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PAPER

Scanning digital holography at 10.6 μm for large scene reconstruction

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Abstract

We demonstrate amplitude reconstruction of a very large scene hologram recorded by means of digital holography at 10.6 microns. Infrared digital holography is characterized by a low vibration sensitivity and a large field of view with respect to the analog technique in the visible range and it is, therefore, particularly suited for outdoor remote monitoring of large scenes. However, given the typical infrared sensor sensitivities, the power density scattered back by a large irradiated scene is usually not sufficient to produce a high signal to noise ratio hologram unless very high power lasers are used. Here we show that Mid Infrared Scanning Digital Holography can solve this problem. In particular, we report on the hologram amplitude reconstruction of a 6 m $\times$ 6 m scene from a distance of 30 m in outdoor condition using a compact 60 W CO_2 laser and a microbolometric camera.

Introduction

Digital Holography (DH) [1] is the natural development of analog holography [2]. In the so-called off-axis configuration [3], holograms result from the interference between the radiation scattered by the target (or transmitted through it), the so-called object beam, and a reference beam directly impinging on the detector array at an angle θ with respect to the object beam direction. If the hologram is recorded with a sufficiently wide angle, during its numerical reconstruction, the two diffraction orders are completely separated and a clear reconstructed image is obtained. However, due to the finite dimension of the camera pixels, beyond a certain threshold value of θ, interference fringes become too narrow to be sampled. This is a specific drawback of DH with respect to classical holography, which ultimately limits the field of view. Furthermore, as for any holographic technique, DH is strongly perturbed by environmental vibrations so that its use is mostly preferred for static target imaging. The above constraints are particularly restrictive for visible DH, which can only be performed on small targets and in an environment where mechanical vibrations are efficiently damped. Conversely, infrared DH inherently benefits from a wider linear field of view and lower mechanical stability requirements [4, 5]. Indeed, regarding the field of view, it is possible to demonstrate [6] that the maximum lateral dimension D of a target at a certain distance d is equal to $D = \lambda d/d_p$, where d_p is the detector pixel pitch and λ is the wavelength, so that the longer the wavelength the wider the linear field of view. Moreover, since the interferometric pattern containing the wavefront information is erased if the amplitude of environmental vibrations occurring during the acquisition process is comparable to the wavelength, an IR holographic system working, e.g., at 10.6 microns is about 20 times more robust against vibrations than a holographic system in the visible range working at 0.5 microns. In this regard, the recent development of Mid IR DH systems based on microbolometric arrays and CO_2 lasers [7, 8] allowed acquisition of holographic videos of human-size dynamic scenes. The wide field of view, combined with the possibility to adjust the focusing depth starting from a single Mid-IR hologram recorded in a lens-less configuration, has recently allowed detecting human targets beyond a curtain of smoke and flames [9] while the phase detection ability of large scenes has recently allowed to demonstrate remote monitoring of the oscillation modes of large structures [10]. The most common coherent

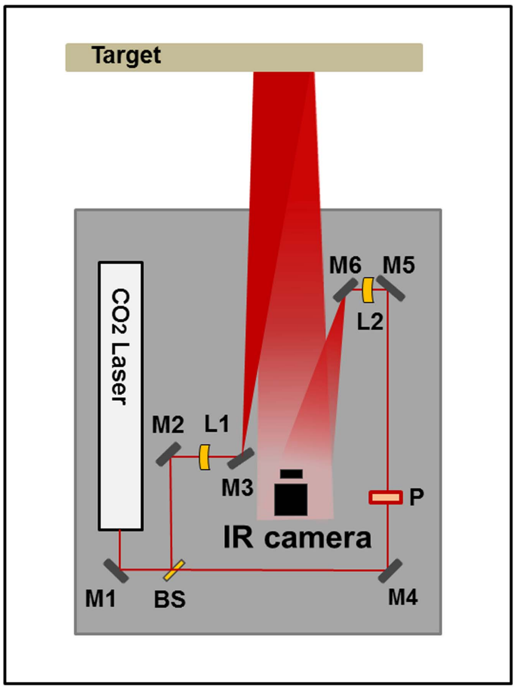

Figure 1. Experimental set-up. M1, M2, M3, M4, M5, M6 mirrors, BS 90/10 ZnSe beam splitter, P Polarizer, L1 ZnSe lens system, L2 ZnSe diverging lens.

sources in the Mid IR range are the well-established CO_2 lasers [11] and the more recent Quantum Cascade Lasers (QCL) [12]. CO_2 lasers are characterized, normally, by both high coherence length and impressively high output powers, up to several kW, which make them extremely suitable for outdoor remote monitoring of large scenes but are, however, quite bulky sources. Conversely, QCLs are much more compact devices but, currently, operate at much lower power than CO_2 lasers. Working at progressively long wavelengths in the far-infrared region would be a desirable goal since it could further increase DH capabilities but the most common sources in this range, THz FIR lasers and THz QCLs, are bulky devices (due to the long optical cavities and to the required cooling systems, respectively) and have, yet, sub-watt output powers [13]. In all these cases, therefore, it is usually not possible to fully take advantage of the very wide field of view offered by IR DH imaging systems. The recording and reconstruction of human size holograms, in the Mid IR range, has already been obtained, in laboratory condition, by scanning the 110 W beam of a bulky CO_2 laser, over a 2 m sample surface and combining the most relevant amplitude images extracted from the hologram movie [8, 9, 14, 15]. In this configuration, however, considering the relatively short recording distance (about 3 m) and the relatively small surface of the sample (about 4 m^2), the power density scattered back by the sample was enough to obtain sufficiently contrasted fringes even by means of a smart irradiation of the sample obtained either by splitting the object beam into two separate beams or by expanding the object beam along the larger dimension of the sample using a cylindrical lens.

In this paper, we report on a Scanning Digital Holography (SDH) configuration in the Mid IR range allowing wide field of view (36 m^2) imaging, in outdoor conditions, with a relatively compact and low power CO_2 laser.

Methods

The experimental setup is shown in figure 1.

The coherent source is a compact radiofrequency (RF) pumped CO_2 laser (by universal Laser Systems), emitting 60 W CW of linearly polarized radiation in the fundamental TEM_{00} mode at 10.6 μm wavelength. The IR detector is a room-temperature microbolometric thermocamera (Miricle 307 k by Thermoteknix) operating, with no objective in front of the detector elements, at a frame rate of 25 Hz. The camera focal plane array is composed of 640 $\times$ 480 amorphous Si elements with 25 μm $\times$ 25 μm pixel pitch. The laser beam is split by means of a beam splitter reflecting 90% of the radiation in the Object Beam (OB) and transmitting the remaining 10% in the Reference Beam (RB). The OB is expanded by means of a ZnSe lens system and it is directed toward the area to be investigated; the RB is re-directed, by means of gold coated mirrors, toward a diverging ZnSe lens before impinging on the thermocamera. A polarizer, inserted in the RB path, balances the intensity of the reference beam with respect to the intensity of the radiation scattered by the target in order to optimize the visibility of the interferometric pattern. The set-up is mounted on a 60 cm × 90 cm breadboard and placed on top of a common table without any vibration damping system.

The target is represented by an urban scene composed of a one-storey building facade, with visible roof and gutter, in front of which a human size mannequin and a small car, with open doors, are positioned. The distance of the scene from the detector is 30 m so that a linear field of view of virtually 12 m × 12 m is available for reconstruction. Even if the RB arm (about 0.5 m) is much shorter than the OB arm (about 60 m), the unbalance of two interferometer arms is still within the coherence length of the laser so that sufficiently contrasted fringes are obtained. The OB is expanded by means of the lens system L1 in order to reach a diameter of about 50 cm upon the target. Considering the wavelength, the power and the divergence of the object beam, it is possible to verify that moving away from the source the power density becomes rapidly safe. The laser OB was scanned horizontally and vertically, by means of two motorized actuators, along a zig-zag path in order to cover ¼ of the entire field of view of the system. The OB scanning speed allowed the entire scene to be covered in about 600 s. While the camera was acquiring 25 holograms per second, our numerical reconstruction was restricted to 5 real-time processed holograms per second.

The holographic reconstruction of the OB wavefront was obtained by means of a numerical implementation of the Rayleigh-Sommerfeld diffraction integral [16]

$$E(x_R, y_R) = \frac{1}{i\lambda}\int\int_{-\infty}^{+\infty} \mathcal{R}(x_H, y_H)H(x_H, y_H)\frac{e^{i\frac{2\pi}{\lambda}\rho}}{\rho}dx_H dy_H,$$

where E, $\mathcal{R}$ are the complex amplitudes of the object and reference beam, respectively, and H is the intensity of the interferogram; x_R, y_R and x_H, y_H are the coordinates on the reconstruction and hologram plane, respectively; ρ is the distance between the generic point (x_H, y_H) and the generic point (x_R, y_R), λ is the wavelength of the employed radiation.

For small values of x_H, y_H, x_R, y_R compared to ρ, it is possible to adopt the so-called Fresnel approximation. In this approximation, the Rayleigh-Sommerfeld integral appears as a two-dimensional Fourier transform. The holographic pattern H is digitized into a 2D $M \times N$ matrix which turns the Fourier Transform into a Discrete Fourier Transform (DFT). In such a way, the complex amplitude of the object beam becomes a discrete function

$$E(m, n) = E(m\Delta\mu, n\Delta\nu) = \frac{e^{i\frac{2\pi}{\lambda}d}}{i\lambda d}e^{i\pi\lambda d\left[\frac{m^2}{M^2\Delta x_{\mathrm{H}}{}^2}+\frac{n^2}{N^2\Delta y_{\mathrm{H}}{}^2}\right]}\mathscr{DF}\{\mathcal{R}(k, l)H(k, l)e^{\frac{i\pi}{\lambda d}[(k\Delta x_{\mathrm{H}})^2+(l\Delta y_{\mathrm{H}})^2]}\},$$

where the reconstructed pixel dimensions $\Delta\mu$, $\Delta\nu$ are connected to the hologram pixel dimensions Δx_{H}, Δx_{H} and the indices m, n, k, l run from 0 to M, N.

As $E(m, n)$ represents the complex amplitude of the reconstructed OB corresponding to the pixel (m, n), it is possible to rewrite it as $E(m, n) = |E(m, n)|\, e^{i\phi(m,n)}$.

A dedicated Matlab routine efficiently computed the above DFT by means of an FFT algorithm returning the amplitude and phase of the object wave-front.

After hologram processing, a mask with lower and upper limits on the intensity values was applied to each hologram amplitude reconstruction in order to eliminate noise and to obtain an image where only the laser irradiated area had not-zero values. Each of the masked images was then added to the previous one so that, after appropriate normalisation, an image of the entire scene, out of about 3000 corrected images, was finally obtained.

Results and discussion

Thanks to the employed scanning procedure one quarter of the available field of view was covered so that, finally, a very large scene of about 6 m × 6 m was imaged. The low vibration sensitivity of Mid IR DH allowed to position the setup on a normal table and to acquire holograms in outdoor conditions with no special care. The high coherence length of our RF pumped CO_2 laser allowed remote monitoring from 30 m distance without any need of adjusting the reference beam path. The quality of the recovered amplitude image is affected by various contributions: first of all the long working distance which reduces the reconstruction resolution, secondly the very high unbalance of the two arms of the interferometer which decreases the fringe visibility and, consequently, the hologram quality, and, finally, the unavoidable ambient vibrations of a real world scenario which further deteriorates the interferogram. As shown in figure 2 the different objects constituting the scene (the car body, the interior part of the car, the mannequin, the building facade, the gutter, …) had different scattering properties so that some of them were much more visible than others. This phenomenon implies a further reduction of the final image quality with a certain decrease of the experimental spatial resolution with respect to the theoretical one [17] (about 1.8 cm × 2.5 cm). The quality of the reconstructed images could however be significantly improved using more performing detectors (for example with larger sensitive area) or

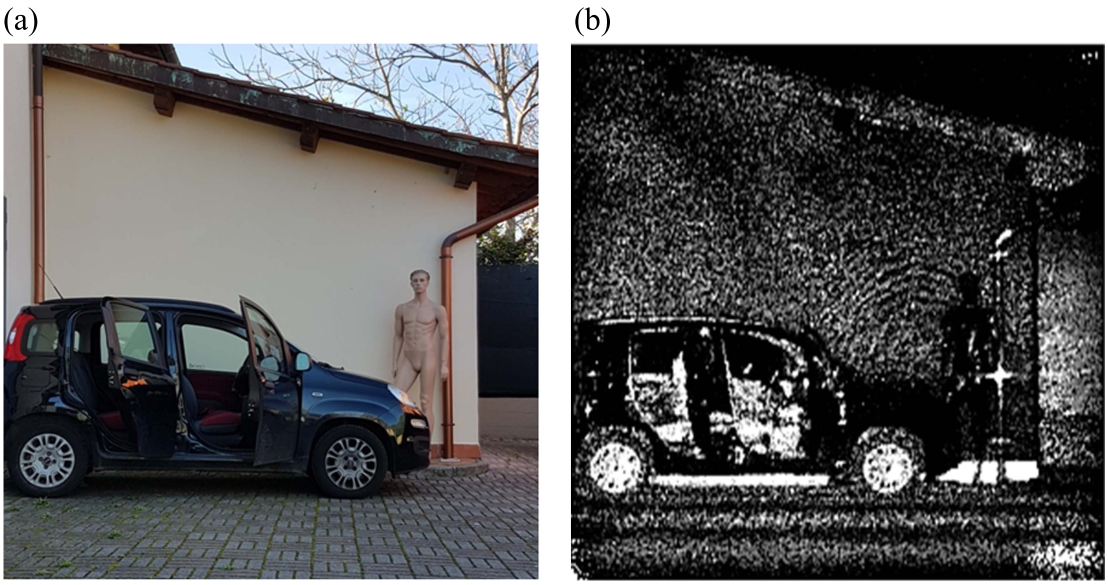

Figure 2. Large field of view scene. (a) Image of the scene. (b) Hologram amplitude reconstruction of the scene.

by means of statistic treatment of images [18, 19] and zero padding procedure [20] to reduce speckle noise and improve the final image resolution, respectively. The scanning speed (set to its maximum value for the opto-mechanical devices at our disposal) could be increased in order to reduce the acquisition time with no reduction of the image quality owing to the high stability of the IR holographic systems. In particular, with a sufficiently fast detector, it should be possible to increase significantly the scanning speed and extract the phase information for each position of the beam allowing deformation/displacement analysis of very large areas in a similar way as in Scanning Laser Doppler Vibrometry [21]. Finally a valuable reduction of the power of the laser, and consequently of its dimensions, could be obtained by means of a more sensitive detector (for example using a cooled sensor) or by means of a more complex and efficient optical configuration to collect the scattered radiation.

Conclusions

The main goal of this work was to explore the limits of Infrared Digital Holography and its potential application for very large scene imaging. Indeed, the holographic technique could give important and unrivalled contribution in specific imaging applications like, for example, 'vision through smoke and flames'. In this work we have demonstrated real world imaging capabilities with a compact and low power laser, out of laboratory conditions, at a very long working distance (30 m) and with a large unbalance between reference and object beam (about 59 m). Despite these extremely challenging conditions, we demonstrated the possibility to cover a field of view of about 36 m^2 of a realistic and complex scene (containing test objects of different materials, surface finishing and dimensions).

An imaging system based on the principle demonstrated in our work, could thus have strategic applications in fire-fighting (mounted on rescue vehicles), in war scenarios (mounted on tanks), in virtual museum applications, in real 3-D television and in non-destructive testing of large objects.

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