Single camera photogrammetry utilizing non-DMD/LCoS based projection systems

Eugene Wong*, Stefan Heist**, Christian Bräuer-Burchardt**, Holger Babovsky*, Richard Kowarschik*

*Institute of Applied Optics, Friedrich-Schiller-Universität Jena, Germany
**Fraunhofer IOF, Jena, Germany

mailto:eugene.wong@uni-jena.de

A method to calibrate unconventional projectors that do not rely on DMD or LCoS projection chips is proposed. The proposed calibration method re-enables single camera photogrammetry in non-fringe projection systems where stereo-camera setups used to be required to obtain 3-D surface measurements.

1 Introduction

Triangulation based optical photogrammetry devices for 3-D surface measurement relying on active illumination methods, such as fringe projection metrology, typically utilize Digital Mirror Device (DMD) or Liquid Crystal on Silicon (LCoS) based projection systems. Measurement performance of these metrology devices is reliant on accurate geometric calibration of the camera and projector. Geometric camera calibration is typically achieved using the Zhang method [1] under the assumption that the camera operates under perspective projection. DMD or LCoS based projectors can be considered as operating under the same perspective projection assumption, but in reverse [2]. As a result, numerous studies have been done geometrically calibrating DMD/LCoS projectors using the same parameterizations such as objective focal length, pixel skewness, and principal point of the projection chip.

With the need for high-speed 3-D measurements comes the need for high-speed projection systems. However, typical off-the-shelf DMD/LCoS projectors have frame rates of ~100 Hz. High projector frame rates are required as ~300 3-D measurements are needed to measure fast dynamic scenes [3]. Recently developed unconventional projectors have been able to achieve such projection speeds but are completely unreliant on chip-based technologies [4–6].

The purpose of geometric calibration is to model the directionality of incoming light rays to the camera image sensor. In the same way, geometric calibration of DMD/LCoS projectors models the directionality of outgoing rays. In triangulation based systems, the 3-D coordinates of a desired object under test requires one to solve the correspondence problem. In the stereo camera case, the projection of the object point in both camera image sensors needs to be determined. Triangulation is then performed between the incident light rays in each camera. For the single camera case, a similar process occurs where the projected projector pixel must be found in the camera image sensor. However, for unconventional non-chip based projectors, parameters under the perspective projection assumption do not exist and the directional ray behavior cannot be conventionally modelled. As a result, 3-D measurement systems employing these unconventional projectors need to utilize a stereo-camera setup. If a method was able to calibrate these unconventional projectors, a single camera configuration can be restored, thus reducing cost, form factor, and weight of such a metrology device.

2 Non-DMD/LCoS projector calibration

The proposed solution is to directly sample the projected illumination frustum. Direct sampling would be particularly advantageous for high-speed array projectors [6] where illumination originates from multiple apertures and each aperture image is generated through micro-clustered lithographically etched patterned glass. Direct sampling is performed by incrementally scanning a white reference plane through the measurement volume. At each plane increment, the camera images the pattern that is projected on the plane. For the array projector device [6], a sequence of six distinct aperiodic sinusoidal fringe patterns is projected to avoid additional phase unwrapping steps normally required in traditional fringe projection. Thus, for each plane increment, six images are taken. As a result, the intersection of a frustum depth slice with a light ray incident on the camera image sensor holds a temporal sequence of gray-value intensities as seen in Fig. 1.

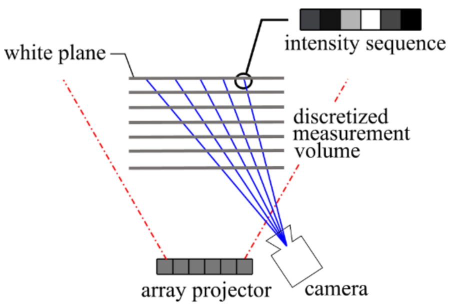

Fig. 1 *Sampling of illumination frustum.*

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With this sampling of the measurement volume, a test object that was illuminated by the array projector and synchronously imaged in the measurement volume would therefore have its surface discretized, with each surface point having a certain depth.

3 Three-dimensional reconstruction

To three-dimensionally reconstruct an object with the proposed method, again the correspondence problem arises. But instead, for each object point's projection onto the camera image sensor, the corresponding depth slice must be found. Correspondence is determined using the normalized cross-correlation between the gray-value intensity sequence of a camera pixel and each depth slice. For each camera pixel of the object image, a search is performed along its incident light ray to find which depth slice it intersects that maximizes the cross-correlation coefficient. Since a surface point can fall in between plane increments, gray-value intensities between depth slices are cubically interpolated.

4 Setup and preliminary results

The measurement setup was configured such that the array projector was placed 100 mm away from the camera along a common baseline. The camera was an IDT NX4-S3 with an objective focal length of 35.0 mm, a quadratic pixel pitch of 13.68 µm, and a resolution of 1024×1024 px imaging in 10-bit grayscale mode. The measurement volume was defined to be ~400 mm × 400 mm × 200 mm (H×W×D) starting 800 mm away from the baseline. A white scattering plane of 400 mm × 400 mm size was manually incremented in steps of 10 mm to sample the illuminating frustum. The test plane was placed approximately perpendicular to the projection direction. Cubic interpolation to obtain a fine estimate of object point corresponding depth was performed in interpolating steps of 0.01 mm.

The world coordinate system, and thus all 3-D measurement coordinates, are made with respect to the camera pinhole. Each corresponding depth slice is converted by determining its rotational pose with respect to the camera coordinate system through solving the perspective-*n*-point problem and by knowing the translational distance to the camera-projector baseline.

A white scattering test object in the shape of a mouse was measured as seen in Fig. 2a. In Fig. 2b, the resulting point cloud for a cross-correlation threshold of 0.9 is shown. Points with lower cross-correlation coefficient are filtered as the found corresponding depth is considered to be untrustworthy. The reason for gaps as well as outlying points in the reconstruction is the large sampling of plane increments throughout the measurement volume.

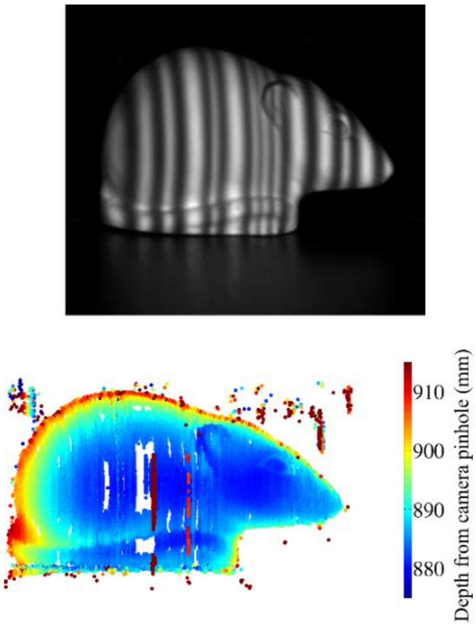

***Fig. 2 (a)** Image of test object in shape of mouse illuminated by aperiodic fringes. **(b)** Resulting point cloud using proposed method.*

5 Conclusion and future work

A method to calibrate unconventional non-DMD/LCoS based projection systems has been shown. With the proposed calibration method that directly samples the illumination frustum, preliminary results show that it is possible to perform 3-D reconstructions. Future work involves optimizing measurement performance through finer sampling of the frustum, improved projected pattern design, and determining optimal setup configuration.

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