Optical imaging of hidden objects behind clothing

Yossi Ben-Aderet,[1,2,*] Er'el Granot,[1] Shmuel Sternklar,[1]
Tzachi Tal,[1] and Natan S. Kopeika[2]

[1]Department of Electrical and Electronics Engineering, Ariel University Center of Samaria, Ariel 40700, Israel

[2]Department of Electrooptical Engineering, Ben Gurion University of the Negev, Beer-Sheva, Israel

*Corresponding author: yossiba2@gmail.com

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Optical impulse-response characterization of diffusive media can be of importance in various applications, among them optical imaging in the security and medical fields. We present results of an experimental technique that we developed for acquiring the impulse response, based upon the Kramers–Kronig algorithm, and have been applied for optical imaging of objects hidden behind clothing. We demonstrate three-dimensional imaging with 5 mm depth resolution between diffusive layers. © 2010 Optical Society of America

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1. Introduction

Over the past several years, there has been an increased interest in security applications to identify objects that are concealed behind clothing. In fact, this problem is a special case of the generic problem of imaging objects embedded in a diffusive medium. Therefore, solutions to this problem can be applied to a wide variety of applications. Time-domain imaging can be employed in reflection mode to image a diffusive medium with submillimeter resolution [1–4]. The general idea behind time-domain imaging is simple: a pulsed laser illuminates the medium, and the reflected light, which includes light deflected from the front surface, as well as delayed light from internal reflections, is detected. If the detector is sufficiently fast, then the reflected light from the hidden object can be discerned.

A simple implementation of this technique is shown in Fig. 1. Light from a nanosecond-pulsed YAG laser illuminates the cloth. A portion of the scattered light is focused onto a detector and the resulting response displayed on an oscilloscope.

Figure 2 shows a picture of the target, which consisted of one of several different types of clothing and a metal object (an unpolished aluminum plate). The resulting impulse response is displayed in the scope, which consists of a double peak due to reflections from the cloth and hidden object. In this preliminary experiment, the time delay between the peaks is about 1.5 ns, due to the separation of about 22 cm between the cloth and metal object.

Although this simple technique works, it is obviously limited by the pulse length. In real scenarios, the distance between the clothing and object can be on the order of a millimeter. Such spatial resolution requires temporal resolution of the order of picoseconds. A streak camera has a sufficient temporal resolution. However, this technology is complicated and expensive. Streak cameras have been used in the past for ballistic imaging in diffusive media in general and biological media in particular [5,6].

We have developed a simpler approach for ballistic imaging [7], which could have many applications in homeland security as well as medical imaging. We acquire the impulse response of the medium with spectral techniques by reconstructing the complex spectral response of the medium, $H(\omega) = A(\omega)\exp[i\varphi(\omega)]$, and then determining the impulse response by a simple fast Fourier transform (FFT). We developed an inherently fast technique for this application based upon the Kamers–Kronig (KK) algorithm [8,9].

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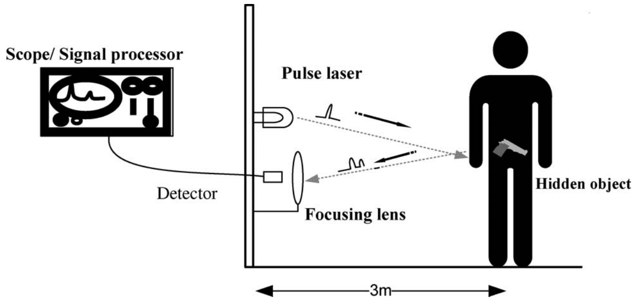

Fig. 1. Illustration of time-domain imaging.

It should be stressed that this technology is totally generic and can be applied to the impulse response of any medium, provided the signal is not buried below the noise level.

2. The Algorithm

The well-known KK relations establish a connection between the real and imaginary parts of a complex function. These relations are very general and are useful in experimental situations where only part of the relevant information can be directly obtained. In our case, the amplitude spectrum $|H(\omega)|$ can be acquired quickly and easily, but the phase $\varphi(\omega)$ procedure is difficult, in practice, because the phase measurements are complicated and relatively noisy. Here, we apply the KK technique to restore the phase spectrum [7–9] from the amplitude spectrum reflected from the cloth. Because the KK can be applied quickly, the entire spectrum can be restored almost instantaneously.

The algorithm is straightforward. The amplitude spectrum $|H(\omega)|$ of the reflected signal is acquired, and then the Kramers–Kronig or the Hilbert transform is used to derive the phase spectrum through the relation

$$\varphi_{\mathrm{KK}}(\omega) = -\frac{1}{\pi} P \int_{\omega_1}^{\omega_2} \mathrm{d}\omega' \frac{\ln|H(\omega')|}{\omega' - \omega}, \qquad (1)$$

where P stands for Cauchy's principal value. In practice, a discrete algorithm is used because the spectrum is acquired as discrete data. Therefore, instead of a time-consuming integral, a much faster FFT-based algorithm can be used [10]. To avoid singularities at the boundaries of the spectral domain, a correction term can be calculated, which was developed by our group [8,9].

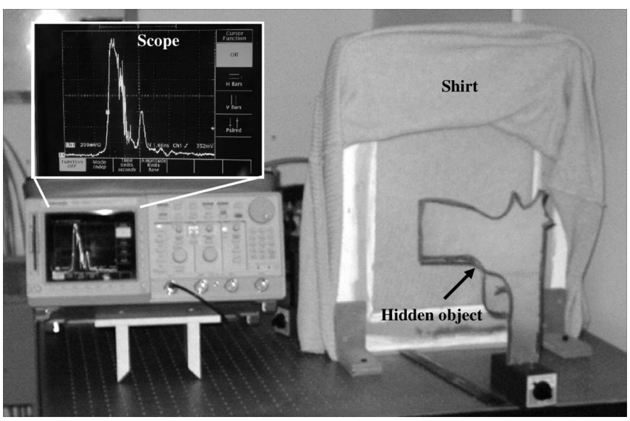

Fig. 2. Experimental setup and results (double peak) as seen on the oscilloscope. The horizontal axis scale is 1 ns/div.

From the two spectra, the full (approximate) transfer function can be reconstructed:

$$H_{\mathrm{KK}}(\omega) = |H(\omega)| \exp[i\varphi_{\mathrm{KK}}(\omega)]. \qquad (2)$$

By applying the inverse FFT on the transfer function, the impulse response of the medium, $h_{\mathrm{KK}}(t) = \mathrm{IFFT}\{H_{\mathrm{KK}}(\omega)\}$, is calculated.

We have recently shown [11] that the impulse response can be reconstructed using an easier and faster procedure than the standard KK algorithm described above. In fact, there is no need to calculate the phase spectrum and only then to use it to calculate the impulse response from the spectral response. The medium's response can be evaluated directly.

In general, the system response to a discrete delta function is [12]

$$h(n) = h_e(n)u(n), \qquad (3)$$

where time is a dimensionless integer n and

$$u(n) = \begin{cases} 1 & n = 0, N/2 \\ 2 & n = 1, 2, \ldots (N/2) - 1 \\ 0 & (N/2) + 1, \ldots N - 1 \end{cases}. \qquad (4)$$

If $h(n)$ is a real finite sequence then the FFT of the even function is equal to the real part of the transfer function:

$$h_e(n) = \frac{1}{N} \sum_{k=0}^{N-1} \Re H(k) \exp(2\pi i k n / N) = \mathrm{IFFT}\{\Re H(k)\}. \qquad (5)$$

Therefore, taking the inverse FFT of the real part of the transfer function and then setting the entire negative part to zero will result in the impulse response:

$$[\mathrm{IFFT}\{\ln|H(\omega_k)|\}u(n)] = \mathrm{IFFT}\{\ln H(\omega_k)\}. \qquad (6)$$

Therefore,

$$H(\omega_k) = \exp(\mathrm{FFT}[\mathrm{IFFT}\{\ln|H(\omega_k)|\}u(n)]), \qquad (7)$$

$$h(t_n) = \mathrm{IFFT}\{H(\omega_k)\} = \mathrm{IFFT}\{\exp(\mathrm{FFT}[\mathrm{IFFT}\{\ln|H(\omega_k)|\}u(n)])\}. \qquad (8)$$

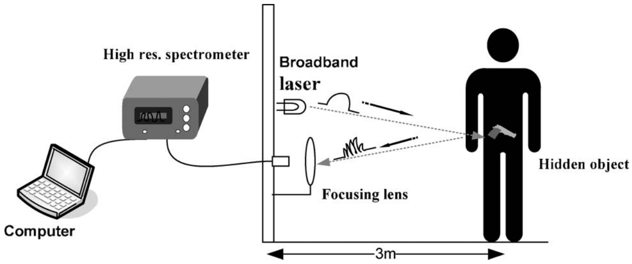

Fig. 3. Illustration of spectral techniques based on KK.

The main benefit of this method is that it is based on Fourier transforms; hence, it is more efficient than the previous method. Using this algorithm, the impulse response of the medium can be acquired in real time. We applied this technique to characterize diffusive media [11].

3. Experiment and Results

Figure 3 shows a schematic of the experiment based upon the KK technique. Instead of using a pulsed laser source, we use a cw source having a broad bandwidth and replace a single high speed detector with a spectrometer, which simultaneously measures the entire amplitude $A(\omega)$ (or intensity) spectrum of the spectral response.

A photograph of the actual experimental system is illustrated in Fig. 4. Light from a spectrally wide (35 nm width) laser source at 1550 nm was directed at a target at a distance of 3 m, which consisted of a shirt and a metal object (an unpolished aluminum plate), positioned 5 mm behind it. A lens collected the reflected light, which was analyzed in a high-resolution (30 pm) wideband spectrometer, and the data sent to a computer for analysis.

In our experiments, the acquisition time per pixel was ~20 msec, which is a short enough time to regard the clothing as stationary and the processing time was ~1 sec. This can be reduced dramatically using dedicated electronics based on our new algorithm.

In Fig. 5, the reconstructed intensity $I_{\mathrm{KK}}(t) = |h_{\mathrm{KK}}(t)|^2$ impulse response is shown, when illuminating a portion of the shirt that hides the object behind it. The reflections from the first layer (the clothing) and the second layer (the hidden metal object) are clearly seen. Despite the fact that the second pulse is orders of magnitude smaller than the reflection from the clothing, it is still a few orders of magnitude larger than the ambient noise, and can easily be separated from the first reflection. The gray line is a typical impulse response when the beam illuminates the clothing alone.

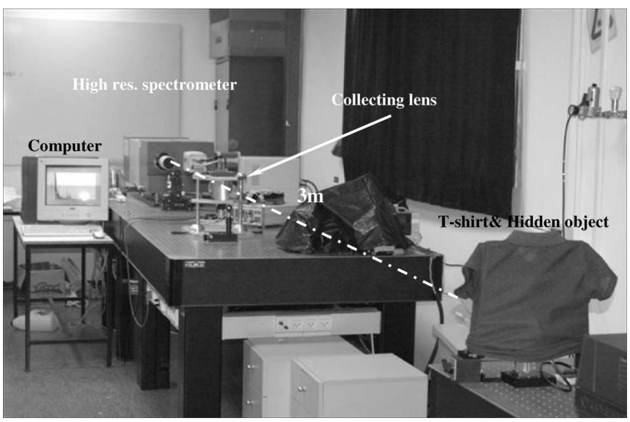

Fig. 4. Experimental system.

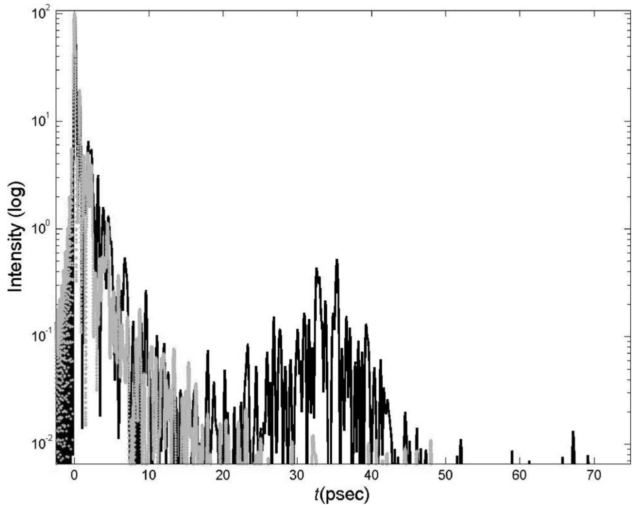

Fig. 5. Typical reconstructed impulse response for shirt alone (gray) and for shirt plus object (black).

As seen in Fig. 5, the ratio between the first pulse (reflection from the shirt) and the second pulse (reflection from the object) was ~200, and the signal-to-noise ratio (SNR) of the second pulse was ~5. Therefore, the object had to be oriented at 90 deg to maximize its reflection and SNR. To increase the solid angle of the measured reflected signal, the system must be improved to reduce noise level and/or increase the signal level (e.g., by improving the spectrometer sensitivity).

A total of 8 × 8 transverse positions were recorded. From this data, the image of the object is reconstructed, as shown in Fig. 6. The spatial resolution depends on the beam's width at the target, while taking into account the time constraints for image acquisition.

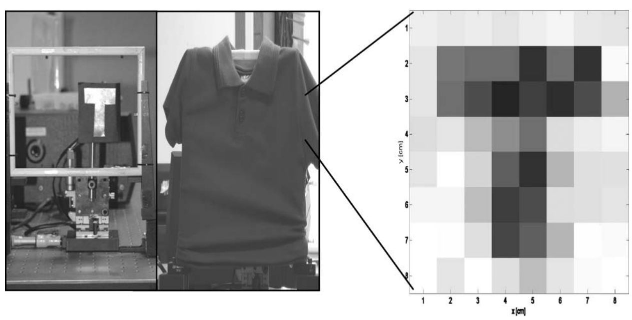

Fig. 6. (Left) Target uncovered and covered by a shirt. (Right) 8 cm × 8 cm final image of the hidden object.

4. Summary

We have developed a new spectral technique for acquiring the optical impulse response of a diffusive medium and have applied it for imaging hidden objects behind clothing. This technique has the potential to be a robust and fast technique for applications that require imaging through a diffusive medium.

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