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Real-time structured light profilometry: a review

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ABSTRACT

The acquisition of high-resolution, real-time three-dimensional surface data of dynamically moving objects has large applicability in many fields. When additional restrictions such as non-invasiveness and non-contact measurement are imposed on the employed profilometry technique, the list of possible candidates is reduced mainly to the broad range of structured light profilometry methods. In this manuscript, the current state-of-the-art in structured light profilometry systems is described, as well as the main advancements in hardware technology and coding strategy that have led to their successful development. A chronological overview of optical profilometry systems that have been reported to perform real-time acquisition, digital signal processing and display of full-field 3D surface maps is presented. The respective operating principles, strengths and weaknesses of these setups are reviewed and the main limitations and future challenges in high-speed optical profilometry are discussed.

1. Introduction

With recent technological advancements in digital projection, imaging and processing hardware, optical surface measurement techniques have evolved rapidly. The demand for non-contact, high-resolution and fast 3D-shape measurement systems is propelled by the medical, industrial and entertainment sector and has driven manufacturers and academic research groups to design a wide variety of optical profilometry techniques. Generally, they vary in terms of hardware configuration, stability, cost, resolution and speed.

Time-of-flight profilometers [1–3] measure the time required for a light pulse to travel from the transmitter to an object and back to the receiver. The object surface is scanned point-per-point in an array of arbitrarily dense sampling points and a depth map is created subsequently. Time-of-flight methods are generally stable, straightforward 3D-measurement techniques and require no calibration to produce absolute depth data. However, axial measurement accuracy (typically 0.1–1 cm) is limited to the temporal resolution of the transmitter-receiver system and cannot be improved through optical magnification.

Image-based techniques analyze how an image is formed and how lighting affects the objects within that image. Three-dimensional surface information is extracted from the two-dimensional representation of the object through (complicated) image analysis. *Shape-from-shading* methods [4,5] recover the surface shape from the image by modeling the gradual variations of grayscale shading in the image and by determining each pixel's relative distance to the imaging source. *Shape-from-focus-and-defocus* methods [6,7] recover the surface shape by correlating the degree of local blur on the object to relative distance from the imaging lens. *Stereo vision* profilometry techniques [8,9] simulate the stereoscopic setup of human vision by employing a second camera placed at an angle with the original camera. Identifying common features on the object in images taken from multiple perspectives or *stereo-matching* allows the object surface shape to be reconstructed using standard triangulation techniques. Image-based profilometry techniques require only a digital camera (or two, in the case of stereo vision techniques) and are generally low-cost setups. However, limited measurement accuracy in depth and computationally intensive digital signal processing requirements reduce their usability in real-time profilometric setups.

Similar to stereo-vision profilometry, *Moiré profilometry* [10,11] requires an additional optical axis in its setup design. By replacing one of the two cameras with a projection device to illuminate the object with structured light patterns, one can avoid the stereo-matching problem. When observed under an angle, the projected patterns are deformed by the object's surface shape. In Moiré profilometry, mechanical interference is induced by placing a demodulation grid - identical but slightly misaligned to the original projection grid - between the object and the camera. Contours of equal height can then be extracted from the resulting interference pattern. Practically, however, the need for a physical demodulation grid complicates the hardware configuration of the experimental setup.

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More recently, various *structured light projection* (SLP) techniques have been reported that employ the same projector–camera setup as Moiré techniques but lack the demodulation grid. Instead, surface height information is extracted directly from analysis of the deformed grid pattern. By eliminating the demodulation grid, SLP techniques allow for a more straightforward and stable experimental setup to be designed. In addition, specific depth extraction can be performed in a number of ways, depending on the nature and the amount of projected patterns.

The remainder of the paper is structured as follows: in Section 2, the broad range of structured light profilometry techniques is subdivided according to general coding strategy, briefly describing their respective operating principles and highlighting their potential applicability in real-time setups. Section 3 discusses the associated problem of phase unwrapping. In Section 4, we give an overview of SLP systems that have been reported to operate in real-time and describe the main advances in digital projection technology and coding strategy that have led to their development. Section 5 discusses the strengths and weaknesses of single-shot versus multi-shot techniques in high-speed setups, summarizes the current limitations of state-of-the-art SLP techniques and describes future challenges. Finally, Section 6 concludes the paper.

2. Structured light profilometry techniques

The low-cost access to fast, high-resolution digital projection systems based on liquid crystal displays (LCD) and digital light projectors (DLP) has enabled the development of a wide variety of structured light profilometry techniques. Structured light or active illumination profilometry techniques illuminate the measurement object with predefined spatially varying intensity patterns and record these patterns as they are deformed by the object shape when observed at an angle with the projection axis. The basic setup of SLP techniques is illustrated in Fig. 1. A structured light modulator (*projector*) projects the pattern onto the scene and an imaging sensor (*camera*) placed at a relative angle with the projection axis records the deformed pattern. Digitalization of this basic projector–camera setup has enabled numerous SLP-techniques to be developed, each with their own respective strengths and weaknesses.

Though they are all unique in their specific implementation, differentiation between them can be made based on whether or not they require multiple projected patterns per 3D measurement (single-shot versus multi-shot techniques), whether or not they use color encoded projection schemes and specific coding strategy. A more precise schematic overview of the different classes of structured light projection techniques is presented in Fig. 2, analogous to the overview created by Geng [13]. Here, we have updated the overview with recently developed techniques, added the family of Fourier-based profilometry techniques and subdivided the set of phase shifting techniques according to their respective projected intensity profiles. Techniques which have been reported to reach real-time (>10 3D frames per second) acquisition, digital signal processing and display of 3D surface maps are marked with an encircled 'R'-symbol. Techniques which require phase unwrapping (see Section 3) as part of their reconstruction algorithm are marked with an encircled 'PU'-symbol.

2.1. Color encoded projection techniques

Color encoded projection techniques employ color as a differentiating tool to uniquely label the object surface. The major advantage of color encoded projection techniques is their potential ability to acquire depth information using only a single projected

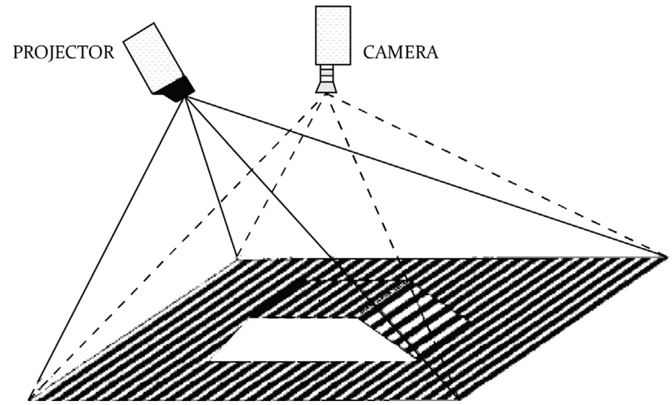

Fig. 1. Standard projector–camera configuration used in structured light profilometry techniques. Figure modified from Sansoni et al. [12].

image. Their disadvantage, however, lies in the fact that a color-independent reflectivity profile of the measurement target is assumed and that the quality of the resulting depth map is greatly influenced by the correspondence between projected and recorded color values. This makes them often unsuitable for practical applications that need to measure (partly) colored objects.

Rainbow 3D cameras [14,15] illuminate the object with a spatially varying color pattern, establishing a one-to-one correspondence between the projection angle and a particular wavelength. This way, each surface point is landmarked with a specific wavelength and can be triangulated if the angle between the projection and camera axes is known. This technique is highly sensitive to the dynamic range and color resolution of the employed CCD chip: with a standard image sensor containing three 8-bit channels, a total of 2^{24} different colors can be represented. Correct triangulation implies a one-to-one correspondence between projected and recorded color value over this entire color range, making rainbow 3D cameras highly sensitive to cross-talk between color channels. By projecting *color coded stripes* [16] onto the target surface, the range of the color-sensitive CCD chip can be subdivided in discrete levels, reducing the in-plane resolution but making the technique more robust to color-dependent reflectivity profiles. A special color coded stripe sequence is based on the unique features of a *De Bruijn sequence* [17,18]. A De Bruijn sequence of rank n on a base set of size k is a cyclic word in which each of the k^n words of length n appears exactly once as we travel through the cycle. This way, a stripe pattern can be constructed that consists of uniquely identifiable local color patterns with a limited set of base colors. *Composite* color coding techniques superimpose multiple phase shifted patterns onto a single color image [19,20]. This color pattern is then projected onto the target statically and is recorded by a color-sensitive CCD chip. By separating the color channels in post-processing, the deformed phase shifted patterns can be reconstructed and the object height profile can be extracted using well-known phase shifting techniques. A combination of color coded stripes and composite color coding techniques consists of encoding multiple patterns into a single color projection image. This way, the ambiguity problem caused by employing phase shifted patterns can be alleviated [21,22]. In any case, one should reduce the decoding error rate by optimizing the color sets by maximizing the distance between adjacent colors in the projected pattern. Another type of color encoding strategy is to project both horizontal and vertical stripes onto the target so that a *color coded grid* is achieved. Adding this extra dimension of encoding facilitates solving the correspondence problem [23,24], although the limited thickness of the projected lines reduces the stability of this technique when compared to the above color encoded methods. Similarly, a *color coded dot array* of pseudo-randomized colored

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