Monitoring Concepts using Image Assisted Total Stations

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Abstract. Image Assisted Total Stations (IATS) unify the geodetic precision of total stations with the areal coverage of images. One or more cameras integrated in total stations deliver accurately geo-referenced and oriented images, an appropriate calibration provided. In combination with image processing and recognition techniques as well as the polar methods of the base instrument, new measurement approaches can be developed. By using image sequences of subsequent measurement epochs, objects or features can be detected and tracked fully automated. In this article, we present current systems, commercially available as well as research prototypes. Different calibration methods and a general mathematical system description are given as the basis for the further described monitoring concepts. The presented application examples – monitoring of structures and geo-risk areas – prove that IATS are particularly suited for the repetitive or continuous check and control of artificial or natural structures.

Keywords: calibration, geo-monitoring, image assisted total station (IATS), structural monitoring.

1. Introduction

Monitoring in the form of a repetitive or continuous check and control of artificial or natural structures is one of the key tasks in engineering geodesy. It is a process of periodically gathering information on the current state of all aspects of the observed object. The repeating measurement of the same target(s) in particular supports the development and usage of automated systems. For this reason, mostly motorized total stations, digital levels, GNSS or digital photogrammetry in combination with automated analyzing and evaluation methods are used. With the integration of cameras into total stations these different sensor classes are fusing to a single universal instrument [Wunderlich et al. 2014]. Moreover, the high accurate height determination and height transfer with invar leveling staffs were recently implemented into Image Assisted Total Stations [Wagner et al. 2016]. In this article we will present more details on this instrument category, current systems and their mandatory calibration.
Furthermore, the application examples will prove the suitability for monitoring tasks.

2. Image Assisted Total Stations

The first theodolites with integrated cameras – the Kern E2-SE and the Wild TM3000V – were released almost simultaneously in the 1980s. These instruments had been primarily used for close range applications in the industrial metrology, but disappeared after a short time, with the introduction of laser trackers [Wagner et al. 2014b]. In the recent years, the interest of the manufacturers raised again to provide image assisted solutions. Since the beginning of this decade all major manufacturers of total stations have released instruments with at least one integrated camera. These instruments are commonly termed Image Assisted Total Stations (IATS).

Each image taken by the integrated camera – including the live video stream – is absolutely orientated by using the instrument’s station and orientation and its mounting offsets. This means that the exterior orientation is directly known in the world or object coordinate system. Currently, the camera images are only used to ergonomically optimize the standard measurement procedure, e.g. by replacing the view through the telescope and/or to transfer it to the range pole via remote control. Furthermore, the image and video function is used as a support capacity for the standard field survey tasks of a total station. Such functions are, for example, documentation, aiming support or an overlay of the live video stream with measurements, planning data or sketches. Some manufacturers offer additional software which allows a further photogrammetric post-processing. If a scanning function is available at the instrument, additional image based support functions, like a scan area selection, are offered.

Nevertheless, the full potential of the combined photogrammetric evaluation and analysis is not yet used in commercially systems, as will be shown in the following sections.

2.1. Commercially available systems

The current generation of commercial IATS was introduced in 2005 by Topcon with the instrument GPT-7000i. This total station was already equipped with two different VGA cameras: (1) a wide-angle camera with fixed focus which is mounted next to the telescope making it possible to rotate with it, and (2) an on-axis (telescope) camera which registers the operator’s view through the telescope including the variable focus. The images of these cameras differ widely. The first camera has a large field of view (FOV) and gives an overview of the surveying area. The second camera image benefits from the magnification of the telescope, resulting in a quite small FOV, but giving a more detailed view. Meanwhile, the Topcon technology is distributed under the term Imaging Station, currently in the 3rd generation [Figure 2.1a].

Trimble released its first IATS under the name of VX Spatial Station in 2007, with a fixed-focus 3-megapixel color camera. The same overview camera is
also used in the subsequent top level total stations series, including the current Trimble S9 [Figure 2.1b].

2009 Pentax introduced a total station equipped with an overview camera in the Visio instruments. In contrast to the other instruments presented here, the video image is not displayed at the standard instrument’s display, but instead at a separate screen above the ocular [Figure 2.1c].

Leica Geosystems followed in 2010 with a built-in overview camera in the Viva instrument series. Instruments of the successive Nova series [Figure 2.1d] – released 2013 – provide an additional focusable telescope camera similar to the Topcon Imaging Station.

2.2. Research prototypes

Research and development ambitions are focused on deriving precise measurement information from (calibrated) camera images. This should be possible in real time for autonomous measuring processes as they are necessary e.g. for monitoring applications. A telescope camera which provides a high pixel-angle ratio, i.e. a high spatial resolution, is of particular interest. Due to limited accessibility to the individual measurement data – in particular to image data – and low data transfer rates of commercial products, in-house developments are frequently used. In general, two different implementations can be distinguished:

1. Clip-on cameras, which are put onto the eyepiece, or replace it,
2. Prototypes, specifically designed or being modified for research purposes.

First named systems offer the advantage that standard total stations can be converted into IATS e.g. only for one special measurement task and reconfigured anytime to their original condition. Examples are the systems of the Brno University [Machotka et al. 2008], of the ETH Zurich (DAEDALUS) [Bürki et al. 2010] or of the i3mainz (MoDiTa) [Hauth et al. 2012].

Current prototypes, such as the Leica IATS1 [Walser 2004], its succeeding small batch series IATS2 [Reiterer et al. 2009, Wasmeier 2009, Wagner et al. 2009]...
The cameras of both types of IATS can be read out and processed via a direct cable connection (e.g. USB) to an external computer in real time. This allows the evaluation of the recorded scene using any image processing software, e.g. an integrated program function of a monitoring system, so the result can be directly used for further sequence control of the total station.

2.3. Calibration

The major advantage of the IATS is the fact that the methods and approaches of (close range) photogrammetry can be used in combination with the precision of a total station. An appropriate system calibration provided, each two-dimensional image coordinate can be expressed as a field angle in the object space. Together with the station coordinates and orientation of the instrument, each captured image is directly geo-referenced and can be used for direction measurements with no need for object control points or further photogrammetric orientation processes.

The objective of an IATS calibration is to determine a function of incremental values, i.e. the angle improvements to which the telescope should be rotated so that the sighting axis would aim to the selected point in the image [Reiterer et al. 2003]. In literature, many different system descriptions of IATS cameras and their calibration may be found. These may be divided into two categories:

1. Methods which are valid for overview and telescope cameras.
2. Methods which can only be used for the telescope cameras.

Representatives of the first category are e.g. Huang & Harley [1989], who extend the collinearity equations by an additional camera rotation and a translation, or Juretzko [2004], who uses a central projection in the form of an oblique gnomonic map projection and an optional empirical correction matrix. Both approaches do not consider instrument errors within their system description. Vogel [2006] instead extends the collinearity equations by additional parameters in form of a photogrammetric collimation axis and vertical index error, camera rotations, and an additional distance between the theodolite and camera projection centers, but also by the classical instrument errors. By reducing the number of parameters, this approach can also be adopted for telescope cameras.

Calibration procedures which are only practicable for the telescope camera can be found in Bürki et al. [2010], a central projection expressed as affine transformation without theodolite errors. Knoblach [2009] extends this approach for the use of different focus lens positions with less parameters. Walser [2004] describes the camera with an affine chip model and takes the instrument errors
into account. Wasmeier [2009] combined this last mentioned approach with the one of Vogel [2006].

An universal description of the relationship between a homogeneous 3D coordinate \( \mathbf{X} = [X, Y, Z, 1]^T \) and its image projection \( \mathbf{X} = [x, y, 1]^T \) is given in Wagner [2016]. The inner (intrinsic) camera parameters \( K \) and the outer (extrinsic) parameters (the rotation matrix \( R \) and the translation vector \( T \)) are thereby combined in a single, compact \( 3 \times 4 \) projection matrix \( P \):

\[
\mathbf{X} = P \mathbf{X} = K[R|T]\mathbf{X}
\]

As shown in figure 2.2 the outer (extrinsic) parameters \( R \) and \( T \) are composed of three different Euclidean transformations:

1. Transformation from the world or object coordinate system into the theodolite coordinate system \( (R_w, T_w) \).
2. Transformation (pure rotation) into the telescope coordinate system \( (R_t) \).
3. Transformation into the camera coordinate system \( (R_c, T_c) \).

![Figure 2.2 Relation between total station center \( S \) and (overview) camera center \( C \)](image)

In case of overview cameras, for which the projection center must be different to the total station center, the collimation axis is projected as a line into the image, c.f. figure 2.2. It means that the point to which the instrument is aiming to, can only be precisely displayed in the image if the object distance is known.

3. Monitoring concepts

By using IATS in monitoring applications, almost any kind of signaled or non-signaled structures can be used as a target. The base is the automatic detection and retrieval of defined points, shapes or textures in the camera image. Any pixel coordinate found can be transformed into theodolite angles by appropriate calibration parameters. By additional (reflectorless) distance
information, a full 3D coordinate can be calculated. Alternatively to a direct distance measurement, a spatial intersection of two devices can be used. This is of particular interest in case of long distances to natural structures, see section 3.2.

In the field of photogrammetry and computer vision numerous algorithms for object detection and localization in images are known. The difficulty is to fully automate these processes, especially under changing illumination conditions and atmospheric influences, as this often appears in surveying tasks. The achievable detection accuracy depends, i.a., on the object size, the resolution, and a sufficiently good focus [Reiterer & Wagner 2012]. Out of the variety of algorithms the following methods have proved to be particularly suitable [Wagner & Wasmeier 2014]:

1. Blob analysis, where objects are segmented from the background by threshold operators based on their grayscale ranges.
2. Edge detection, which detects and localizes discontinuities in images mostly by first- or second-order derivatives.
3. Template matching, which tries to find and localize objects based on a training pattern, e.g. by correlation.
4. Feature matching, where the neighborhood of pixel locations is numerically described by (statistical) information to be used for matching.

In the following sections we will present IATS monitoring applications using some of the methods mentioned above. These examples fully exploit the new potential of integrated cameras in total stations going beyond the present manufacturers’ solutions.

3.1. Monitoring of structures

As part of Structural Health Monitoring (SHM) the functionality of components and structures is i.a. derived from changes in their natural oscillation frequencies. As shown in Wagner et al. [2013] IATS are very suited for this field of application. The study describes two use cases where one or more active LED targets are tracked in the camera image and vertical movements and oscillation frequencies are derived.

Figure 3.1 shows the set-up of a measurement at the Fatih Sultan Mehmet Bridge (2nd Bosphorus Bridge) in Istanbul, Turkey. Several infrared (IR) LED targets – powered by high-performance rechargeable batteries – were attached to the underside of the bridge in a regular grid. The IATS prototype used was positioned on a pillar next to the western abutment of the bridge. During the measurements the telescope of the total station remained motionless directed to the targets. The images were recorded with a frequency of 25 Hz and analyzed in real-time. By using low camera exposure times (only) the IR targets are visible as bright spots in the images, see screenshot in figure 3.1. In the figure, the IR-LED targets are highlighted for clarity, the red circle indicates the target observed by the IATS. The pixel position of the blob structure’s gravity center can easily
be extracted by a blob analysis. Recording rates of several hundred hertz can be
achieved by reducing the resolution and/or decreasing the field of view. However,
this may lead to the fact that only one single target can be observed, especially
when using the telescope camera which comes along with a limited FOV. With
the observation of several targets simultaneously, in contrast, possible rotational
motions of the observed object could be uncovered.

![Figure 3.1 Structural Health Monitoring of the Fatih Sultan Mehmet Bridge (2nd
Bosphorus Bridge, Istanbul) using IATS](image)

In principle this monitoring approach does not differ from the classical
photogrammetric method as the total station is "only" used as a carrier system
of the camera. However, the additional sensors also bring significant advantages.
The stability of the camera alignment can be continuously monitored by the total
station’s angle readings and the built-in inclinometer. If necessary, it can be
corrected by adjusting the exterior orientation of the images. Furthermore, the
station and orientation of the system can be achieved by control points which do
not have to be visible inside the image. The measurement results can therefore
easily be transferred into any reference coordinate system. In particular in the
case of repetitive measurements for a short time period, the measuring system can
be set up, the measurements performed, and afterwards removed simply and
quickly.

It should be noted that in the given study an IATS prototype was used
which allows a direct access to the (telescope) camera images including high data
transfer rates. A similar procedure has recently been implemented using a
standard (commercially available) instrument [Ehrhart & Lienhart 2015].
Further, no active but passive artificial targets, as well as features of natural
structures were used in this case. However, the main drawback of using state-of-
the-art IATS is the (currently) limited frame rate of 10 fps and thus a maximally analyzable oscillation frequency of 5 Hz.

![3D displacement vectors of a local deformed area, directly derived from two different measurement epochs (exaggerated by factor 10)](image)

**Figure 3.2**

### 3.2. Geo-monitoring

The combination of images analysis and total station methods brings further advantages in many kind of application. The areal-based detection of non-signalized natural objects in images is particularly useful in the field of geo-monitoring. In Wagner *et al.* [2014a] two IATS are used in stereo configuration for high-resolution, long-range stereo monitoring of geo-risk areas. A pre-selected region of interest (ROI) is subdivided into an image bundle whose single images are automatically acquired by both IATS. The images are composed to a spherical panorama for each station using the high accurate exterior orientation, which is determined by the total station’s angles. Image matching techniques – in this case image feature description and detection methods – are then used to generate dense disparity maps by which the object surface can be reconstructed via spatial intersection. The density of the generated point cloud is thereby comparable with that of a laser scanner. The footprint, however, is many times smaller. If multiple epochs of the same area are measured, it is possible to search for corresponding points not only in the stereo pair but also in the two images of the subsequent epoch. In this way, significant 3D displacement vectors can be directly derived. In particular for movements perpendicular to the viewing direction, this is difficult for most other measurement methods. **Figure 3.2** shows an example of an 3D displacement vector field directly derived from two different measurement epochs. A local (significant) translated patch in the center is clearly visible, while the surrounding stable area stays stable (shows only short vectors).

A similar approach for geo-monitoring is described in Wagner [2016]. The instruments of the method mentioned above are replaced here by one single modern total station. The scanning capability of such an instrument is used to generate RGB+D images. This decreases the maximum range of the measurement method compared to stereo observations, but it also reduces the costs of equipment and field work effort. A spherical panorama from the pre-selected observation area is generated in the same way as in the previous method.
Additionally, the same area gets also scanned – depending on the instrument used with up to 1000 points per second. The point cloud is projected into the previously generated spherical panorama and by transforming the distances from the station into grey or color values for each pixel, a depth image (D-channel) is formed. As the reference shape of the panorama is a sphere, each pixel coordinate directly corresponds to a theodolite angle. In conjunction with the depth information a 3D polar coordinate can be tapped/extracted straight from the RGB+D image. Different epochs – generated in permanent or periodical operation mode – can now be analyzed by image matching methods. If an object has been moved between two subsequent measurements, corresponding points in both panoramas define the start and end point of a 3D displacement vector immediately, c.f. figure 3.2. Using RGB+D images combines the advantages of both acquisition methods (imaging and scanning) and is the first method which utilizes the full potential of a modern total station and its various built-in sensors.

4. Conclusion

The usage of image information in the measurement process is an established feature of modern surveying. A continued automation of the multi-sensor system total station can be expected. Monitoring concepts which are using image information are consequently the next step not only in research applications. The studies conducted so far – including the presented ones – clearly proved their suitability, also in terms of the achievable accuracy. However, the used approaches, especially the implemented image processing algorithms, have to be developed further and adopted to be robust enough for geodetic needs. The main issue is the reliability of the results under changing illumination and atmospheric outdoor conditions alike. This will slightly shift the innovation potential from the last decade’s sensor technology focus back to evaluation strategies and will not be achieved by the manufacturers only, but will give opportunities for research and third-party applications.

References


Koncept monitoringa korištenjem mjernih stanica s ugrađenim CMOS senzorima


Ključne riječi: geo-monitoring, kalibracija, mjerne stanice s ugrađenim CMOS senzorima (IATS), monitoring građevina.

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