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Spatial calibration of large volume photogrammetry based metrology systems

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ABSTRACT

Photogrammetry systems are used extensively as volumetric measurement tools in a diverse range of applications including gait analysis, robotics and computer generated animation. For precision applications the spatial inaccuracies of these systems are of interest. In this paper, an experimental characterisation of a six camera Vicon T160 photogrammetry system using a high accuracy laser tracker is presented. The study was motivated by empirical observations of the accuracy of the photogrammetry system varying as a function of location within a measurement volume of approximately 100 m^3. Error quantification was implemented through simultaneously tracking a target scanned through a sub-volume (27 m^3) using both systems. The position of the target was measured at each point of a grid in four planes at different heights. In addition, the effect of the use of passive and active calibration artefacts upon system accuracy was investigated. A convex surface was obtained when considering error as a function of position for a fixed height setting confirming the empirical observations when using either calibration artefact. Average errors of 1.48 mm and 3.95 mm were obtained for the active and passive calibration artefacts respectively. However, it was found that through estimating and applying an unknown scale factor relating measurements, the overall accuracy could be improved with average errors reducing to 0.51 mm and 0.59 mm for the active and passive datasets respectively. The precision in the measurements was found to be less than 10 μm for each axis.

1. Introduction

A number of commercially available multi-camera real time photogrammetry systems [1–3], are used extensively in applications such as gait analysis [4], animation in the entertainment industry [5] and increasingly as tracking systems in robotics [6–9]. The technique is attractive due to the associated benefits of fully non-contact sensing, six degree-of-freedom (6 DOF) measurement, high temporal sampling rates (up to kHz frequencies), multiple simultaneous object tracking (up to 1000's) and the potential for high accuracy and precision measurements. The accuracy of such systems is dependent upon numerous variables such as the number and resolution of cameras deployed, the dimensions of the measurement volume, the positional configuration of cameras around the measurement volume and the accuracy of the intrinsic and extrinsic parameters computed from the calibration procedure for each camera.

A detailed review of the instrumental errors associated with all the above aspects was provided by Chiari et al. [10]. To date, detailed accuracy studies have focused upon

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relatively small volumes typical of some biomechanical applications. Due to the small measurement volumes involved it has been possible to obtain relatively high accuracy/precision tracking. In [11], the authors evaluate a Vicon MX system composed of five F40 (4 MP, CMOS) cameras for measurement of bone deformation in a $400 \times 300 \times 300\ mm^3$ volume. Under optimal conditions the absolute error and precision for displacements of 20 μm were 1.2–1.8 μm and 1.5–2.5 μm. In [12], the authors consider the suitability of a two camera Qualisys ProReflex-MCU120 (658×500 pixels, CCD) for measuring micro displacements of teeth. In a field of view of size 68.18×51.14 mm, the accuracy of displacements ranging from 20 to 200 μm, was found to be ±1.17%, ±1.67% and ±1.31% in axis wise terms. The corresponding standard deviations were ±1.7 μm, ±2.3 μm and ±1.9 μm. The authors in [13] present a systematic experiment to determine the static accuracy and precision of a Vicon 460 system composed of five Mcam-60 cameras (1012×987 pixels, CMOS). The experiment was conducted for a $180 \times 180 \times 150\ mm^3$ volume suitable for the capture of small magnitude biomechanical motion. Dense accuracy measurements were obtained by driving a retro-reflective target affixed to an XYZ scanner (15 μm linear encoder accuracy) to 294 positions according to a $7 \times 7 \times 6$ grid with 30 mm uniform spacing. The influence of several variables was considered: camera positioning around the volume; manual versus scanner based dynamic calibration (controlled arbitrary path); error associated with measurements outside the calibrated volume through calibrating a $90 \times 90 \times 75\ mm^3$ sub-volume; marker size and use of lens filtering. Following analysis of the effect of different variable combinations, the optimal set of variables yielded an overall accuracy of 63 ± 5 μm and 15 μm precision. In general it is concluded that major factors in determining overall accuracy include the arrangement of cameras, the marker size (larger markers promoting greater accuracy) and lens filtering to smooth irregular target boundaries. The above studies were confined to small measurement volumes of no more than $0.04\ m^3$, and errors outside the calibration volume were significantly greater as would be expected. These small measurement volumes are at least 3 orders of magnitude smaller than the present authors' interests where our application for photogrammetry tracking relates to automated robotic inspection [8,14]. Our research into accurate spatially correlated non-destructive testing (NDT) measurements uses a combination of both mobile semi-autonomous robots [14] and fixed 6 axis industrial robots [15] to deliver NDT measurements to a variety of test samples. The typical measurement volume exceeds $100\ m^3$ and our applications demand absolute accuracies of significantly less than 1 mm (industrial robot repeatability can routinely attain values of 100s of μm or better over their full working envelope).

Accuracy investigations for larger volumes have typically considered only a small region of the measurement volume [16,17]. In [16], the authors compare the accuracy of several motion capture systems in a gait analysis context. A subject holding a rigid bar with targets affixed 900 mm apart was instructed to traverse a 3 m linear path through the measurement volume (area 10 m × 6 m). Photogrammetry systems composed of between two and six cameras were used to estimate the length of the bar. In this study, the mean absolute errors varied substantially between 0.53 mm and 18.42 mm. In [18] a "principal points indirect estimate – PIE" approach is reported to provide a rapid calibration approach with an error of 0.37 mm RMS over a volume with a diagonal approximately 1.5 m in length. Accuracy studies for larger volumes, on the scale of 100's m^3, typical of robotics applications have not been reported in the literature. This is surprising as many UAV tracking applications [6] are therefore making unwarranted assumptions about overall system accuracy performance.

There exist a number of commercially available photogrammetry systems for non-contact, high accuracy, measurement of large structures [19,20] using retro-reflective/white light targets. These systems can provide sub-millimetre accuracy but operate offline. The use of photogrammetry systems in very large scale environments (on the scale of km) is the domain of target-less systems for obvious practicality reasons. Single and multiple camera based systems are used extensively in robotics applications for vehicle pose estimation and environment modelling [21]. Since the target geometry is not known a priori, such systems offer less accuracy than those using targets. Indeed, systems such as that presented in the paper are often used to verify the accuracy of algorithms used by target-less systems.

This article presents a systematic experimental evaluation of the static positional accuracy and precision of a six camera photogrammetry system providing coverage over a $6.8 \times 3.8 \times 3.8$ m ($98\ m^3$) calibrated volume. The error associated with the positional estimates from this system were considered over a measurement volume of dimension $3.9 \times 3.05 \times 2.3\ m^3$ ($27\ m^3$). A high accuracy and precision laser tracker Leica Absolute Tracker AT901B [22] was employed to provide ground truth measurements of the position of a target scanned in four planes dividing the measurement volume vertical height. With reference to the variables identified in [13], an optimal camera arrangement was adopted such that overlap amongst the camera field of views was maximised thus ensuring at least two cameras were available for triangulation at any point in the volume. Dense accuracy measurements were collected inside the calibrated region using large markers of diameter 38.1 mm. The variable of interest in this article centres upon the choice of calibration artefact used for dynamic calibration. The dynamic calibration procedure requires a calibration artefact with known dimensions to be swept through the volume enclosed by the cameras. From the resultant point cloud the relative pose and optical parameters for each camera are determined. These parameters can have significant impact upon system accuracy as they directly affect how a 3D world point is projected onto a 2D image point. Two datasets were collected using different calibration artefacts. The first employed standard retro-reflecting spheres to reflect IR light projected from the cameras, while the second employed actively modulated light emitting diodes (LEDs) to provide active illumination.

The contributions of this paper are threefold: firstly dense spatial measurements over a large volume