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# Imaging solutions for harsh environments

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**Abstract**

This paper presents a quantitative assessment of uncertainty for the stereo calibration at different cameras angle and control object 3D reconstruction. Stereo-photogrammetry with high resolution commercially available digital cameras is applied to deliver a 3D data from a pair of 2D images. The main goal of the project is the reconstruction of the 3D model from the images obtained underwater in a high vibration manufacturing environment. The crucial step in obtaining high accuracy 3D data is stereo-rig calibration. Robust camera calibration is a critical step in 3D reconstructions in order to extract precise quantitative measurements from 2D images. Two AV 6600 monochrome 29 Megapixels GigE cameras were calibrated at four different angles to ensure that the angle of the stereo rig and variation in image contrast would not influence significantly the final results. All the images were undertaken in the high vibration manufacturing environment. It was shown that calibration of the cameras set at the angle of 15$^o$ reduces significantly 3D reconstruction accuracy. However, it does not influence reprojection error, which is less than 0.5 pixels.

## 1. Introduction

Stereo-photogrammetry for reconstruction of three dimensional (3D) geometry using pairs of two dimensional (2D) images is a non-contact, non-destructive technique used for quantitative measurement of surface geometry from optical digital images [1]. The fundamental principle used to determine 3D geometry and provide depth from 2D images is triangulation [2]. Stereoscopically positioned cameras are used to capture object of interest and the triangulation process determines surface 3D coordinates which can be used to determine its geometry or inspect its quality [3]. It is a passive technique which requires a proper lighting to achieve required contrast. Imaging smooth metallic and reflective objects require high contrast pattern to provide correspondence points for triangulation. Increasing the exposure time and decreasing frame rate may help when imaging the static objects and help to keep a sufficient depth of field (DOF). Otherwise the examined object needs to be illuminated at the proper angle to avoid reflection. Moreover, the lens aperture can be increased but it may result in shallow DOF.

Stereo photogrammetry has been shown to give reliable information about object surface properties [4]. If vibrations occur in the environment where the images are taken, the two independent cameras need to be synchronised to take simultaneous images.

The goal of this project is to image metallic components in harsh environments. However, it is a very complex process and preliminary the uncertainty of the methodology need to be understood. The first steps of the application is AV 6600 monochrome 29 Megapixel (MP) GigE cameras synchronization, imaging in the real time and understanding of the calibration errors in a vibrating manufacturing environment using passive methodologies.

Cameras in a stereo rig need to be placed at a certain angle in order to image the object. The image needs to be sharp and, ideally, no reflection should occur. To ensure that the geometric layout of the cameras to the object and angle of the stereo rig would not influence final results, calibration and

reconstruction accuracy was studied for different cameras angle setups.

## 2. Material and Method

The AV 6600 monochrome 29 MP GigE cameras were synchronized in C-sharp Monochrome sensors were chosen since they are more suitable than colour ones for metrology applications or 3D modelling when subpixel accuracy is needed. They are more accurate because each pixel in the sensor corresponds to a real pixel that can be measured.

The analysis of experimental camera calibration was undertaken to check differences in results for different angle setups between two cameras for the large length scale object. It was important to evaluate how much the angle between cameras influenced reconstruction accuracy.

### 2.1. Cameras calibration

The calibration is a prerequisite in 3D reconstruction in order to extract precise quantitative measurements from 2D images [5]. It was carried out to compute cameras intrinsic and extrinsic parameters then used in the 3D reconstruction. A Matlab Bouguet Toolbox [6] for camera calibration was used in this study. A flat calibration checkerboard grid pattern (390 x 330 mm, 13 grids in x and 11 in y direction, each square, internal grid is 30 x 30 mm) was imaged in a number of orientations in order to calibrate each camera. It was performed for the cameras set at four different angles.
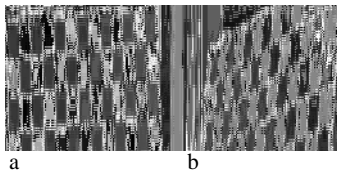


a                    b

Fig. 1 – View of the calibration grid imaged with left (a) and right (b) camera.

### 2.2. Stereo camera rig separation angle

The analysis of experimental camera calibration was undertaken to check differences in results for different angles between two cameras. It was important to examine how much the angle between the cameras influenced reconstruction accuracy. A stereo rig was used to capture checkerboard grid patterns in number of orientations for calibration and 3D reconstruction accuracy assessment. The calibration protocol was repeated using a stereo rig with camera separation angle of $15^{o}$ $30^{o}$, $60^{o}$ and $90^{o}$, as seen in Figure 2.
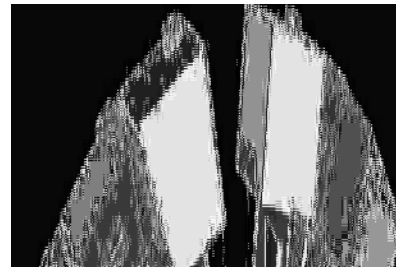


Fig. 2- Angle separation for cameras calibration.

### 2.3. Reconstruction

The calibration images were used to check the reconstruction accuracy. The distance between six squares in the grid was measured for three translations to control the variation. Reconstruction was achieved by triangulation software used in the first author's previous study in Matlab [7]. It required selection of the same point in the right and left 2D images. An epipolar line [1] from the focal point of one camera to the point of the left image assisted with point selection on the right image. 3D coordinates obtained from the triangulation were used for the measurements.

### 2.4. Vibration

It is important to ensure that there is no mechanical vibration induced by any other device for the benefit of the measurement accuracy. For such a purpose vibration in the robotic metrology cell, where the calibration routine was carried out, was monitored by the use of KEYENCE LKG5000 series high resolution and high speed laser displacement sensor. The laser was pointing at the camera, which was mounted on a stationary tripod. For increased rigidity the laser displacement sensor was attached to the robotic arm while the robot was stationary. Then, the vibration on the camera was measured for 1000 seconds, which was long enough to observe long term vibration stability of the camera. The measurement frequency was selected as 2 kHz.
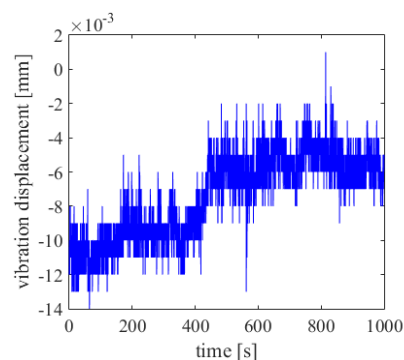


Fig. 3 – Vibration displacement vs time.

## 3. Results

The cameras were synchronized to less than a millisecond. This delay was not significant in imaging of the rigid body translation.

The results of the stereo calibration for 90° angle setup are presented in Figure 4. It provides the extrinsic parameters describing the grid orientations in relation to both cameras. Precise calibration results in accurate representation of the physical stereo system. There is a good agreement of 97.5% (± 0.5%) for the extrinsic parameters of all angle  setups within the manual measurements.
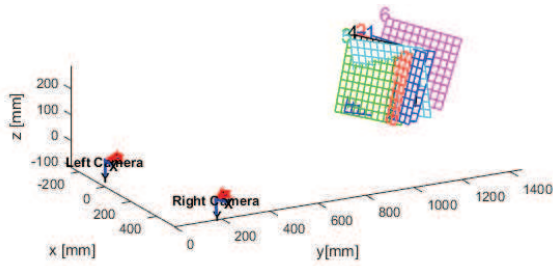
Fig. 4 - Extrinsic parameters presented in 3D plot for stereo camera calibration.
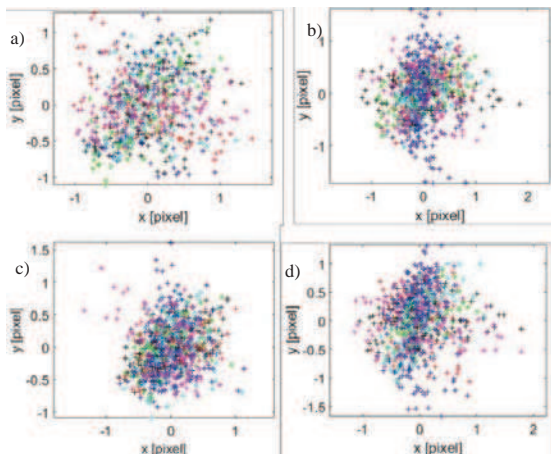
Fig. 5 - Pixel (reprojection) errors for a left camera calibration for three separations angles: a) 15°,  30°, 60° and 90°.

The pixel reprojection errors for the left camera calibrations at four different angles are presented in Figure 5 and in table 1.

Table 1- The mean of the reprojection errors (in pixels) for the left and right camera.

| | Reprojection error | | | |
|---|---|---|---|---|
| | Left camera | | Right camera | |
| degree | x | y | x | y |
| 15 | 0.46 | 0.45 | 0.48 | 0.43 |
| 30 | 0.35 | 0.39 | 0.46 | 0.46 |
| 60 | 0.40 | 0.49 | 0.55 | 0.47 |
| 90 | 0.40 | 0.48 | 0.51 | 0.49 |

3D reconstruction accuracy assessment results are shown in table 2.

Table 2- The mean of the reprojection errors (in pixels) for the left and right camera for the 30mm internal grid separation.

| | % reconstruction error | | |
|---|---|---|---|
| | translation | | |
| degree | max | average | min |
| **15** | 5 | 2 | 0.3 |
| **30** | 2.3 | 0.8 | 0.03 |
| **60** | 2.3 | 1.4 | 0.1 |
| **90** | 2.6 | 1.6 | 0.3 |

The setup with cameras separation of 15° resulted in  high error.

The measured vibration data (presented in Figure 3 in section 2.4), where it can be seen that the amplitude of measured vibration is around 1 micron, and the drift is 5 microns in 1000 seconds. Based on this observation it can be concluded that the camera mounted on a base is isolated and free of any vibrations.

## 4. Conclusion

This paper presents calibration accuracy assessment  of industrial AV 6600 monochrome 29 MP GigE cameras  which will be applied for the objects geometry examination in the harsh and wet environments.

Calibration grid imaged with the cameras set at different angles and grid positioned at various orientations caused the significant change in contrast and lighting. This  has influenced the results accuracy. Despite the change in the image intensity and highly vibrating environment,  the Bouguet Calibration Toolbox showed that the grid corners extraction results in reprojection error of less than 0.5 pixel. It is a very promising result for such a high resolution cameras. However, the 3D reconstruction results showed that the  best outputs are derived for the angle of 30 and 60 degrees between the cameras. The error is significantly high for the angle of 15 degrees.

It was showed that the light intensity has a significant impact on  the final results. Future work will focus on  an additional

light implementation. This will be projected on the object surface to increase the image contrast. It is believed that this will improve the quality of the data obtained in the harsh environment. Additionally, the cameras will be fixed and operated via robot to mimic human errors. The repeatability test will be undertaken for the robust output.

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