Early detection, permanent monitoring and documentation of critical locations at the surface in mining areas

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ABSTRACT

Being responsible for the legacy risks of the underground hard coal mining in Germany, RAG is developing a remote sensing-based monitoring workflow for the early detection and long-term monitoring of ground movements in areas affected by near-surface mining in the southern Ruhr region, Saar region and Ibbenbueren. The workflow to detect surface fractures like sinkholes is based on high resolution airborne imagery and simultaneously recorded ALS data. As a part of RAG's overall concept in the field of multi-sensor monitoring of ground movements this workflow has been steadily improved and will be further on. The complete monitoring area that is covered by the workflow is about 415 km². This paper first outlines the procedure of detecting ground movements by remote sensing. RAG uses an approach with annual simultaneous multispectral image and laser scanning flights. Due to the often small scale phenomena of sinkholes of only a few meters in diameter, a high accuracy of the sensor technology as well as all preceding processes like the determination of control points and reference surfaces is necessary. The process of accuracy assessment is done using continuous GNSS measurements for tie points and the projection centers of the aerial imagery as well as classic photogrammetric stereoscopic measurement. The derivation of geospatial products such as high resolution ortho imagery and digital elevation models will be covered as well as the processing of these datasets to reveal information necessary for risk analysis. The approach is based on the detection of subsidence structures in single date elevation models by pattern recognition as well as the calculation of differences between those datasets. The processing is followed by a step of data enrichment from different mining related data and stored in a specially created database. This enriched data source is provided through a modern GIS application which enables the employees to do the risk analysis and to document their findings. Ongoing research projects are evaluating the future use of artificial intelligence and machine learning to further automate the workflow.

I. INTRODUCTION

As one of the legal successors of the German coal mining industry, RAG is responsible for monitoring, securing and rehabilitating areas under the influence of pre-industrial near-surface mining. In NRW alone, there are a total of about 31000 old adits.

The area of responsibility of RAG with approx. 7400 shafts and surface openings in North Rhine-Westphalia and Saarland.

This near-surface mining still poses risks today, in some cases hundreds of years later. Sinkholes in which parts of the earth's surface above old shafts and ducts collapse, sometimes spontaneously, can not only cause damage to infrastructure and buildings, but also pose a danger to people.

Since 2013, RAG has been developing a large-scale monitoring system based on remote sensing for the early detection of suspected areas (Figures 1 and 2). Of particular interest here is subsidence in the terrain, some of which are only a few centimeters (Spreckels *et al.*, 2016).

In addition to classic time series analysis of digital terrain models, the monitoring concept enables the analysis of individual time slices using specific evaluation algorithms. This involves a targeted search for mining-specific terrain types in a data set.

Figure 1. Near surface mining induced sinkhole. Image courtesy, RAG.

The results are then enriched by various attributes and combined with a variety of data available at RAG. The results are stored in a database, that then again enables an analysis over several periods. The database represents a working foundation to employers which specifically work on risk management of post mining areas and assist the decision making about further actions like planning remediation of old shafts.

One of the challenges of this project is the shear amount of data to be processed. The raw data of the aerial surveys alone have a size 100 TB per year and the current flight campaign must be compared to former flight campaigns, so a large amount of data storage is needed.

Figure 2. Aerial image detail view of a refurbished sinkhole. Image courtesy, RAG.

A. *Aerial Imaging and Airborne laserscanning*

The basis for this monitoring is provided by high-resolution aerial surveys. These are performed annually outside the vegetation period to obtain the clearest possible view of the ground. Depending on the total area to be covered the UltraCam Falcon or UltraCam Eagle cameras from Vexcel Imaging are used here. The ground sampling distance (GSD) of the image flights is about 3 cm while recording 4 spectral channels: RGB and near infrared. Since 2015, the image flights have been carried out simultaneously with the airborne laser scanner IGI Litemapper 7800 on board, that records the terrain in the form of a 3D point cloud with approx. 10 to 20 points/m², depending on the relief characteristics.

B. *Ground control points and ALS control planes*

Since the ground motions that must be recorded in the study area are about >10 cm, it is necessary to set up a stable configuration of ground control points (GCP) for the accuracy verification of the aerial survey (Figure 3). Since the ground resolution of the images is about 3 cm, the accuracy of the GCP measurements in position and height should be about 1 cm to enable accurate measurements and comparisons for accompanying flight campaigns. Since GCP are measured using GNSS methods in the SAPOS reference network, most of the time those accuracies are not obtained, mainly because of too long base lines to the reference stations and possible individual movement components on the SAPOS stations (Schulz and Schäfer, 2022; Niemeier and Tengen, 2022).

Therefore, RAG has planned and set up its own network of GNSS base stations, around the areas affected by post mining (Spreckels 2022; Spreckels *et al.*, 2020). This network is connected to SAPOS and allows GNSS measurements with much shorter baseline lengths. This network was set up in 2017 and since then two approaches of measuring were pursued. In both approaches each ground control point is measured twice, with the first approach measuring 60 minutes each and the second approach measuring 15 minutes each. This new network is still in construction. The system is still being tested and a decision which method will be used will be probably made within the next year.

Figure 3. Measurement of ground control points. Image courtesy, RAG.

However, these control points can only be used for aerotriangulation of the acquired images. The airborne laser scanning data are directly referenced on board the aircraft without control points, which leads to an insufficient linkage of the individual flight strips. This results in position and height errors of up to 30 cm at the boundaries of the flight strips. To eliminate such errors, first only the images are triangulated and then a photogrammetric measurement of roof surfaces is performed. These roof areas are finally used as reference areas for ALS data (Figure 4).

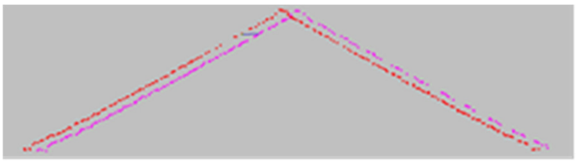

Figure 4. Position and resulting height offset at the edge of the ALS flight strip (Spreckels *et al.*, 2016).

II. RAG INVESTIGATION AREAS

A. *Ruhr*

In the Ruhr region only areas around the river Ruhr and south of it are part of the monitoring, because only in these areas of the Ruhr near surface took place (Figure 5). Due to the geology the coal seams outcrop here or lie close under the surface.

This region covers about 135 km² which leads to about 6000 aerial images captured by the UltraCam Falcon annually and processed in two blocks. The whole area is covered by 104 ground control points.

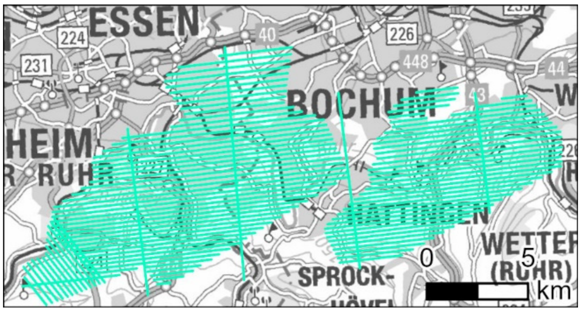

Figure 5. Overview of the monitored areas in the Ruhr Region. Image courtesy BKG, RAG.

B. *Ibbenbüren*

Coal mining in the Ibbenbüren region has a history of about 500 years in a relatively small area. Here, coal-bearing layers were partially lifted to the surface by an igneous intrusion.

The aerial survey in this area covers about 55 km² which leads to about 1700 aerial images annually and 37 ground control points (Figure 6).

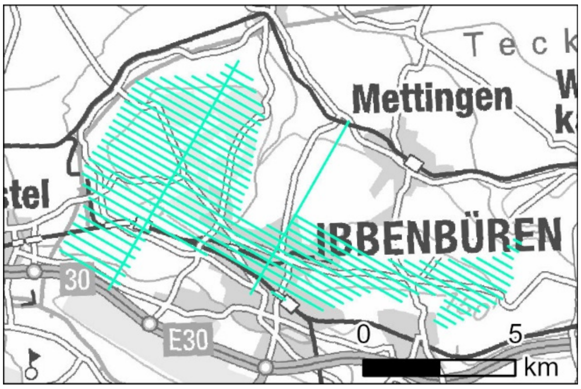

Figure 6. Overview of the monitored areas in Ibbenbüren. Image courtesy BKG, RAG.

C. *Saarland*

The monitoring in the Saar region covers an area of about 281 km² which leads to about 9500 aerial images captured with an UltraCam Eagle. 225 ground control points are used to assure accuracy (Figure 7).

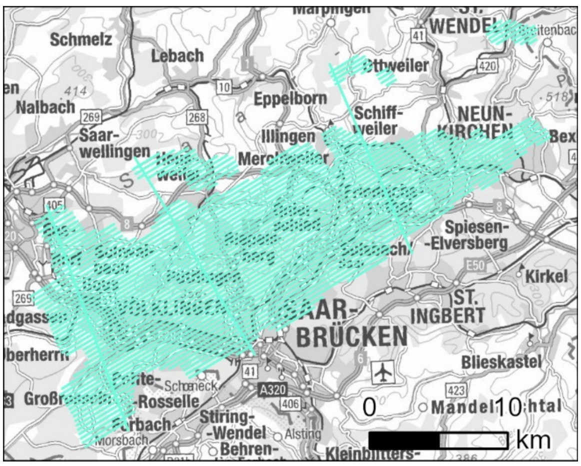

Figure 7. Overview of the monitored areas in the Saar Region. Image courtesy BKG, RAG.

III. Data processing

This chapter will present an overview of the geospatial products derived from the captured remote sensing data as well as their storage and further analysis.

A. *Derived products*

As previously mentioned, the main products of the aerial surveys are high resolution aerial images as well as ALS point clouds. The first product derived is a bundle adjusted block of images of each area using Agisoft Metashape. This allows stereoscopic measurements in images pairs from which the control planes (*e.g*. roofs) for the adjustment of ALS data is retrieved. The images are then mosaicked to a seamless 4 channel orthophoto which allows easy navigation and primarily visual analysis.

The adjusted ALS point are processed using LAStools software. The first processing step includes the classification of ground points from which a sparse digital terrain model is derived for rectification of the orthophoto. Afterwards the point clouds are classified to distinguish between points that represent vegetation and those representing buildings and manmade structures like bridges and powerlines. The final digital terrain model used for further analysis is then calculated using the ground and building points. The buildings are kept in the output data because there are no points recorded under them representing the earth surface.

B. *Depression detection*

Based on the high-resolution digital elevation models RAG has developed an ArcGIS Pro workflow which finds mining specific surface structures in a single time slice of those datasets. Typical surface structures of near surface mining are small scale depressions near to shafts or above adits. The workflow is designed in a way that it is only sensitive to depression like structures like mounds that lay underneath the surrounding terrain. The results are in vector format so further analysis can be performed using GIS software (Figure 8).

While the workflow detects numerous features, a filtering is required. Therefore, the resulting data is intersected with multiple RAG datasets such as coal seam outcrops, known locations of shafts and risk areas. The results of this process are then saved into a database and enriched with additional attributes which are calculated on the datasets. These attributes include *e.g*. the date of first occurrence, the distance to the next shaft, the depth of the depressions, the count of ALS points inside the depression geometry, the diameter and perimeter, the average slope of the depression as well as a shape index that describes the roundness parameters of the depression.

The system recognizes multiple occurrences of depressions in different time slices and links them in the database so that it is possible to monitor changes of each specific depression over the time. The monitoring capabilities include accessing the height differences of a selected depression to any other time slice it was found in, as well as changes in the perimeter.

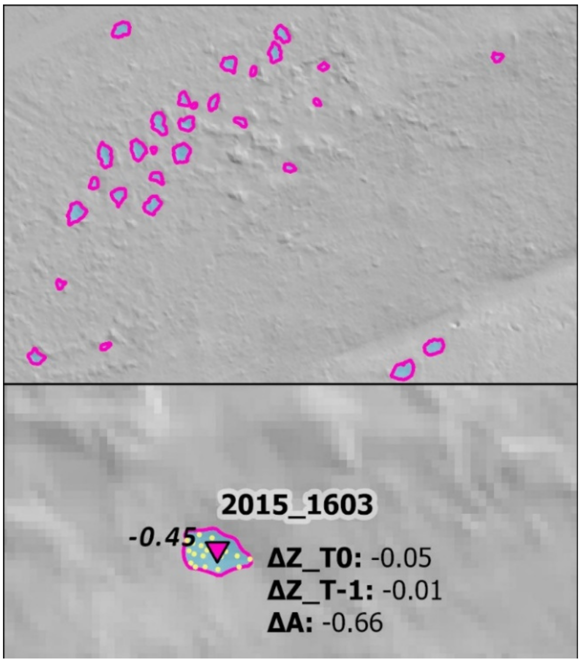

Figure 8. Graphical representation of depressions in the monitoring application. Upper image: view of a cluster of depressions in a forested area. Lower image: Detailed view with additional information.

C. *ABMon-Application*

The depression database as well as all the other derived products must be prepared for subsequent work and made available to employers of the risk management in a suitable form.

Therefore, RAG uses many of ArcGIS built in features to build up an application where all the derived products of the aerial survey as well as additional RAG datasets are available in thematic views (Figures 9 and 10). These views may be customized by each user, depending on their specific task. By default, there are four views available, which are linked, so if one map is moved all the others move too. These views include the orthophoto, the shaded relief derived from the digital elevation model, a topographic map as well as old mining plans that were digitized and georeferenced. With this user interface, which can be customized by every employee a broad variety of risk management workflows can be performed. Beside the standard map view there also is the possibility of grouping the data by for example all depressions with certain height differences between time slices. Furthermore, it is also possible to apply filtering based on external data like shafts or risk areas. Another functionality is a time slider through which it is possible Another feature is the time slider, which provides the possibility to visualize changes in the found depressions over time in a simple way. Finally the application offers the possibility to generate reports which allow the users to simply document their work and share it.

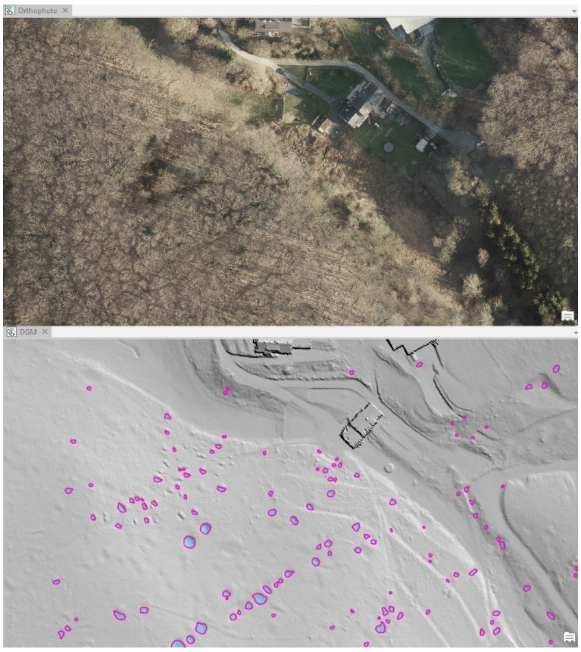

Figure 9. Screenshot of a subsection of the ABMon application. Left image: orthophoto. Right image: shaded relief with detected depressions represented by polygons. Image courtesy: RAG.

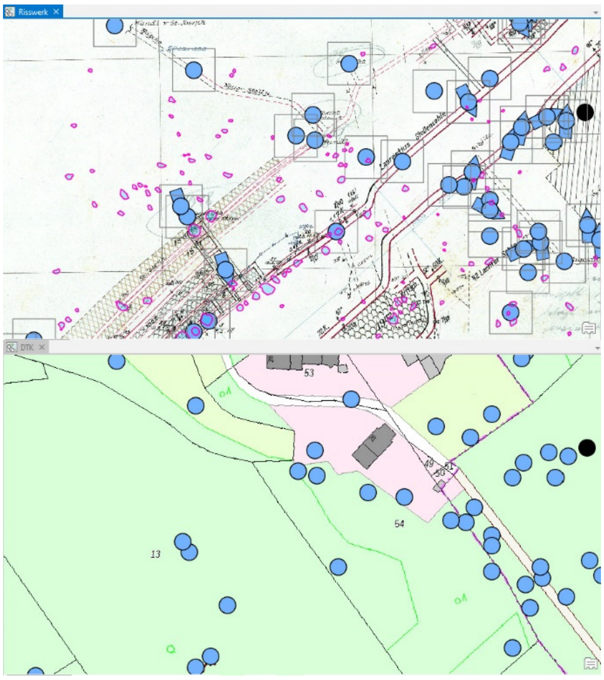

Figure 10. Screenshot of a subsection of the ABMon application. Left image: Mining plan with depressions and locations of know shafts. Right image: Topographic map with location of known shafts. Image courtesy: RAG.

IV. Conclusions and Outlook

While several years of aerial surveys with the goal of detecting ground movements in areas influenced by near surface mining have shown that it is possible to achieve the required accuracies, work is still in progress related to analysis of the derived geospatial products.

With the development of the depression database as well as the monitoring application RAG has taken a step towards dealing with the consequences of near surface mining in a sustainable way. Until now most of the tools rely on standard GIS functionality but the fact that all the recorded and processed data is archived offers the possibility to quickly react to possible future developments of algorithms and advances in geospatial technology.

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