Real Time Multispectral High Temperature Measurement: Application to control in the industry

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ABSTRACT

Many devices are used to realize non-contact temperature measurements. Whenever the body to be controlled behaves as a black body, all the devices inferring the true temperature from the body radiation are accurate and reliable. On the other hand, when it exhibits a behavior different from the black body, emissivity compensations need to be done. In case of a known emissivity, the spectral system (single wavelength) is used whereas, for gray body (unknown but constant emissivity in a narrow bandwidth) a bicolor system is more likely to be utilized. For all other cases, assumptions about the emissivity variations as a function of the wavelength and the temperature have to be ascertained and multispectral system or “hybrid-systems” which are a mix between spectral and multispectral systems have been built and used in particular cases.

In this paper, a real time multispectral imaging system based on two CCD cameras is presented. The system is herein carefully characterized and applications such as vision control system are presented. An extension of the system with three cameras is also exposed in the perspectives.
I. INTRODUCTION

In many industries, such as the automotive, glass, aeronautics or nuclear industries, some mechanical parts are exposed to severe constraints: abrasion, corrosion, high temperature, friction, mechanical stresses... For such parts to properly behave, they have, to improve some of their surface properties (better hardness, better resistance to abrasion, wear and corrosion resistance.....), to undergo a surface treatment (quenching, laser heating, laser cladding, plasma-nitriding....) which involves surface temperature changes.

Among the sensors developed to control the processes, information provided by CCD sensors seem to be the best trade-off between high accuracy control, low cost system and multifunctional system. Indeed, signal provided by a CCD is useful for accurate metrology (dimensional control, aspect control, color control, shape control....) like in machine vision applications, as well as for radiometric analysis or high temperature measurements if the sensors are properly calibrated and carefully used.

Inferring temperature from observed or measured radiations coming from the object has been studied for many years, whereas low temperature measurements imply an expensive sensor working in the mid or high infrared spectra, high temperature measures can be done in the near infrared and in the visible.

For temperatures ranging from 350°C to 600°C, CCD based systems have recently been developed and show interesting results.

Many devices which realize non-contact high temperature measurements can be found on the market but their use is often restricted to observations of objects of known emissivity. Indeed if the body to be controlled behaves as a black body, all the devices inferring the true temperature from the body radiation are accurate and reliable. On the other hand, when it exhibits a behavior different from the black body, emissivity compensations need to be done.

Therefore, in case of a known emissivity, the spectral system (single wavelength) is preferentially used, for gray body (constant emissivity in a narrow bandwidth) a bicolor system is more likely to be utilized. For every other case, assumptions about the emissivity variations as a function of the wavelength and the temperature have to be ascertained and multispectral systems or “hybrid-systems” which are a mix between spectral and multispectral systems have been built and used in particular cases. Unfortunately, most of the proposed systems are often single point temperature evaluations, restricted to controlled environment which often prevent their use for most of the industrial processes which are subject to experimental condition fluctuations (water, vapor) or material emissivity changes (oxidation, surface changes...) leading to enormous errors in the temperature estimation.

To partially overcome this problem, in this paper, a real time multispectral imaging system based on two CCD cameras is presented, carefully characterized, and its applications in vision control discussed.

The present paper is organized as follows: the first part presents the theoretical basis of the spectral temperature measurements and its limitations. Through the second part, multispectral theory and systems are exposed with an emphasis on our real time high temperature multispectral system. Its
calibration procedure, experimental errors, accuracy and its limits are discussed. A subsection presents an application of our system. Finally the conclusion summarizes the paper and presents the outlook of our work for the near future.

2. MONOCHROMATIC TEMPERATURE MEASUREMENTS: THEORY, RESULTS AND LIMITATIONS

Non contact temperature measurements are based on the detection and the analysis of thermal radiations emitted by an object. Planck’s law (equation 1) describes this phenomenon for an ideal surface, the blackbody (see Figure 1). The blackbody is a perfect emitter that emits more thermal radiation than any other objects at the same temperature.

\[ L^0_\lambda (T) = \frac{C_1}{\pi \lambda^2} \cdot \frac{1}{\exp(C_2 / \lambda T) - 1} \]

(1)

With : 
- \( T \) : temperature (in K)
- \( \lambda \) : wavelength (in m)
- \( C_1 / \pi \) : first radiation constant, \( 1.191062 \cdot 10^8 \text{W.m}^{-4} \text{sr}^{-1} \)
- \( C_2 \) : second radiation constant, \( 1.438786 \cdot 10^4 \text{W.m} \)
- \( L^0_\lambda \) : spectral radiance \( \text{W.m}^{-3} \text{sr}^{-1} \)

Figure 1: Radiance emitted by a black body for different temperatures. Dash line represents Wien’s law (wavelength for which the radiance is maximal) given by : \( \lambda_m T = 2898 \ \mu \text{m.K} \)
The temperature of a blackbody surface is immediately determined from the surface emitted flux. The emissivity is defined as the ratio of radiation emitted by the real surface to that emitted by the blackbody at the same temperature and for the same spectral bandwidth (equation 2). The emissivity never exceeds unity, thus, the radiometer, viewing a real target, always indicates an apparent temperature referred to as the spectral radiance temperature, $T_\lambda$, lower than the true surface temperature $T_s$.

$$
\varepsilon_\lambda L^\lambda_{T_s} = L^\lambda_{T_s} \tag{2}
$$

With: $L^\lambda_{T_s}$ : spectral radiance at temperature $T_s$

$L^\lambda_{T_\lambda}$ : spectral radiance at temperature $T_\lambda$

$\varepsilon_\lambda$ : emissivity at wavelength $\lambda$.

The spectral equation (equation 3), derived from Planck’s law, is used to infer the true temperature $T_s$ from the knowledge of the apparent temperature $T_\lambda$, calculated using the measured spectral radiation $L^\lambda_{T_\lambda}$, and the spectral emissivity $\varepsilon_\lambda$ at the wavelength $\lambda$.

$$
\frac{1}{T_s} = \frac{1}{T_\lambda} + \frac{\lambda}{c_2} \ln \varepsilon_\lambda \tag{3}
$$

With : $T_s$ : true surface temperature

$T_\lambda$ : apparent temperature at wavelength $\lambda$

$c_2$ : second radiation constant.

The sensitivity of spectral radiance temperature with respect to change in emissivity (holding $T_\lambda$ constant) is:

$$
\frac{dT_s}{T_s} = \frac{\lambda T_s}{c_2} \frac{d\varepsilon}{\varepsilon} \tag{4}
$$

According to equation 4, the emissivity uncertainty greatly influences the precision of the measurements. The lower the working wavelength is, the more accurate the temperature measurement is (see figure 1, the steepest part of the curve belongs to the low wavelength range), and the smallest will the error due to emissivity variation be. For instance, for $\lambda = 0.85\mu m$ and for a body heated at $1400^\circ C$, an emissivity variation of 10% causes an uncertainty of 0.66% in temperature, whereas the uncertainty goes up to 0.854% for $\lambda = 1.1\mu m$.

Thus, an a priori knowledge of the spectral emissivity is necessary to infer the temperature of an object from the measurement of emitted radiation.

Unfortunately, the emissivity depends not only upon the object surface properties (oxidation, surface state, temperature, roughness), but also upon the experimental conditions (observation angle) as well as on the observation spectral band pass $^5$. The figures below present different cases for which the emissivity respectively varies as a function of the temperature and as a function of the observation angle.
Figure 2: Upper figure: variation of the emisivity for various metals (oxidized or not) versus temperature for a wavelength of 0.65 µm.

Lower figure: variation of the emissivity versus the observation angle for rubber at ambient temperature for a wavelength of 4 µm.

In order to cope with all these possible errors about the emissivity, a real time low cost system performing multi-spectral temperature measurements was developed. This system and the obtained results are presented throughout the next sections.

3. MULTI-WAVELENGTH METHODS
Assuming the relationship between emissivity and wavelength is known, multispectral or multi-wavelength methods infer the true target temperature from measurements of the spectral radiance at different wavelengths. Numerous multispectral methods have been developed over the last few years, Tsai\textsuperscript{14} summarizes most of the existing bi-spectral methods or emissivity compensation methods, whereas Dewitt\textsuperscript{15} and Chrzanowski\textsuperscript{16} present industrial results regarding the temperature accuracy. Dewitt proposed a four spectral band pyrometer for temperature measurement of a laser irradiated carbon surface. Hiernault\textsuperscript{17} and Gardner\textsuperscript{18} developed a six wavelength pyrometer for metal melting application. They assume a linear variation of the emissivity versus the wavelength. A multispectral method with up to 200 narrow bandwidths was developed by Hunter\textsuperscript{19}.

However, most of these studies fail to take into account the variation of the emissivity with the temperature, which could lead to important errors,\textsuperscript{20} and do not provide a temperature map but only singular values of the temperature.

To conclude, multispectral methods are more robust against experimental fluctuations than spectral methods and provide the opportunity of choosing different emissivity law variations, however at the present time the commercial realization of a real time multispectral and spatial temperature imager for a low cost has not yet been feasible. Thus, for these stated reasons, we developed our own high resolution dual-wavelength real time temperature imager dedicated to high temperature measurements.

The next subsection presents the dual wavelength method or ratio method.

3.a) Dual wavelength method: theory

Introduced by Campbell in 1925, the two-colour or dual wavelength method estimates the target temperature from the ratio of two measured spectral radiances. Using spectral filters with narrow band-passes, the dual-wavelength system simultaneously acquires the spectral radiance emitted by a body at two wavelengths $\lambda_1$ and $\lambda_2$. The true temperature is then inferred from the ratio temperature as described by equation (5).

$$\frac{1}{T_s} = \frac{1}{T_r} + \frac{\Lambda_r}{C_2} \ln \varepsilon_r$$

(5)

where

$T_s$: indicated true or surface temperature

$T_r$: ratio or colour temperature

$$\frac{1}{T_r} = \Lambda_r \left( \frac{1}{\lambda_1 T_{\lambda_1} - \lambda_2 T_{\lambda_2}} \right)$$

(6)

$\varepsilon_r$: ratio or colour emissivity.

$$\varepsilon_r = \frac{\varepsilon_1}{\varepsilon_2}$$

(7)

$\Lambda_r$: ratio wavelength

$$\Lambda_r = \frac{\lambda_1 \lambda_2}{\lambda_2 - \lambda_1}$$

(8)

According to equation 5, the indicated ratio temperature coincides with the true target temperature, whenever emissivities $\varepsilon_1$ and $\varepsilon_2$ are equal, or $\varepsilon_r = 1$ (grey body definition)
For the dual wavelength method, an a priori relation about the emissivity variation, but not the emissivity value, is required in order to infer the target temperature.

The relative uncertainty in true temperature depends on the uncertainty in emissivity variation, according to equation 9.

\[
\frac{dT}{T} = \frac{\Lambda T}{c_2} \frac{d\varepsilon_r}{\varepsilon_r}
\]  (9)

The equivalent wavelength \( \Lambda_r \) will always be equal or greater than \( \lambda_1 \) and even greater than \( \lambda_2 \), \(( \Lambda_r > \lambda_1 > \lambda_2)\), thereby increasing the effects of emissivity uncertainty and consequently the relative error in temperature too.

The selection of the two wavelengths \( \lambda_1 \) and \( \lambda_2 \) is crucial and greatly influences the accuracy of the method. The difficulty is to choose two wavelengths sufficiently close enough to validate the gray body hypothesis but distant enough to improve the precision measurement. A thorough literature survey on the material emissivity should be done prior to each experiment. For known emissivity material, the ratio method would be substituted for the spectral method. Our system being versatile (as presented below), two spectral temperatures (assuming the emissivity is known for the two wavelengths) as well as the ratio temperature are provided.

For situations where the object emissivity is unknown and variable, or when the target is obscured by gas, fumes, or water vapor for instance, as in most industrial applications, the ratio method can provide reliable measurements, assuming that the spectral radiance measurements at the two wavelengths are simultaneous and optically identical.

3.b) Dual wavelength method : calibration procedure and uncertainties

3.b-1) Calibration

In our application, two CCD cameras are used to assess the temperature of the target. When compared to a conventional IR area array, CCD sensors are relatively inexpensive and more affordable to industry; their spectral response extends into the near infrared region, (around 1 µm) and enables one to easily detect thermal radiations from objects with temperature ranges from 800 to 2200°C. This range can be slightly narrowed or widened according to the selected integration time (IT) or the numerical aperture (NA) of the camera.

When connected to a frame grabber simultaneous temperature measurements at different wavelengths at a rate of 25 frames per second can be performed. The experimental set up of the two-wavelengths temperature measurement system is presented in figure 2.
A commercial integrative sphere was first used to check the linear relation between the pixels grey level and the homogeneity response of all pixels. In our case, no significant differences among the pixels were detected. Our system was then set in front of a calibration target (commercial high temperature regulated black body) (see figure 3) and different calibration procedures were realized (temperature variations, variations of the optical aperture (NA) of the CCDs, variation of the integration time IT of the CCDs) in order to obtain a full range of measurability. Figures 4 and 5, respectively represents the grey level variation versus the temperature for different NAs and for different ITs.
Figure 3: Our real time two wavelength system set in front of the black body for calibration purposes.

Figure 5: Variations of the Grey level versus the temperature for various NAs. “Ouverture” in the figure caption is proportional to the NA.
Knowing the theoretical relations between each IT and each NA, we experimentally verified these, in order to be able to extrapolate the temperature value for any combinations (IT, NA) of our CCDs.

Thus, for each camera (camera + associated filter), various experimental data points were taken; then an approximation function which relates the temperature to the grey level (NG) of the pixel was determined as presented by equation 10 and figure 7.

\[
NG = \frac{A}{\exp\left(\frac{B}{T}\right) - 1} \quad (10)
\]
From equation 10, it is easy to infer the relation (equation 11) linking the temperature to the grey level (see figure 8).

\[ T = \frac{B}{\log\left[1 + \frac{A}{NG}\right]} \]  

The calibration procedure was simultaneously (synchronous acquisitions) realized for the two CCDs, leading to the final results presented in figure 9.
Figure 9: Temperature versus grey level; Experimental data points and approximations based on Planck’s law for the two CCDs equipped with interference filters respectively centered at 750 nm and 950 nm.

Taking the Wien’s approximation for both curves (Wien’s law is an approximation of Planck’s Law for $C_2 \gg \lambda T$) and the spectral radiance can be expressed as:

$$L^0_{\lambda}(T) = \frac{C_1}{\pi\lambda^3} \cdot \frac{1}{\exp(C_2 / \lambda T)} \quad (12),$$

the ratio of the two grey levels is obtained by non linear regression (Levenberg Marquadt) as expressed by equation (13) and displayed in figure 10.

$$R(T) = A e^{\frac{\theta}{T}} \quad (13)$$
From equation (13), it is straightforward to infer the relation (equation 14) which expresses the temperature as a function of the ratio of the grey levels (see figure 11).

\[
T = \frac{B_r}{\log \left( \frac{R}{A_r} \right)} \quad (14)
\]
Figure 11: Temperature versus ratio of the grey levels from CCD1 and CCD2 based on experimental points.

Figure 12 presents the final results with different ITs, different NAs and the final interpolation (dash-line) based on Wien’s Law.
Figure 12: Temperature versus ratio of the grey level of CCD1 and CCD2 for various NAs and ITs configurations. The dash-line represents the final approximation.

3.b-2) Uncertainties

All the uncertainties and errors were characterized for spectral temperature measurements (one wavelength) and for dual wavelength temperature measurements. CCDs being sometimes unsteady, grey level variations over a certain period of time for each CCD were determined and found to be plus or minus one unit independently from its original value. Then, to compensate for the slight variations (spatial and temporal) of the black body radiator, the effective grey level is calculated in a window whose size is identical to that of a single spot high precision commercial optical pyrometer, the measurements being done ten different times (time evolution of the black body); the noticed grey level variations were found negligible (less than half a unit).

Finally, the grey level differences between the experimental data points and the approximation based on Planck’s Law were calculated. An example for spectral temperature measurement is given in figure 13.
Differences in temperature between the approximation and the experimental data are then inferred from the grey level differences: this is realized by first calculating the derivative of the temperature approximation to the grey level, as expressed by formula 15. Then multiplying the obtained results with the data points previously obtained and displayed in figure 13, resulting in the fact that the low temperatures are more affected.

\[ T = \frac{B}{\ln\left(1 + \frac{A}{Ng}\right)} \]

\[ \frac{\partial T}{\partial Ng} (Ng) = \frac{AB}{\left(1 + \frac{A}{Ng}\right)(Ng)^2 \left[\ln\left(1 + \frac{A}{Ng}\right)\right]^2} \]  

Figure 13 shows the grey level differences between the experimental data points (NGexp) and the approximation (NGApprox) for spectral temperature measurement. Figure 14 displays an example of the final temperature difference between the experimental data of figure 13 and the approximation (in Kelvin) for various temperatures. The final maximal experimental error for spectral measurement is 1.33 K.
Identical calculations were carried out for the ratio method but this time using the derivative as the expression given by formula (16):

$$T = \frac{B}{\ln \left( \frac{R}{A} \right)}$$

$$\frac{\partial T}{\partial R} (R) = \frac{-B}{R \left( \ln \left( \frac{R}{A} \right) \right)^2} \quad (16)$$

leading to a maximum error of 5.77 K, which is about a maximum of 0.5 % for our temperature range.

Our fully characterized system was then used in real situations.

3.c) Dual wavelength method : results.
Different heat treatment processes were controlled with our system which is implemented on C++ and multithread programming. The two CCDs are connected to an IC-ASYNC frame grabber (up to 4 CCDs realizing synchronous acquisitions) and temperature measurements are realized at a rate of 25 im/s on a 512*512 resolution basis. This spatial resolution enables FFT to be performed on primary images from a calibration grid in order to realize a cross-correlation product and infer from it the displacement vector which exists between the pixels of the two images.

Figure 15 presents a sample of copper which has been heated by electromagnetic induction. The curves are cross-sections of the image. The upper curve represents the temperature for the ratio...
method whereas the others are spectral temperatures. Pure copper has a fusion point of 1356K. The dual-wavelength method which makes the assumption of the grey body behavior gives an accurate result whereas the spectral temperatures are wrong due to the lack of information about the emissivity.

Figure 15: (a) Temperature image of a copper sample heated up to its fusion point. (b) Temperature profiles marked by an horizontal line in figure 15 (a): upper curve ratio method, middle curve spectral temperature method ($\lambda = 750$ nm), lower curve spectral temperature method ($\lambda = 950$ nm)
Other experiments were carried out with this set-up \(^{21}\) (simulation of smokes, oxidation,…), all the results were found correct and compared on some points with values obtained from thermocouple.

4. CONCLUSION

In this article, we presented an experimental system composed of two CCD arrays which were set so as to realize bicolor temperature measurements in order to control and optimize heat treatment processes. The radiations incoming from the hot zone are equally separated by a beam splitter into two CCD arrays equipped with different interferential filters. The temporal resolution is 25 images per second while the spatial resolution is 512 x 512 pixels. This system, applied to gray bodies, enabled us to control the heat surface treatment such as the laser cladding process. This device should soon also be used in a laser welding application, in which experimental conditions fluctuate. Also, in the near future we envision an extension our method to a version with 3 wavelengths in order to be able to introduce a slight (linear) variation of the emissivity with the wavelength. The primary results are promising \(^{21}\) and will soon be presented elsewhere.

REFERENCES


