Optics Communications 368 (2016) 134–140

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

# Three-dimensional ghost imaging using acoustic transducer

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ARTICLE INFO

*Article history:*
Received 20 December 2015
Received in revised form
24 January 2016
Accepted 26 January 2016

*Keywords:*
Coherence imaging
Photoacoustics
Image formation theory

ABSTRACT

We propose a novel three-dimensional (3D) ghost imaging method using unfocused ultrasonic transducer, where the transducer is used as the bucket detector to collect the total photoacoustic signal intensity from spherical surfaces with different radius circling the transducer. This collected signal is a time sequence corresponding to the optic absorption information on the spherical surfaces, and the values at the same moments in all the sequences are used as the bucket signals to restore the corresponding spherical images, which are assembled as the object 3D reconstruction. Numerical experiments show this method can effectively accomplish the 3D reconstruction and by adding up each sequence on time domain as a bucket signal it can also realize two dimensional (2D) ghost imaging. The influence of the measurement times on the 3D and 2D reconstruction is analyzed with Peak Signal to Noise Ratio (PSNR) as the yardstick, and the transducer as a bucket detector is also discussed.



## 1. Introduction

Ghost imaging, as a newly emerging optical imaging method, has arouse broad concern because of its advantages on imaging in complex environment, separation between detection and imaging and so on. The incipient experiment of ghost imaging was conducted with entangled photons [1–3]. The original ghost imaging realized with pseudo-thermal light emerged many achievements [4–12]. In the recent several years, with the successive achievements on lensless ghost imaging [13], true thermal light ghost imaging [14,15] and advanced algorithm to enhance the PSNR [16–21], ghost imaging ceases from being just a hypothetical theory, and many of the researches are turning into a series of practical applications [22–31]. For example, in researches on optical encryption [22,28], ghost imaging was applied in 3-D optical encryption that a larger key space can be generated, on biomedical imaging [29], and on remote sensing, the 3-D ghost imaging ladar has been manufactured which can image objects from over 1 km and obtain 60 cm axis solution. By taking the structural properties of the recovered images into account, the reconstruction quality can be further improved [31]. However, achievements on 3D ghost imaging within a short distance are rarely reported.

As a burgeoning imaging method, photoacoustic imaging possesses both the advantages of the thermal imaging's high solution and ultrasonic imaging's nondestructive examination and strong penetrating power, which endows it with broad application prospect [32–36]. Photoacoustic imaging is based on the photoacoustic effect, which is aroused by the sound wave emitted by the object when irradiated by laser pulse and absorbing photons. The photoacoustic signal is acquired by an ultrasonic transducer, and processed by a reconstruction algorithm, it can provide the object's optic absorption characteristics [33]. Considering the similarity which both signals detected by the unfocused transducer and the bucket detector are corresponding to the optic absorption characteristics of the objects, a possibility appears that the photoacoustic imaging method can be applied to ghost imaging.

We propose a novel 3D ghost imaging scheme, in which the bucket detector is replaced by an unfocused ultrasonic transducer. Here, the total light intensity obtained by the bucket detector is replaced by the photoacoustic signal, and with a proper modification on traditional ghost imaging algorithm, the object's image can be reconstructed. Since the ultrasonic signal acquired by the unfocused transducer is a time sequence of the spatial sound pressure changing rate against time, the reconstruction result is a 3D deconstruction of the original target. In comparison to the traditional 2D ghost imaging, in our scheme when the laser pulse illuminated on the object reaches a certain intensity, a photoacoustic sequence signal can be obtained by the transducer on the object arm. Meanwhile, the light distribution is recorded on the reference arm records. As long as the object's axial depth on light path direction is no more than the light field's axial correlation depth [37], the object's 3D image can be restored by assembling the transducer-centered spherical surfaces reconstructed by the

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http://dx.doi.org/10.1016/j.optcom.2016.01.078

3D ghost imaging algorithm.

## 2. Method

The traditional ghost imaging is consisted of an object arm and a reference arm. As shown in Fig. 1(a), the pseudo-thermal source is acquired by a laser passing through a rotating ground glass and generating a constantly changing speckle pattern, which is separated into two identical beams by a splitter. On the object arm, beam ‘a’ is projected on the object, modulated by its transmission coefficient $T(x, y, z)$, and acquired by a bucket detector with no spatial solution, where it is recorded as bucket signal $B_n$. On the reference arm, the speckle pattern on beam ‘b’ is directly acquired by a spatial-distinguishable CCD, and recorded as $I_n(x, y)$. $z_1$ represents the distance between pseudo-thermal source and the object, and $z_2$ represents the distance between pseudo-thermal source and the reference CCD plane. When $z_1 = z_2$ or $|z_1 - z_2|$ is less than the light field axial depth [37], the correlation operation Eq. (1) as below can reconstruct the object's image $\boldsymbol{T}_{GI}$ using the $B_n$ and $I_n(x, y)$ from N measurements.

$$T_{GI}(x, y) = 1/N\cdot\sum_{n=1}^{N}(B_n - \langle B_n\rangle)I_n(x, y) \tag{1}$$

where the total light intensity is $B_n = \iint I_n(x, y)T(x, y)dxdy$, and its average value is $\langle B_n\rangle = 1/N\cdot\sum_{n=1}^{N}B_n$. As shown in Fig. 1(b), the modification is on the object arm, replacing the bucket detector with an unfocused ultrasonic transducer and $z_1$ represents the distance between pseudo-thermal source and the central surface of the object. The object and transducer are both placed in viscous transparent media such as water or oil in which the ultrasonic wave declines slower during transmission. The laser path on the object arm is defined as axis ‘z’. A photoacoustic signal is stimulated when a laser pulse is projected on the object with the spatial light absorbing coefficient matrix $T(x, y, z)$, and collected as a time sequence by an unfocused transducer on the right end of axis ‘z’, the nth measurement of which is recorded as $P_n(t)$. Finally, by using the $P_n(t)$ and $I_n(x, y)$ of $N$ measurements in our 3DGI method, a reconstruction of the object can be acquired as $T_{3DGI}(x, y, z)$.

The principle of unfocused ultrasound transducer is shown in Fig. 2. The transducer's wavefront is a spherical surface, so the time sequence $P(t)$ as in the square at time $t_1$, $t_2$, $t_3$ are the total photoacoustic signal intensity of all the sources on the surfaces centered at the detecting point with radius of $R_1 = v_s t_1$, $R_2 = v_s t_2$, $R_3 = v_s t_3$. Since the acoustic pressure signal acquired by the transducer at each moment is a representation of the total optical absorption characteristics on the corresponding spherical surface, so functionally the transducer can be considered equivalent to the bucket detector.

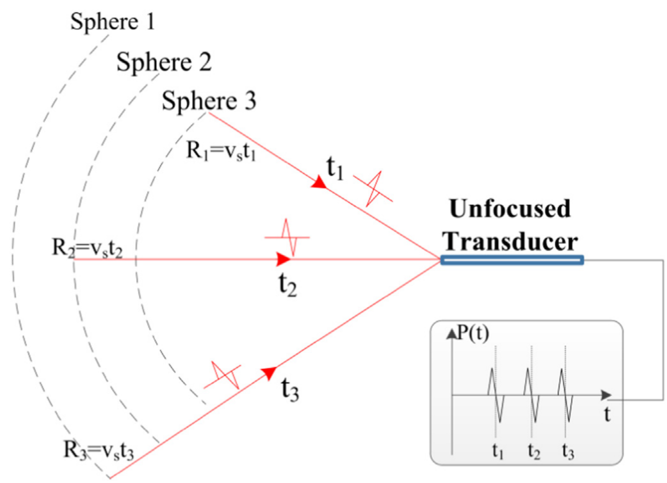


**Fig. 2.** Schematic diagram of unfocused ultrasonic transducer . $V_s$: sound velocity.

If the laser pulse lasts shorter than the acoustic confinement time, the acoustic pressure $p(\vec{r}, t)$ at moment $t$ and transducer location $\vec{r}$ in viscous media can be shown as below [32]

$$p(\vec{r}, t) = (\beta/4\pi C_P)\frac{\partial}{\partial t}\int d\vec{r'}\frac{1}{\left|\vec{r} - \vec{r'}\right|}\cdot H\left(\vec{r'}, t - \frac{\left|\vec{r} - \vec{r'}\right|}{v_s}\right) \tag{2}$$

where $\beta$ represents the thermal coefficient of volume expansion, $C_P$ represents specific heat capacities at constant pressure, $H$ represents the heating function and $\vec{r}\,'$ represents the sound source location. $H$ can be disassemble as below

$$H(\vec{r'}, t') = A_e(\vec{r'})H_t(t') \tag{3}$$

where $A_e$ is the specific or volumetric optical absorption, and is the laser distribution in time domain. The light field projected on the object is a speckle pattern and pulsing, so Eq. (3) can be modified as below

$$H(\vec{r'}, t') = A_e(\vec{r'})\delta(t')I(\vec{r'}) \tag{4}$$

where $I(\vec{r}\,')$ is the light intensity at location $\vec{r}\,'$ of the speckle pattern on the object. Combining Eq. (4) with Eq. (2), the following equation is established

$$p(\vec{r}, t) = \beta/4\pi C_P\cdot\frac{\partial}{\partial t}\int d\vec{r'}\frac{A_e(\vec{r'})I(\vec{r'})}{\left|\vec{r} - \vec{r'}\right|}\delta\left(t - \frac{\left|\vec{r} - \vec{r'}\right|}{v_s}\right) \tag{5}$$

Integrating the $p(\vec{r}, t)$ in the nth measurement, $p_n(\vec{r}, t)$, in time domain, we can obtain the following equation with proper

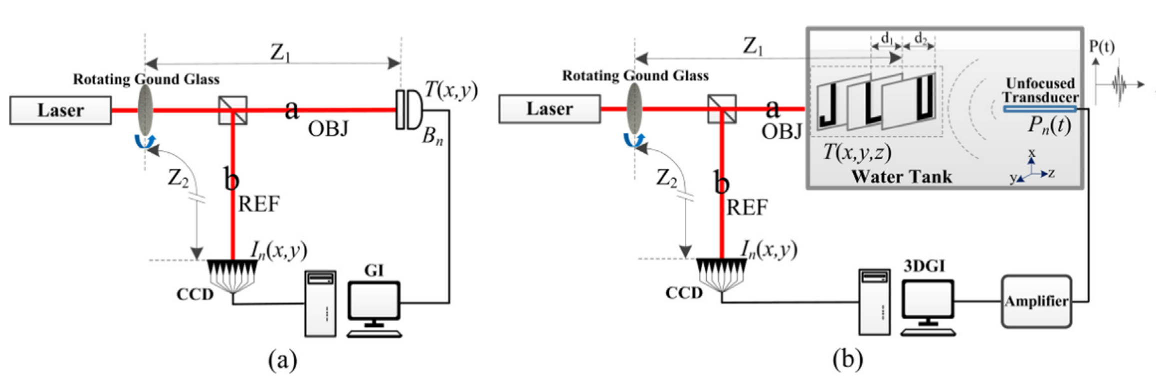


**Fig. 1.** Schematics of GI and 3DGI systems. (a) Traditional 2DGI method. (b) 3DGI method. OBJ: Object Arm; REF: Reference Arm. $z_1$: the distance between pseudo-thermal source and the object plane. $z_2$: the distance between pseudo-thermal source and the reference CCD plane.