Single Pixel Thermal Imaging via Adaptive Sampling

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Abstract

We describe a novel approach to long-wavelength infrared imaging, or *thermal imaging*. We exploit an agile architecture with a single low-cost thermal sensor that can be independently actuated in two dimensions to collect narrow field-of-view spatial "samples" of the scene of interest, equipping it with a simple *adaptive sensing* methodology to guide the sampling process toward spatial regions of interest, to effectively produce high-resolution thermal images from relatively few samples. We provide experimental evaluations to demonstrate the viability of our approach.

Background

Some Thermal Imaging Preliminaries:

- All objects with temperatures above absolute zero emit electromagnetic radiation (according to the *black body radiation* law).
- The "peak" wavelength at which energy is emitted decreases with increasing object temperature.
- Objects having temperatures between about 0°C and 100°C emit their peak energies at wavelengths in the *long-wavelength infrared* regime (∼8000-15000nm), much longer than the wavelengths of visible light (∼400-700nm).
- Long-wavelength IR imaging (aka *thermal imaging*) has emerged as a valuable tool with residential, industrial, and medical applications (see Figure 1 below).

Figure 1: Thermal images can indicate residential heat losses, industrial faults, and even certain cancers. (*images from Wikipedia*)

Problem Statement & Our Approach

Low-cost visible light sensors (e.g., CMOS and CCD) are **not** receptive to long-wavelength IR radiation. Instead, thermal imaging systems require expensive sensors and can cost upwards of $3,000 or more to produce high resolution images!

We develop an alternative approach that uses a *single* steerable long-wavelength IR sensor capable of "sampling" at user-specified points in the scene, and is equipped with a multi-stage *adaptive sensing* strategy designed to *automatically* acquire only "informative" samples of the scene.

Enabling idea: *Edges* often convey most information in (thermal) images.

Our adaptive sensing approach (described next) exploits the fact that edge detail is naturally "unveiled" by the multi scale (Haar) wavelet representation of the image (see, e.g., Figure 2 below)

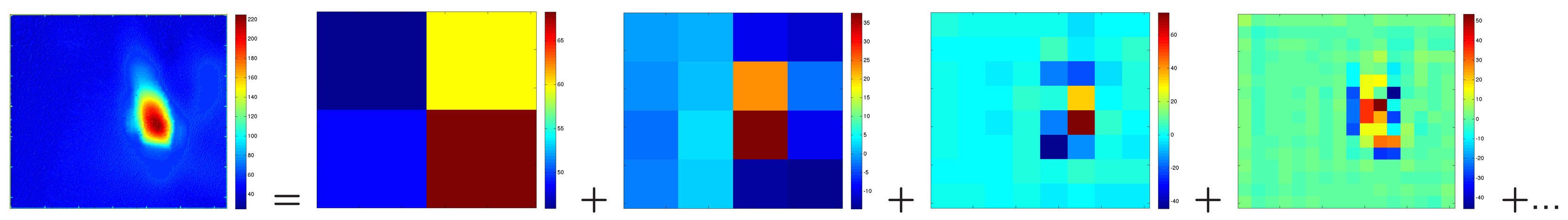


Figure 2: Multiresolution (Haar) decomposition of a thermal image (far left). Contributions at increasingly finer scales (moving from left to right) are restricted essentially to the vicinity of *edges* in the original image.

Adaptive Sensing Methodology

We consider a multi-step sampling and refinement strategy, where subsequent steps focus samples onto (sub)regions of interest. Our overall approach is as follows.

Initialize: Let $\mathcal{I}^1$ be the whole image domain (e.g., n^2 virtual grid points overlaid on an $n \times n$ pixel scene), choose some $m \ll n^2$, and $\lambda > 0$.

Iterate: For $k = 1, 2, \ldots, \log_2(n) - 1$

- Randomly choose m points $\Omega_k \subset \mathcal{I}^k$ (without replacement, and without duplicating previous choices) and collect m samples $\mathbf{y}_k = \{y_{i,j}\}_{(i,j)\in\Omega_k}$
- Reconstruct the image by enforcing sparsity in a *partial* Haar wavelet basis. Let $\mathbf{W}_{k+1}$ be a matrix whose columns are basis elements for the first (coarsest) $k+1$ levels of the Haar wavelet basis, and solve (e.g., using FISTA [2]):

$$\widehat{\theta}_k = \arg\min_{\theta} \|\mathbf{y} - \mathbf{W}_{k+1}\theta\|_2^2 + \lambda\|\theta\|_1 \qquad (1)$$

  where $\mathbf{y}$ contains *all* previously collected samples.
- Identify coefficients of $\widehat{\theta}_k$ at the finest (i.e., $(k+1)$-st) scale that are "significant"; let $\mathcal{I}^{k+1}$ be the grid points contained in the union of supports of those significant fine-scale coefficients.

The *final* estimate is obtained by (1) with $\mathbf{W}$ as the complete Haar basis.

Hardware Platform

Our overall design is based on independent two-dimensional actuation of single long-wavelength IR sensor*, and was inspired by the *Cheap Thermocam* project [1] (as well as the Rice *single-pixel* camera [3]).

Highlights of our (≈400$) device:

- Two (individually controlled) stepper motors* steer the IR sensor toward points on a (finely-spaced) grid of points defined on the scene (see Figure 3 below)
- Thermal sensor interfaced with a *Raspberry Pi* (*R-Pi*) via its I²C serial bus; stepper motors interfaced with the R-Pi via USB. (See Figure 4 below)
- The adaptive sampling-and-refinement algorithm (summarized above) is implemented directly on the R-Pi (in the *Python* programming language).

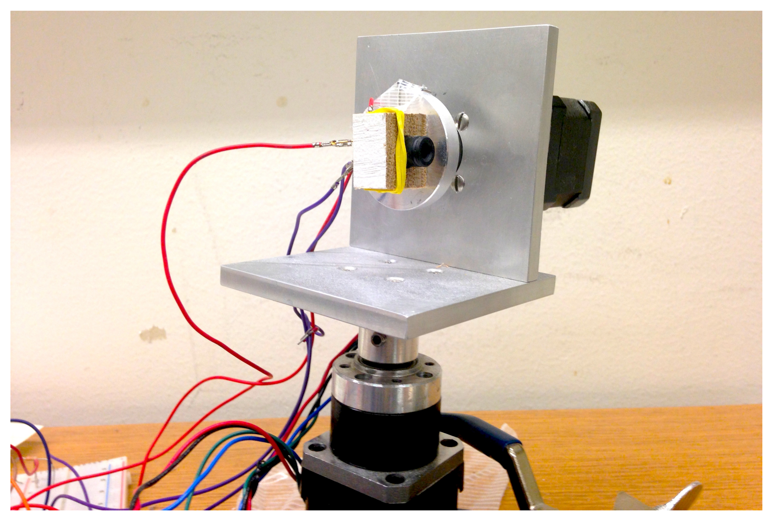


Figure 3: Image sensor and stepper motor assembly.

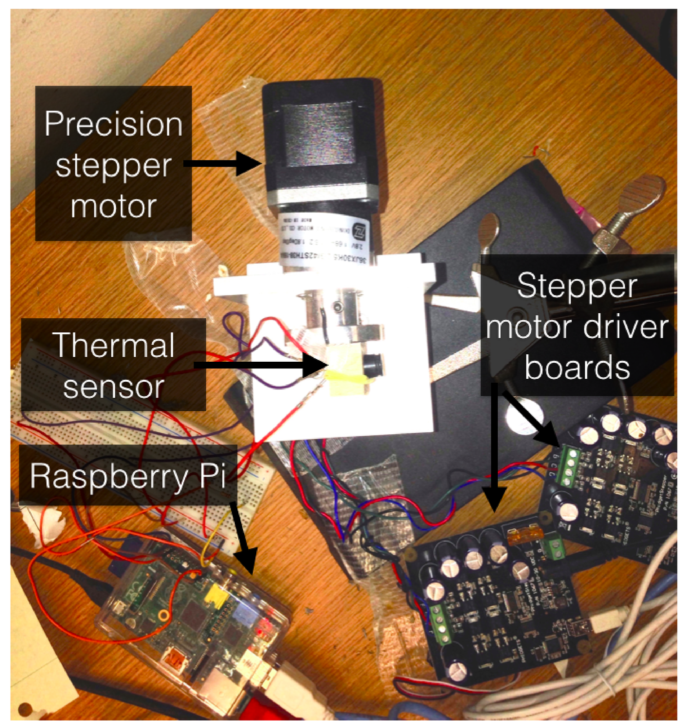


Figure 4: Top-down view of hardware.

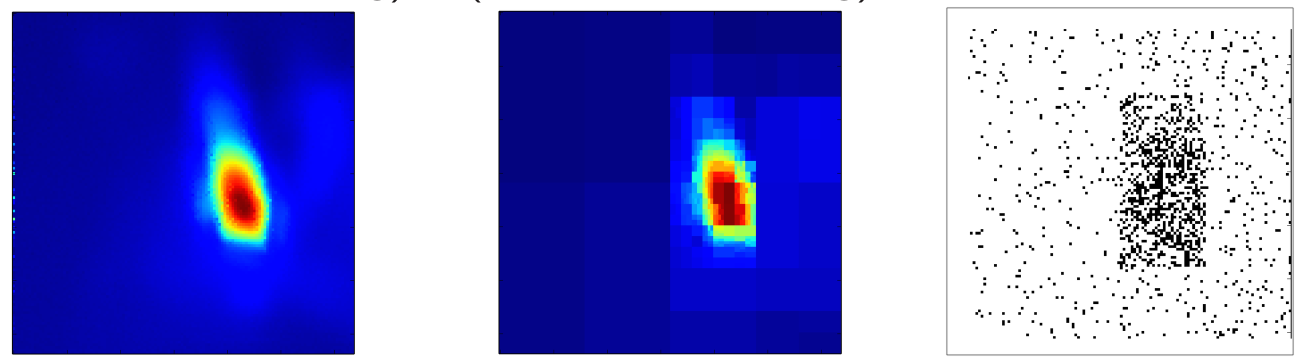
*We used the Melexis MLX90614 infrared sensor, and Phidgets stepper motors and driver boards.

Experimental Evaluation

We evaluated our approach on a "test scene" comprised of a hot soldering iron against a concrete block-wall background.

For $n \in \{64, 128, 256\}$ we virtually partitioned the scene into a $n \times n$ array of possible sampling locations, and compared the reconstructions obtained via *exhaustive sampling* of all n^2 sampling points, and by the aforementioned adaptive sampling method. A graphical comparison of the reconstructions for the $n = 128$ case is provided below, along with a depiction of the sampling locations (determined automatically) using our adaptive sampling method.

True image (Exhaustive Sampling) | Our Reconstruction (Adaptive Sampling) | Adaptively Sampled Locations



We also tabulated the image acquisition time for each approach (shown below). Overall, we see that the adaptive sensing approach yields $10\times$ or more improvements in acquisition time.

Image dimension	Exhaustive Sampling Time (min)	Adaptive Sampling Time (min)
$n = 64$	3.14	0.36
$n = 128$	12.56	1.43
$n = 256$	50.244	5.74

Conclusions & Next Steps

We demonstrated (experimentally) the viability of a novel, low-cost "single pixel" adaptive sampling thermal device for long-wavelength infrared (thermal) imaging.

Ongoing extensions to this initial effort include:

- establishing rigorous justification for our sensing strategy (e.g., using analyses along the lines of [4]), and
- implementing sampling-path planning strategies designed to minimize the acquisition time at each sampling step.

We also plan to investigate extensions of this basic architecture to other single-sensor imaging problems (e.g., terahertz imaging?).

References & Acknowledgments

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[4] R. Willett, R. Nowak, and R. M. Castro. Faster rates in regression via active learning. In *Advances in Neural Information Processing Systems*, pages 179–186, 2005.

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