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Report on the Doctoral Thesis by Agata Walicka: Application of terrestrial laser scanning for the monitoring of changes in the mountain river bed

1) Background

Ms. Walicka has chosen a topic of high scientific and practical relevance. Monitoring of river beds is important for hydrological applications. In this context, remote sensing techniques, which, unlike other methods, deliver data without physical contact with the object of interest, have been gaining increasing attention. However, standard methods are based on a comparison of height data only. Whereas they can identify areas where changes have occurred, they cannot be used for a precise monitoring of mass transportation between different epochs of data acquisition, because it is impossible to determine the shift of individual particles (e.g., rocks) between these epochs.

This is where Ms. Walicka's thesis comes into play. She presents a method for detecting individual rocks and for determining their movement between different epochs, which could form the basis for finding out not only how much mass was moved between epochs, but also how the movement occurred. For that purpose, she uses terrestrial laser scanner data.

2) Content of the thesis

Ms. Walicka has submitted a cumulative thesis. It is written in English and consists of two main parts. The first part presents an overview of her work, describing related work in point cloud processing and showing how the papers collected in the thesis contribute to the solution of the research questions posed by the candidate. The second part of the thesis consists of the five research articles which constitute this cumulative thesis. Three of them appeared in peer-reviewed journals, two articles were published in conference proceedings of the International Society of Photogrammetry and Remote Sensing (ISPRS Archives) and were accepted on the basis of a peer review of extended abstracts.

Section 1 of the thesis presents the motivation for this research. It gives a brief overview over existing techniques for determining sediment transport and describes why terrestrial laser scanning (TLS) can provide a good alternative to these techniques. Finally, Ms. Walicka presents four research hypotheses which she wants to investigate in her thesis. They are essentially related to the question whether or not it is possible to detect and track rocks in time series of TLS data of riverbeds in an automatic way.

Section 2 gives an overview over fundamental techniques and related work in point cloud processing. After describing different ways of defining distances between points and point neighbourhoods, hand-crafted features that are

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representative for a point and its local neighbourhood are introduced. This is followed by a categorization of clustering techniques and a brief overview over machine learning methods. A very brief categorization of instance segmentation methods, i.e. methods that do not only assign class labels to points but additionally identify groups of points corresponding to individual objects, is also given. The last subsection deals with point cloud matching, which is required for tracking points across data from different epochs, and covers both, matching methods for coarse registration and the iterative closest point (ICP) method for fine matching.

Section 3 presents an overview over the five articles constituting the thesis and describes how these articles interact to answer the research questions posed in section 1. The first article (Water, 2019) describes the problem domain, the data acquisition and the dataset used throughout the thesis. It also provides a proof-of-concept that the identification of rocks in multi-temporal TLS data is possible using manual measurements. Articles 2 and 3 deal with the first main methodological contribution of Ms. Walicka, a method for instance segmentation of rocks in TLS data. In this context, the conference paper (article 2, ISPRS Archives, 2018) introduces the principles and some preliminary experiments, whereas the journal article (article 3, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 2022) describes the final method and extensive experiments. Articles 4 and 5 are dedicated to the second major methodological contribution, the tracking of rocks in time series of TLS data. Again, the conference paper (article 4, ISPRS Archives, 2019) presents a first proof-of-concept and experiments for parameter tuning, whereas the journal article (article 5, Measurement, 2021) describes the final method and gives an extensive evaluation.

Section 4 summarizes the conclusions of the thesis. The results of the individual steps of the workflow presented in the five papers confirm that an identification of rocks is possible with an accuracy of 67%-88%, depending on the complexity of the scene, if the rock size is at least 10 cm. The re-identification of rocks of that size is also possible, with an accuracy of 85%. These results confirm the research hypotheses stated in section 1; they also show the limitations of the developed methods.

Paper 1 (Water, 2019): This paper embeds the methods developed by Ms. Walicka in the application domain of hydrology. It presents the study site and the acquired data, a section of a river in Poland scanned in the October of every year from 2011 to 2016. A synthetic riverbed with manually displaced rocks serves as a second test dataset. The paper also presents two semi-automatic workflows for measuring the displacement between rocks in datasets acquired at different epochs. The first one identifies potential areas of change by a comparison of grid-based digital elevation models (DEM), whereas the second one directly compares the point clouds. The actual displacement measurements are performed manually.

The results achieved for the synthetic riverbed shows that most rock movements could be detected, and for the detected movements, the displacements could be determined with an accuracy of about 4 cm. The results obtained for the real riverbed showed that the comparison of point clouds was to be preferred over the comparison of DEMs because it was not affected by interpolation artefacts in occluded areas. Some determined movement patterns are analysed from the point of view of hydrology.

A major limitation of using TLS for detecting and tracking rocks is rock size. The authors claim that only movements of rocks larger than 10 cm can be determined, which defines the scope of the investigations in subsequent papers. The georeferencing accuracy (1-2 cm) is identified as another limiting factor, along with occlusions and varying point density. The TLS point cloud is compared to another one acquired by dense matching using images acquired by a UAV. The image-based point cloud is shown to be a bit less accurate, but also more complete than the one obtained by TLS. The main methodological contribution of the thesis, the automation of the workflow for identifying rocks and their movements over time, is left for future work in this article.

Paper 2 (International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences 2018): This paper describes a first variant of an algorithm for the detection and segmentation of individual rocks in TLS point clouds. The algorithm consists of two steps. The first one is a classification of the point cloud, assigning a class label (*rock* vs. *background*) to each individual point. For the classification, an existing plug-in (CANUPO) for a commercial software package is used. Point classified as *background* are eliminated, and the remaining points form the input to the DBSCAN algorithm, which identifies clusters of such points that are candidates for individual rocks. Each cluster is analysed according to whether it is likely to correspond to a single rock or not by analysing profiles in two directions defined by a principal component analysis; if a cluster is found to correspond to multiple rocks, the points of the cluster are processed by the clustering algorithm again using different parameters. Thus, larger clusters are split into smaller ones if required. The evaluation based on two test sets from a TLS scan of the riverbed shows that the use of multi-scale features yields the best results and that in the first test set, a point-based overall accuracy of 84% can be achieved. For a second test set, the results are reported to be slightly worse, but no numerical evaluation is given. The evaluation of the instance segmentation reveals that 72%-76% of the individual rocks can be detected and identified using that approach, but no false positive rate is presented.

Paper 3 (IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 2022): This paper describes the final version of the rock instance segmentation method presented in this thesis. Compared to paper 2, a different classification method is used and a more sophisticated overall workflow is proposed. First, the point cloud is downsampled and classified. Classification is based on Random Forests and hand-crafted geometrical features, followed by a majority filter for smoothing the labelling results. Points that are expected to be near the boundaries of objects are eliminated based on a simple criterion for the local surface variance and the remaining rock points are split into clusters corresponding to individual rocks using the DBSCAN algorithm. In an additional post-processing step, small clusters are added to larger ones. The boundary points and the points eliminated in the thinning process are added to the detected instances, and finally, false positive detections are eliminated based on a geometrical criterion.

In the experiments, feature selection is used to define a set of seven geometrical features for classification, extracted from three different neighbourhood sizes (5cm - 20cm). Furthermore, the hyperparameters of the random forest classifier are tuned. The accuracy assessment on the test set reveals that the point-wise classification is very accurate, with F1 scores for the class *rock* of 90% after the majority vote. The evaluation on the basis of the detected rocks reveals an object-based completeness and correctness between 67% and 83% on the two datasets serving as the test set, which can also be considered a good result. Post-processing is found to reduce the number of false positives considerably. A major influencing factor is the object size: larger objects are more likely to be detected than small ones. A comparison to a state-of-the-art method also shows the superiority of the proposed method.

Paper 4 (International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 2019): This paper presents the first version of the algorithm for finding corresponding rocks in TLS datasets acquired at different epochs and, thus, for measuring the movement of the rock between these epochs. This problem is solved by point cloud matching. Having identified and segmented a rock in the first dataset (a step carried out manually in this paper), its position and orientation in the second point cloud are determined. The matching procedure starts with the extraction of keypoints and keypoint descriptors from both point clouds. Ms. Walicka proposes a new keypoint detector based on local Gaussian curvature; the keypoint descriptor consists of a set of hand-crafted geometrical features. Keypoints from the two point clouds are matched based on the similarity of the descriptors, and RANSAC is used to robustly estimate initial values for the transformation parameters describing the shift and the rotation of the rock between the acquisition dates. Finally, ICP is used for the precise determination of the transformation parameters. The experiments focus on the determination of an optimal set of hyperparameters for all processing steps. Results are only presented for a small subset of the TLS data from the epochs 2011 and 2013.

Paper 5 (Measurement, 2021): This paper presents the final version of the method for finding corresponding rocks in TLS datasets acquired at different epochs. Compared to paper 4, the set of features included in the keypoint descriptor is expanded and new constraints are proposed for selecting triplets of potential matches in the RANSAC procedure for estimating initial values for the transformation parameters. Fine registration is split into two different stages, using different hyperparameters for correspondence rejection in ICP. Finally, the method is embedded in a loop involving different search windows, which allows for the detection of larger rock displacements.

The evaluation of the method is based on two datasets, one without any movements and the other one with real movements, altogether consisting of 33 rocks. The results show that the new feature helps to determine the parameters for rocks that did not move and that a combination of a coarse registration with and without this additional feature achieves the best results. In this combination, the matching procedure succeeds in 85% of the cases. The geometrical accuracy of the transformation parameters is evaluated based on an additional execution of ICP after transforming the corresponding point clouds into the same coordinate system, resulting in residual transformation parameters that are very close to those of an identical transformation. The main reasons for failure are identified to be occlusions, rotations by 180° about a horizontal axis and matching errors.

3) Evaluation

Ms. Walicka has presented a PhD thesis of high scientific quality. Both methodological contributions are relevant and go beyond the state of the art in the field of point cloud processing. The first contribution, i.e. the method for rock detection and segmentation, adapts existing methods for segmentation and machine learning to create a new workflow that allows to solve a difficult problem. The evaluation is thorough and shows that the new method achieves a high accuracy. The second contribution, i.e. the method for determining the movement of rocks, introduces a new keypoint detector and embeds it in a workflow that combines and adapts existing concepts to solve another difficult research problem. Again, the results presented by Ms. Walicka are very good. The two methods were published in two articles in very good journals (papers 3 and 5); the related ISPRS Archives papers (papers 2 and 4) show how the candidate developed her approach and provide some additional insights in design and parameter choices. While not addressing methodological aspects, paper 1 presents the data used in the thesis and embeds its developments in the application domain. In the first part of her thesis, Ms. Walicka shows a good overview of the state of the art as well as a good understanding of the methodological foundations of her work. The overview in section 3 clearly shows how the five papers collected in this cumulative thesis interact and contribute to the solution of the same basic problem, the analysis of the movement of individual rocks in flowing water. The research questions are clearly posed, and the answers given in the conclusion section are sound. The evaluation of the individual steps of the workflow is thorough and the results achieved by Ms. Walicka are very good. At the same time, she remains critical of her own methodology and does not overlook its limitations.

There are also a few minor weaknesses of the thesis. In her overview on the state of the art, Ms. Walicka opts for breath rather than depth of description. Some topics could have been presented and discussed in more detail, e.g. instance segmentation or features extracted from point clouds. Her method for finding corresponding rocks is only embedded in work on point cloud matching; she could also have discussed tracking by detection, an alternative strategy frequently used in Computer Vision. A drawback of her matching-based approach is that it is unclear how a time series could be processed if new rocks appear in the test area after some epochs. Ms. Walicka's argumentation concerning the restriction of her experiments to rocks being larger than 10 cm also remains unconvincing; experimental results involving smaller rocks and a subsequent analysis of the results as a function of rock size would have strengthened her arguments. A generic weakness of the thesis is the discussion of the use of photogrammetry instead of TLS. Here, the argumentation is entirely based on point clouds generated by dense matching, which contain more errors than TLS point clouds. Ms. Walicka overlooks that photographs offer much more information, namely radiometry and texture, which can deliver additional features that are useful both for classification and for matching; as a result, photogrammetry could still lead to better results than TLS. Finally, Ms. Walicka does not present a full workflow for detecting and tracking rocks over time. In particular, the registration method is only demonstrated for a very small number of rocks that were segmented manually. It is clear that the generation of reference data is difficult for a larger number of rocks, but the excellent dataset at her disposal would at least have given her the option do present qualitative results for the detection of rocks in the entire test area and for tracking these rocks over all epochs.

It has to be emphasized that all of these weaknesses are minor. They do not detract from Ms. Walicka's scientific achievements, and they do not endanger the acceptance of her thesis in any way.

During the defence, the candidate should answer the following questions:

- What is the reason for the conclusion that particles smaller than 10 cm in diameter cannot be recognized?
- Why was the DBSCAN method used for segmentation, and which alternatives could have been used?
- How is the problem of instance segmentation solved by deep learning methods, and why was the random forest classifier chosen instead?
- Is a comparison to photogrammetric methods conclusive if it is only based on the quality of the point cloud? Would not colour and texture information be very helpful both for classification and tracking, so that the loss in accuracy of the point cloud could be compensated?
- Why was a fixed fraction of points used for thinning in the instance segmentation approach? Would it not be preferable to thin the point clouds so that after thinning they have a fixed geometrical resolution?
- How are the classes *rock* and *background* defined?
- Post processing of the random forest classification results is based on a majority vote. Could more principled statistical approaches such as Conditional Random Fields be used for this purpose?
- The strategy followed in this thesis could be called "tracking by matching", only requiring the detection of rocks in the first frame. An alternative, frequently used in Computer Vision, is "tracking by detection", in which the detector is applied to the data of each epoch and correspondences between detections are established afterwards. Why was the first strategy chosen in the thesis? How would these strategies compare for the application solved in this thesis?
- What are the limitations of the matching method with respect to the max-

imum displacement of a rock between two epochs?

- How is the selection of 1000 RANSAC trials justified? Could this parameter not be chosen on the basis of requiring a certain probability for success?
- Are all relative maxima of Gaussian curvature used as keypoints, or are weak local maxima eliminated?
- How could the methods presented in this paper be combined into a complete workflow for determining the movement of all rocks inside a test area over all epochs? Which steps are still missing?
- How could the results of such an overall workflow contribute to the determination of mass transport? Is it enough or are additional methods required, e.g. for measuring the movement of sand? Could optical flow methods offer a solution?
- What are the most promising directions of future work?

To summarize, there is no doubt that the candidate provided an original solution of a relevant scientific problem and acquired deep but also broad knowledge about the topics of the thesis. The quality of the language and the layout of the dissertation are almost perfect, the list of references is comprehensive. The methods developed by Ms. Walicka as well as her experiments are well described, and the discussion of the results is sound.

In my opinion, the doctoral dissertation fulfils the requirements for a doctoral degree in particular under Article 13 of the Act of March 14, 2003 Ustawa o stopniach naukowych i tytule naukowym oraz o stopniach i tytule w zakresie sztuki (Dz.U. 2003 Nr 65 poz. 595 z późn. zm.).

Thus, the **final conclusion** drawn from the evaluation of the thesis is **Positive (sufficient)**.

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