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The use of high-resolution photogrammetry for the survey and analysis of rock-climbing walls

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Abstract. In climbing, the routes that lead through a wall are mainly represented in two-dimensional maps. These climbing maps, also called "topos," help climbers and alpinists to plan their routes and find a way through the complex structures of a vertical or partially overhanging rock face. Today, a trend towards more realistic visualization techniques can be seen, where 3D representations are used for different geometric and topographic features (Kolecka, 2012). In this paper the focus is on 3D visualization and high-resolution data capturing at rock walls. Unmanned Aerial System (UAS) - based data collection has been conducted to collect digital images that are used to generate various outputs using a photogrammetry workflow. The photogrammetric processing of digital imagery results in dense 3D point clouds, digital surface models (DSM), textured 3D models and orthophotos of the test sites. How accurately is it possible to survey a vertical rock and how high the spatial resolution of the outputs will end up being is answered in this paper. After the data collection and the photogrammetric processing, a 3D climbing guide is created to answer the question if an enhanced visualization of climbing routes can be achieved. There are certain morphological features within the rock face that play a major role in climbing. For one, the climbing holds are important for climbers to continue the movement upwards. Other important factors are the dip angle and the dip direction of different rock facets. In this thesis the 3D point cloud is clustered into different sized facets, that share the same dip angle which is the angle of the center point of a cluster to a horizontal plane and the same dip direction which is the orientation of such a facet (Thanh, 2008). Using the analysis results, an automated climbing route construction is performed.

Keywords. 3D Point Cloud Analysis, Photogrammetry, 3D-Modelling, UAV

1 Motivation and research questions

Nowadays, a trend towards more realistic visualization techniques can be seen, where 3D representations are used for different geometric and topographic features (Kolecka, 2012).

Following the technological evolution, the paper is focusing on the 3rd dimension of climbing map visualization and the relevance for this sport. 3D climbing maps are widely unknown but can provide a lot of information about slopes, and surface morphology of rock walls (Kouti, 2019). The research question of this thesis is: *How accurately can a high vertical rock face be surveyed, using photogrammetric-processing and airborne data collection?*

There are several morphological objects that need to be considered when climbing. Important structures are the parts of the wall itself. A rock wall consists of three main elements namely overhanging parts, ramps, and vertical parts. *To what extent can climbing-specific elements, such as overhangs, ramps and vertical faces be derived from the collected data and is it possible to perform a least cost path analysis, showing the easiest route and the hardest route, based on the collected 3D data of a climbing wall?*

For visualization and for communication, existing climbing routes are documented in a 3D model. The created 3D climbing guide can be useful for climbers and for the tourism sector. So, another question arises: *Can an improved visualization of the existing climbing routes be created, based on 3D data?*

2 Methods

2.1 Conceptual model

To visualize all entities and their relationships to each other, it is necessary to create a conceptual model in the form of an Entity-Relationship-Diagram (ERD) (Chen, 1976). This logically constructed model shows all the objects that are captured by the photogrammetric survey in the course of this paper and the objects that are related to them. The ERD shows how a climbing garden is composed.

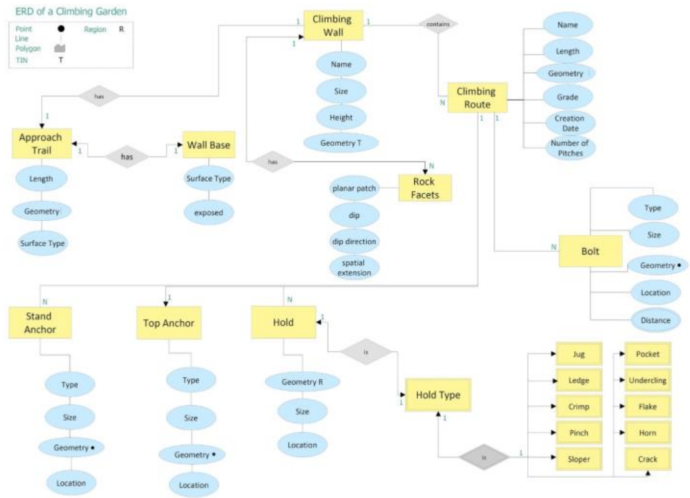

Figure 1: Conceptual model of a climbing garden in form of an ERD

2.2 Conceptual Workflow

The conceptual workflow of this paper contains several steps. First, the photogrammetric survey resolution requirements are determined based on the measurements of the various climbing-specific morphological structures on the real rock face. This leads to the mission planning phase. The next step is the data acquisition part. Once the data is collected, it is processed and validated. Now the climbing routes are digitized, the morphological structures are derived, and the automated route construction is performed in the analysis steps.

2.3 Data Acquisition

The data acquisition part is performed, using two different UAS-models. For this project it is clear to use a powered, VTOL Platform because of the vertical takeoff and landing possibilities of such a system (Eisenbeiß, 2009). The Leica Aibot AX20 is used as the carrier platform. This platform was specifically designed for professional applications (Leica-Geosystems, 2021). The Sensor used on the Leica model is a Sony A7rIII with 42mp. Besides the Leica model, a more consumer level system was used to collect the data. Due to the fact, that the Leica Aibot is very expensive the goal was to generate a comparable data quality with a cheaper UAV. The second UAV that was used is the DJI Mavic 2 Pro. The drone features a 20mp Sensor and a 1" Image Sensor. Ground Control Points are distributed all over the rock face, so that the scale-based optimization can be performed within data processing using known measurements of reference Points (Oats et al., 2019). The drones are used in a semi-automatic way, following a vertical flight path. The mean camera distance to the wall lies at 2.6 m. The UAS has a defined starting point at the top of the wall and lowers to the wall base collecting 1 image every 2 seconds.

2.4 Data processing

The UAV imagery is processed in Agisoft Metashape. The program-environment is used to generate a Orthomosaic, a Digital Surface Model, a dense point cloud and a 3D textured mesh of the rock walls. After the dense cloud is created, a scale-bar-based optimization is performed. The scale bar optimization is a valid method to orient the outputs, to give them a precise scale and to enable the option of precise measurements within them (Agisoft, 2020). Based on the dense point cloud, two different types of surfaces can be generated to display the geometry of a 3D model. A mesh is built, using a polygonal model based on the dense cloud information. This surface is best suitable for closed objects. A textured model is built using a mosaic blending mode with color correction and hole filling being enabled (Agisoft, 2020). The next step is the creation of a Digital Surface Model. The 3D model as well as the 3D point cloud can be exported for the inspection and derivation of climbing specific morphological structures. The orthomosaic and the DSM can be further analysed in a GIS-Environment.

2.5 Data validation and analysis

For the validation of the processed data, two different options are available within Agisoft Metashape. First the model reprojection error can be calculated. It is calculated as a root mean square error (RMSE) and gives out the distance between the location on the image where a remodeled 3D point can be projected and the original projection of the same point, detected on the image (Agisoft, 2020). The other option for validation and accuracy testing is the calculation of the GCP error. The error gives out the Root Mean Square Error for the spatial location of the coordinates for each GCP marker. It indicates, how far the average GCP error is from zero

(Hellmann, 2018). This influences the overall accuracy of the model.

For analysis the textured 3D model is transferred to a 3D rendering-software, where existing climbing routes are digitized based on the 3D data of the rock faces. In the rendering environment, an enhancement of the photorealistic texture of the model is performed and additional objects are added to create a better visualization of the whole area around the main wall as well.

The next analysis part is to investigate the 3D Point cloud for climbing-specific morphological structures and for route planning scenarios. The software CloudCompare is used to investigate the 3D point cloud for climbing specific structures like overhangs, ramps and sheer faces and for performing geological measurements to find climbable and not climbable zones on the wall. Those zones can be used for route planning purposes. Some of the most important morphological features of a climbing wall are the wall facets and their respective tilting and the angle. Those facets are derived by identifying planar joints within the rock wall. The derivation of the features works by identifying facets on the rock face and by fitting elementary planes to planar surfaces in the point cloud (Dewez et al., 2016). The dip angle and the dip direction of every single rock facet on the wall are calculated from the azimuth of the steepest part of the best fitted plane. Using those facets within an 3D space makes it possible to explore the whole climbing wall bit by bit with every rock facet being clustered, when having the same dip angle and the same dip direction. A combination of those two measures makes it possible to investigate whether the desired facet is overhanging, a ramp or a vertical part of the wall (Dewez et al., 2016).

3 Implementation

3.1 Data Acquisition & Processing

At one of the study sites, the goal was to use a vertical flight path in order to increase the accuracy and to get pictures from the wall at multiple angles. This means that the UAV's sensor always spotted the wall facets orthogonal. With every strip the pilot angled the UAV, so that the lens is perfectly normal to the individual wall part. Multiple angles can be reached this way, which decreases the risk of getting data holes in the 3D model (Agisoft, 2020).

For the UAS-mission, terrestrial scanning methods are combined with airborne scanning methods. The wall base in the research area is highly vegetated, which makes it impossible to fly in those parts. The approach of walking along the wall base with a terrestrial sensor and then combining the UAV images with the terrestrial images was tested. As ground control points for scale-based optimization of the data natural objects like distinctive stones were measured.

Figure 2: One of the test sites: A 135m high gneiss-rock wall

3.2 Data Visualization

On top of the polygonal mesh a photorealistic, generic texture was built with the size of $4(4086)$ pixels, resulting in a 16k texture.

Now that the 3D model and the texture are built, the model can be exported out of Agisoft, to perform further analysis and visualization tasks. Within a 3D modelling-software the 3D wall model is the base for digitizing existing climbing routes onto the rock face.

3.3 Rock Facet derivation

Some of the most important morphological elements for climbers are the different wall facets with their distinct size and angles. When a wall has a lot of overhanging patches it is more difficult to climb than a wall with a lot of ramp-like patches (Parks, 2020). The dip angle for a rock facet ranges from 0° - 90° and shows the angle between the plane of a facet surface at its steepest point and a horizontal plane. The dip direction of the individual rock facets shows the orientation and is defined as a positive angle from the North direction (0°) clockwise to the horizontal projection of the fall line of the facet (Thanh, 2008).

Using the Software CloudCompare, the rock facets for the walls were derived. The first step was to subsample the point cloud to make the computations faster and less error prone. Due to the GSD of about $5^{mm/pixel}$ this point cloud results in a total of 15 million points. In this analysis step the focus lies on big wall patches and therefore no high density of points is needed (Dewez et al., 2016). The fast-marching algorithm is used in this study. It subdivides the initial point cloud into minor cells, with the goal to extract the smallest possible entity that has a planar behavior (Dewez et al., 2016). The min points per facet parameter depends on the point density of the point cloud. In this case the distance between points is at 5 cm. To ensure that also small facets get clustered as their own the min points per facet was set to 50 points.

The maximum distance represents the distance between a selection of planar surface points and the best fitting plane. The max distance was estimated by fitting a plane to an unambiguous planar surface, that needs to be in the final facet clustering. Then the distance between the best fitting plane and the rock facet was derived out of the 3D point cloud. After computing the distance, the Gaussian distribution of the point distances to the plane has been investigated and the maximum distance for that particular plane was determined.

3.4 Automated route construction

After the calculation of the rock facets, the data is transferred into a GIS-environment, to perform raster-based analysis. The calculated facets are in 2D format after completion and are saved as polygons. To make the dataset ready for a least cost path analysis, the polygon data is transformed to a raster format. Within the facets attribute table, the dip direction and dip angle combinations were selected with SQL statements and then stored with a discreet weight value. The 776 rock facets were labeled and summarized based on their dip angle to dip direction combination and weighted with discrete values ranging from 1 to 10, where 10 indicates an overhanging rock section with a dip angle ≤ 60° and a dip direction in the range of 0°-89°. The weight 1 indicated a flat- ramp like rock section, with a dip angle of ≤ 60° and a dip direction in the range of 90° - 270°. The dip angle to dip direction ratios are validated, using real world measures at the study site.

4 Results

4.1 3D Climbing guide

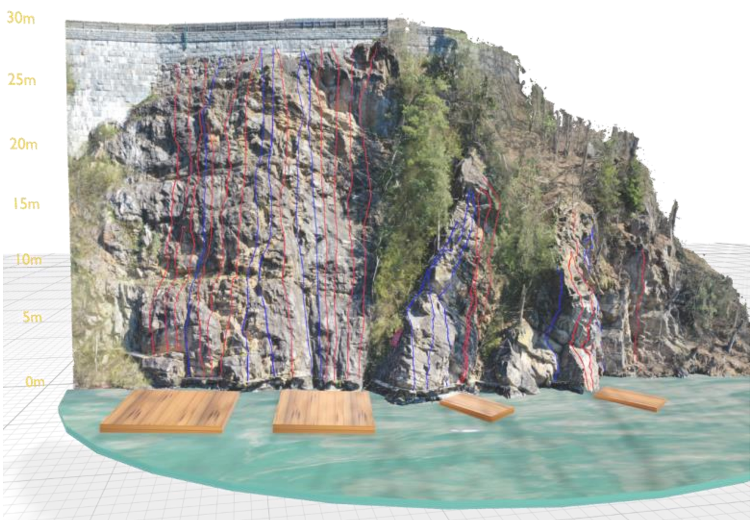

Figure 3: 3D climbing guide with 32 digitized existing routes

In Figure 3 the 3D climbing guide is shown with all the 29 routes digitized at a high level of detail. The routes were digitized based on experts' knowledge and based on existing route descriptions. The product shows, that a high level of detail can be provided to climbers when working with 3D data. The route numbering, the route names and descriptions are implemented in the digital version of this 3D-guide. The entire model together with the metadata can be fully investigated under the following link.

https://sketchfab.com/3d-models/jungfernsprung-model-b9b1eb2e14b14b64845bcaed4e144e64

4.2 Derivation of rock facets

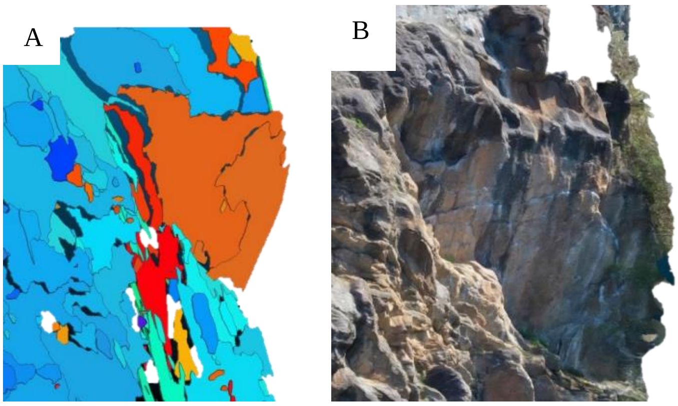

Figure 4: A: Overhanging part of the research area wall, derived as a facet from the 3D point cloud. B: The same overhang shown in the textured 3D model for comparison

In Figure 4 the derived rock facets can be seen. On the right there is the same location shown with the textured 3D model. This overhanging wall part, displayed in orange, is the most critical part at the wall when it comes to climbing. Based on the automatic derivation of the facets, the difficult parts and the easier parts can be derived reliably and quickly.

4.3 Automated climbing route construction

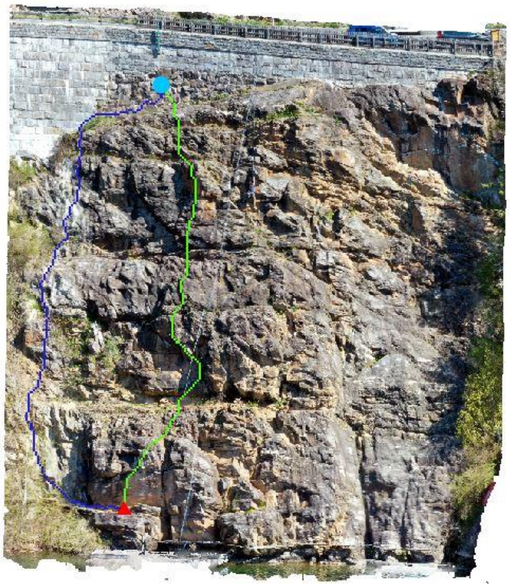

Figure 5: Automated derived climbing routes at the study site

In Figure 5 the visualization of the easiest and the hardest climbing route at one location of the climbing wall is shown. The basis of the visualization is a high resolution orthomosaic, that was created within the processing of the 3D-data. This orthomosaic was then transferred to a GIS-environment for analysis together with reclassified slope and dip-raster sets containing the automatically derived facets of the wall. The result shows, that the green route, which is considered the hardest route, directly passes the overhangs on the climbing wall. The purple route, which is the easiest, circles around every overhanging rock facet that was derived from the wall.

5 Validation of the results

The results of the photogrammetric processing have been validated using the scale-based error estimation and image optimization.

To investigate how a 3D climbing guide is received by users, a survey was conducted. This survey is intended to provide information about how potential users perceive the handling of a 3D climbing guide that can be called up on a cell phone. In addition, the test persons dealt with a 2D climbing guide from the same test area and were asked to make a comparison. The survey was conducted online and the subjects were given access to the 3D models presented in this paper. 100% of the 23 test persons stated that the visibility of the climbing routes in the 3D model is better than in the 2D climbing guide. 3 test persons additionally stated that the ability to zoom into the model makes a significant contribution to being able to view difficult key points more closely. One test person additionally stated that the numbering of the routes with the automatic zoom to the start of the route is helpful in finding the starting point. When asked if the test subjects would use such a 3D climbing guide on their next climbing trip, 100% of the test subjects answered "Yes". One respondent also stated that the cell phone would always be with them on a climbing trip anyway, and that the 3D models could therefore always be accessed, as long as it was possible to download the models offline, as there is no Internet access available in some areas. When asked if a 3D climbing guide could be a welcome innovation in the field of sport climbing, 100% of respondents answered "yes".

The derived facets are validated visually. By looking at the different rock sections, the overhangs and the flat sections can be compared directly to the derived facets results. This makes it possible to visually compare the derived facets based on their dip/dip direction. Another way of comparing is by overlaying the facets outcome onto the textured 3D model.

The validation of the derived routes is possible by talking to experts who can climb along those routes and it depends on their personal interpretation of what is difficult and what is not. Another way of effectively validating the derived routes is by investigating nearby routes and their difficulty grading.

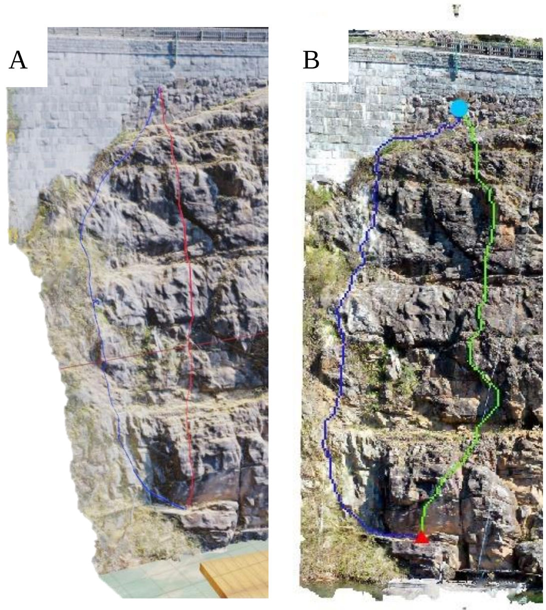

Figure 6: A: The existing climbing routes from the distinct start- to endpoint. The blue route is the easiest on the wall whereas the red route is the hardest one between those points. B: The automatically constructed routes show the blue route using flat terrain and the green route directly passing overhangs and sheer faces

6 Conclusion

The 3D climbing guide was presented to climbers of the area and the feedback they gave was very positive. Never have they seen a comparable visualization of the climbing crag and they really liked the look and the convenience of zooming in and really checking out certain parts of the routes. Also, the clean visibility of the different routes was highlighted by the climbing community of the area. The writer of this thesis will produce more and more 3D models of climbing walls. First a browser-based beta-version will be launched to see how the community thinks about the 3D-climbing models. When the feedback is positive an application will be created in the future. The different morphological features, that were derived from the 3D point clouds, like the facets, will be implemented within the app to help climbers plan their routes and increase safety on the wall.

The automated construction of the hardest and easiest climbing routes can be used efficiently to establish new climbing walls, where nobody has ever been before. By using this analysis, a possible route can be found through a high alpine wall and experts who want to climb the route can be involved in the reclassification and weight-setting for the different raster datasets.

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