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DEFORMATION MONITORING USING A NEW KIND OF OPTICAL 3D MEASUREMENT SYSTEM: COMPONENTS AND PERSPECTIVES

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Abstract: High accuracy 3D representation and monitoring of objects is an increasing field both in science and industrial applications. Up to now many tasks like monitoring of building deformations or displacements were solved by means of artificial targets on the objects of interest. Meanwhile mature optical 3D measurement techniques are available. Such image-based systems can perform their measurements even without targeting. They use the texture on the object surface to find "interesting points" which can replace the artificial targets. Example for a monitoring task is the stability control during the whole construction process of engineering buildings like bridges, high-rise buildings, dams, etc. This paper gives an overview of a new type of optical 3D measurement system and its components. It uses learning-based object recognition techniques to search for relevant areas to collect robust interest point candidates to be long-term tracked to provide a deformation database. The task of deformation analysis is on one hand based on a traditional geodetic deformation analysis process and on the other hand on a new developed procedure called deformation assessment. The main goal of this development is to measure, analyse and interpret object deformations by means of a highly automated process. We focus on key functional components, development stage and perspectives of the developed system.

1. INTRODUCTION

The increasing number of objects located in highly populated areas that are involved in deformation processes has extended the demand for rapidly working and easily usable deformation measurement systems. Deformation measurement enables the early detection of damage, infrastructure failure or potential hazard in order to be able to react appropriately and in time. The causes for such deformations are manifold. To name a few, changes of ground water level, tidal phenomena, tectonic events, or human underground construction can be the reason for deformation of buildings, bridges, dams, tunnels and railway tracks.

A great variety of optical 3D measurement techniques like laser scanners, photogrammetric systems, or specific image-based measurement systems are available to achieve this need. An example for such a monitoring task is the stability control during the whole construction process of engineering buildings like bridges, high-rise buildings or dams.

Most state-of-the-art sensors need to be placed on-site (i.e., directly on the region or object that undergoes a deformation) which is often not possible in hazardous terrain. It is therefore necessary to apply remote monitoring methods that can perform their measurements without the dependence on targets placed on the object. Important representatives are based on laser scanning (Bauer et al. 2005) or terrestrial synthetic aperture radar (McHugh et al. 2006), both leading to multi-temporal images containing distances to the scene in each pixel. They work mainly in viewing direction, i.e., they can determine only one coordinate component of deformations. Furthermore, the footprint of such sensors is relatively large (in the range of decimetres), such that a precise location of each measurement is not possible. Accuracy of such sensors in most cases is a few centimetres.

To close the gap between these low-resolution, medium-accuracy sensors and conventional (co-operative target-based) surveying methods, image-assisted total stations (IATS) are a straightforward solution, able to provide high-density deformation fields with high accuracy (down to mm range) in all three coordinate directions. IATS can perform their measurements even without targeting; they use the texture on the object surface to find points of interest.

In an interdisciplinary ongoing research project (2006-2008) lead-managed by the Vienna University of Technology and Joanneum Research Graz (*"Multi-Sensor Deformation Measurement System Supported by Knowledge-Based and Cognitive Vision Techniques"*) a new kind of image-based measurement framework using IATS systems is under development. It is based on new techniques originally developed in the area of Artificial Intelligence, which shall be used for the task of deformation measurement, analysis and interpretation. The developed system consists of a number of sub-systems, regarding image processing, point detection and 3D measurement, deformation analysis and deformation interpretation. We report on the new developed measurement system, its functionality and development stage.

2. IMAGE-BASED MEASUREMENT SYSTEM

The basis for the measurement system is an image-assisted total station. Such measurement systems have a CCD/CMOS camera in the optical path. The images of the telescope's visual field are projected onto the camera's chip. It is possible to capture mosaic panoramic images performing successive camera rotation, if computer-controlled motors drive the axes of the measurement system. With appropriate calibration these images are accurately geo-referenced and geo-oriented since the horizontal and vertical angles of rotation are continuously measured and fed into the computer.

Recently, research interest in the area of image-based measurement systems has been increased. *Leica Geosystems* developed a prototype of an image-assisted total station with the purpose of defining a hybrid or semi-automatic way to combine the strength of the traditional user-driven surveying mode with the benefits of modern data processing (see Walser 2003). The work described herein is based on this sensor. Furthermore, *Topcon* and *Trimble* introduced tacheometers that provide focused colour images (Topcon 2007, Trimble 2007), and at the *Technische Universität München* an image-based measurement system for object recognition was developed (Wasmeier 2003). One important step for the development of an automated image-based measurement system is the integration of so-called *feedback techniques* (e.g., precise line scanning (Buchmann 1996) or corner detection). Such techniques are summarized under the concept of *Intelligent Tacheometry* or *Intelligent Scanning* (Scherer 2004).

Institute of Geodesy and Geophysics at the Vienna University of Technology has long-term experience in the development of total stations, image-assisted theodolites and IATS. Worth mentioning are the work done by Fabiankowitsch 1990, by Roic 1996, by Mischke 1998, and by Reiterer 2004.

The optical system of our system is reduced to a two-lens system consisting of a front and a focus lens. Instead of an eyepiece, a CCD/CMOS sensor is placed in the intermediate focus plane of the objective lens. The image data from the image sensor are fed into a computer using a synchronized frame grabber. The variable camera constant and principle point location resulting from the focus mechanism is compensated by a calibration step and precise focusing encoders.

The new image-based measurement system consists of different components: an image-sensor, system control unit (a workstation including a frame grabber and controlling software), a system for deformation analysis (realised by the integration of *GOCA* – GNSS/LPS/LS-based online Control and Alarm System) and deformation assessment, a knowledge-based decision system (KBS), and a graphical user interface (GUI).

Basic idea of the measurement system is to use the IATS as core component and extend it by several sensor units – the result is a flexible multi-sensor system. In a first step, we introduced a Terrestrial Laser Scanning Device (TLS) into the system. A simplified architecture of the system is shown in Figure 2.

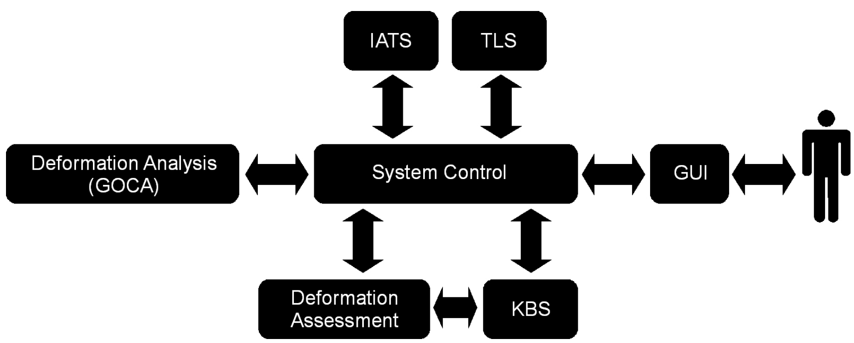


Figure 2 - Simplified architecture of the developed system.

The fusion of IATS and TLS combines the robust and dense point clouds gained by TLS with highly accurate single or sparse point cloud measurements by an IATS system. A combination of these sensors is a promising solution for any type of deformation measurement (laser scanners currently undergo a considerable increase of maximum range, accuracy and acquisition speed).

Particularly in large regions with unknown deformation distribution a laser scanner system can provide key information about quick surveying decisions. Scanning a region twice within a certain fraction of time expected to show reasonable deformation allows for simple comparison of laser distance images and straightforward determination of candidate deformation regions.

The developed measurement procedure is shown in Figure 3 and starts with the capturing of overview images by an external wide-angle (WA) camera attached at the top of the IATS.

This processing step makes is possible to evaluate the whole "scene" and to make some first decisions. As a matter of course this "overview-scene" could also be generated capturing images by the internal IATS camera and by stitching them together – due to this sequence is more time consuming, our approach is based on the WA-image. On the basis of the captured overview-image, scene analysis by means of an object segmentation tool can be done. In the following detailed images can be captured by the internal IATS-camera. These images are the basis for the subsequent image point detection and the 3D point measurement (see Section 3). A precondition for deformation analysis is the existence of more than one measurement epoch – provided that such measurements are available the developed system can process a classical deformation analysis followed by the so-called deformation assessment (see Section 4). As a last step automated deformation interpretation can be done.

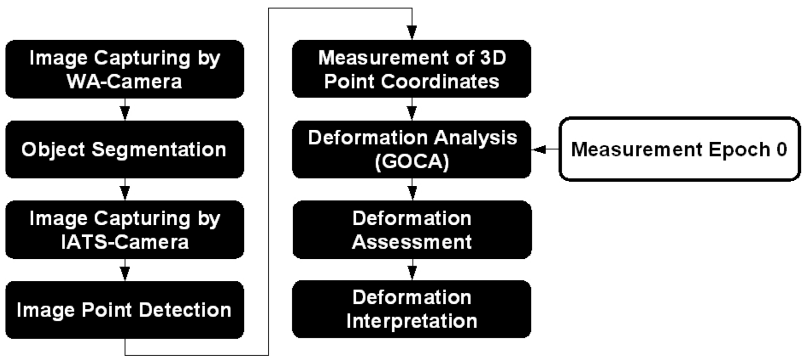


Figure 3 - Developed measurement procedure.

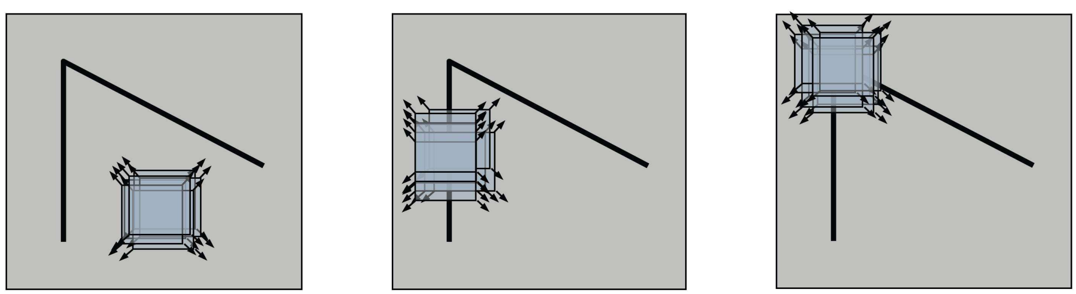
As mentioned above the measurement procedure starts with the capturing of one or more overview images by means of the wide-angle (WA) camera. On the basis of these images a "segmentation" procedure will be executed. Its results can be used in a following step to find robust regions of interest (ROIs). The structuring of a object can be realized by a detection of striking object parts or object features, e.g. for a façade such features can be windows, since windows are the most important structure elements on façades in this context. For such a analysis process all necessary knowledge about possible objects has to be integrated into the knowledge base.

Due to the developed measurement system provides several types of data (traditional tacheometer measurements, LS data, images) we have decided to integrate more than one object segmentation procedure. We have developed two methods, which are working on the basis of images, and one method, which is working on the basis of TLS point clods. In a later research and development step the choice of a suitable method depending on object and scene conditions by means of a knowledge-based approach is envisaged. More details about the developed structuring algorithms can be found in Reiterer et al. (2008).

3. IMAGE POINT DETECTION

For the task of point detection, the internal camera of the IATS captures images covering the extracted ROIs[1]. On the basis of these images, point detection can be done. Processing algorithms, which extract interesting points (IPs), are called interest operators (IOPs). They highlight points that can be easily found by using correlation methods. There is a huge number of interest operators (e.g., Förstner 1987, Harris 1988, Moravec 1977), however no interest operator is suitable for all IP types.

The IOP algorithms implemented in our system can be classified as intensity-based methods (see Schmid et al. 2000). These methods go back to the development done by Moravec 1977. His detector measures the grey value differences between a window and a window shifted in the four directions parallel to the rows and columns of the image. An interest point is detected if the minimum of these four directions is superior to a threshold. Today there are different improvements and derivatives of the *Moravec* operator. Among the most well known are the Förstner and the Harris operator, which represent two methods implemented into our system. Additionally, we have integrated the *Hierarchical Feature Vector* (HFV) operator based on a dense texture matching approach (Paar and Bauer 1996). The principle functionality of an IOP is shown in Figure 3.



(a) (b) (c)

Figure 3 - Basic idea of an interest operator (Mpaltsavias and Papasaika 2007) – a window is shifted over the image: (a) “flat” region – no changes in all directions; (b) “edge” – no change along the edge direction; (c) “corner” – significant change in all directions.

One advantage of the suggested processing sequence (ROI detection and subsequent point detection) is the restriction of IPs on specific areas (see Figure 4). On the basis of the extracted image points, measurement in object space can be performed, which is comparable to a measurement captured by a conventional tacheometer (horizontal angle *Hz*, vertical angle *V* and distance *D*). These values are directly usable for 3D deformation analysis.

[1] The internal camera is used instead of the WA-camera due to the larger image scale and in consequent the higher accuracy of image point detection.

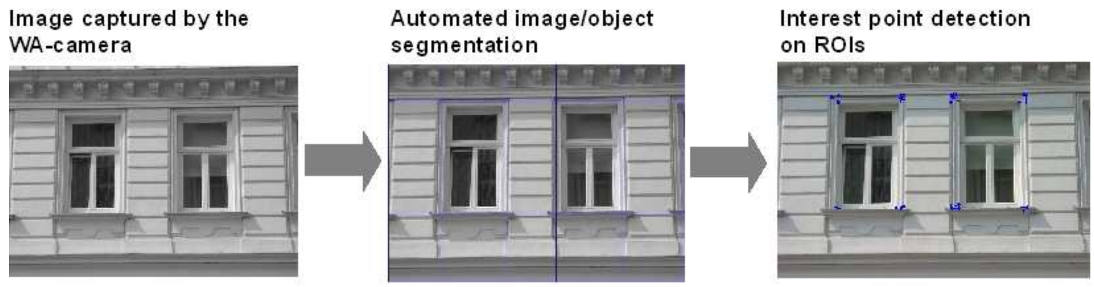


Figure 4 - Processing sequence of image point detection: An overview image is captured by the WA-camera. In a second step image/object segmentation is done. IPs are detected in the images captured by the internal IATS camera (overlaid to the WA-image).

4. DEFORMATION ANALYSIS

For monitoring an object involved in a deformation process, the object and its surrounding has to be modelled, which means dissecting the continuum by discrete points. On one hand, these points should characterize the object, on the other hand, their movements represent the object's movements and distortions. Modelling the deformation of an object means to observe the characteristic points in certain time intervals by means of a suitable measurement system in order to properly monitor the temporal course of the movements. The principle of a classical deformation analysis will be not described in the paper at hand – details can be found in Pelzer 1985. To perform such a classical deformation analysis, the *GOCA* software has been used. GOCA (GPS-based Online Control and Alarm System) is a development of the University of Applied Sciences Karlsruhe (GOCA 2007). It uses data from different sensors (e.g., GNSS/GPS, total stations, and in the future laser scanner) and is designed for the mentioned classical type of an absolute deformation network.

The software is able to determine the reference points coordinates (initialisation) and object points coordinates (georeferencing) by a network adjustment. With measurements in different time epochs the investigation of instable reference points and a deformation analysis (trend estimation, Kalman filtering, Finite-Element-Method (FEM), and, in consequence, alarm management and further prediction) will be performed. The advantage of the GOCA software is the ability to perform these steps in real-time or as a near online monitoring process.

The communication between the measurement system and the GOCA software is realized by using the GKA data interface (for documentation of this interface see GOCA 2007). The result of this deformation analysis is a list of points, which had moved significantly between the epochs, including the covariance information of this deformation.

It is notable that the procedural method of the GOCA software aims to process single points and their motion. If a classical deformation analysis is proceeded, an interpretation of the determined deformation (reasons, effects, etc.) has to be done by an expert (geological-, civil- or structural engineer). The main idea of the deformation measurement system presented in this paper, is to enable the system to generate automated a interpretation on the basis of the deformation analysis information.

After deformation analysis has been successfully performed, the data has to be prepared for the mentioned automated interpretation. Until this stage of the process, the deformation investigation was done for all points measured on the objects surface. Now the segmentation done earlier in the process comes into operation. A first step is to find a description of the deformation of each ROI. This description is based on the splitting of the determined deformation into its basic motion components by means of an affine transformation.

To get the transformation parameters for the whole ROI, including their standard deviation, all points of the ROI with a significant motion are bundled and a Gauss-Helmert equalization is performed. A precondition for this processing sequence is a minimal number of three points per ROI (the distribution of these points in the considered region is almost irrelevant – see Lehmann and Reiterer 2007).

To make the extracted numerical values more suitable for the subsequent processing steps we use a fuzzification procedure. This procedure translates the input values (deformation parameters) into linguistic concepts, which are represented by abstraction ("fuzzy") sets. Fuzzification is done by means of overlapping triangle membership functions.

The mentioned method only handles translations along (t_x, t_y, t_z) and rotations (α, β, γ) around the coordinate axes.

Because of the preconditions of the ROIs (small, enclosed areas with homogeneous deformations) this fact is not a disadvantage. The system follows a local-to-global information integration strategy and the combination of the results of the ROIs in a later step offers the possibility of detecting changes in the outer (rigid body motions) and inner (distortions, bending) geometry of the object.

To realize such a conclusion about the deformation of the whole object a deformation pattern for the object has to be formed by grouping the results of the regions. As a grouping by the specific parameters or/and fuzzy values of the ROIs turns out to be circuitous and ineffective, a more general description on the basis of *deformation cases* was developed.

A deformation case is a unique combination of fuzzy values of the specific motion parameters. By means of well-known prototypical deformation cases a special kind of codebook of deformation characteristics can be implemented. To get the mentioned generalized description a matching between cases in the database (codebook) and a new (unknown) case can be processed by case-based reasoning (CBR). CBR is a methodology from the field of Artificial Intelligence that can use different techniques to solve a problem by using the solution of a similar former problem (Watson 1999).

The bandwidth of useable techniques is quite large. In this project fuzzy logic and knowledge-based system techniques are used. Both methods are implemented in our system and are based on fixed knowledge.

The cases in the case base are artificial prototypical combinations of fuzzy values of the deformation parameters. Thereby all combinations of the motions (rotations and translations) are included and also the scaling of the parameters is considered.

The CBR system compares every case with the cases in the case base and determines a measure of similarity, the so-called *score*.

The result of the case-based reasoning tool is a list where every ROI is assigned to one of the prototypical cases. Because of the time-consuming runtime of the CBR Shell alternatively a second system for description generating (hard-coded comparison of the fuzzy values with the prototypical cases) was implemented. This method accelerates the runtime of the system but makes it impossible to adjust the case base when the system is in use.

After the generalized description of each ROI was obtained, it is possible to merge these descriptions to one deformation pattern and make an interpretation on basis of this deformation pattern.

As mentioned before a main goal of our research work is to extend the classical deformation analysis to a more global working deformation assessment procedure. The subsystems described are currently in prototype state and integrated into a common program framework. Additionally, a deformation interpretation tool will extend the deformation classification part in the near future. The main task of this interpretation part is to generate assumptions and hypotheses, which have to be stated and tested, by automatically requiring new measurement data from subsystems or by asking a human supervisor (if available). Both sources of information may lead to verification of temporarily stated assumptions or hypotheses.

5. CONCLUSIONS

We presented a new kind of optical 3D measurement system. As core component for this system an IATS is used, which can be extended by a terrestrial laser scanning device. The main task of the development has been the automation of different decision-makings in the course of deformation measurement and -analysis.

The presented system is currently under development. The vision for the next years is the development of a fully integrated and automated measurement system, supported by image-based measurement and laser scanning techniques. Also the fusion with other sensors (GNSS, PMD, etc.) will be a challenging task. Such an integrated system represents an approach for an automated on-line working system.

The degree of automation can be very high, whereas by decision-making, human interaction remains an important part of the workflow even though the amount of decisions done by the user can be considerably reduced to a minimum.

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