



Infrared digital holography: applications and perspectives

Eugenio Pugliese, Massimiliano Locatelli and Riccardo Meucci

National Institute of Optics (CNR-INO), Largo E. Fermi 6, 50125, Florence, Italy

Infrared Digital Holography (IRDH) is emerging as a powerful technique for various applications such as non-destructive evaluation and vision in harsh environments. At the National Institute of Optics (CNR-INO), pioneering work has been carried out over the past decade to explore the capabilities of both long-wave (LWIR) and short-wave (SWIR) digital holography for building structural health monitoring and for imaging through obscuring media such as smoke and flames. This review describes the key publications that demonstrate the advantages of IRDH in these applications, such as lensless acquisition, real-time processing and robust performances. By combining advanced interferometric methods and numerical wavefront reconstruction, IRDH represents a unique solution for structural diagnostics and emergency response. © Anita Publications. All rights reserved.

doi: [10.54955/AJP.34.5-6.2025.237-243](https://doi.org/10.54955/AJP.34.5-6.2025.237-243)

Keywords: Infrared Digital Holography, IR Radiation, Environmental sensing, Interferometric imaging technique.

1 Introduction

Digital Holography (DH) is a cutting-edge interferometric imaging technique that enables full-field, non-contact and high-resolution reconstruction of both amplitude and phase information of an object wavefront. Traditional digital holography, developed in the visible spectrum, has proven invaluable in fields such as microscopy, metrology, and non-destructive testing [1,2,3]. Digital Holography has been explored also in other regions of the electromagnetic spectrum, such as in the X ray region [4] and in the infrared (IR) range. In particular, its extension into the infrared spectral region opens up new and significant application domains, particularly in environments where visible light imaging is severely limited or impossible.

Infrared Digital Holography (IRDH) leverages the unique physical properties of IR radiation, such as a larger field of view, a lower vibration sensitivity and reduced scattering which allows to penetrate obscurants including smoke, dust and fog. These advantages make IRDH particularly suitable for applications in structural health monitoring, emergency response, industrial inspection, and environmental sensing. For example, it allows to reconstruct phase maps of large surfaces of buildings out of laboratory controlled conditions thus enabling structural monitoring. Furthermore, in fire or disaster scenarios, visible cameras fail to provide reliable imagery due to intense smoke and thermal emission. IRDH overcomes these challenges by combining coherent light sources in the IR range with digital sensors and advanced numerical reconstruction algorithms, enabling visualization and measurement even in highly adverse conditions.

At the National Institute of Optics (CNR-INO), extensive research has been conducted to explore both long-wave infrared (LWIR, typically around $10.6\ \mu\text{m}$) [5] and short-wave infrared (SWIR, near $1.55\ \mu\text{m}$) [6] holographic systems. The LWIR range benefits from lower vibrations sensitivity, larger field of

Corresponding authors

e mail: eugenio.pugliese@ino.cnr.it (Eugenio Pugliese);

massimiliano.locatelli@ino.cnr.it (Massimiliano Locatelli); riccardo.meucci@ino.cnr.it (Riccardo Meucci)

view and high power lasers, while the SWIR range offers greater availability of compact, fiber-coupled laser sources and cameras, allowing for portable and versatile devices. Both spectral bands present unique trade-offs in terms of resolution, sensitivity, and system complexity.

This paper provides a comprehensive review of the advances achieved, over the past decade, in IRDH. Emphasis is placed on two main application areas: structural monitoring through detection of vibrations and modal shapes, and vision through obscuring media such as smoke and flames, which are critical for firefighter safety and disaster management. We demonstrate how IRDH systems integrate lensless interferometric setups, real-time data processing, and robust reconstruction methods to deliver high-fidelity imaging and measurement under real-world conditions.

By presenting theoretical background, experimental results, and discussion of practical challenges, we aim to highlight the potential of IRDH as a versatile and powerful tool that bridges gaps in current sensing technologies. It also outlines future directions, including miniaturization, multispectral imaging, and integration with artificial intelligence, which could further expand the impact of IRDH across scientific, industrial, and emergency response fields.

2 Theoretical Background

DH is an interferometric technique where the radiation scattered back by an object irradiated with coherent radiation (the object beam) interferes with an appropriate beam (reference beam) on a digital sensor to produce an intensity interferometric pattern, called the hologram.

The holographic reconstruction of the object complex wave-front is obtained [2] by means of a numerical implementation of the Rayleigh-Sommerfeld diffraction integral,

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

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) , and λ is the wavelength of the employed radiation.

For small values of x_R, y_R, x_H , and y_H 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,

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

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

As $E(m, n)$ represents the complex amplitude of the reconstructed object wave-front corresponding to the pixel (m, n) , it is possible to rewrite it as,

$$E(m, n) = |E(m, n)| e^{i\phi(m, n)}$$

The above DFT is calculated by means of an FFT algorithm so that it is possible to retrieve both amplitude and phase of the object wavefront. This enables accurate 3D surface profiling and motion detection. In IRDH, longer wavelengths reduce scattering, enable larger field-of-view (FOV), and ease sampling constraints, making it suitable for long-distance, real-world measurements.

3 Structural monitoring with long-wave Infrared Digital Holography

To obtain a realistic assessment of the seismic vulnerability and state of conservation of a structure, such as a building, a bridge, a wall, etc., it is necessary to experimentally measure the amplitude and frequency of the natural oscillation modes of the structure under examination. Frequencies, damping ratios, and mode shapes of a structure are, indeed, key parameters directly correlated to its health and stability. Monitoring their evolution over time is, therefore, essential for preventing deterioration and seismic vulnerability. Such data are crucial for seismic risk analysis, post-earthquake assessments, and routine health monitoring of bridges, towers, and heritage buildings. Operational Modal Analysis (OMA) [7], based on accelerometers or seismometers, provides an accurate evaluation of such parameters but requires the placement of sensors directly on or inside the structure, limiting its applicability to large-scale or inaccessible sites. These techniques are, therefore, invasive and require significant investment of qualified personnel and time. For this reason, it is currently not possible to reach a systematic monitoring and we are far from developing a seismic identity card for structures and infrastructure that could mitigate the damage that periodically occurs due to seismic events and to natural deterioration of our structural and infrastructural heritage.

In a seminal 2016 study [8], Poggi *et al* demonstrated long-wave IRDH for the remote monitoring of building oscillation modes. Using a 10.6 μm CO₂ laser and a microbolometric camera, they achieved sub-micrometric resolution in measuring structural displacements. The system was tested both in laboratory conditions and in the field at the Florence Firefighters Department training tower. Comparison with seismometric data revealed excellent agreement, with displacement accuracies of 0.1 μm . The system employed an off-axis interferometric configuration that allowed spatial separation of diffraction orders during reconstruction. Multiple acquisitions were processed using real-time algorithms that extracted phase shifts over time, enabling precise temporal resolution of structural oscillation frequencies and amplitudes. The technique was subsequently applied for the monitoring of various historical buildings, such as Palazzo Medici Riccardi in Florence [9] and the Radicofani Fortress in Siena [10] in comparison with seismometers and accelerometers, to demonstrate its reliability (Fig 1).

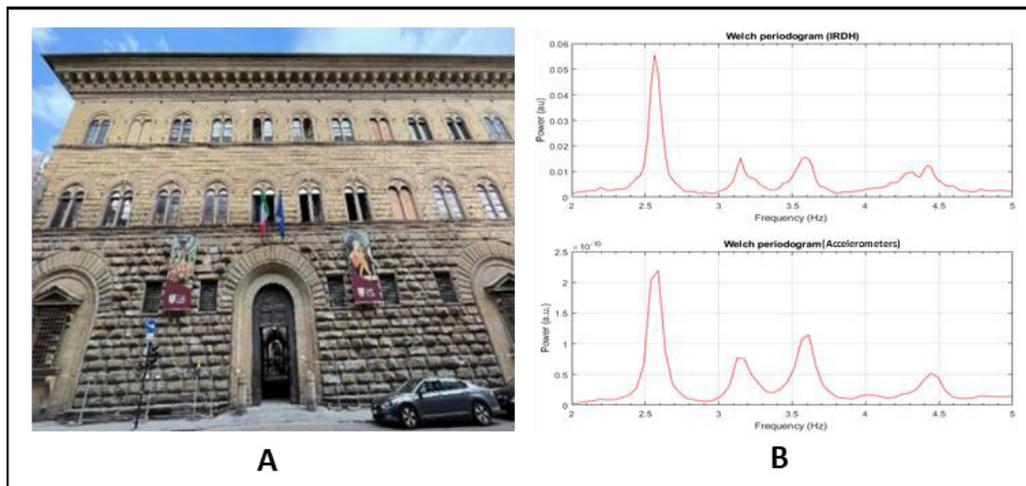


Fig 1. (A) Palazzo Medici Riccardi. (B) Comparison between frequency spectrum obtained by means of IRDH and accelerometers.

Compared to conventional sensors such as accelerometers and seismometers, digital holography offers several advantages. This technique eliminates the need for invasive sensor placement and offers

broad-area vibration mapping in real time, paving the way for safer and faster infrastructure assessments. While accelerometers provide point-wise measurements, IRDH enables simultaneous acquisition of full-field displacement maps, making it especially useful for identifying complex modal patterns and localized structural anomalies. Moreover, DH is entirely contactless, which is advantageous in applications involving historic or fragile structures where sensor installation is impractical or invasive.

An alternative technique to seismometers/accelerometers is ground-based Synthetic Aperture Radar (GbSAR) [11,12], which allows remote monitoring of structural displacements. However, due to the long wavelength typically employed, GbSAR cannot detect micrometric or sub-micrometric motions, which are often indicative of early damage. Furthermore, the use of GbSAR frequently requires the placement of artificial reflective targets on the structure to identify the regions under observation precisely. In contrast, IRDH provides sub-micrometric sensitivity in real time, with no need for target installation or physical contact. It can, therefore, serve as a complementary or substitute solution in scenarios where traditional techniques are impractical or insufficiently sensitive. Furthermore, IRDH provides higher temporal resolution and is not subject to atmospheric distortion or line-of-sight ambiguities. Unlike radar systems that measure relative displacements over longer periods and larger scales, IRDH is capable of resolving fast transient vibrations at the micron level in real time. These properties make it complementary to other interferometric methods, bridging the gap between high-resolution local sensing and large-area monitoring (see Table 1).

Table 1. Comparison between Seismometers/accelerometers, Radar and IRDH. ✓ satisfied criterion, × not satisfied criterion.

	Seismometers, accelerometers	Radar	LWIRDH
Large applicability	✓	×	✓
Low invasiveness	×	✓/×	✓
Measurement speed	×	✓	✓
Portability	✓	✓	✓
Sensitivity	✓	×	✓
Frequency range	✓	✓	✓

4 Imaging through smoke and flames: LWIR Approach

In the field of fire disasters, one of the major challenges rescuers encounter during their operations (especially in enclosed spaces such as tunnels, buildings, etc.) is poor visibility caused by dense clouds of smoke and flames. Poor visibility not only makes it difficult to locate people in danger or objects of interest such as gas cylinders or electrical panels, but often prevents operators from orienting themselves effectively and safely, putting their safety at risk. This happens because the human eye and standard visible-light cameras are unable to see in an environment filled with smoke and flames. IR cameras, while in principle capable of seeing through smoke (and are in fact used by firefighters for this purpose), however, do not allow vision in the presence of high-temperature smoke and flames, as these IR radiation sources saturate the sensor or otherwise mask the weaker signals coming from the surrounding environment.

In a 2013 paper [13], Locatelli *et al* presented a lensless digital holography setup based on a 10.6 μm continuous-wave CO_2 laser and a pyroelectric or bolometric sensor. This system recorded holograms of dynamic, human-sized targets in the presence of smoke and flames. Thanks to the coherence of the laser source and the wavelength's low susceptibility to scattering and emission from flames, the system allowed the clear visualization of people otherwise invisible to both the naked eye and thermal cameras. Key advantages include real-time video-rate acquisition, robustness to vibrations, and effective rejection of incoherent

background radiation. Experiments conducted in a controlled fire scenario revealed that standard visible and thermographic cameras failed to produce usable imagery when flames obscured the scene. Conversely, the LWIRDH system succeeded in reconstructing clear images of human figures through dense smoke and flames (Fig 2). The use of lensless acquisition prevented saturation from flame radiation while, since the image in digital holography is written in the interferometric pattern, the radiation of the flames, not contributing to interference, is removed from the reconstructed image. These features make LWIRDH particularly attractive for search-and-rescue operations in burning structures.

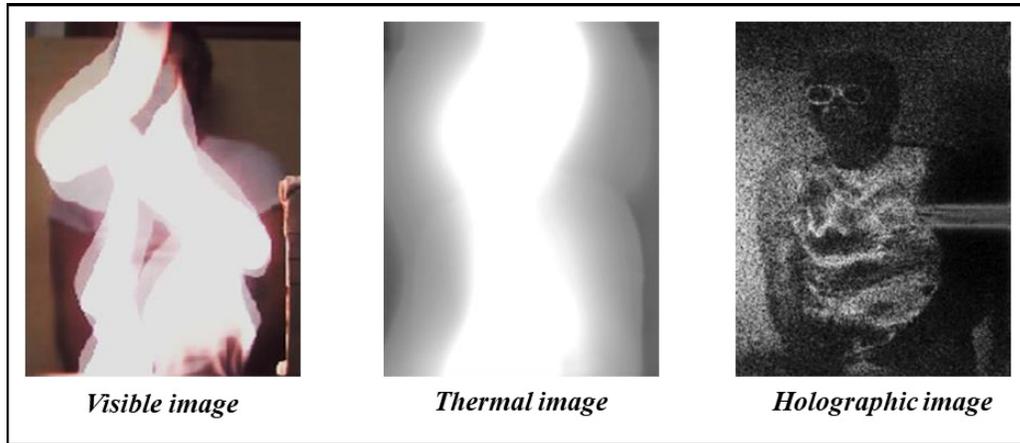


Fig 2. Visible, thermal and holographic images of a person hidden behind a curtain of flames.

5 Imaging through smoke and flames: SWIR approach

In a recent 2023 study [6], Locatelli *et al* developed a compact and portable SWIR DH system using a 1.55 μm fiber laser and an InGaAs camera. The system was configured in an off-axis interferometric setup and demonstrated video holography with exposure time up to 10 microseconds. Despite increased scattering compared to LWIR, the SWIR system successfully captured images through smoke and flames under real-world fire conditions. A unique feature was its portability: the setup, excluding the laser source, occupied a volume of only 30×7×10 cm and was handheld like a flashlight. This opens new avenues for field-deployable vision devices for first responders.

The SWIR DH device was tested in multiple scenarios, including handheld imaging and tracking through plastic materials opaque in the visible spectrum. It enabled visualization of liquid levels inside containers and recognition of a target obscured by smoke and flames (Fig 3).

The high frame rates and sub-millisecond exposure time contributed to stable fringe visibility even during handheld operation. While SWIR is slightly more susceptible to scattering than LWIR, it offers a practical trade-off by enabling compact, energy-efficient, and eye-safe systems suitable for wearable or robotic platforms (see Table 2).

Table 2. Comparison between Visible, Thermal, LWIRDH and SWIRDH imaging. ✓ satisfied criterion, × not satisfied criterion.

	Visible imaging	Thermal imaging	LWIRDH	SWIRDH
Vision through smoke	×	✓	✓	✓
Vision through flames	×	×	✓	✓
Portability	✓	✓	×/✓	✓

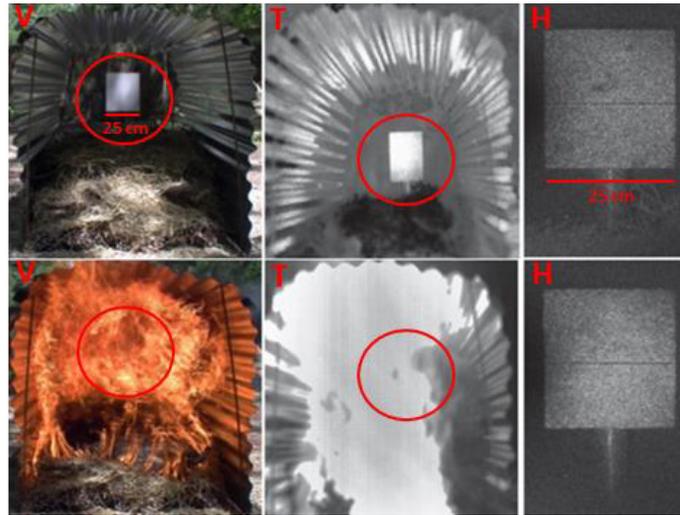


Fig 3. Visible (V), thermal (T) and holographic (H) images of a rectangular metallic target (inside the red circle, in V and T), in normal conditions (upper images) and in presence of a curtain of smoke and flames (lower images).

6 Discussion

IRDH developed at CNR-INO has distinct strengths: lensless, non-contact imaging, insensitivity to ambient light and vibrations, high phase sensitivity and the ability to operate through obscurants like smoke and flames. The LWIR configuration excels in clarity and robustness in harsh conditions, while SWIR offers portability and system compactness. Key limitations include computational demands for real-time reconstruction, system calibration under varying thermal conditions, and limited commercial availability of components at long wavelengths. Nevertheless, these systems are suitable for field integration in structural diagnostics, fire rescue, and defence.

The success of these systems depends heavily on coherent light sources, low-noise IR sensors, and advanced image reconstruction pipelines. The choice between LWIR and SWIR should be application-specific, considering trade-offs in resolution, robustness, portability, and cost. Future integration with artificial intelligence and machine learning could further enhance image interpretation and automate anomaly detection. Hybrid systems combining multiple wavelengths or integrating with other sensing modalities (e.g., LiDAR or thermal imaging) may also emerge as valuable tools.

7 Conclusions and Perspectives

CNR-INO's contributions to IR digital holography illustrate the readiness of this technology for deployment in real-world scenarios. With demonstrated use cases ranging from structural monitoring to emergency imaging, these systems can address critical needs in safety, infrastructure, and surveillance. Future work may focus on miniaturization, UAV-mounted platforms, integration with AI-based interpretation, and expansion into multi-wavelength DH systems for enhanced contrast and resolution.

Moreover, the real-time capability and robustness of IRDH systems suggest their use beyond emergency and engineering applications, potentially extending into biomedical imaging, industrial quality control, and environmental sensing. As technology progresses and IR components become more affordable, we anticipate a growing adoption of digital holography in diverse interdisciplinary fields.

References

1. Goodman J W, *Introduction to Fourier Optics*, 3rd ed., Roberts and Company, Greenwood Village, 2005.
2. Schnars U, Jüptner W, Digital recording and numerical reconstruction of holograms, *Measurement Science and Technology*, 13(2002) 9, pp R85–R101.
3. Grilli S, Ferraro P, De Nicola S, Finizio A, Pierattini G, Meucci R, Whole optical wavefields reconstruction by digital holography, *Opt Express*, 9(2001)294–302.
4. Pfau B, Eisebitt S, X-Ray Holography. In Jaeschke E, Khan S, Schneider J, Hastings J, *Synchrotron Light Sources and Free-Electron Lasers*, Springer, Cham, 2020.
5. Allaria E, Brugioni S, De Nicola S, Ferraro P, Grilli S, Meucci R, Digital holography at 10.6 μm , *Opt Commun*, 215(2003)257–262.
6. Locatelli M, Pugliese E, Poggi P, Euzzor S, Meucci R, SWIR digital holography and imaging through smoke and flames: unveiling the invisible, *Opt Express*, 31(2023)42090–42101.
7. Rainieri C, Fabbrocino G, *Operational Modal Analysis of Civil Engineering Structures*, (Springer New York, NY), 2014.
8. Poggi P, M Locatelli M, Pugliese E, Donne D D, Lacanna G, Meucci R, M Ripepe M, Remote monitoring of building oscillation modes by means of real-time Long-Wave Infrared Digital Holography, *Sci Rep*, 6(2016)23688; doi:10.1038/srep23688.
9. Pugliese E, Locatelli M, Bocchi F, Poggi P, Jafrancesco D, Falzone G, Signorini N, Spina D, Meucci R, IR Digital Holography for Remote Sensing of Structures, *IEEE Transactions on Geoscience and Remote Sensing*, 61(2023)1–7.
10. Pugliese E, Lacanna G, Locatelli M, Schiava D M, Signorini N, Meucci R, Holographic and seismic comparative modal analysis on Radicofani fortress, *Journal of Cultural Heritage*, 72(2025)36–41.
11. Bamler R, Hartl P, Synthetic Aperture Radar Interferometry, *Inverse Problems*, 14(1998)R1–R54.
12. Pieraccini M, Miccinesi L, Ground-Based Radar Interferometry: A Bibliographic Review, *Remote Sens*, 11(2019) 1029; doi.org/10.3390/rs11091029.
13. Locatelli M, Imaging live humans through smoke and flames using far-infrared digital holography, *Opt Express*, 21(2013)5379–5386.

[Received: 09.05.2025; accepted: 30.06.2025]