be as shown in Figure 1. The component functions are set forth in Table 1.

Video telemetry system for temperature measurement

Temperature is the principal external influencing factor that affects the parameters of the constructional material. **Temperature** is a scalar physical quantity that approximately characterizes the average kinetic energy of particles of a macroscopic system in the state of thermodynamic equilibrium per one degree of freedom [2].

Thermo-video telemetry – a method of measuring the temperature of industrial products with the help of video cameras and subsequent information processing.

The essence of the method is in obtaining information about temperature and its distribution over the surface of the object in question from video cameras equipped with photorecorders, which are used to convert the video image into a digital signal [3]. After video information is processed (in the range from infrared to ultraviolet

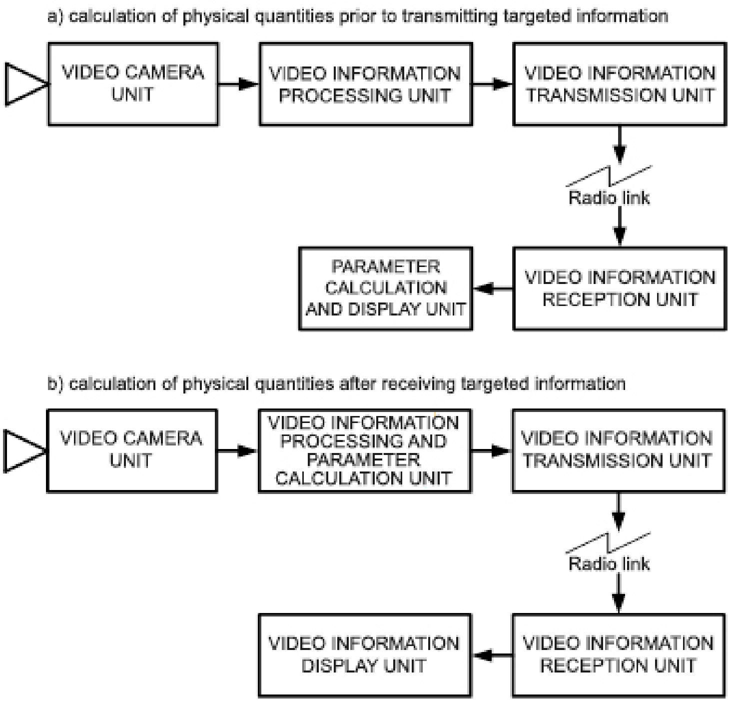

Fig. 1. Generalized functional diagram of a video telemetry system

radiation), pyrometric methods are implemented to calculate the integral value of temperature[1] in the controlled zones under examination by a color spectrum [4] or brightness[2] — a method based on Planck's law and the principles of spectral and brightness pyrometry [5 - 7].

In accordance with (6.10) with account for (6.11), we shall graph ε(T) for the most common types of metals (Figure 2), prior to this we shall tabulate coefficients a and ρ_0 (Table 2) [5].

Thus, adequate surface temperature measurement using pyrometers is conditioned by the correct choice of a temperature measurement range and spectral range in which it is possible to measure the temperature of this type of objects. The emissive ability of every material in accordance with (6.10) depends on the temperature and concurrently, taking (1.3) into account, it can change for the same material in different areas of the spectrum [9].

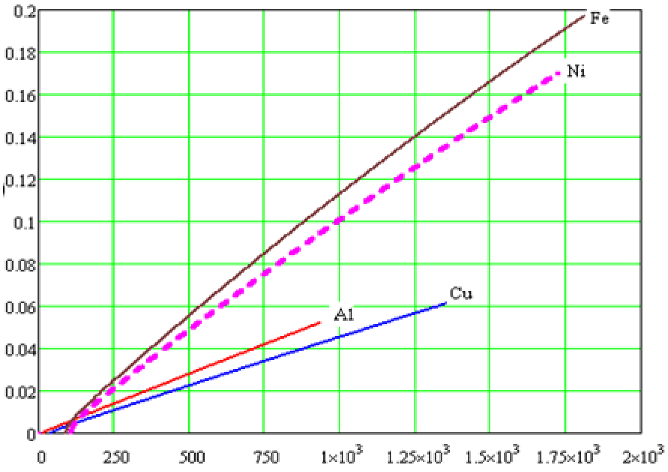

Fig. 2. ε(T) graphs for different types of metals

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[1] When calculating temperature parameters, it is necessary to take into account the full radiation power of a black body at temperature *T* (**radiation temperature** T_r **of a body** – the temperature of an absolutely black body at which its radiant exitance *R* is equal to the radiant exitance R_m of the given body in a wide range of wavelengths) over the whole range from $\lambda = 0$ to $\lambda = \infty$, determined by the Stefan–Boltzmann law [8]:

$$R_0(T)=\sigma_0 T^4 \tag{1.1}$$

where $\sigma_0 = 5.6696 \times 10^{-8}\ \frac{W}{m^2K^4}$ is a given constant.

Seeing that the physical law expressed by equation (1.1) concerns measuring the temperature of an absolutely black body, the measured energy of a real gray body is determined by equation (1.1) with an accuracy of ε, known as the **integral (or full) coefficient of thermal radiation**:

$$\varepsilon = \frac{R_0(T)}{\sigma_0 T_a^4} \tag{1.2}$$

This quantity is the ratio of the radiation energy emitted by the material at temperature T to the radiation energy emitted by a black body at the same temperature T, whence it follows that:

$$T_a = {}^{T}\!/\!_{\sqrt[4]{\varepsilon}} \tag{1.3}$$

[2] **Brightness temperature** T_b **of a body** – the temperature of an absolutely black body at which its spectral exitance f(λ,T) for a particular wavelength is equal to the spectral exitance r(λ,T) of the given body for the same wavelength.

Table 1. Functionality of video telemetry system components

Component	Functions
Video camera unit	- video shooting of observed object, - conversion of video image to electric signal, - conversion of video signal to digital stream,* - information stream compression* - video stream transmission through a unified interface.*
Video information processing unit	- video stream reception through a unified interface,** - temporary video stream storage, - software-based physical quantity calculation using already developed methodologies in accordance with calibration results,*** - application of anti-jamming coding to information stream (encoding), - acquisition of telemetry information regarding the functional state (system constituent performance capability), - preparation for transmission of targeted data via radio link.
Video information transmission unit	- targeted information stream modulation, - amplification of modulated information stream, - transfer of information stream to the required frequency range, - information transmission through a high-frequency link to antenna-feeder device.
Video information reception unit	- target information reception via a radio link, - information stream demodulation.
Parameter calculation and display unit	- target information decoding, - acquisition of raw data (video images or information about physical quantities),**** - numeric representation of the measured parameters using required units of measurement (e.g., SI system), - visual or graphical display of measured parameters.
* - function realization is possible in the video information processing unit ** - in the event of video signal digitization in the video camera unit *** - function realization is allowed in the parameter calculation and display unit **** - reverse operation of preparation for targeted data transmission via radio link	

Table 2. Thermal properties of some metals

Metal	Resistivity of metal at 20°C (ρ_0, ohm-cm)	Coefficient of thermal variation of resistivity ($\boldsymbol{\alpha}$)	Melting temperature, (K)
Aluminum	2.82×10^{-6}	3.6×10^{-3}	933
Copper	1.72×10^{-6}	4.0×10^{-3}	1356
Iron	9.80×10^{-6}	5.0×10^{-3}	1808
Nickel	7.24×10^{-6}	5.4×10^{-3}	1726

For defining the gray body temperature it is sufficient to measure the power Y(λ,T) emitted by the unit surface area of the body in a fairly narrow spectral interval (proportional r(λ,T)) for two different waves [5]. The ratio of Y(λ,T) for two wavelengths is equal to the ratio of the dependences f(λ,T) for these waves, expressed by the ratio:

$$\frac{Y(\lambda_1,T)}{Y(\lambda_2,T)} = \frac{r(\lambda_1,T)}{r(\lambda_2,T)} = \frac{f(\lambda_1,T)}{f(\lambda_2,T)} \quad (1)$$

The temperature T can be derived mathematically from the given equality. The temperature thus obtained is referred to as “color temperature”. The color temperature of a body, determined by formula (1), will be equal to the actual temperature, assuming that the monochromatic absorption coefficient does not strongly depend on the wavelength. Otherwise, the concept of color temperature loses its meaning. According to [2, 4], “the color temperature of a gray body coincides with the actual temperature, and can also be calculated from Wien›s displacement law”.

The more widely used pyrometers for controlling industrial product surface temperatures work in the spectral sensitivity range of 7 to 14 (up to 18) μm. Nonetheless, pyrometers are mostly based on the principle of measuring total radiation [10].

The estimation accuracy of the measured object surface temperature with the application of total-radiation pyrometers depends on the correct definition of ε.

In this case, temperature measurement in controlled areas is carried according to color spectrum[3] [4] or brightness, based on Planck's law and the principles of spectral and brightness pyrometry.

Thermo-video systems based on the pyrometric method[4] of temperature measurement are applicable for object thermal control. With their help, it is possible to control deterioration of thermal protection and mechanical damage to the structure.

Hot bodies with temperatures exceeding 250–300°C are of particular interest within the framework of the present paper. Temperature values [4, 11] given in Table 3 call for special attention from the operator during temperature monitoring after video information processing because breakage of various materials occurs in the vicinity of the given temperatures.

With the purpose of expanding the temperature range for temperature monitoring in the chosen image field, cameras should be installed in twos pointing at one field-of-view in a protective heat-insulated enclosure [12]. One camera will be equipped with a virtual phase charge-coupled device and the other – with an infrared charge-coupled device. Both cameras should be set to the same field-of-view and should simultaneously send the received information streams to the information display equipment. Since photorecorders have differing resolutions, equal fields-of-view for two cameras can be provided by installing lenses with different pupil diameters of objective lenses and different focal lengths.

Considering the use of a wide spectral band, the video camera should be equipped with special lenses and photorecorder devices for data reception in the infrared, visible and ultraviolet bands. Such lenses are: a "sapphire window" (for the wide range 0.2 -6.0 μm), quartz glass (for near ultraviolet band, visible and near infrared bands 0.2-2.2 μm), optical silicon (for near and middle infrared band 1.2-6.0 μm), germanium (for middle infrared band 1.2-15.0 μm) [10]. As for photo recorders, for the 0.2-1.0 μm band virtual phase charge-coupled devices should be used; for the 1.2-5.3 μm band – infrared charge-coupled devices with thermoelectric coolers (Peltier) [15], for the 8-14 μm band – microbolometer modules [10].

Table 3. Melting and deformation temperatures of some types of metals

Material	Melting point, K	Temperature of irreversible changes in the crystal lattice, K
Aluminum	933	723
Titanium	1933±20	1156
Iron	1812	1042
Tungsten	3695	1473
Steel (mean values)	1720…1795	1258
Nickel	1726	956

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[3] According to [4], **spectral exitance r(l,**T)=dW/dl is the amount of energy emitted by the body's surface unit per unit of time at one unit wavelength (near the wavelength of interest l). In other words, the quantity is numerically equal to the ratio of energy dW emitted by a surface unit per unit of time in a narrow wavelength interval from l to l+dl, to the width of the interval. It depends on the body temperature, wavelength, as well as on the nature and state of the surface of the emitting body. The SI system r(l, T) base unit is [W/m^3].

Radiant exitance R(T) is related to the spectral exitance r(l, T) the following way:

$$R(T) = \int_0^\infty r(\lambda, T)\, d\lambda, \text{ [W/m}^2\text{]}, \tag{3.4}$$

According to [5], **the color temperature T_c of a body** is the temperature of an absolutely black body at which the relative distributions of spectral exitance of a black body and of the body in question are as close as possible in the visible region of the spectrum.

The color temperature is the radiation temperature of separate chemical elements; it is displayed on the spectrograph in the form of individual spectral lines emitting at a particular frequency (wavelength).

The method of spectral (color) pyrometry is based on the Planck distribution in the wavelength range, namely [3]:

$$Y = \frac{2\pi hc^2}{\lambda^5} * \frac{1}{e^{\frac{hc}{kT\lambda}}-1} * \varepsilon_\lambda, \tag{3.5}$$

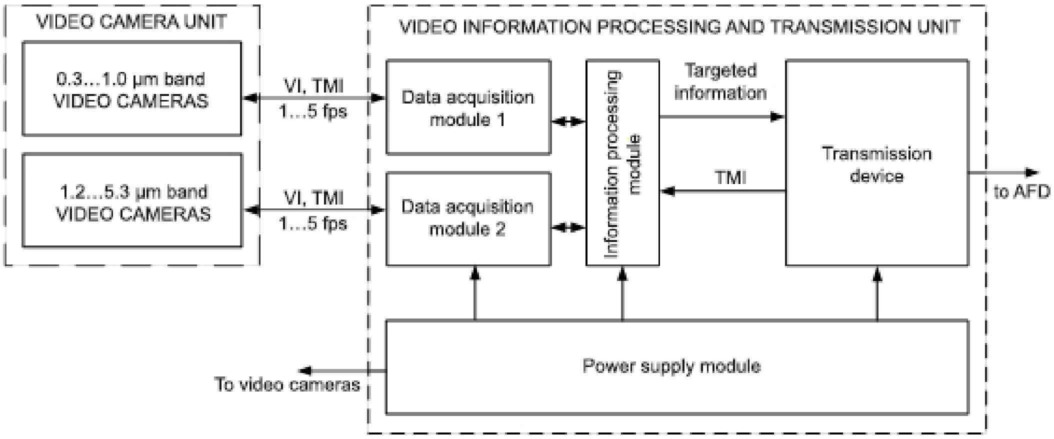
where $k = 1.8\times10^{-23}$ J/K is Boltzmann's constant, $h = 6.63\times10^{-34}$ Js is Planck's constant, $c = 3\times10^8$ m/s is the speed of light, T is temperature (K), λ is wavelength (m), ε_λ is the integral coefficient of thermal radiation.

[4] The spectral pyrometer is calibrated against the radiation of an absolutely black body (on the same wavelength) in degrees of brightness temperature T_{ij}, related to the thermodynamic scale by the ratio [13].

$$\frac{1}{T_{aij}} - \frac{1}{T_{ij}} = \frac{\lambda_{ij}}{1.438} \ln \varepsilon_{\lambda ij}, \tag{4.6}$$

where T_{a_ij} is the actual (calibrated) average temperature in the controlled zone of the image field,

$$T_{a\_ij} = \frac{1.438 T_{ij}}{1.438 + \lambda_{ij} T_{ij} \ln \varepsilon_{\lambda ij}} \tag{4.7}$$



AFD – antenna-feeder device
VI – video information
TMI - Telemetry information on the status of TVTS devices

Fig.3. Temperature measuring video telemetry system functional diagram

For measuring temperatures of power-loaded areas of industrial products the 500…3000 K [4, 9] temperature range should be chosen. However, in areas with high radiation under the influence of ionizing flux, the spectral components of the thermal radiation of materials can radiate both in the visible and, even, in the ultraviolet region. Various materials (for example, metals), depending on the chemical properties and atom structure, have their own radiation spectrum and it can be located in different parts of the bands in question. In addition to this, as the temperature rises the spectral density of radiation shifts from the infrared band towards the ultraviolet band. For this reason, to ensure higher accuracy and thermal control efficiency, the maximum measured temperature should be increased up to 9500 K and, in doing that, the 0.3–5.3 µm band will be used.

Figure 3 depicts a functional diagram of the transmitting part of the temperature measuring telemetry system. It includes two types of video cameras that differ in spectral bands, photorecorder resolution and lens materials. Data acquisition modules receive information streams (or video signals), carry out their digitalization (if needed) and provide temporary video information storage.

Before transmitting information through a wireless channel, it is necessary to ensure anti-jamming coding and compression that are carried out by the video information processing module. Figure 4 gives an overview of the video information compression algorithms [7, 14].

Moving on to the receiving part of the video telemetry system for temperature measurement — the functional diagram of the temperature measurement unit is given in Figure 4. Video information in the information display equipment is sent to a packet decoding device with a frequency of 1...3 fps and in output we receive the brightness value. The image field in question is divided into zones. The total amount of dots in an image field defined by the resolution of the photorecorder is divided into zones with an area ranging between 5×5 pixels and 20×20 pixels. The choice of the required zone for temperature monitoring is made either by the operator or in automatic mode upon introduction of a threshold temperature when programming the processor of the video telemetry system. The information about the brightness or chromaticity of the object (usually gray)[5]

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[5] All bodies in nature partially reflect the radiation falling on their surface; therefore, they do not belong to absolutely black bodies.

If the monochromatic absorption coefficient of a body is the same for all wavelengths and is less than one ($\alpha(\lambda,T) = \alpha T = \text{const} < 1$), then such a body is referred to as gray. According to [4], "to determine the absorption capacity of bodies relative to electromagnetic waves of a certain wavelength the concept of the monochromatic absorption coefficient is introduced – the ratio of the monochromatic wave energy absorbed by the body surface to the energy magnitude of the incident monochromatic wave:

$$\alpha(\lambda,T) = \frac{W_{abs}(\lambda,T)}{W_{inc}(\lambda,T)} \qquad (5.8)$$

The quantity $\alpha(\lambda,T)$ can take on values from 0 to1. Kirchhoff demonstrated that for all bodies, regardless of their nature, the ratio of spectral exitance to the monochromatic absorption coefficient is the same universal function of wavelength and temperature $f(\lambda,T)$ as the spectral exitance of an absolutely black body:

$$\frac{r(\lambda,T)}{\alpha(\lambda,T)} = f(\lambda,T) \qquad (5.9)$$

Table 4. Comparative analysis of video information compression algorithms

Parameter	MPEG-2	JPEG2000	H.264
Transform	Discreet cosine transform	Discreet wavelet transform	Hadamard transform and integral discreet cosine transform
Video processing	Intraframe statistical, interframe encoding and the use of the motion vector for prediction	Intraframe statistical	Intraframe statistical, interframe encoding and the use of the motion vector for prediction
Recommended field of application	Video image encoding	Static image encoding	Dynamic image of rectangular format encoding
Possibility of lossless compression	Yes	Yes	Yes
Typical compression ratio range	15-50	20-150	40-200
Compression ratio with noticeable resolution loss	Higher than 1:50	Higher than 1:150	Higher than 1:200
Computational complexity	Medium	Medium	High
Disadvantages	Low compression efficiency	Irreversible information loss at high compression ratios	Complex algorithms, resource-intensive encoding and decoding

in the given zone and the results of its comparison with the radiation energy matrix in the decision making device, with account of wavelength, the value of brightness (spectral temperature) in the zone in question, is calculated [3].

The thermodynamic temperature of the controlled area of the measured object image field is determined by comparing the received values with the data of spectral pyrometry calibration ratios [11].

Conclusion

Thus, a thermo-video telemetry system (TVTS) is a system of video telemetry for contactless temperature (radiation of physical bodies[6] – objects) measurement in a wide temperature range via optical method application by the integral coefficient of radiation[7] of power-loaded industrial products.

The distinctive features of the observed object thermo-video telemetry are the following:

- contactless temperature measurement
- wide range of measured temperature for object points
- video rendering of temperature distribution across observed object surface
- a visual representation of the temperature dynamics of the object surface as a whole
- prompt detection of anomalous temperature zones.

Temperature measuring video telemetry systems will allow for a substantial decrease in the quantity of temperature sensors and cables with a simultaneous increase in the quantity and improvement in the quality of the information received about the temperature of

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[6] The integral coefficient of radiation is temperature-dependent. In the case of dielectric materials ε(T) it usually decreases with the increase of temperature. This has to do with the fact that the refractive index of materials increases with the temperature. Yet, the electrical conductivity of metals decreases as the temperature rises due to the thermal excitation of the molecular lattice, which causes the increase of ε(T). It should be noted that ε does not change for water and is approximately equal to 1 (one), for graphite ε ≈ 0.95…0.98. The approximate expression is known for the temperature-dependent integral coefficient of radiation for metals [5]:

$$\varepsilon(\mathrm{T}) \approx 0.5737\sqrt{\rho(T)\mathrm{T}} - 0.769\rho(T)\mathrm{T} \qquad (6.10)$$

$$\rho(T) = \rho_0(1 + \alpha(T - 293)) \qquad (6.11)$$

where ρ(T) is the temperature-dependent resistivity of the metal, ρ_0 – resistivity of the metal at 20°C (293 K), α – coefficient of thermal variation of resistivity.

[7] The spectral pyrometer is calibrated against the radiation of an absolutely black body (on the same wavelength) in degrees of brightness temperature T_{ij}, related to the thermodynamic scale by the ratio [4]

$$\frac{1}{T_{aij}} - \frac{1}{T_{ij}} = \frac{\lambda_{ij}}{1.438} \ln \varepsilon_{\lambda ij} \qquad (7.12)$$

where T_{a_ij} is the actual (calibrated) average temperature in the controlled zone of the image field,

$$T_{a\_ij} = \frac{1.438 T_{ij}}{1.438 + \lambda_{ij} T_{ij} \ln \varepsilon_{\lambda ij}} \qquad (7.13)$$

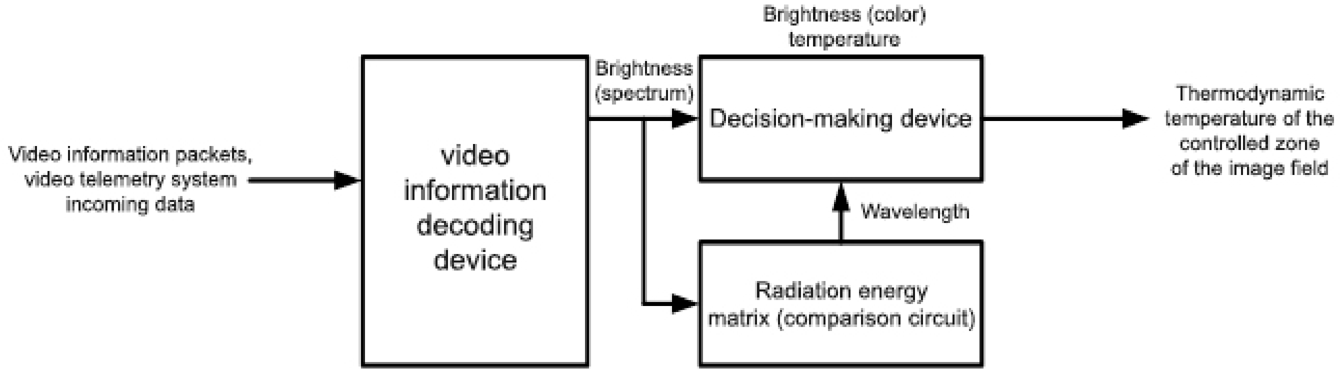

Fig. 4. Functional diagram of temperature measuring unit

power-loaded elements of the object or product by carrying out both point and zone monitoring to track temperature parameters.

The implementation of thermo-video telemetry will permit to increase the controlled area of the surface of the controlled object of the industrial product and, at the same time, it will widen the range of the measured temperature and reduce the temperature information flow. Thermo-video telemetry will promptly analyze standard, contingency and emergency situations by monitoring anomalous temperature zones in power-loaded areas via video images of the surface of the observed object.

The paper proposes a method for measuring the temperature of observed object power-loaded areas with use of a thermo-video system along with:

– introducing definitions concerning video telemetry control of industrial products

– developing a generalized functional diagram of a video telemetry system

– developing a functional diagram of the transmitting segment of the temperature measuring video telemetry system

– formulating the requirements to the spectral range of the thermo-video telemetry system for measuring temperature in the power-loaded areas of industrial products

– developing a functional diagram of the temperature measurement unit of the video telemetry system

– carrying out a comparative analysis of the existing video information compression algorithms

– formulating the requirements to the implementation of a video telemetry system and its distinctive features.

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