Smart Sensing of Systems Thermal Behavior Using Low Cost Infrared Cameras

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Abstract— **Diagnosis through the analysis of thermal images is widely used and is one of the favorite tools of predictive maintenance. Due to the high cost of infrared cameras, this analysis is carried out through periodic manual inspections reusing the sensor element for several applications. The recent appearance of low-cost infrared cameras has enabled the development of static applications that observe and analyze the thermal behavior of critical systems over time. This work presents a proposal of an intelligent thermal sensor that acquires and processes low resolution images in real time with energy restrictions. The proposed thermal image processing is based on the analysis of local maxima and spatial and temporal gradients centered on these maxima. The standard IEEE 21451-001-2017 was applied used for signal processing. The image acquisition and processing are executed into a 16-bit microcontroller resulting in a compact thermal sensor with low cost and low power consumption and with the ability to understand and classify the thermal evolution of the observed system.**

Keywords- infrared cameras; microcontrollers; real time; thermography; thermal image processing; low cost, low power.

I. INTRODUCTION

The term intelligent sensor was created in the 80's and referred to a transducer that had the capacity of digital transmission, signal conditioning, along with the possibility of identifying itself on a sensor network. The challenge at that time was to have "Plug and Play" devices, necessary for the complex systems that man began to design. In order to make transducers of different brands identifiable, the IEEE 1451 family of standards [1] was initiated, which introduced the Transducer Electronic Data Sheet, the electronic data sheet of the transducer, TEDS.

Currently the challenge is different. An intelligent sensor should validate its own measurements, extract information and knowledge directly from the sensory signal in order to interact with other sensors or transducers, and with the acquisition system. This "sharing" enables the execution of sensory fusion algorithms and streamlines data mining processes as well as increasing the reliability of the observed system.

There is an inverse relationship between processing of sensory signal and data flow in bits / sec. As the signal processing increases, the number of bits needed to report an event decreases significantly. A sensor based on images could report the complete image to be processed remotely (data), a compressed version of the image, (information) or an extraction of some feature of relevance to the application (knowledge). These three report classes generate thousands of bits / sec, up to a few bits / sec, in the case of reporting only states such as, for example, normal / abnormal. The technological convergence allows this type of analysis and generates new sensing paradigms, such as the particular case proposed in this work of continuous thermal image analysis. Thermography has a huge field of application. For example, in medicine [2],[3]. In [4], there is a complete survey of applications.

This paper presents a thermal image acquisition and processing system that employs low-cost IR cameras. This system is oriented to the permanent monitoring of a critical process or device that requires frequent monitoring of its thermal evolution. The frame acquisition and processing are carried out in a 16-bit microcontroller, generating a solution on a chip. In the subsequent sections, the nature of a thermal image and infrared camera technology are first described with an emphasis on its strengths and weaknesses. Then, the implementation of the microcontroller communication - IR camera for the configuration and image acquisition, is detailed. Section IV describes the algorithms used in the analysis of the image and the implementation in the microcontroller. Finally, experimental results and conclusions are presented.

II. INFRARED TERMOGRAPHY

A. Thermal imaging cameras

A thermography camera is a device that detects the emission pattern of a scene in the spectrum of the infrared wavelength. In Fig. 1 the electromagnetic spectrum is observed detailing the bands corresponding to the infrared zone. The camera used in the tests for this work [5] has a sensitivity lower than 50 mK (milli Kelvin), in the LWIR (Long Wave Infrared) region from 8 to 14 µm.

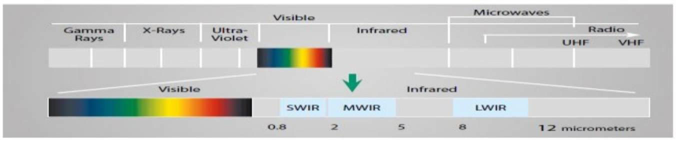

Fig. 1. Electromagnetic spectrum. The infrared band is divided into two main sub-bands: Short Wave IR corresponding to a wavelength of 2 to 5 µm and Long Wave IR from 8 to 12 µm.

Thermographic cameras are basically composed of a lens transparent to infrared energy and a matrix of M x N sensitive elements that translate this energy into an electrical signal. Therefore, IR cameras provide the average energy radiation in each subdivision of the scene as projected to each element of the sensor array through the optical system. In the particular case of the camera used in this work, the resolution is 80 x 60 sensitive elements. Each detector element is a vanadium oxide microbolometer, in which the temperature varies according to the incident radiation. The temperature changes produce a proportional variation in the resistance of each detector. Through sensing circuits and A / D converters, the matrix information is sent sequentially through standardized protocols described in section III.

B. Radiation and surface temperature

The radiation power of a surface is given by the Stefan-Boltzmann law:

$$\in = \varepsilon \sigma T^4 \tag{1}$$

Where ε is the emissivity, $\sigma = 5.67\ 10^{-8}\ W/m^2K^4$, is the Stefan-Boltzmann constant and $\boldsymbol{T}$ the surface temperature in Kelvin.

The emissivity is the ratio of emission referred to the emission of the ideal black body, for which it takes the unit value. The emissivity is low for polished metals. As the emissivity is determined by the characteristics of the surface of the object, a painted metal changes its emissivity according to the paint used. Table 1 shows the approximate values of emissivity for some materials, [6].

TABLE 1. APPROXIMATE VALUES OF EMISSIVITY FOR DIFFERENT MATERIALS.

MATERIAL	ε
Black body	1
Human skin	0.98
Water	0.98
Asbestos	0.98
Ceramics	0.95
Mud	0.95
Cement	0.95
Paper	0.95
Plastic	0.95
Wood	0.85
Rusty copper	0.68
Stainless steel	0.1
Polished copper	0.02
polished aluminum	0.05

If the object emissivity in the scene is not known, eq (1) presents two unknowns; ε and T, since IR cameras are sensitive to **radiation** in infrared spectrum.

This simplified analysis leads to two forms of using thermography: qualitative and quantitative analysis. The technique of qualitative thermography consists of detecting thermal gradients and abnormal patterns in the inspection scene. The defect causing this thermal pattern will be located by comparison with other objects with the same condition. One of the advantages of this technique is that it does not need an exact measurement of the temperature, therefore normal / abnormal classification is based on comparative analysis.

Quantitative thermography obtains the temperature at each point of the scene, which implies knowing the emissivity of the objects. Most applications are based on qualitative analysis since the information on the thermal behavior of the object is a function of the spatial distribution of relative temperatures. In fixed applications, like the one proposed in this work, it also allows to obtain the temporal distribution when observing the same scene over time. This additional dimension makes it possible to detect abnormal operating conditions or overload by calculating the temporal scene gradients of regions.

To illustrate these concepts, Fig. 2 shows the thermal image of a distribution transformer captured with our acquisition system. The transformer has a uniform distribution of temperatures, but a colder rectangular area is observed. This zone corresponds to the metallic identification plate of the electric machine which, having a low emissivity coefficient, is erroneously seen as colder.

In a fixed acquisition application, the low emissivity elements are known in advance, therefore, they can be discarded from the thermal behavior analysis.

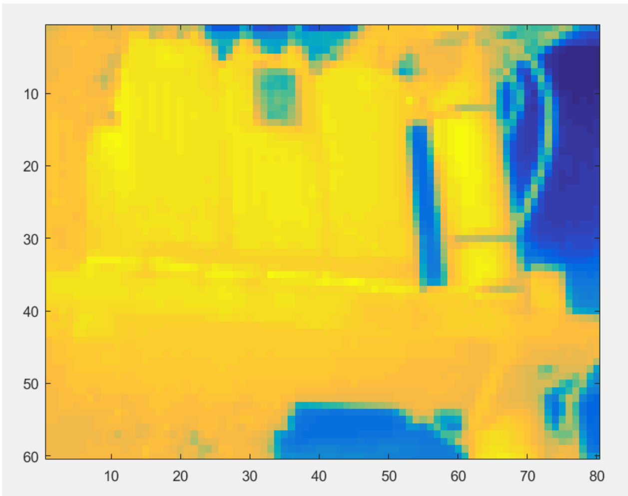

Fig. 2. Thermal image, obtained with our acquisition system, of a distribution transformer. The coldest rectangle observed corresponds to the metallic identification plate of low emissivity. A homogenous distribution of temperatures is observed.

III. ACQUISITION SYSTEM

A. Thermal camera

The thermal sensing device is a FLIR camera, LEPTON series. This device integrates fixed focus lenses, a matrix of 80x60 infrared sensors, and electronics for digital array processing. It can operate either in its default mode or be configured in other multiple modes, by means of commands and an integrated control interface (CCI). In Fig. 3, the main specifications are detailed.

Highlights:

- Sensibilidad térmica < 50mK.
- Functions for integrated thermal image processing, automatic compensation of thermal environments, noise filters, non-uniformity correction and gain control.
- Low consumption in operation (150 mW).
- Low consumption in Standby mode (4 mW).

Especification	Description
Characteristics	
Sensor technology	Uncooled microbolometers of Vanadium Oxide.
Spectral range	Infrared wavelength, 8 to 14 uM
Output format	14 bit or 8 bit (AGC enabled)
Electrical	
Input clock	25 MHz nominal
Video interface	VoSPI
Supply voltage	1.2 V, 2.5 V, 2.8 V
Environmental	
Temperature range	(-)10 ºC a (+)65 ºC

Fig. 3. Thermal camera specifications.

The image, inside the camera, is processed by a series of algorithms to improve it, some by default and others that can be enabled by means of the CCI serial interface. Two algorithms are highlighted:

- NUC: Non-uniformity correction block.
- AGC: Full resolution conversion algorithm.

Operation modes:

Telemetry mode. This mode is disabled by default; if activated, it includes in the output frame a series of data bytes with information about camera operational states and their configuration. The telemetry can be at the beginning (Telemetry as Header) or at the end (Telemetry as Footer) of the frame.

Radiometric Modes. These modes are also disabled by default. These modes affect the transfer function between the incident radiation and the output pixel. The radiometry enabled is preferred when the output of the camera is to be understood as a proportional temperature scene. In this mode the conversion is constant over the entire operating range. It must be considered that radiometric modes require the ACG mode disabled.

Radiometry disabled: In this configuration, the temperature is interpreted close to half the conversion range, that is, if the temperature of a scene pixel is equal to the temperature of the camera, the value of the A / D converter will be in the middle of the range. The response to radiation changes with the temperature of the camera itself. In this mode, the output temperature per pixel must be adjusted with respect to the ambient temperature in the camera.

Radiometry enabled: the device internally adjusts the value of each pixel to try to compensate the effect of the camera's own temperature. In this mode the temperature of each pixel is independent of the camera temperature.

AGCmode: Automatic gain control is a method to optimize the wide conversion range to leave it more appropriate for a visualization system. The range compression is done by a proprietary modification of the algorithm for equalization of cumulative histograms (Lepton's Variant of Histogram Equalization).

A1. Control interface:

The Lepton infrared camera includes a control interface (CCI), similar to I2C. The difference over I2C is that the control interface is 16 bits wide.

In general, this interface can be used for three types of commands:

- *Get: data reading,*
- *Set: data writing,*
- *Run: function execution.*

A2. Video Interface:

The transfer protocol is SPI, which allows a fast and reliable data transfer. It is based on packets without timing and without flow control requirements. The camera is slave for this protocol.

All transfer of data packets (VoSPI packets) is controlled by the master and once the corresponding packets are received in a frame, the master can choose to deselect the device or continue the transfer of data packets. In this case discard packets are generated (VoSPI discard packets) until a new frame is generated.

A3. Packet format VoSPI:

The video package consists of 4 bytes for header and 160 bytes for pixel data. In the header are both the line identifier, 12 bits, and the 16-bit CRC code using the following generator polynomial:

$$x^{16} + x^{12} + x^{5} + x^{0} \qquad (2)$$

ID	CRC	Pixels
4 bytes		160 bytes

ID	CRC	Pixels
xFxx	xxxx	Useless Data

Fig. 4. Pixels frame sent by the SPI interface for valid and discarded data. Bottom, discard frame coded by ID 0XxFxx.

For each pixel two bytes are sent, therefore, one frame is a complete line of 80 pixels. The discarded VoSPI frame differs from the valid ones by the ID. All frames with a 0xF in the third nibble are discarded, the data and the CRC are invalid. The discarded frames have the function of maintaining the data flow through the SPI while a new frame is available.

B. Microcontroller

The microcontroller adopted was the DSPIC33EP256GP502 mainly due to four reasons: execution speed, RAM size, cost, and 16-bit architecture for efficiently processing pixels also packed into 16 bits. It has 32Kb of RAM, operates at 70 MIPS and has SPI, I2C and USART interfaces, necessary for this system. To send commands and acquire images during development, a USB-USART FT230 converter was added.

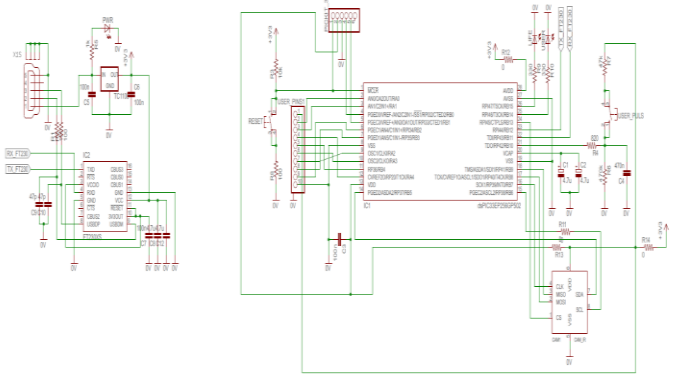

Fig. 5. Schematic diagram of the IR system.

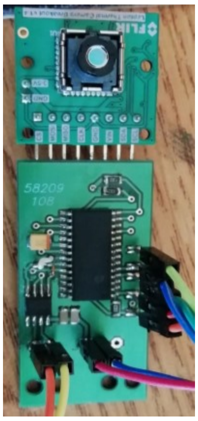

Fig. 6. Smart sensor hardware prototype.

Fig. 5 shows the schematic diagram and Fig. 6 a photo of the implemented device.

C. Driver

The driver has been developed with the purpose of provide a simple interface for camera configuration and to capture images via USB during the development stage. The final system includes a low power RF transceiver, TMR-433-LT,[7], instead the USB port. The driver functions are:

- Initialize communication peripherals.
- Initialize the camera and verify its normal operation.
- Wait for capture commands, configuration, image transmission, thermal distribution, scene validation and thermal image processing.

The software was developed following the State-Cooperative multitasking paradigm in C language.

The most important function of the driver is to establish synchronism with the camera via the SPI interface. For synchronization, all the line video frames must be discarted until a disposable video frames until a line identifier corresponding to the start of a valid frame (ID = 0x0000), see Fig. 7.

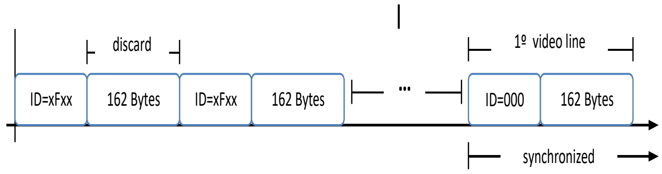

Fig. 7. For synchronism, the first frame with ID = 0000 must be detected.

The external system only interacts with the microcontroller over the USB protocol or the RF link to acquire the image, specify a new configuration of the capture mode, or require thermal analysis according to the algorithms described in the following section.

IV. THERMAL IMAGE PROCESSING

A. Design considerations

The processing on the thermal image was designed to be done using the resources of the microcontroller. As it is not known in advance the scene for the final application and to be generic algorithms were implemented that extract common characteristics to numerous applications. In addition, there is the possibility of sending the complete frame through the RF link to be processed remotely.

In general, in a thermal image, it is useful to determine the absolute value of hot spots, the spatial temperature gradient centered on these points and their temporal evolution.

B. Maximum of the IR image

For the detection of the image maximums and hot spots, the IEEE 21451-001-2017 standard [8] was used. This standard provides a framework for sensor signal knowledge extraction applied smart sensors. In our particular case, the image is considered as an array of 60 one-dimensional signal segments of 80 elements. According to the standard, the signal is coded as a union of known segments. In [9], [10] there is a complete description of the coding. Each frame consists of 4800 pixels, and as a result of applying the sampling technique suggested in IEEE 21451-001, pixels are marked only at the junction of segments, leaving a considerably smaller amount, which is a function of the scene and a predetermined interpolation error. These pixels are called essential and this way of describing the information is considered as a compression without loss of the information structure. In the union of an ascending segment with a descending one, a local maximum is obtained directly. The rows of the image are processed sequentially to obtain the essential pixels and the local maxima controlled by an interpolation error.

C. Feature extraction algorithms

The acquired frame is subdivided into 16 regions of 20 x 15 pixels each. This subdivision is made for two reasons. First, it simplifies the thermal behavior analysis and adapts it to the microcontroller resources and second, a digital signature of the scene is obtained that is used to validate it, taking into account that the thermal processes are slow and the objective of the smart sensor is to observe processes continuously.

For each region *i,j* with *i=1, 2, 3,4 and j=1, 2 ,3,4* the following five processes are performed.

1- Number of essential pixels. (**Cpix**)

2- Average value of the essential pixels. (**Mpix**)

3- Number of maxima. (**CMax**)

4- Highest value. (**MMax**)

5- Difference between the average of the maximum and the average of the essential pixels. (**DifMpixMax**)

Therefore, 80 indicators are obtained that describe the scene. There are simple to compute, and they are used to validate and analyze it.

D. Scene validation

Validating the scene in this context means that the same image is being acquired or that there is meaningful thermal energy in the scene. The difference between two consecutive frames obtained in a much shorter time than the thermal time constants involved, must be small. Two main reasons generate big differences. First that there is no significant thermal energy in the scene, for example, the machine is off, and second that the scene changed abruptly, for example, some object or person was interposed. To validate a scene, a difference less than a threshold, *Thd,* must be obtained in a number of consecutive frames *Kd*. For the validation processes 1 and 2 are used according to the following equations:

$$dif1 = \sum \left| Cpix_{i,j,n} - Cpix_{i,j,n-1} \right| \quad (3)$$

$$dif2 = \sum \left| Mpix_{i,j,n} - Mpix_{i,j,n-1} \right| \quad (4)$$

Where $i = 1, 2, 3,4$; $j = 1, 2, 3,4$ and n is the current frame and n-1 the previous one, with a temporal difference much lower than the thermal constants involved. A new frame will be validated if the following inequality is met:

$$dif1 + dif2 < Thd \quad (5)$$

for *Kd* consecutive frames.

E. Thermal analysis of validated frames

Two basic processes are executed: the temporal growth of the maxima and the spatial evolution of the thermal energy in each region. The resulting values are calculated for each of the 5 processes in each region. Based on the results, the regions that require attention for their follow-up are selected. For example, in a region without maximums no subsequent calculation is made. The absolute maximum of the image is searched, and the temporal evolution of neighboring regions is recorded in successive frames, see Fig. 8.

F. Experimental results on real images

Thermal images of a power transistor heatsink were processed. 30 frames were acquired at 20 second intervals. In Fig. 9 the thermal image of the dissipator is observed and in Fig. 10 the temporal evolution of the maximum **MMax** of each image.

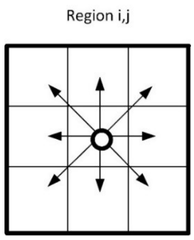

Fig. 8. Neighboring regions centered on the absolute maximum of the image.

Fig. 11 shows the initial and final thermal state of the dissipator after 10 minutes of testing. The five processes were calculated, and it is important to highlight the importance of process number five, **DifMpixMax**, since an increase in this value implies that the heat is concentrating on small surfaces or the rate of heat generation is greater than that the evacuation. In Fig. 12 the capture of the thermal image of an electric motor is observed, which through the ventilation grids can be inferred the winding temperature. Fig. 13 shows a capture of the low side terminals thermal behavior of a distribution transformer, a real application of our system.

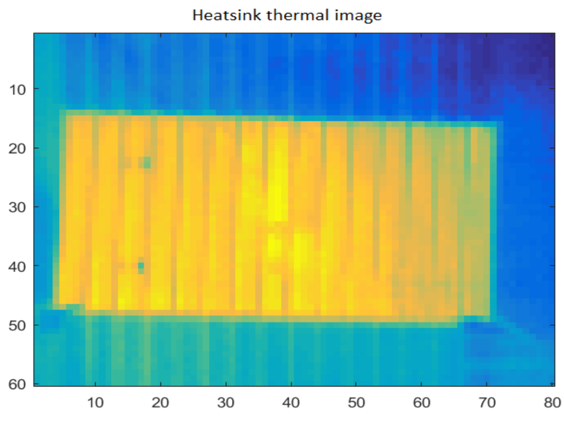

Fig. 9. Thermal image of the heatsink under test.

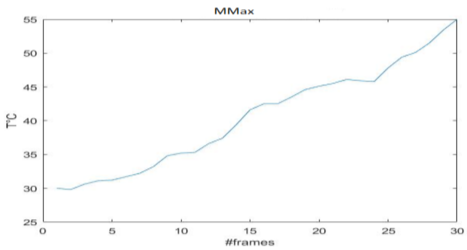

Fig. 10. Temporal evolution for **MMax** of the the heatsink image

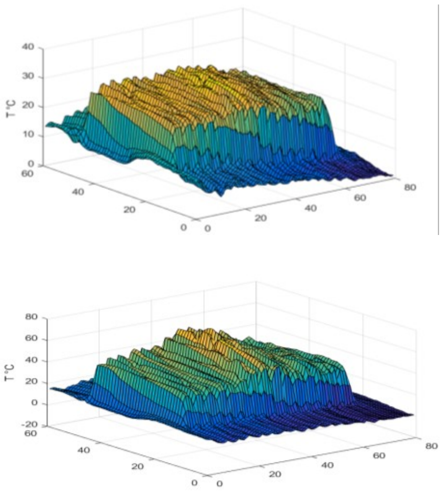

Fig. 11. Heatsink temperature distribution at the beginning (top) and at the end of the test (bottom). Image processing at 20 second interval during 10 minutes.

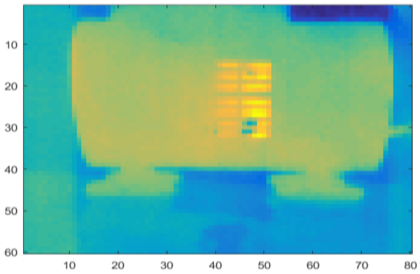

Fig. 12. Thermal image of an electric motor in which the temperature of the windings can be measured through the ventilation grids. Captured with our acquisition system.

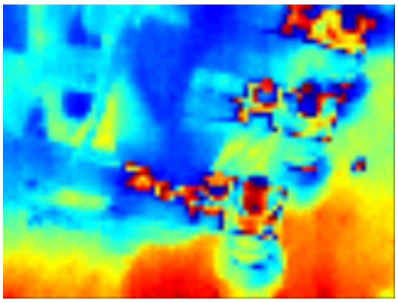

Fig. 13. Capture of an implemented monitoring system for the low side terminals of a distribution transformer.

V. CONCLUSIONS

Thermography has the great advantage of observing a process or device without contact. The smart sensor presented in this paper provides a resolution of 80 x 60 pixels. Although it is low, it is like observing the process with 4800 thermometers. By lowering the costs of infrared cameras, applications with fixed captures are triggered that allow to evaluate the thermal behavior with the paradigm of an intelligent sensor. The applications are innumerable, not only to infer abnormal patterns, but also to validate the correct performance of a system, for example, verify that it reaches its steady state normally. Five indicators of thermal behavior in 16 regions are proposed. Tracking the temporal and spatial evolution of these parameters allow us to infer the system thermal behavior. System monitoring is achieved by acquiring and processing the thermal image at regular intervals. The acquisition and processing time are approximately 100 ms. Due to the thermal inertia of the systems, the observation interval is of the order of minutes or hours. Therefore, the intelligent sensor energy consumption is very low since the complete sensor system adopts a low energy state; camera, microcontroller and RF transceiver. In addition, since the image processing is done locally, it is not necessary to transmit the image, but normal, abnormal conditions and the value of the hottest points.

In some applications, the minimum values of an image are also important, as for example in energy efficiency studies. Local maximums and minimums are immediate results of the IEEE 21451-001-2017 standard and can be implemented in low cost microcontrollers in the acquisition point.

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