Imaging thermal properties by super resolution far-infrared thermography

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Non-contact thermal imaging quantifies temperature by detecting the sample surface radiance in the mid- to far- infrared spectral band via Stefan-Boltzmann's law and the grey-body approximation. It offers the main advantage of non-invasive absolute temperature measurements over wide (>cm^2-sized) sample areas. However, the spatial resolution of thermographic sequences is intrinsically limited by the combined effect of light diffraction at the thermal-camera collecting lens (i.e., Abbe's law) and of heat diffusion across the sample: the spatial resolution of low-cost commercially available microbolometer cameras is typically limited to the mm- range, thereby hampering the routine exploitation of conventional far-infrared thermography for microscale imaging applications. Furthermore, temperature maps are not easily converted into quantitative images of any sample thermal property (e.g., the thermal conductivity), which would be beneficial instead for a variety of applications ranging from the characterization of cultural heritage artifacts to the development of heat transfer models for biological soft materials for disease diagnosis and hyperthermia-based therapeutics.

We tackle here both these limitations by combining the implementation of a super-resolution far-infrared image acquisition scheme [1] with quantitative data analysis protocols aimed at the space-resolved extraction of the sample thermal properties [2,3].

Our strategy takes advantage of the photo-thermal effect primed by the sample absorption of modulated and raster-scanned visible laser light. A sequence of sparse temperature variations is laser-primed on the sample and, by the automated non-linear surface fit of the images acquired by a thermal camera, the location of light-absorbing and heat-releasing species is retrieved with an uncertainty that is only assigned by the signal-to-noise ratio of the detected temperature increments and by the tunable excitation laser spot size. By the centroid coordinates of all the localized temperature peaks, a super-resolution image of the sample can be reconstructed at sub-diffraction ~10-50 µm resolution on a typical far-infrared camera with ~300-µm diffraction-limited resolution and ~400-µm pixel size on the sample plane [1].

The amplitude and temporal kinetics of laser-primed temperature variations are exploited instead to extract information on the sample thermal properties. To this aim, we rely on the analytical/numerical solution of the three-dimensional heat equation in the presence of focused laser-light illumination, and by properly modelling camera-based temperature detection via Stefan-Boltzmann's law, we provide the theoretical framework to model experimentally detected temperature increments as a function of both instrumental parameters and the sample thermal properties. We outline therefore the data analysis protocols to recover, on both thermally thin and thermally thick solid-state samples, either the concentration of laser-excited photo-thermal probes or the sample thermal conductivity over the broad 0.1-100 W/mK range.

We finally provide experimental validation of our results and report two exemplary applications demonstrating the feasibility of the proposed approach. On the one hand, we focus on cultural heritage conservation, and we characterize the deterioration state of eighteenth-century tin organ pipe fragments by spatially mapping the product of the sample thickness and thermal conductivity. Such a parameter, which is related here to sample oxidation, is pointed out as a relevant indicator for the non-destructive characterization of the sample conservation state [2]. On the other hand, we demonstrate quantitative far-infrared super-resolution thermography on biological tissues, and provide the space-resolved quantification of the molar concentration of melanin pigments in excised murine melanoma biopsies at 40-µm spatial resolution [3]. By coupling temperature maps with the extraction of thermal properties at high spatial resolution, our results significantly expand the capability of state-of-the-art infrared imaging technology in capturing the structural heterogeneity of the imaged tissue in a label free configuration, and suggest potential impact in complementing standard histopathological analyses of pigmented skin lesions ex-vivo.

References

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