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Review Article

Sensor modelling and camera calibration for close-range photogrammetry

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ABSTRACT

Metric calibration is a critical prerequisite to the application of modern, mostly consumer-grade digital cameras for close-range photogrammetric measurement. This paper reviews aspects of sensor modelling and photogrammetric calibration, with attention being focussed on techniques of automated self-calibration. Following an initial overview of the history and the state of the art, selected topics of current interest within calibration for close-range photogrammetry are addressed. These include sensor modelling, with standard, extended and generic calibration models being summarised, along with non-traditional camera systems. Self-calibration via both targeted planar arrays and targetless scenes amenable to SfM-based exterior orientation are then discussed, after which aspects of calibration and measurement accuracy are covered. Whereas camera self-calibration is largely a mature technology, there is always scope for additional research to enhance the models and processes employed with the many camera systems nowadays utilised in close-range photogrammetry.

1. Introduction

This article provides a review of the state of the art in photogrammetric camera calibration with specific focus upon close-range applications. It also analyses selected recent developments in camera technology, sensor modelling, automated calibration approaches and photogrammetric accuracy aspects. Although fully automatic camera calibration is now a routine procedure for many users of photogrammetry, the calibration issue continues to receive research attention due to the ongoing emergence of new camera systems. These developments in turn open up new practical applications and requirements.

1.1. Background

Analytical camera calibration by means of the self-calibrating bundle adjustment was developed in the early 1970s (Brown, 1971) and became a standard tool in close-range photogrammetry (CRP) systems in the 1980s (Fraser and Brown, 1986; Wester-Ebbinghaus, 1988). As distinct from the characteristics of aerial camera calibration in topographic photogrammetry, those adopted for close-range applications, in particular industrial vision metrology, are characterised by

- High-accuracy requirements in object space, translating to image space precision at the 0.1 pixel level or better.
- Single and multi-sensor imaging configurations with a large variety of different camera and lens types.
- Geometrically irregular imaging networks (e.g. multi-station convergent imaging).
- An absence of control point and camera station constraints.
- Project-specific operational conditions.

Based on the utility and flexibility of self-calibration, a wide variety of cameras ranging from point-and-shoot, to 'bridge' cameras, to DSLRs (digital single-reflex cameras) and to purpose-built metric cameras are nowadays employed across the broad arena of CRP applications. However, it has long been recognised that cameras and lenses of high metric quality provide the best results, due in large part to the fact that they lend themselves to calibration of high metric integrity and stability. Also widely recognised are well-proven rules that apply in self-calibration to the recovery of camera parameters of optimal accuracy and reliability, where

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maximum reliability in this context implies a minimisation of the impact of gross observation errors upon the estimation of calibration parameters. These rules include:

- Adoption of multi-station convergent imaging networks incorporating a diversity of camera roll angles (i.e. mixed landscape and portrait orientations).
- Fixed zoom/focus and aperture settings with no lens change or adjustment during image acquisition, with a preference for unifocal lenses.
- Well-defined object points amenable to high-accuracy image measurement (e.g. targets on a test field, often realized as automation-friendly coded targets, or natural feature points supporting high accuracy image matching).
- Sufficient variation in scale within the imagery to support the reliable recovery of the camera interior orientation (IO) parameters of principal distance and principal point offset (e.g. scale variation provided through the provision of depth variation in the object point array).
- Comprehensive and unsystematic coverage of the available sensor format in order to enhance determination of lens distortion parameters.
- Incorporation of high observational redundancy to enhance the reliability of calibration parameter estimation (automated processes mean that a trivial amount of extra work is involved in measuring 10-, 20- or 50-image networks).
- Adoption of an appropriate and complete camera model within the self-calibrating bundle adjustment, which in turn should incorporate robust outlier detection.

Although the workflow for digital camera self-calibration can be conducted as an on-line or off-line process, it is generally the latter which is employed. Image acquisition and image measurement/-data processing invariably happen at different times and in different locations, though with fully automatic camera calibration the issue of human operator skill level is fortunately no longer a factor influencing results.

1.2. Camera developments

Introduction in the early 1990s of the then called 'still video' digital cameras had a dramatic and positive impact upon CRP, immediately extending the fields of applications and providing the means for full measurement automation in niche areas such as industrial and engineering metrology. The evolution of consumer-grade digital cameras and especially DSLRs afforded a significant acceleration within the processing pipeline in off-line measurement applications. Moreover, subpixel image operators, e.g. centroiding or template matching, provided a new level of image measurement accuracy, to routinely better than the 0.1 pixel level, which corresponds to <1 μm. This in turn led to a new challenge in calibration, namely the question of whether the physical relationship between the camera body, lens and sensor could provide metric stability to the same accuracy level.

Beyond incorporating integrated removable memory, digital cameras provide the option of a direct transfer of image data to a processing unit that can then process the images automatically in real time. The processor can be integrated into the camera body or placed in a separate computing unit, e.g. a connected computer. In both cases, the acquired images can be processed at a certain frame rate, say between 1 Hz and 500 Hz, depending upon the complexity of the scene being imaged, the amount of data and the data interface specifications. This on-line capability has led to a large number of new applications, for instance in industrial process control, medical surgery and robotics. These applications are usually characterised by a set of cameras that are mounted in fixed positions relative to each other, which are generally employed for a given period of time without re-calibration. Consequently, the cameras have to be calibrated in advance, with the calibration remaining stable over a long period of time. An aspect of note here is that the parameters of IO are often calculated independently from the exterior orientation (EO) parameters, thus removing the issue of possible correlations between interior and exterior parameters in the initial bundle adjustment, as will be discussed in later sections of this paper. The question of pre-calibration also arises for those single-camera applications where a suitable imaging network geometry cannot be provided, e.g. for unmanned aerial vehicle (UAV) flights above flat terrain or in very narrow imaging configurations with small intersection angles in object space.

Whereas the foregoing discussion has concentrated on cameras that might well be regarded as 'standard', since these are the most commonly adopted in practical photogrammetry, the development of digital cameras has reached a point where it is nearly impossible to list all available classes, permutations and combinations of cameras and imaging sensors. Among this huge variety of cameras, we find many that have found relevance and application in CRP. Categories include:

- Multi-camera set-ups (e.g. stereo cameras, multi-camera systems).
- High-speed cameras, e.g. with 12,000 fps at 1000 × 1000 pixel resolution.
- Panoramic cameras equipped either with fisheye or spherical lenses, or driven by a scanning unit (linear or circular).
- Zoom lenses, as are commonly integrated into consumer-grade cameras.
- Fisheye lenses.
- Miniaturised cameras (e.g. mobile phones, endoscopes, augmented reality glasses etc.).
- Cameras with mirrors.
- Multispectral and thermal imagers.
- 3D imaging devices (e.g. time-of-flight cameras, light-field cameras).

As long as cameras can be modelled according to the principle of a pinhole camera, with additional parameters to model lens distortion, they can be calibrated via standard photogrammetric means. In cases where either specific accuracy demands require more sophisticated parameter models, changes in IO occur during acquisition of an image series, or the physical imaging model cannot be described by central projection, such as with wider field-of-view fisheye cameras, extended calibration approaches need to be applied.

1.3. Calibration state of the art

The state-of-the-art in classical photogrammetric camera calibration has been addressed by several publications and textbooks, e.g. Fryer (1996), Remondino and Fraser (2006), Fraser (2013), Luhmann et al. (2014). These reports are based upon experience gained over the 25 years that digital cameras have been employed for photogrammetric measurement, and in them specific parameter sets, configurations and analysis techniques for camera calibration are recommended. The reported approaches are also implemented within well-known photogrammetric systems, to provide both a dedicated camera calibration capability and a mechanism for 3D accuracy enhancement via the self-calibrating bundle adjustment.

The task of camera calibration has also been addressed within the large computer vision (CV) community. CV researchers have concentrated on developing easy-to-use and fully automated calibration procedures based primarily on linear approaches with