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A structured light method for underwater surface reconstruction

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ABSTRACT

A new structured-light method for 3D imaging has been developed which can simultaneously estimate both the geometric shape of the water surface and the geometric shape of underwater objects. The method requires only a single image and thus can be applied to dynamic as well as static scenes. Experimental results show the utility of this method in non-invasive underwater 3D reconstruction applications. The performance of the new method is studied through a sensitivity analysis for different parameters of the suggested method.

1. Introduction

Three dimensional surface imaging has been an active area of research for decades and was reached a stage of maturity, thanks to digital cameras and ever-increasing computational power. Applications of 3D surface imaging range from traditional mapping applications, structural monitoring, cultural heritage documentation, quantifying landform change to forensic, medical, biology and many other fields.

There are different methodologies for 3D reconstruction using optical cameras, such as stereo and multi camera imaging, photometric stereo, structured light and shape from X techniques, to name a few. Researchers have extended some of these methods to adapt to the underwater environment. Examples of such pioneering studies in underwater photogrammetry include (Kotowski, 1988; Höhle, 1971; Bruno et al., 2011; Telem and Filin, 2010). Also there are several books and studies (Remondino and El-Hakim, 2006; Luhmann et al., 2013; Szeliski, 2010) that discuss the pros and cons of each methodology, where the same pros and cons are still valid for underwater 3D reconstruction.

In this paper our focus is on extending structured light techniques in a specific case of a two phase environment where the camera is underwater and the projector is above water. Structured light techniques simplify the problem of 3D reconstruction with the help of controlled illumination. They basically consist of acquiring 2D image(s) of the scene while illuminating the scene with spatially varying intensity pattern(s). The nonplanar geometric shape of the surface distorts the projected structured-light pattern as seen from the camera. Then the information from the distortion of the projected structured-light pattern is used to extract the 3D surface shape.

Numerous structured light techniques for 3D surface imaging are currently available. The techniques that have been developed range from those that require multiple images (multi-shot techniques) (Ishii et al., 2007; Sato and Inokuchi, 1987; Valkenburg and McIvor, 1996; Huang and Zhang, 2006; Bruno et al., 2011) to reconstruct a surface to those that require only a single image (single-shot techniques) (Geng, 1996; Payeur and Desjardins, 2009; Fernandez et al., 2010; Maruyama and Abe, 1993; Ulusoy et al., 2009; Sagawa et al., 2011). Multiple-shot techniques can be used in cases where the target is static and the application does not impose any constraint on the acquisition time. Generally, multiple-shot techniques may often result in a more reliable and more accurate 3D reconstructed surface. Because of this, if the target is static, multiple-shot techniques are recommended. However, if the target is moving, using single-shot techniques is required. A more detailed overview of available structured light techniques can be found in Geng (2011) and Salvi et al. (2004).

In all of above-mentioned structured light techniques, the assumption is that the projector and the camera are in the same (homogeneous) medium, e.g. both camera and projector are placed underwater or in an open-air environment. However, there may be applications that require the projector and the camera to be in different mediums or in which the light must pass through an inhomogeneity. For example, consider air–sea interface studies that need simultaneous estimation of water surface and sea floor in shallow waters. Subsurface inspection of harbor facilities, bridges or vessels may also be enabled by illumination or imaging from outside the water. In this paper, we seek to develop a structured-light

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technique that employs a projector above water and an underwater camera for estimation of both the water surface and sea floor. In this case, the water surface is dynamic and changes instantaneously. Because of dealing with a dynamic surface, the method has to use a single image. A unique color pattern was generated from a projector located above the water and images were acquired with a camera located under water. With this unique color pattern only one image was required to reconstruct both the water surface and the sea floor.

2. Problem statement

Consider a light ray emitted from the projector and represented by a vector $\mathbf{v} \in \mathbf{R}^3$. Let S be a nontrivial subspace of a vector space $\mathbf{R}^3$ and assume that $\mathbf{v}$ is a vector in $\mathbf{R}^3$ that does not lie in S. Then the vector $\mathbf{v}$ can be uniquely written as a sum of its orthogonal projections $\mathbf{v}_{\|S} + \mathbf{v}_{\perp S}$, where $\mathbf{v}_{\|S}$ is parallel to S and $\mathbf{v}_{\perp S}$ is orthogonal to S (Lay, 2011). The vector $\mathbf{v}_{\|S}$, which actually lies in S, is called the projection of $\mathbf{v}$ onto S. If $(\mathbf{v}_1, \mathbf{v}_2)$ form an orthogonal basis for S, then the projection of $\mathbf{v}$ onto S is the sum of the projections of $\mathbf{v}$ onto the individual orthogonal basis vectors (Lay, 2011). Thus, a 3D light ray can be represented by its orthogonal projections on XZ and YZ planes. For illustration purposes, we only show orthogonal projections of light rays on XZ plane in Fig. 1.

Consider a typical structured-light system in which both camera and the projector are in the same medium, see Fig. 1(a). A projector illuminates the object with a spatially varying structured light and an imaging sensor is used to acquire a 2D image of the scene. In this case, the projected structured-light pattern distorts solely due to the geometric shape of the object surface. As shown in Fig. 1(a), the geometric relationship between an imaging sensor, a structured-light projector, and an object surface point can be expressed by the triangulation principle as

$$D = B\frac{\sin(\psi_p)}{\sin(\psi_c + \psi_p)} \tag{1}$$

Now consider the scene in Fig. 1(b) where the projector is located above water and the camera is under water. In this case, the distortion of the pattern is due to both the geometric shape of the water surface and the geometric shape of the object surface. To recover the object surface, one should consider distortions from the water surface. Note that, the path of light ray in this case has two parts; one above water and one under water. Both parts are 3D rays and their orthogonal projections on XZ plane are shown in Fig. 1(b). While a real water surface inherently contains variability in both the X and Y directions, for simplicity here we will consider the X-axis lying in the wave propagation direction and the Y-axis which is orthogonal to it separately, as is commonly implemented in Airy wave theory (Airy, 1845).

To demonstrate the effect of water surface shape on the projected pattern, consider the scene in Fig. 2 where a projector illuminates an underwater flat object while its line of sight is perpendicular to the object's surface. These plots show the effect of refraction of the projected rays when they enter the water. Fig. 2(a)–(c) illustrate the behavior of the rays against a flat, sloped, and sinusoidal water surfaces, respectively. As can be seen, each ray has a different refraction behavior based on its incidence angle. When a light ray passes through the water surface, Snell's law can describe the relationship between the angles of incidence and refraction of that ray, i.e.

$$n_w \sin(\theta_i^w) = n_a \sin(\theta_i^a) \tag{2}$$

where n_a represents the refractive index of the air and n_w is the refractive index of the water. Also, θ_i^a and θ_i^w respectively represent the incidence angle and the refraction angle of the ith ray.

Because of the refraction effect, a unique projected pattern will have different shapes, even on a flat object at the same distance from the projector, depending on the water surface shape. If one can estimate the water surface, then it is possible to predict the path of each projected ray and account for the refraction effect on the distortion of the projected pattern on the underwater object. The method used to estimate the water surface is discussed in Section 3.3.

In order to estimate the geometric shape of the water surface and underwater objects, the camera-projector system must first be calibrated. In the next section, the details of the camera-projector (system) calibration will be explained.

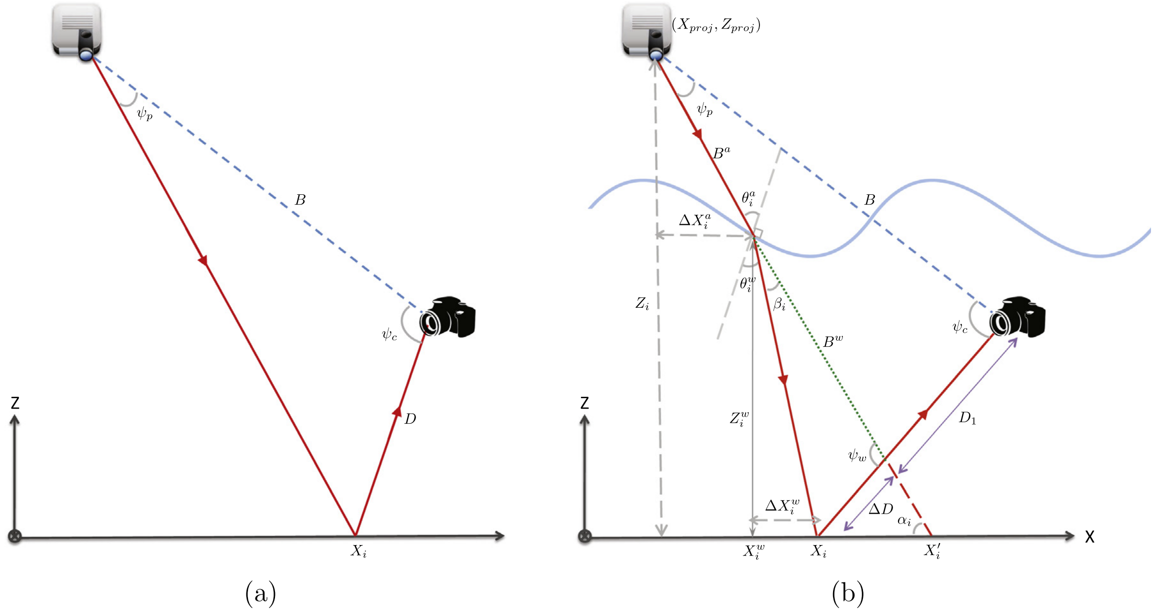

Fig. 1. Orthogonal projection of a 3D ray in XZ plane in a projector-camera system: (a) both camera and the projector are in the same medium, (b) camera and the projector are in different medium, in this particular case the projector is above water and the camera is underwater. The ray refracts after hitting the water surface based on its incidence angle θ_i^a.