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AUTOMATED DETECTION OF EARTH PYRAMIDS AT DEVIL'S TOWN USING PHOTOGRAMMETRIC POINT CLOUDS

Abstract:

The Devil's Town site is a unique geomorphological formation in southern Serbia, comprising over 200 earth structures. This site has been monitored using non-invasive techniques and a high-resolution point cloud was generated through photogrammetric imaging with an Unmanned Aerial Vehicle (UAV). In this study, automatic detection of the earth pyramids was performed using local maxima detection algorithm in order to create a digital inventory across different time epochs, enabling comparisons between past and present conditions of these geomorphological features. The results were compared with an official digital geomorphological inventory produced through manual mapping, achieving an overall accuracy (OA) exceeding 70%.

Keywords: UAV photogrammetry, earth pyramids, digital geomorphological inventory, local maxima filtering

АУТОМАТСКА ДЕТЕКЦИЈА ЗЕМЉАНИХ ПИРАМИДА ЂАВОЉЕ ВАРОШИ КОРИШЋЕЊЕМ ФОТОГРАМЕТРИЈСКИХ ОБЛАКА ТАЧАКА

Сажетак:

Ђавоља Варош представља јединствену геоморфолошку формацију у јужној Србији, која обухвата више од 200 земљаних структура. Ова локација је праћена применом неинвазивних техника, и облак тачака високе резолуције генерисан је фотограметријским снимањем беспилотном летелицом. Извршена је аутоматска детекција земљаних пирамида применом алгоритма за детекцију локалних максимума, са циљем израде дигиталног инвентара кроз различите временске епохе, чиме је омогућено поређење претходног и садашњег стања ових геоморфолошких облика. Добијени резултати упоређени су са званичним дигиталним геоморфолошким инвентаром, при чему је остварена укупна тачност већа од 70%.

Кључне речи: фотограметрија са беспилотном летелицом, земљане пирамиде, дигитални геоморфолошки катастар, филтрирање локалних максимума

1. INTRODUCTION

The Devil's Town geosite, located in southern Serbia, is renowned for its striking landforms—naturally sculpted earth pyramids formed through intensive erosional processes. These unique geomorphological features have long intrigued both scientists and tourists alike. Due to their fragile nature, regular monitoring is essential to understand erosion patterns and ensure long-term preservation. In recent years, advancements in remote sensing and UAV photogrammetry have enabled the development of more precise and non-invasive monitoring approaches. Therefore, the DEMONITOR project is dedicated to monitoring this rare geological phenomenon. Over a three-year period, earth pyramids are being observed using advanced, non-invasive techniques, including aerial photogrammetry with unmanned aerial vehicles (UAVs), terrestrial laser scanning (TLS), interferometric synthetic aperture radar (InSAR), and geophysical surveys [1]. These methods aim to quantify changes such as erosion rates, rockfall occurrences, and ground subsidence. The DEMONITOR project seeks to leverage these technologies to generate accurate, repeatable, and objective data for geospatial analysis and heritage preservation. This will allow for the development of appropriate preventative or stabilization measures, which will ultimately result in the permanent site's conservation.

This project builds upon the pilot project MEĐA, conducted by part of the DEMONITOR research team between 2017 and 2018 [2]. In that project, two data acquisition campaigns were carried out at the test site—in November 2017 and November 2018—using both terrestrial laser scanning (TLS) and UAV-based methods. The initial acquisition served as a baseline, generating a so-called "zero-state" 3D model of the terrain. Each subsequent acquisition produced a new point cloud with the same reference system, resolution, and precision. By comparing the newer 3D models to the baseline, spatial differences resulting from the erosion of earth pyramids could be identified and quantified [3]. During the Demonitor project, UAV photogrammetry and terrestrial laser scanning (TLS) surveys were conducted in February and November 2024, and in July 2025.

Photogrammetrically captured images can be used for 3D modelling of the site; however, previous studies have shown that such models alone may not provide reliable results for erosion monitoring [4]. The primary advantage of using UAVs for photogrammetric imaging lies in their ability to capture both nadir and oblique views, offering improved access to hidden or shadowed features that are not visible from ground level. This capability significantly enhances the completeness and accuracy of the resulting 3D models.

In this study, 3D models of the earth pyramids were generated using UAV-based photogrammetry and identified through analysis of derived photogrammetric products such as point clouds and orthomosaics. The resulting data should then be compared with an official digital geomorphological inventory produced by manual mapping. It is planned to annually update the inventory during the course of the Demonitor project, but also upon its completion, so that it could be used for change detection and potentially for updating and producing touristic guides and brochures.

2. STUDY AREA AND MATERIALS

2.1. SITE DESCRIPTION

Devil's Town (Đavolja Varoš) is a remarkable geomorphological and geological site, protected as a natural heritage landmark in southern Serbia. It comprises over 200 pyramidal or columnar landforms, ranging in height from 2 to 15 meters, many capped with resistant andesite rock fragments (Fig. 1). These striking formations are continuously shaped by erosion acting on soft volcaniclastic deposits, leading to processes of collapse, subsidence, or the emergence of new pillars. Influenced by a variety of environmental factors, their ongoing transformation raises important questions regarding long-term stability and preservation, particularly under the impacts of climate change.

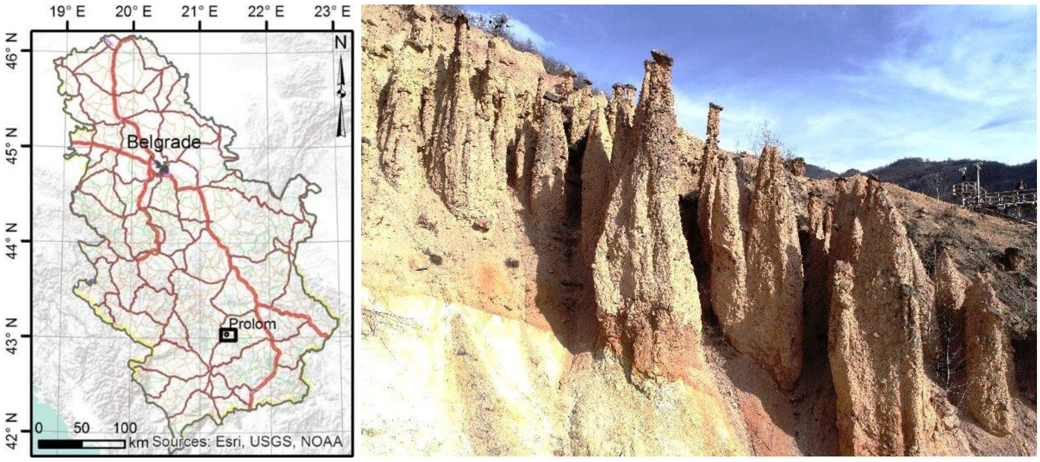

Figure 1. Devils' town location in Serbia (left) and its landforms – earth pyramids (right).

2.2. DATA ACQUISITION

Two UAV photogrammetric acquisition flights were conducted till now for this project, in February and November of 2024 under similar weather conditions to ensure consistency. To minimize noise caused by vegetation, both surveys are scheduled during the non-vegetative season (late autumn/early spring). A multirotor UAV quadcopter – DJI Phantom 4 PRO, equipped with a high-resolution RGB camera with mechanical shutter, was used to capture overlapping nadir and oblique images. Nine Ground Control Points (GCPs) were placed for accurate georeferencing (Fig. 2).

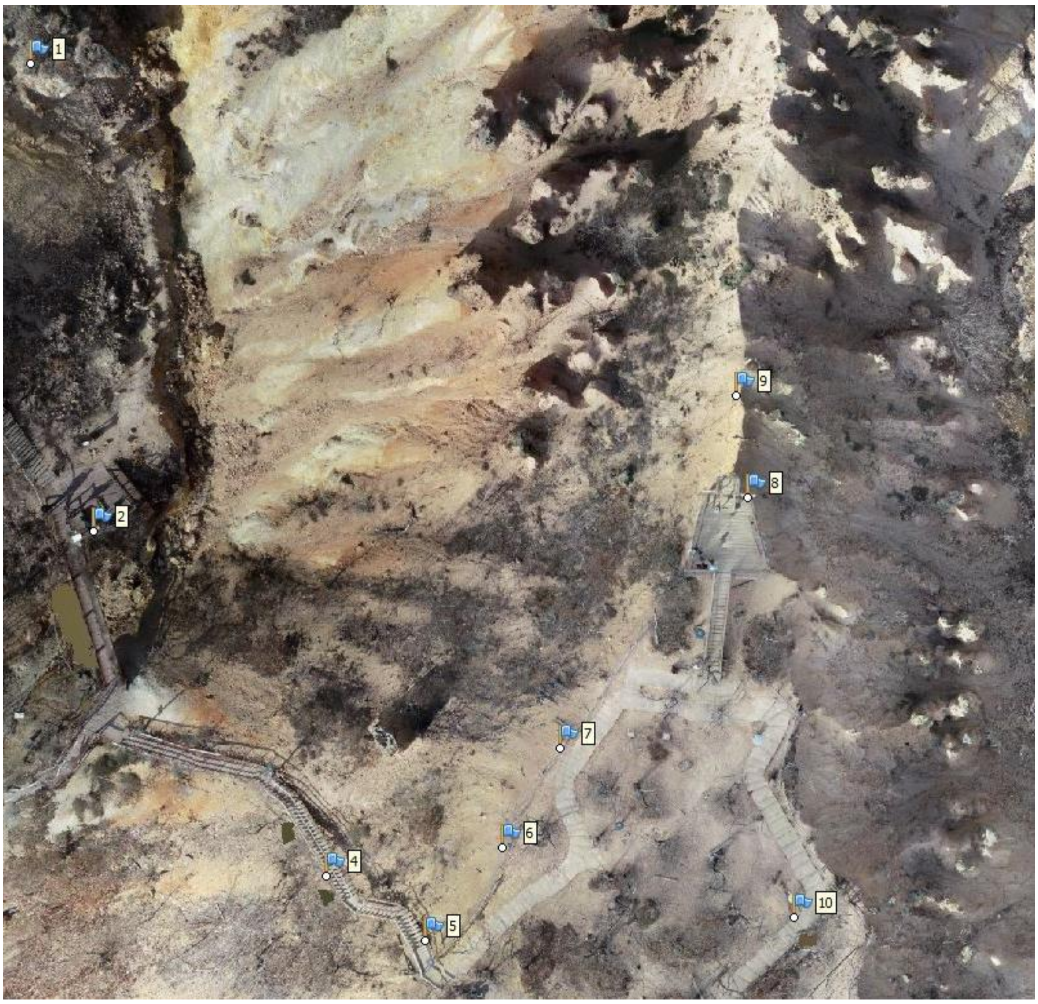

Figure 2. Spatial distribution of GCPs across the site (created by author).

In the previous project, all UAV photogrammetry flight missions were planned to ensure complete coverage of the area of interest, with a sufficient number of overlapping images required for 3D reconstruction. The images were acquired vertically from nadir perspective at altitudes of 50 m or 80 m above ground level. The flight paths followed a double-grid pattern, incorporating both longitudinal and transverse directions to maximize image overlap. In contrast, image acquisition for the DEMONITOR project was conducted manually during a free-flight mission [1]. This approach allowed for greater flexibility and improved coverage of these complex landforms. As a result, a significantly larger number of images were captured during the mission, enabling the acquisition of a higher level of detail and reducing the number of shadowed areas on the objects (Fig. 3). A total of 688 images were collected from an average distance of approximately 20 meters.

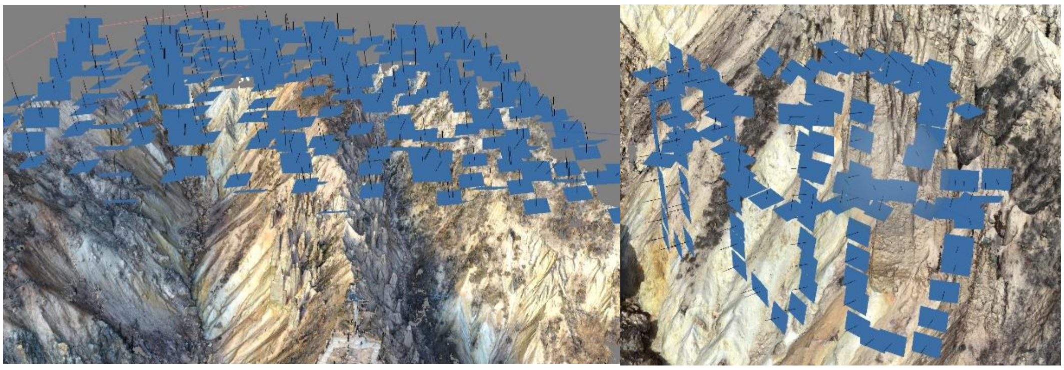

Figure 3. Two type of flight plans– an automated flight plan (left), a manual free-flight plan with the UAV operating at a distance of less than 20 meters from the earth pyramids (right) (created by author).

3. METHODOLOGY

3.1. PHOTOGRAMMETRIC PROCESSING

Spatial data collection using photogrammetric methods involves several key stages. The first phase is flight preparation, which includes creating a flight plan. The flight plan was designed to ensure sufficient image overlap—typically 80% transverse and 80% longitudinal—as well as an adequate number of flight lines and images per line to ensure complete coverage and data quality. Second phase is stabilizing and marking GCPs in the field. These points, evenly distributed across the site, are essential for georeferencing the 3D model, and their coordinates must be accurately determined.
First, the photogrammetric data will be processed to generate a point cloud. The software solution Agisoft Metashape [5] was used to generate point clouds from UAV imagery using structure-from-motion (SfM) techniques [5]. It represents an advanced solution for 3D modelling based on images, which aims to generate high-quality 3D content from images. The images can have any position, but under the condition that the object to be reconstructed is visible in at least two images. Image alignment and point cloud generation were fully automated.

3.2. AUTOMATIC DETECTION OF EARTH PYRAMIDS

Due to the distinctive shape of the earth pyramids—resembling steep, tree-like forms similar to coniferous canopies—it was considered appropriate to test algorithms originally developed for treetop detection and individual tree segmentation. Many such algorithms are available in the R programming language **Error! Reference source not found.**, particularly within the lidR package [8].
Once the point cloud is generated, the Local Maxima Filtering (LMF) algorithm [9] was applied to detect the precise locations of apex points of earth pyramids across the site. These detected points should serve as seeds for subsequent segmentation. Same methodology was used in plethora of papers dealing with individual tree detection [10], [11], [12], **Error! Reference source not found.**.

4. RESULTS AND DISCUSSION

4.1. PHOTOGRAMMETRIC PROCESSING

After the bundle block adjustment, the Root Mean Squared Error (RMSE) on the GCPs was 1cm, indicating high positional accuracy. A dense point cloud was subsequently generated, containing approximately 48 million points in total. The resulting Digital Surface Model (DSM) had a spatial resolution of 2.7cm. Additionally, the generated digital orthophoto mosaic – orthomosaic featured a very high spatial resolution, with a ground sampling distance (GSD) of 6.75 mm, made possible by the short flight altitude and close proximity of the UAV to the objects of interest. As it can be seen, free-flight mission with manual imaging resulted in a point cloud with higher level of detail with reduced number of shadowed areas on the objects (Fig. 4).

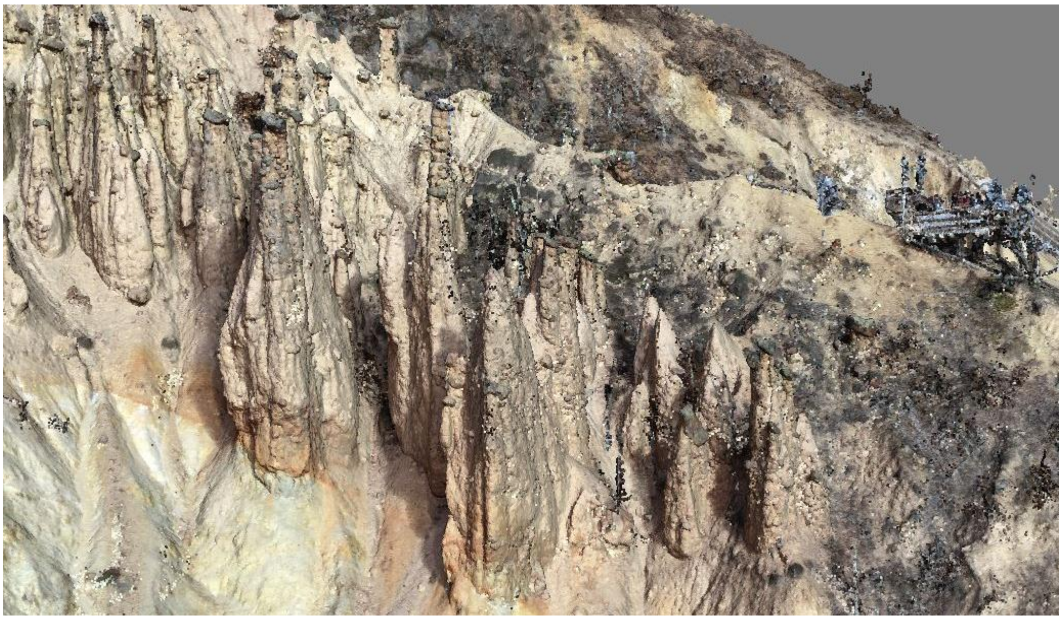

Figure 4. High-density point cloud representing the earth pyramids with fine details

4.2. AUTOMATIC DETECTION OF EARTH PYRAMIDS

After detecting the apex points of the earth pyramids, a total of 155 points were detected (Fig. 5). These points were compared with the digital inventory of earth pyramids [14], revealing that 112 out of 155 pyramids were correctly detected, while 43 were falsely detected which gives OA of 70.9%.

It can be seen also from the orthomosaic below which points are true tops of the pyramids and which are not. The main reason for these misclassifications is that the point cloud was not thoroughly classified into ground points and pyramid points, leaving some points corresponding to vegetation and small shrubs. The search radius for the local maxima algorithm was set to 0.5 m, meaning that pyramids located closer than this distance could not be distinguished as separate features.

Furthermore, some of the detected points may correspond to the tops of small trees or shrubs. These results highlight the need for more accurate point cloud classification prior to detection in order to minimize such misclassifications. However, a major limitation of this approach is the difficulty in detecting pyramids that are located very close to each other. Adjusting the search parameters to detect all pyramids may lead to a large number of falsely detected features. While identifying falsely detected pyramids may be relatively straightforward, the main challenge remains the reliable detection of pyramids that are located too close to one another.

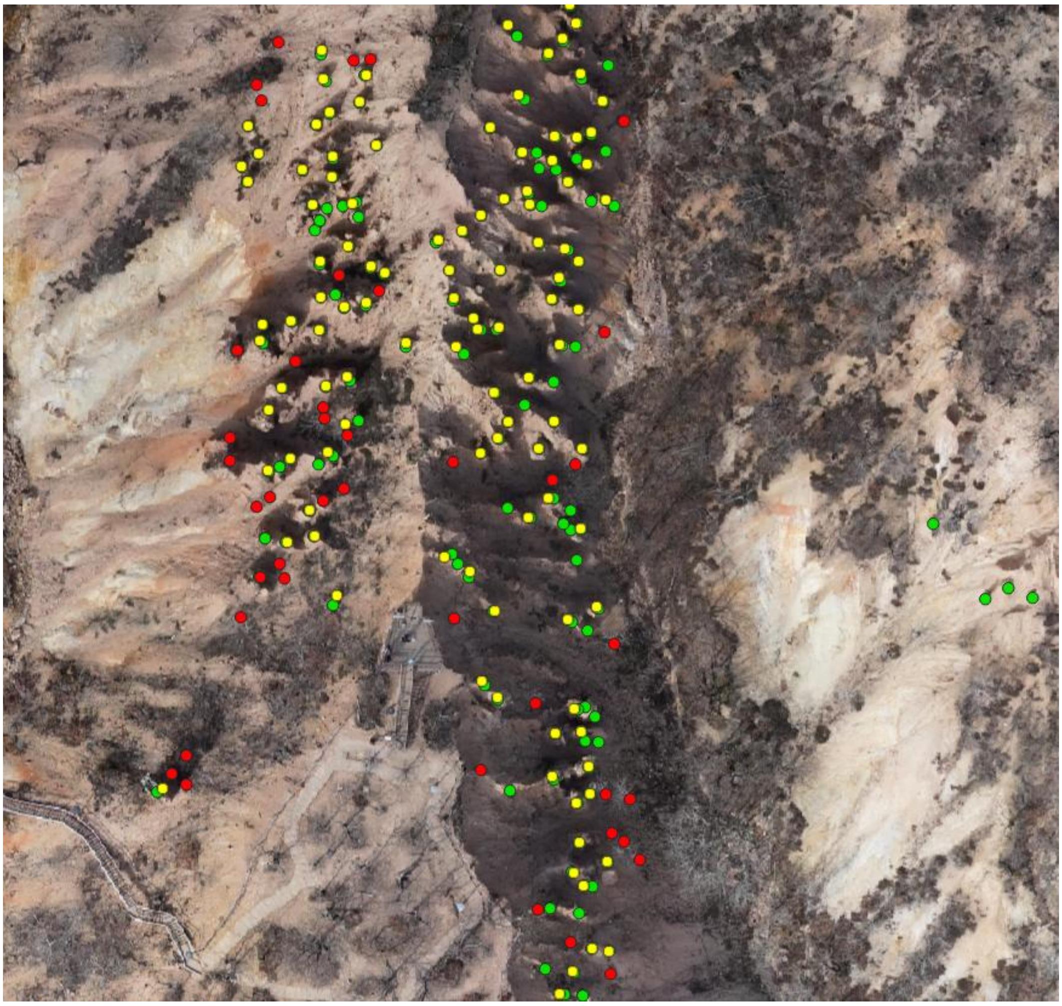

Figure 5. Earth pyramids detections – green dots are manualy mapped earth pyramids from digital inventory, yellow dots are correct detections and red dots are false detections of earth pyramids (created by author).

After the pyramid detection is completed, the detected points can be overlaid on the colorized point cloud, enabling visual verification of the method in 3D (Fig. 6).

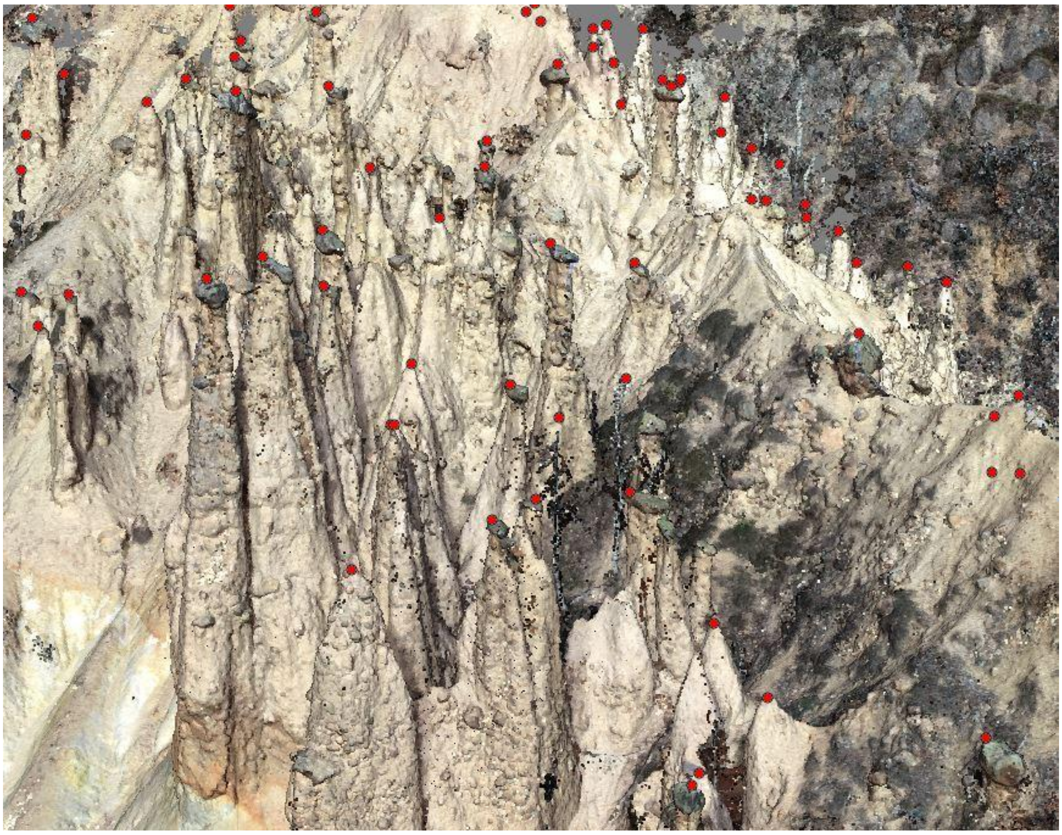

Figure 6. Detected apex points of the earth pyramids visualized in the 3D point cloud (created by author).

5. CONCLUSION AND FUTURE WORK

This research highlights the effectiveness of UAV-based photogrammetry for high-resolution 3D modelling and monitoring of complex geomorphological features such as the earth pyramids of Devil's Town. The generated dense point cloud demonstrate that manual free-flight UAV missions can significantly improve model quality by minimizing shadowed areas and capturing finer surface details.

Using the Local Maxima Filtering (LMF) algorithm, 148 apex points were detected, enabling the initial delineation of individual pyramids. However, limitations related to the search radius and vegetation interference emphasize the need for more refined point cloud classification techniques to improve detection accuracy. These findings provide a solid foundation for further automated monitoring of erosional processes and landform change at this geosite.

In future work, a more advanced point cloud classification algorithm will be applied to separate ground points from non-ground points. Additionally, methods will be implemented to distinguish points belonging to the earth pyramids from those associated with vegetation and other surrounding objects.

Machine learning algorithms will also be used to identify which detected points represent true pyramid apexes and which do not. These apex points could further be used as seed points for point cloud segmentation, enabling the extraction of individual pyramids and the determination of their geometric characteristics, such as height and widths at the top, middle, and base of the pyramid. Another task would be the detection of pyramids that have an andesite cap on the top and those that do not, as this represents a clear indicator of the potential for a pyramid to collapse within a period of several years.

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