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Enabling Low-light Digital Holography with a Quanta Image Sensor

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Abstract: We demonstrate a digital holographic imaging system where the hologram is captured by a quanta image sensor (QIS), and the object wavefront is then computationally retrieved. This scheme enables digital holography at a very low signal level via individual photon detection.

1. Motivation

With the capability of capturing the object wavefront, digital holography (DH) has been extensively studied, with a wide range of applications [1]. However, it is still a nascent area when it comes to photon-starved scenarios. The driving force for such research is the need to capture holograms in low light with fast-moving objects. Conventional image sensors, which generate digitized signals by accumulating the detected photons, are often insufficient to meet this technical challenge. In this work, we investigate a way to record and reconstruct holograms by detecting the arrival of the individual photons. Specifically, the quanta image sensor (QIS) [2, 3] is used in our digital holographic imaging system, which detects the single photon with high sensitivity and picosecond temporal resolution (e.g., 1000 frame per second [4]). The feasibility of our imaging system is demonstrated by proof-of-concept simulations, which open the possibility of digital holographic imaging with ultimate sensitivity at an extremely low signal level.

2. Principle

Different from the traditional sensors, such as complementary metal-oxide semiconductor (CMOS) and charge-coupled devices (CCDs), QIS forms images from the single-photon detection instead of accumulating photon charges during an exposure time interval [2]. When a single photon arrives at the effective sensing area of a jot (the unit structure of QIS), the digital signal will be generated by a very low sensing capacitance that offers enough charge gain [2]. The arrival of photons is well described by Poisson statistics. Over an integration period, the probability of the number of photon electrons $N(x,y)$ that arrive at an effective jot area at (x,y) is given by the probability mass function

$$\mathbb{P}\{N(x,y)=k; H(x,y)=h\} = \frac{e^{-h}h^k}{k!}, \tag{1}$$

where $H(x,y)$ is the quanta exposure at (x,y), which depends on factors such as quantum efficiency, carrier collection efficiency, incident photon flux, and integration time [2].

In the single-bit QIS, a binary value is returned from each jot according to the one-bit quantization with threshold $k=1$, where logic "0" stands for no photoelectron, and "1" represents one or more detected photoelectrons. Mathematically, the observed measurement $U(x,y)$ is

$$U(x,y) \stackrel{\text{def}}{=} \begin{cases} 1 & \text{if } N(x,y) \geq 1, \\ 0 & \text{otherwise,} \end{cases} \tag{2}$$

which has a Bernoulli distribution

$$\mathbb{P}\{U(x,y)=0; H(x,y)=h\} = e^{-h}, \tag{3}$$

$$\mathbb{P}\{U(x,y)=1; H(x,y)=h\} = 1-e^{-h}. \tag{4}$$

The final image is formed by a spatio-temporally merged groups of jots called a "jots-cube".

Fig. 1 shows the DH recording and reconstruction process with a QIS. As shown, the grayscale hologram (Fig. 1(c)) was reconstructed from the raw QIS binary output tensor (Fig. 1(b)) with high fidelity and fringes visibility, from which the object intensity map was successfully recovered. Moreover, a USAF resolution target

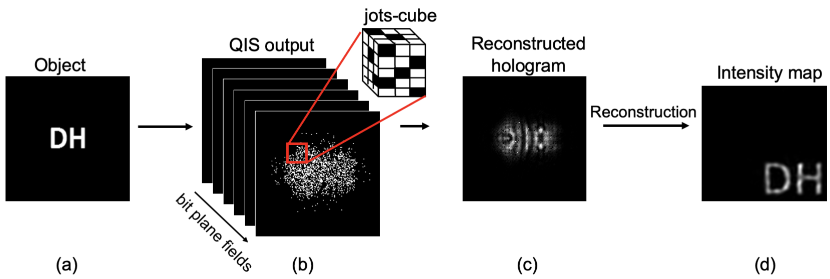
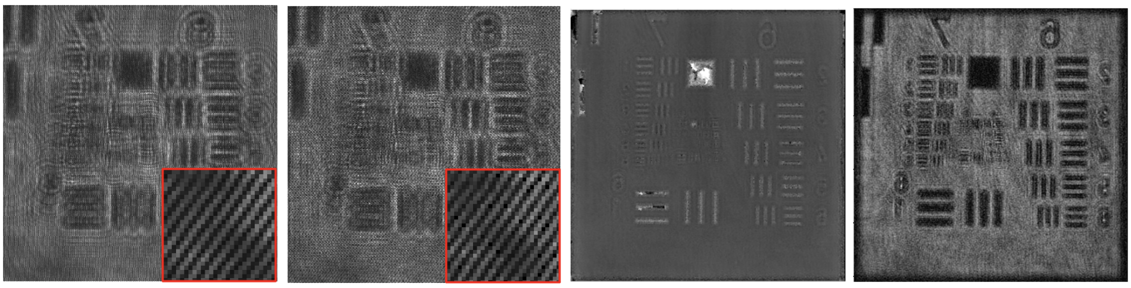


Fig. 1: Reconstructing an intensity object from the off-axis hologram recorded by QIS. (a) The intensity object. (b) Raw QIS binary output. (c) Reconstructed hologram. (d) Reconstructed intensity map.

from an open-source DH library [5] was further used for verification. The hologram (Fig. 2(a)) was recorded by illuminating with a laser source ($\lambda = 405\,\text{nm}$) and CMOS detection (1024×1024 with $3.35\,\mu\text{m}$ pixels). The synthetic one-bit QIS observations were generated based on the quantized Poisson statistics (Eq. (1-3)). As indicated in Fig. 2(b), the fringe pattern is preserved in the QIS hologram. Fig. 2(c) and (d) demonstrate the successful retrieval of the object wavefront.



(a) CMOS hologram (b) QIS hologram (c) Retrieved phase map (d) Retrieved intensity map

Fig. 2: Reconstructing the USAF resolution target. (a) is the sample hologram recorded by CMOS [5]. (b) is the hologram reconstructed from the QIS output that is simulated from (a). The patches on the bottom right corner are the scaled interference fringes. (c) and (d) show the retrieved phase and intensity of the target from the QIS hologram, respectively.

3. Conclusion

In this work, we propose a novel imaging system for digital holography with high photon sensitivity. Using the QIS, holograms are formed based on the single photon detection. Its feasibility is proved by successfully reconstructing the object wavefront. This work paves the way for low-light digital holographic imaging, which has a great potential in applications under photon-starved scenes.

4. Acknowledgements

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