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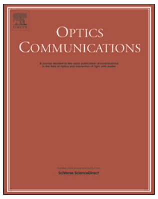

Structured-light-assisted wireless digital optical communications

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ABSTRACT

Camera-projector-pair-based digital optical communications are attractive for safe and flexible usages, while the state-of-the-art systems suffer from various disadvantages or distortions of communication channels, including the irregularity and the non-uniform albedo of projection surfaces, the radial distortion of optical lenses, etc. In this paper, we present a novel method for digital optical communications. Assisted by structured light illumination, we overcome those disadvantages and accurately derive the models of the communication channels. First, by deriving accurate model-free coordinates maps for the camera-projector pair, we overcome the issues caused by the irregularity of projection surfaces and the radial distortion of optical lenses. Second, by normalizing received digital optical signals with calibrated system parameters, we overcome the issue arising from the non-uniform albedo of projection surfaces. Thus, with the models and all pixel-wise operations, we finally achieve robust and real-time wireless digital optical communications. Experimental results verify the validity of the proposed method.

1. Introduction

Recent presence of liquid-crystal display (LCD) screen-camera links [1–5] have created a interference-free, low-cost and secure passway for indoor optical communications. Typically, an LCD screen (as a transmitter) sequentially displays a series of patterns carrying source signals, and, simultaneously, a camera (as a receiver) records each screen image, from which the transmitted signals are subsequently retrieved by using computer vision techniques. In order to improve the ease of use as well as flexibility of the communication system, by replacing the LCD screen with a projector, Pei et al. [6] proposed the projector-wall-camera system, since, compared with an LCD screen with fixed size, the size and position of a display region illuminated by the projector can be adjusted more easily. However, the existing projector-camera communication systems [6] require the display surfaces to be flat and uniformly textured (*e.g.* a white flat wall), and, thus, they suffer from disadvantages such as surfaces with arbitrary shape and non-uniform texture.

In this paper, by employing phase measuring profilometry (PMP) [7], known as a robust structured light illumination (SLI), which is typically used for reconstructing the 3-D surfaces of scanned targets, we present a novel method achieving robust and real-time digital optical communications. First, by deriving accurate model-free coordinates maps for a camera-projector pair, we overcome the issues caused by the irregularity of projection surfaces and the radial distortion of optical lenses. Second, by normalizing received digital optical signals with calibrated system parameters, we overcome the issue of the non-uniform albedo of projection surfaces. Thirdly, with all pixel-wise operations, real-time communications can be achieved. Experimental results verify the performance of the proposed method.

2. Method

By employing PMP [7], we can sufficiently make use of all the parameters derived from PMP patterns, to model the channels, *i.e.* projection surfaces, of optical communications.

Along the horizontal direction of the camera, a PMP-patterned image, I_n^x, is expressed by [8]

$$I_n^x = A^x + B^x \cos\left(\phi^x - \frac{2\pi n}{N}\right), \tag{1}$$

where the three unknowns, A^x, B^x and ϕ^x, are the direct component, the modulation and the phase, respectively, and n and N are known and they are the index and the number of the phase shifts, respectively. Note that $I_n{}^x$, A^x, B^x and ϕ^x are functions of the coordinates, (x^c, y^c), in the camera space. The terms A^x, B^x and ϕ^x are

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computed by [8]

$$A^x = \frac{1}{N}\sum_{n=0}^{N-1} I_n^x, \tag{2}$$

$$B^x = \frac{2}{N}\sqrt{\left[\sum_{n=0}^{N-1} I_n^x \sin\left(\frac{2\pi n}{N}\right)\right]^2 + \left[\sum_{n=0}^{N-1} I_n^x \cos\left(\frac{2\pi n}{N}\right)\right]^2} \tag{3}$$

and

$$\phi^x = \arctan\left[\frac{\sum_{n=0}^{N-1} I_n^x \sin\left(\frac{2\pi n}{N}\right)}{\sum_{n=0}^{N-1} I_n^x \cos\left(\frac{2\pi n}{N}\right)}\right], \tag{4}$$

respectively. Likewise, along the vertical direction of the camera, we have $I_{n,}^{y}$ from which A^y, B^y and ϕ^y are computed.

Theoretically, A^x and B^x equal to A^y and B^y, respectively, and thus we let

$$A = \tfrac{1}{2}\left(A^x + A^y\right) \tag{5}$$

and

$$B = \tfrac{1}{2}(B^x + B^y), \tag{6}$$

with which we can detect the valid projection area and normalize the transmitted signals as follows. First, Eq. (3) indicates that, if $I_n{}^x$ is a constant, the term B^x should be zero. Therefore, in practice, if B at (x^c, y^c) is larger than a very small threshold T^v, we know (x^c, y^c) is within the valid projection area [8]. Second, given a captured transmitted digital optical signal, *e.g.* S, we normalize it by

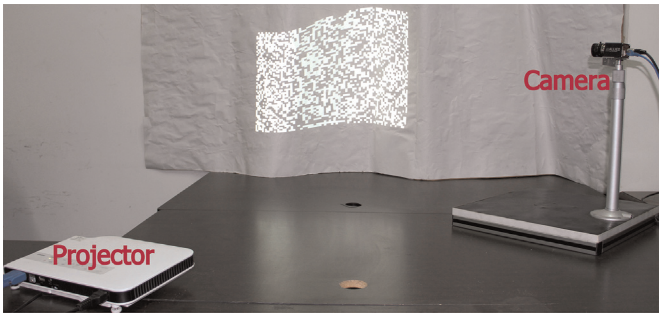

Fig. 1. The setup of digital optical communication system.

$$\hat{S} = \frac{S - A}{B}, \tag{7}$$

where, with range of $[-1, 1]$ in theory, $\hat{S}$ can be easily binarized into $\bar{S}$ according to a threshold T^b=0. Note that S carries binary signals and only has two possible intensity levels at a pixel. Correspondingly, to normalize S, A and B are required to be

$$A = \frac{I^{min} + I^{max}}{2} \tag{8}$$

and

$$B = \frac{I^{max} - I^{min}}{2}, \tag{9}$$

respectively, where I^{min} and I^{max} are the lower and the higher intensity value of S. Eqs. (8) and (9) can be easily satisfied by adjusting the parameters of projected patterns.

With previously computed ϕ^x and ϕ^y, which are both of range $[0, 2\pi)$ and are known as the normalized horizontal and vertical coordinates in the projector space, we can construct two integer-valued coordinates maps as [9]

$$M^x = \text{round}\left(\frac{W\phi^x}{2\pi}\right) \tag{10}$$

and

$$M^y = \text{round}\left(\frac{H\phi^y}{2\pi}\right), \tag{11}$$

where $W \times H$ is the spatial resolution of the projector. Thus, for $\bar{S}$ at (x^c, y^c), through simply looking up M^x and M^y as

$$(x^p, y^p) = [M^x(x^c, y^c), M^y(x^c, y^c)], \tag{12}$$

its corresponding coordinates, (x^p, y^p), in the projector space, is quickly obtained.

Finally, by mapping each valid value of $\bar{S}$ from (x^c, y^c) to (x^p, y^p), we can recover the transmitted signal S. Obviously, interpolations and statistical methods may be involved according to cases.

3. Experimental results

As shown in Fig. 1, our communication system is composed of a Prosilica GC650M camera with a resolution of 640 × 480 and a Casio XJ-A155V projector with a resolution of 800 × 600. The camera and the projector are respectively controlled by two desktop computers. We conduct two experiments to show the

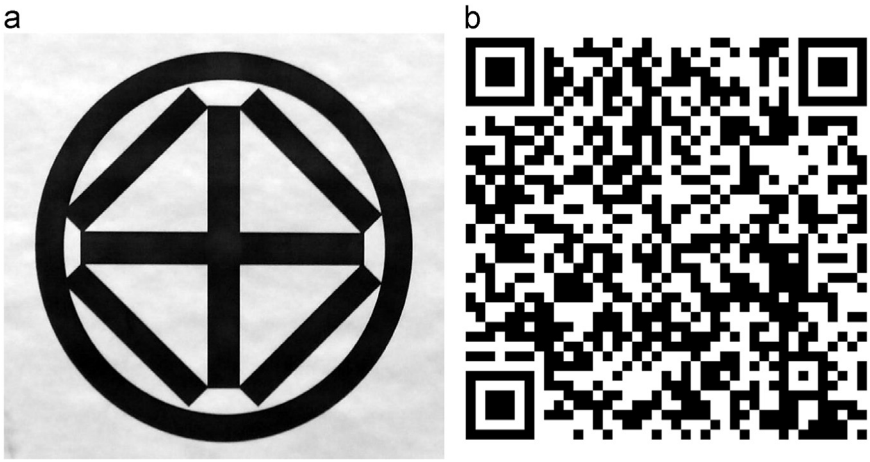

Fig. 2. (a) Flat textured surface; (b) transmitted QR code.