INVERSE TRIANGULATION WITH SPATIOTEMPORAL CORRELATION USING A VARIABLE PSEUDORANDOM PATTERN PROJECTOR FOR 3D STEREO MEASUREMENT

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Abstract: In this paper, we propose an innovative 3D reconstruction approach based on stereo vision that combines inverse triangulation with a spatiotemporal correlation algorithm. The inverse triangulation technique enables the correspondence search to be performed systematically in the object space, using a structured 3D grid centered on each point of interest (X, Y, Z). These 3D points are projected onto the image planes, and subpixel-interpolated intensities are extracted from a sequence of temporal images to compute the correlation values. For each (X, Y) tuple, the Z value is determined by the correlation peak. The images capture a pseudo-random laser pattern that changes over time. The proposed approach is intended for future applications in the underwater inspection of offshore structures in the oil and gas industry.

Keywords: Inverse triangulation, Spatiotemporal correlation, active stereo, random pattern laser projection.

1. INTRODUCTION

To support the reconstruction process, active stereo vision techniques typically rely on the projection of structured light patterns [1]. These techniques aim to enrich the scene with additional texture for point correspondence between images, enabling measurements on low-texture surfaces or under unfavourable lighting conditions. Among such techniques, fringe projection combined with phase-shifting algorithms can be highlighted [2], as well as color-coded fringe patterns [3], in which the structured-light stereo approach is proposed to recover dynamic shapes with reduced occlusion and extended viewing range. Another strategy involves the projection of random patterns generated from coherent light, such as laser illumination forming a granular random pattern of bright and dark regions, known as speckle, as demonstrated in [4] and [5], which validate the robustness of single-shot 3D measurement techniques in dynamic scene analysis. In [6], a comparison between variable laser speckle projection and LED array projection using temporal correlation on the accuracy of 3D reconstruction is investigated. As show in [7], the influence of different speckle projection patterns on the accuracy of 3D reconstruction in underwater conditions was investigated. In [8], a pseudorandom-grid structured-light pattern is projected using a DOE, and 3D reconstruction is achieved by triangulating grid-points identified by a CNN. To the best of our knowledge, no previous work uses the inverse triangulation with spatiotemporal correlation.

In this paper, unlike conventional stereo matching which relies on matching image-space windows [9], the proposed approach performs correspondence search using three-dimensional regions (3D patches) defined in object-space. The proposed innovation uses inverse triangulation [10], and spatiotemporal correlation with variable pseudorandom pattern projection. This approach enables an object space organization of the point cloud with range and resolution defined by the user. This algorithm was successfully applied in fringe projection and temporal correlation [10][11], but in this work is applied for the first time in spatiotemporal correlation using a laser pseudorandom pattern projector.

2. METHODS AND PROCEDURES

The proposed active stereo vision measurement system uses a pair of 2048×2048 resolution cameras with a baseline of 320 mm and stand-off of 1.5 m, with Xenon Topaz $2.0/25$ mm lenses and band-pass filters at (465 ± 70) nm. The structured light projector uses a blue laser with wavelength of 450 nm, 100 mW and a diffractive element to project a $30° \times 30°$ divergent $40{,}000$ dots pseudorandom matrix, integrated to a pair of counter-rotating wedge prisms to control the displacement of the pattern in object space. The acquisition of T images is hardware synchronized with the angular displacement of the prism pair. Figure 1 shows (A) the test bench, (B) the projection onto spheres and (C) a diagram to illustrate the developed laser projector.

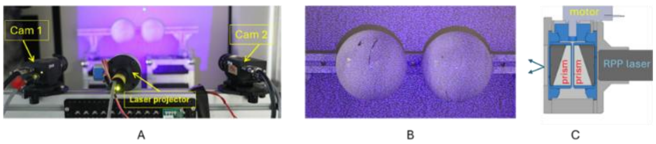

Figure 1. (A) Test bench, (B) projected pattern on spheres and (C) laser module cross section with the counter-rotating wedge prisms and step motor.

3D reconstruction begins with the definition of a regular 3D point grid on object space, with a defined step size along the X, Y, and Z directions. For each Z in the correspondence search process, a 3D rectangular patch composed with the coordinate of interest at center and its $N \times N$ neighbors are mathematically projected in both images. The intensities of the correspondent subpixel positions of the projected points are interpolated over T images, resulting in intensity vectors of length $N \times N \times T$ used to compute the correlation value via Zero-mean Normalized Cross-Correlation (ZNCC) [9]. This process is repeated for each (X, Y, Z) point within the measurement volume, and for each (X, Y) pair, the Z coordinate is defined by the highest correlation value along the Z axis. The use of spatiotemporal correlation aims to reduce the number of required images while also minimizing the size of the 3D patch in object space, ensuring that the resulting vector is still sufficiently large for accurate correlation. A diagram of the inverse triangulation for the spatiotemporal correlation can be seen in Figure 2.

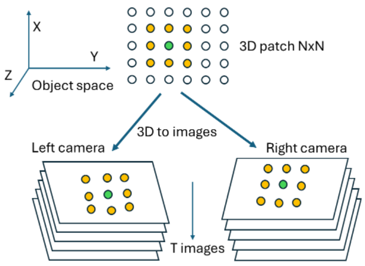

Figure 2. Inverse triangulation for 3D point projection onto images and ZNCC correspondence.

The evaluation methodology uses acquisitions of different calibrated geometries: a planar surface, spheres, and a pipe-like part. The first evaluation determines the minimum number of motor steps required to generate sufficient displacement of the projected pattern by analyzing the mean absolute deviation (MAD) of regions across image sequences. Once the minimum number of steps was defined, all subsequent acquisitions were performed using this value and 0.5 mm step size in the 3D grid. Acquisitions with many images (i.e., 20) were used to determine the optimal size of the 3D patch ($N \times N$) and the number T of temporal images, aiming to balance the reduction of $N \times N \times T$ with the quality of the plane measurement. The measurements of the spheres and the pipe were performed using the determined values to access the resulting measurement quality.

3. RESULTS AND DISCUSSION

A 10 motor steps showed the highest pattern variability while minimizing the total required displacement, corresponding to a 1.8° rotation of the prisms. The standard deviation (0.28 mm) of distances between a fitted plane and the measured points determines the optimal patch size ($N \times N \times T$) as ($3 \times 3 \times 5$).

The analysis of the results for the calibrated spherical artefacts resulted in a standard deviation of 0.29 mm and a scaling deviation of +0.53 %. In addition to the shape analysis, the reconstruction of the surface of a pre-calibrated cylindrical specimen was also assessed, resulting in a standard deviation of 0.4 mm.

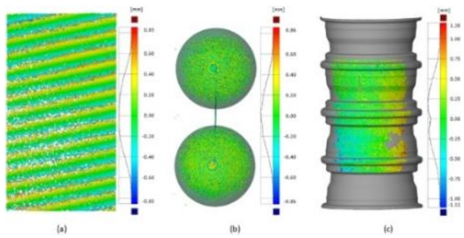

Figure 3. Main results (a) plane fit, (b) spheres fit and (c) cylindrical geometry.

4. CONCLUSIONS

The proposed space-time correlation technique with inverse triangulation proved to be effective for 3D reconstruction using active stereo vision under pseudo-random structured light projection. The movement of the pseudo-random pattern ensured sufficient spatial texture variation across the image sequence, which was fundamental for the reliability of the correlation. However, the evaluation was performed only with the projected pattern kept static. The method demonstrated good metrological performance in terms of scaling and surface deviations when tested on the three calibrated geometric standards. Although these results are compatible with the demands of the target application, future efforts are being made to improve the grid refinement while avoiding higher computational cost that strongly depends on the step size, and a faster projection rate.

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