PROJECT FINAL REPORT

Grant Agreement number: 216105

Project acronym: REAL 3D

Project title: Digital holography for 3D and 4D real-world objects' capture, processing, and display

Funding Scheme: Collaborative Project

Period covered: from 1.2.2008 to 30.4.2011

Name of the scientific representative of the project's co-ordinator[1], Title and Organisation:

Mr. Arto Eljander, Accounting Manager, Financial Services Department, University of Oulu, Pentti Kaiteran katu 1, 90014 Oulun Yliopisto, Finland

Tel: +358-8-553 4133, Fax: +358-8-553 4170, E-mail: firstname.lastname@oulu.fi

Mr. Thomas Naughton, University of Oulu, Oulu Southern Institute, Vierimaantie 5, 84100 Ylivieska, Finland.

Tel: +358-40-3511635, E-mail: firstname.lastname@oulu.fi

Project website Error! Bookmark not defined. **address: www.digitalholography.eu**

[1] Usually the contact person of the coordinator as specified in Art. 8.1. of the Grant Agreement.

4.1 Final publishable summary report

[INSTRUCTIONS FOR THIS SECTION: This section must be of suitable quality to enable direct publication by the Commission and should preferably not exceed 40 pages. This report should address a wide audience, including the general public.
The publishable summary has to include **5 distinct parts** described below:

- An executive summary (not exceeding 1 page).
- A summary description of project context and objectives (not exceeding 4 pages).
- A description of the main S&T results/foregrounds (not exceeding 25 pages),
- The potential impact (including the socio-economic impact and the wider societal implications of the project so far) and the main dissemination activities and exploitation of results (not exceeding 10 pages).
- The address of the project public website, if applicable as well as relevant contact details.]

Executive summary

The "Real 3D – Digital holography for 3D and 4D real-world objects' capture, processing, and display" project is a research project funded under the Information and Communication Technologies theme of the European Commission's Seventh Framework Programme, and brings together nine participants from academia and industry. This three-year project marks the beginning a long-term effort to facilitate the entry of a new technology (digital holography) into the three-dimensional (3D) capture and display markets.

Functional models of four digital holographic 3D capture, processing, and display scenarios were developed to target the work, encompassing (i) the full 360° of perspectives of reflective macroscopic 3D scenes, (ii) microscopic reflective 3D scenes, (iii) transmissive or partially transmissive microscopic 3D scenes, and (iv) capture of 3D scenes at infra-red wavelengths.

The results of Work Package (WP) 2 "Strategies for 3D information extraction from digital holograms" will allow the public (general and scientific) to share a common knowledge on the state of the art of the various features of holographic technology as well as to share a common language and terminology for definitions and concepts. Deliverable 2.1 is almost exclusively public access, and represents the scientific/technical basis for discussions for later WPs in Real 3D and wider afield. It will allow industrial entities new to digital holography to immediately gain a practical overview of the capabilities of digital holography, written by the experts in the field, and is extremely timely. The digital hologram file format will define a standard enabling interoperability between groups, and products, lowering costs and ensuring stability.

At the end of the project, WP3 "Hologram capture" has resulted in strategies for capturing reflecting and transparent microscopic/macroscopic objects in different scenarios that have been experimentally verified. A capture system capable of capturing wavefields reflected from a macroscopic object simultaneously from six directions is working. It consists of six self-contained compact holographic capture devices that have commercial potential. This experimental proof of concept will supply the necessary evidence to enthuse industry.

WP4 "Hologram pre-processing" is an enabling workpackage that will allow more efficient hardware implementations through the invention of novel procedures for noise reduction and resolution enhancement, thus making high resolution digital holography more economical. It also resulted in techniques for speckle reduction in microscopic reflective scenes, and techniques to calibrate and register the six-camera setup. Additionally, contributions to the very difficult and currently unavoidable problem of gaps in field recording and field display have brought realisation of a visually pleasing multi-device holographic display that much closer.

By collecting full information on digital holographic and non-digital holographic techniques for 3D imaging and display, and by performing comparisons of their performances and evaluation of their compatibility or complementarities, WP5 "Compatibility with other technologies" situates the currently maturing 3D digital holographic techniques in the context of existing technologies. From this work, industrialists and laboratories willing to develop real 3D imaging have at their disposal a concrete basis and a comprehensive view of the ways digital holography can be introduced in the world of the existing 2D and 3D acquisition and display technologies, including helpful studies beyond visible wavelengths. This will more easily allow the transition of existing closely related industry to move into the digital holography field, and will promote the opportunity for novel fruitful marriages between digital holography technology and existing technologies. WP5 will also provide coding and compression software to facilitate online and real-time networking applications and products.

The final results of WP6 "Management of holographic data for numerical reconstruction" provide algorithms and tools allowing convenient interaction with 3D digital and optical hologram reconstructions. The different modalities are totally transparent to the user who will be able to modify intuitively some parameters while immersed in the 3D reconstruction (point of view, reconstruction distance, and so on). The novel concept has been developed to adapt digital holograms to the "half-way house" of conventional stereoscopic displays. The expected results from WP6 are essential for future practical commercial products, allowing ease of use and interactivity.

In WP7 "Management of holographic data for optoelectronic reconstruction" the procedures have been developed for enhanced holographic data preparation for flat displays (including multi-spectral data), and for multiple flat displays in a circular configuration thus laying the groundwork for future curved displays. By determining the most serious sources of error at reconstruction stage (including speckle noise and the aforementioned gap problem), numerical and experimental strategies have been developed to overcome or limit the influence of these errors on the final 3D reconstruction configuration. Detailed analysis has been performed to ascertain the conditions under which stereo viewing is possible. This will reduce the cost of eventual trials and provide important information for any digital hologram display manufacturing concerns.

Better scientific and technical understanding of dynamic holographic displays for holographic video, and advancements in such displays, is one long-term influential output of WP8 "Novel displays." Several novel laboratory proofs of concept consisting of many optoelectronic display devices in piecewise partial circle arrangements have been constructed and analysed, and their superiority over current technologies demonstrated. Each of the displays developed in this WP will have the potential to spark the initial interest of companies and venture capitalists by showcasing novel possibilities for the technology.

Recommendations have been made for future research and further development. Specifications targets for the components required to achieve commercial holographic 3D products have been set. An industry-focused report highlights the possibilities and barriers for commercialisation of the Real 3D technology (sensing, processing, and display). From a socio-economic perspective, in addition to the commercial impact mentioned throughout this report, it is envisaged that 3D displays will increase productivity, may save lives in a medical scenario (such as keyhole surgery, or better diagnosis through holographic microscopy), and may have wider societal impact in terms of improved education and personal communication experiences.

Summary description of project context and objectives

The "Real 3D – Digital holography for 3D and 4D real-world objects' capture, processing, and display" project is a research project funded under the Information and Communication Technologies theme of the European Commission's Seventh Framework Programme, and brings together nine participants from academia and industry. This three-year project marks the beginning a long-term effort to facilitate the entry of a new technology (digital holography) into the three-dimensional (3D) capture and display markets.

Current and newly-developed 3D displays have the disadvantage of requiring special eyewear, limit the number of simultaneous viewers, discard completely certain depth cues (such as blurring) thus causing fatigue, or else encode only a small number of distinct different views. It can be argued that there is only one known technology that can capture a full 3D scene in a single shot, including phase information, and re-project that light field perfectly thus overcoming all of the above disadvantages. This is the family of techniques that reconstruct the whole wavefront from a 3D scene: holography itself, and integral imaging under certain circumstances. All other techniques are only 3D under a whole host of conditions, such as requiring viewers to be in a "sweet spot" to observe the stereo, requiring users to be tracked by some intelligence built into the display (thus fundamentally limiting the number of simultaneous viewers), or encoding horizontal parallax only.

To take a small number of examples, we can point to the following problems with current stereoscopic cinema (or 3D cinema as it is known), and explain how a holographic display has the potential to solve them, thus setting the context for the project:

1. Accommodation-vergence rivalry: this problem arises when a viewer's eyes converge or diverge in response to disparity between the left and right images, giving the illusion that part of the scene is coming in front of or behind the screen, but all the time the eyes must accommodate (i.e. focus) exactly on the cinema screen. This causes strain in the visual system. Holography avoids this because each object in the 3D scene comes to a focus in its own virtual plane.
2. Fixed depth of field: the objects in focus in the scene is determined by the cinematographer and there is no possibility to see clearly objects in the 3D scene that the cinematographer has not captured in focus. Similarly, if the cinematographer makes everything in focus, a major illusion of depth that the brain uses is removed. With holography, the viewer decides what is in focus at the moment they look at the scene, and can change what is in focus to any degree of depth resolution, up to how good their eyesight is, just like looking at real-world 3D scenes. Whatever is not focussed on by the viewer will appear out of focus to a degree proportional to its distance from the in-focus object, also as in the real-world. This blurring is a powerful depth cue which is used by all 2D cinematographers, but which cannot be extended beyond its 2D properties in 3D cinema.
3. No motion parallax: when users move their heads slightly in 3D cinema, the objects do not move as they should if it was a 3D scene (closer objects moving more than farther ones, very far objects not moving at all). This can give rise to visual discomfort. With holography, parallax works as it does with real-world scenes, both horizontally (moving one's head to the right, for example) and vertically (standing up, for example).
4. Only one perspective: everyone in the 3D cinema sees the same perspective decided by the cinematographer. Changing seat does not give you a new perspective of the 3D scene, as is the case in live theatre (for better or for worse), and as is the case with holography.

5. No vertical stereoscopy: in-plane tilting of one's head breaks the illusion of 3D in 3D cinema. So, for example, it is not possible to rest ones head on a loved ones shoulder and enjoy 3D cinema. With holography, one's eye orientation can even be completely vertical (head tilted sideways by 90 deg.) and the 3D perception is maintained.

These examples give a flavour of the challenges to conventional stereoscopic displays: all challenges that could be solved in unison with a holographic display.

Display is only one half of holography. The other core property of holography is that it can be used to capture 3D scene information too. Unfortunately, while conventional holograms already today provide us with all of the advantages listed above, they are not dynamic. By replacing the conventional holographic plate with a digital camera and an optoelectronic 2D screen, we can capture and display holographic video. When holograms are in this convenient electronic form we can apply the capabilities of modern computers and conventional data networks to them. Therefore digital holography provides us with a third core property to go with capture and display: that of hologram data processing. By processing the hologram data we can, for example, improve its quality after capture, extract the 3D properties of the 3D scene captured, synthesise new holograms, simulate reconstruction of the 3D object from the holograms with software, and optimise the hologram data for display on optoelectronic devices. While digital holography has already found considerable use, so far, the main applications of digital holography have been in specialist fields such as the bio-medical field where it brings unique advantages to 3D microscopy, and industrial metrology of larger objects with only predictable movement. The full implications of bringing a digital version of holography into the world of 3D video acquisition and 3D display, or how effective it would be, are as yet unknown. The full 3D information encoded in digital holograms has not yet been exploited.

In this project, we work towards eliminating current obstacles to achieving the world's first fully functional 3D video capture and display paradigm for unrestricted viewing of real-world objects that employs all real 3D principles, hence our acronym "Real 3D." The primary outputs are:

Output 1. A 3D holographic acquisition system based on digital camera technology, with over 30 million pixels of side length 3.45 μm, arranged nonuniformly in a partial circular configuration around a space of diameter 10 cm that will be capable of holding a real-world 3D scene. The acquisition system will be capable of recording holographic video of the 3D scene.

Output 2. A 3D holographic display system based on liquid crystal on silicon (LCOS) technology, with 12 million pixels of side length 8 μm, arranged nonuniformly in a partial circular configuration of diameter of at least 10 cm. The reconstruction system will be capable of displaying holographic video of the 3D scene.

Output 3. The signal/image/information processing theories, techniques, and tools required for the processing, analysis, and synthesis of the data from capture to display, including adapting the data captured for display on alternative configurations and on conventional 3D displays.

Output 4. Reports containing the hard scientific data, in terms of functionality, performance, resolution, restrictions, data quality, and visual perception, that would be required by a company to take our proof-of-concept outputs and develop the next stage in the commercialisation of this 3D technology. In addition, reports on the theories, techniques, and tools that enable this technology.

Functional models of four digital holographic 3D capture, processing, and display scenarios will be developed to target the work, encompassing (i) the full 360° of perspectives of reflective macroscopic 3D scenes, (ii) microscopic reflective 3D scenes, (iii) transmissive or partially transmissive microscopic 3D scenes, and (iv) capture of 3D scenes at infra-red wavelengths.

The projects goals under headings of reviews, capture-side, processing, and display-side can be given in more detail. In terms of reviews, what is required are complete state-of-the-art reports on 3D acquisition, 3D information, and 3D display techniques, and analysis of compatibilities between the data from different kinds of sensing techniques, a taxonomy of super-2D data representations to find a common language to distinguish between the subtleties of levels of 3D information between stereoscopic and true 3D, an analysis of all of the properties and potential future functionality and definition of a digital hologram file format, a study of the state of the art in digital holographic and non-digital holographic 3D imaging techniques with a view to find synthesis opportunities, and a timely survey of the state-of-the-art in dynamic holographic displays.

In terms of processing, the primary hologram capture arrangement, extensible in principle to 360 deg., should be fully implemented. Techniques to overcome flaws in existing hologram designs (keyhole problem, twin image presence, problem of gaps between sensors) should be addressed with solutions ranging from optical solutions, solutions involving digital image processing, and solutions requiring the capture of multiple different holograms of the same scene. Experiments with Fresnel holography, lensless Fourier holography, rainbow digital holography, phase-shifting digital holography, and infrared holography should be performed, with final emphasis on those associated with the Scenario 1 proof of concept. Separately, non-real-time optical arrangements for capturing 360 deg. hologram data of 3D objects should be developed, and several hologram videos of rotated microscopic and macroscopic objects of very high quality captured for testing purposes.

In terms of processing of holograms, solutions should be found for the keyhole problem, dc and twin reduction problems, data compression techniques for hologram video suitable for network transmission, reconstruction on tilted planes, effective extraction of information about 3D objects encoded in digital holograms, extended focus imaging to overcome the naturally small depth of field in hologram reconstructions, and to the problem of how to calibrate and manipulate hologram data from a piecewise planar capture curvature to a possibly different piecewise planar display curvature.

In terms of display, the data management process should be defined that connects capture hardware and techniques, processing, and optoelectronic reconstruction, including with respect to the arrangements required for stereoscopic viewing. Novel multi-device optoelectronic displays for digital holograms, including for colour holography, should be designed and built. At least one of these should in principle be extended to 360 deg. Modification and display of digital holograms using conventional display technology, such as stereoscopic displays and head-tracking displays, should give the 3D illusion of the scene that has been captured holographically. A visual perception study should be undertaken to compare perception of 3D scenes with stereoscopic display technology, optoelectronic display of digital holograms, and conventional holograms.

Technical objectives specific to the proofs of concept are as follows.

- In Scenario 1: six compact hologram capture devices developed and implemented, hologram requirements specified to maximise viewer impact, a comprehensive report on, and the best procedures identified for, hologram processing (dc removal, twin reduction, speckle reduction, gap problem), multi-camera hologram video compressed, an equivalent six-device optoelectronic display fully developed and evaluated experimentally, ability to adapt the display to overcome the gap problem, and visual perception experiments conducted.
- In Scenario 2: holograms of microscopic objects captured with dual wavelengths, the data processed to admit extended focus images and reconstructions on tilted planes,

the data conditioned for networked conventional stereo displays to allow efficient remote manipulation of the 3D scene capture, and speckle reduction to aid 3D scene understanding.

- In Scenario 3: a two-axis rotation setup designed and implemented, data captured with same of transmissive biological specimens, a tomographic reconstruction algorithm developed to accurately obtain volumetric data as well as prepare the data for direct optoelectronic reconstruction, holographic reconstructions from phase-only display devices using eye-safe LED or other illumination.
- In Scenario 4: holograms acquired in the infrared, promising novel applications demonstrated such as capturing objects of relatively large dimensions, in the presence of visible occlusions, and for silicon defect analysis possibly aimed at the microelectromechanical industries, procedures to optoelectronically display the resulting data on versatile relatively-compact setups and on wider-viewing-angle setups using multiple displays.

Significant effort is required in terms of dissemination and exploitation activities, including international scholarly journal articles, invited and contributed conference papers, academic book chapters, wide-audience symposia, general-public presentations, newspaper interviews, international technical magazines, an industry trade journal, webpage with paper reprints and quarterly news updates, follow-up research grants and research projects, techniques and know-how, software routines and platforms, and several patent applications should be submitted or in preparation by the end of the project.

The project should be managed as set out in the Description of Work, including focusing the workplan towards a small set of demonstrable functional scenarios each boasting capture/processing/display novelties, continued maintenance for secure technical collaboration of the Optima web-based teaching environment, secure server for very large files, secure software versioning and control system, updating of the technical contributions archive, a regular internal reporting schedule at the Principle Investigator level, the Work Package Leader level, and (where non-overlapping) at the scenario-level, a four-Beneficiary Board should be established that meets regularly by teleconference, a twice yearly Consortium general assembly meeting, and many scenario-specific inter-Beneficiary face-to-face technical meetings.

Description of the main S&T results/foregrounds

The work can largely be described in terms of the three verbs in the title of our project: capture, processing, and display.

1. Hologram Capture

1.1 Hologram Capture - macroscopic objects

The primary model of capture consisted of six capture devices. The main scientific foreground of BIAS in the Real 3D project is the development and the construction of this device, called the HoloCam, which is a digital holographic sensor capable for capturing the three-dimensional information of a moving scene. A schematic sketch of this sensor is depicted by figure 1 and a technical sketch is shown by figure 2. A photograph of the HoloCam can be found in subsection 1.5.

The HoloCam is a compact device which includes all optical components required for generating superposition between the wave field scattered by the captured object and the known reference wave field within the CCD plane. The captured interference pattern, called digital hologram, contains the whole information of the wave field scattered by the object, including the amplitude as well as the phase information of the object wave field. Thus, by reconstructing this hologram the original wave field scattered by the object can be recovered. However, the main feature of this HoloCam is a reflecting phase only Spatial Light Modular (SLM) located within the optical path of the reference wave which has a spherical shape by default. The SLM allows for modifying the phase distribution of the reference wave just by electronic means. Hence, the HoloCam provides a very simple possibility for applying the reference wave to specific capturing requirements as for example given if capturing with Digital Lensless Fourier Holography. This capturing scheme is based on a spherical reference wave with its source point in or close to the object plane. Using conventional holographic capturing setups extensive mechanical methods like shifting the reference wave source point or adding additional optics are necessary. But using the HoloCam the effort for adapting its spherical reference source point to the object position is reduced to inscribing a proper complex transmittance to the SLM in order to shift the source point virtually. The benefit of the HoloCam is also demonstrated if a change from in-line holography to off-axis holography is required or temporal phase shifting is needed, just to name its most important applications. Further information about the HoloCam and digital holograms captured by it can be found in Deliverable 3.3.

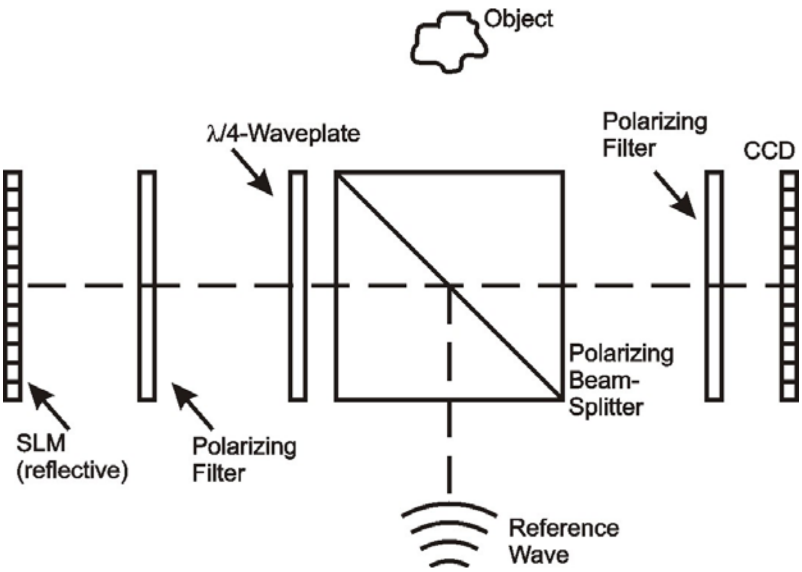


Figure 1: Schematic sketch of the HoloCam

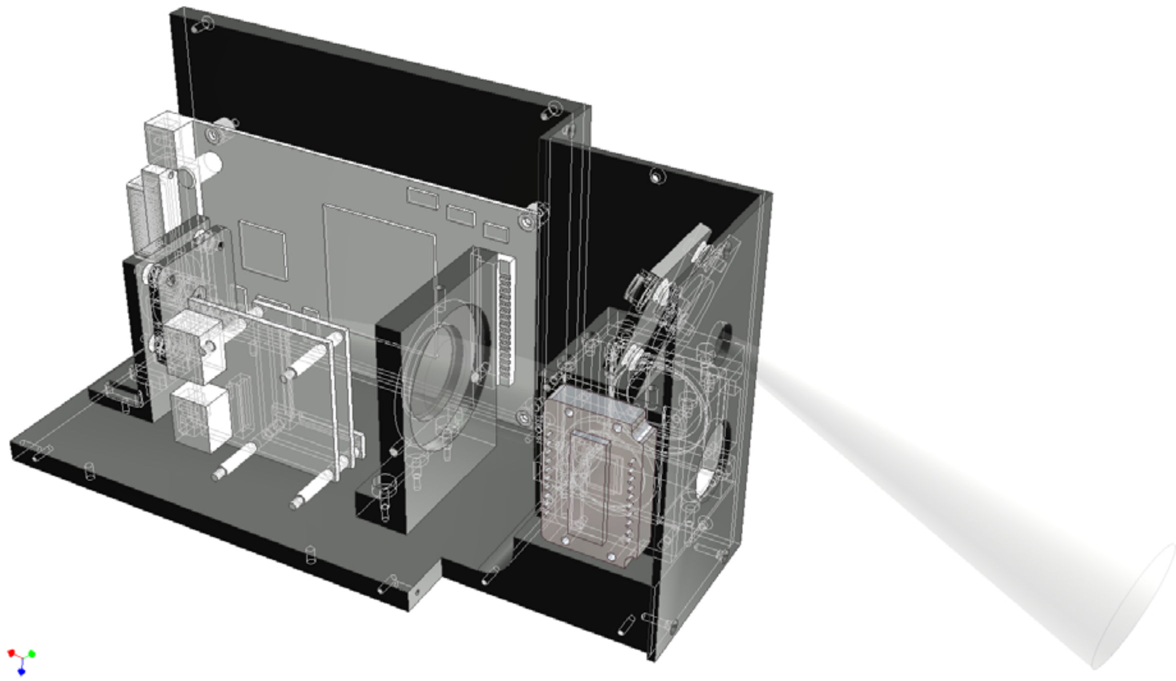


Figure 2: Technical sketch of the HoloCam

Based on the concept of a compact digital holography capturing device, a digital holographic capturing system consisting of six HoloCams were developed and constructed. By arranging them in a partial circle, the system allows for capturing a larger dihedral angle of the wave field scattered by a scene simultaneously in time. For this purpose, the capturing system was equipped with a trigger unit. For performing also capturing of dynamic scenes, the applied light source was chosen to be a pulsed laser with a pulse duration in the range of nanoseconds and a pulse energy of about 10 millijoules. The back view of this capturing system is shown in figure 3. A photography showing the front view can be found in subsection 1.5. Further more detailed information regarding this multi-cam setup and hologram videos captured by it can be found in Deliverable 3.3. Several digital holographic videos have already been captured using this setup. Figure 4 shows a selection of numerical reconstruction of digital holographic video captured with the HoloCam on the left hand side in figure 3. The video frame rate was 10 Hz. The captured object was a watch whose hands are all moving in real time.

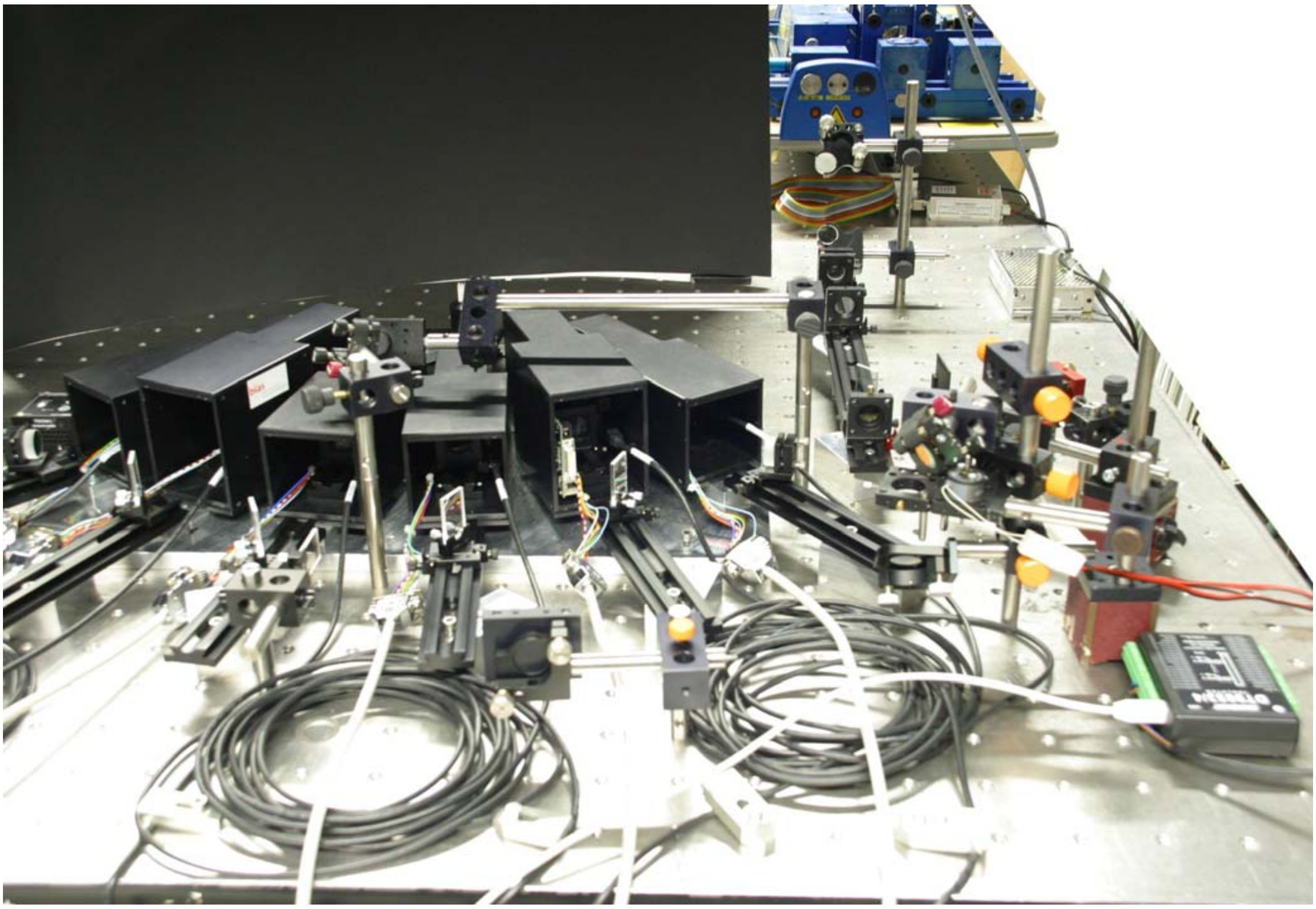


Figure 3: Photography of the digital holographic capturing system for capturing dynamic scenes from six directions simultaneously in time – back view.

Static macroscopic scenes

In NUIM (see Fig. 5) we recorded the static case PSI holograms for the final demonstration of Scenario 1. We recorded over 10,000 digital holograms during the Real3D project and we built up significant experience and expertise in this area. We designed and constructed at least ten different optical recording systems, the most recent of which is shown below. We developed Labview software that allowed us to record videos of digital holograms. Using a simple interface this software allowed us to control a rotation stage (used to rotate object) and translation stage (used to move illuminating diffuser for speckle reduction) and to calibrate using a novel technique developed in NUIM *(1 poster)*. We also developed methods to reduce vibration during recording.

Study of Imaging Properties of Digital Holography

We undertook a comprehensive investigation of image formation in digital holography. In particular we looked at the effect of the physical parameters (camera aperture, pixel size, sampling rate, digital quantization, laser wavelength, object size and distance to camera, low light conditions, planar vs. spherical reference, in line vs. off axis reference wave) of the recording system on the quality (resolution, 3D angular perspective as well as noise were considered) of the reconstructed image *(2 conference proceeding, 2 journal papers)*.

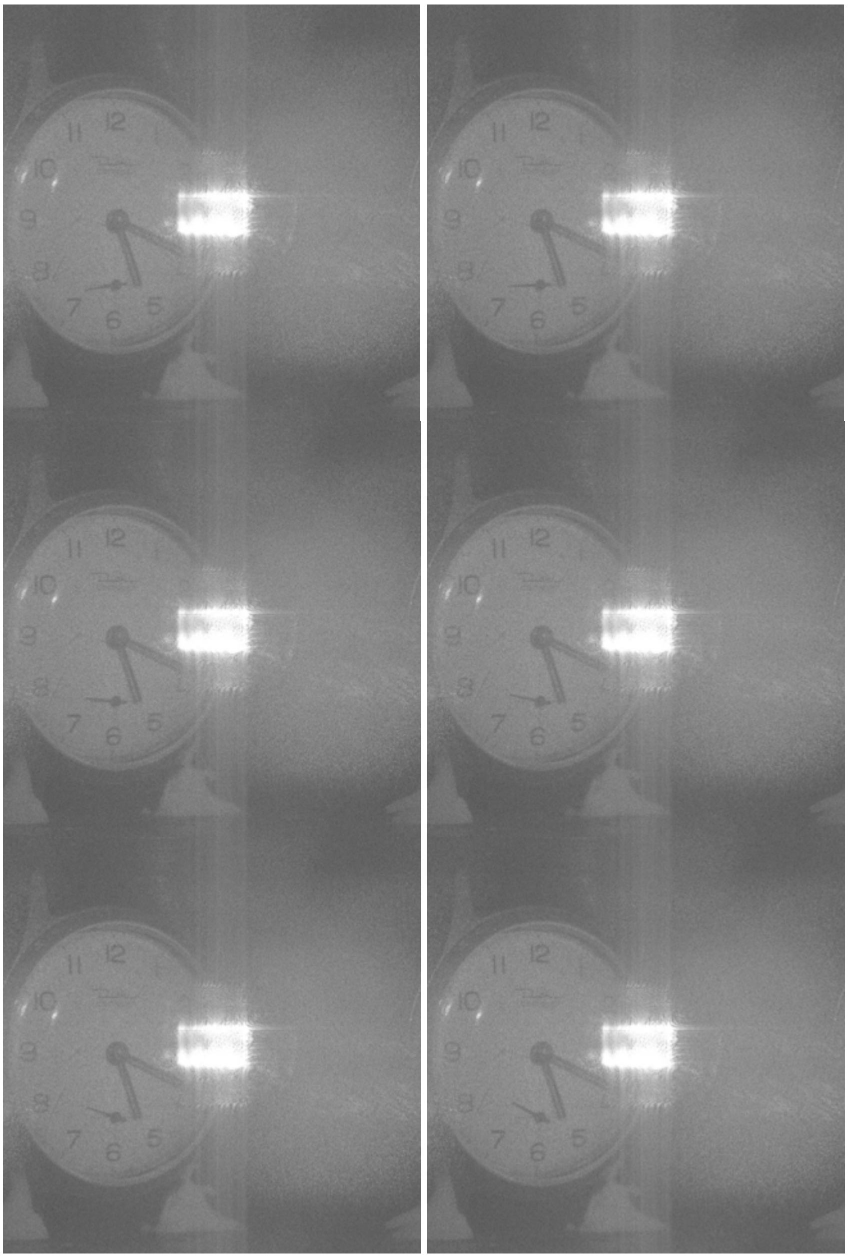


Figure 4: Numerical reconstructions of a digital holographic video of a watch captured at BIAS. The time distance between two holograms is 1s.

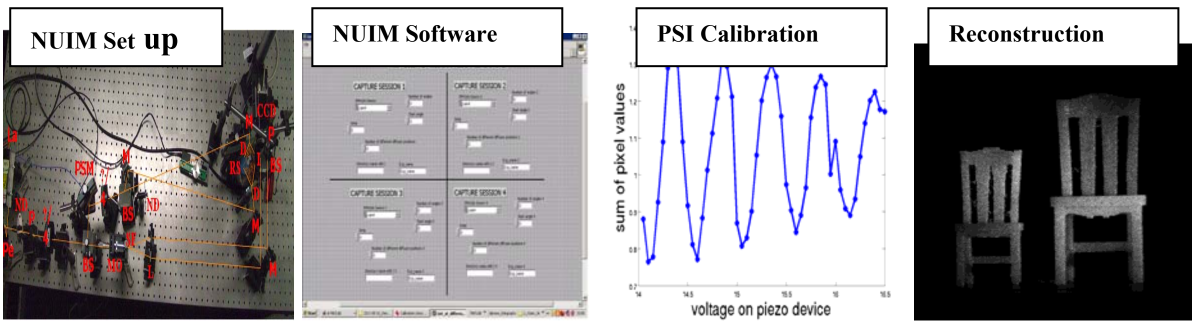


Fig. 5 Recording in NUIM in Scenario 1; We show most recent recording setup and interface of Labview software for creating static case videos. We show result from using calibration software and reconstruction with speckle reduction

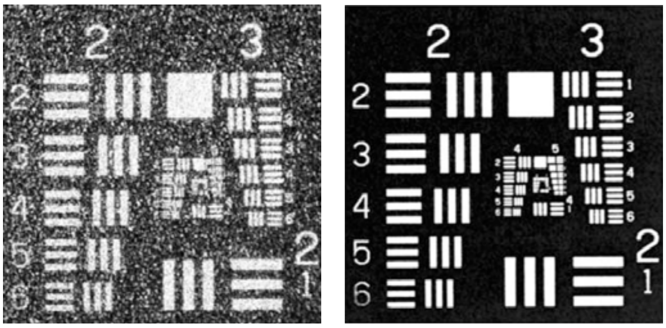


Fig. 6 Results of using twin reduction by speckle reduction method taken from Opt. Lett. paper (before and after)

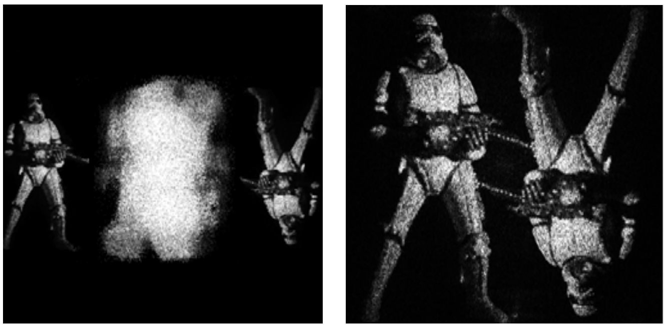


Fig. 7 Results of using the small angle off axis method using the lensless Fourier architecture (before and after)

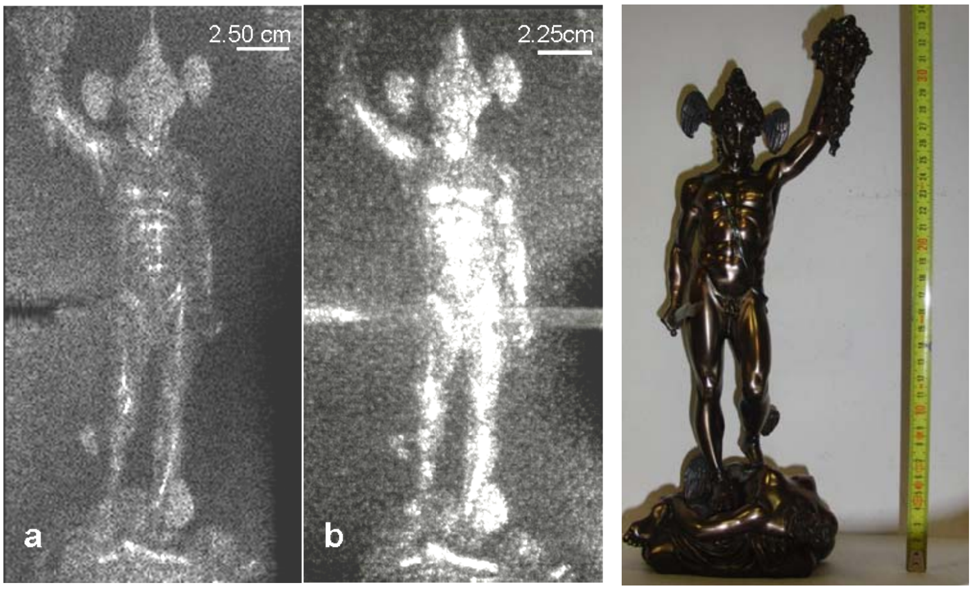


Figure 8 Perseus object captured by CNR

Based our study of image formation, we review all existing architectures and filtering methods for digital holography *(2 conference papers)* and we designed a number of new recording/processing techniques;

New Recording/Processing Techniques

We developed and tested three novel methods for recording digital holograms; (i) The first is twin/DC reduction by speckle reduction *(1 conference proceeding, 1 journal paper)*. A result from using this technique is shown in Fig. 6; (ii) Twin/DC reduction by segmentation *(1 conference paper, 1 journal paper)* which is described later in the "Hologram processing" section, and (iii) Small angle off axis digital *holography (1 conference paper, 1 journal paper* *in preparation).* By lowering the power of the object wavefield relative to the reference we can eliminate the object DC term and maximise the bandwidth of our camera allowing for better resolution and angular perspective, see Fig. 7. We are currently investigating impact on fidelity of phase measurement for DHM.

Infrared holograms of large objects

CNR captured IR holograms of large objects, i.e. metallic statuettes, up to 40 cm high, by means of CO_2 laser. Then we demonstrated that an efficient and reliable reconstruction in the visible range, of digital holograms recorded with a long IR wavelength, can be accomplished by suitably operating a spatial light modulator (SLM), therefore offering the possibility of obtaining, in principle, direct 3D vision at long IR in real time. In Fig. 8(a) and (b) are shown the numerical and optical reconstruction of the IR hologram , while in Fig.8(c) there is a photo of the Perseus statue.

1.2 Hologram Capture - microscopic objects

As academic institution, the goal of EPFL has been to develop new tools available for the international academic and industrial institutions. Full 3D vision for macro- and Micro-vision is one major field where such innovative tools are needed. True 3D data acquisition is required in view of a full 3D image restitution on a 3D or full holographic displays. In Real 3D project the acquisition of 3D data has been achieved either at a macroscopic scale by the recourse to (Digital Holography: DH) the use of multiple Holographic lensless cameras at multiple incidences (scenario 1), or at a microscopic scale by the recourse to the techniques of Digital Holographic Microscopy (DHM). For macroscopy, DH must accommodate speckle imaging and the quantitative measurement of object morphology is more difficult. For Microscopy (scenario 2), it is possible to exploit fully the capability of DH to provide the complex wavefront. In particular, the phase information can be directly related to the object morphology and quantitative data concerning object shape and also internal constitution can be derived from holographic measurements. The main outcome of the research and developments performed by EPFL in the project Real 3D is the full acquisition of the 3D conformation of small objects, biological objects in particular. Full coherence tomography approach has been developed to determine full quantitative 3D conformation and composition (in term of refractive index distribution) of small transparent objects.

Optical tomography using digital holographic microscopy

In this task, EPFL has developed a complete microscope for optical tomography in transmission using DHM. This task includes an experimental setup with full object rotation and 3D digital reconstruction of semi-transparent biological objects using the theory of diffraction tomography. The acquired data at various angles has been used to provide a full dataset to be displayed on opto-electronic devices, SLM arrays, as shown in demonstrator by Bilkent University (scenario 3).

Full 3D imaging of diffracting semitransparent biological objects is achievable using this technique with our rotation setup. The long term objective is to retrieve the scattered data from the full two-Pi or further, four-Pi solid state angle. This device with its future extension combining reflection and transmission measurements is planed to be patented in the future.

A tomographic holographic microscope has been designed and realized during the project. It is illustrated in figure 9. It brings the maximum flexibility in the combination of a variable incidence illumination beam and orientation of the specimen.

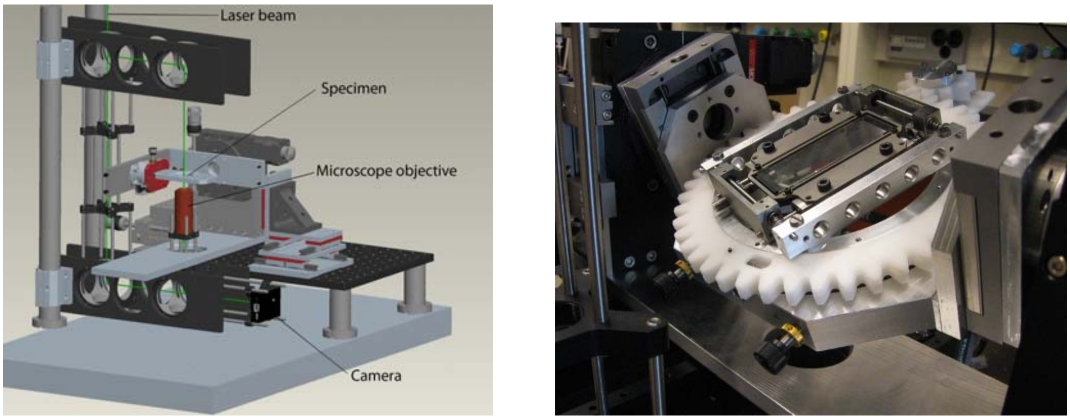


Figure 9: Digital holographic microscope for transmission tomography and rotating part of the setup.

The setup can be completed with a second microscope objective in order to collect also the backscattered light. The whole Ewald sphere could then be obtained and the entire part of spatial frequencies accessible with the method could be filled.

3D reconstruction using diffraction tomography

The theoretical description of diffraction tomography was given by Wolf in 1969. The principle of the method is to record the diffraction field in several directions in space and to compute its Fourier transform for each direction. It can be shown that, due to diffraction, this Fourier transform lies on a cap of sphere whose position in the frequency space depends in particular on the illumination and acquisition geometry. By considering many different acquisitions (rotation of the object, beam scanning, wavelength diversity…) the 3D Fourier space can be filled. Then, the quantitative refractive index of the object can be deduced from the 3D inverse Fourier transform. In the frame of the real 3D project, the method has been applied to the determination of conformation and composition of transparent objects and more particularly biological cells. A software package named “Theodor” has been developed for that purpose.

To achieve diffraction tomography, digital holography has been shown to be particularly well-suited due to its ability to retrieve the complex amplitude of the scattered field. In order to understand the limits of the first Born approximation have been evaluated by performing comparisons between the complex field obtained from Born approximation and from Mie theory and the results have been extrapolated to nay shape transparent specimens.

The achieved works have demonstrated the ability of our setup, used with the method of diffraction tomographic reconstruction, to image biological objects refractive index in 3D.

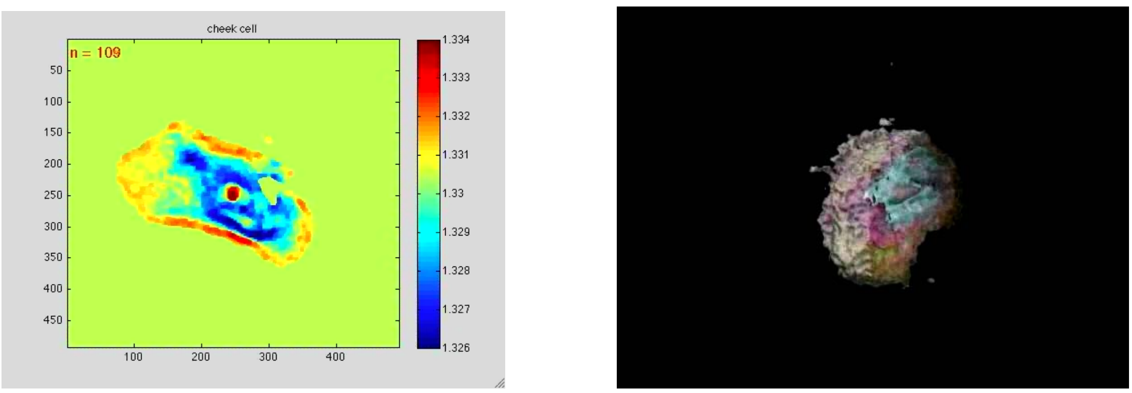


Figure 10 a) and b) illustrate the results obtained by the diffraction tomography technique: Figure 10 a) shows an isolated section of an epithelial cheek cell : the cytoplasm and nucleus can be distinguished, whereas figure 2 b) shows the corresponding 3D image integrating the various sections of the epithelial cheek cell.

Extension to near infrared spectral range

It has been demonstrated that Digital Holographic Microscopy (DHM) performances combined with the possibilities offered by transmission measurements in the near Infra-Red (NIR) domain provides a powerful and versatile tool for silicon micro-components characterization (scenario 4). Using this technique allows measuring various specimens of MEMs, whether for surface or in-depth profile measuring. 3D morphology and metrology or profile measuring or defects detection of silicon components. Furthermore, measurements are fast, accurate and do not require complex optical adjustment. To illustrate these abilities, we present measurements of silicon micro-lenses array and silicon wafers leading to accurate determination of the micro-lenses profile and to precise localization and size measuring of the silicon wafers scratches.

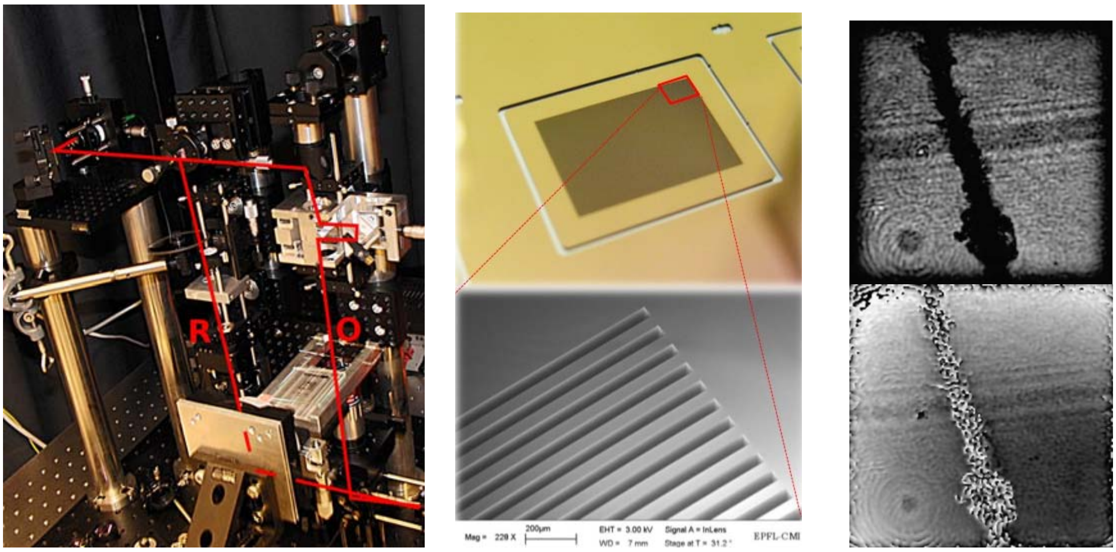


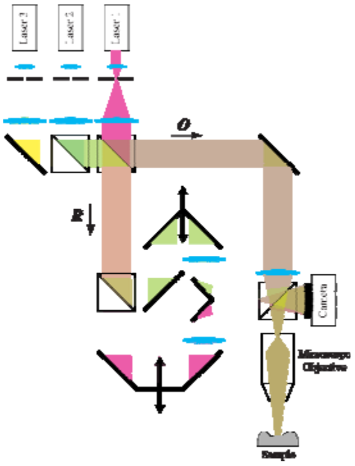
Figure 11 a) shows the optical DHM working in the NIR at a wavelength of 1.28 nm. Figure 2 b) illustrates the DHM technology to image buried channels in silicon (channels buried in silicon for chip cooling). Figure 11 c) images of defects buried in the bulk of the wafer: upper part amplitude image, lower part phase image.

Measurements are fast, accurate and do not require complex optical adjustment. To illustrate these capabilities, we have presented measurements of silicon micro-lenses array and silicon wafers leading to accurate determination of the silicon micro-lenses profile and to precise localization and size measuring of the silicon wafers scratches. The results of these measurements have been transferred to Bilkent Univ. for 3D display (scenario 3).

Dual-wavelength integration

As LT is a commercial institution, the main results are the improvements of the specifications of the DHM microscope (precision, measurement range, image quality) and the development of new applications that will open new market for the instruments. Currently, the main result is certainly the dual-wavelength integration, because it allowed more sales during the project by the increase of the measurement range of DHM. But at short-term, extension of depth-of-focus, and especially reflectometry DHM, in combination with high reconstruction rate (GPU programming), are features that customers are very interested by.
The dual-wavelength integration is the more important result achieved in Real 3D project. Indeed, it has allowed the development and the commercialization of new models of DHM

microscope: R1100 family (alternative dual-wavelength) and R2000 (simultaneous dual-wavelength), to the most complex DHM (R2200) that integrates 3 different wavelength allowing two different combinations of simultaneous wavelength acquisition for a measurement range about 3nm (nanometric resolution) and 15nm (lower resolution) (Figure 12).



(a)

(b)

Figure 12: DHM R2200 manufactured by LT integrating 3 different sources for two different simultaneous dual-wavelength acquisition. (a) setup and (b) commercial instrument.

Apart of the physical integration of dual-wavelength through optical elements arrangements, needed modification of the electronic devices (not relevant for the project, but necessary for the microscope operation), or software coding for keeping the commercial software dual-wavelength compatible, the GPU programming research through the project allowed to achieve 15 fps in dual-wavelength mode (camera limited on standard DHM). It can be mention here that very recent results, obtained on prototype software developed for a customer, achieve 60 fps for dual wavelength reconstruction, making DHM a unique solution for high speed investigation on in-line production for example.

Reflectometry DHM

Finally, LT could see last two years, that there is a large interest of customer to investigate multiple semi-transparent structures such as SIMS, transparent liquid deposed on wafer, structure deposit, among others. The development of dual-wavelength, and now the eventual possibility to use alternatively three wavelengths allows measuring makes available research and development on a reflectometry DHM. The results were very promising and allow nowadays preliminary prototype software sales. An official module integrating most efficiently with the commercial Koala software is in development and will continue after Real 3D project. Figure 13 presents an example of the capability of DHM for multiple semi-transparent structure measurement, here a deposition of SiO2 on a Si wafer.

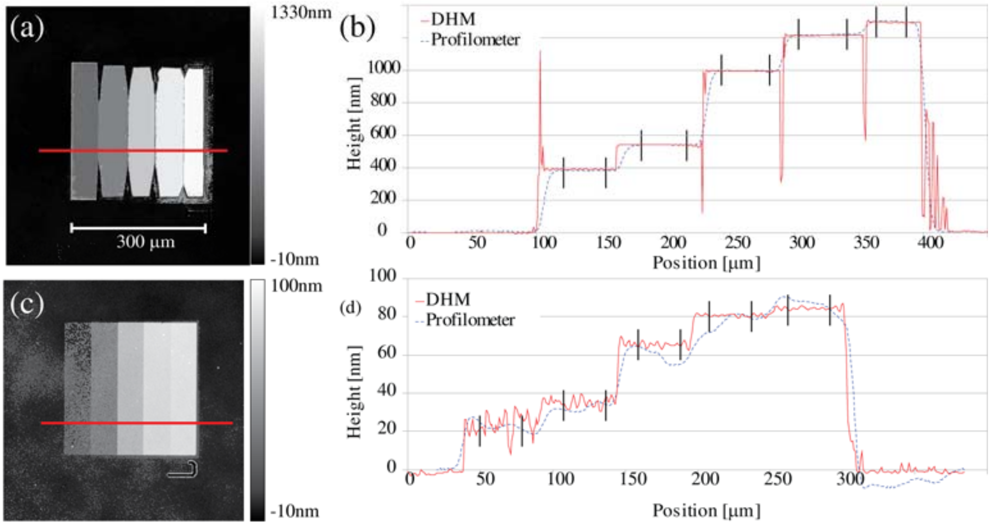


Figure 13: Refectometry DHM measured deposition of SiO2 on a Si wafer. Topography of (a) low, and (c) high resolution test targets; (b, d) respective profiles comparison between DHM [8 pixels average profile along red line in (a,c)] and TencorAlphastep 200 profilometer.

2 Hologram processing

Super-resolution (keyhole problem)

CNR investigated a method to enhance the resolution in digital holographic microscopy. To this aim the numerical aperture of the optical system is increased by means of an electro-optically tuneable phase grating or an amplitude grating inserted between the object and the CCD. The CCD records three spatially multiplexed holograms corresponding to three diffraction orders along each diffraction direction. Each hologram carries different information about the object. The hologram corresponding to the zero order contains the low object frequencies, while the holograms corresponding to the first orders collects the rays scattered at wider angles carrying information about higher frequencies. This kind of technique allows to enhance the resolution up to three times along each of the diffraction direction typical of the used grating.

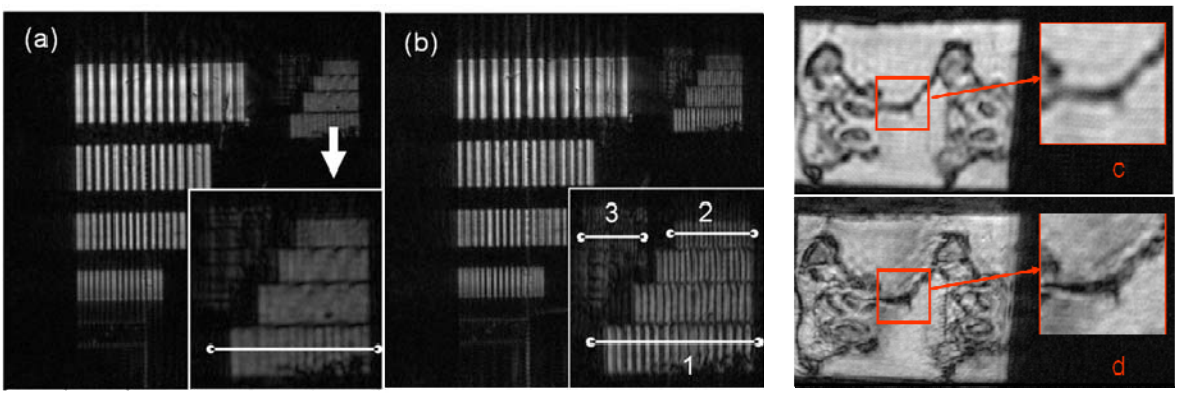


Figure 1

Fig.14(a) and (b) show the amplitude reconstructions of a digital hologram of a target, respectively without and with a grating in the setup: the resolution enhancement is clearly visible. In the numerical reconstruction, the images coming from the different multiplexed holograms are automatically superimposed in the final reconstructed image. This is the main advantage of the proposed technique in respect to other methods used to enhance the numerical aperture, in which different multiplexed holograms are superimposed by means of difficult numerical procedures. The simplicity of this technique allows us to apply it to any kind of sample with unknown frequency spectrum, i.e. a biological sample. In fig. 14(c) and fig.14(d) , the amplitude reconstructions of a digital hologram of a slice of a fly's head, respectively without and with a grating in the setup, is shown. Also in this case, the resolution enhancement is clearly visible. On the other hand, this automatic superimposition prevents us from finely refocusing the different reconstructions before their overlapping.

Extended depth of focus

CNR proposes a method to manage the depth of focus in digital holography. The principle consists in applying an affine geometric transformation to the original hologram. In particular, two cases have been analyzed: a linear stretching or a quadratic deformation. In the latter case we are able to put simultaneously in focus, and in one reconstructed image plane, different objects lying at different distances from the hologram plane (i.e. CCD sensor). The adjustments of the affine geometric transformation parameters allows having in focus in a single image plane horizontal and vertical wires, lying, respectively, to 150 and 100 mm from the CCD. (see figure 15).

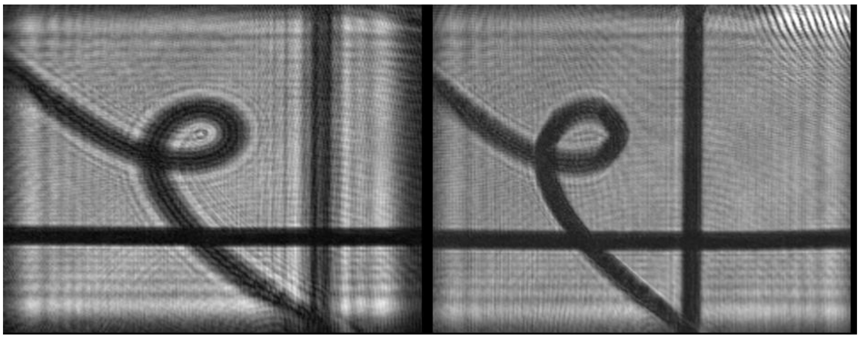


Figure 15

A quadratic deformation is also applied to Fourier-type holograms to retrieve the EFI image of a tilted object. In Fig.16(left) we show the numerical reconstruction of the acquired hologram for an object tilted with an angle $\varphi = 55°$. It is clear that the left part of the object, where there is the number "0", results to be in-focus, while the right part, with the number "1", is out of focus and that the focusing gradually worsen going from left to right side. If we apply the quadratic deformation before performing the reconstruction (with an opportune choice of the deformation parameter), we obtain the image shown in Fig.16(right). In this case the α value is $2.1 * 10^{-5}$

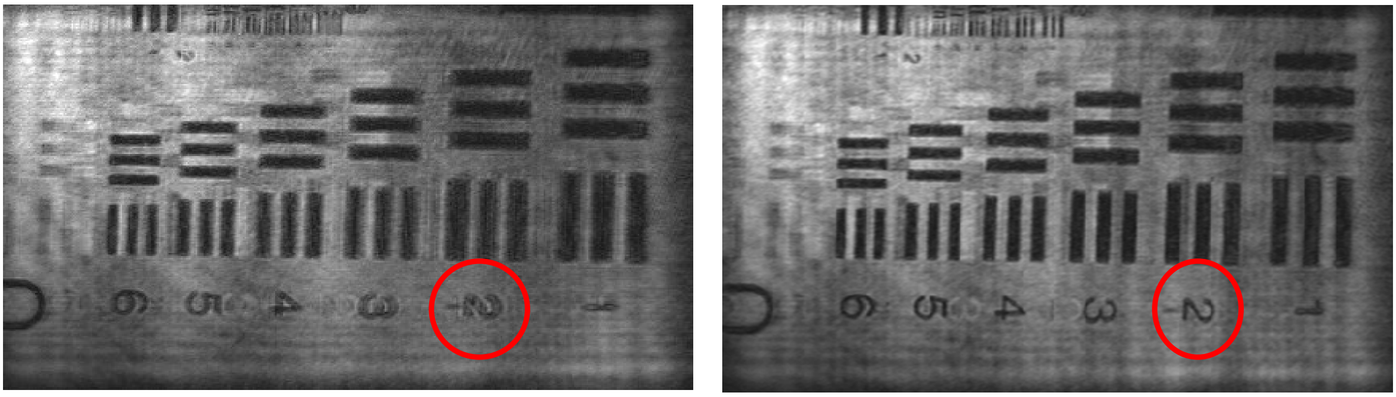


Figure 16

As to the linear hologram deformation, for Fresnel-type hologram, it cause the change of the observation plane. It means that, even if the hologram is reconstructed to a certain distance d, the image plane correspond to a different distance, that is d/α^2 where α is the deformation parameters. This properties has been exploited to synthesize 3D dynamic scene, combining multiple digital holograms of different objects recorded in fixed positions. The dynamic effect is obtained by an out-of-plane displacement created through a flexible adaptive geometrical transformation of the holograms. The synthetic holograms can be given as input to any SLM array for optical reconstruction. Figure 4 shows the optical reconstruction of a synthetic hologram of Pulcinella and an astronaut obtained by the combination of two different holograms. Figure 17(a) shows a scheme of the movements performed by the two objects (back-and-forth along the z-axis with rotation); while in fig. 17(b) four frames of the 3D scene optically reconstructed moving the projection screen at four different distances are shown.

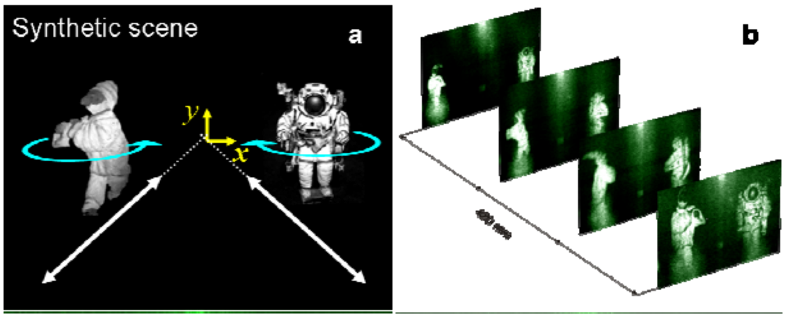


Figure 17

Extended depth of focus was also demonstrated by LT. This modality was not integrated into Scenario 2 because it limits too much the real-time capability of the DHM. With the recent results of reconstruction rate given before, extension of the depth of focus becomes now a realistic module to integrate in the commercial software and will be an important module for micro-optics customers in particular. Figure 18 presents an example of the application of this module and the interest for DHM to have it.

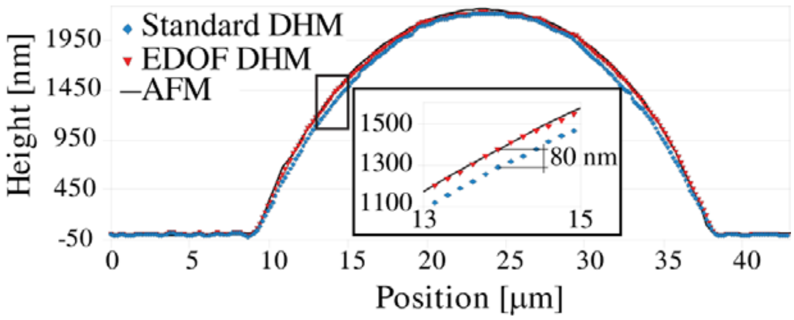


Figure 18: Extension of depth of focus of phase contrast to retrieve the correct microlens shape.

Software to enhance the Quantitative Phase Image in Digital Holographic Microscopy

Shot noise in DHM can significantly affect our ability to unwrap the phase image to obtain a quantitative measurement with nanometre resolution of the thickness or surface profile of an object. At NUIM, we investigated the influence of shot noise, which occurs for quickly moving objects on the accuracy of phase measurement and developed a theoretical relationship between the two. Based on an analysis of the characteristics of this noise we designed a computer algorithm using time frequency filtering to aid in its reduction. The code was written to process the same size tiff images as produced by the Lyncée Tec microscope. We implemented the algorithm in CUDA, for real time application (takes up to 1 hour in Matlab or C). In Fig. 19 we show the result of reducing the shot noise in the phase image. We have also shown the method works well in reducing all other sources of noise.

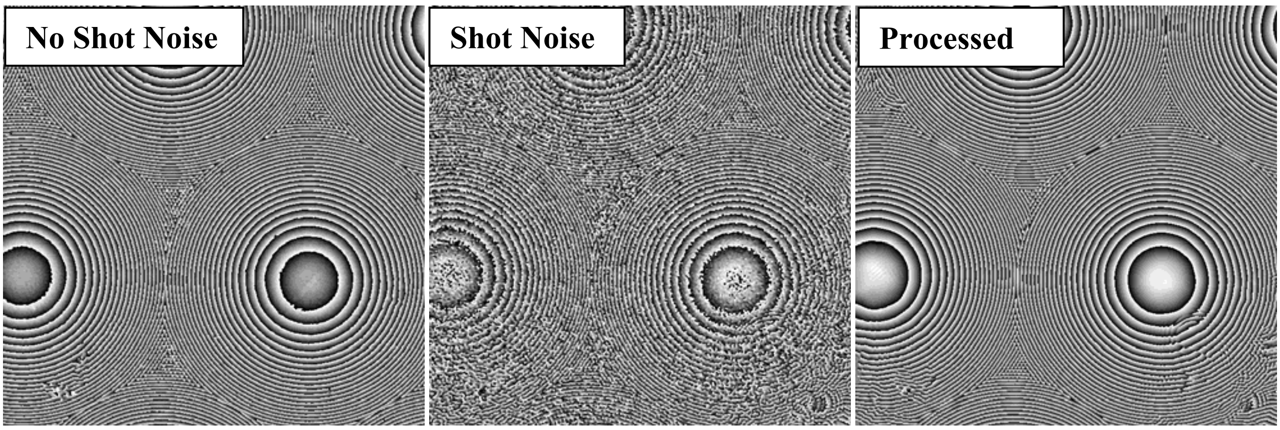


Fig. 19, Microlens array at 10x. We show; phase of reconstruction when time aperture was large resulting in little shot noise; The time aperture is approximately 1ms resulting in a noisy reconstruction; After processing with NUIM software

Software for Twin Reduction in Digital Holographic Imaging in Scenario 1

NUIM developed software using CUDA for real time twin and DC reduction in Scenario 1. These filtering algorithms have been written to run on one GPU or on multiple GPUs. GPU implementation allows us to run the algorithm across many threads in a multi core environment. This offers a significant speed up over the conventional single thread algorithm and allows for real time implementation of the numerical filter processing in Scenario 1. This real time filtering software allows us to use an in line recording architecture allowing us to maximise the angular perspective of the display system. In Fig. 2 below we show the results of the software where we numerically propagate to the twin image plane, then create a segmentation mask and remove the twin image and finally return to the hologram plane.

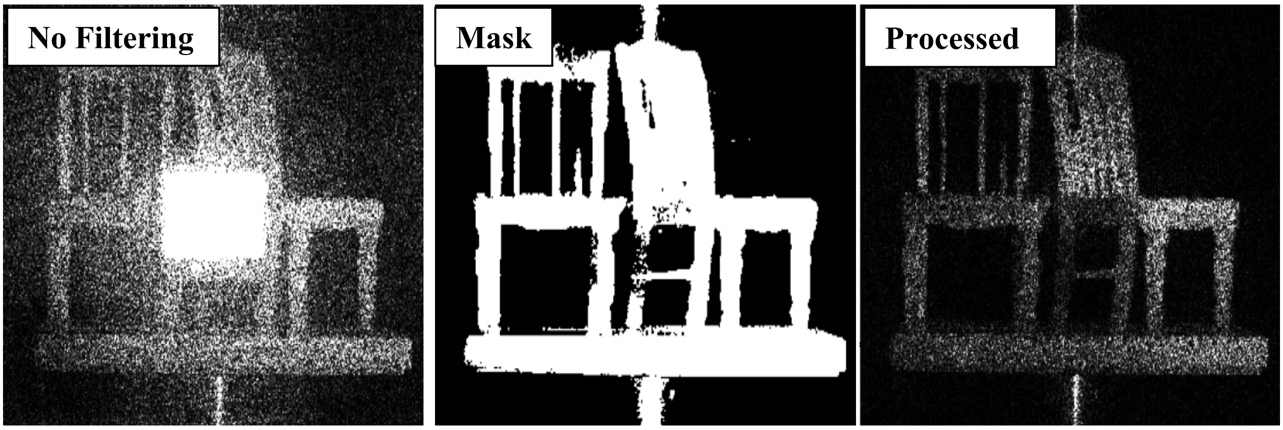


Fig. 20, Results of NUIM software for Scenario 1; We show the reconstruction when the software is not used. We also show the segmentation mask automatically created to filter the twin image and the reconstruction with NUIM software.

Software for High Speed Numerical Propagation

NUIM have also produced a suite of innovative high speed numerical propagation algorithms; We developed and disseminated software written in CUDA for the parallel numerical implementation of paraxial (Fresnel) and non-paraxial propagation algorithms *(1 journal paper)*. In addition we developed a novel zooming algorithm for digital holography allowing us to generate numerical reconstructions with any sampling rate or field of view *(1 book chapter, 1 conference paper)*. We developed a set of algorithms for Digital Gabor Microscopy *(1 journal paper)* and we also developed an algorithm that could reconstruct a digital hologram recorded using an arbitrary optical system made of lenses and sections of free space *(1 journal paper)*. We also designed a novel speed up technique for all of these algorithms which involves precompiling and storing values used in the algorithms resulting in a twofold speed up *(2 conference papers)*. Finally we investigated reconstruction using fixed point arithmetic on portable hardware devices such as FPGAs *(1 journal paper)*.

Study of Speckle and Other Noise Sources and their Reduction in Digital Holography

NUIM investigated the 3D speckle size from general optical systems with a limiting aperture in any plane in the optical system and we derived fundamental formula for the speckle size in the x, y and z dimensions in terms of the wavelength of the light and the parameters of the optical system *(1 journal paper)*.

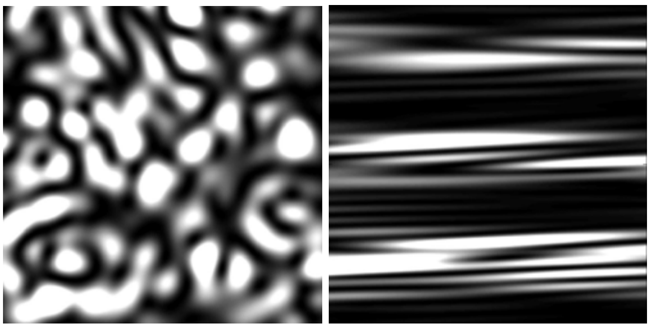


Fig. 21 (a) Speckle in x, y on retina in square region in res chart; (b) Speckle in z direction around retina for three bars

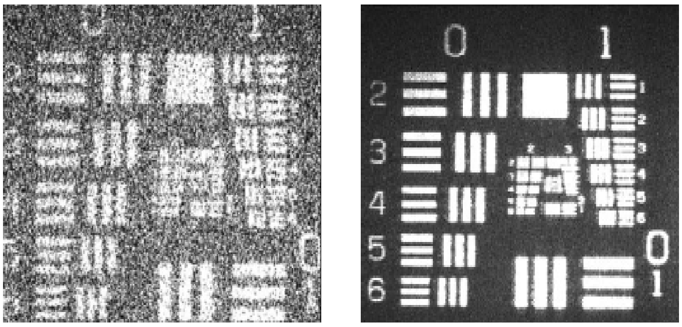


Fig. 22 (a) (From Appl. Opt. paper) reconstruction of 1 bit DH (high quantization noise) (ii) after speckle reduction

We proceeded to investigate the speckle from optoelectronic reconstructions of digital holograms in Scenario 1 and to profile various techniques that could be used to reduce this speckle based on the use of diffusers, broadband illumination, and vibrating elements *(1 journal paper in preparation)*. As an example in Fig. 21 below we show a simulation (using a digital hologram of a resolution chart) of the speckle that is incident on the retina of the observer at 400mm from the real image. We also investigated methods for numerical speckle reduction *(1 conference paper)*. Finally we looked at other noise sources *(1 conference paper)*; In particular we showed that quantization noise can appear as a speckle like noise in the reconstructed image and we showed it could be reduced by speckle reduction, see Fig. 22 *(1 journal paper)*.

Registering CCDs and SLMs in Circular Digital Holography Configurations

NUIM developed a method for the registration of the angular positions of the cameras in BIAS using a chessboard object, see Fig. 23 *(1 conference paper, 1 poster)*. We also developed a method for calibrating the SLM positions I in WUT using computer generated holograms of cross hair targets distributed in three dimensions, see Fig. 24.

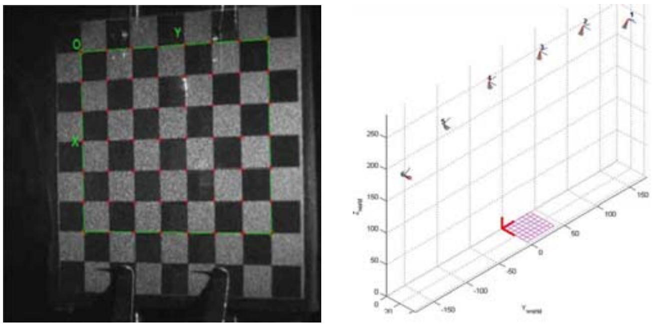


Fig. 23 (a)Speckle reduced reconstruction of chessboard object with corner detection and (b) camera position estimation

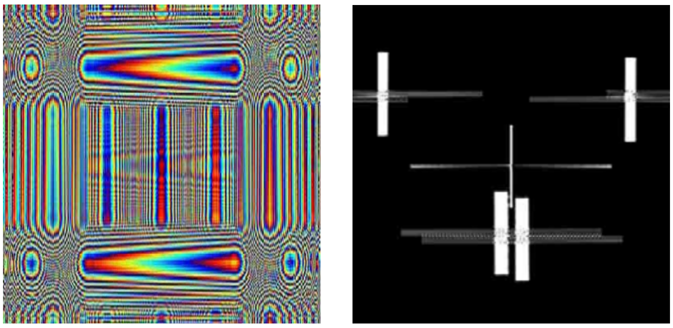


Fig. 24 (a) CGH phase of a cross hair target on a tilted plane and (b) Reconstruction of 5 targets in different 3D positions

UOULU has conducted research on extraction of 3D information from digital holograms of dynamic real-world 3D objects. Typically, for smoothly reflecting or weakly scattering transmissive objects close to the digital camera, one can use phase information very effectively to determine shape through phase unwrapping. If the object is too rough and far from the camera, the phase information is too corrupted by speckle. This can be solved through holographic interferometry by taking two captures of the static scene. However, if the scene is unpredictably dynamic, one may only get one hologram capture. This is where UOULU's technique are applicable. The primary one, based on extracting two perspectives from a single digital hologram and applying stereo disparity techniques to recover depth information, has been shown to be applicable for both macroscopic and microscopic (free-space propagated) scenes, and to work adequately in the presence of noise where other techniques fail (see Figs. 24 and 25).

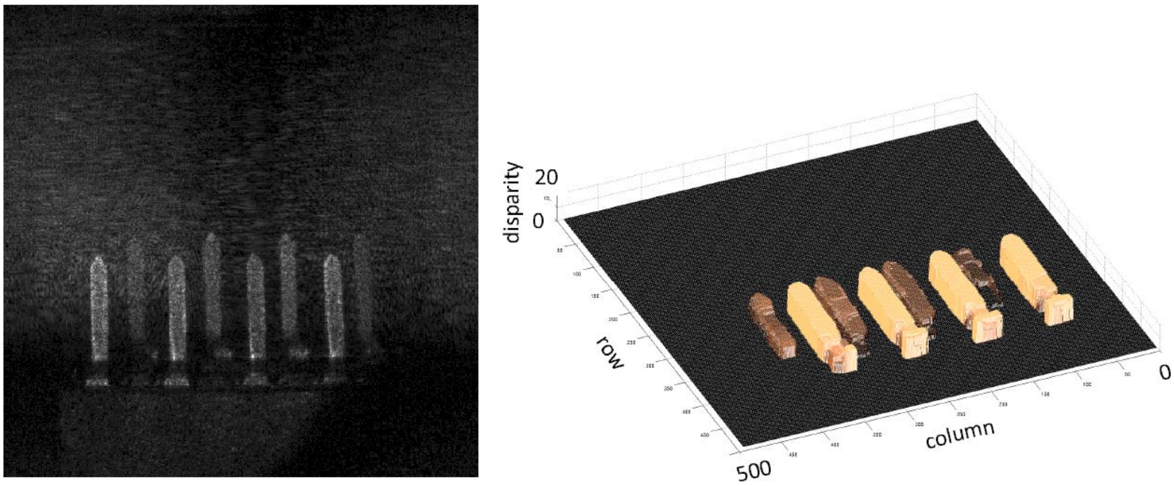
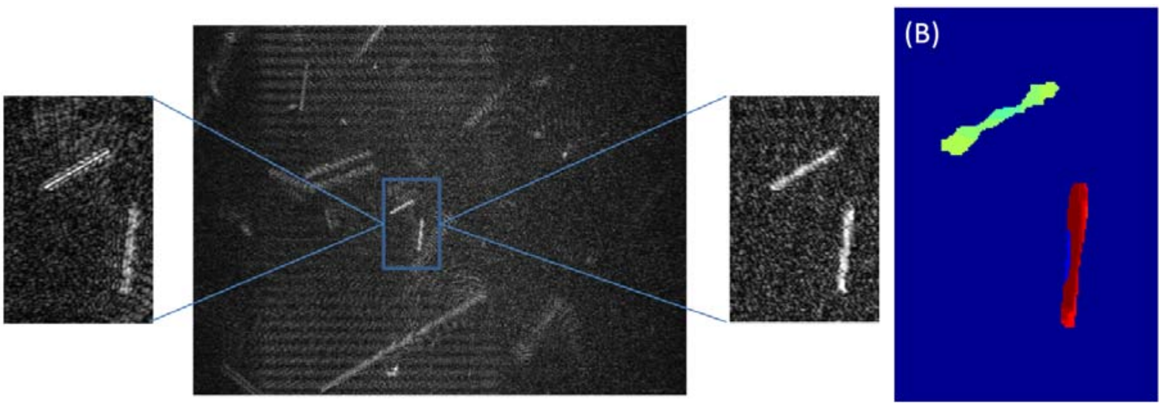


Figure 24 Reconstruction of one perspective from a digital hologram, and the resulting depth map.



(a) (b)

Figure 25 (a) Amplitude of reconstruction from a Gabor microscope. Fibre lengths were 100-400 µm with approximate diameter 7µm. The small image on the left is a zoomed-in version of the left perspective reconstruction, and on the right a zoomed-in version of the right perspective, showing only a few pixels of disparity, and (b) resulting colour coded depth map.

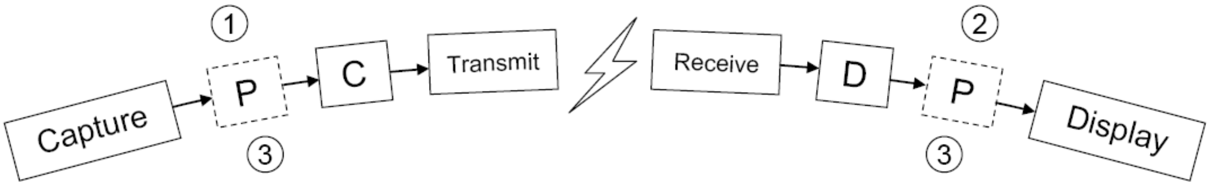


Figure 26 General architecture of the software framework seen in the Scenario 1 demo. The numbers denote options for the processing step (P). C and D represent compression and decompression, respectively.

UOULU has defined a file format standard for digital holograms that uniquely is cognisant of both macroscopic and microscopic digital holography research fields. In addition, a network protocol and suite of compression algorithms (with quality of service capability) have been defined tailored for transmitted holographic video where quality, compression ratio, and timeliness must be balanced dynamically. Compression ratios of 25 or more were obtained for hologram video but at the expense of enormous compression time. Compression ratios of at most 4 were achievable in the online [1 superframe (combined frames from 6 cameras) per second] systems. It was used successfully in UOULU's software framework architecture that links capture at BIAS, compression, transmission from Germany to Poland over the internet, decompression, processing using NUIM software, and display at WUT (see Fig. 26). UOULU also defined image processing based speckle reduction algorithms for fast refresh rate displays that are applicable to single capture holograms (of dynamic scenes, for example). Most image processing based speckle reduction techniques operate on the intensity of the reconstructed object from the hologram. These techniques are not suitable for optoelectronic display. Importantly, UOULU's techniques work in the hologram domain so they constitute some of only a small amount of work on numerical speckle reduction algorithms specific to optoelectronic display.

Bilkent University has worked primarily on novel holographic video displays within the Real 3D project (described in the following section), however its hologram processing -related achievements include an algorithm for multiple Graphic Processing Unit (GPU) accelerated computation of digital holograms of point-cloud 3D scene/object models was developed and implemented, and novel space-frequency digital processing techniques are adopted to solve a long lasting difficult theoretical problem of diffraction field computation between arbitrarily curved surfaces.

Warsaw University of Technology has worked primarily on the development of the model of primary holographic display which serves to visualize real-world macroscopic 3D objects and scenes (described in the following section). This included the development of strategies for data management, methods, hardware, software and experiments connected with the primary holographic display. In relation to hologram processing, WUT's achievements include:

- Determination of the scheme of data management required for full process (from capture to display and binocular visualization) supporting optoelectronic reconstruction of digital holograms of real world 3D objects and scenes (2 conference papers)
- Development and implementation of the theory of imaging in capture and display system in circular configuration based on Wiener distribution function. This allows to determine the parameters of imaging in primary display (2 journal papers, 1 conference paper)
- Development of the theory for visual perception obtained in holographic display system in circular configuration (1 journal paper, 1 conference paper)
- Development of several hardware/software based techniques leading to the enhancement of display parameters (speckle reduction, solution of the gap problem and

increase of the spatial bandwidth by means of additional SLM(s)) (1 journal paper, 1 journal paper and 1 conference in preparation)

- Development and analysis of selected algorithms required for preprocessing of data transmitted from capture systems (phase shifting digital holography, tilted plane, defocusing, phase subtraction- for holographic interferometry); development, implementation and dissemination of the software (with the m.a. algorithms) written in CUDA for high speed parallel numerical data processing (2 journal papers, 2 conference paper)
- Development and implementation of the Display Application architecture based on multithreading architecture (3 GPUs)

3. Hologram display

Holoeye jointed the Consortium with the main task of supporting project partners with implementation of digital holographic systems, based on LCoS SLMs. The feedback from the partners has caused the changes and advances in our products, that we briefly give below.

SLM - Technology

New sequences for addressing the Pluto phase SLM were developed and tested. This helped to reduce effects of the digital pulse code modulation, basically the flicker noise. The SLMs were individually calibrated for the specific wavelengths in the visible range for minimization of the zero order intensity. We introduced changes into the technological process, so that a thicker cover glass will be used for future builds. Those new panels will show a significantly reduced curvature in comparison with old versions.

A new EDID was implemented in order to increase the number of addressed pixels. The SLM (Pluto and 1080p) has a native resolution of 1952x1088 pixels. But the normally addressed area is restricted to 1920x1080 (HDTV). The new EDID gave the possibility to address through ASIC all 1088 lines of the SLM, so the accessible area is now 1920x1088 pixels. However the unaddressed pixels increase the level of the zero order (non-modulated light). Therefore unaddressed rows are blocked with a custom designed aperture frame.

SLM - Multidisplay arrangement

In the discontinued model 1080P, the control electronics allowed to run up to 3 SLMs, using only one DVI signal (unfortunately the placement of the SLMs relative to each other was very limited due to construction reasons, i.e. cables and electronics). This product was replaced by Pluto SLM, that has better performance, lower flicker noise and very compact driver board, but the driver board of this SLM supports only one device. Then we developed and implemented a signal splitter, that converts and splitts the R, G and B components of the standard DVI signal, so that one can still use 3 SLMs with one DVI output of the graphic card. Furthermore, one is not limited with bulky electronics anymore and can arrange SLMs in the setup in a much more flexible way.

SLM - Speckle issues

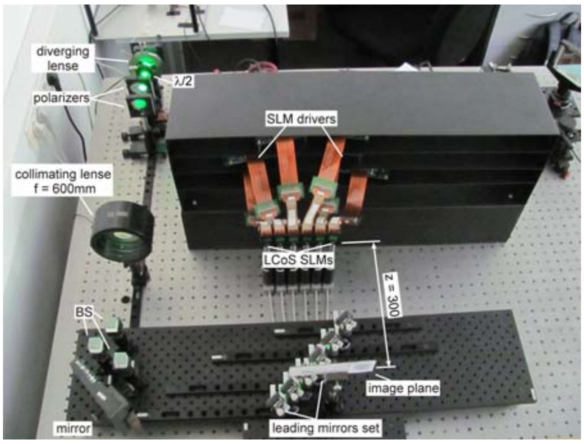
Holoeye researched the commercial market for availability of low speckle coherent sources. A low-speckle diode laser from Schäfter-Kirchhof (with spectral linewidth of 1,5 nm) and an SLD (superluminescent diode) from Superlum (spectral linewidth of 11 nm) were evaluated in comparison with He-Ne laser. The SLD is a temporally incoherent point source with high degree of spatial coherence. Such properties make SLD even more applicable for visualization applications as low-speckle laser (however the influence of the dispersion has to be considered). An engineering sample of the phase SLM with 6.4 micron pixel size running at

180 Hz was tested. The tests with a binary FLC SLM are planned for the time when it will be accessible.

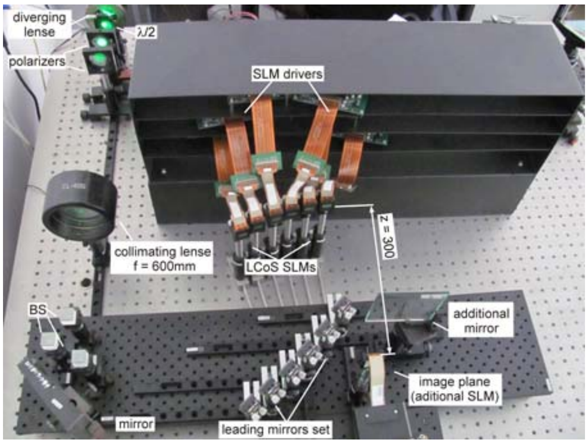
Model of primary display

The model of primary holographic display system at WUT is based on a set of 6 reflective spatial light modulators (SLMs) which are arranged uniformly distributed over an angle in space (Fig.1a). Each of the SLMs is illuminated by an individual reference wave which can be adjusted with respect to a predefined calibration procedure to ensure that the generated wave fields do correctly overlap throughout the entire reconstruction volume. The display system can be operated in two modes which both are based on the real image of the actual hologram in order to provide a three dimensional representation of a recorded scene:

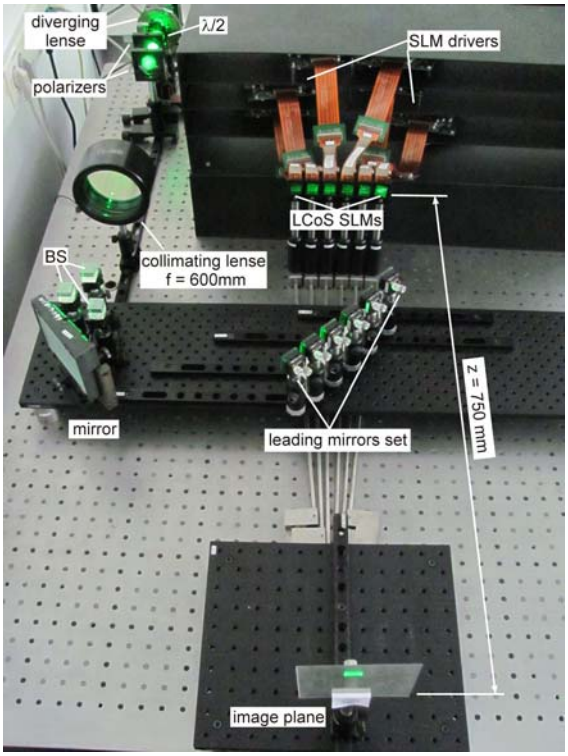
- In the so called "naked-eye-mode" the objects to be optically reconstructed appear to hover in space in front of a set of 6 windows defined by the apertures of the SLMs (Fig.1a). As a special benefit, when in naked-eye-mode, the display can be reconfigured to double the viewing angle and to close gaps and in the optical reconstruction which arise from the inactive space between the individual SLMs. This is accomplished by means of a temporal multiplexing approach based on an additional SLM in the plane of the real image of the hologram (Fig.27b). The examples of images obtained in this mode are shown in Fig.28.



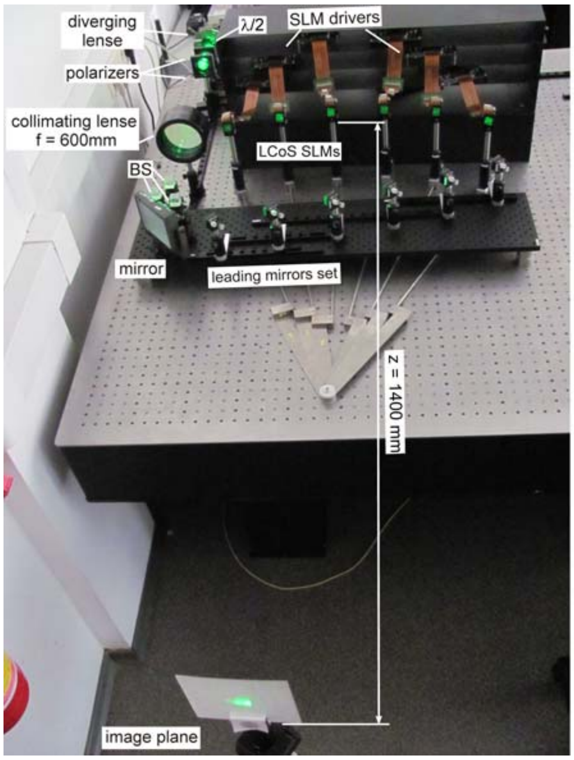
a)



b)



c)



d)

Fig.27 Photos of primary display system adapted for different capture systems and observation modes for: (a) static objects and naked eye observation gaps present, (b) static objects and naked eye observation, gaps removed by additional SLM, (c) static objects and asymmetric diffuser observation mode, (d) dynamics object and asymmetric diffuser observation mode.

- In the so called “diffuser-mode” a holographic asymmetric diffuser is used as a projection screen which is inserted in the plane of the real image of the hologram (Fig.1c,d). The asymmetric diffuser is an optical device which scatters light mostly in one direction. In the display it is used to widen the viewing angle in vertical direction while preserving the parallax in the horizontal direction. The examples of images obtained in this mode are shown in Fig.3 including its application for 3D static (Fig.3) and varying in time (Fig.4) object viewing as well as for monitoring of an object changes by means of holographic interferometry (Fig.5).

The display is a flexible device, easily reconfigurable (Fig.1 a-d) in order to match different holographic capture configurations based alternatively on a single camera and a rotated, static object (NUIM, CNR), a multiple camera capture system for varying in time objects or scenes (BIAS), as well as to any configuration for which computer generated holograms have been calculated (WUT, Bilkent, OULU, outside partners).

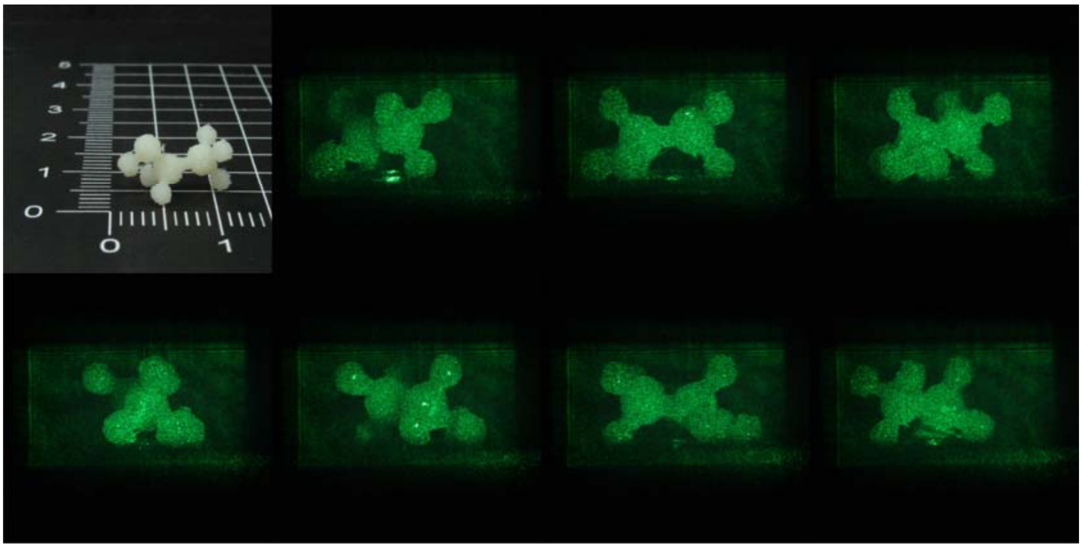


Fig.28 Exemplary reconstructions of 3D molecule (the "naked-eye-mode" and reconstruction with 6SLMs)

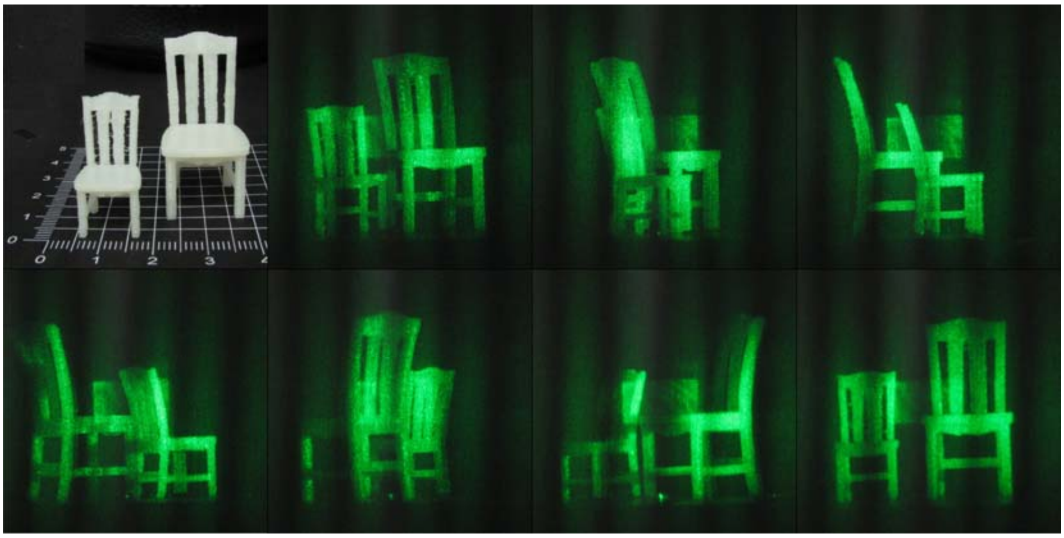


Fig.29 Exemplary reconstructions of chairs (the diffuser mode and reconstruction with 6 SLMs)

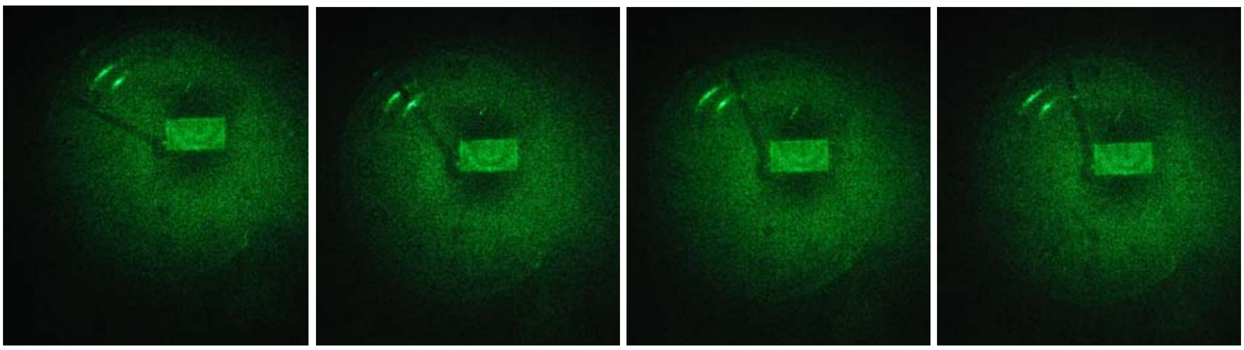


Fig.30 Exemplary reconstructions of a working watch: the reconstructions shows the selected images from a video sequence (the image from a single SLM due to the gap problem)

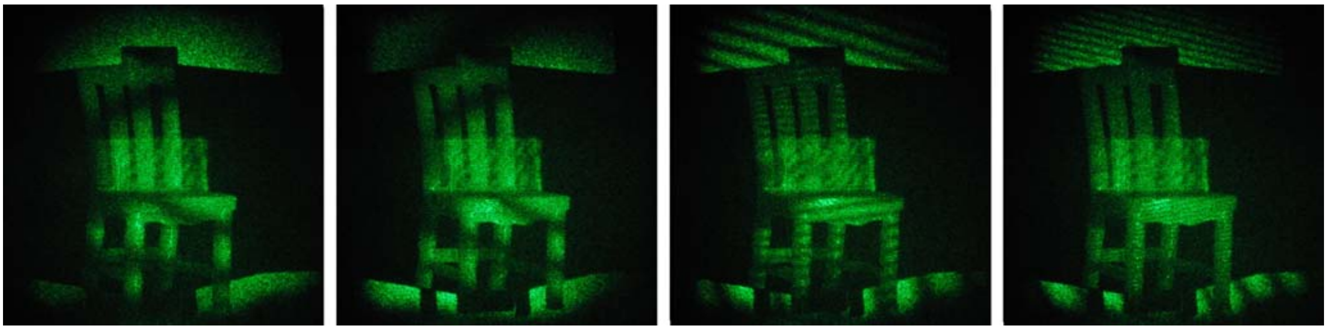


Fig.31 Exemplary optoelectronic reconstructions of holograms of “a chair” under tensile load (holographic interferometry). Note the number of fringes at different parts of the 3D scene

- Development, implementation and testing of the primary model of holographic video display system based circularly arranged, reconfigurable multiple spatial light modulators. The system is capable of displaying 3D holographic images and video which is observable with an angle of view depending on the mode of observation and configuration of a capture system (for data capture for static objects naked eye observation display viewing angle (no gaps) is 35deg, for asymmetric diffuser mode (ASM) and data captured for static object – 11.2deg (with nondisturbing gaps - 0.8deg), for ASM and data captured for varying in time object - 51.6deg (but with disturbing gaps -7.1deg) (1 book chapter, 1 paper, 2 conference papers)

A 3D video display system, which is based on quasi-real time capturing of holograms of real world variable in time objects , their coding, compression, transmission, decompression, preprocessing and efficient display was implemented and tested (Scenario1). This is pioneering work which for the first time provides full system from holographic data capture of real world real 3D object up to its quasi real time display in wide angle holographic display (1 book chapter, 2 papers in preparation) .

Bilkent University has worked primarily on novel holographic video displays within the Real 3D project. In addition an integral imaging based 3D video capture and display system, which is based on discrete electronically refreshable Fresnel lenslet arrays written on an spatial light modulators, is designed, analyzed, implemented and tested. Fast methods to compute holographic patters for spatial light modulator displays are also developed and implemented. The main achievements are:

- A real-time phase-only color holographic video display system using LED illumination was designed and implemented
- An extensive survey on holographic 3D video displays was completed
- Specifications of a digital holographic 3D video display system was determined based on experimental and theoretical studies
- A planar configuration multiple spatial light modulator holographic 3D video display system is designed and implemented
- A circularly arranged multiple spatial light modulator based holographic video display system was designed, implemented and tested. The system is capable of displaying

3D holographic video which is observable by naked eye with an angle of view of about 20 degrees.

- A 3D video capture and display system, which is based on integral imaging principles with a novel technique to achieve an electronic digital Fresnel lenslet array, was designed and implemented.
- All designed 3D video displays were used both for the display of computer generated 3D video scenes, as well as experimentally captured 3D information through a holographic capture and processing chain.

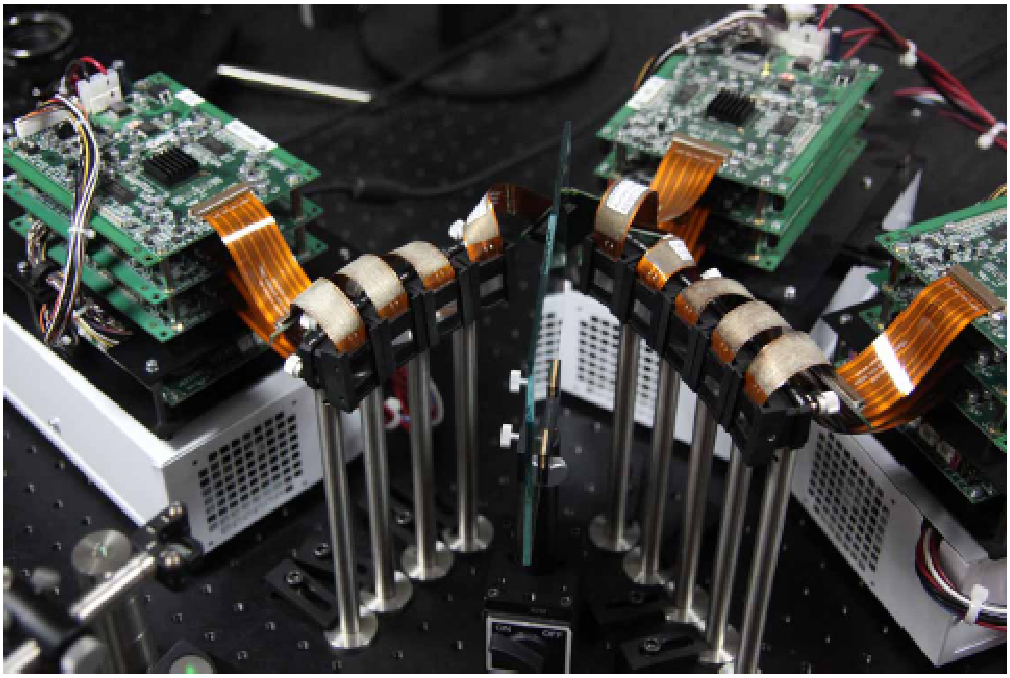


Fig. 32 SLMs and SLM modules of the circularly arranged holographic display (From F. Yaraş, H. Kang and L. Onural, "Circular Holographic Video Display System", Optics Express, vol 19, no 10, pp 9147-9156, May 2011. Copyright, OSA, 2011.)

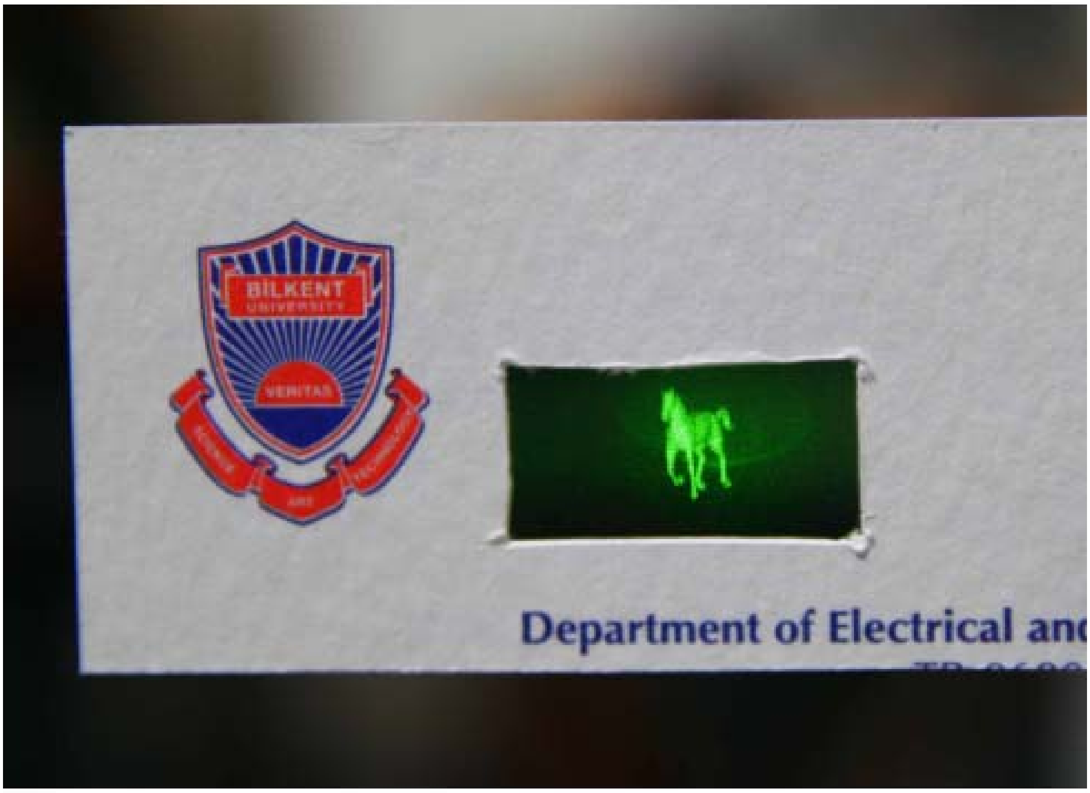


Fig. 33 A frame of holographically reconstructed ghost-like 3D video of a running horse floating in the air. The 3D image is visible by the naked eye, and the size is about 1cm by 2cm. The frame is included to demonstrate that the floating image is a real image located at the same distance as the frame ; the horse is seen through the rectangular cut. (From F. Yaraş, H. Kang and L. Onural, "Circular Holographic Video Display System", Optics Express, vol 19, no 10, pp 9147-9156, May 2011. Copyright, OSA, 2011.)

UOULU defined a 3D object standard, and a checklist for holographic displays to standardise their comparison and to define targets for development. Also, visual perception tests were conducted with the displays in Warsaw, Bilkent, a trial version of the Scenario 2 proof of concept at LT, its own displays in Finland (see Fig. 34). In the main, the studies have used the staircase method to define various perceptual thresholds in relation to the displays, such as minimum observable compression error, or minimum number of pixels in a hologram to observe various 3D phenomena. UOULU also conducted eye-tracking experiments with high quality conventional holograms (in anticipation of high quality digital hologram displays) to understand how people look at them compared to 2D screens and conventional stereoscopic screens (see Fig. 35). The visual perception studies results have quantified three-dimensional properties of various conventional displays showing hologram reconstructions, and optoelectronic displays reconstructing holograms, have quantified various perceptual thresholds, and have informed display builders of the priorities in choosing compromises for holographic displays.

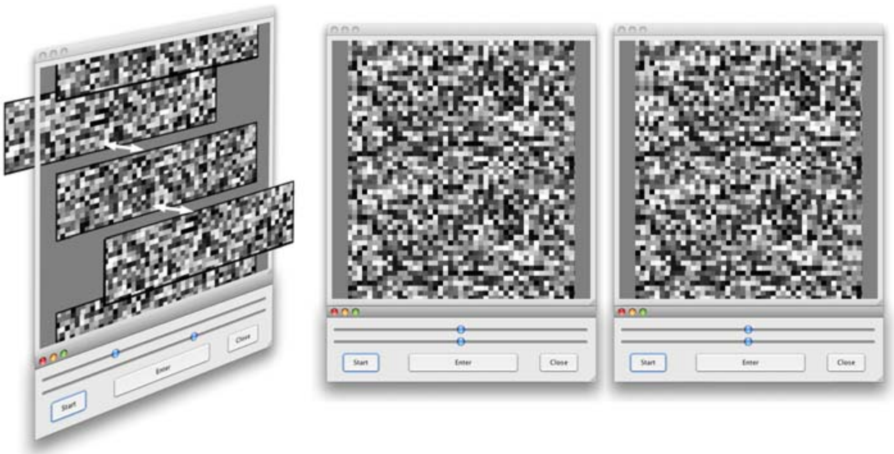
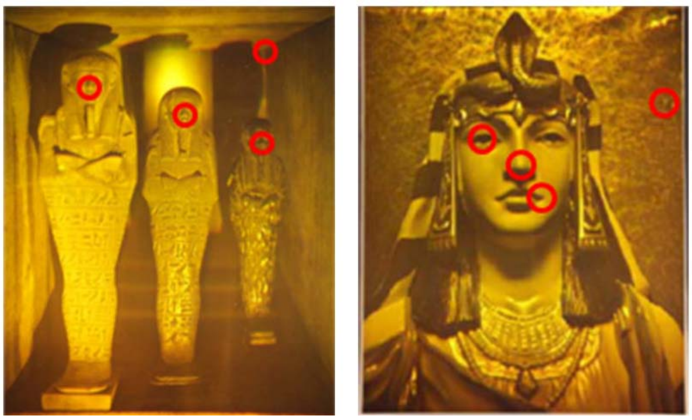


Figure 34 Illustration of the stereoscopic depth estimation tool developed at UOULU that allows one to record and quantify the depth seen in another display (such as a holographic display). The tool generates depths through stereo correspondence of regions of the noise patterns, without any other depth cues for the viewer.

(a)

(b)



(c)

Fig 35 (a) Eye-tracking laboratory at UOULU, showing (L-R) EyeLink II control computer, stereoscopic screen, EyeLink II eye-tracking head-mounted apparatus, and conventional hologram. (b) Front of the eye-tracking apparatus (courtesy of SR Research). (c) Photographs of conventional holograms with points of interest for the study circled.

The potential impact of the project (including the socio-economic impact and the wider societal implications) and the main dissemination activities and exploitation of results

UOULU

Three-dimensional displays will undoubtedly have a big impact on society, from biomedicine, to design, to entertainment. This consortium's efforts on defining what could possibly be the ultimate 3D display bring all of that weight of potential social impact.

UOULU's techniques for representing digital holograms on conventional 3D screens could be a useful way of extracting the 3D information inherent in the holograms and displaying it in high resolution with a pleasing viewing experience. It represents an inexpensive if imperfect method of hologram display, and could form the bridge between technologies while optoelectronic hologram display techniques mature. It is applicable to any potential hologram products, such as hologram capture in medicine, biotechnology, and metrology where viewing the direct hologram reconstruction is necessary.

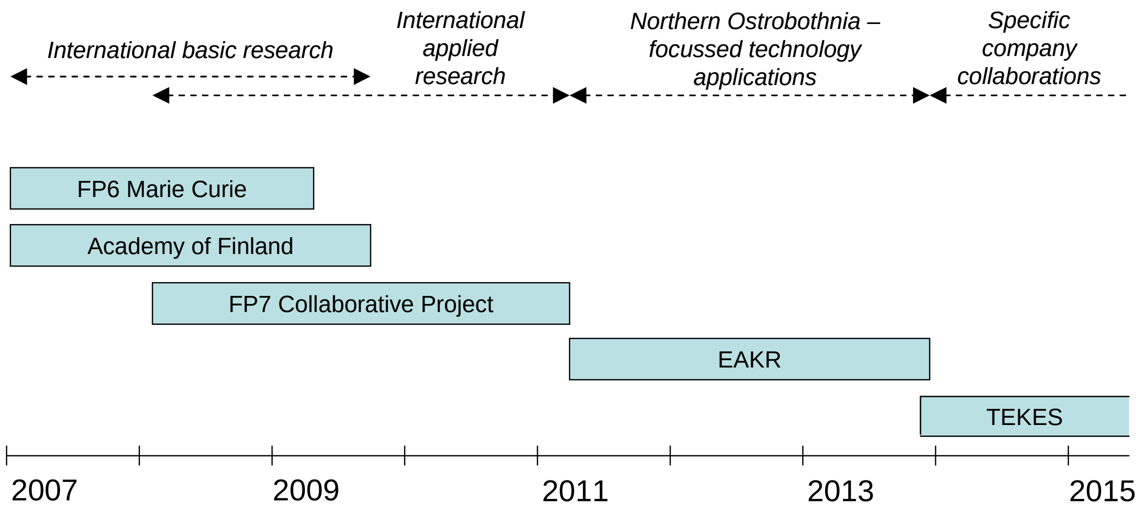
The file format (including its compression and transmission protocols) and hologram display evaluation standards may speed up technology development in the way that standard usually do. The speckle reduction techniques may make holographic displays more acceptable if they improve the viewing experience. The eye-tracking techniques may improve understanding of how the visual system perceives 3D displays and aid in the development of those displays. The Scenario 1 integration framework may make it easy to connect capture and display groups in the future, thus promoting collaboration and research advancement.

Dissemination activities and exploitation of results

UOULU has 53 entries in the Dissemination Tables A1 and A2 in Deliverable 9.5. These include 6 journal papers published or in press, edited one conference proceedings volume, one refereed book chapter (Javidi and Fournel, Eds., "Information Optics and Photonics: Algorithms, Systems, and Applications" Springer, 2010), 9 invited papers at international OSA/SPIE/EOS academic conferences, and 16 contributed papers to those conferences, and numerous informal/press/general audience disseminations. Separately, UOULU has 8 manuscripts in various states of preparation for journal submission.

UOULU has 12 entries in Table B2 in Deliverable 9.5., with explanations. They include know-how, techniques and software, and standards (hologram file format and evaluation of holographic displays). These types of exploitable foreground put UOULU in a strong position for future research funding from the public and private sectors. UOULU is following up with companies Samsung, Nokia, and VTT who have shown interest in collaboration.

Funding for some parallel research projects has been received from FP6 Marie Curie Programme, the Academy of Finland, and EC Regional Development Funds (RDF), and these have been mutually supportive. This included an optical laboratory funded from outside the FP7 programme (UOULU had no hologram capture tasks in Real 3D) and an eye-tracking apparatus also largely funded from outside FP7, that nonetheless were useful to the Real 3D project. The most recent RDF funding (called EAKR in Finnish), to specialise UOULU's Real 3D technology to digital holographic microscopy, while simultaneously interesting a class of northern Finland companies who require advanced microscopy but have not considered DHM before, dovetails with the "Real 3D" project perfectly as shown in the below internal UOULU digital holography research strategy diagram. It will fund new equipment and personnel and maintain the digital holography laboratory in UOULU for three more years. The final stage "TEKES" refers to a programme that combines national and private sector funding.



UOULU organised the 9th Euro-American Workshop on Information Optics 2010 (http://www.oulu.fi/oeinst/wio2010/) which was held in Helsinki from 12-16 July 2011. Full details are in Deliverable 1.4a. A major theme of the workshop was FP7 projects and collaborations.

Interaction with several other FP7 projects, including MOBILE3DTV, 3D4YOU, 3D VIVANT, and ALPHA are detailed in Deliverables 1.4a and 9.5.

BILKENT:

The work conducted at Bilkent targets futuristic holographic 3D video displays. The obtained results constitute proof-of-concept designs and implementations of such holographic 3D video displays. The achieved results (played 3D videos) in our laboratories significantly advanced the state-of-the-art in this field. 3D video, 3D television and 3D cinema are already widely accepted modes of entertainment; such technologies also have a significant potential to be utilized in many diverse fields ranging from medicine, dentistry, defense, video games, education, art, architecture, city planning, archaeology, etc. However, currently widely used 3D technology is based primarily on old stereoscopic techniques which do not render realistic 3D images, and thus, support rather limited quality of viewer experience. True 3D displays like holographic systems, on the other hand, target physical duplication of wavefields, and therefore, have the potential to yield ultra-realistic 3D video experiences.
Therefore, the demonstrated displays constitute sophisticated pioneering work on futuristic 3D displays which may affect the entire society via common media channels like TV and cinema. If this happens, the economic activity associated with appropriate forms of 3D content generation, delivery and display, as well as design, manufacturing, distribution and maintenance of underlying equipment will be very large.

Dissemination activities and exploitation of results

Five journal papers and seven conference papers are already published by authors from Bilkent University. Two additional conference papers, with joint authorship, including authors from Bilkent University, are published. A patent application is filed. Many invited talks and keynote speeches are given in prestigious conferences by Levent Onural.

CNR

-Personnel

7 Researchers, 1 lab Technician and 3 PhD student were employed for varying amounts of time as part of the Real3D project.

-Software

We developed a new software that allows to manage the depth of focus in digital holograms reconstructions. It could find application in a commercial DHM (digital holographic microscope)

-IR holograms

The possibility to acquire digital holograms of large objects, by means of IR laser sources, pave the way to new kind of application of digital holograms, for example in the field of the cultural heritage.

In fact, acquiring infrared digital holograms of a statuette, both in a fixed position and while it rotates, the holograms can be used to compose a dynamic 3D scene that, then, can be optically reconstructed by means of spatial light modulators (SLMs). This kind of reconstruction allows to obtain a 3D imaging of the statuettes that could be exploited for virtual museums.

Dissemination activities and exploitation of results

-Patent

A patent has been filed in Italy on a new method for extending the depth of field in digital holographic reconstruction and for imaging tilted object either macro- as well as microscopic objects.

-New funding

We submit a project about the exploitation of IR holograms in the field of cultural heritage to the Italian Ministry of Research (action PON – funded by EU) that has been evaluated very positively.

-Publications

As part of the Real3D project, CNR published the following journal papers:

1) S. Grilli et al. Opt. Expr. 16, 8084 (2008),
2) M. Paturzo et al. Opt. Express 16, 17107-17118 (2008),
3) M. Paturzo et al. Opt. Lett. 33, 2629-2631 (2008),
4) L. Miccio et al. Opt. Express 17, 2487-2499 (2009)
5) P. Maddaloni et al., Appl. Phys. Lett. 94, 121105 (2009).
6) L. Miccio et al., Opt. Lett. 34, 1075-1077 (2009)

The movie of the dynamic holographic phase-maps reported in this paper has been selected by the OSA Infobase web as Image of the week March, 26 2009.

7) M. Paturzo et al," Opt. Express 17, 8709-8718 (2009)

http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-17-11-8709

This paper has been selected to appear in: OSA Virtual Journal for Biomedical Optics

Vol.4 Iss. 7, July 1 (2009). http://www.opticsinfobase.org/vjbo/virtual_issue.cfm?vid=88
8) P. Ferraro et al., Opt. Lett. 34, 2787-2789 (2009)
9) M. Paturzo and P.Ferraro, Opt. Express 17, 20546-20552 (2009)
http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-17-22-20546
10) M. Paturzo and P. FerraroOpt. Lett. 34, 3650-3652 (2009)
11) A. Pelagotti et al., IEEE/OSA Journal of Display Technology 6, 465-471 (2010).
12) M. Paturzo et al. Optics Letters 35 (12), 2112-2114 (2010).
13) A. Pelagotti et al. 3D Research, Springer Publishing, 1 (4), 1-10, (2011).

CONFERENCES:

We presented the work, developed in the Real 3D project, to the following conferences:

1) SPIE Photonics Europe (Strasbourg 2008);
2) CIMTEC ’08 (Acireale-Italy).
3) SPIE Europe Optical Metrology” 15-18 June 2009 Munich (Germany) INVITED.
4) OSAV’ 08 - The 2nd International Topical Meeting on Optical Sensing and Artificial Vision, 12–15 May 2008, Saint Petersburg, Russia.
5) 4th EOS Topical Meeting on Advanced Imaging Techniques – Jena (Germany).
6) WIO 2009 Paris, France, July 20-24, 2009.
7) OμS’09-Optical Microsystem, Capri, 27 -30 sett. 2009.
8) Fringe'09, 6th International Workshop on Advanced Optical Metrology, 14 - 16 September 2009, Stuttgart, Germany.
9) The 22nd Annual Meeting of the IEEE Photonics Society Belek-Antalya, Turkey | 4 - 8 October 2009
10) Fotonica 2010 Pisa 25-27 Maggio 2010
11) 23rd annual meeting of the ieee photonics society Denver, Colorado | 7 - 11 November 2010
12) Spie Optical Metrology Munich (Germany) 23-26 Maggio 2011
13) Biophotonics 2011 Parma 08-10 June 2011

Book chapters

1) “Deformation of digital holograms for full control of focus and for extending the depth of field” M. Paturzo and P. Ferraro in "Information Optics and Photonics" B. Javidi and T. Fournel eds. (Springer, 2010), pp. 177-185.
2) “Improving numerical aperture in DH microscopy by 2D diffraction grating” M. Paturzo, F.. Merola, S. Grilli and P.Ferraro in Coherent Light Microscopy, Imaging and Quantitative Phase Analysis Ferraro, P.; Wax, A.; Zalevsky, Z. (Eds.) (Springer, 2011)

EPFL

This fundamental works in 3D metrology and imaging provide promising perspectives in industrial metrology as well as in biology and medicine. Expected benefits in biology and medicine are great: functional studies, brain tissue function, erythrocyte deformation in healthy and pathological cells protein production, apoptosis and cellular death, presence and role of pathogens: plasmodium, E-coli, amoeba and so on. The impact on life science in general, green technologies is also expected to be significant. The concept of “cell factory”, protein production by yeasts, algae and other biological agents can be monitored and optimized. The effect of polluting agents can be documented precisely
In metrology applied to micro-engineering, silicon foundry and microelectronics in particular, the imaging technology has been adapted to this particular domain by extending the spectral range of DHM: near infrared imaging has been developed in order to investigate

the internal structure of complex 3D silicon microelectronic devices. These developments are expected to have a large impact on microelectronic industries. Imaging complex 3D MEMs structures is needed in the future silicon microtechnology.
From the point of view of societal implications, it is obvious that these works will impact human welfare, medicine, green technologies and microelectronics industries. The indirect impact on the motivation of young searchers to develop companies and on the employment will be also significant.

Dissemination activities and exploitation of results
Dissemination of the knowledge acquired in Real 3D project has been provided by EPFL through numerous participation to international events and conferences. Invited talks (OSA DH meeting Miami) (ICMAT Singapore) and many others have insured a good view of the objectives and realization of Real 3D. Many peer reviewed and conference proceedings (more than 10) have been published and others are still on the way. These publications are at the top level in the field of coherent imaging and will provide innovative ideas to other research groups and industrial exploitation.
Patenting tomographic imaging is an issue which has required more efforts than expected in the duration of the project but will be achieved soon. Many patents have been already filed, which indirectly protect the field of competence.
The acquired knowledge will definitely contribute to promote new research projects and European cooperations in the field of metrology and bio-imaging

HEPAG

We realized the need for a three-channel version of commercial product Pluto.
The demand on the high resolution phase SLM for digital holographical visualization systems, that we've seen during the Real3D project, have motivated the development of the 4k microdisplay with apropriate investments gathered by our company

Dissemination activities and exploitation of results
Holoeye organized the 3rd International Workshop HoloMet 2010 on Perspectives of Optical Imaging and Metrology Balatonfüred/Hungary: June 13 – 16, 2010 (in cooperation with Institut für Technische Optik, Stuttgart University, TTI GmbH, COS and Holography Group, Dept. of Physics at Budapest University of Technol. & Economics). Our presentation at Holomet 2010: Spatial light modulators as "wavefront processors". Grigory Lazarev. Holomet 2010, Perspectives of Optical Imaging and Metrology. Balatonfuered, Hungary, 13-16 Jun 2010
Book chapter “Trends and applications of LCOS spatial light modulators” for the book “Optical Imaging and Metrology (eds. Wolfgang Osten and Nadya Reingand, Wiley) is currently prepared by the Holoeye employees, involved in the project.

LT

The results of the Real 3D project enable to improve the measurements quality of Lyncée products and to increase their application range. Both enlarge the number of potential customer and the income of Lyncée. As a consequence, it enables to maintain and create new jobs by ensuring the continued existence and growths of Lyncée.
Being in touch with the European top researcher groups in holography is essential for

Lyncée management team to keep a good view on the possible improvement and evolution of the technology on the middle and long term. It enables to evaluate the current research trends and to be prepared for the future and to be ready to catch new opportunities.
The real 3D project also enables Lyncée employees, who have for most of them PhDs in the field in the field of digital holography and numerical computing to make use of their research skills. This has a strong influence on the motivation and the wellbeing of Lyncée employees. It is important to provide them with a good surrounding to exercise their jobs.
On the European, the Real 3D project reinforces the collaboration between the research groups and industry working in the digital holography field. It enables to reinforce the European leader position in this field. Lyncée has discussion within the other members of the consortium for submitting proposal for European projects. Real 3D is a true lever to develop new collaborations. This helps Lyncée to develop progressively a European network for research. This also spread the awareness of the scientific community and of the general public on the astonishing evolution of the Digital Holography, boosted by the evolution of the power of computers and by the technical evolution of cameras and lasers.
Finally in a more general framework, moving to real 3D microscopic measurements and display should enable scientific advances. It should help progresses of global understanding, improvement reliability of electronic devices. For instance in life science, Lyncée hopes to contribute in this way to the general understanding of the cellular complex mechanisms leading to cancers and other diseases.

Dissemination activities and exploitation of results
Within the frame of this project, Lyncée has made several disseminations in the form of scientific publications. Lyncée has written 9 scientific publication as main author, and 12 as co-author. This is to our opinion an important number for an industry as Lyncée. This form of dissemination is highly important for Lyncée: it provides “scientific demonstration” of the functionalities of its DHM. A good example is the paper for the extended depth of focus which demonstrates extended focus by comparison of nmeasurement taken with various measurement tools. These publications are used directly for supporting sales as “proofs” . Our customers, who are often scientists and are perfectly able to read and understand the publications. We are now completing these publications with so-called “application notes” for non scientific customers, with of course, reference to the paper. Another example are the results on SiO2 structures which have already generated sales.
Lyncée has already a large portfolio of patents. It has a good experience on patent strategy and knows very well the price (cost and resources) of a patent to have them first accepted and second over its whole cycle of life. With its portfolio, Lyncée has a good sense of what are good and bad patents, and how it is difficult to defend software patents in case of infringement. According to its expertise, Lyncée has not filed new patents in the frame of this project. After a careful evaluation, Lyncée has not yet use his rights on patents filed by consortium partners within the frame of the Real 3D project. This is not a sign of a low level of achievement of the project. In the frame of academy-industry cooperation it would be important to valuate also all the information which constitutes the “know-how”. And the best for know-how would be to recognise it without publication and without patents. In this respect Lyncée find very valuable all the know-how recorded in the frame of Real 3D.
Lyncée records already and expect future sales issues from developments made in the frame of Real 3D. It also expects to participate to other joint project with other members of the consortium.

NUIM

Personnel

1 PhD student and 3 Postdoctoral Researchers were employed for varying amounts of time as part of the Real3D project. We believe the career development of these engineers and scientists will have a socio economic impact in the future.

New understanding of digital holography

NUIMs research in Real3D contributed to the understanding of the science of digital holography. Specifically we investigated what the limits are in digital holography and what factors contribute to these limits. We believe that our publications and disseminations in this area will lead to future research and new directions for the future development of this science. We believe that in the future digital holography will become an established 3d imaging modality and that our research as part of the 3D project will have contributed to its development.

Design of Novel Systems

As part of our research we proposed and built a number of novel methods for recording and processing in 3D digital holographic imaging. We believe these ideas may become standard techniques in metrology in years to come, thereby benefitting the economy at large.

Design of Useful Software

We have developed a number of software packages for use in digital holography, including parallel programs for noise filtering. We hope that this software will benefit companies such as BIAS and LyceeTec in the future and that it will have a positive impact in related scientific development.

Speckle Reduction

We believe our research in speckle in digital holography and speckle reduction will form the basis of speckle reduction in this area for years to come.

Dissemination activities and exploitation of results

Public Lectures

Over the course of the Real3D project, NUIM gave two public lectures on 3D imaging and the Real3D project

- Damien Kelly "3D Technologies; 3DTV into the future," Presented to the ESBI at Trinity College Dublin, Fen 2nd 2009
- Bryan Hennelly "On-going Research in Digital Holography; From Star Wars to Fruit Flies," Presented to the School of Engineering at University College Dublin July 2nd 2009

Conference attendance

Travel to conferences to promote the Real 3D project and publicly disseminate our work. At each of the conferences listed below we presented at least one poster or presentation with associate conference proceeding

- SPIE annual meeting conference, San Diego, USA, 2008 (1NUIM member)
- World in Optics Conference: Paris 2009 (2 NUIM members),
- FRINGE conference, Stuttgart 2009 (1 NUIM member)
- OSA conference Vancouver 2009 (1 NUIM member)
- SPIE annual meeting conference, San Diego, USA, 2009 (1NUIM member)
- BIGGS conference Clare, Ireland 2009 (4 NUIM members)
- BIGGS conference Clare, Ireland 2010 (1 NUIM member)
- China Ireland conference, Maynooth, Ireland 2009 (4 NUIM members)

- PIERS Conference, Boston, MIT (1 NUIM member)
- Photonics Ireland Conference, Kinsale, Ireland, 2009 (3 NUIM members)
- Optoinformatics Conference, Maynooth 2010 (2 NUIM members)
- SPIE conference Prague, 2011 (1 NUIM member)
- SPIE Metrology conference Munich, 2011 (1 NUIM member)

Publications

As part of the Real3D project, NUIM has had 15 conference proceedings published and journal papers published in the following journal s

- Optical Engineering (1 journal paper)
- Optics Communications (2 journal papers)
- Journal of the Optical Society of America A (JOSA A) (2 journal papers)
- Optics Letters (2 journal papers)
- Applied Optics (1 journal paper)
- Journal of 3D Research (1 journal paper)
- Journal of the European Optical Society (JOES) (1 journal paper)
- *International Journal of Digital Multimedia Broadcasting* (1 journal paper)
- Journal of Display Technology (1 journal paper)

New grants

We have recently obtained an IRCSET postdoctoral fellowship grant to fund a researcher in digital holographic microscopy for 2 years. We are hoping to apply for new grants in the area of digital holography from Science Foundation Ireland and from FP7 in the near future.

Public Software

We have developed a number of public software packages for use in digital holography as discussed in Question 1 of this report. This software is publicly available upon request.

WUT

The work conducted at WUT targets the holographic 3D video displays which combine a real world 3D object/scenes holographic capture with the . The obtained results constitute proof-of-concept designs and implementations of such holographic 3D video display which provides physical duplication of wavefields, and therefore, have the potential to yield ultra-realistic 3D video experiences and eventually in future provide a revolution in such areas as 3D video, 3D television and 3D cinema and a variety of related applications.

Personnel

4 PhD student and 5 Postdoctoral Researchers were employed for varying amounts of time as part of the Real3D project. We believe the career development of these engineers and scientists will have a socio economic impact in the future.

Education

8 students (master students from specializations: Photonics Engineering and Multimedia Technologies) participated directly in the works and experiments connected with realization of Real3D project . Also the novel understanding of digital holography and 3D displays and the developed methods have been introduced in the study program for these specializations (benefit for more than 100 students including Erasmus Mundus Master “OpSciTech” students). The knowledge gained by students will have an impact for further progress in 3D

technologies.

New understanding of digital holography and monocular and binocular visual perception

WUT research in Real3D contributed to the understanding of the science of digital holography. Specifically we investigated what are the limits are in the case of multi CCD capture and multi SLM display in different configurations, what factors contribute to these limits and how it transfers into visual perception of an image composed of several views. We believe that our publications and disseminations in this area will lead to future research and new directions for the future development of this science.

Design of Novel Systems

As part of our research we proposed, developed and implemented a number of novel methods and hardware solutions for processing and viewing complex information (phase and amplitude) of real world objects. We belive that these solutions will taken up by companies and fully or partially used to develop new of enhance existing product (eg digital holographic interferometry system, or minidisplay for mobile phones).
A strong cooperation with another WUT group focused on 3D art and historical objects archiving has started to combine the expertise of both groups.

Design of Useful Software

We have developed a number of software packages for use in digital holography, including parallel tilting, defocusing and interferometric phase determination. We hope that this software will benefit companies such as BIAS, Hepag and LyceeTec in the future and that it will have a positive impact in related scientific development.

Optical metrology

We believe that the possibility to monitor by means of our display behaviour (displacements/deformations /strains) of highly responsible 3D engineering objects (simultaneously from different views in wide angle of view or even for 360deg)is and will be highly required by such industries as : space, aviation, robotics, biomedical. We believe these ideas and systems may become standard techniques in metrology in years to come, thereby benefitting the economy at large.

General impact

The demonstrated primary model of holographic display and the total processing chain supporting data from capture to display constitute sophisticated pioneering work on 3D holographic displays which may affect the entire society via common media channels like TV and cinema. If this happens, the economic activity associated with appropriate forms of 3D content generation, delivery and display, as well as design, manufacturing, distribution and maintenance of underlying equipment will be very large.
Finally, in a more general framework, moving to real 3D macroscopic video and holographic measurements should enable scientific advances. It should help progresses of global understanding of binocular viewing of complex information representing arbitrary 3D objects. Also it should enhance reliability of highly responsible 3D engineering elements and provide general understanding of engineering and biological objects.

Dissemination activities and exploitation of results

Five journal papers and eight conference papers are already published by authors from WUT. Two papers and one book chapter are in the process of review. Many invited talks are given in prestigious conferences (3D StereoMedia, Photonics Europe, Interferometry: Techniques and Analysis, Symposium of Image Processing) by Małgorzata Kujawinska. The new holographic laboratory organized during the project is the most often visited site during a variety of national and foreign scientific and industrial visits at Mechatronics Faculty. The achievements of Real3D project are widely explained and discussed during

these visits. The knowledge generated during Real3D project is widely disseminated through our academic teaching activity (at engineer, master and PhD levels).

The address of the project public website, if applicable as well as relevant contact details.

www.digitalholography.eu

Furthermore, project logo, diagrams or photographs illustrating and promoting the work of the project (including videos, etc…), as well as the list of all beneficiaries with the corresponding contact names can be submitted without any restriction.

UOULU	Mr. Thomas Naughton, University of Oulu, Oulu Southern Institute, Vierimaantie 5, 84100 Ylivieska, Finland Tel: +358-40-3511635, E-mail: firstname.lastname@oulu.fi Mr. Arto Eljander, Accounting Manager, Financial Services Department, University of Oulu, Pentti Kaiteran katu 1, 90014 Oulun Yliopisto, Finland Tel: +358-8-5534133, Fax: +358-8-553 4170 E-mail: firstname.lastname@oulu.fi
BIAS	Name: Professor Ralf B. Bergmann Institution: Bremer Institut für angewandte Strahltechnik GmbH Address: Klagenfurter Straße 2, 28359 Bremen, Germany E-mail: Bergmann@bias.de Phone: +49(0)421 218 58 002 Fax: +49(0)421 218 58 063
Bilkent	Prof. Dr. Levent Onural Dean of Engineering Mühendislik Fakültesi Bilkent Üniversitesi TR-06800 Ankara Turkey Ph: 90 312 2664133 e-mail: onural@bilkent.edu.tr

CNR	Dr. Pietro Ferraro, Head of Napoli Unit of CNR-INO Via Campi Flegrei 34, 80078 POZZUOLI (NAPOLI), Italy tel. +39-0818675041, fax +39-0818675118 e-mail: pietro.ferraro@inoa.it Simonetta Grilli, Researcher at CNR-INO, tel. +39-0818675040, e-mail : simonetta.grilli@inoa.it Melania Paturzo, Researcher at CNR-INO, tel. +39-0818675040, e-mail :melania.paturzo@inoa.it
EPFL	Christian Depeursinge, honorary professor EPFL Station 17, 1015 – Lausanne, Switzerland
HEPAG	Dr. Grigory Lazarev Holoeye Photonics AG Albert-Einstein-Str. 14 12489 Berlin Germany lazarev@holoeye.de Phone: +49 30 639 23 666 Fax: +49 30 639 23 662
LT	Yves Emery, PSE-A, CH-1015 Lausanne, Swizerland, yves.emery@lynceetec.com , Tél: + 41 21 693 02 20
NUIM	Dr. Bryan Hennelly Research Fellow, Department of Computer Science Room 2.25 Callan Building, National University of Ireland, Maynooth, Co. Kildare, Ireland Ph: +353(0)17083849 Fax: Ph: +353(0)17083848 Email: bryanh@cs.nuim.ie
WUT	Prof. Dr. hab. Malgorzata Kujawinska Warsaw University of Technology Institute of Micromechanics and Photonics 8 Sw. A. Boboli St 02-525 Warsaw Poland Ph: +48 22 2348489 e-mail: m.kujawinska@mchtr.pw.edu.pl

If you wish, please include any photographs illustrating and/or promoting the work of the project.

BIAS

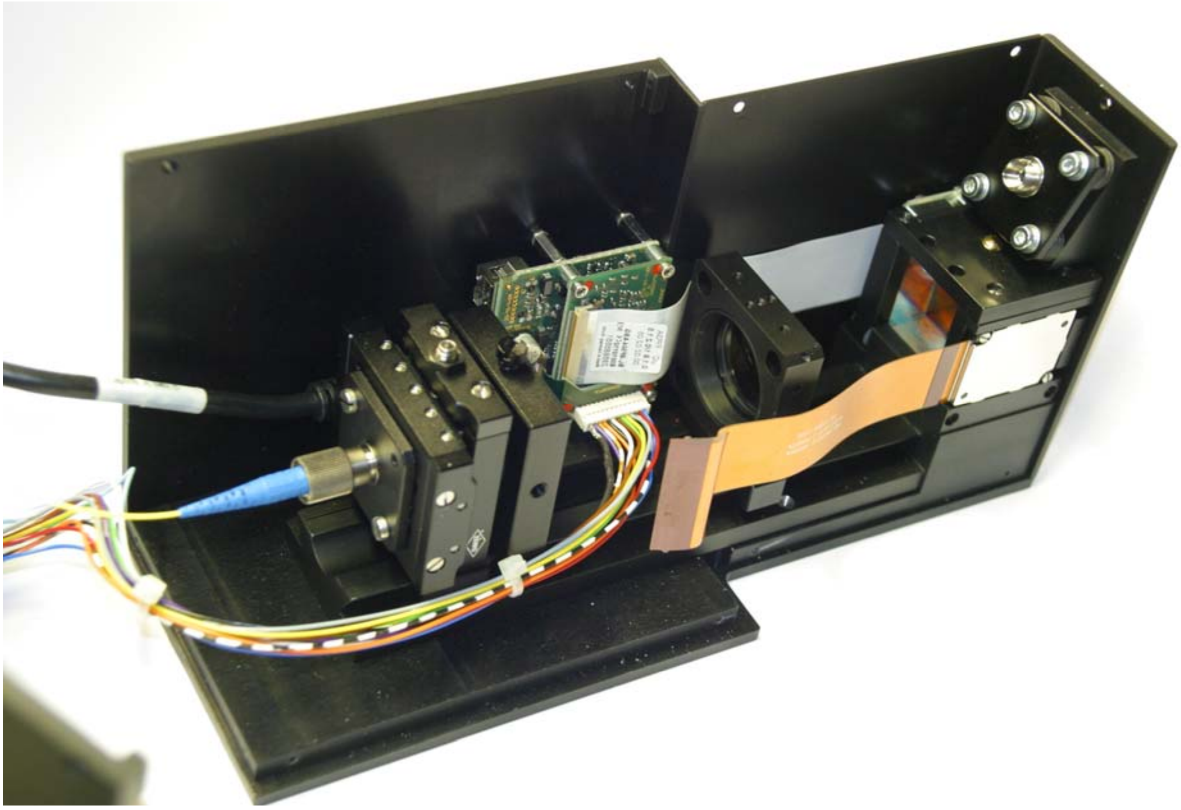


Figure: Photography of the HoloCam

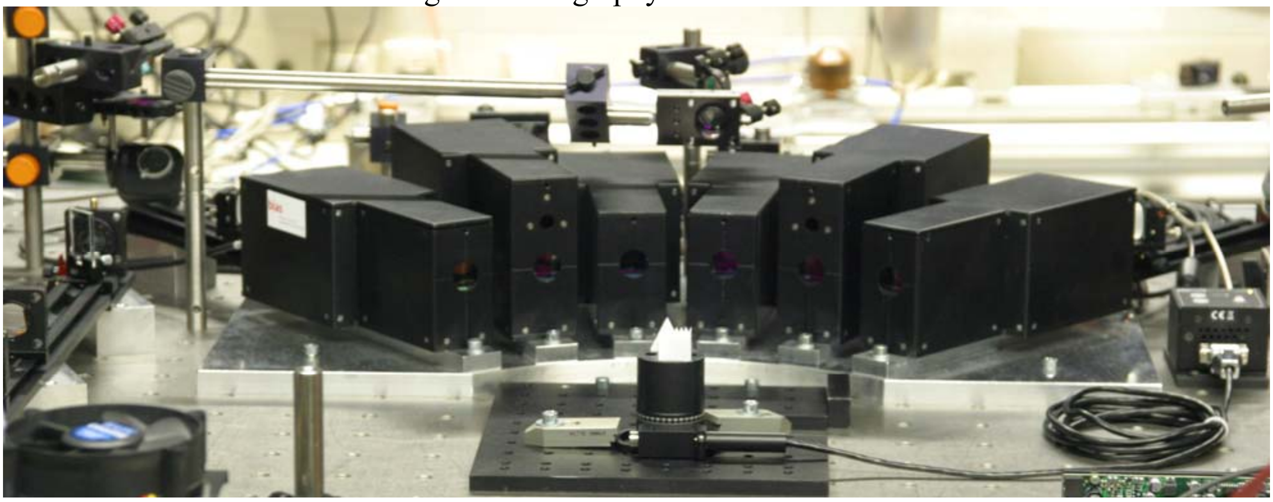


Figure: Photography of the digital holographic capturing system for capturing dynamic scenes from six directions simultaneously in time – front view.

EPFL The images of cells and microelectronic devices shown in the document can be used to illustrate the achievement of the project.

UOULU All images with UOULU in the caption can be used freely by the Commission with suitable reference.

4.2 Use and dissemination of foreground (D9.5)

A plan for use and dissemination of foreground (including socio-economic impact and target groups for the results of the research) was established at the end of the project.

The plan is reported in Deliverable 9.5 which includes the required Dissemination activities tables: Section A (Public) and Section B (Confidential) following the Final Report template provided by the EC.

4.3 Report on societal implications

Report on societal implications was made at the end of the project following the structure of the Final Report Template. It is reported in Deliverable 9.6 Awareness and wider societal implications which replies to the questions set in the Final Report Template in order to assist the Commission to obtain statistics and indicators on societal and socio-economic issues addressed by projects.