Automated Surface Documentation of Large Water Dams Using Image and Scan Data of Modern Total Stations

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Key words: dam monitoring, image assisted total station (IATS), terrestrial laser scanning, imaging, damage detection

SUMMARY

Large water dams are critical structures and therefore require monitoring in regular intervals with geodetic and geotechnical sensors to detect anomalies in their behavior. An important aspect related to dam safety is the concrete's state, which dam engineers currently assess by visual inspections and photo documentation. This methodology revealed several insufficiencies, which motivated different research groups to develop and apply new technologies such as Terrestrial Laser Scanning (TLS) and Imaging with inspection drones. In this paper, we present a new approach for surface documentation and evaluation of concrete dams, considering scan and image data of a state-of-the-art total station. In a case study at an Austrian concrete dam, we demonstrate the potential of merging geometry and texture information to derive a textured 3D surface model of the dam. Consequently, we rectify images of the dam's surface to obtain metric information without requiring direct access. Moreover, we introduce a novel surface monitoring solution, which automatically identifies and quantifies surface changes on concrete surfaces. We apply image-processing techniques directly on-site to detect existing and newly emerged concrete defects on the dam's surface such as cracks, erosion and sinter formations. The instrument starts an automatic acquisition of high-resolution data for a detailed documentation of the present defects. With multiple image sequences of the same region, we perform an automatic change detection analysis. Our proposed approach aims to provide a valuable basis for an objective assessment of the concrete's state of large water dams.

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1. INTRODUCTION

Understanding the behavior of large dams is of great importance to maximize operational lifetime and thus to reduce the risk of a sudden failure. Dam engineers adopt appropriate measurement schemes for individual dams to register relevant and characteristic parameters for dam safety assessment. By comparing the observed behavior to statistical or deterministic models (Schweizerisches Talsperrenkomittee, 2003 and Bukenya, 2014), structural anomalies are identified. Regarding health monitoring of large concrete dams, damage detection is besides deformation analysis another crucial component, as emphasized by the International Commission on Large Dams (ICOLD, 2013).

Today, competent experts perform the damage detection by visually inspecting the dam's surface and its surroundings, where special emphasis is put on well-known deficiencies of concrete dams such as cracking, spalling, pop outs, erosion and leakage. In order to detect changes on the concrete surfaces and to monitor the long-term deterioration process, a detailed documentation of the current dam's state is required.

For that purpose, dam engineers make records, sketches and take photos from accessible points of view. Additional to the inspection results summarized in a report, the inspector creates a CAD drawing indicating the approximate size, shape and position of the defects (e.g. see example for an Austrian dam in Fig. 1).

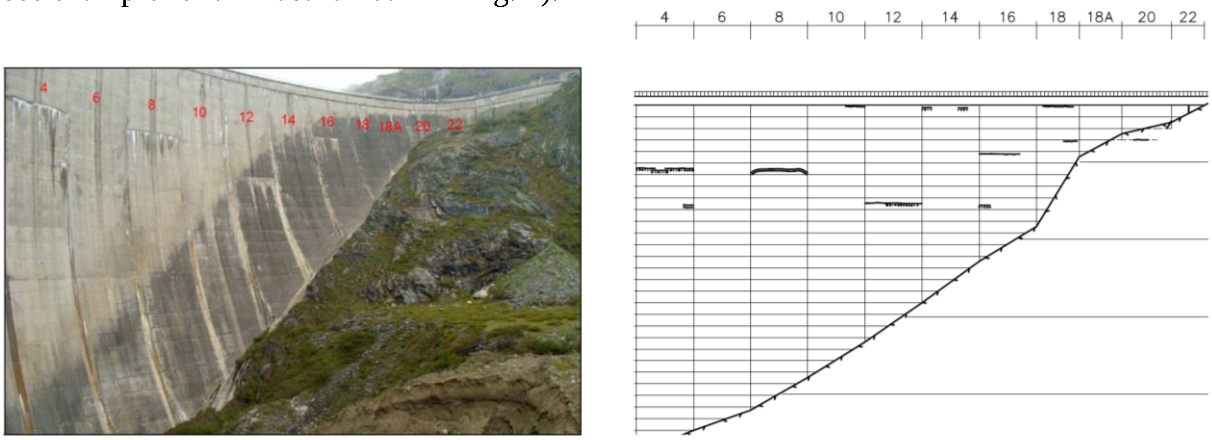


Figure 1: Photograph of the downstream side of the Drossen dam (left), corresponding CAD drawing showing defect locations (right, Verbund, 2011)

From the perspective of dam operators, this approach has proved insufficient. The documentation is inaccurate, often incomplete and subjective. A better photo documentation has been achieved by abseiling or elaborately operating a suspended platform with a remote-triggered camera from the dam crest (Sensefly, 2016). The recent development of Unmanned Aerial Vehicles (UAV) facilitated the process of acquiring close shots of the dam's surface substantially. Henriques and Roque (2015) gathered overlapping images with an UAV covering the full dam and processed it photogrammetrically. Camp et al. (2013) used also photogrammetry to derive the surface geometry of a concrete dam in France from images captured using a camera with a telescopic lens. A method for actively acquiring point clouds is Terrestrial Laser Scanning (TLS), which provides the necessary information for rectifying the images captured with a mounted Single Lens Reflex (SLR) camera from selective setup points (e.g. Berberan et. al., 2011). To register scans and images from multiple setup points, surveyors commonly use reference points, from which coordinates are determined with a tachymeter in advance. In the case of the Portuguese Alto Ceira dam, Berberan et al. (2006) used 21 retro-reflective targets to reference three setup points.

The latest high-end instruments of different total station manufacturers (Leica 2016, Topcon 2016, and Trimble 2016) comprise imaging and scanning functionalities, which opens up new fields of application such as surface mapping. Consequently, using these so-called Multi Stations promises to facilitate the documentation process of dam surfaces. In this paper, we present an approach for surface documentation and evaluation of an Austrian arch dam. Considering scan and image data of modern total stations, we propose a procedure in Section 2 for deriving a photorealistic 3D model of the dam's surface. Additionally, we introduce a novel system concept for automatic on-site detection and mapping of concrete deficiencies with high-resolution in Section 3. In this surface monitoring solution, we apply state-of-the-art processing techniques to the scan and image data while exploiting the hardware features of the hybrid instrument. In Section 4, we demonstrate the potential of multi temporal orthoimages, processed from data of a Multi Station, for detection and quantification of surface changes on an arch dam.

2. MAPPING THE SURFACE OF CONCRETE DAMS WITH MODERN TOTAL STATIONS

2.1 Measurement campaign at an Austrian arch dam

We performed measurements at the Drossen dam, which is located near Kaprun in Salzburg. With a maximal height of 112 m and a crest length of about 360 m, it is one of the largest concrete arch dams in Austria. Together with the Mooser dam, it impounds the Mooserboden reservoir (see Fig 2.).

Figure 2: Measurement site, overview image showing the two concrete dams of the reservoir Mooserboden (left, source: Verbund), frontal view on the downstream side of the Drossen dam with the instrument set up at point P_1 (right)

Due to the large object-to-instrument distances (up to 200 m) and the scan range limitations, at least two setup points were required to cover the full dam. In order to speed up the data acquisition, we decided to use two Multi Stations simultaneously set up at P_1 and P_2 (see Fig. 2 left). We used fix points with known coordinates to reference measurements from both instruments in the national reference system.

We chose a Multi Station Leica MS50 and a Leica MS60, both providing the same image and scan related specifications (Leica 2013, Leica 2015). The used Multi Stations are also image assisted total stations (IATS) offering two cameras: the Overview Camera (OVC) and the On-Axis Camera (OAC). The OVC is a wide-angle camera with fixed focus and a large field of view (FOV) located above the telescope (see Fig. 3), whereas the OAC has a small FOV but benefits from the telescope's 30× magnification, providing image content rich in detail. Calibration of the OAC (cf. Ehrhart and Lienhart, 2015) gives an angular resolution of approximately 1.96″/px in horizontal and vertical direction, which corresponds to a spatial resolution of 1 mm at 100 m distance. The Multi Stations MS50 and MS60 acquire up to 1000 points per seconds with an accuracy of 2 mm at 100 m according to the specifications of the manufacturer.

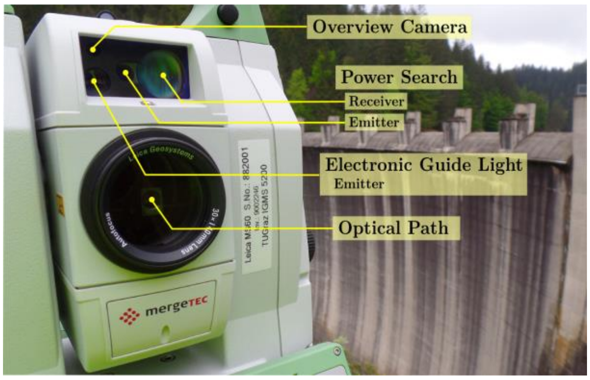


Figure 3: Illustration of the relevant components of the Multi Station MS60

Altogether, we acquired point clouds with around 10 million points and 300 OVC photos completely covering the Drossen dam. The fully automatic acquisition of scan and image data took about 4 hours in total.

2.2 Processing of scan and image data

The term "surface mapping" refers to the process of combining geometry and texture content of an object's surface. The principle workflow for processing the acquired scan and image data to derive a textured 3D photo model is illustrated in Fig. 4 and explained below.

TLS data processing consists of point cloud registration, filtering, outlier elimination and hole filling procedures. We then use the modified point cloud to reconstruct a continuous digital representation of the surface with a combined approximation-interpolation method. We partition the data space into voxels, for which we compute characteristic points by averaging the respective points inside. This step provides a simple but effective approximation method and hence noise reduction. Eventually, we use 3D Delaunay triangulation to compute a triangle mesh, i.e. a set of triangles connecting the averaged point cloud.

Dependent on the properties of the captured images, we apply automated image processing techniques to reduce radiometric differences and thus to obtain a homogenous texture.

The camera model (i.e. interior and exterior camera orientation) establishes the spatial reference for projecting the images onto the triangle mesh. Using a Multi Station with a calibrated camera, the surveyor directly obtains photos with orientation parameters. The projection process, also referred to as texture mapping, produces a photo realistic 3D representation of the object, which we then map onto a plane to generate an orthoimage with metric information.

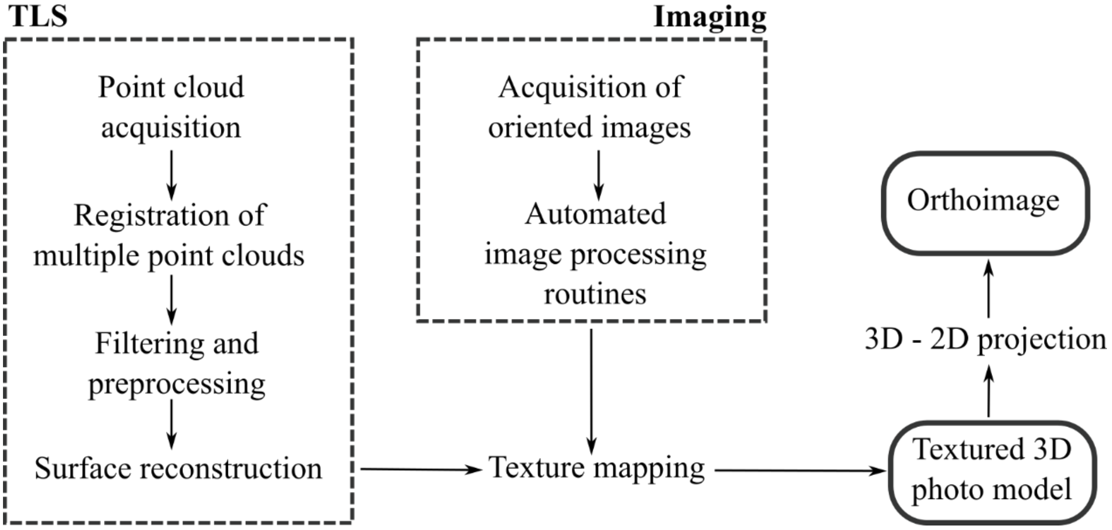


Figure 4: Workflow for deriving textured 3D photo models from scan and image data

2.3 Results

Following the processing procedure described in Section 2.2, we derived a textured 3D photo model of the Drossen dam. The right-hand side of the model is depicted in Fig. 5 (same section as in Fig. 1).

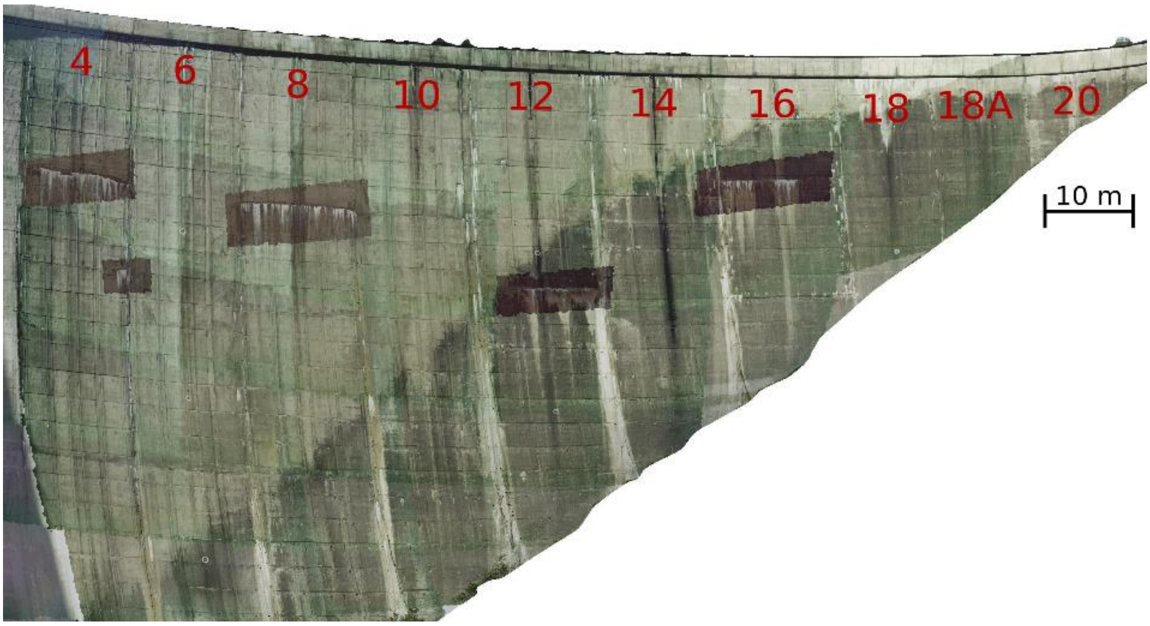


Figure 5: Textured 3D photo model of the Drossen dam (showing the same area as Fig. 1)

Apart from OVC images covering the complete dam, we captured OAC images of selective defects and used them for texture mapping as well. Hence, large-scale textures and high-resolution textures are combined in one model providing a detailed documentation for areas of interest at relatively low memory capacity and computational cost. For defect regions, we generate orthoimages with sequences of overlapping high-resolution OAC photos (see Fig. 6). While easy to handle, orthoimages provide a valuable data basis for an objective assessment of the concrete's state. It is now possible to measure on the dam's surface without requiring direct access.

Figure 6: Orthoimage of a defect region on the downstream side of the Drossen dam (block 16), derived from 21 OAC textures (1 pixel corresponds to 2 mm on the surface)

2.4 Operational capability of Multi Stations

Gong et al. (1999) demonstrated the potential of a scanning and imaging theodolite prototype for computing textured 3D models well before the introduction of commercially available Multi Stations. The state-of-the-art instruments proved suitable for mapping the surface of concrete arch dams. In the following, we summarize the insights gained from our studies.

- Despite the scanning functionality, Multi Stations are not comparable to full laser scanners. Due to limitations in the measurement rate, data acquisition requires considerably more time.
- The image quality of Multi Stations is highly dependent on the ambient light conditions. As photo settings are limited, it is likely to capture oversaturated or dark and noisy images, especially when photographing from the downstream side of the dam.
- Therefore, Multi Stations cannot yield viable data at any time but only at cloudy, bright days.
- Benefiting from classic total station capabilities, the handling of Multi Stations is easy. The competent surveyor can use prisms, which are initially set out for traditional deformation measurements, to reference scan and image data of the Multi Station as well. Hence, no additional hardware or accessories are required.
- With the station setup and the calibration of the Multi Station cameras (cf. Ehrhart and Lienhart, 2016), the orientation parameters are directly known for each image.
- Investigations showed that the surface's geometry is reproduced with millimeter accuracy and textures are aligned at subpixel level.
- Based on our findings, we therefore conclude that the time-consuming scanning process has to be performed only once for each dam. Using stable points for referencing, we can combine newly acquired image data with scan data from the initial measurement campaign.
- Hence, it is possible to generate 3D photo models and orthoimages of defects for subsequent measurement epochs, requiring only a few minutes of data acquisition.

3. DEVELOPMENT OF A SURFACE MONITORING SOLUTION FOR VISUAL CHANGE DETECTION

Large civil structures commonly feature some concrete deficiencies, which, in principle, do not necessarily pose a risk to the structure's safety. Therefore, knowledge about the exact crack length and width (e.g. Fig. 6) is not required but detecting any visual changes in the defect region is rather crucial for Structural Health Monitoring (SHM).

In the past, various research institutes developed different systems to assist the operator in visual inspection and change detection. Stent et al. (2013) used a flatbed trolley with a synchronized overlapping array of cameras to inspect tunnel linings. From the initially acquired reference images, they used Structure for Motion (SfM) techniques to recover 3D geometry and image processing techniques to register new images captured at subsequent surveys.

Stratmann et al. (2008) introduced a new system to record cracks at concrete structures by pressing the developed SLR camera attachment against the structure. The system provides high-resolution quality images for crack delineation and enables the measurement of crack length and width with an accuracy a few hundredths of a millimeter. However, this approach turned out to be very costly as direct access to the structure is required.

Consequently, autonomous devices established themselves for the purpose of visual inspections. Dyke et al. (2015) used images gathered with an UAV to emphasize the potential of computer vison routines for SHM of bridges. Likewise, Lee et al. (2007) developed a system, which automatically acquires images using a camera mounted on a telerobotic platform and performs crack detection on bridges.

Regarding the approaches applied in the past, Multi Stations clearly constitute a promising approach for assisting the visual inspections of civil engineering structures. Huep (2010) demonstrated the potential of combining classic total station capabilities with scanning and imaging features for modelling concrete cracks in 3D space.

We introduce a novel surface monitoring solution for concrete dams using Multi Stations which

- automatically acquires scan and image data,
- identifies old and new defects, and
- evaluates the extent of the automatically detected surface changes.

3.1 Operating principle

The primary objective is to detect any changes on the dam's surface, that is, the appearance of new defects and the extent of deterioration in existing ones. In principle, we exploit the spatial information of the Multi Station and use images to derive semantic information for visual change detection. We divide our evaluation into two parts: the on-site detection and acquisition and the change detection analysis, which we perform in a subsequent step (see Fig. 7).

We developed an application to carry out all required work processes on-site on a standard laptop. To this end, we use the GeoCOM protocol to communicate with the Multi Station Leica MS50/60. Having defined the contours of the dam's surface, the instrument starts full dam photo acquisition with the OVC. Applying image-processing techniques to the OVC images, we localize defect regions on the dam (cf. Section 3.2). Using the known camera model, we refer results from the image processing to spatial information, i.e. horizontal (Hz) and vertical (V) angles. We then automatically acquire high-resolution scan data and OAC photos with the Multi Station of all potential defects. To distinguish between false detections and true defects and thus to minimize the time and effort required, the operator performs a manual classification on-site. However, to enhance the entire acquisition process, we propose an automatic classification procedure based on foreknowledge. Therefore, we establish a database containing coordinates of true defects as well as mistakenly identified defect regions in past surveys. The results of the automatic defect identification is hence dependent on the scope of effort spent on machine learning (in terms of spatial or semantic information).

According to the procedure described in Section 2.2, we process the data to derive 3D photo models and orthoimages for each measurement epoch. Multi-temporal orthoimages provide the basis for our change detection analysis of existing defects on a dam's surface. Accordingly, we use image-based processing techniques to automatically localize and quantify surface changes (cf. Section 3.3).

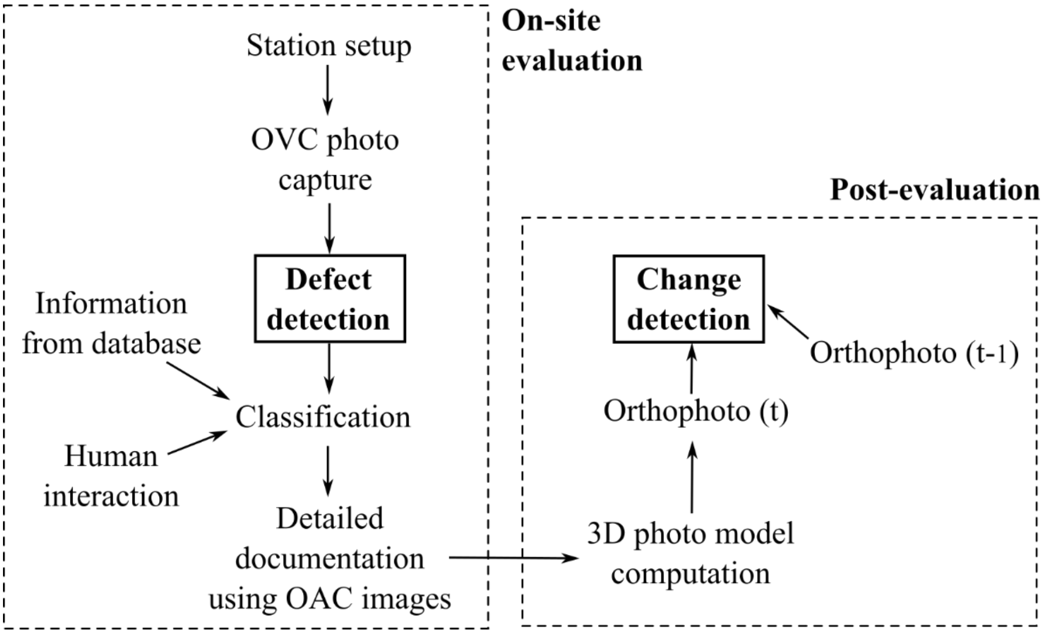


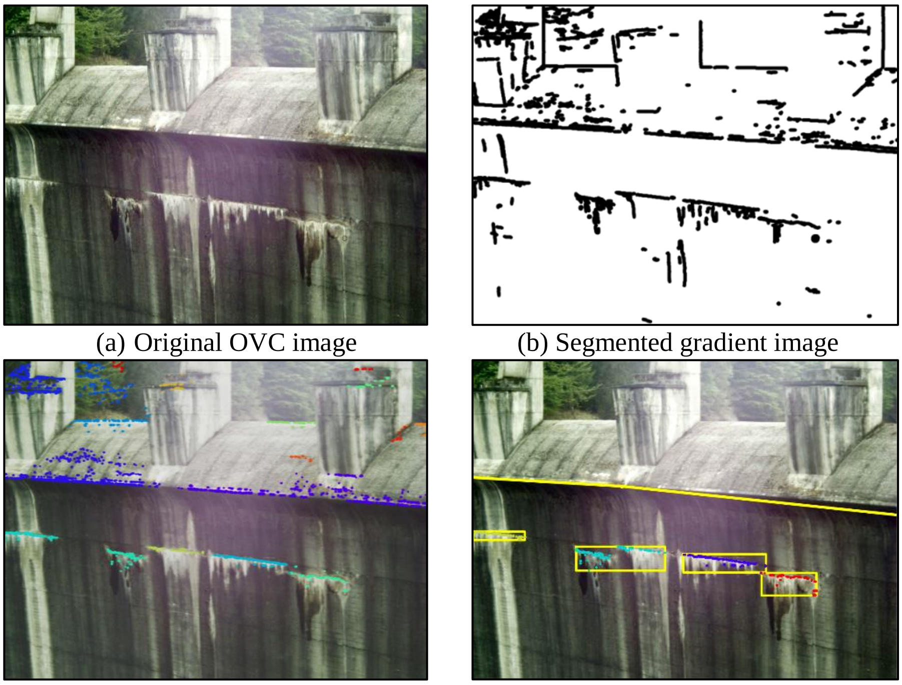
Figure 7: Operating principle of the proposed surface monitoring solution

3.2 Automatic on-site defect detection and documentation

The goal is to develop a computer algorithm for damage detection performing similar to a human inspector. The knowledge about the visual appearance of concrete defect is crucial for the recognition. For example, white spots on a concrete surface usually imply sinter formation, which may result from cracking or block joint openings. Wet areas, pop outs and other deficiencies evoke recognizable visual irregularities. Consequently, we analyze the captured OVC photos on these characteristics.

Many researches around the world addressed the issues of manual, visual inspections by applying image-processing techniques. However, most of the publications focus on detecting and analyzing cracks (e.g. Rabah et al. 2013, Valenca et al. 2013, Mohan and Poobal 2016). We generalize our analysis to detect any kind of concrete deficiencies on a dam using the captured OVC images. Our approach consists of four major steps:

1. **Pre-Processing**: The image resolution and the number of channels define the image matrix dimensions. For further processing, we convert the RGB images (width×height×3) to grayscale images (width×height×1). Dependent on the image noise, we apply a Gaussian smoothing with variable kernel size (e.g. 11 px).
2. **Image feature description:** Information and feature extraction require appropriate image processing techniques. To address sinter formations, we consider a minimum value of pixel intensity. In contrast, we compute image gradients in both directions to detect any visual irregularities. Pixels with high gradient values constitute potential feature points. We then reduce the image color depth from 8 bit to 1 bit producing a binary image (cf. Fig. 8b). Pixel intensities or gradients above a threshold equal zero (black), while all other pixels values are set to 255 (white). By using Otsu's method (Otsu, 1979), we achieve an automatic threshold selection.
3. **Clustering:** The spatial distribution of the extracted individual pixels defines the criteria to generate coherent pixel clusters (cf. Fig 8c). The algorithm *Density-Based Spatial Clustering of Applications with Noise* (DBSCAN) defines a cluster as a set of pixels, within which the data density is sustainable higher than outside. Ester et al. (1996) suggest a heuristic for the variables in the DBSCAN algorithm.
4. **Spatial Filtering:** The procedure described so far is not able to distinguish between the dam surface and other objects (e.g. vegetation, cf. Fig. 8c upper part). To enhance the detection results, we exploit the known camera model of the Multi Station (cf. Section 2). We transform the discrete points representing the contour line of the dam's surface into the image space. We create a polygon to filter out the clusters, which do not cover the dam (Fig. 8d).



(a) Original OVC image (b) Segmented gradient image

(c) Grouped image regions (d) Filtered and identified defects

Figure 8: Important steps of the defect detection algorithm

Eventually, we compute the direction to the defects using the pixel coordinates and the known camera model of the representative MBRs (minimum bounding rectangle, see Fig. 8d).

3.3 Visual change detection of surface conditions

The detection of visual changes in images is a well-researched topic in the field of remote sensing (cf. Lu et al. 2004). Consequently, a wide range of approaches developed for automatic unsupervised change detection analysis in the past years. However, it turns out that these algorithms are well suited not only for large-scale satellite images but also for high-resolution orthoimages of concrete defects.

One approach is to compare the pixel intensities of two images by e.g. differencing, rationing or by image regression (cf. Lu et al. 2004). It is simple, easy to implement but is sensitive to the acquisition conditions. Therefore, it is essential to pre-process the data, i.e. to match the images in terms of radiometry and spatial coverage.

We adopted the basic procedure for change detection analysis according to Niemayer et al. (2007) to orthoimages derived from the OAC of a Multi Station. The analysis consists of following steps:

1. **Pre-Processing and image registration**: We again consider only 1-channel images, i.e. grayscale images. To get both images (I^1,I^2) to overlap, we apply an image transformation based on homologous points found in both images. We compute and match SIFT features and eliminate outliers with the RANSAC.
2. **Image differencing:** The registration process yields images referenced in a common coordinate system. It is thus possible to subtract overlapping image regions for comparison (I_d).
3. **Thresholding:** We map the difference image to a binary image (I_b) by thresholding (see Section 3.2). The threshold results from a statistical analysis performed using Otsu's method.
4. **Clustering:** We group individual pixels to coherent regions with the already mentioned DBSCAN algorithm to derive a change map (Π_σ). The clusters represent characteristic surface changes.
5. **Evaluation:** We compute the area of the clusters to quantify the surface changes $\Delta\sigma$.

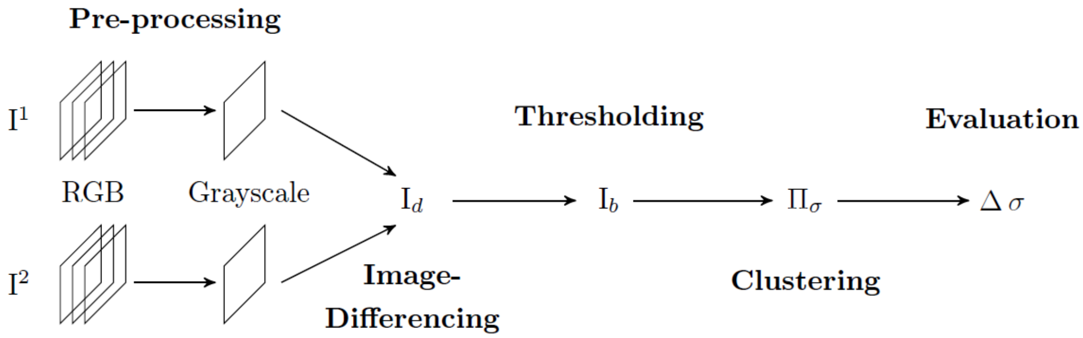


Figure 9: Illustrated workflow for intensity-based change detection analysis

In comparison to the automatic defect detection algorithm (cf. Section 3.2), no filtering is required. That is because mistakenly identified changes have no impact on the further data processing. In the end, the definitive safety assessment of the dam remains the task of the competent dam engineer.

4. CONCLUSION

Visual inspection and documentation of the concrete's state constitute crucial components in health monitoring of large water dams. In this paper, we presented a new approach for surface documentation using scan and image data of modern total stations. The proposed method is easy to perform for surveyors and requires less effort in data acquisition and processing compared to other measurement principles (e.g. documentation with UAVs).

The used Multi Stations benefit from classic setup routines providing referenced point clouds and oriented images at the time of measurement. Hence, if stable points with known coordinates exist for referencing the measurements, the surveyor has to perform the time-consuming scanning process only once. It is thus possible to combine geometry acquired at the initial measurement epoch with photos captured at different measurement times to derive textured 3D models and orthoimages.

We introduced a novel surface monitoring solution to address the risks related to visual changes on dam surfaces. By applying image-processing techniques to the acquired overview images, we automatically detect concrete deficiencies. With a database containing information from previous surveys, the system identifies newly emerged defects directly on-site. Subsequently, the instrument takes telescope images and scans dense point clouds of selective defects. As a result, the developed system provides multi temporal orthoimages with high resolution, which we utilize to detect and to quantify changes on dam surfaces.

Our proposed approach delivers data, which is accurate, complete and objective. However, our system does not intend to replace the human inspector but it aims to provide a valuable data basis to enhance the safety assessment of large concrete dams.

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BIOGRAPHICAL NOTES

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