IMAGE-BASED DETECTION AND MATCHING OF HOMOLOGUE POINTS USING FEATURE-VECTORS – FUNCTIONALITY AND EVALUATION IN A DEFORMATION MEASUREMENT SYSTEM

A. Reiterer [a, *], N.B. Huber [b], A. Bauer [b]

[a] Institute of Geodesy and Geophysics, Engineering Geodesy, Vienna University of Technology - alexander.reiterer@tuwien.ac.at
[b] Institute of Digital Image Processing, JOANNEUM RESEARCH, Graz - benjamin.huber@student.tugraz.at, arnold.bauer@joanneum.at

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ABSTRACT:

Engineering geodesy has undergone significant changes in recent years. The automation in the area of tacheometer measurement systems has begun years ago with automatic target recognition (ATR) and tracking features. Image processing has become a powerful tool of science and industry and is therefore an ideal enhancement for traditional tacheometers. Combining a conventional tacheometer with an imaging sensor poses a hybrid approach wherein a CCD or CMOS sensor is integrated in the optical path of the tacheometer's telescope. Such an image-based tacheometer is capable of capturing mosaic panoramic images through camera rotation, if the axes of the system are driven by computer controlled motors. With appropriate calibration these images are accurately geo-referenced and oriented. The captured images can be used for further image processing and detection of homologue points in stereo pairs of images as well as over multiple measurement epochs in order to be used for geodetic deformation analysis.

At the *Institute of Geodesy and Geophysics of Vienna University of Technology* a new kind of image-based measurement system is under development (research project "*i-MeaS – An Intelligent Image-Based Measurement System for Geo-Hazard Monitoring*"). The system is based on automated 3D point detection and automated point matching over different measurement epochs. We report on the recent state of the implemented point detection procedure, its functionality and development stage.

1. INTRODUCTION

1.1 Motivation and Aims

Engineering geodesy has undergone significant changes in recent years. Most obvious is the transition from analog to digital operating modes. Automation of surveying instruments is indeed in high demand. The automation in the area of tacheometer measurement systems has begun years ago with automatic target recognition (ATR) and tracking features. Image processing has become a powerful tool of science and industry and is therefore an ideal enhancement for traditional tacheometers.

In the last years a strong trend towards image- and laser-based measurement systems can be noticed in the field of geodesy. Both techniques are well suited for object reconstruction or ongoing deformation measurements because of the high degree of possible automation.

Combining a conventional tacheometer with an imaging sensor poses a hybrid approach wherein a CCD or CMOS sensor is integrated in the optical path of the tacheometer's telescope.
Such an image-based tacheometer is capable of capturing mosaic panoramic images through camera rotation, if the axes of the system are driven by computer controlled motors. With appropriate calibration these images are accurately geo-referenced and oriented as the horizontal and vertical angles of rotation are continuously measured and fed into the computer. The captured images can be used for future image processing and point detection.

1.2 Related Work

Former research work was mainly focused on fundamental problems like calibration (WALSER 2003, WASMEIER 2009), image pre-processing (ROIC 1996), manual (SCHERER 2004) and automated point detection (MISCHKE & KAHMEN 1997, REITERER 2004). The aspect of repeatability which is of particular interest for geodetic deformation analysis remained untouched (examinations concerning the accuracy of manually detected points were partly carried out by MISCHKE & KAHMEN 1997 und WASMEIER 2009). In the past couple of years intensive research on the development of a deformation measurement system based on image-based tacheometers has been carried out at the Institute of Geodesy and Geophysics on the Vienna University of Technology.

1.3 Overview

A current research project (*i-MeaS – An Intelligent Image-Based Measurement System for Rock Fall Monitoring*) concentrates on the concrete application of geo-monitoring (rockfall, landslide, etc.). The measurement system is based on two image-based tacheometers (modified Leica TCRA 1201 with integrated 5MP CMOS camera) connected with a central

* Corresponding author.

controlling computer. Using two synchronized measurement devices, object points can be determined by spatial forward intersection thus enhancing measurement distance and accuracy.

This article introduces new methods for the detection of homologues points measured by image-based tacheometers and gives an insight into the achievable accuracy of this new technology.

2. DETECTION AND MATCHING OF HOMOLOGUE POINTS

The mentioned determination of 3D object points by spatial forward intersection requires the detection of homologues points in corresponding image sections. In order to make use of these points in a geodetic deformation analysis, it is also necessary to recognise these points in multiple measurement epochs (this can also be referred to point tracking). Therefore, point matching can be seen as a two step process: (1) inside one measurement epoch in corresponding stereo images, and (2) over multiple epochs.

In the following we describe in detail the implemented matching procedure, which is used (with necessary adaptations) for both tasks.

2.1 Process

The manual recognition of homologue points in overlapping image sections may seem as a trivial task but forms a complicated problem when implemented in an automated environment. The developed process can be divided into three independent tasks:

- First step: The single images have to be analysed for their information content. Points with a potentially high repeatability (so called "Interest Points") are detected and their image coordinates are saved. The hereby used process is called "Interest Point Detection".
- Second step: Every detected "Interest Point" gets an orientation and information about the detected scale in order to be able to compare images of different size or taken from different view points. Dependent on orientation and scale the environment of the point is captured and saved in form of a descriptive feature vector. This operation is called "Interest Point Description".
- The final step consists of a mutual matching procedure wherein the before generated feature vectors are compared and matched against a reference set generated from a corresponding image to obtain homologues pairs of points.

A main requirement for our application is a high invariance towards changes in environmental conditions such as illumination or transformations in the image domain like differing viewpoints. Furthermore the time span used to measure and calculate one epoch is restricted by the frequency of the measurements. Ultimately the used operators must be deployable on standard field capable hardware.

In the following, two algorithms which fulfil the mentioned requirements will be explained in detail.

2.2 SIFT – Scale Invariant Feature Transform

The „Scale Invariant Feature Transform“ operator, in short SIFT (LOWE 2004) was developed by David Lowe at the University of British Columbia and describes a method for automated "interest point detection", feature extraction ("interest point description") and mutual matching.

Stable "Interest Points" are calculated using the "Difference of Gaussian" (DoG) method (LOWE 2004). The original image data is repeatedly being convolved with a Gauss kernel and subtracted from the image source – this process is iteratively applied to each layer of the image pyramid. The technique poses an approximation of the "Laplacian of Gaussian" method which can also be used for point detection with the benefit of much faster computation. Subsequently an orientation is assigned to the detected "interest points" by calculating the direction of the local gradients of the image in a certain neighbourhood of the points. All further computation steps are relative to the orientation and the scale of the "interest point" in order to achieve a high degree of invariance towards transformations in the image domain.

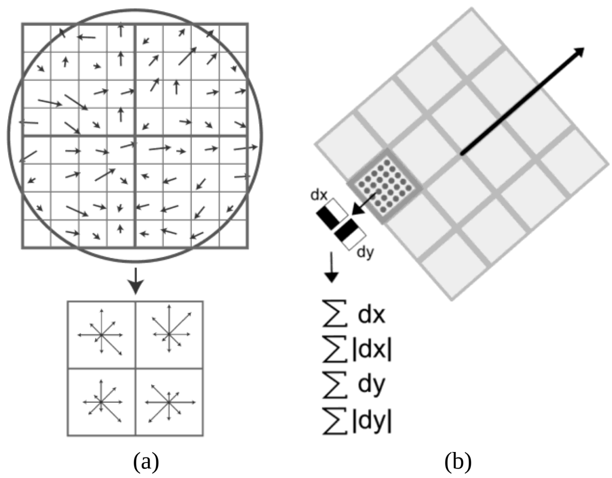


Figure 1: (a) SIFT: aggregation of histograms of oriented gradients (LOWE 2004); (b) SURF: 4 descriptor vector values gained from each of the 5x5 wavelet responses (EVANS 2009).

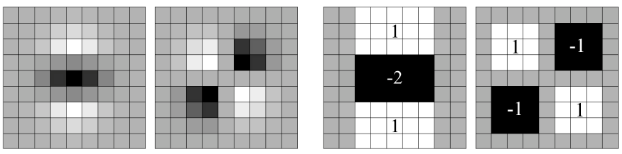
In the following the neighbourhood of the "interest points" is analysed. Since a simple accumulation of the pixel intensities is known to be highly variant towards changed environmental conditions, the weights and directions of the image gradients (relative to "scale" and orientation of the "interest points") are aggregated into a histogram of oriented gradients (see Figure 1a). The class width of these histograms is equivalent to the orientation, while the class' content consists of the sum of the gradients' weights. The classes represent the categories of data in which a certain proportion of cases fall and are further also referred to as "bins". Experiments show that the best results can be expected by using 4x4 histograms each consisting of 8 bins based on a grid of 16x16 image points. This process results in a "feature vector" of 128 values which is normalised in order to gain further invariance against changing illumination conditions. Ultimately the "feature vectors" are matched based on their Euclidean distance thus supplying the corresponding homologue point pairs.

2.3 SURF – Speeded Up Robust Features

The SURF operator is the algorithm which is used for the project at hand. SURF was developed at the ETH-Zurich – the acronym stands for „Speeded Up Robust Features" (BAY ET AL. 2006). This algorithm uses an approach similar to the above described SIFT operator but lays a special focus on reduced computation time.

One of the main differences to SIFT is declared by the use of so-called "integral images". These images consist of a calculated matrix containing for every pixel the accumulated sum of the intensities over a rectangular area between the current pixel and the image origin. This allows the calculation of the sum of the intensities of an arbitrary rectangle in the image domain by only three additions and four memory accesses respectively which strongly reduces further computation time (especially of integration over a rectangular area in the image).

For the purpose of "Interest Point Detection" the SURF operator uses the determinant of the Hessian matrix (BAY ET AL. 2006). Through the application of highly approximated filters (see Figure 2) "blob"-like structures are detected as extrema of the determinant of the Hessian matrix. In combination with integral images these calculations can be executed with a minimum of effort.



(a) (b) (c) (d)

Figure 2: Filter kernel for the second derivation of the Gaussian (a and b) and crude approximation through box-filters (c and d) (Bay et al. 2006).

A further speedup of the algorithm is gained by the exchange of a conventional image pyramid (wherein the resolution of the original image gets repeatedly down-sampled) through an iterative calculation of different scales. The calculation can be done by approximated filters of different size which can be computed in constant time – the number of filter scales is defined by the preset octaves. One octave in an image pyramid typically stands for bisection of the original image size or in this case a doubling of the box filter's size respectively.

In the SURF algorithm, "Haar-Wavelet-Filter" responses instead of image gradients are used for the calculation of the "descriptors". The orientation of the "descriptor" again relies on the orientation and scale of the particular "interest point". The "descriptor" is calculated using a quadratic 4x4 grid around the point and computing "Haar-Wavelet-Responses" of 5x5 regularly distributed points. On the basis of the results 4 values are calculated and added to the "feature vector" (see Figure 1b). This results in a vector of 4x4x4 = 64 values.

The matching is carried out the same way as for the SIFT operator. The only difference is the fact that through the use of the "Hessian Matrix" for "interest point detection" a simple indexing of the resulting points can be implemented. Since the sign of the Laplacian matrix is known, points can be divided into "blob"- like structures which are dark on a light background and vice versa. In the best case (50% dark points on light background and vice versa) matching time can be reduced by 50%.

For the i-MeaS system an adapted open source implementation of the SURF operator (EVANS 2009) is used. The above described process for "point detection" and "description" is (to a large extend) computed in parallel and integrated into the measurement system. For this special application an additional distinction between the matching of homologues points in overlapping stereo images and the tracking of these points over multiple measurement epochs in time had to be drawn. The implemented approach is based on storing the "feature vectors" of homologues points found in a defined reference epoch and sequentially comparing them with "feature vectors" extracted from corresponding images in the following epochs.

The main adaptations of the used operator are regarding computational speed and integration into the measurement framework. As mentioned before enhancements where made to enable a parallel computation in order to use the full resources of modern multi-core CPUs. Furthermore the above stated indexing of detected points and the resulting matching speedup were implemented. The communication with the main measurement system makes use of pre defined interfaces in a simple ASCII file format. This way the whole parameter setting can be controlled and certain image pre-processing steps can be automatically initiated if necessary.

These parameters control the behaviour of the used SURF algorithm and allow optimisations for a particular situation. The most important parameter is the threshold which is used in the first step, the "point detection". This threshold is applied to the results of the calculation of the determinant of the Hessian matrix. It filters the detected points whereas the amount of accepted "interest points" increases with a decreasing threshold. The amount of different scales at which points are detected is defined by the "octave" parameter whereas one octave implies a doubling of the box-filter equivalent to a bisection of the image in a classical image pyramid. These octaves are then further divided into several intervals which can also be set. The sampling step also has to be specified. This parameter can be used for a further speedup of the computation at the cost of accuracy when set to a value greater than one pixel.

3. EVALUATION OF POINT DETECTION AND MATCHING

Through the implementation of automated point detection and matching algorithms the necessity arises to evaluate the accuracy and reliability of the system as well as other extrinsic influencing factors. Thus the next section is dedicated to an evaluation concerning overall quality and performance of the developed prototype system.

In literature examinations and evaluations of the used algorithms and operators can be found, e.g. BAUER ET AL. (2007). A comprehensive study comparing the performance of local descriptors can be found in MIKOLAJCZYK & SCHMID (2005). According to them SIFT and SIFT-like descriptors reach their highest accuracies under viewpoint changes of up to 30°. Results in the area of textured as well as in structured scenes were significantly better then previous algorithms could achieve. The developers of the SURF operator (BAY ET AL. 2008) showed that their algorithm reaches a similar performance and robustness against changes in environmental conditions while the computation time was reduced by a factor of around five. These results were approved in an independent evaluation in 2007 (Bauer et al. 2007).

For the project at hand variable tests were carried out to evaluate the results of the automated point detection process. They can be divided into three main groups.

- offline-tests (simulations),
- online-tests under laboratory conditions,
- online-tests under real conditions.

3.1 Offline-Tests (Simulations)

In a first step offline tests where carried out in order to verify and optimize the point detection and matching process. For the evaluation image data from the image-based sensor system i-MeaS (5MP) was used as well as images taken with a high resolution "digital single-lens reflex" (DSLR) camera (12MP).

A central issue arising from the use of a specific automated point detection process is the selection of appropriate parameters for the used algorithms (see Section 2). For the evaluation of the point detection and matching process a simple supporting tool was developed and implemented. Its main purpose was to help compare and evaluate the repeatability, the quality of the results and the computation time needed by different existing operators. The separated development of the image analysis component and the measurement system which were combined and integrated later via previously defined interfaces enabled a completely autonomous development and testing of the respective parts.

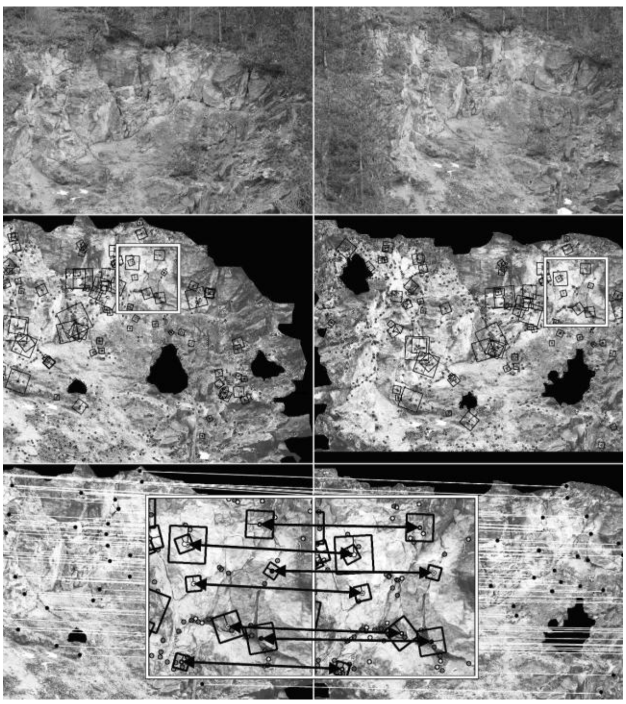


Figure 3: Operator Test, *top*: original 12MP stereo images, *middle*: interest points in masked area including descriptor size and orientation of matches (framed sample sub-region), *bottom*: zoomed out sub-region showing homologue points (including descriptor window) connected by arrows (background displays all other matches)

Figure 3 shows the application of the SURF-operator, wherein areas not suitable for deformation analysis (e.g. vegetation) were masked manually. A higher image resolution increases the amount of detected "interest points" (using the same set of parameters) in an almost linear manner thus extending the computation time. This means that the sensors used in the i-MeaS project pose a well compromise for an online-system regarding resolution and computation time. However, an increased amount of available object points may still improve the quality of deformation representation (a chart illustrating this relation can be found in Section 3.3).

Extensive offline-tests should also determine the optimal set of parameters for the adaption of the used operator (different image resolutions as well as the influence of changed illumination conditions were simulated). It could be demonstrated that the influence of illumination could be greatly reduced by applying specific image pre-processing operations (excluding edges created by cast shadows which can still generate significant problems and has yet to be addressed individually). A standardized set of parameters controlling the SURF-algorithm proved to be not practicable – particularly in regard to the constitution of the surface (structure, colour, etc.) which requires additional adaptations.

The customisation of the parameters for the point detection algorithm to a specific test object or site poses a central challenge for an automated system. As mentioned before current development is focusing on rock surfaces. Vegetation and other non-stable or unwanted objects in the image domain have to be masked in the course of selecting a reference epoch. An automated detection of these structures may be addressed in future research but has to deal with serious problems from the field of image segmentation. In the future an adaption of the respective sets of parameters can be done online based on previously known or automatically measured attributes of the object or site.

3.2 Online-Tests under Laboratory Conditions

Primary objective of the online-tests under laboratory conditions was the confirmation of the simulation results (see Section 3.1) in the controlled environment of a measurement lab. In order to carry out an automated point detection using image-based tacheometers a couple of conditions have to be formulated. Aside from known manufacture deficiencies of geodetic instruments (axis error), additional problems caused by the imaging sensor system have to be considered. In the present measurement system this is addressed by a highly complex calibration procedure (WALSER 2003, WASMEIER 2009). Simplified this means that the mechanics' and imaging sensors' imperfections are considered so that every point on the imaging sensor can be related to its own specific angle values (vertical and horizontal angles).

The online-tests are focused mainly on the evaluation of the repeatability of the automated point measurements – the multi-sensor-system consisting of the tacheometer and the imaging sensor will be considered as one single device (a separate examination will be carried out for later evaluations).

In the course of the laboratory test an adequate target panel was stably mounted in a distance of approximately 4m from the sensors. The two imaging tacheometers were oriented and focused in the direction of the panel (the captured images covered a part of the target). Subsequently points were detected using the SURF-operator and their 3D-coordinate in the object domain were calculated by means of spatial forward intersection. Both tacheometers were first rotated by 90° before targeting the panel again and obtaining the formerly measured 3D-points once more. This process was repeated 10 times thus creating a test series containing 10 measurement epochs. In each epoch about 250 points were detected and tracked over time. It was shown that the maximal difference between the reference- and the following epochs was 0.1 mm. This value lies within the measuring tolerance of the system. Hence it was clearly shown that the limiting factor is not the imaging chip but the tacheometer on which the multi-sensor system is based.

In order to address the issue of changing illumination conditions and their influence on the point detection and matching process the above described 10 measurements were complemented by another set of 10 epochs. The configuration was enlarged by an additional light source illuminating the target from different angles. The tests have shown that changes of illumination conditions can be considered in a satisfactory manner using appropriate image pre-processing steps (histogram equalization) and optimised image capturing (shutter speed). The consideration of irregular illumination like cast shadows poses a much greater challenge. Simulations regarding this factor of influence have yet to be carried out. However first conclusions can be drawn based on tests executed under real conditions (see Section 3.3).

In addition these online-tests have to take the influence of temperature into consideration (thermal stability). This influence factor has been extensively covered by WASMEIER (2009) – therefore it should only be referred to the existing literature for the sake of completeness.

3.3 Online-Tests under Real Conditions

In order to test the measurement system including the used operators and algorithms under realistic field conditions a fixed installation of the sensor system was conducted over several days. The installation was made on the "Pasterze", the largest glacier in the eastern Alps. A lower, debris covered part of the glacier as well as a geologically stable rock face was chosen as test site. Main purpose of the test was not the examination of accuracies but the evaluation of the point detection and matching process and the consecutive calculation of 3D-coordinates on the object under realistic environmental (especially illumination) conditions.

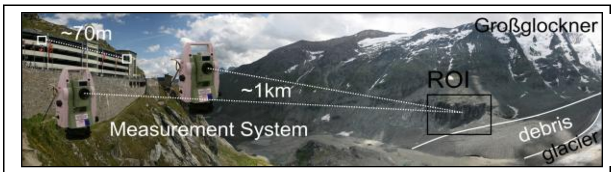


Figure 4: Panorama of measurement site at the Pasterze glacier, including scanning position (left) and region of interest (ROI) on the object (area covers about 370m x 120m)

The two imaging tacheometers were positioned in a mutual distance (base) of ca. 70m and an average distance to the object of 1000m. A stable positioning towards the monitored object could be carried out based on local conditions. The angle of sight can be described as optimal whereas the relatively small base length compared to the large distance to the object did not represent an ideal configuration. However, due to the primary focus on point detection and matching this did not pose a further problem. An overview over the region of interest (ROI) on the object is given in Figure 4.

The region of interest was covered by 11x23=253 images with an overlap of 20% by both scanning positions. The scanning process took approximately 30 minutes for each of the two positions. Caused by the implementation (prototype system) only sequential image capturing is possible, resulting in a combined scanning time of about one hour per measuring epoch.

Immediately after the image capturing the automated point detection process is started. As already mentioned in Section 2 the first measurement epoch is defined as reference epoch – for the test in sum 9 epochs have been measured. As a first step homologue stereo points are detected in all image pairs and the results are saved in "descriptive feature vectors". Caused by the long computation time of this operation the process was processed offline. This was made possible by the modular structure of the system: the process of measurement can be saved at certain pre-defined stages, aborted and continued later on. In consecutive epochs the feature vectors of an image pair are not mutually matched but against the respective previously saved vectors of the reference epoch. Caused by the reduced size of the saved vectors (containing only the homologue points of the reference epoch), computation time decreases to only a fraction of a full matching run. In a third step the remaining points are mutually matched to ensure a stereo relation of the tracked points in the current epoch.

The main parameter settings we used for the tests are: threshold of 0.001 and 4 octaves divided into 4 intervals. This ensures a high amount of detected "interest points" and homologue points in the reference epoch, resulting in a high amount of points being tracked over time without overly increasing computation time. It has to be mentioned that illumination conditions strongly varied both between corresponding stereo epochs (fast moving clouds) as well as between the former and consecutive epochs (time of day) this factor was compensated by a histogram equalisation.

Figure 5 shows a compressed analysis of a sample set of stereo- and consecutive epochs well suited to represent the region of interest. It illustrates the total amount of "interest points" found, the amount of matched homologue points in the reference- or zero-epoch and the points that could be tracked in a consecutive epoch (first, fourth and fifth line from top respectively, absolute scale on horizontal axis to the left) under the influence of different threshold parameter settings (values on vertical axis). Furthermore the corresponding computation time in seconds is shown on the right.

The point quality was assessed by a manual review of the visual representation of the results to determine the amount of false matches. This was done up to about 2500 detected homologue points resulting in a false matching rate of 5-10% in the reference epoch which could be reduced to zero for points tracked in the consecutive epoch because of the chosen multiple matching strategy. With a increasing matching rate (amount of homologue points detected) in the reference epoch more and more homologue points get lost in the course of the epoch matching.

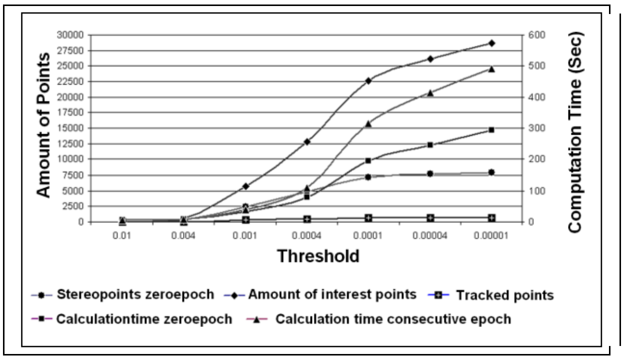


Figure 5: Overview over the test series – SURF-Operator

The measurements under realistic conditions (changing illumination, shadows, etc.) provide a sufficient amount of points for a representation of potential deformations. A remaining problem is the distribution of these points, which is currently only defined by mathematically defined local extrema in the image domain. A regular distribution of the points can be reached by a suitable grating of the image (the used process could be applied to each cell of a regular grid with different parameter settings). The systems most urgent problem is currently the computation time of the process. The detection of interest points and the necessary matching takes about 90-120 seconds for one pair of images (dependent on the amount of detected interest points) in the reference epoch and 30-45 seconds in the consecutive epochs. For the whole region of interest this means an overall computation time of about 440 minutes in the reference epoch and 155 minutes in a consecutive epoch respectively – these values refer to the limited computational power of a conventional field notebook (2.4 GHz Intel Core 2 Duo, 2GB Ram). The runtime shows that the current system is not suitable for an online application. The prototypical implementation of the point detection and matching will be greatly enhanced regarding computation time (reduction of the factor four to five) by reimplementation, optimisation, parallelisation, etc.

4. CONCLUSION AND PROSPECTS

The present article describes the first evaluation results of image-based deformation measurements. The used point detection and matching mechanisms have been described in detail. It could be shown that the developed system concept poses a promising approach which allows measuring large point clouds with high accuracy. The influence of illumination conditions can be strongly reduced by means of appropriate image pre-processing steps whereas the issue of cast shadows requires further research.

The advantage of such a measurement system compared to terrestrial laser scanning lies in the detection of distinctive points on the object (in contrast to an unstructured point cloud). The disadvantage is the necessity of constant illumination during the measurement which is not the case for terrestrial laser scanning.

Ongoing work concentrates on the improvement of the point detection and matching. In a first stage the use of available position and orientation information of the sensor was neglected in order to examine the robustness of the used process and operator. The next step will be the integration of this data through the use of epipolar geometry which can significantly reduce computation time and false matches thus increasing the accuracy. Furthermore the measurement system will be integrated in a geo-monitoring-framework which incorporates an alerting and early-warning-system as well as an interpretation and classification of the occurred deformations. Details about the corresponding research project can be found on the following website:
http://info.tuwien.ac.at/ingeo/research/imeas.

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