Super-resolution thermographic imaging using blind structured illumination

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Abstract

Using an infrared camera for thermographic reconstruction has many advantages compared to ultrasound reconstruction: no coupling media is needed and it makes it possible to measure the temperature of many surface pixels both simultaneously and without contact. From the measured surface data, a sub-surface structure, embedded inside a sample or tissue, can be reconstructed and imaged when heated by an excitation light pulse. The main drawback is the strong degradation of spatial resolution with increasing imaging depth, which results in blurred images for deeper lying structures. In this work, it is shown that this degradation can be circumvented by using blind structured illumination, combined with a non-linear joint sparsity reconstruction algorithm. We demonstrate this by imaging a line pattern and a star-shaped structure through a metal sheet with a resolution four times better than the width of the thermal point-spread-function. The structured illumination is realized by parallel slits cut in an aluminum foil, where the excitation is carried out either by a flashlight, which passes the foil through the slits, or by a VCSEL array illuminating pseudo-random line patterns. This realization of super-resolution thermographic imaging demonstrates that blind structured illumination allows thermographic imaging without high degradation of the spatial resolution for deeper lying structures. The ground-breaking concept of super-resolution can be transferred from optics to diffusive imaging by defining a thermal point-spread-function, which gives the principle resolution limit for a certain signal-to-noise ratio, similar to the Abbe limit for a certain optical wavelength.

1. Introduction

In non-destructive imaging of opaque or turbid samples, the spatial information about subsurface structures, such as defects, can be extracted from measured surface data, such as acoustic pressure for ultrasonic imaging or temperature for thermographic imaging. The information about the defects is transferred from the samples interior to its surface by acoustic waves or heat diffusion, respectively.

Recently, we showed that the entropy production of these propagation processes limits the transferred information [1,2]. This poses a principle resolution limit, similar to the Abbe limit in optics. Thermodynamic fluctuations are reason for the entropy production,
which reduces the available information about the subsurface structures in the measured surface data. They are extremely small for macroscopic samples, but are highly amplified due to the ill-posed problem of image reconstruction. For macroscopic samples, the resolution limit depends only on the amplitude of these fluctuations.

Diffusive processes show a high entropy production with increasing diffusion length. Therefore, the resolution limit for thermographic imaging is found to be proportional to the subsurface depth and is described by a depth-dependent thermal point-spread-function (PSF) [2]. Similar to optics and acoustics, the blurring of imaged structures for thermographic imaging is modelled by convolution with this thermal PSF. Structures smaller than the width of the PSF cannot be resolved in conventional thermographic imaging. Circumventing such a principle resolution limit is called super-resolution. We discuss how blind (unknown) structured illumination combined with non-linear reconstruction algorithms using sparsity of the imaged structures allows thermographic imaging without high degradation of spatial resolution for deeper lying structures.

By adequate structured illumination [3], the spatial frequencies of the imaged object are downshifted by frequency mixing, resulting from the multiplication of the illumination pattern with the spatially varying optical absorption coefficient of the object. These downshifted spatial frequencies can be imaged if they lie within the low-frequency passband given by the Fourier transform of the PSF. Usually, in structured illumination, reconstruction algorithms use information about the illumination patterns for calculating the images. However, even small errors in the patterns can lead to artefacts in the final images [4]. Therefore, blind structured illumination was proposed where the knowledge of the illumination pattern is not necessary. Here, it is assumed that illumination patterns are positive and their sum is uniform [4]. Recently, two reconstruction algorithms using joint support and sparsity (called also block sparsity) were proposed which were applied for acoustic-resolution photoacoustic microscopy [5,6] and for thermographic imaging [7].

2. Experimental Setup

The spatial resolution limit, given by the PSF, could be greatly improved by utilizing blind structured illumination combined with a non-linear joint sparsity reconstruction algorithm. Fig. 1 shows one experimental set-up: a 3 mm thick steel sheet (common structural steel with a thermal diffusivity of 16 mm²s⁻¹) was painted black on both sides for light absorption and radiation purposes. On the front side, absorbing patterns such as parallel lines and a star-shaped pattern were created by using aluminum tape as a reflecting mask. As a result, only the unmasked (black) patterns absorb light from the optical flash light excitation (xenon gas discharge tube PBC -6000 from Blaesing using 6 kJ electrical energy and 2ms pulse duration). An infrared camera (IrcamEquus81kMPro) was used to measure the temperature evolution on the back side. In the first attempt, the structured illumination was created by parallel slits cut in aluminum foil, where the excitation from a flashlight could penetrate. A slit mask with 1 mm wide slits at a distance of 10 mm to each other was moved in the horizontal x-direction with a step size of 0.2 mm. The slits were not only oriented in the vertical y-direction, but also were also rotated ±45° in the x-y-plane (see Fig. 1). 55 patterns for each direction were used for illumination, resulting in 165 illumination patterns in total.
3. Results and Discussion

The theoretical lateral width (FHWM) of the thermographic PSF was evaluated to be 5.9 mm using the 3 mm thickness of the steel sheet and a signal-to-noise ratio (SNR) of 144 for the used thermographic measurements [7]. This could be experimentally validated. By using 55 different patterns of structured illumination and our iterative joint sparsity algorithm (IJOSP) [5], it was possible to resolve 1 mm thick lines at a distance down to 0.6 mm, which results in a resolution enhancement of approximately a factor of four. With “conventional” deconvolution (Richardson-Lucy-Deconvolution) the line pairs only down to a distance of 1.3 mm could be resolved, which demonstrates the capability of our super-resolution thermographic reconstruction method. The disadvantage is the higher number of structured illumination measurements, but for a fair comparison we have used for the “mean-signal” reconstruction and the Richardson-Lucy-Deconvolution the averaged signal of all 55 structured illumination pattern signals. The used measurement time is therefore equal for all compared methods.

A similar enhancement in spatial resolution could be demonstrated by reconstructing the image of a two-dimensional star-shaped structure using 165 different patterns of structured illumination.

REFERENCES


