

Holographic 3D Photography Under Ambient Light

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Abstract— We achieve three-dimensional photography of continuous objects and scenery under ambient (sunlight) illumination based on self-interference of two beam-split copies of the object's optical field with differential curvatures. The apparatus consists of a beam-splitter, a few mirrors and lenses, a piezo-actuator, and a CCD camera. No lasers or other special illumination is used for recording or reconstruction. Holographic images of daylight-illuminated outdoor scenes are obtained using a telephoto lens configuration. From the recorded hologram, images are reconstructed and numerically propagated to desired focal planes for viewing.

Keywords— Incoherent digital holography, three-dimensional photography.

I. INTRODUCTION

Photography records a two-dimensional projection of the intensity profile of an object onto a fixed plane. In contrast, holography records sufficient information to recreate the three-dimensional optical field emanating from an object, including both the amplitude and phase of the optical field [1]. The three-dimensional recording is made possible by the interference of the object's optical field and the reference optical field, and therefore requires coherence between the two. In D. Gabor's original conception, the reference is realized from a part of the illumination undisturbed by the object [2]. The invention of the lasers made it possible to provide a coherent reference field explicitly [3]. The coherence is at the core of the holographic principle, but it has been a major impediment to a wider range of applications of holography, requiring special illumination sources such as lasers and significantly constraining optical configurations. While practical methods have been successfully developed for displaying holograms using incoherent illumination [4], recording of holograms under incoherent illumination has been more problematic, until recently.

A number of principles have been proposed since early in the development of conventional, i.e. analog, holography to record holograms using incoherent sources [5]. For objects with spatial incoherence, the approach of generating two copies of the object field and arranging for self-interference between them has been implemented. Examples include the triangular interferometer [6] and conoscopic holography [7]. But in analog holography, such holograms of objects consisting of more than a few point sources are impractical because of the rapid accumulation of incoherent background. Digital holographic implementation of self-interference is a key to

realizing holography of incoherent object fields. Digital implementation of conoscopic and triangular holography have been demonstrated [8, 9], but the recent introduction of Fresnel incoherent correlation holography (FINCH) by J. Rosen fully demonstrated the ability to generate holographic images of incoherent object fields, including arc lamp illumination of macroscopic objects and 3D fluorescence microscopy [10, 11].

This report is a demonstration of holographic recording of outdoor scenes under natural daylight illumination using self-interference incoherent digital holography (SIDH). The optical system is based on self-interference with differential curvature. Conceptually similar to FINCH, but in place of the spatial light modulator, a beam splitting prism and two mirrors of different curvatures are used to generate two copies of the object field. Superposition of the two copies with different curvatures leads to Fresnel zone pattern interference from each source point. The spatial incoherence of the object points leads to rapid build-up of incoherent background which is removed by standard phase-shifting digital holography [12]. Detailed theoretical description of image formation by incoherent digital holography has been given in [13]. Several such phase-shifted interference patterns are acquired by a digital camera and analyzed to generate a complex hologram by arithmetically combining the multiple frames. The resultant hologram can then be numerically propagated to any desired distance to reconstruct the optical field. We have previously demonstrated the ability to capture ambient source holograms in separate color channels which were recombined to produce full-color holographic scenes [14]. Here we show the ability to produce improved image quality using unfiltered broadband natural sunlight.

II. EXPERIMENTS

The general apparatus, Fig. 1, consists of the input optics,

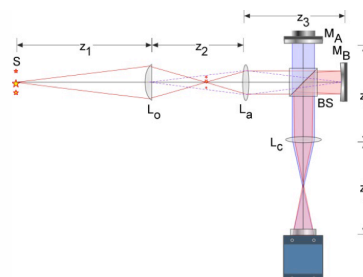


Figure 1. Apparatus for SIDH. L's: lenses; M's: mirrors; BS: beam-splitter.

the interferometer, and the imaging optics. The input optics consists of a pair of lenses that form a telescope. The interferometer consists of a beam-splitting cube and two mirrors, one is a plane mirror mounted on a piezo-actuator, which is driven by a ramp signal for phase shifting. The other is a curved mirror, of 600 mm focal length, to generate differential curvature. The imaging lens is chosen as appropriate for flexibility in magnification and physical dimensions of the apparatus.

To obtain interference, the distances of the two mirrors are matched. Proper adjustment can be verified by imaging a single LED source for fringes. Several exposures of an incoherent illuminated scene are captured while the phase-shifting piezo-mounted mirror travels through at least one full 2π phase excursion. The complex hologram is calculated from these N intensity profiles, I_n , by $H = \sum_{n=0}^{N-1} I_n \exp(i2\pi n / N) / N$.

Fig. 2 summarizes some results of the current apparatus in a telescopic configuration. Fig. 2A is a standard camera phone photo of a scene marked with red boxes to indicate locations

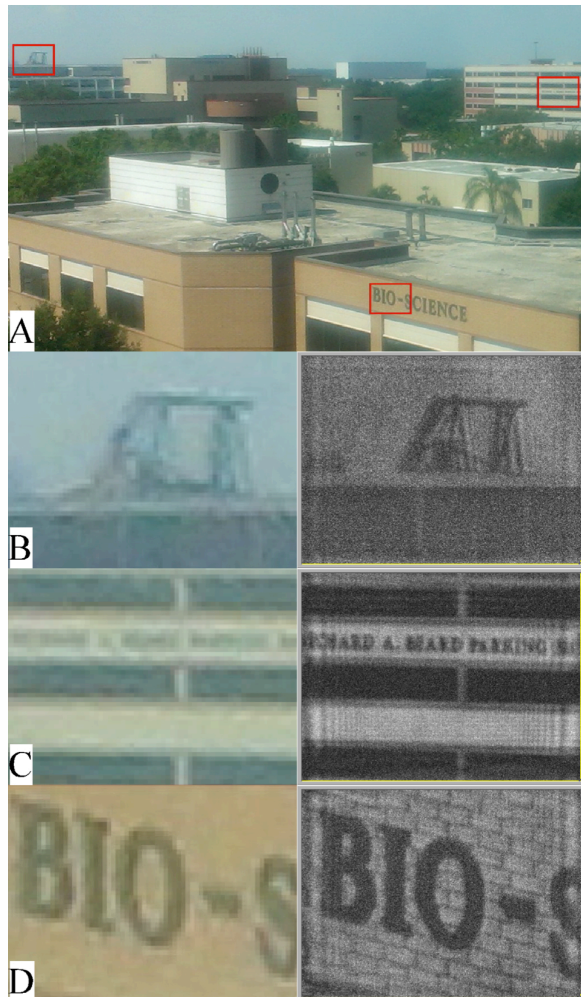


Figure 2. A) Cell phone camera image of a scene with regions of interest indicated by red boxes. Rows B) through D), Zoomed region of interest from A) on left and holographic reconstructions from telephoto-configured SIDH camera on right.

photographed using the holographic camera. Fig. 2B,C, and D are the enlarged regions of interest from the photo in Fig. 2A (left) and the grayscale holographic image (right).

III. DISCUSSION AND CONCLUSION

A major challenge in producing holographic images from pure broadband natural light by SIDH is the severely decreased temporal coherence. Careful consideration was taken when choosing our lens and mirror geometry to ensure that optical path differences between self-interfering points would remain mostly within this coherence envelope even during phase-shifting. Specifically, the field size applied to the mirrors and the curvature of the curved mirror should be kept to a minimum for a given application. Additionally, to aid in discerning the reduced contrast of interference associated with broadband incoherent sources, we have implemented a 14-bit (verses 8-bit) camera in the current study. With these constraints in mind, we have improved the effectiveness of SIDH for continuous outdoor sunlight scenes.

Currently we have proposed and are working on a single-shot SIDH method which will eliminate the need for phase-shifting by incorporating a slight tilt to the plane mirror [15]. This off-axis method may be quite important for dynamic biological applications, such as fluorescence microscopy; however, it may cost some lateral resolution and may not be suitable for broadband incoherence.

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