Development of a Photogrammetric 3D Measurement System for Small Objects using Raspberry Pi Cameras as low-cost Sensors

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Abstract

Photogrammetry enables the creation of 3D models using relatively simple technology. However, the time required to capture the images is often high, meaning that this method is not suitable for capturing numerous objects, for example when digitizing museum collections. Systems based on several permanently installed cameras generally use high-quality cameras. However, this results in a significant increase in hardware costs.

This thesis investigates the solution of using several low-cost cameras mounted on a fixed frame. The core of this investigation is the construction of a photogrammetric measurement system for small objects, which consists of Raspberry Pi cameras. The programming of an interface to synchronize the cameras and the development of a way to calibrate the cameras are planned as part of this. The next step will be to check the accuracy of the recording. Ideally, the end result should also enable a photogrammetric layman to generate 3D models in acceptable resolution and quality quickly and without a long familiarization period.

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The digitization of cultural objects in museums presents a dual opportunity: firstly, to preserve the objects and collections themselves, and secondly, to make them available to the general public as 3D models in virtual exhibitions on the Internet. Cultural artefacts of significance can be recorded using laser scanners, 3D handheld scanners or photogrammetry employing the structure-from-motion method. In order to efficiently record and model the considerable number of culturally significant objects, automated recording systems and automated evaluation processes are required.

As part of a project at HafenCity University, a photogrammetric measurement system for small objects (up to $40\,\mathrm{cm}$ in diameter) was developed. The system comprises 24 low-cost Raspberry Pi cameras (Fig. 1). This entailed an investigation into the number of cameras required, the arrangement of the cameras, the technical recording parameters (e.g. camera constant, distortion, etc.) and the synchronization of the cameras. Additionally, a procedure for calibrating the cameras was developed. The images are transferred to the analysis software automatically, with the generation of 3D point clouds and textured 3D models being carried out in the commercial software package Agisoft Metashape. The photogrammetric images are scaled using calibrated control points (ring coded targets and ArUco marker) and various scales in object space, which can be automatically and clearly measured in the image data.

The Raspberry Pi Camera Module 3 was employed as the camera ($c = 4.74\,\mathrm{mm}$), which is operated by a Raspberry Pi Zero W. In comparison to other low-cost cameras, such as webcams or the ESP32 CAM, the cameras have a high geometric resolution of 12 megapixels (4608×2592 pixels) and relatively large pixels of $1.4\,\mu\mathrm{m}$ (Raspberry Pi Foundation, 2023), which, subjectively, results in excellent image quality. Further camera parameters: focus is motorized from $10\,\mathrm{cm}$ to ∞, field-of-view is $66^\circ \times 41^\circ$ and the f-stop is F1.8. The number of cameras for the prototype was defined in conjunction with the type of frame. This was achieved by modelling the frame setup and its cameras in 3D visualization software Blender, and rendering the individual images of the potential camera positions. The images were then imported into Agisoft Metashape, where a 3D model was calculated. This process entailed assessing the feasibility of the calculation and evaluating the extent of coverage afforded to the test object.

In order to produce the best possible images, it is essential that the object is sufficiently and evenly illuminated. Individually controllable LED light strips were attached to the aluminium rods as a light source, allowing individual areas to be switched off, for example, in order to reduce glare. Furthermore, different light colours can be set in order to enable status messages or to influence the lighting of the object. The system is controlled via a Raspberry Pi 4, which also controls the cameras. To reduce disturbing light effects from outside, a fabric cover was pulled over the aluminium frame (Fig. 1 left). The total cost of the materials for the system setup, including the power supply, was $2000\,\mathrm{EUR}$, which therefore could be defined as a low-cost photogrammetric system. The software for controlling the measuring system was mainly written in Python. A number of preliminary studies were carried out before and during the construction of the actual measurement system. These were used to check the feasibility of the system and to determine and optimize the necessary steps. The main focus was on determining the camera constants and the distortion of the cameras using OpenCV. In order to improve the depth of field of the images focus stacking was also investigated. After completing the design and construction of the prototype, various tests were carried out to check the accuracy of the system. The recordings with the cameras are triggered via the software button in the desktop software, the web interface or via a button. The exposures of the cameras are synchronized and the images are then generated. The Raspberry Pi Zero W sends the images and the detected and measured ArUco markers to the Raspberry Pi 4, which calculates the camera positions and stores the data. The desktop software then downloads the data and transfers it to the SfM software Agisoft Metashape, which generates a point cloud and the 3D model of the captured object.

As test objects a small Moai figure (height $14\,\mathrm{cm}$) as illustrated in Fig. 2, an Einstein bust (height $15\,\mathrm{cm}$) and the test body Testy (height $38\,\mathrm{cm}$) was used, which has already been used for accuracy tests of 3D handheld scanners (Kersten et al., 2016). These three test bodies were scanned using the high-precision structure light system Zeiss GOM ATOS 5 (system precision 10-30 microns) as reference.

The triangulated reference data was compared with the point cloud from the low-cost measurement system using the CloudCompare software. The tests demonstrated that the utilization of the turntable led to markedly enhanced object coverage and elevated accuracy, attributable to the augmented number of images. The most favourable outcome of the comparison between the point cloud and the reference data was an average deviation of $0.14\,\mathrm{mm}$ mm and a maximum deviation of $1.4\,\mathrm{mm}$, achieved through the utilization of a turntable with four rotations and 32 steps (Fig. 3). The results of the remaining two test bodies will be presented in the paper. The project demonstrated that a photogrammetric measurement system based on Raspberry Pi cameras can be developed as a low-cost system, and that the additional use of a turntable to capture the test object can increase the coverage of the object and the accuracy of the capture.

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