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Trends in the Development of Video Telemetry Systems for Measuring the Temperature of Thermally Loaded Areas of Launch Vehicles

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Abstract. Nowadays the appearance of publications, scientific and research, and also research and development works on the creation of video monitoring systems for rocket and space technology products is caused by a well-known fact about the most reliable information channel – vision (human vision provides 95% of information on surrounding objects), hence the inclusion of video information in the control system significantly increases the reliability of information from existing telemetry facilities of objects to track their normal functioning, as well as for rapid and unambiguous identification of the causes of abnormal and emergency situations that occur during the flight of rocket and space technology products.

The article proposes a method for processing information from a video telemetry system about the temperature of thermally loaded elements of launch vehicles and upper stages by a remote contactless method with visual representation by converting a signal received from video cameras based on the principle of color pyrometers and Planck distribution. To implement the algorithm for processing video information for calculating the temperature, a block diagram of the solver is developed. A method for presenting video information and temperature measurements is presented provided that there is a color video image with a reduced frame rate and wide spectral range.

Keywords: video telemetry, thermo-video telemetry, temperature, pyrometric methods, launch vehicles, upper stages

General provisions

Nowadays there are many research and development works on visual control of technological processes that accompany the motion of launch vehicles (LV) (for example, separation of stages, fairing, payloads, etc.) [1]. It is worth noting that in the process of rocket operation it is subjected to the influence of external factors, which must be controlled by information-measuring systems. The main external influencing factor that affects the parameters of structural materials is temperature. At present, in practice, temperature sensors are used in combination with local temperature switches (LTS).

More recently, it has been proposed to measure physical quantities remotely in a non-contact manner by means of signals from video cameras. There are areas or objects in the rocket and space technology (RST) products where the average temperature in operation exceeds (1200–1500) K (e.g., areas of the outer shell of LV subjected to strong mechanical stresses).

For such areas the contact method of temperature measurement by means of temperature sensors is not applicable due to the significant release of energy in one form or another (thermal, kinetic, etc.). In this case, the designated objects are most susceptible to the emergence of abnormal and emergency situations. Consequently, there is a need for a system that controls by non-contact method the temperature of the problem area and the correctness of the technological processes of separation of components of a space object, opening of structures (solar panels, antennas), maneuvering of space objects on board of LV.

It is proposed to switch from video control to video measurements, in particular, of temperature, by building a thermo-video telemetry system [2, 3]. Thermal-video telemetry (TVT) will make it possible to provide operative analysis of abnormal situations due to tracking of abnormal temperature zones by the video image of the surface of the product in question obtained from LV and boosters (e.g., gas generators and rocket engine pumps, rocket engine areas subjected to high temperature).

Information on the thermal environment of the observed temperature-loaded object of LV needs processing and presentation in the form of temperature measurements and color images of the temperature field distribution, thus we propose a method of processing information on the temperature of the observed object based on the principle of color pyrometers.

Comparative analysis of video control systems for use in rocket and space technology products

A comparative analysis of video control systems produced by Rocket Cam Ecliptic Enterprises Corporation [4], OCAM-2 Kayser-Threde [5], IRZ JSC (BSVK [on-board video monitoring system]) [6], as well as the main characteristics of the autonomous video control system (ASVC) [autonomous video monitoring system] produced by Joint Stock Company “Russian Space Systems” (Table 1) were reviewed in the studies on the subject of video control systems for LV. As can be seen from the table, AVCS assumes higher resolution of the photorecording device as compared to analogues and application of dynamic algorithm of video information compression H.264 with reserving the reference frame for one or two steps.

All four systems have the same construction principle. They consist of video cameras, processing device, and transmitting device (see Fig. 1).

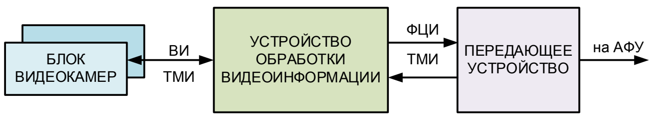

Fig. 1. Generalized functional diagram of video control.

As for temperature measurement systems by means of a signal received from video cameras (thermo-video telemetry systems), they have been used so far in the space industry both in our country and abroad. There are practically no publications on this topic, but nevertheless many experimental works are carried out and the theoretical base and measurement methods are regularly updated, since temperature is a key factor influencing the parameters of structural materials.

The main attention in the available sources (e.g., [7–14]) in the use of video facilities is paid to the protection of video cameras from radiation, in some cases video cameras are employed to identify at railway stations and airports passengers with elevated temperature, as well as to monitor the temperature in gas streams and pipelines. At the same time, video cameras have not been found to be used to measure temperatures in a wide range (e.g. from 300 to (5000...7000) K on thermally loaded components of industrial facilities or in particular on RST). In addition, the observation usually uses only the infrared and visible range of the emitted spectrum of heated bodies.

Table 1. Comparative analysis of existing video monitoring systems.

No.	Characteristic name	Characteristic value			
		Foreign production		Domestic production	
		RocketCam Ecliptic Enterprises Corporation (the USA) [4]	OCAM-2 Kayser-Threde (Germany) [5]	BSVK IRZ JSC[6]	ASVC JSC "RSS"
1	Number of connected video cameras	Up to 8	Up to 4	3	Up to 7
2	Photo-recording device resolution, pixels	768 × 494	720 × 576	From 320 × 240 to 2048 × 1536	From 720 × 576 to 1280 × 960
3	Frame rate, frame/sec	25	25	16	Up to 25
4	Video compression algorithm	JPEG MJPEG	JPEG 2000	JPEG MJPEG	MJPEG H.264
5	Buffer storage capacity	–	–	20 MB	4 GB
6	System weight, not more than, kg	4.5	12*	10**	6
* – weight including two transmitters and two video cameras; ** – weight including transmitter.					

Unsuccessful launches of LV in 2013–2016 (e.g., 02.06.2013, 16.05.2014, 16.05.2015 –Proton-M, 01.02.2013 – Zenit-3SL, 22.08.2014 – Soyuz-ST-B, 01.12. 2016 – Soyuz-U) show that the existing means of telemetry of the state of objects (for unambiguous operational conclusion on the causes of accidents) is not enough, thus the appearance of research work and development of methods for measuring the temperature of thermally loaded elements of RST by video telemetry are very relevant, and their results deserve the quickest introduction.

Thermo-video telemetry will provide a rapid analysis of abnormal situations by tracking abnormal temperature zones on the video image of the surface of the product in question obtained from the spacecraft and LV.

Hence, the reason for choosing this direction of research is the need for video monitoring of the most important processes accompanying the movement of spacecraft and LV including the control of thermal conditions of advanced rocket products.

Distinctive features of thermo-video telemetry are:

– non-contact temperature measurement;

– a wide range of temperature measurement of the object points;

– visual representation of the thermal environment of the object under observation;

– visual presentation of the object temperature dynamics as a whole;

– rapid detection of anomalous temperature zones.

Methodology for measuring the temperature of energy-stressed areas

The information about the thermal environment is supposed to be displayed on the screen of the PC monitor in the form of a color video image. For this purpose, temperature calculation by pyrometric methods should be based on the principles of spectral ratio pyrometers or color pyrometers, namely temperature determination by the ratio of radiation intensities in two wavelengths λ_1 and

λ_2 [7, 15]. The higher the sensitivity of the method, the wider the spectral range, i.e. the less λ_1 and the greater λ_2.

The algorithm for calculating temperature is based on the Planckian distribution in the wavelength range, namely [15].

$$Y = \frac{2\pi hc^2}{\lambda^5} * \frac{1}{e^{\frac{hc}{kT\lambda}}-1}. \quad (1)$$

Metals generally have a small emission coefficient in the infrared region, which usually increases with increasing metal temperature. The spectral emission coefficient ε_λ of a metal increases as its electrical conductivity decreases. The electrical conductivity of the metal decreases with increasing temperature due to thermal excitation of the molecular lattice, which causes the emission coefficient to increase [15].

We should express the ratio of intensities of the current image in the considered area and the "cold" image

$$\frac{Y_{cold}}{Y_{ij}} = \left(\frac{\lambda_{ij}}{\lambda_{cold}}\right)^5 * \frac{e^{\frac{hc}{kT_{ij}\lambda_{ij}}}-1}{e^{\frac{hc}{kT_{cold}\lambda_{cold}}}-1} \quad (2)$$

If $T_{cold} = T_{aver.}$ = 20 °C, we can find T_{ij} from (1):

$$T_{ij} = \frac{c_1}{\lambda_{ij}} \frac{1}{\ln\left[1+\frac{Y_{cold}}{Y_{ij}}\left(\frac{\lambda_{cold}}{\lambda_{ij}}\right)^5\left(e^{\frac{hc}{kT_{cold}\lambda_{cold}}}-1\right)\right]}. \quad (3)$$

To display video information in terms of tracking the thermal conditions of the object in the ground processing of information requires the use of an algorithm for wavelength conversion from the infrared and ultraviolet range to the visible wavelength range based on the Wien's displacement law:

$$b = T\lambda, \quad (4)$$

where b is the Wien's constant equal to 2896 μm × K.

Hence

$$T = b/\lambda. \quad (5)$$

Consequently, the longer the wave, the lower the temperature:

$$T, \text{K} = t, \text{°C} + 273. \quad (6)$$

The conversion of wavelengths into the visible spectrum is made according to the ratio [16]:

$$\lambda_{vr} = \frac{(\lambda-\lambda_{min})\Delta\lambda_{vr}}{\Delta\lambda_{width}} + \lambda_{min\_vr} \quad (7)$$

where λ is the current value of the wavelength, λ_{min} is the minimum value of the wavelength in the selected range, $\Delta\lambda_{vr}$ is the width of the visible range, $\Delta\lambda_{vr\_min}$ is the minimum value of the visible range, $\Delta\lambda_{width}$ is the width of the selected range.

The result is a video image, an example of which is shown in Fig. 2. Of most interest are the areas of the image field displayed during processing, colored dark purple or black circles bordered in dark purple.

Methodology for displaying thermal information

The operator's real-time video view is necessary to analyze the video image with the ability to determine the temperature in the area of interest of the object (spacecraft, LV).

The program interface should include the following components.

1. The option of selecting a viewing area with an appropriate designation. Location according to the view areas of thermally stressed elements of LV is set in the operational documentation (OD) for the "Video information display (VID) program for tracking the thermal environment of LV elements".

2. Option to select the spectral subrange. Spectral subranges are set according to Table 1; each of them corresponds to its temperature range.

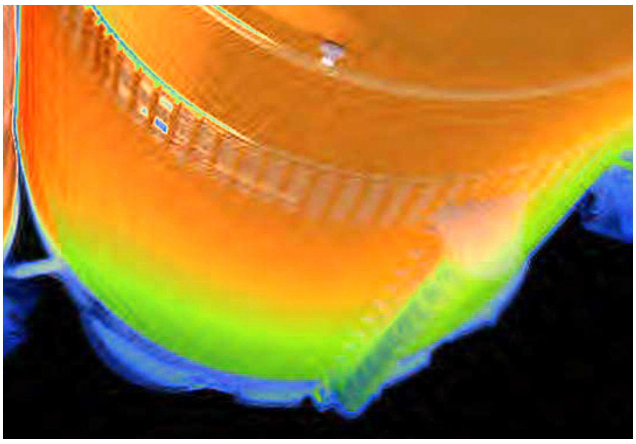

Fig. 2. The synthesized color image produced by a thermo-video telemetry system.

Such partitioning of subranges is performed with respect to wavelengths, reference values of ranges (near-ultraviolet, visible, etc.) [15, 16], as well as based on the analysis of existing photorecording devices and lenses [17, 18].

For rapid detection of thermally stressed zones of the object of observation during monitoring of temperature parameters it is proposed to use low resolution photographic recording devices (for example, 256 × 290, 352 × 288) mainly in the near and medium infrared range with a frequency of 1–3) frames per second [17].

The most attention is paid to heated bodies with temperatures above 250–300 °C (Table 1 shows the values of temperatures at which an irreversible change in the crystal lattice structure and melting temperatures occurs for the most commonly used materials in the design of RST products) [19]. At lower temperatures, a detailed analysis of the heated body surface (up to a point) is not required. It is enough to be limited to a small area of the image field. For a less detailed study of the thermal environment in the mid- and far-infrared region, it is sufficient to see the magenta-fringed black areas on the screen, in the IR2 tab (using charge-coupled infrared devices: IR CCD), to track the spectral temperature below 525 K at the maximum of the thermal flux [15]. It is also possible to track lower temperature values at the considered radiation wavelength, and the minimum possible temperature that can be tracked is also determined by the sensitivity of the CCD. CCD sensitivity, in turn, is determined by the level of CCD noise (mainly readout noise). The temperature values given in Table 2 require special attention when the operator monitors the thermal environment after ground processing of video information, since in the vicinity of these temperatures the destruction of some or other material takes place [20].

Table 2. Melting and strain temperatures of some types of metals

Material	Melting temperature, K	Temperature of irreversible change of crystal lattice, K
Aluminum	933	723
Titanium	1933 ± 20	1156
Iron	1812	1042
Tungsten	3695	1473
Steel (medium values)	1720–1795	1258
Nickel	1726	956

In order to monitor the thermal environment in the selected image area, it is proposed to install two thermal housings separated by some distance: one with VPhCCD (charge-coupled device with “virtual phase”), the other with IR CCD [17]. Both cameras must be tuned to the same field of view and send simultaneously received streams of information to the ground station [20]. Table 3 shows the subrange of wavelengths corresponding to CCD models and lenses.

Along with visual control, high temperature measurements are also offered, as well as monitoring of sudden temperature fluctuations of telemetry objects for a more detailed analysis of abnormal and emergency situations. Measurements are conducted by the method based on the Planck’s law, pyrometric methods by color spectrum or brightness. A color (or black-and-white) video image is displayed on the PC monitor screen at a frequency of up to 3 fps, the temperature-hazardous areas of the image field are highlighted in red.

Given methods of monitoring the observed objects make it possible to exercise video control of technological processes and thermal adjustment of LV and measure the temperature of the thermally loaded regions by a remote contactless method by means of video cameras while significantly reducing the flow of information transmitted from the item to the ground receiving station via the “onboard-Earth” channel and give discrete commands for repeated operations of deployment of components of the automatic spacecraft in case of their non-fulfillment according to the cyclogram to prevent emergency and emergency situations.

It should be noted that with regard to the use of video cameras onboard the RST products, when the video cameras are located at large distances from the observed object, it is possible to use long-focus lenses [21]. When reducing the distance from the object to the lens, to maintain the model and performance of the lens, it is required to increase the depth of field, that is, to increase the aperture number by reducing the effective aperture of the lens. The program must provide for setting the nominal temperature: the temperature at which the material retains its performance for a long time. This depends on the material of which the observed object and its components are made. The nominal temperature is set in advance. –

3. An option to display the temperature in a zone selected by the operator.

Hence, the operator’s actions when using the program should be as follows:

– selection of the viewing area in accordance with OD;

– selection of the spectral subrange;

– selection of the viewing area of interest for temperature measurement.

Table 3. Wavelength subrange corresponding to CCD models and lenses

Subrange name	Wavelength range, μm	Color (spectral) temperature range *, K	Video recorder type	Lens type
UV	0.3–0.38	9653–7621	VC with VPhCCD	Long-focus quartz glass lens
Visible range	0.38–0.74	7621–3914		
IR1	0.74–1.10	3914–2630		
IR2	1.10–5.5	2630–525	VC with IR CCD	Long-focus optical silicon lens
IR3	5.5–8.0	525–362	IR systems with deep thermal cooling	Long lens from germanium
IR4	8.0–15.0	362–190	Microbolometer receivers	

* – temperature ranges are taken at the maximum intensity of thermal radiation obtained according to the Wien's displacement law.

Conclusions

The following results were obtained during the work:

– the reasons for the need to develop and apply video systems on the RST products were outlined;

– a technique has been developed to calculate the temperature by the intensity of thermal radiation at different wavelengths, which allows calculating the temperature values of the observed objects by a remote non-contact method;

– a technique has been developed for displaying information on the thermal environment while obtaining color video images and numerical values of temperature, which permits visualizing the thermal environment of the observed object and promptly determining the thermal hazardous zones;

– spectral ranges according to actually existing photorecording devices and optical materials, which are the input data for the development of the information display program on the thermal environment, are presented.

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