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A Digital Model for a Structured Light Scanning System

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Abstract

Structured light scanning is gaining more attention in manufacturing metrology, as it greatly reduces measuring time and provides, in many applications, adequate precision by using high-quality cameras and projectors. Knowledge of such a system's working principle can help avoid scanning errors and improve reliability. To simulate the structured light scanning behaviour, a preliminary digital model or virtual structured light scanning system program is proposed in Python, where some principal parameters, like camera intrinsics, lens distortion, and extrinsic cameras-projector coordinates transformation parameters, can be adapted to the actual system configuration. In the proposed virtual scanning system, the virtual projector's illumination of the input (virtual object) point cloud, the virtual camera's image formation, and the 3D reconstruction from the synthetic images are simulated on several geometric examples. The reconstructed 3D geometries show high similarities to the input geometries' ground truth. Future work should improve surface light reflection model and introduce error models to faithfully simulate an actual structured light scanning.

Structured light scanning, virtual simulator, manufacturing metrology, 3D reconstruction.

1. Introduction

Stereo vision systems can be classified into passive or active vision systems [1-3]. The "active'', structured light stereo vision is used more in manufacturing metrology, providing higher accuracy than the passive one [4]. Adequate knowledge of such a system's working principle helps identify scanning errors and optimize scanning procedures. A configurable virtual system contributes to a comprehensive understanding of its working procedure. Pinhole camera simulator is available in Open3D [5] and Unity [6], but the structured light projection simulator and the processor of 3D reconstruction from synthetic images are not seen to the author's knowledge. Hence, we proposed a virtual structured light scanning system composed of camera image formation and structured light projection simulator, as well as a 3D reconstruction processor.

The paper presents in the following order: Section 2 shows the methodology of virtual system construction; Section 3 shows several simulation results on different geometric point clouds inputs; Section 4 discusses the results and suggests future works.

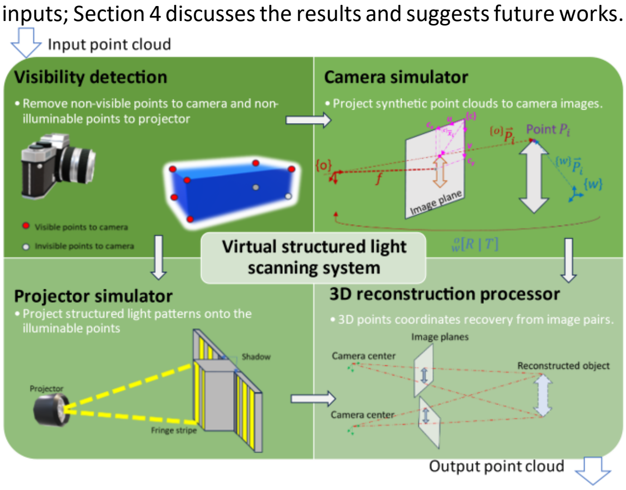

Figure 1: Virtual system structure. The input is virtual points in world frame; the output is reconstructed points in left-camera frame.

2. Methodology

The digital model is composed of four main sections, shown in Figure 1, with two camera simulators and one projector simulator. It can conduct 3D reconstruction from the stereo cameras as well as from one camera and one projector (left camera as an example). Several assumptions are made to reduce the computer's simulation and processing time, including: a) only radial distortions compose the main lens distortion; b) the skew coefficient in the camera intrinsic matrix is considered zero; c) the Lambertian model simulates the diffuse reflection model; d) no ambient environmental factors (e.g. light and temperature) affect the scanning results. Eq. (1) simulates the pinhole camera model. ${}^{\{w\}}\vec{\boldsymbol{P}}_{\boldsymbol{i}}$ and ${}^{\{c\}}\vec{\boldsymbol{x}}_{\boldsymbol{i}}$ are the world frame homogenous 3D point vector and camera image pixel frame homogenous 2D coordinates vector; ${}^{o}_{w}[\boldsymbol{R} \mid \boldsymbol{T}]_{3\times4}$ is the extrinsic transformation matrix from the world frame to the camera optical center frame; s is a scaling factor; $\boldsymbol{K}$ is the camera intrinsic matrix as in Eq.(2) . A quadratic model simulates the lens radial distortion, and a complete model can be found as in [7, 8]. The projector is constructed based on an inverse camera model. Structured light fringe patterns are chosen based on [9] and illuminates the front points to the viewpoint identified from [10] using Open3D library [5]. 3D reconstructed points are recovered from synthetic images from the camera simulator.

$$s\,{}^{\{c\}}\vec{\boldsymbol{x}}_{\boldsymbol{i}} = \boldsymbol{K}_{3\times3}\,{}^{o}_{w}[\boldsymbol{R} \mid \boldsymbol{T}]_{3\times4}\,{}^{\{w\}}\vec{\boldsymbol{P}}_{\boldsymbol{i}} \tag{1}$$

$$\boldsymbol{K} = \begin{bmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

3. Virtual scanning results

Figure 2 shows the reconstructed 3D point clouds (blue) from synthetic images generated by the camera simulator compared to the input ground truth point clouds (red) on some surface geometries. Reconstruction results are plotted by the code in Open3D library [5]. The alignments between point clouds are conducted using methods in [11] with an initial global registration followed by a local refinement. Figure 2 shows that: a) the reconstructions by stereo-cameras have lower inlier RMSE than the by camera(left)-projector; b) surfaces in the shadow cannot be reconstructed (the second row in Figure 2) since no corresponding features can be matched between cameras and projector; c) reconstructed error-points can appear in the surface discontinuity (the third row in Figure 2). A more detailed comparison of post-alignment between reconstructed point clouds and input point clouds has been conducted using CloudCompare software [12] in Figure 3 for one example in Figure 2. The reconstruction using stereo cameras has more aligned points than using camera(left)-projector. The ratio of Cloud-to-Cloud (C2C) distance outlier points (> 0.25 mm) to inlier points (≤ 0.25 mm) is lower using reconstruction from stereo cameras than using camera(left)-projector (186/95560 to 626/4526). The spread of C2C distance inliers in the reconstructed 3D point clouds using stereo cameras is narrower than using camera(left)-projector seen from the color bar in Figure 3.

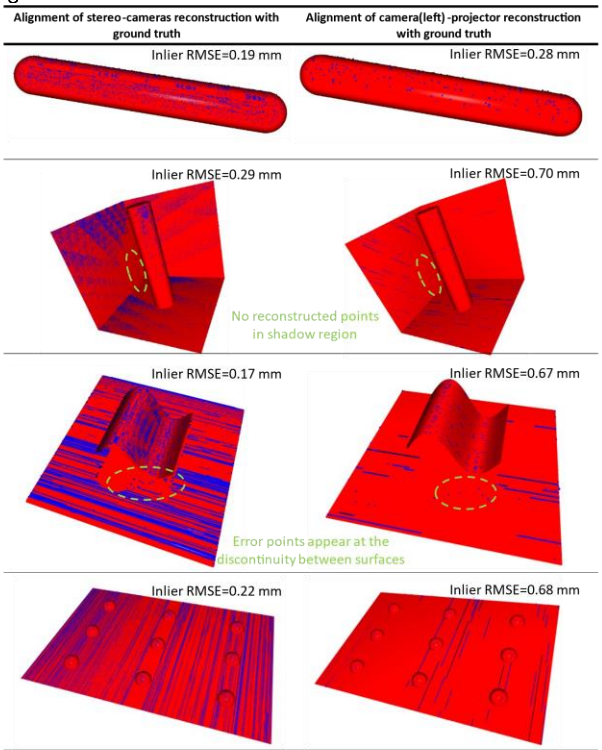

Figure 2: Alignment of the blue reconstructed 3D point clouds to the red system's input point clouds (ground truth).

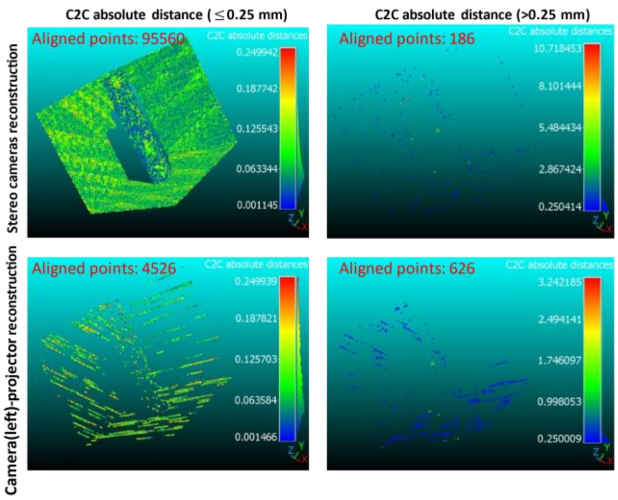

Figure 3: C2C absolute distance deviation maps of reconstructured 3D point clouds post-alignment to the input point clouds.

4. Discussion and future work

A preliminary version of a digital model of a virtual structured light scanning system is proposed, with its potential to produce a digital shadow of a particular system. It uses open-source libraries to simulate a detailed structured light scanning procedure.

However, some aspects of the proposed virtual system have not been addressed yet, e.g., the temporal-computational cost and a comprehensive reflection model, which could be improved using Tensor calculation in future work.

The potential outcomes of this work are: it can help understand the overall scanning procedure in a structured light scanning system, including the camera image formation, structured light illumination, structured light encoding and decoding, and 3D reconstruction from images using photogrammetry; furthermore, it could serve as a virtual counterpart (digital shadow) of a real structured light scanning system to identify the errors and uncertainty in the scanning procedure if the real scanning results are compared to its virtual scanning with the same system configuration.

Future works can focus on the validation of the proposed virtual scanning system's capability to simulate the actual industrial structured light scanning, the tuning of the system parameters on the scanning procedure, the improvement of mathematical models to obtain better simulation results, and the identification of scanning uncertainties sources and the prediction of the scanning errors and uncertainties.

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