High-resolution digital terrain modelling of a rugged alpine terrain by fusing data from terrestrial laser scanning and UAV photogrammetry

Michal Gallay, Ján Kaňuk, Ján Šašak, Jozef Šupinský, Jaroslav Hofierka
Institute of Geography
Faculty of Science, Pavol Jozef Šafárik Univeristy in Košice
Košice, Slovakia
michal.gallay@upjs.sk

Jozef Minár
Department of Physical Geography and Geoecology
Faculty of Natural Sciences, Comenius University
Bratislava, Slovakia
jozef.minar@fns.uniba.sk

Abstract

The alpine landscape is rugged, dominated by glacial morphogenesis, comprising specific landforms of different sizes and shapes with a marked vertical relief and hierarchical-ordering of the forms. Digital geomorphometric analyses of such a land surface in a high level of detail can exploit mainly data acquired by airborne laser scanning or photogrammetry. However, the level of detail captured is limited to several meters or decimetres in these datasets for the relatively high above ground flying heights. Terrestrial laser scanning (TLS) and close range photogrammetry generate 3-D point clouds of ultra-high spatial resolution but their application is limited by extreme environmental conditions. TLS data often contain data shadows in alpine landscape resulting in inhomogeneous spatial distribution of the acquired 3-D point cloud. Such data properties cause creation of overly smoothed surfaces or artefacts in digital elevation models (DEMs) interpolated into a grid (raster). The sub-horizontal field of view in TLS can be compensated by sub-vertical field of view of digital cameras installed on unpiloted aerial platforms (UAVs). Such a photogrammetric 3-D reconstruction of terrain with UAVs is based on structure-from-motion (SfM) image matching techniques. The measurement precision and accuracy of UAV-SfM is lower than with TLS but the UAV-SfM data can be used in filling the TLS data voids. In this paper, we present the results of combined use of TLS and UAV-SfM for high-resolution modelling of a glacial cirque in the Tatry Mountains, the Carpathians, Europe. The achieved accuracy (1 standard deviation) of mutual co-registration of 18 TLS positions was 4.2 mm. The accuracy of georeferencing the final TLS data in the national cartographic system was 33.2 mm based on 15 ground control points. The UAV-SfM dataset was spatially co-registered on the TLS dataset with the accuracy of 137 mm and point filling the TLS voids were used to generate the final DEM of 0.5 m cell size from the combined point clouds.

I. INTRODUCTION

Digital elevation models capturing microtopography of the earth surface have been widely applied in geosciences since terrestrial laser scanning (TLS) and Structure from Motion photogrammetry from unpiloted aerial vehicles (UAV-SfM) widely emerged as methods for landscape 3-D mapping [1, 2, 3]. The level of topographic detail the methods record is in the order of few centimetres for UAV-SfM to millimetres for TLS which is given by the short range between the sensor and the mapped surface [4]. The sub-horizontal field of view in TLS often results in data voids in complex terrain configurations such as caves, forests or rocky alpine terrains. The voids can be avoided by scanning from various positions or by recording data from vertical perspective by remote sensing instruments installed on unpiloted aerial platforms (UAVs). The extremely high spatial resolution of mapping and also high measurement accuracy has opened new horizons for geomorphometry in the way the geomorphic processes and resulting landforms can be digitally analysed. Benefits of combined use of TLS and UAV-SfM were demonstrated in mapping the microscale structure of various kinds of landscapes; [5] presented a useful summary of advantages and disadvantages. Harsh environmental conditions and complicated accessibility of some types of terrain still remain a challenge for capturing the micromorphology by these methods.

In this paper, we present a case study of combined use of TLS and UAV-SfM in the upper part of a deglaciated cirque in Tatry, the highest mountain range of the Carpathians, which belong to the most extensive mountain range in mainland Europe. Despite the altitudes are not comparable to Alps or Himalayas, the area mapped has a difficult access and other constraints for mapping such as high level of legal natural protection and no road network. The aim was to generate a highly detailed and accurate digital terrain representation of the area which will be used for validating existing hypothesis on glacial formation of the Tatry Mountains and studying the dynamics of contemporary geomorphic processes.

II. Area of Interest

The area of interest (AOI) comprises the upper part of the Malá studená dolina Valley in the eastern part of the Tatry Mountains, Slovakia (Fig. 1). The massif was subject to several stages of alpine glaciation in the Pleistocene [6]. for which it is deeply dissected by glacial throughs and cirques, displaying the most pronounced glacial morphology within the Carpathians.

The Malá studená dolina Valley is incised into the southern part of the crystalline core consisting of biotite granodiorite-tonalite to muscovite-biotite granodiorite [7]. The AOI comprises three compound cirques surrounded by headwalls up to 400 - 500 m high which form the upper part of the valley (Fig. 2). The altitudes range from ~ 2000 to ~ 2600 m a.s.l. The pronounced glacial morphology of the area is modified by prominent gravity and cryogenic depositions forming extensive talus cones descending from the lower sections of the headwalls and ablation till and nivation ridges covering the central parts of cirques floor. The bottoms of the cirques are situated at ~2000 and 2190 m a.s.l., respectively. Rock steps up to 400 m high represent the transition from compound cirques down to the trough at the southeast edge of the area of interest.

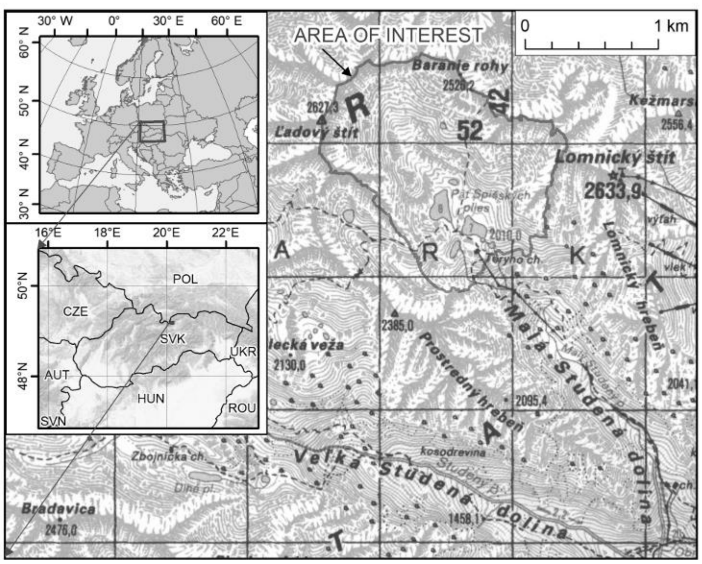

Figure 1. Location of the area of interest. Background topographic map RETM50 © Geodetic and Cartographic Institute of the Slovak Republic.

Figure 2. Laser scanning in the cirque of the Malá studená dolina Valley in Tatry viewed towards the north, 13 September 2017.

Almost the entire extent of the Tatry Mountains is protected by law as a national park (TANAP) with the highest level of natural protection in Slovakia. Moreover, the surveyed valley is specially protected within the natural reserve of Studené doliny for being a refugee of various plant and zoological species and for outstanding natural beauty. Therefore, the human activities are limited and road access by car is restricted to lower parts of the mountains up to about 1500 m a.s.l. with tourist resorts. Upper parts are accessible only by foot via trails or elsewhere with mountaineering equipment and special permission.

III. Methods and Data

The area of interest was mapped in two campaigns in late summer of 2017 with four persons involved to carry the equipment and perform the field work. The total weight of equipment of 50 kg had to be carried walking for about 3 hours up the valley to the area of interest where the mountain cottage of Téryho chata was the base for an overnight stay. The devices involved two dual-frequency GNSS receivers Topcon Hyper II, a Riegl VZ-1000 long range laser scanner with an integrated Nikon D-700 camera, a UAV quadcopter DJI Phantom 4 with an integrated 12 megapixel FC330 camera (focal length = 3.61 mm) mounted on 3 axes gimbal.

First, the site was surveyed on 13 - 14 September 2017 when the snow cover was at minimum that year. The sky was clear; the maximum air temperature was about 15°C, and the wind speed was 8 – 12 m/s. The land surface was dry which was favourable for TLS. During the first field campaign, the work began at 13:00 setting up a GNSS base station which position was located by real-time kinematic (RTK) GNSS positioning with a mobile broadband connection to the network of the Slovak real-time positioning service (SKPOS) within the national S-JTSK03 coordinate system (EPSG code: 5514) with overall accuracy below a centimetre (1σ). The baseline to the closest SKPOS base station in Gánovce was 20 km southeast. Meanwhile, the TLS and UAV-SfM surveys had begun.

TLS was undertaken from the south and west side of the valley for a safer transport of the scanner and walking conditions. TLS scans were acquired from 15 positions during the two days with varying increment of laser measurement of 0.02° to 0.06° and pulse repetition frequency of 70 kHz to 300 kHz allowing for scanning up to ranges of 450 m to 1400 m. TLS scans were oriented relative to each other by the iterative closest point (ICP) method in the RiScanPRO software by Riegl. There were 4-5 GCPs distributed at a distance of 5 - 10 m around 4 scan positions (Fig. 3). The GCPs were located with RTK GNSS surveying for georeferencing the point cloud within the national coordinate system.

Flying the UAV was performed in a manual mode from a single start position for almost 40 minutes in total at flight altitudes of 400 - 500 m above ground. The acquired photographs were processed in the Photoscan 1.3.3 software by Agisoft. The process of image matching was performed with the accuracy

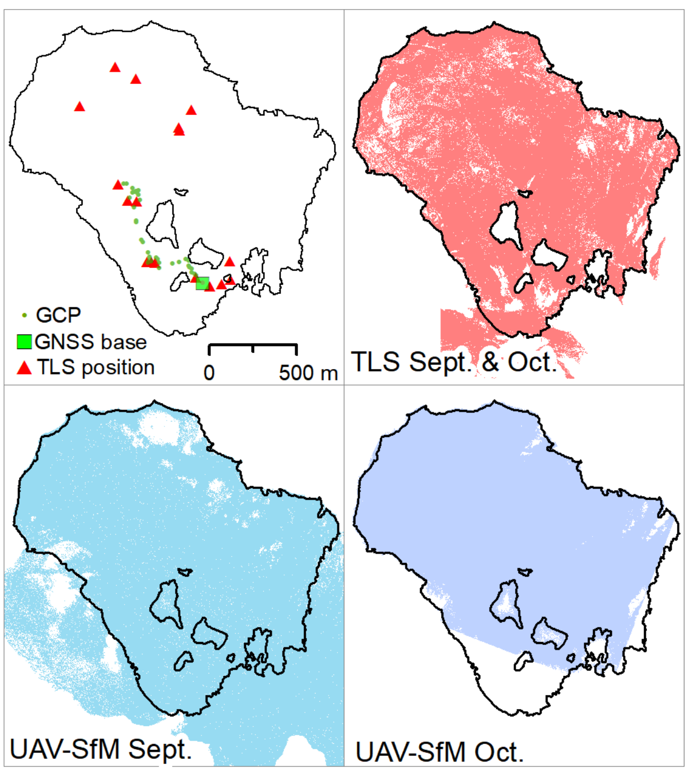

Figure 3. Instrument positions and data coverage.

setting ‘High’ and the depth map filtering was controlled by the parameter ‘Aggressive‘ for removing the outliers. The strategy for the ground control of the UAV-SfM was in locating identical points between the UAV photographs and the TLS point cloud coloured by RGB values. Subsequently, the generated point cloud was aligned to the TLS point cloud by the ICP method in RiScanPRO.

The second campaign on 19 October 2017 was needed to acquire more data from the uppermost parts of the valley. This time the sky was slightly dimmed by haze and the air temperature was about 5°C with mild wind. There were remnants of the first snow cover in some places which had remained since the first snow from a week before. The field work involved only TLS and UAV-SfM. Scans from 7 positions were acquired and the individual point clouds were registered one after another to the TLS point cloud generated from the first campaign. By this means a unified and georeferenced TLS point cloud was created. The UAV-SfM was performed from flying height of about 250 m above ground for 40 minutes. The processing was done in the same software and settings as described above. The final point cloud was aligned to the unified TLS point could with the ICP method.

The final point cloud originated from merging the TLS with the points of the UAV-SfM clouds in areas of no TLS coverage for the absorption of a laser pulse (snow) or data shadow. This final point dataset was decimated with a 50 cm octree filter to balance the homogeneity of the spatial distribution and purpose of the terrain analysis. The decimated point cloud was used for interpolation of a gridded DEM of 50 cm cell size by the parallelized v.surf.rst method [8] in GRASS GIS 7.3 [9] with tension and smooth parameters set to 20 and 0.8, respectively.

IV. Results and Discussion

The conducted surveys resulted in georeferenced TLS and UAV-SfM 3-D point clouds (Fig. 3), and orthoimagery. The point clouds were clipped to cover 2 km^2 of the AOI excluding water surfaces (five tarns). In terms of the level of detail and measurement accuracy, it is a unique dataset which has no other data alternative for the specific territory of Tatry. The average point density of the original unified TLS data was over 130 points/m^2 but the point spacing was not uniform. The parts of the area most distant from the scanner were sampled by the scanner approximately every 0.5 m. Decimation adjusted to this largest point spacing resulted in a more uniform density of 5.7 points/m^2. The UAV-SfM mapping in the first and second campaign generated a uniform point cloud of 3.6 and 50.1 points/m^2, respectively. The final decimated point cloud used for DEM interpolation (Fig. 4) contained 12 million of regularly distributed points with density of 5.7 points/m^2.

The internal consistency of the points can be inferred from the relative alignment of the individual TLS point clouds and UAV-SfM clouds. The standard deviations of the sequential ICP alignment of the 21 TLS point clouds ranged between 2.6 mm to 12.9 mm, but it decreased to 4.2 mm after aligning all TLS point clouds to the fixed scan positon 7. The accuracy of aligning the UAV-SfM point clouds of the first and second mission to the final TLS data was 11.8 cm and 13.7 cm, respectively.

The absolute accuracy of the final point cloud was assessed as a cloud-to-cloud distance between 38 independent GCPs measured with RTK-GNSS and the georeferenced TLS point cloud. The resulting mean distance (georeferencing accuracy) was 6.0 cm and the root mean square distance was 7.95 cm. Validation of the final DEM derived from the final point cloud using the same GCPs resulted in a root mean squared error of 63.5 cm. The value is higher than for the point cloud validation as the interpolation involved surface smoothing and the input number of points was decimated in comparison with the original point cloud.

The final DEM represents land surface of various morphometry (Fig. 4). On one hand, there are planar forms such as steep cliffs, smooth rôches moutonnées and glacially polished surfaces. On the other hand, scree slopes, plucked surfaces or moraines form rugged land surface. These forms are not quantitatively depicted in contemporary maps or digital elevation datasets available for this area of the Tatry Mountains. Airborne lidar was successfully deployed in Poland for a state-wide mapping. The point density in the Polish part of Tatry reaches 4 points/m^2 with vertical accuracy of 15 cm [10]. In Slovakia, airborne lidar has not been deployed on the state-level to date. Contours of topographic maps are the main data source traditionally used for generating DEMs of Tatry in Slovakia, but they are replaced with symbols of steep and rocky surface (Fig. 1). The maps originated from photogrammetric measurements using aerial imagery which, however, was hampered by shadows in such a markedly vertically dissected landscape. The associated vertical and horizontal error in the order of few meters did not allow for ascertaining the absolute and relative elevations with sufficient accuracy for the purposes of detailed study of the recent processes and valley development.

The TLS and UAV-SfM outperform the manned airborne mapping techniques providing highly detailed dataset with consistent internal accuracy in the order of millimetres also for overhangs and cliffs where no data coverage existed before. Furthermore, the accuracy of mutual alignment of the TLS point clouds is very high despite the distances between some scan positions were several hundreds of metres long and the complex topography introduced data shadows. Therefore, UAV-SfM proved to be a useful alternative to recover the lidar-shadowed areas with fairly accurate elevation points.

The data collection in such environment is controlled and limited by the weather which can change rapidly and dramatically. In the first mission, conducting UAV-SfM was the priority for the forecasted strong winds that day afternoon. Therefore, there was not sufficient time for placing and measuring any GCPs within the hardly transient AOI. Placing GCPs would improve the absolute accuracy of UAV-SfM data [11].

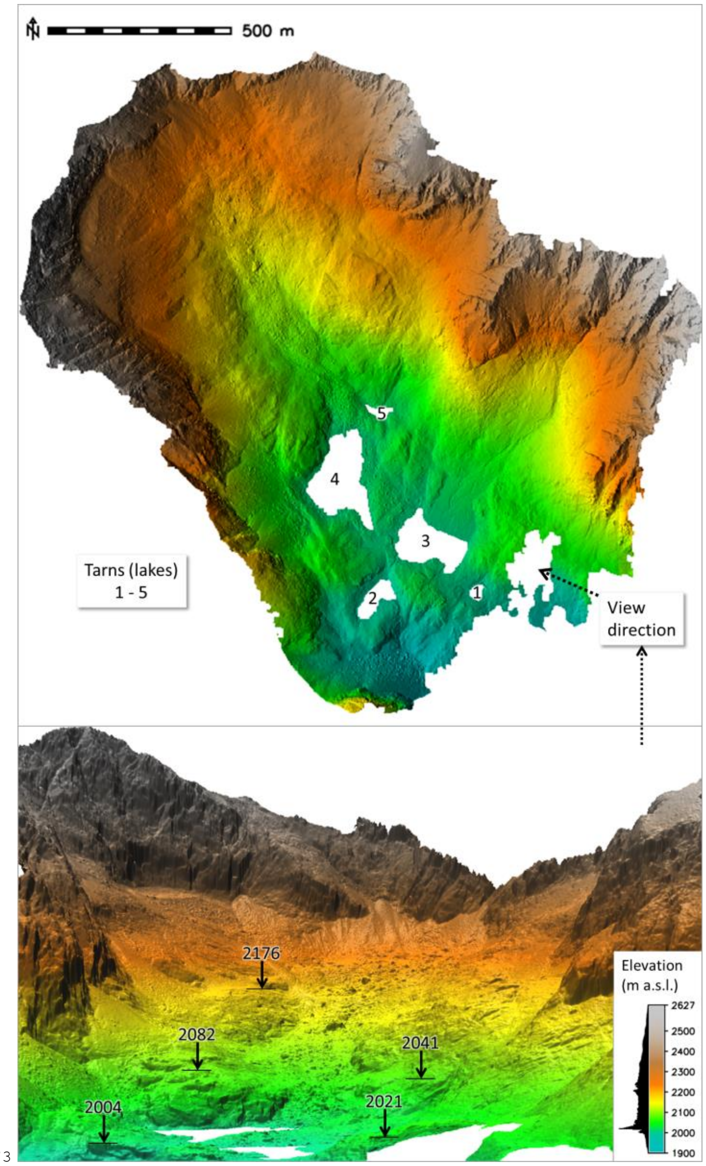

Figure 4. Final raster DEM (0.5x0.5 m cell size) resulting from a combination of TLS and UAV point clouds. Perspective 3-D view of the DEM is similar to that of Fig. 2. The values refer to local maxima altitudes of glacially polished bedrock. The areas of lakes 1-5 (tarns) are masked out.

Despite the wind conditions were not optimal (wind speed 8-12 m/s), flying the UAV was possible and safe. The strong sunlight was not favourable for photogrammetric processing for marked contrast between areas shadowed and under direct sunlight. Therefore, the second mission was needed as the weather did not allow achieving appropriate data coverage in the upper parts of the valley. However, it is a complex problem to find ideal weather conditions and match their occurrence with time available for the field work.

V. Conclusions

The generated point clouds present the most detailed 3-D representation of the alpine topography in the Tatry Mountains to date. The high density and accuracy of such a dataset enables geomorphometric analysis on a microscale level allowing for the study of geomorphic and ecological processes in this pristine environment. The generated data can serve as the reference surface for snow depth studies in the area or for assessing rock mass balance in subsequent surveys such as in [12, 13]. The derived DEM serves its purpose to identify local glacially smoothed surfaces and compare their absolute altitudes within the area. By this means, relative and absolute dating of glacial formation of the cirque and the through can be improved having implications to a wider context of the Tatry Mountains. The DEM also enabled experiments with new geomorphometric parameters as presented in [14]. Challenge for future research remains in distinguishing multiple hierarchies of landforms by using the high-resolution DEM or the original point clouds. For the complex topography and considerable vertical dissection, advantages of a 3-D mesh surface can be exploited for terrain modelling as [15] demonstrated in a cave.

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