Image Reconstruction through Scattering Media Using a Single-Pixel Camera

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Abstract:

Improved techniques to efficiently image (at optical wavelengths) objects embedded in or obscured by highly scattering media are desirable due to the large number of potential applications, most notably in the arena of biomedical imaging. In this experiment, we tested the performance of an image reconstruction technique utilizing Hadamard analysis and single-pixel photodetection of both forward and backscattered light. Resolution targets were fabricated and obscured by scattering media, and subsequently illuminated with structured light patterns projected by a digital micromirror device. Outgoing scattered light was collected and focused onto a photodiode, and the resulting signal analyzed in order to reconstruct an image. We tested imaging of reflective targets illuminated with incoherent white light, and are currently doing the same with fluorescent targets illuminated by a supercontinuum laser source tuned to the proper excitation frequency.

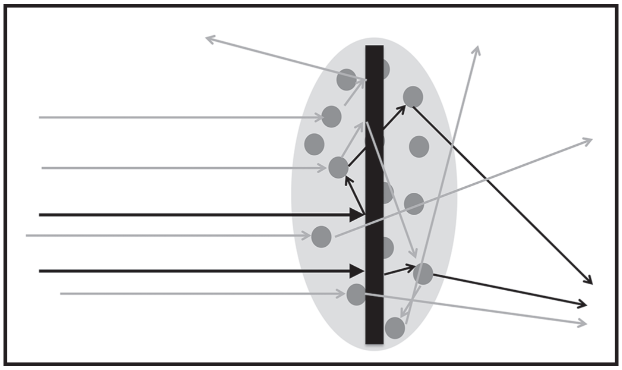

Figure 1: Incident light is scattered due to impurities in a medium. The bold rays represent the few "ballistic photons" that make it to an obscured target without scattering.

Introduction:

Certain types of materials scatter light in complex and unpredictable fashions due to the presence of irregularities/impurities, or "scattering centers," suspended throughout the otherwise regular medium. One example of this type of material is biological tissue, and so a viable technique to image objects obscured by or embedded in highly scattering media is highly sought after for its potential applications in biomedical fields.

If an object is embedded inside a highly scattering medium and subsequently illuminated by light, the light that propagates through and exits the system can be divided into two classes. Assuming the object is embedded at a depth greater than the transport mean free path of light, the majority of photons will be scattered away from their initial trajectory before reaching the object. These are the **multiply scattered photons**, and it is very difficult to retrieve any useful information about the embedded object. However, some photons will travel in effectively a straight line towards the object, either through forward scattering or avoiding scattering altogether. These **ballistic photons** will subsequently interact with the object, and their subsequent behavior will depend on the object's optical properties along the photon's initial trajectory. The technique we test for imaging through scattering media depends on the collection of these ballistic photons.

To accomplish this, we "scan" our medium/object ensemble by projecting light in a sequence of patterns, each illuminating some particular fraction of the ensemble. Formally, these **Hadamard patterns** are an orthonormal basis of 2D Walsh functions, and thus completely sample the ensemble. We collect the emergent light signal with a photodiode (a "single-pixel camera"). This signal consists of a noisy "blur" from the multiply scattered photons, as well as important fluctuations resulting from the ballistic photons, the intensity of which are related to the object's optical properties in the areas illuminated by a given Hadamard pattern. Collecting this signal for a complete set of patterns allows us to reconstruct an image of the embedded object.

Experimental Procedure:

We fabricated high-contrast imaging targets using standard deposition and lithography techniques, in general using silver or aluminum resolution patterns on glass. We used a variety of scattering materials throughout our experiments, including commercial diffusers, polyester resin with TiO_2

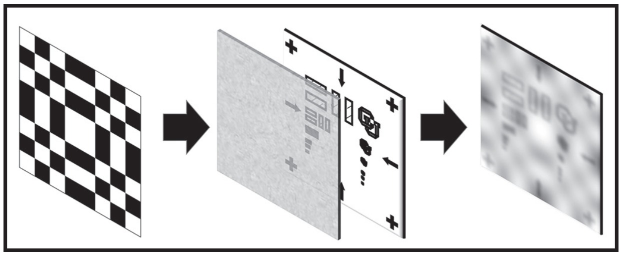

Figure 2: Projecting a light pattern on an obscured sample. The emerging light consists of diffuse noise plus "ghost" fluctuations related to the projected pattern and the properties of the target.

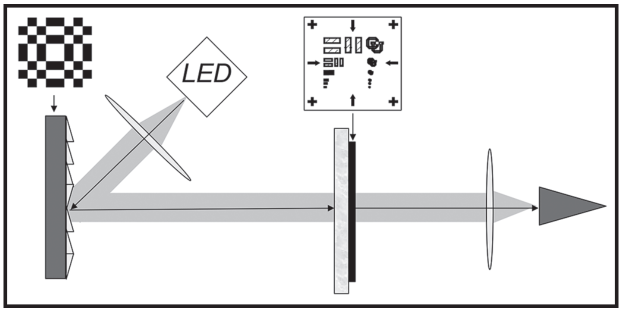

Figure 3: Simplified optical setup for transmission mode. Detector is located behind the scattering layer/target.

impurities, and gelatin. In each experiment, the target was obscured by the scattering layer and placed into our optical setup. The Hadamard patterns were projected in rapid succession using a Texas Instruments Digital Micromirror Device, an FPGA-controlled array of two-orientation mirrors.

The single-pixel imaging technique was tested in transmissive, reflective, and fluorescence experimental configurations, using several types of objectives with magnifications between 10× and 50×. In our transmissive setup, we used a high-powered white LED source. The photodetector was placed on the far side of the scattering layer and target, so as to collect the light transmitted through the ensemble. The second, "reflection mode" configuration involved using a standard beam splitter to capture the light scattered backwards from the ensemble instead. Finally, we used imaging targets with fluorophore-heavy photoresist rather than reflective metal. For this setup, we replaced our LED source with a supercontinuum laser tuned to the excitation frequency, and the beam splitter with an appropriate dichroic mirror.

In each experiment, the spatially resolved cross-correlation measurement between projection and response was summed over for the full set of patterns and normalized to a grayscale intensity value (0-255) in order to reconstruct an image.

Results and Future Work:

For our transmission mode experiment, we were able to achieve submillimeter resolution through several types of scattering media, each with thicknesses of several millimeters. An example set of images from this setup is shown in Figure 4. We subsequently demonstrated limitations with this imaging technique in more complicated optical setups. In reflection mode, the high level of backscattered light coming from the very front layer of our scattering media results in a high level of noise that makes extracting a useful signal much more difficult than in transmission. Our fluorescence experiment is an attempt to address this problem, as we use a dichroic mirror to filter out laser light coming off the front of the medium. More advanced detection systems are necessary for fluorescence imaging due to the very low amount of light making it to the detector; thus, future work involves combining a detection system such as a photomultiplier tube with sophisticated computer algorithms to compensate for noise levels.

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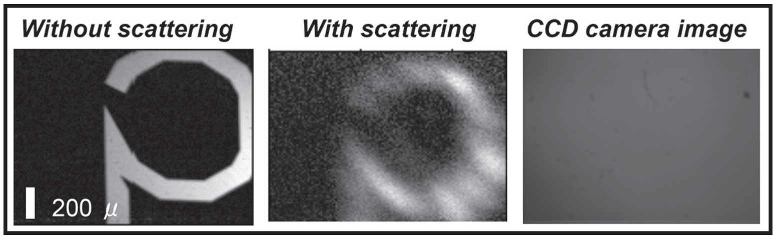

Figure 4: Sample image set from transmission experiment.