Digital holographic sensor network and image analyses for distributed potable water monitoring

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Abstract

Water-related diseases affect societies in all parts of the world. On-line sensors are considered as a solution to the problems of low sampling density and time-consuming culturing methods associated with laboratory testing for microbiological content in potable water. Digital holographic microscopy (DHM) has been shown to be well suited to image microscopic objects, especially in laboratory environments, and has the potential to rival state-of-the-art techniques such as advanced turbidity measurement. In this paper, we provide a solution that permits DHM to be applied to a whole class of on-line remote sensor networks, of which potable water analysis is one example.

Keywords: digital holographic microscopy, water quality, compression

1 Introduction

Water-related diseases (WRDs), such as diarrhea, typhoid fever, and hepatitis A, remain one class of major global health concerns [World Health Organization and others, 2010]. Nearly ninety percent of diarrheal diseases are caused by bad quality drinking and bathing water [World Health Organization and others, 2004]. To increase safety and to ensure high microbiological quality of potable water, the use of on-line sensors has been suggested [Lopez-Roldan et al., 2013]. Digital holographic microscopy (DHM) is an imaging technique that is well suited for imaging three-dimensional (3D) objects [Javidi et al., 2005, Garcia-Sucerquia et al., 2006, Mudanyali et al., 2010]. Digital holography can be regarded as an enhancement of light scattering approaches [Wyatt, 1968] with the following desirable properties: (i) the scattering from the object is captured holographically so that the scattering can be reversed in software thus generating an in-focus image of the object at any distance from the camera, (ii) a relatively large volume can be imaged so that the object does not have to be in any special location, and (iii) multiple objects can be sensed and distinguished simultaneously.

2 Design choices

We identify four major design choices for an on-line DHM sensor: I) optical hardware and architecture, II) location of data processing and analyses, III) processing and analysis algorithms, and IV) hologram video compression.

2.1 Optical hardware and architecture

The trade-offs between various interferometer architectures and illumination choices have been well-studied. For example, a free-space propagation DHM avoids the need for an expensive microscope objective, but suffers from a depth-dependent spatial resolution, and vibration-sensitive alignment of a pinhole, to produce the spherical wave.

2.2 Location of data processing and analyses

Due to the large volume of data in holographic video of real-world objects, networked holographic video applications have an ever-present problem of how to optimally partition the data processing between the capture side (before network transmission) and the display side [Kujawinska et al., 2014].

2.3 Processing and analyses algorithms

As the system is required to be near-real-time, algorithms need to be optimized and chosen on the basis of the specific application. In the literature, objects have been found in hologram reconstruction volumes using amplitude analysis [Restrepo and Garcia-Sucerquia, 2012], edge detection [Kempkes et al., 2009] and contrast analysis [Pitkäaho et al., 2014]. However, a different set of methods is appropriate for each application.

2.4 Hologram video compression

Hologram video compression is necessary because in practice the limiting factor on the sampling density of the system is the data throughput over the network. The principle employed in this compression strategy is to partition (temporally and spatially) the regions of pixels in the hologram video sequence according to how much information they contain about the sensed particles, and represent those regions with a number of bits per pixel proportional to how much information they contain. We include pixels with varying numbers of bits of representation (including the possibility of zero bits. Starting from the second hologram in the video sequence, and for each hologram, we apply the steps as shown in Fig. 1. Holograms are subtracted from their predecessor to generate a subtraction hologram.

3 Results

To verify the effectiveness of the design, a physical implementation using inexpensive off-the-shelf components was designed, built, and evaluated in an active potable water facility. The imaging sensor was an in-line DHM, illustrated in Fig. 2, whose principal components were a 405 nm laser module (CNI PGL-D8-405-50), a flow-through channel (Ibidi, 81121µ-Slide 0.1 Luer), a 40X microscope objective (Olympus PLN 40X), and a1280×1024 pixel CMOS camera with a 5.3µm pixel pitch (IDS Imaging UI-1242LE-M). The sensor was evaluated in a laboratory environment with test objects such as a static resolution chart, 1µm latex beads and living *E. coli* in water flow.
For tests in an active potable water facility, a portable version of the sensor was assembled in a commercially available aluminum case that contained a low-calculating-power computer unit (Thinclient Zotac Zbox), the imaging and sample circulation components as described above, and a 3G modem (Huawei E367). The flow speed was controlled with a variable-area flow meter (Kytola instruments LH-).
The Finnish wholesale potable water company Vesikolmio Oy (Nivala, Finland, www.vesikolmio.fi), which serves water to 50,000 people and annually delivers 3,7 million $m^3$of water, provided access to one of their ground water pumping stations. The system was installed in this station before the ultraviolet water purification system for a testing period of two months. During the two-month testing period the system was capable of capturing multiple holograms that contained microparticles. An example result is shown in Fig. 3. The 3D locations of all of the particles in the field of view can be obtained through automated means [Kempkes et al., 2009,Pitkäaho et al., 2014].

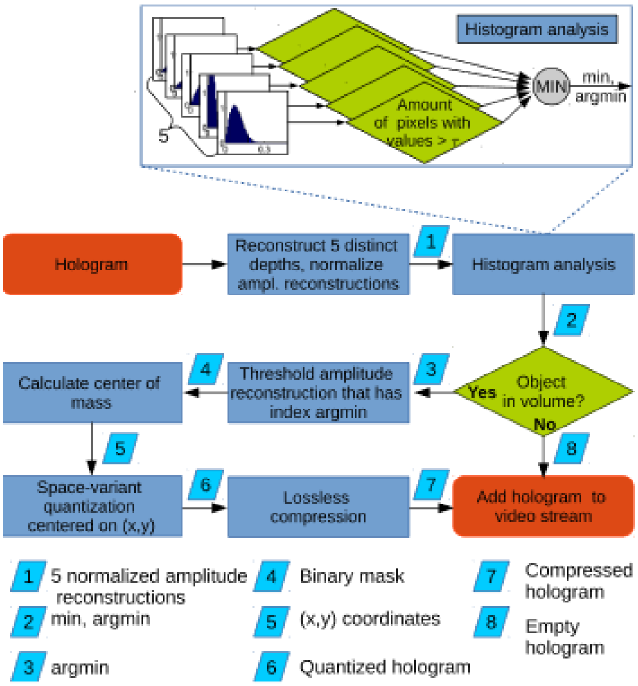

Figure 1: Compression principle. The input for the compression algorithm is a subtraction hologram and the output is a compressed hologram. The inset shows how the histogram analysis is executed.

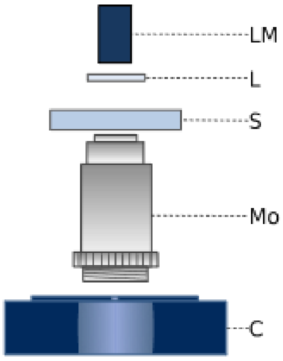

Figure 2: Imaging sensor components. Light from the laser module (LM) is collimated by the lens (L) and transmitted through an aperture containing the sample (S). Magnification is realized with the microscope objective (MO) and the hologram is captured with the digital camera (C).

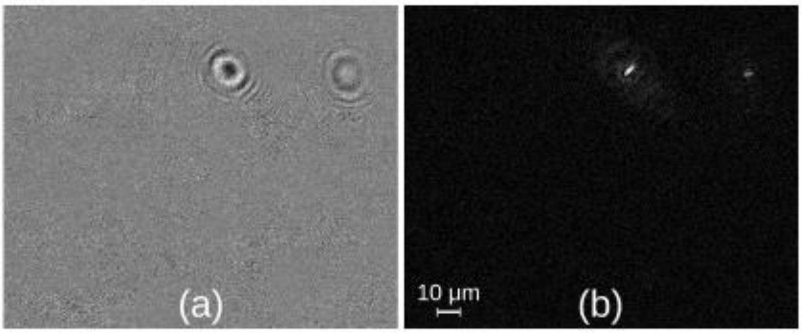

Figure 3: (a) subtraction of two temporally different holograms, (b) intensity reconstruction at 159 mm from the hologram plane where a single microscopic object is in focus.

4 Conclusions

In this paper, we described a system that satisfies the requirements of an on-line DHM sensor system that can be used in distributed water quality monitoring. An example implementation of the system was described and results from an active water potable water facility were shown.

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