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# High throughput dual-wavelength temperature distribution imaging via compressive imaging

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ABSTRACT

Thermal imaging is an essential tool in a wide variety of research areas. In this work we demonstrate high-throughput double-wavelength temperature distribution imaging using a modified single-pixel camera without the requirement of a beam splitter (BS). A digital micro-mirror device (DMD) is utilized to display binary masks and split the incident radiation, which eliminates the necessity of a BS. Because the spatial resolution is dictated by the DMD, this thermal imaging system has the advantage of perfect spatial registration between the two images, which limits the need for the pixel registration and fine adjustments. Two bucket detectors, which measures the total light intensity reflected from the DMD, are employed in this system and yield an improvement in the detection efficiency of the narrow-band radiation. A compressive imaging algorithm is utilized to achieve under-sampling recovery. A proof-of-principle experiment was presented to demonstrate the feasibility of this structure.



## 1. Introduction

Optical radiation pyrometry, which eliminates the fragility concerns that currently limit thermocouple measurements, provides an effective and practical approach to temperature measurements in a high-speed or noncontact situation. Noncontact radiometric temperature measurements are based on blackbody emission theory [1,2]. In general, to deduce the temperature from the measurement of emitted radiation, the value of the surface emissivity $\epsilon$, must be known. Therefore, in conditions that do not allow the independent measurement of target emissivity, the true temperature cannot be measured by the conventional radiometric methods.

Ratio pyrometry (also called two-color pyrometry or dual-wavelength pyrometry) [3,4], which measures the ratio of energy collected at two adjacent wavelengths, is widely used for high-temperature measurement in various fields [5–10]. Wavelength ranges are chosen to be as close as possible, such that the effect of material-specific peculiarities (reflectance, emissivity) and optical obstructions (e.g., smoke, dust, or dirty lenses) from the target are nearly-identical for both wavelength ranges. The influences on measurements can be corrected by calculating the ratio. The availability of infrared (IR) array sensors conveniently provides two-dimensional temperature distribution measurements that overcome the shortcomings of traditional point pyrometers. There are several possible procedures that can be used to complete two-color temperature distribution imaging with IR cameras. (1) In a single-camera system, different filters mounted on a rotating filter wheel in front of the detector are employed to split the measured radiation. However, the results may lose accuracy in the case of a fast-moving or non-stationary target because the measurement alternates between the two channels [10,11]. (2) Two synchronized cameras fitted with filters capture the radiation divided by a beam splitter (BS). However, the price of the cameras used in such applications is high, which makes the two-camera solution unreasonable for practical applications [9,11]. (3) A double detector (sandwich design) fitted with filters can be used, but this device is challenging to employ when wavelengths vary [10,12]. Specialized optical image splitters have also been constructed for dual-wavelength imaging, these are able to project two identical images side by side on the camera with complex optical structures [11,6]. The limited usage of the double wavelength thermal imaging arises from the complex dual light path design and the cost of IR array sensors. In

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addition to the dual light path design, the detection of weak radiation after the narrow-banded filters is another obstacle in the two-color temperature imaging system.

The 'single-pixel camera' [13,14] technique, which provides an approach to imaging in scenarios in which multi-pixel sensors are not available due to cost or technological constraints, exhibits superiority in many optical schemes [15–18], especially in some spectral imaging configurations [19–21]. Compressed sensing (CS) algorithms [22,23], which utilize the sparsity of a target in a certain domain, enables single-pixel cameras to recover an image with far fewer measurements than the Nyquist limit.

In this work we demonstrate thermal imaging from a modified single-pixel camera for double wavelengths, which enables high-quality thermal imaging while lowering the complexity in the optical design of a device and exploiting high throughput detection. The advantages of the proposed method are (1) A digital micro-mirror device (DMD) is utilized to display binary masks and split the incident radiation, which eliminates the need for a BS. Pixel registration and fine adjustments of the two images are unnecessary because of this reflected structure. (2) The high throughput bucket detector measures many pixels simultaneously and so results in an improvement of the detection efficiency. This is helpful, because the radiation in a narrow-band is often very difficult to detect. (3) Compression algorithm is utilized for accurate reconstruction with measurements less than that of the pixels to be resolved. (4) Changing wavelengths is simple using this method.

The manuscript consists of four sections. In the second section, the method is presented. The experimental procedure is discussed in the third section. An experimental thermal image with a resolution of $256 \times 256$ pixels is acquired to show the feasibility of this structure. A proof-of-principle experiment was performed to show the superiority of high throughput detection.

## 2. Method

### 2.1. Double-wavelength temperature measurement

The relationship between radiation energy and the true temperature of a target in a monochromatic wavelength $\lambda$ is obtained by using Planck's radiation law

$$M(\lambda,\varepsilon,T) = \frac{C_1}{\lambda^5}\cdot\frac{\varepsilon(\lambda)}{e^{C_2/\lambda T}-1}, \tag{1}$$

where $M$ is the energy of radiation, $\lambda$ is the wavelength, $T$ is the true temperature, $C_1 = 3.7403$ [J/m$^3$] is the 1st radiation constant, $C_2 = 14387.69$ [μm K] is the 2st radiation constant, $\varepsilon(\lambda)$ is the emissivity of the target at wavelength $\lambda$. When $T < 3000$ K, using Wien's approximate formula, Eq. (1) can be simplified to

$$M(\lambda,\varepsilon,T) = \frac{C_1}{\lambda^5}\cdot\varepsilon(\lambda)e^{-C_2/\lambda T}. \tag{2}$$

The two-color thermometry constructed operates at two wavelengths $\lambda_1$ and $\lambda_2$ . Ignoring the bandwidths of the two wavelengths, Eq. (2) yields

$$R(T) = \frac{M(\lambda_1,\varepsilon(\lambda_1),T)}{M(\lambda_2,\varepsilon(\lambda_2),T)} = \frac{\varepsilon(\lambda_1)}{\varepsilon(\lambda_2)}\left(\frac{\lambda_2}{\lambda_1}\right)^5 \exp\left[\frac{C_2}{T}\left(\frac{1}{\lambda_1}-\frac{1}{\lambda_2}\right)\right], \tag{3}$$

where $R(T)$ is the ratio between the energies of the two wavelengths. Then, the temperature ratio $T_r$ is

$$T_r = \frac{C_2\left[(1/\lambda_1)-(1/\lambda_2)\right]}{\ln R(T) - 5\ln(\lambda_2/\lambda_1) - \ln(\varepsilon(\lambda_1)/\varepsilon(\lambda_2))}. \tag{4}$$

From Eq. (2), the relation between the ratio temperature $T_r$ and the true temperature $T$ can be derived

$$\begin{aligned} \frac{C_1}{{\lambda_1}^5}\cdot e^{-C_2/\lambda_1 T_r} &= \frac{C_1}{{\lambda_1}^5}\cdot\varepsilon(\lambda_1)e^{-C_2/\lambda_1 T} \\ \frac{C_1}{{\lambda_2}^5}\cdot e^{-C_2/\lambda_2 T_r} &= \frac{C_1}{{\lambda_2}^5}\cdot\varepsilon(\lambda_2)e^{-C_2/\lambda_2 T}. \end{aligned} \tag{5}$$

From the above equation,

$$T_r = \frac{1}{\frac{1}{T} + \frac{\ln(\varepsilon(\lambda_1)/\varepsilon(\lambda_2))}{C_2\left(\frac{1}{\lambda_1}-\frac{1}{\lambda_2}\right)}}. \tag{6}$$

For the dual wavelength method, an *a priori* relation for the emissivity variation, but not the emissivity value, is needed to infer the target temperature. Supposing the target is a gray-body ($\varepsilon$ is independent of wavelength) or has equal emissivity at $\lambda_1$ and $\lambda_2$, then $\varepsilon(\lambda_1) = \varepsilon(\lambda_2)$, and $T_r = T$.

The accuracy of the dual-wavelength method is crucially dependent on the selection of the two wavelengths $\lambda_1$ and $\lambda_2$. The expected temperature of the target and the spectral sensitivities of the detectors influence the choice of wavelengths. According to Wien's law, the wavelength $\lambda_{rmax}$ for which the radiance is maximal is given by $\lambda_{rmax}T = 2898$ μm K, the higher the temperature, the shorter the radiation wavelength $\lambda_{rmax}$. Another factor that affects the accuracy is the interval between the two wavelengths, which should be sufficiently small to validate the gray-body hypothesis but large enough to ensure a sufficiently precise measurement.

### 2.2. Compressive imaging

The CS reconstruction algorithm employs optimization to detect a sparse $n$ dimensional signal with $m < n$ measurements by pursuing the sparse solution of the minimum $l1$-norm in the optimization program. If we denote the object as an $n$-dimensional vector $O(x)$, we assume that there exists a transformation matrix $\Psi$ to the sparse basis such that $O(x) = \Psi \cdot O'(x')$, where $O'(x')$ is sparse. The *a priori* knowledge that the object can be sparsely expressed in a known basis is general, because many natural objects are indeed sparse in the appropriate basis. In CS, the measurement process can be formulated as

$$y = A\Psi O'(x') + e, \tag{7}$$

where $A$ is an $m\times n$ measurement matrix ($m < n$) and $e$ is the noise. In this paper, a complementary measurement method is adopted [18]. Thus, $A$ is a $-1/1$ binary matrix with zero mean. Because $m < n$, the observation vector $y$ does not specify a unique $O(x)$. In CS, the $O'(x')$ of the minimum $l1$-norm that yields a good agreement with the measurements is pursued through

$$\begin{aligned} O'(x') &= \arg\min\left\{\left\|A\cdot\Psi\cdot O'(x') - y\right\|_2^2 - \tau\left\|O'(x')\right\|_1\right\}, \\ O(x) &= \Psi\cdot\hat{O}'(x') \end{aligned} \tag{8}$$

where $\hat{O}(x)$ is the reconstructed image and $\tau$ is a constant scalar that weights the relative strength of the two terms. In compressive imaging methods, the binary matrixes are generally realized via spatial structure illumination, and the observation vector $y$ corresponds to the signal from a bucket detector that collects all of the modulated light. Various iterative algorithms [24–26] have been developed to solve the optimization problem specified by Eq. (8).

In dual-wavelength temperature distribution imaging, two images taken at different wavelengths are necessary. We employ a modified single-pixel camera system to capture the two images $I_{\lambda_1}(x)$ and $I_{\lambda_2}(x)$. The temperature distribution of the target is obtained from the ratio of two images,

$$R(x) = \frac{\sigma_1 I_{\lambda_1}(x)}{\sigma_2 I_{\lambda_2}(x)}, \tag{9}$$

where $\sigma_1$ and $\sigma_2$ characterize the optical efficiencies and detector sensitivities of the real system at the two wavelengths, respectively, and can be obtained by calibrating the instrument using a blackbody source at a known temperature.