Processing of optically-captured digital holograms for three-dimensional display

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ABSTRACT

In digital holography, holograms are usually optically captured and then two-dimensional slices of the reconstruction volume are reconstructed by computer and displayed on a two-dimensional display. When the recording is of a three-dimensional scene then such two-dimensional display becomes restrictive. We outline our progress on capturing larger ranges of perspectives of three-dimensional scenes, and our progress on four approaches to better visualise this three-dimensional information encoded in the digital holograms. The research has been performed within a European Commission funded research project dedicated the capture, processing, transmission, and display of real-world 3D and 4D scenes using digital holography.

1. INTRODUCTION

Digital holograms of real-world objects[1] are in a convenient form for processing, numerical reconstruction, and two-dimensional (2D) display, but current display technology does not yet allow convincing full-field display of digital holograms in the general case. The numerical reconstructions are routinely in the form of a 2D image (intensity or phase) slice through the reconstruction volume, an extended focus image, or a depth map from a single perspective. These are fundamentally 2D (or at most 2.5D) representations and for some scenes are not certain to give the human viewer a clear perception of the three-dimensional (3D) features of the scene encoded in the hologram (occlusions are not overcome, for example). Furthermore, the optical setup for the capture of macroscopic objects (an object positioned far from the small digital sensor to adequately sample the reflected field) often severely limits the amount of the objects three-dimensional information that it is possible to record. Typically, for centimetre sized objects positioned tens of centimetres from a centimetre sized sensor, only a small angular range (approximately ten degress) of different perspectives is possible. This must be increased if useful digital holography content is to be produced for 3D displays.

We outline our progress on digital holographically capturing larger ranges of perspectives of three-dimensional scenes. Three approaches are reported: simultaneous capture using multiple cameras, and two resolution improvement approaches. Simultaneous capture by multiple cameras of a macroscopic object is facilitated by the use of a technique to mitigate the effects of the keyhole effect. Resolution in digital holographic microscopy is enhanced by increasing the numerical aperture of the optical system by means of an electro-optically tunable hexagonal phase grating. Thirdly, several captures with a single digital camera are stitched to form a larger synthetic aperture hologram.

Four approaches are taken towards allowing the human viewer perceive the 3D information. Firstly, in a single hologram approach, we consider exploiting the multiple perspectives and inherent motion parallax available in

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Three-Dimensional Imaging, Visualization, and Display 2009,
edited by Bahram Javidi, Jung-Young Son, Manuel Martinez-Corral, Fumio Okano, Wolfgang Osten,
Proc. of SPIE Vol. 7329, 73290A · © 2009 SPIE · CCC code: 0277-786X/09/$18 · doi: 10.1117/12.821866

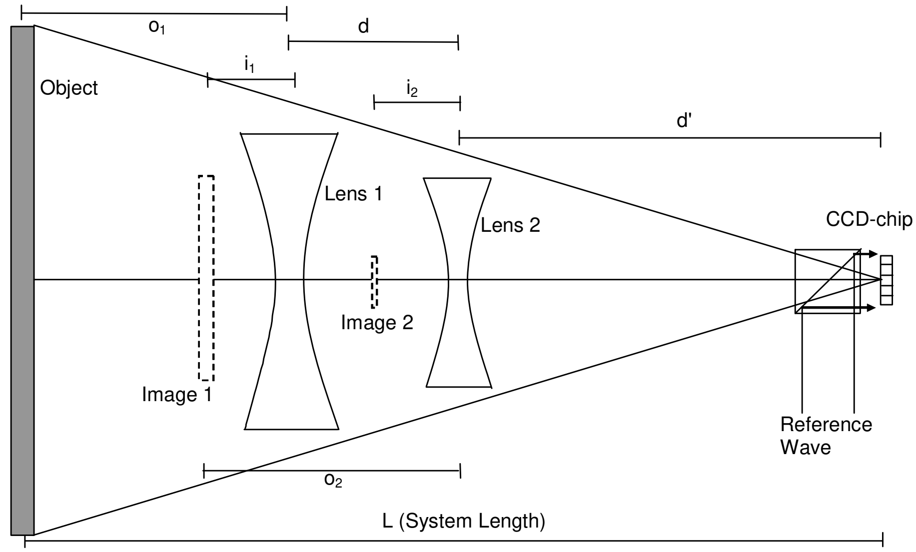


Figure 1. A hologram capture arrangement using concave lenses that records a demagnified virtual image.

some digital holograms to design algorithms to numerically extract the 3D information about the scene. Secondly, also a single hologram approach, we consider modifying the holograms for conventional 3D screens so that the human viewer's stereo perception does the processing to perceive the scene in 3D. Thirdly, we consider taking multiple holograms from different perspectives in a microscope configuration and designing algorithms to combine them to numerically extract the 3D information. Finally, we consider an optoelectronic display of the full optical wavefront. The research has been performed within a European Commission funded research project dedicated the capture, processing, transmission, and display of real-world 3D and 4D scenes using digital holography with the acronym Real 3D that runs from 2008 to 2011 with the collaborating institutes listed on the title page.

2. CAPTURE

In the literature, multiple hologram captures of rotated objects have formed the basis for works with macroscopic objects[2] and microscopic objects.[3] For dynamic 3D scenes a multiple camera setup may be warranted, but this is made infeasible by the 'keyhole problem, which dictates that relatively large objects (in the order of 10 cm) must be positioned relatively far from the camera (usually a small sensor in the order of 1 cm). This makes a circular arrangement of cameras, for example, very space consuming. A more compact arrangement is a prerequisite for such a multi-camera proposal.

Figure 1 shows a configuration using concave lenses that produces a demagnified virtual image allowing objects to be brought closer to the camera than in the conventional lensless configuration. An implementation is shown in Fig. 2 showing the relative sizes of the sensor and object to be captured. The object and reconstructions from holograms of it are shown in Fig. 3. A two-camera experiment is illustrated in Fig. 4, with reconstructions shown in Fig. 5.

An alternative approach to increasing resolution, this time relevant to digital holographic microscopy, is shown in Fig. 6. Resolution in digital holographic microscopy is enhanced by increasing the numerical aperture of the optical system by means of an electro-optically tunable hexagonal phase grating.[4]

Finally, several digital hologram frames captured with a single camera can be combined to synthesise a new hologram with improved reconstruction properties. The change in conditions from frame to frame can include rotation of the object, in-plane translation of the camera, and changing the illumination on the object. In the approach we outline the light diffracted from the object is rotated across the face of the sensor from frame to frame. We ensure there is significant overlap between frames and stitch them together in space and spatial

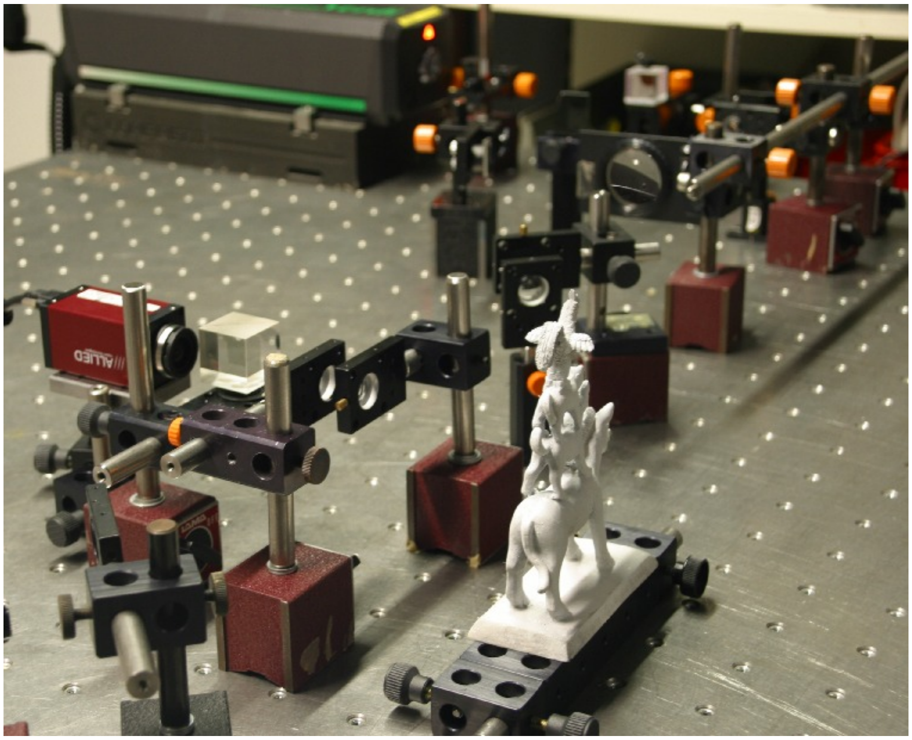
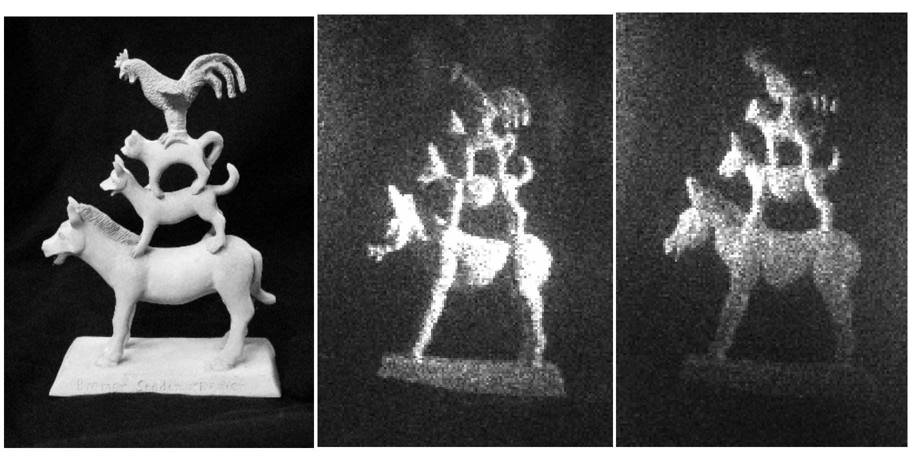


Figure 2. An implementation of the arrangement shown in Fig. 1.



(a) (b) (c)

Figure 3. An example object captured: (a) photograph of the object, (b) a digital reconstruction from a hologram where the object was illuminated from a single direction, and (c) the improved results (fewer voids representing regions in shadow) by illuminating the object from two directions.

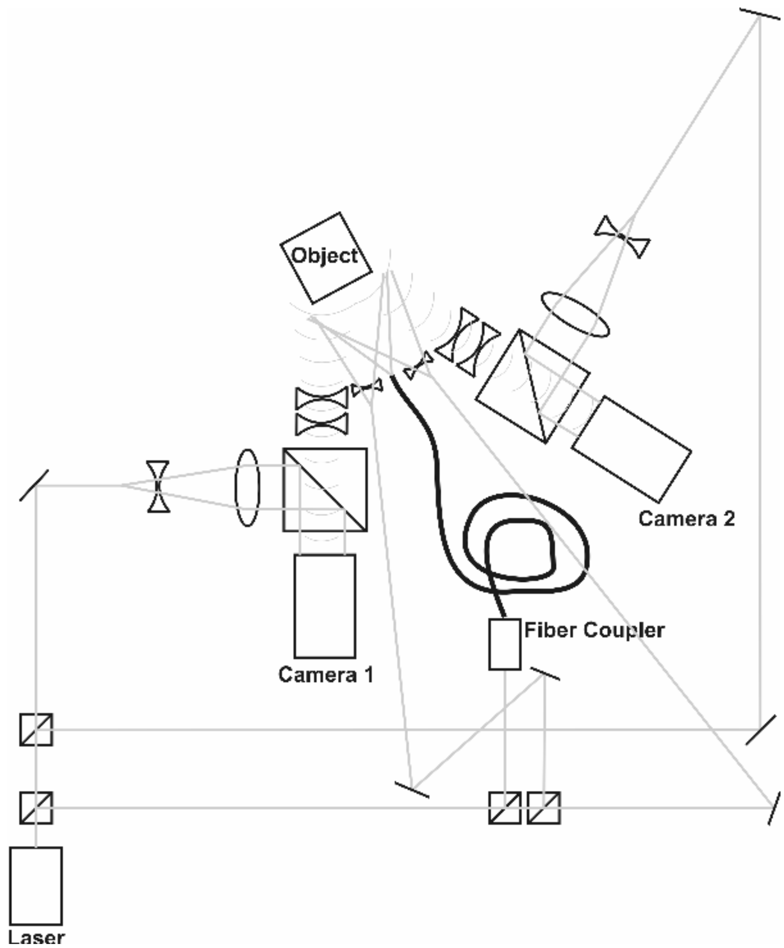


Figure 4. Apparatus for the two-camera setup. Exclusive use of fibre for object beam delivery will allow for easy modular deployment and reconfiguration of each camera arm, and reduce the number of parasitic reflections in the arrangement.

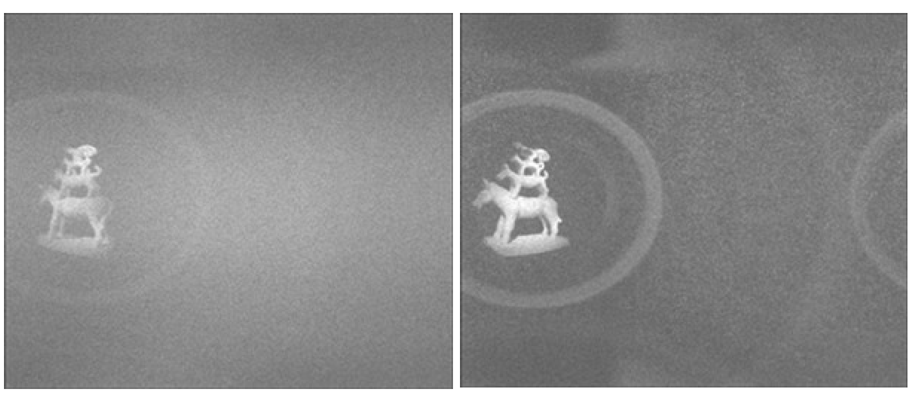
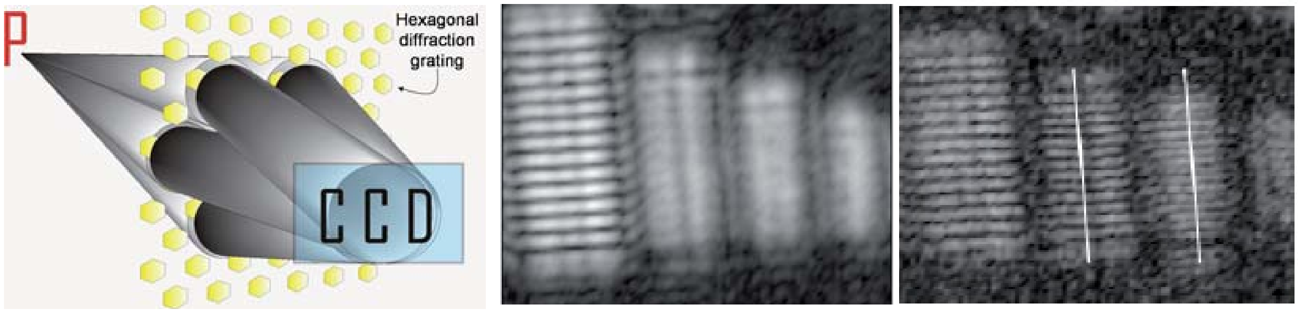


Figure 5. Reconstructions from holograms captured using the two-camera setup, showing in each case the full reconstruction field of view after the dc term is removed.



(a) (b) (c)

Figure 6. Resolution in digital holographic microscopy enhanced by increasing the numerical aperture of the optical system by means of an electro-optically tunable hexagonal phase grating: (a) ray diagrams of the object wave with such a hexagonal diffraction grating in the setup, and amplitude reconstruction of the digital hologram (b) without and (c) with a grating in the setup.

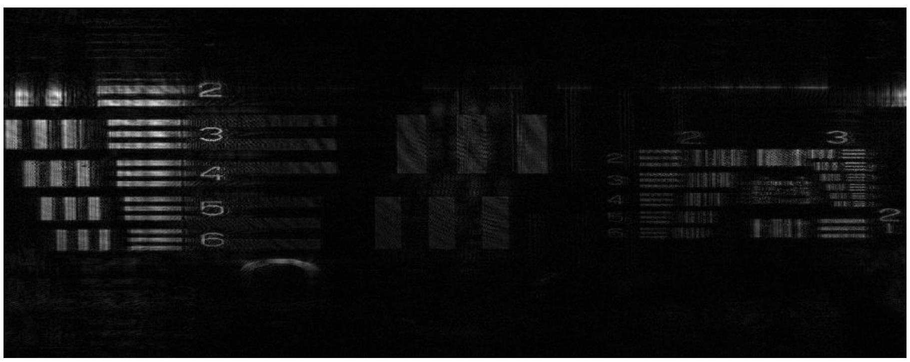


Figure 7. A reconstruction from a synthetic aperture digital hologram of a USAF resolution chart. The aperture has been increased horizontally, giving rise to the horizontally stretched image and higher resolution in that direction.

frequency. This approach is most appropriate for 3D objects where any change in the angle of incidence of the object beam can give rise to significant changes in the diffracted field. For the case of a 2D object a synthetic aperture digital hologram reconstruction is shown in Fig. 7). This reconstruction is from a digital hologram with 2650 pixels in the horizontal direction that has been synthesised from six holograms each with horizontal dimension of 1392 pixels.

3. PROCESSING FOR CONVENTIONAL 3D DISPLAY

In the absence of fully functional optoelectronic holographic displays, digital holograms are usually reconstructed for display on 2D screens. This can prove inconvenient when there is genuine 3D information available in the hologram. In order to better visualise the 3D scene encoded in the digital hologram in the immediate term, we propose to adapt current off-the-shelf 3D displays for digital hologram data.

Many conventional 3D displays are stereoscopic in nature. They present a different image to each eye to create the perception of a 3D world in the viewer. In the first digital hologram approach, two perspectives reconstructed from a single digital hologram of a macroscopic object are displayed as a conventional stereo pair on an autostereoscopic screen. Test users perceived the object stereoscopically, and the some effects of noise on stereo perception were studied.[5]

Some 3D displays require a depth map as part input, from which multiple perspectives are synthesised. Depth maps of objects encoded in digital holograms can be obtained from a single perspective using phase unwrapping[6] or a depth from focus algorithm.[7] In an alternative approach, two perspectives are reconstructed according to

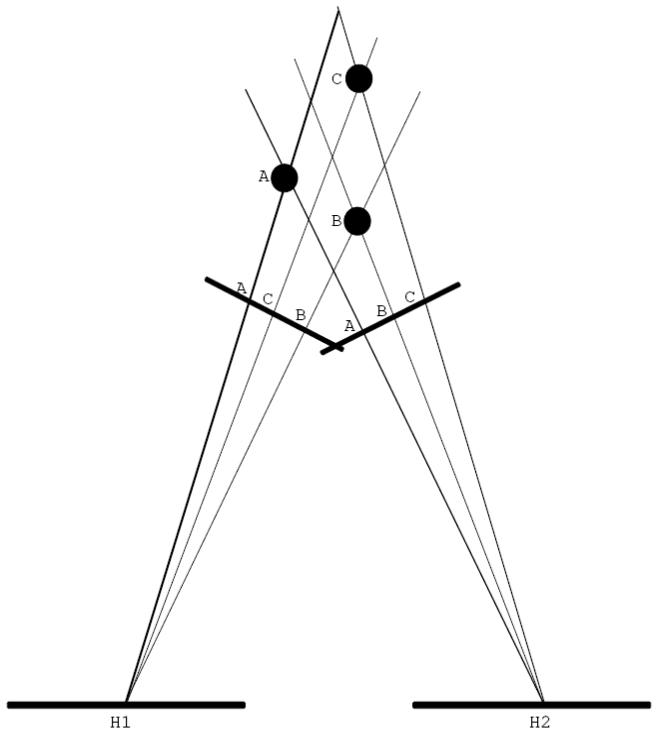


Figure 8. Calculating stereo disparity from a single digital hologram. H1 and H2 are spatially separated sub-regions from a single digital hologram that give rise to different perspective reconstructions; A, B, and C are points in 3D space whose projection onto each reconstructed intensity image is shown.

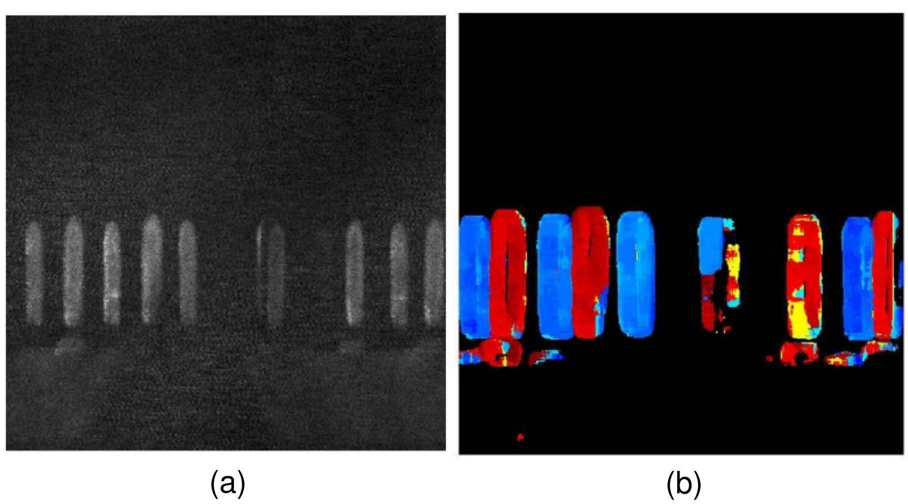


Figure 9. Stereo disparity using a single hologram: (a) a reconstruction from a test digital hologram, (b) the results of calculating stereo disparity (equivalent to a depth map) from that digital hologram.

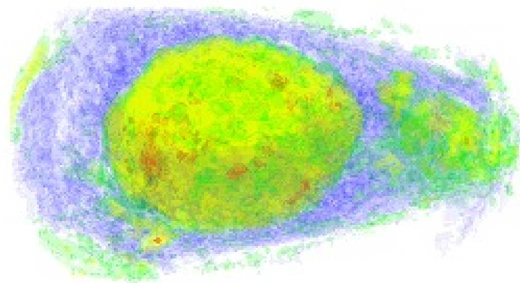


Figure 10. One rendering of the full 3D point cloud of an amoeba, using data captured as described in Ref. 3.

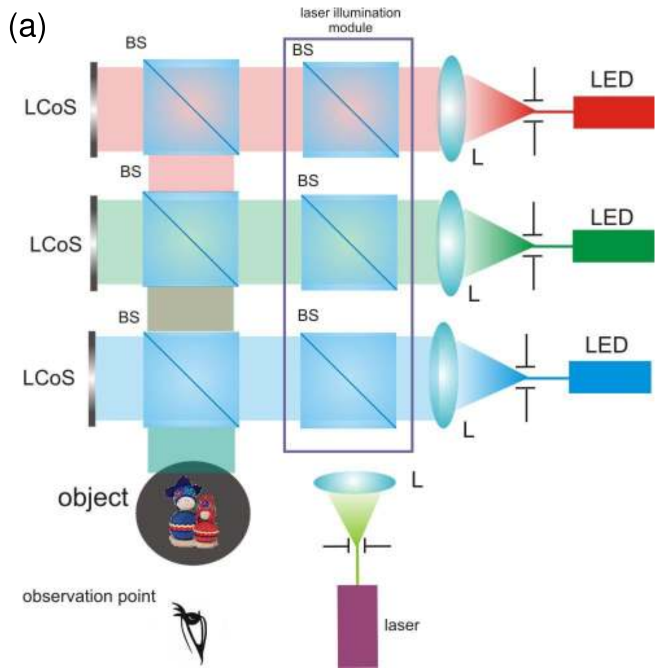
the geometry shown in Fig. 8. A conventional process of analysing the stereo disparity in the two perspectives reveals the depth of regions in the scene (see Fig. 9). This approach can be advantageous when there are only small differences in depth between objects, in particular when all objects in the reconstruction appear in focus because their depth differences are less than the depth of field of the hologram reconstruction. In such a situation, a purely focus-based depth resolution approach will not be successful.

In the third approach, we recall an existing tomographic approach in digital holography[3] and improve the algorithm to produce a 3D point cloud of refractive index values that can be visualised using any 3D computer graphics platform (see Fig. 10).

4. OPTOELECTRONIC DISPLAY

The most natural approach for the visualisation of digital holograms of real-world objects is by optoelectronic reconstruction.[8,9] However, there are significant problems associated with this. Principal among them is the relatively low spatial resolution of current display devices such as LCD and LCoS spatial light modulators (SLMs), not much smaller than 10 µm inter-pixel spacing in current off-the-shelf devices. Typically, a diffraction range of only a few degrees is possible in visible light, which is not sufficient to cover both eyes. Combining multiple SLMs is an option, but generating a coherent superposition of multiple diffracted wavefronts is itself extremely challenging as even wavelength-scale uncorrelated vibrations between the devices will destroy the mutual coherence between the SLMs. We are numerically and experimentally studying the challenges associated with building a working multi-SLM hologram reconstruction device to the display the data captured in a multiple camera arrangement.

The simplest way to ensure that vibrations are minimised between SLMs is to mount them to a single backplane, as illustrated in Fig. 11. Such an arrangement has been successfully implemented for the incoherent combining of reconstructions using different wavelengths, permitting for example colour reconstruction[10] (see Fig. 12). It could also be used to generate side-by-side wavefronts that would increase the spatial extent of the optoelectronic reconstructed field. With that in mind, we have tested our chosen SLMs – relective LCoS devices from HOLOEYE (Berlin, Germany). The setup illustrated in Fig. 13(a) seeks to test the extent of the field reconstructed when the device is illuminated from the normal. With a reconstructed real image after 300 mm, Fig. 14(a) does show relatively good quality reconstruction outside the extent of the LCoS dimensions, but a dc generated from a border of unaddressed pixels is noticable. With an oblique illumination of the LCoS [as shown in Fig. 13(b)] corresponding to a multi-SLM display possibly in a circular configuration, the extent of the LCoS device is again visible as a dc term in the reconstruction, with a suspected warping of the signal outside the spatial extent of the LCoS. In consultation with the manufacturer, we believe these artifacts can be eliminated through optimisations in the operation of the devices. In the main, the outlook for a multi-LCoS optoelectronic digital hologram display is promising.



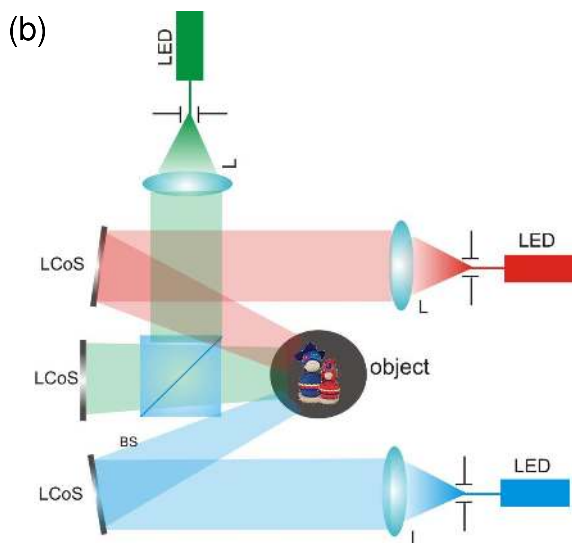


Figure 11. Two schematics showing possible ways of combining the optical signals from multiple SLMs. In this figure, the different coloured sources are for illustration purposes, and could be replaced by apertures emiting mutually coherent illumination for the purposes of generating a single coherent wavefront.

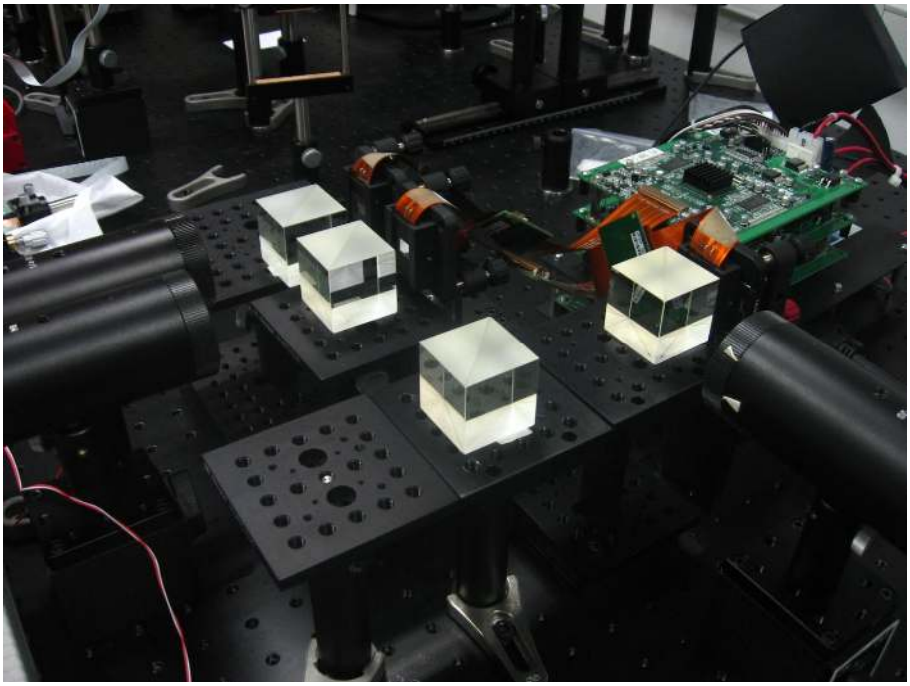


Figure 12. Optical realisation of the proposal in Fig. 11(a).

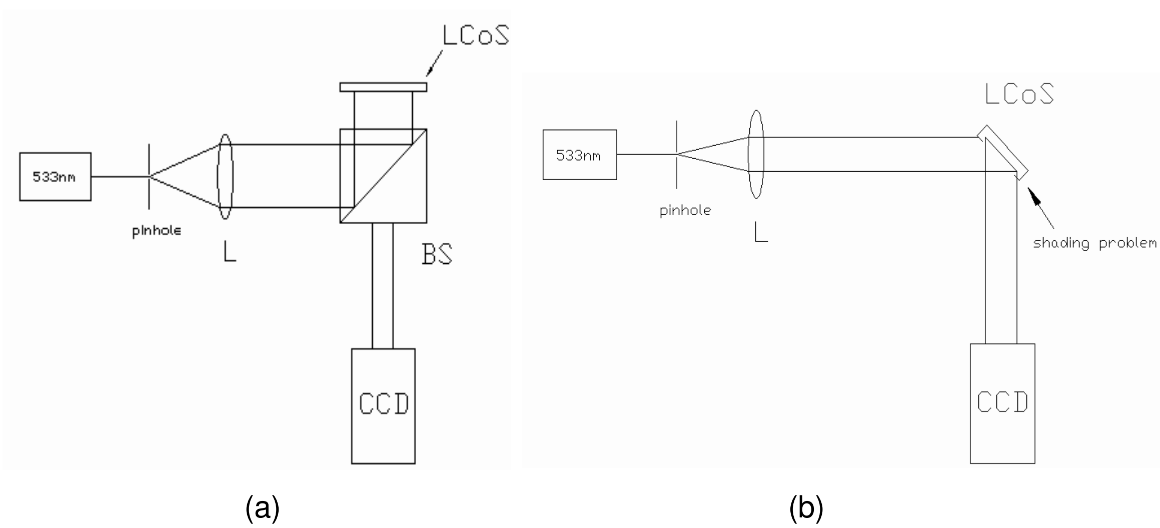


Figure 13. Two experimental configurations to test performance of LCoS devices.

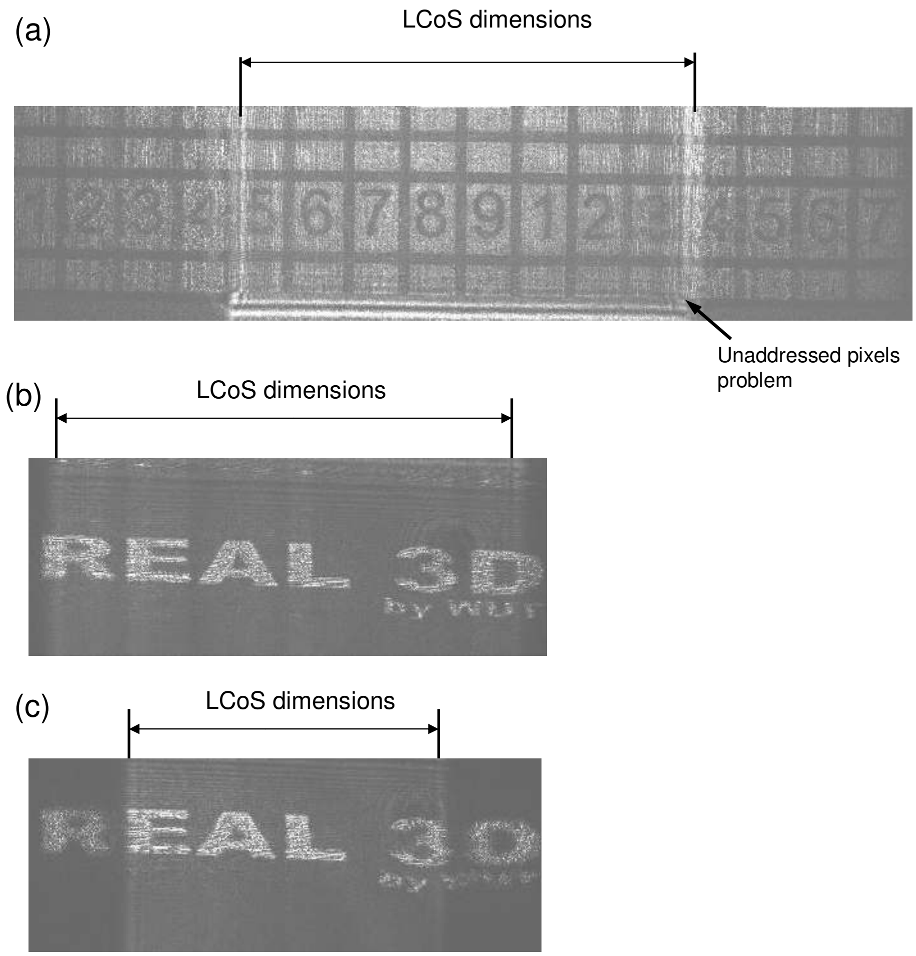


Figure 14. Results from performance test of LCoS devices highlighting the issues that must be considered in a multi-SLM display.

5. ACKNOWLEDGEMENTS

The Real 3D project funded by the European Community's Seventh Framework Programme FP7/2007–2013 under grant agreement no. 216105.

REFERENCES

1. T. Kreis, *Handbook of Holographic Interferometry*, Wiley-VCH, Berlin, 2005.
2. Y. Frauel and B. Javidi, "Neural network for three-dimensional object recognition based on digital holography," *Optics Letters*, vol. 26, pp. 1478–1480, 2001.
3. F. Charrière, N. Pavillon, T. Colomb, C. Depeursinge, T.J. Heger, E.A.D. Mitchell, P. Marquet, and B. Rappaz, "Living specimen tomography by digital holographic microscopy: morphometry of testate amoeba," *Optics Express*, vol. 14, pp. 7005–7013, 2006.
4. M. Paturzo, F. Merola, S. Grilli, S. DeNicola, A. Finizio, and P. Ferraro, "Super-resolution in digital holography by a two-dimensional dynamic phase grating," *Optics Express*, vol. 16, pp. 17107–17118, 2008.
5. T. Lehtimäki, K. Sääskilahti, R. Näsänen, and T.J. Naughton, "Processing of optically captured digital holograms for three-dimensional display," *Three-Dimensional Imaging, Visualization, and Display 2009*, Proc. SPIE vol. 7329, article number 7329-11, 2009.
6. E. Cuche, P. Marquet, and C. Depeursinge, "Simultaneous amplitude-contrast and quantitative phase-contrast microscopy by numerical reconstruction of Fresnel off-axis holograms," *Applied Optics*, vol. 38, pp. 6994–7001, 1999.
7. C.P. McElhinney, B.M. Hennelly, and T.J. Naughton, "Extended focused imaging for digital holograms of macroscopic three-dimensional objects," *Applied Optics*, vol. 47, pp. D71–D79, 2008.
8. M. Sutkowski and M. Kujawińska, "Application of liquid crystal (LC) devices for optoelectronic reconstruction of digitally stored holograms," *Optics and Lasers in Engineering*, vol. 33, pp. 191–201, 2000.
9. O. Matoba, T.J. Naughton, Y. Frauel, N. Bertaux, and B. Javidi, "Real-time three-dimensional object reconstruction by use of a phase-encoded digital hologram," *Applied Optics*, vol. 41, pp. 6187–6192, 2002.
10. F. Yaras, H. Kang, and L. Onural, "Real-time color holographic video display system," *3DTV-Conference 2009, Potsdam, Germany, 4-6 May 2009*, IEEE Press, 2009.