3-D capture, processing, display, and perception with digital holography: results from a European-funded project

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What kind of 3D display can holography give us?

Well- and widely-known properties:
- Arbitrary number of viewers at arbitrary locations, each with a unique perspective
- Viewer movement permitted
- Motion parallax both vertically and horizontally, tilting head allowed
- Viewer can naturally focus at different depths in scene (no accommodation/convergence rivalry)
- As with state-of-the-art: autostereoscopic and video frame rates

Outline

- Motivation for a digital holographic 3D imaging and display system
- Overview of the three-year European Commission “Real 3D” project
- Objectives and demonstrations
- Selection of results so far in year 3 (approx. 4 months from end)

Properties of conventional holograms

Goodman “Fourier Optics”
Objective: We will work towards eliminating the current obstacles in achieving a fully functional holographic 3D video capture and display paradigm for unrestricted viewing of real-world objects.

Digital holography for 3D and 4D real-world objects' capture, processing, and display ("Real 3D")
www.digitalholography.eu

Demonstrator 1

Macroscopic opaque objects
Six cameras in a partial circle arrangement
Video mode
Processing (dc, twin, speckle, registration, tilting, phase)
Compression, network transmission, decompression
Optoelectronic reconstruction
Infrared capture for large (human sized) objects

Demonstrator 2

Microscopic reflective objects
Video mode
Processing (dc, twin, speckle, phase unwrapping, EFI, tilted planes)
Multiple wavelengths
Network transmission
Conventional stereo/multiview display

Demonstrator 3

Microscopic transparent or semi-transparent objects
Tomography
Processing (e.g. point cloud generation, computer generated hologram)
Optoelectronic reconstruction
Demonstrator 4

Nonvisible objects captured in infrared
Microscopic structures (e.g. silicon) with wavelength range 1.2-1.5 μm
Macroscopic objects (e.g. organic polymer) with wavelength 10.6 μm
Unique advantages (semiconductor, composite testing, scale)
Phase object preparation
Optoelectronic reconstruction

Brief overview of Description of Work

- Designing and/or constructing novel digital hologram capture devices
  - employing multiple detectors and/or multiple wavelengths
  - capturing amplitude, phase, and mixed amplitude-phase objects
  - scalable to 360° range of perspectives for macroscopic moving objects
  - two axis rotation for static objects
  - macroscopic and microscopic regimes, for both scientific and consumer applications

• Advanced signal/image processing techniques to appropriately condition the data between capture and display
• Appropriate representation of the data to facilitate handling, processing, transmission, and display

• Designing novel digital hologram display devices
  - based on full-field 3D display technology
  - based on conventional 2D/autostereoscopic display technology
**Brief overview of Description of Work**

- **Capture**
  - Conditioning
  - Representation
  - Processing
  - Transmission

- **Display**

- **Market analysis**

- **Visual perception**

  - Studies on visual perception of 3D data encoded in digital holograms
  - Designing methodologies to quantify 3D perception in holograms

**Problems developing digital hologram sensing and optoelectronic display system**

- Large camera pixel pitch (3um – 9 um) compared to holographic film (< 1 um)
- Small sensor size (~1 cm²) compared to holographic film (~1 m²)
- Large display pixels (> 10 um)
- Difficulties associated with off-axis arrangements with minimal angles
- Difficulty of extracting true 3D information from a digital hologram (common 2.5D limitation)
- 3D registration of nonoverlapping camera apertures (to map to arbitrary configuration of display devices)
- Maintaining alignment and coherent superposition of multiple displayed fields

**Demonstrator 1**

- Macroscopic opaque objects
- Six cameras in a partial circle arrangement
- Video mode
- Processing (dc, twin, speckle, registration, tilting, phase)
- Compression, network transmission, decompression
- Optoelectronic reconstruction
- Infrared capture for large (human sized) objects

**Flowchart:**

- Capture ➔ Processing ➔ Transmit ➔ Receive ➔ Display
  - dc reduction
  - twin reduction
  - tilted planes
  - defocusing
  - speckle reduction
  - amplitude equalisation
The schemes of (a) holographic data capture by multiple CCDs and (b) display using LCoS SLMs in the circular configuration.

Compact digital hologram camera

Allows for the manipulation of the reference wave with LCoS (phase shifting capabilities, varying object position in lensless Fourier holography, correction of optical aberrations).

Compact digital hologram camera

Processing

This project has a broad scope, however much of the work relates to capturing 3D scenes using holographic techniques and the optical or numerical display of this data for end-user applications. While holographic capture provides a method for accessing some 3D information contained in an optical scene, there are also several difficulties with the data that need to be addressed; both by carefully designing the capture and display architectures; and by performing appropriate numerical processing of the captured data.

It is this later processing stage that is the focus of NUIMs work. Here we discuss processing algorithms to reduce the deleterious effects of the DC and conjugate image terms, to improve the spatial resolution of captured holograms using synthetic aperture techniques, to describe and combat the effects of speckle noise, and implementing fast numerical algorithms to model the propagation of wave fields in optical systems and to process these propagated field.
Processing

Synthesized 3D scene combining multiple optically recorded digital holograms of different objects. Compositing moving 3D objects in a dynamic 3D scene. Video can be displayed and observed in 3D.

Demonstrator 1


Parallax

Composition of two flat objects separated by 30 mm

Optical reconstruction (HUD)
Pictures of (a) SLMs and SLM Modules, (b) side view of the setup; (c) cone mirror and (d) SLMs and beam splitter.
Visual perception requirements

SLM optical reconstruction, at visible wavelength, of digital holograms acquired in the long IR region (10.6 μm).
Integrated recording-reconstruction of 3D object in far IR region.
Paves the way to 3D vision in a spectral region that may be interesting for certain applications.

We have decided on a methodology for the visual perception experiments: using perceptual thresholds. By measuring perceptual thresholds it is possible to characterise perceptual display quality in a highly objective way.

We have defined requirements for the tests, and the basic metrics (contrast, depth information, recognition of objects).

A set of detailed requirements for the 3D scenes has been drafted, at the scene level, object level, physical requirements, properties to be avoided, dynamic properties.

Motivation: to inform designers of optoelectronic hologram display device, suggest suitable test objects, compression guidelines, provide intermediary stereo display for holograms.

Visually lossless compression of digital hologram sequences

We find that numerical quality metrics such as the NRMS error, that has been extensively used in similar studies, cannot predict reliably how visible the compression errors are.

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Visual perception requirements

Comparing numerical error and visual quality in reconstructions from compressed digital holograms

QNT compressed lower quality than original

Percentage of responses

Numerical error

Main technical achievements to date

In Demonstrator 1,

• a compact hologram capture device has been developed,
• hologram requirements have been specified to maximise viewer impact,
• a comprehensive report has been developed on numerical twin and speckle reduction techniques with several examples implemented,
• the best procedures for hologram processing have been identified,
• hologram video has been compressed,
• the display side components have been fully specified and evaluated experimentally, and
• visual perception experiments have been designed.

Demonstrator 2

Microscopic reflective objects
Video mode
  Processing (dc, twin, speckle, phase unwrapping, EFI, tilted planes)
Multiple wavelengths to extend longitudinal range
Network transmission
Conventional stereo/multiview display

Extended focus image

Ferraro et al. 2008
Fibre lengths: ~100 – 400 µm

Microscopic objects
fibres on glass plate tilted in different angles
Microscopic objects
fibres on glass plate tilted in different angles

- **DISPLAYING HOLOGRAMS**
  - The other side of holography, reconstruction, can be performed:
    - numerically by computer (2D or 2½D), displayed on 2D screens
    - optoelectronically (full 3D field)
  - Drawbacks of optical reconstruction include speckle, cost, and technological limitations of current SLMs
  - Drawbacks of any single digital reconstruction include:
    - speckle
    - limited depth of field
    - single perspective (occlusions not overcome)
    - calculation time grows superlinearly with hologram size
    - not certain to give human a clear perception of scene’s 3D features
  - The challenge is to utilise the convenience of digital reconstruction while overcoming its drawbacks

- **Preparation of the data for stereo display**
  Optically captured digital holograms can be reconstructed either
  (i) numerically and displayed on a computer screen in 2D, or
  (ii) reconstructed optically and viewed directly by the eye in 3D.

**Figure 1.** Different perspectives. (a) showing the scene from left perspective, (b) showing the scene from right perspective, (c) hologram data of left perspective, (d) hologram data of right perspective.
RESULT: Increased detail visibility – effect

- On vertical axis percentage of yes responses to question: "Are details completely visible?"

- Increased detail visibility – effect
  - more details visible in stereo image than average of the two single images
  - for some window sizes, even more than each of the single images

Experimental results

Cumulative distributions of sharpness matches at a viewing distance of 150 cm for four observers.
Enhancement of 3D perception of numerical hologram reconstructions by motion and stereo

Stereoscopic depth estimation tool

K562 leukaemia cell captured using a transmission DHM T1000®) and provided by: Tristan Colomb, Yves Emery Lyncée Tec Inc, 1015 Lausanne, Switzerland

For the cell object presented as non-stereo and with rotational back and forth motion the matched stereoscopic depth was 1.78 cm and when presented as stereo and with motion it was 4.26 cm. The true depth on the display was about 5.8 cm.

The difference between static and motion presentation was statistically highly significant.

Note that without motion depth estimates for the cell object, with or without stereoscopic presentation, could not be produced. Thus, the interaction of motion and stereo was particularly substantial in this case.
Enhancement of 3D perception of numerical hologram reconstructions by motion and stereo

In the basic research literature, nearly all studies of cue interaction seem to have used synthetic computer generated objects. Our study with natural like complex objects confirms the existence of the interaction of stereo and motion.

The present study clearly demonstrates that the viewing method can have a great effect on depth perception of numerical hologram reconstructions presented on conventional displays. If depth cues are weak in holographic reconstructions, it will probably be highly beneficial for the observer to have a possibility to use both motion and stereo presentation in order to maximise 3D information.

This conclusion is particularly relevant in such cases where the objects viewed are novel to the observer - as was in the case of the microscopic cell object of this study - and, therefore, the interpretation of image features and monocular depth cues can be difficult.

It also suggests that motion has a particularly strong relative additive effect on perceived depth when stereoscopic cues are weak or ambiguous — as in the case of blur or when only high spatial frequencies are present.

When the stereoscopic cues are strong the additive effect of motion is absent or small.

Display on conventional 3D displays

The haptic display (left) is particularly interesting and we are discussing possibilities of exploitation and use with our industrial consortium partners.

The last stage of the research outlined here will involve synthesis of conventional display techniques, e.g. combining headtracking with stereo display.

Benefits of the work in general:
- Can simulate all properties of conventional hologram (except vertical parallax, accommodation-vergence rivalry)
- More convenient way to illustrate 3D info (for microscopic data) with potential commercial possibilities.
- Consumer electronics brings DH to a wider audience.
- Can feedback into optoelectronic display (macroscopic objects) by allowing us to prepare for their arrival, e.g. 3 publications attached to D8.3 on visual perception of holograms.

EXPERIMENTAL STUDY: MOBILE DEVICE WITH INTERACTIVE TILT

- Holograms used for 1st data set:
  - Holograms used for 2nd data set:

EXPERIMENTAL RESULTS WITH TILT

- Subjective evaluations done by 9 test users
- Effect of noise was evaluated on scale 1=disturbs very little, 7=disturbs very much
- Evaluations showed, that using tilt decreases the amount of perceived noise.
- Tilting supports 3D perception.
Main technical achievements to date

In Demonstrator 2,
• holograms of microscopic objects have been captured with dual wavelengths,
• the data has been processed to admit extended focus images and reconstructions on tilted planes,
• the data has been conditioned for conventional stereo displays and to allow efficient manipulation of 3D properties of scenes,
• and visual perception experiments have been conducted.

Demonstrator 3

Microscopic transparent or semi-transparent objects
Tomography Processing (e.g. point cloud generation, computer generated hologram) Optoelectronic reconstruction


A tomographic digital holographic microscope including object rotation on two axes and beam scanning has been built (Figure 1) and used to record holograms that are directly displayed on opto-electronic device (SLM) or used for tomographic reconstruction (result on Figure 2).
Demonstrator 3

Section of the 3D reconstruction of two red blood cells using 669 images.

Three different views of the reconstructed object from simulated scattered fields. Internal features and the refractive index distribution are well reconstructed.

Main technical achievements to date

In Demonstrator 3,
• the two-axis rotation setup has been finalised and data has been captured of transmissive biological specimens
• on the processing side, a tomographic reconstruction algorithm has been finalised to accurately obtain volumetric data
• for display, multi-colour holographic reconstructions from phase-only SLMs have been obtained using LED illumination

Optical Setup

F.Yaras and L.Onural, “Color Holographic Reconstruction Using Multiple SLMs and LED Illumination,” IS&T / SPIE Electronic Imaging 2009 18-22 Jan. 2009 San Jose, CA, USA
Demonstrator 4

Nonvisible objects captured in infrared
Microscopic structures (e.g. silicon) with wavelength range 1.2-1.5 μm
Macroscopic objects (e.g. organic polymer) with wavelength 10.6 μm
Unique advantages (semiconductor, composite testing, scale)
Phase object preparation
Optoelectronic reconstruction

Holograms of silicon micro-objects have been recorded in transmission using digital holographic microscopy in infrared (1.5 microns). Internal structures at several heights have been identified by propagation of the measured complex field from one hologram.

Focusing the top (a) and bottom (b) scratches engraved into two silicon wafers.
Main technical achievements to date

In Demonstrator 4,
• holograms have been acquired in the infrared and promising novel applications have been demonstrated such as capturing objects of relatively large dimensions and silicon defect analysis
• procedures are available to optoelectronically display the resulting data on versatile relatively-compact setups and on wider-viewing-angle setups using multiple displays

Conclusion

• A European Commission –funded project has begun in the area of digital holography
• Microsystems technologies are used for both 3D imaging and 3D display
• Objective: eliminating the current obstacles in achieving a fully functional holographic 3D video capture and display paradigm for unrestricted viewing of real-world objects
• A broad range of results have been achieved in the first year
• Years 2 and 3 will focus on demonstrators of the full chains from capture, processing, transmission, and display.

For all publications, please go to www.digitalholography.eu/publications.html

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