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Single shot laser speckle based 3D acquisition system for medical applications

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A B S T R A C T

The state of the art techniques used by medical practitioners to extract the three-dimensional (3D) geometry of different body parts requires a series of images/frames such as laser line profiling or structured light scanning. Movement of the patients during scanning process often leads to inaccurate measurements due to sequential image acquisition. Single shot structured techniques are robust to motion but the prevalent challenges in single shot structured light methods are the low density and algorithm complexity. In this research, a single shot 3D measurement system is presented that extracts the 3D point cloud of human skin by projecting a laser speckle pattern using a single pair of images captured by two synchronized cameras. In contrast to conventional laser speckle 3D measurement systems that realize stereo correspondence by digital correlation of projected speckle patterns, the proposed system employs KLT tracking method to locate the corresponding points. The 3D point cloud contains no outliers and sufficient quality of 3D reconstruction is achieved. The 3D shape acquisition of human body parts validates the potential application of the proposed system in the medical industry.

1. Introduction

Medical practitioners require the three-dimensional (3D) geometry of human surfaces in various medical procedures such as maxillofacial surgery, plastic surgery, prosthetics, and orthotics. This information overcomes the limitations of direct anthropometry [1] and assists the surgeons in preoperative surgical planning [2] and postoperative surgical analysis [3].

As of now, the medical industry has seen explosive growth in the utilization of optical 3D surface scanners due to their ability to capture 3D shapes accurately without having direct contact with the patients. These scanners not only provide accurate 3D measurements of complex human structures that are impossible to measure with traditional methods, but also enable the additive manufacturing for healthcare [4]. And all, their “easy to use” facet eliminates the need of a trained practitioner to operate the equipment.

Optical 3D scanners are roughly categorized into passive and active scanners. The passive approaches recover the 3D information using only image data relying on detecting the ambient light reflected from the object. The images can be acquired from one or more cameras. Some passive techniques have been investigated for 3D measurements in several medical applications [5–7]. Since these techniques work with natural features obtained directly in the ambient light, they may achieve good accuracy and density from the measuring objects that have a rough surface but fail in the absence of texture. Active scanning systems were invented to overcome this problem. Such systems introduce an additional light or some kind of radiation with the assistance of a projection device. Instead of relying on ambient light, active 3D sensors observe the reflection of projected light in order to probe the 3D geometry of the object. The radiation or light used in these systems is generally eye safe and harmless to patients [8–10]. Laser line scanning is one of the prominent active technique for measuring skin surfaces and has been commercialized [11,12]. A laser swipes through the object to be measured projecting a line or a dot. The imaging sensor records the range maps or surface profiles of the object as the laser moves across the object. The range maps or surface profiles can be converted to 3D coordinates by a laser triangulation method to construct a 3D model. The accuracy of these systems is relatively high, but they measure only one line or point at a time making them highly sensitive to movements. For humans, particularly babies and the elders, it is very difficult to remain still for more than few seconds.

Structured light (SL) scanning solved this problem to some extent by capturing the whole field of view instead of a line or dot. These systems project light coded patterns on the object under investigation. In most cases, the geometry of the patterns is known prior to projection. The 3D reconstruction is performed by calculating the difference between

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the projected and the returned (deformed) patterns. SL projection is the most common active method and a plethora of SL techniques can be found in the literature [13]. These techniques are mainly classified into multiple shot and single shot. The former group can realize depth on pixel level using temporal coded light patterns. The outcome of this is the high-resolution and accurate 3D reconstruction. These attributes make them highly preferred in clinical environments [14–19]. The recent evolution in hardware resources and new acquisition techniques capacitates the 3D measurements of moving objects even if the series of patterns must be realized [20]. Fringe projection profilometry considered to be the faster among other SL methods [21]. A basic fringe projection system analyzes the fringes with one of the fringe analysis methods and recovers a phase map to calculate the 3D coordinates [22]. A number of different fringe projection techniques have been introduced that use a small number of fringe images and achieve good quality 3D reconstructions of moving objects [23–26]. For fast generation and changing of patterns, new projection techniques have also been introduced such as laser speckle projection [27,28], array projection [29,30] and GOBO projection [31].These techniques contain necessary motion compensation and can be applied to obtain 3D data from human skin surfaces in the dynamic environment. However, the techniques that require image sequences for 3D measurements of moving object can be affected by the smearing effect. High-speed measurements can be achieved using aforementioned multiple shot SL methods but they are not regarded as “motion-robust” methods [32].

The concept of extracting all the information (required for 3D reconstruction) within the single exposure time of the camera is known as single shot 3D sensing. Single shot structured light methods make use of the features that lies strictly in the spatial domain making them entirely robust to the motion. The fundamental coding strategies in single shot SL methods can be classified into continuous and discrete [33]. A smooth and dense digital profile of simple objects can be obtained by continuous coded methods like fast Fourier fringe analysis [34] as every pixel is encoded. For more complex structures like a human hand, color fringe pattern (containing red, green and blue channel) has been proposed [33]. The major problems associated with using color in SL scanning are crosstalk between color channels and chromatic aberration. The partial color calibration must be performed to achieve the accuracy prior to every imaging. These problems limit the applicability of such methods. In discrete coded patterns like pseudo-random arrays [35] and De Bruijn sequence [36], the size of the codeword governs the density of the measured object surface and in most cases, the density of the 3D point cloud is not sufficient to generate good quality 3D models. Additionally, complex decoding algorithms are required in most cases of single shot SL methods [37,38]. In a recent survey, Van der Jeught et al. mentioned some other limitations of acquiring 3D information from single shot SL patterns such as extensive digital signal processing and vulnerability to contrast variations [39].

Despite recent efforts to get the 3D data of patients using fast 3D acquisition techniques, more research is needed to find new methods of 3D acquisition that are completely robust to the motion. This paper presents a single shot 3D sensing system that is capable of acquiring good quality 3D models of human skin surfaces and can be used for 3D visualization and measurements in the clinical applications. The proposed system is implemented using the principles of stereophotogrammetry and laser speckle projection. In conventional laser speckle based 3D reconstruction approaches, a number of patterns is generated by using an acousto-optical deflector [27,28] and 3D coordinates are calculated by establishing the correspondence between the images using image correlation technique. An excessive total is preferred to achieve the maximum accuracy. In contrast, our system employs a feature tracking algorithm to establish the stereo correspondence instead of region based matching and require only one stereo pair.

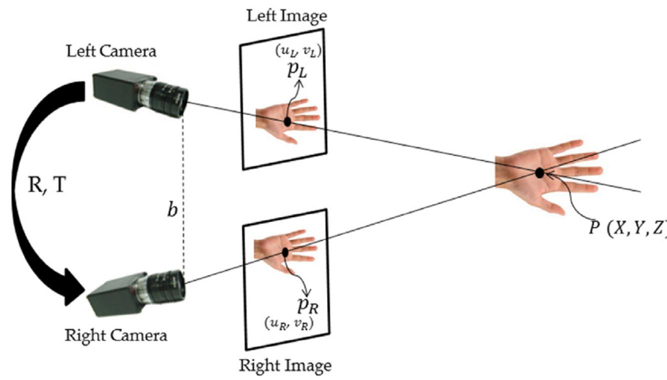

Fig. 1. A basic stereo camera setup and 3D reconstruction principle.

2. Preliminaries and principles

2.1. Stereophotogrammetry

Stereophotogrammetry is an established 3D measurement technique that uses two images of the scene taken from different viewpoints. In practice, a stereo vision system is employed for image acquisition in stereo-photometric systems. Fig. 1 shows a basic stereo vision system composed of two cameras that are displaced horizontally from each other by a distance b called the baseline of the system. The images captured by the left and right cameras are considered as one stereo pair. To understand the working principle of stereophotogrammetry, consider a point P in the 3D world coordinate system imaged in both images of the stereo pair. The point P is identified in the left and the right camera images as p_L and p_R respectively. The perspective projections of P in the 2D image plane of the left and the right camera are (u_L, v_L) and (u_R, v_R) respectively. Assuming the pinhole camera model, the 3D coordinates of P can be reconstructed from the projections of P on both image planes using a triangulation method [40], if the rotation R and translation T between the cameras are known.

2.1.1. Correspondence problem

Detection of conjugate pairs in stereo image is known as stereo matching or the correspondence problem. It is a central topic in stereo photogrammetry and triangulation strictly relies on the resolution of correspondence problem. Although it seems simple, stereo correspondence is a very challenging task. The main hurdle when realizing the correspondence is the uniform texture which poses homogenous regions. Homogeneous regions can be problematic because they contain the same characteristics and it becomes ambiguous to determine which points in the left image correspond to its counterpart in the right image. When correspondences are detected where two points in the image coordinates of different cameras do not represent the same point in the 3d world coordinates. The 3d coordinates lie far away from the actual surface when recovered and thus called outliers. These outliers can significantly decrease the accuracy of the 3D measurements.

2.2. Laser speckle projection in stereophotogrammetry

Laser speckle pattern proved as a good solution to the correspondence problem in stereo-photogrammetric systems [27,28,30,41]. The laser speckle pattern carries high information content and provides certain properties to the object surface which are preferred to solve the correspondence problem correctly i.e., non-periodic and isotropic texture [42]. Compared to the use of other projection devices like DLP or array projector, the laser provides the prospect of an overall compact system and the light patterns generated by the laser are spatially more coherent and have higher brightness [43]. Correlation between the left and right images of the stereo pair with laser speckle pattern can be cal-