3D representation of a bauxite mine in the frame of m4mining project

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ABSTRACT

Mining companies worldwide routinely monitor their excavation activity. Until a few years ago terrestrial measurements, aerial photogrammetry and remote sensing using very high-spatial resolution satellite data were the usual methodologies. In particular, executing precise terrestrial measurements with topographic equipment of Differential GNSS constitutes a time-consuming procedure. Although the absolute precision of individual points is extremely high (mm level), it is challenging to survey large land areas. At the same time, Terrestrial Laser Scanners (TLSs) provide comparable accuracy by collecting millions of points per second, decreasing the surveying time substantially; yet, deploying these sensors inside the quarries continues to be problematic. While costly, with aerial photogrammetry data from large quarry areas is collected at a cm level accuracy. Satellite data present the same pros and cons as aerial photogrammetry in terms of area coverage, accuracy, and cost. The advent of Unmanned Aerial Vehicles (UAVs) and the development of high-accuracy cameras and light-wise LiDAR sensors open new opportunities for the monitoring of quarries. In the present study we evaluate and compare the 3D point clouds derived from high-accuracy UAV cameras to the respective data collected by TLS. An open pit bauxite mine in Greece, monitored in the frame of the m4mining project, is selected as the study area. "M4mining" is an EU-funded project that aims at confining the resolution gap between satellite- and UAV-acquired data for mine monitoring. The 3D point clouds derived from UAV flight campaigns and TLS measurements are compared in terms of point density and fidelity of topographic representation. The current work proposes an effective and precise methodology to accurately 3D map a site, using cost-efficient data, acquired by UAV and TLS.

Keywords: Quarry, 3D models, UAV, TLS, bauxite, m4mining

1. INTRODUCTION

Open pit mines (or quarries) are subject to continuous morphological changes due to the mining activities (excavations, explosions, etc.) and thus topographic surveys are indispensable for the mine monitoring and the estimation of the remaining mineral quantity. Furthermore, systematic monitoring of geological and geomorphological characteristics is continuously required to prevent undesirable events such as erosion, landslides, and deformations of the terrain [1,2]. In the past, mine monitoring was performed using terrestrial measurements, aerial photogrammetry and remote sensing using very high-spatial resolution satellite data [3]. When mine monitoring is performed using conventional surveying methods, many hours of fieldwork are required, and the danger of a safety accident occurrence increases. Although classical topographic surveying is characterized as a robust technique for the accurate metric analysis and monitoring of quarries, sometimes it is difficult to perform without disturbing the vital excavation operations of the mine.

Therefore, an alternative method is needed to obtain and utilize safe and accurate survey results. Terrestrial Laser Scanning (TLS) and Unmanned Aerial Vehicle (UAV) photogrammetry are remote non-invasive techniques, which nowadays acquire a more important role in mining mapping and monitoring. Moreover, these new technologies and their applications are fully adaptable to the very fast modifications of the mine morphology. The application of TLS and/or UAV photogrammetry represents an appropriate and effective solution if one considers the availability and frequency of data collection required in the exploitation of this type of monitoring [4].

The potential of UAVs for routine operations at surface and underground mines has been examined in various studies [5-8]. Including two review studies aiming to provide a comprehensive summary of the current state of UAV technology and its applications in the mining industry were recently published [9,10]. A DSLR camera (Olympus E-P1) onboard an aerial

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octocopter platform was used for the 3D modeling and accuracy assessment of a granite quarry in Villacastin, Segovia, Spain [4]. Two low-cost UAVs (DJI, Phantom 3 Pro and Phantom 4 Pro) were used [11] for cartographic products for both the mine restoration management and as a way of monitoring mining activity as a whole. The same low-cost commercial UAV (DJI Phantom 4 Pro) has conducted several flight campaigns to identify settings that produce the most accurate and detailed topographies in a mining highwall. The study proved that a facade UAV flight campaign combined with a nadir camera angle resulted in the best accuracy [12]. In another study [13], the potential of UAV photogrammetry for determining the changes due to development of operations in mines was investigated. The accuracy of the UAV results was validated using ground control points, and the earthwork volume was compared to field survey measurements.

The combination of TLS and UAV data for 3D representation in mining environment has been documented in many studies. One of the first studies comparing the 3D data derived from UAV and TLS surveys for mine mapping and monitoring was presented in 2015 [14]. In it, authors presented a framework for the integration of UAV-based photogrammetry and TLS for the 3D mapping and monitoring of open-pit mine areas and for the accurate 3D modeling of the side slopes, in three open-pit phosphate mines in Yunnan province, China [14]. In another study [1], the volume of stockpiles in Hup Seng Quarry, Malaysia, was initially estimated using UAV data (DJI Inspire 1). The results were compared to the respective data collected by the GLS-2000 TLS. The comparison has focused on survey planning, data collection, data processing, and volume comparison of the stockpile. The combination of close-range terrestrial digital photogrammetry and TLS for discontinuity characterization on five highway rock cuts was examined in British Columbia and Alberta, Canada [15]. 3D Point clouds derived from a Leica P40 TLS and a DJI Spreading Wings S1000 octocopter equipped with a Sony ILCE-7R camera respectively, were compared for measurement of the repose angle of granular materials in terrain conditions [16]. Fieldwork executed in two case studies (Ulu Choh Quarry and Jelapang Rock Slope) in Malaysia proved that the combination of a TLS and UAV survey created a very accurate 3D point cloud for rock slope stability analysis. The digital photogrammetric procedure accelerates the data acquisition phases and mitigates several drawbacks of the traditional mapping methods [17]. The University of Brescia has completed the 3D mapping of an open pit mine located in Botticino, a famous location of marble extraction in North Italy. They combined 3D data from TLS and UAV photogrammetry to create the initial 3D representation of the mine. Afterward, in order to examine the possibility of a fast update of the model, they used a mobile laser scanning system (Gexcel Heron) and simultaneous localization and mapping (SLAM) technology [18]. In another case study, a quarry (Dreveník quarry) in the Slovak Republic, was surveyed in only one day using UAV photogrammetry and TLS measurements. A UAV with Real-time kinematic (RTK) capabilities (DJI Phantom 4) and a TLS (Leica RTC360) were employed. The derived point clouds were georeferenced using a dual-frequency GNSS sensor (Leica GS07) [19]. According to the study, both point clouds are qualitative, accurate, and suitable as a basis for systematic quarry monitoring. Each technology presents specific advantages: TLS provides a significantly higher point density and a better representation of the terrain while UAV provides simplicity of data acquisition, flexibility, and lower purchase cost [19]. The specific results are in full accordance with those presented in a recent study comparing the 3D point clouds of UAV photogrammetry and TLS to other sources of 3D data [20]. An analysis of the features and efficiencies of the same two technologies was presented [21]. Two separate point clouds were created from TLS and UAV data to perform waste stockpile volume computations. The researchers tried to generate an optimal computation technique based on the fusion of the two-point clouds. A commercial UAV (DJI Inspire 1 Pro) and TLS (Leica P40) were used for data acquisition over a waste stockpile site in Jipyeon-ri in Sejong City, South Korea. According to the results, the fused 3D point cloud proved to be the most accurate. Similar volumes were computed by the three 3D models (UAV, TLS, fused) [21]. The combination of 3D data derived from UAV (DJI Phantom 4 Pro) and TLS (Faro Focus 120S) provided a solid background to generate a 3D surface model of an active limestone quarry in the Mecsek Mountains in southern Hungary [22]. It demonstrated the applicability of the UAV and TLS methodologies in the structural geological survey of inaccessible or vegetation-covered areas and their effectiveness in the calculation of geological reserve.

“M4mining” is an EU-funded project aiming at confining the resolution gap between satellite and UAV-acquired data for mine monitoring. Active and non-active mines in Greece, Cyprus, and Australia are mapped as case studies using multispectral and hyperspectral sensors on board UAVs and satellite platforms. In the frame of the project there is a need for very fine and highly accurate 3D models of the quarries. The current study evaluates the 3D point clouds derived from high-accuracy UAV cameras to the respective data collected by TLS

2. M4MINING PROJECT

The “m4mining” project aims to provide an integrated remote sensing approach for mapping and monitoring active and inactive mining sites. Hyperspectral and multispectral imaging combined with 3D surface measurements will be utilized for material identification from the detailed mine face to the site-scale using -UAVs and satellite sensors. Central to the proposed work is a synergistic unification of UAV and satellite-based processing algorithms, workflows, and decision-making tools at timescales required to impact active and inactive mining operations and environmental and risk management of tailings and waste sites. Active and abandoned mines in Cyprus, Greece, and Australia are used as test sites.

3. STUDY AREA

The studied bauxite mine is in Central Greece near to the city of Amfissa, (Figure 1). It is located inside the alpine zone at an altitude of 1750m and it is currently inactive.

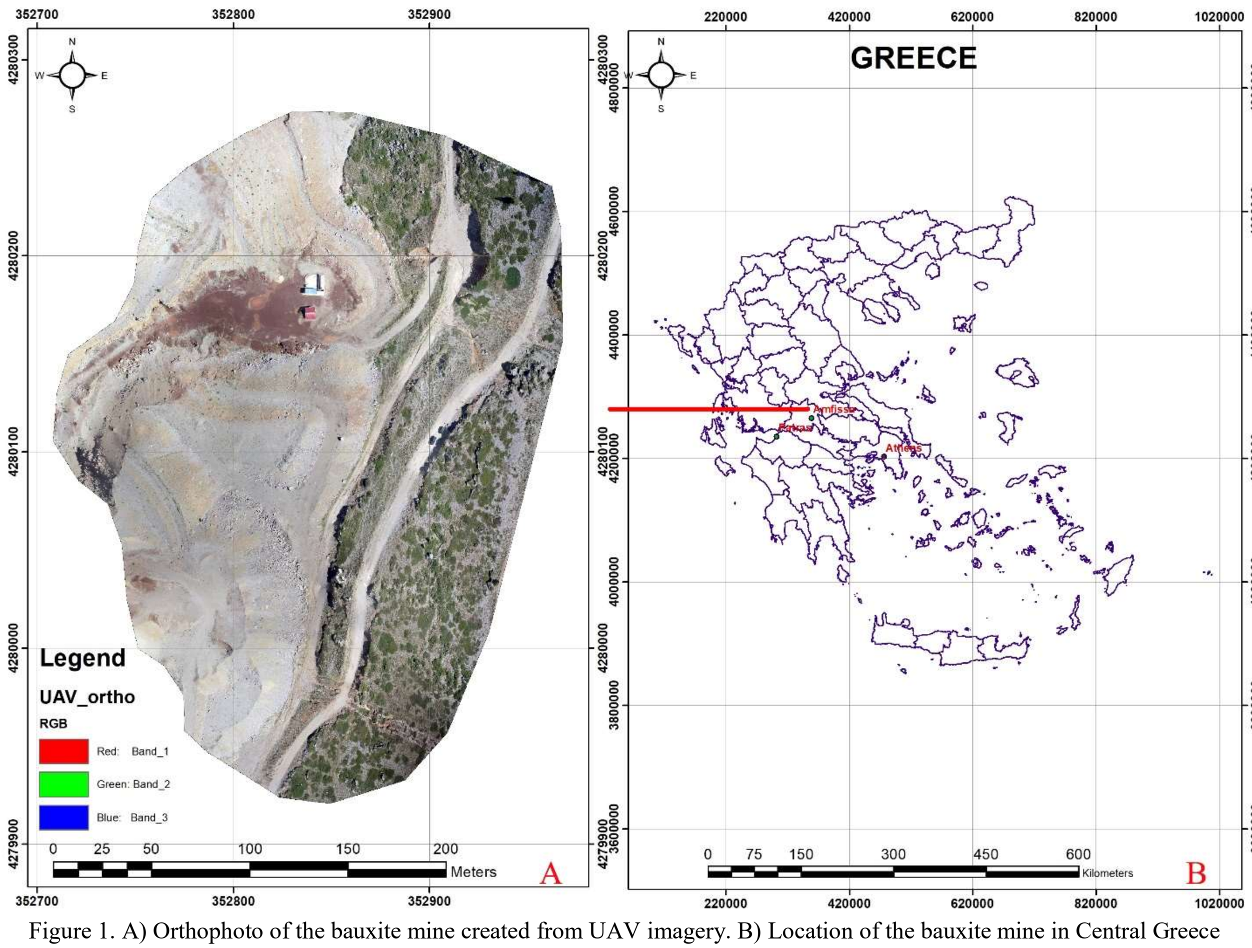

Figure 1. A) Orthophoto of the bauxite mine created from UAV imagery. B) Location of the bauxite mine in Central Greece near to the city of Amfissa.

Greece has the most important bauxite deposits (containing about 50–60% $Al_2O_3.H_2O$) in Europe and produces almost two million tons of bauxite per year. The major exploitable bauxite deposits are in the Focida prefecture (Parnassos Mountain), at the northern flank of the Gulf of Corinth [23]. The first mining explorations in the broader area of Oiti-Ghiona-Parnassos mountains started in 1924, bringing the first resources of “poor iron ore” to light. These resources are officially recognized as “bauxite resources” and the first exploitation company, "Itea Aluminum Mine," was originally founded in the same year. In 1934, Bauxites Parnasse S.A. was founded for further exploitation of bauxite. In 1935 the first contract of cooperation between the newly founded company and the French Lafarge was signed to produce aluminum from the bauxite. In 1938, bauxite production at the Parnassos-Ghiona mines reached 180,000 tons per year. In 1967 the interest in new bauxite deposits shifted from Mount Parnasse to the Ghiona mountain. For many years the mining operations utilized both surface and underground methods.

4. FIELD WORK AND DATA ACQUISITION

To date, two field campaigns have been completed in the specific study area. Filed work included 3D mapping of the mine and extensive bauxite sampling. 3D mapping was performed using a Leica P50 TLS, and a DJI P4 pro UAV. The first campaign was performed on March 27th, 2024 while the second was executed on July 16th, 2024.

During the first campaign, strong winds didn't allow the execution of a photogrammetric flight. Instead, an oblique UAV flight was performed and many very high-resolution images were collected and processed in Agisoft Metashape software (Figure 2).

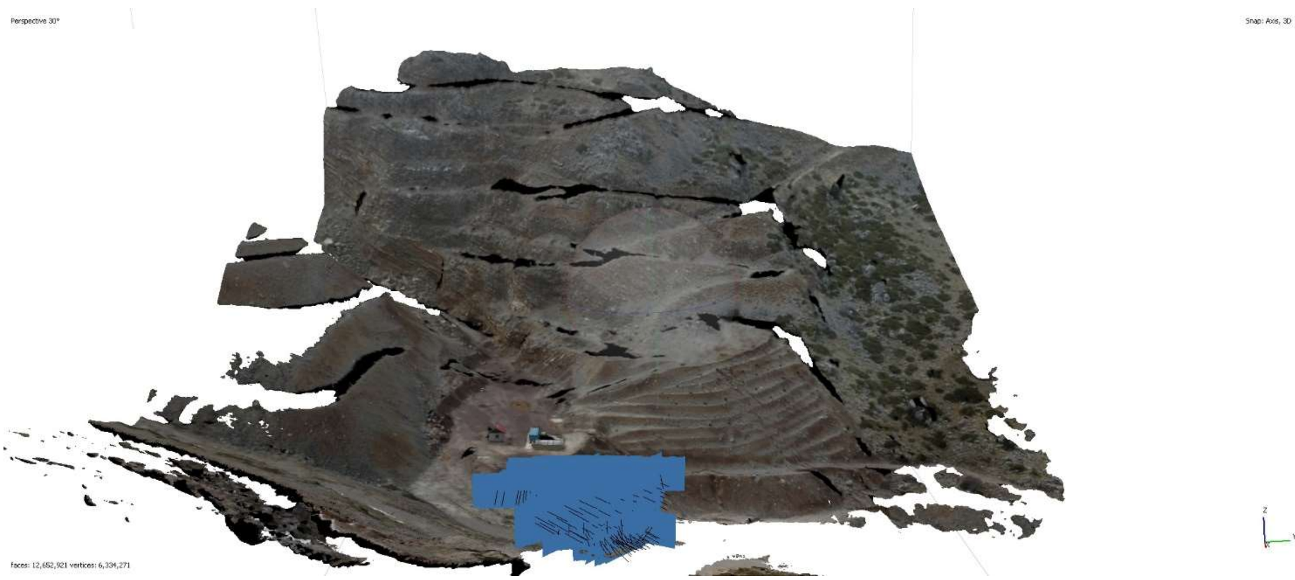

Figure 2. Processing of UAV images acquired during an oblique flight campaign.

A TLS survey has been also performed and a point cloud of the bauxite mine was created. Due to the weather conditions the deployment of square black and white targets for the georeferencing of the TLS point cloud was not possible. A 3D point cloud of the broader area was developed (Figure 3).

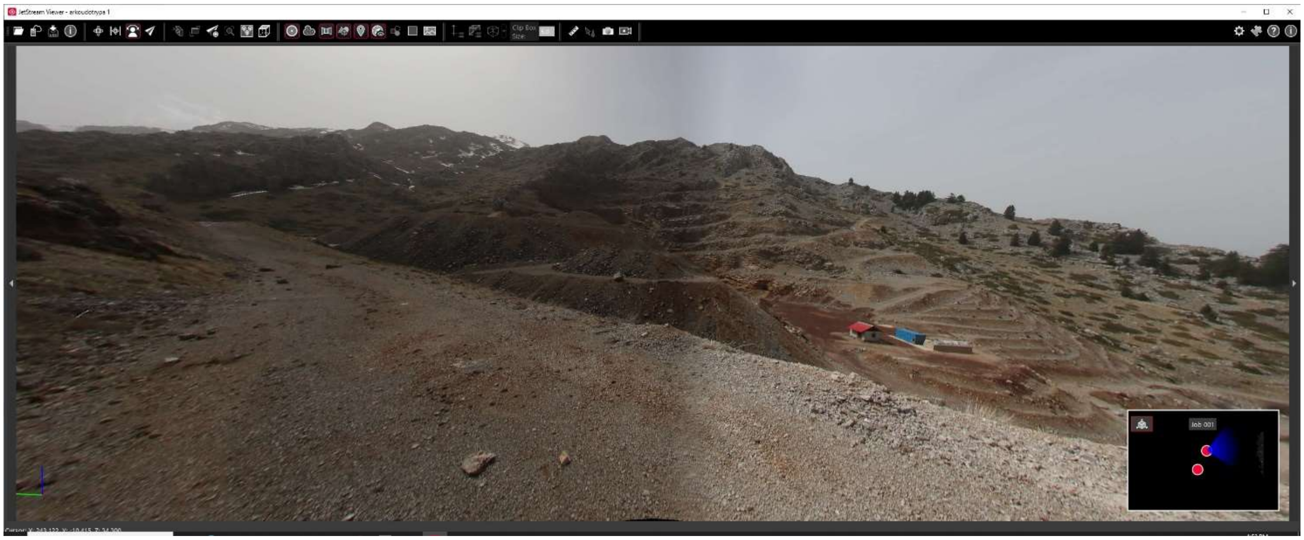

Figure 3. Creation of a 3D point cloud from the TLS data. Mine facility buildings can be seen in the middle of the point cloud. Snow can be detected in the upper part of the quarry.

During the second field campaign two photogrammetric grid flight campaigns were executed at 100m above ground level (AGL). The processing of the UAV data was performed in Agisoft Metashape (Figure 4) and a Digital Surface Model, an orthophoto and a 3D point cloud were produced. The collected UAV imagery was processed according to Structure from Motion (SfM) photogrammetry into Agisoft Metashape software. SfM transforms the overlapping, multi-view UAV images into a 3D object model [24,25,26]. In the current research, UAV imagery was aligned using the highest-quality option, which is associated with enhanced quality during 3D reconstruction. In addition, an ultra-high-quality setting was selected for the creation of the dense point cloud.

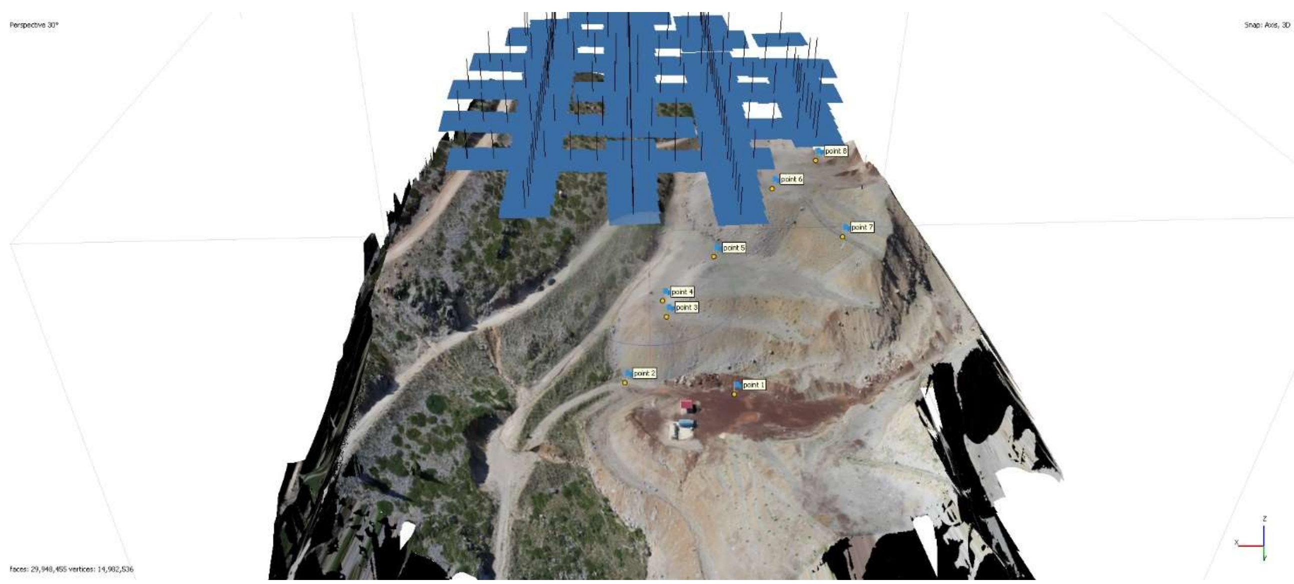

Figure 4. Processing of UAV image acquired during the second field campaign on July 16th 2024. The double photogrammetric grid was executed at 100m AGL. In blue are the ground control points used for the georeferencing of the data to the Greek Geodetic Reference System (EPSG 2100).

A TLS campaign was also performed, and another 3D point cloud was created (Figure 5). Noticeably, square black and white targets (4.5") were distributed over the test sites during the UAV and TLS surveys to minimize the georeferencing errors. These targets were measured using a Leica GS08 GNSS receiver. The use of such targets for the georeferencing and the fusion of point clouds was described in detail in other studies [20,27,28].

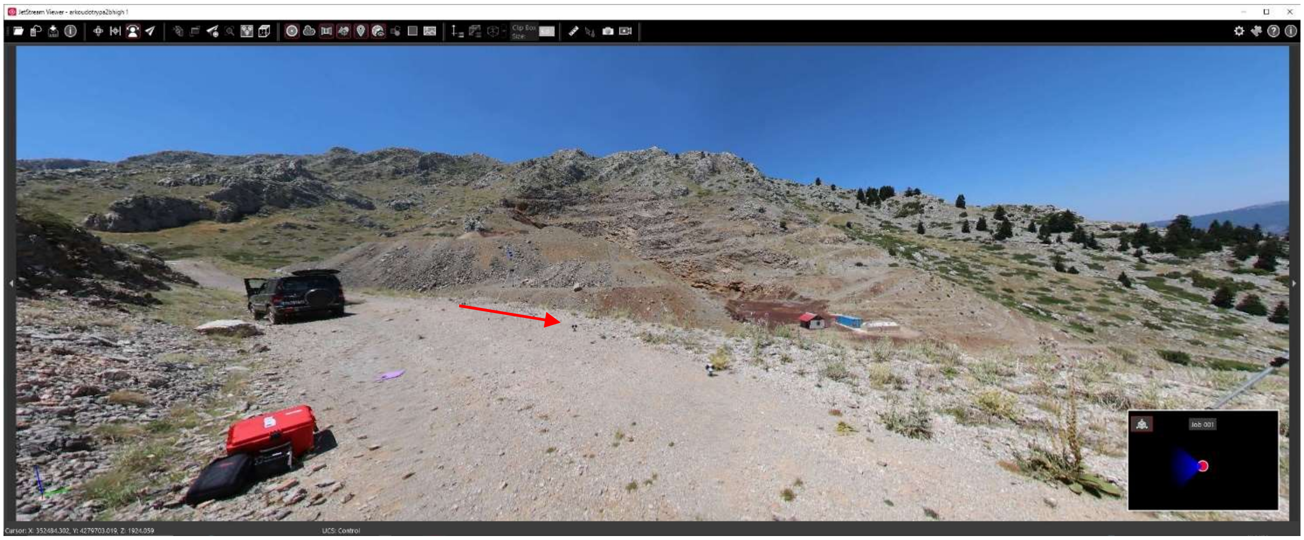

Figure 5. Creation of a 3D point cloud from the TLS data. Mine facility buildings can be seen in the middle of the point cloud. The red arrow shows a square black and white target used for the georeferencing of the 3D data.

5. 3D POINT CLOUDS FUSION

UAV and TLS surveys are regularly performed over the mining areas in order to produce an accurate 3D representation of the relief. In this framework, for the current study, UAV and TLS point clouds were generated covering the bauxite mine in Central Greece. Specifically, Figure 6 illustrates the point cloud created by UAV imagery, while Figure 7 displays the corresponding point cloud that emerged from the TLS surveys. Despite the higher density and therefore the increased precision of the TLS representation, there are areas without any information (Figure 7). These areas are with a flat shape and are located at higher altitudes regarding the scanning position. To resolve this issue, UAV and TLS point clouds were fused. The joined point cloud is displayed in Figure 8. The fusion enhanced the density of the cloud and the spatial coverage of the initial clouds. Added to the above, a comparison of the density of the different point clouds is presented in Table 1. The UAV-derived point cloud has more than 149 million points while the respective one from the TLS has a density of 32 million points. It is worth mentioning that the high density of the UAV point cloud is related to the large coverage and not to the spatial resolution of the product. The fused cloud incorporates the total volume of 3D points, reaching 181 million points.

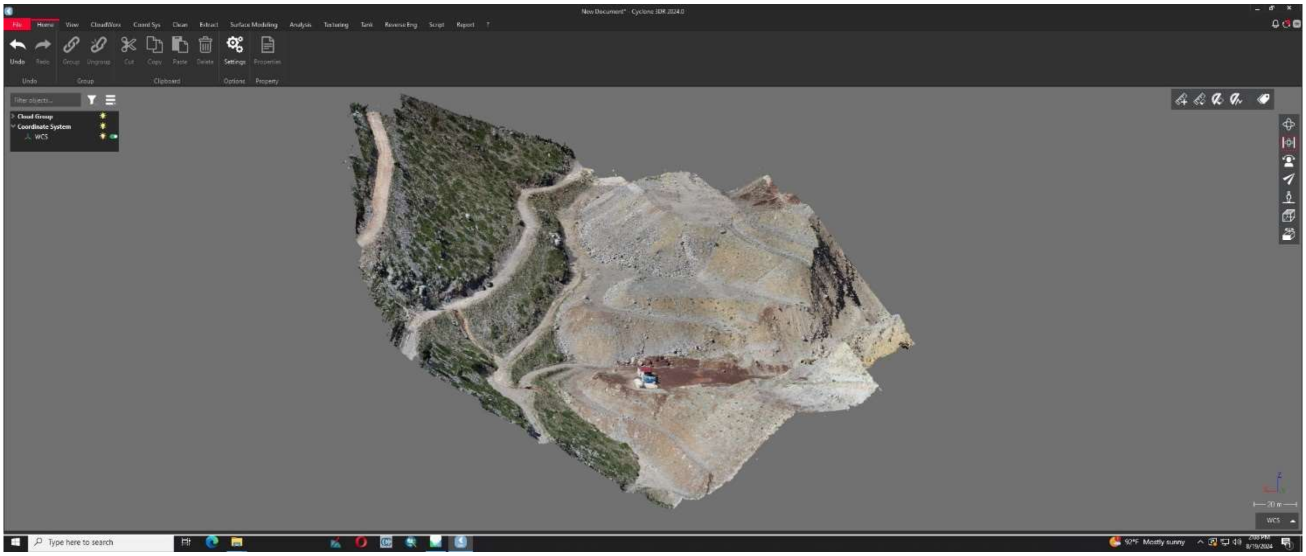

Figure 6. Point cloud generated from UAV survey on July 16th, 2024.

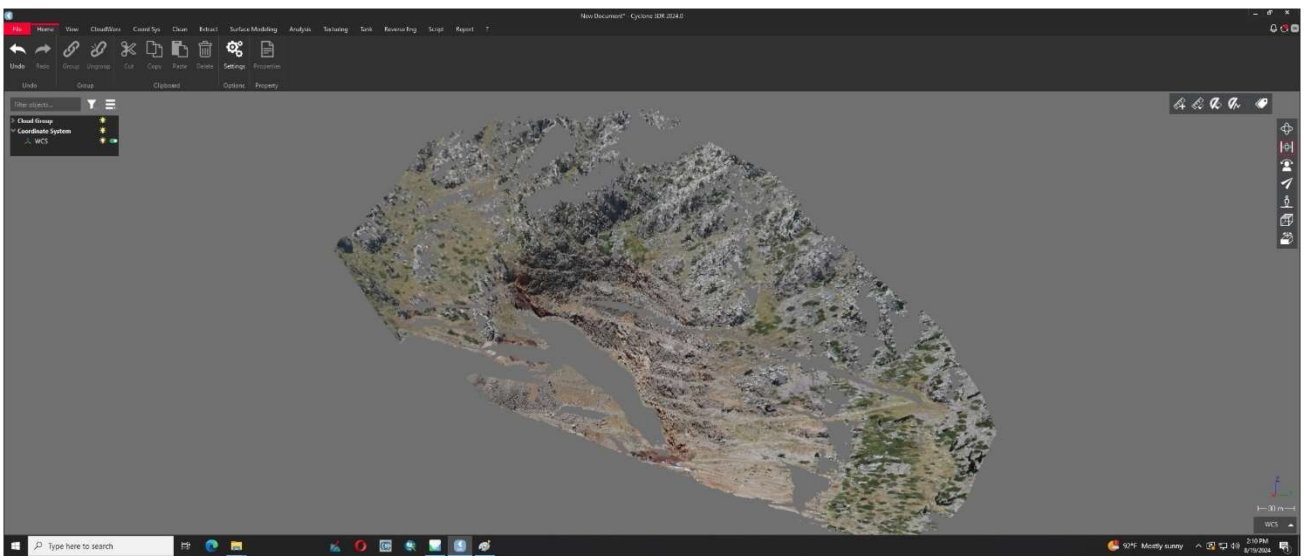

Figure 7. Point cloud generated from TLS survey on July 16th, 2024.

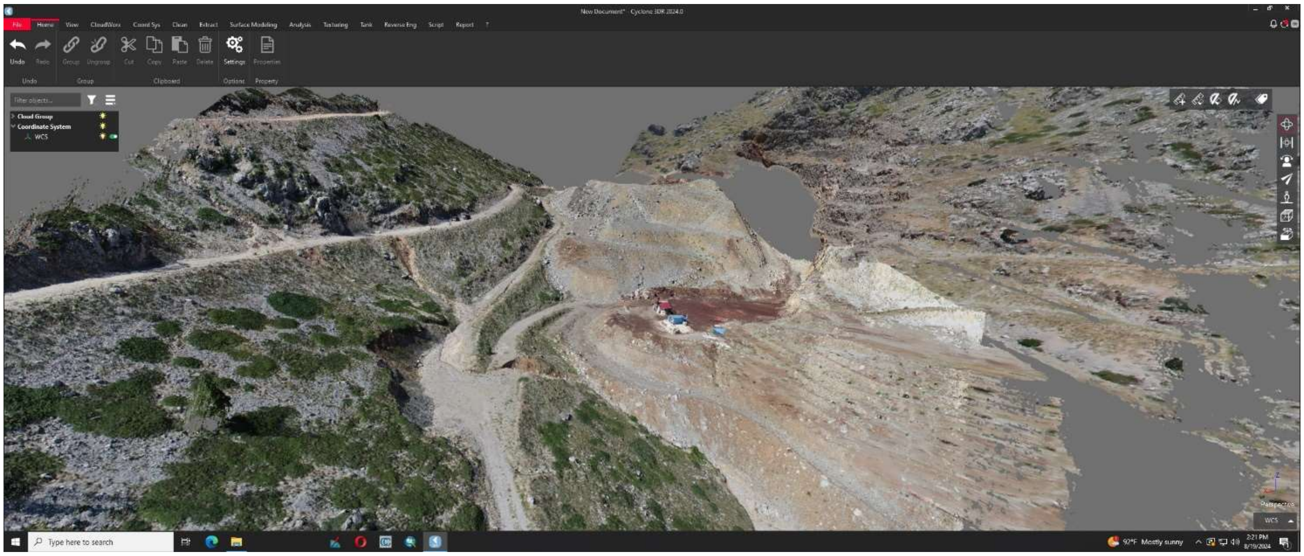

Figure 8. Point cloud arising from the fusion of UAV and TLS data, acquired on the same date.

Table 1. Point cloud density of the generated 3D models of the bauxite mine.

3D model	**Number of points**
UAV point cloud	149,843,609
TLS point cloud	32,038,053
Fused point cloud	181,881,662

From the fused point cloud, a very accurate Digital Surface Model (DSM) has been extracted (Figure 9). The specific DSM is used for the more precise planning of the UAV flight campaigns and more accurate data acquisition.

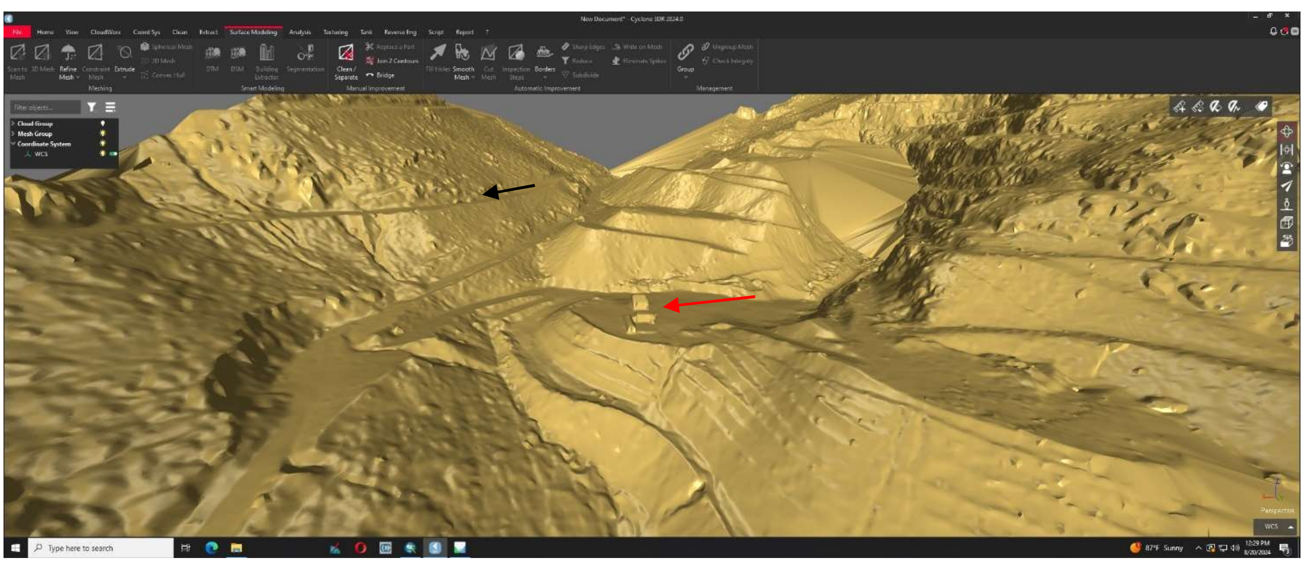

Figure 9. DSM derived from the fused 3D point cloud. The red arrow shows the mine facility buildings, while the black arrow shows the two vehicles that we used for transportation.

6. CONCLUSIONS

The current work proposes an effective and precise methodology for the accurate 3D mapping of a bauxite mine, using cost-efficient data, acquired by UAV and TLS. Notably, due to the very steep slopes and adverse weather conditions, as the specific mine is in the alpine zone, UAV and TLS surveys encountered difficulties and were repeated twice. The collected UAV imagery was processed using Agisoft Metashape, where the TLS data was processed using Leica Cyclone. The key points of the current research are:

- Precise 3D mapping of the mine can be achieved using a combination of UAV and TLS surveys.
- UAV and TLS data fusion enhances the spatial coverage and point density of the 3D model and creates a very accurate and realistic representation of the relief.
- The methodologies are complementary. TLS presents higher density and millimetre accuracy while UAVs offer a broader coverage. TLS is more convenient for the steep slopes, while UAV offers better representation of the flat areas.
- Accurate georeferencing of the 3D data sets is a prerequisite for the fusion of the clouds.

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REFERENCES

[1] Tamin M. A., Darwin N., Majid Z., Mohd Ariff M. F., Idris K. M. and Manan Samad A., "Volume Estimation of Stockpile Using Unmanned Aerial Vehicle," 2019 9th IEEE International Conference on Control System, Computing and Engineering (ICCSCE), Penang, Malaysia, 2019, pp. 49-54, https://doi.org/10.1109/ICCSCE47578.2019.9068543

[2] Kovanič, Ľ.; Peťovský, P.; Topitzer, B.; Blišťan, P., "Spatial Analysis of Point Clouds Obtained by SfM Photogrammetry and the TLS Method—Study in Quarry Environment," Land 2024, 13, 614. https://doi.org/10.3390/land13050614

[3] Nikolakopoulos K. G., Koukouvelas I., Argyropoulos N., and Megalooikonomou V., "Quarry monitoring using GPS measurements and UAV photogrammetry," Proc. SPIE 9644, Earth Resources and Environmental Remote Sensing/GIS Applications VI, 96440J (20 October 2015); https://doi.org/10.1117/12.2195402

[4] González-Aguilera D., Fernández-Hernández J., Mancera-Taboada J., Rodríguez-Gonzálvez P., Hernández-López D., Felipe-García B., Gozalo-Sanz I., and Arias-Perez B., "3D modelling and accuracy assessment of Granite quarry using unmanned aerial vehicle," ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci., I-3, 37–42, 2012, https://doi.org/10.5194/isprsannals-I-3-37-2012

[5] Green, J. "Mine rescue robots requirements: Outcomes from an industry workshop," In Proceedings of the 6th Robotics and Mechatronics Conference (RobMech), Durban, South Africa, 30–31 October 2013; IEEE Computer Society: Washington, DC, USA, 2013; pp. 111–116, (2013).

[6] McLeod, T., Samson, C., Labrie, M., Shehata, K., Mah, J., Lai, P., Wang, L., Elder, J.H., "Using video acquired from an unmanned aerial vehicle (UAV) to measure fracture orientation in an open-PIT mine," Geomatica, 67, 173–180, (2013).

[7] Ranjan, A., Panigrahi, B., Sahu, H.B., Misra, P., "SkyHelp: UAV Assisted Emergency Communication in Deep Open Pit Mines," In Proceedings of the 1st International Workshop on Internet of People, Assistive Robots and ThingS-IoPARTS'18, Munich, Germany, 10 June 2018, pp. 31–36.

[8] Dunnington, L., Nakagawa, M., "Fast and safe gas detection from underground coal fire by drone fly over," Environ. Pollut. 2017, 229, 139–145.

[9] Shahmoradi, J., Talebi, E., Roghanchi, P., Hassanalian, M., "A Comprehensive Review of Applications of Drone Technology in the Mining Industry," Drones 2020, 4, 34. https://doi.org/10.3390/drones4030034

[10] Loots, M., Grobbelaar, S., and van der Lingen, E., "A review of remote-sensing unmanned aerial vehicles in the mining industry," Journal of the Southern African Institute of Mining and Metallurgy, vol. 122, no. 7, pp. 387–396 http://dx.doi.org/10.17159/2411- 9717/1602/2022
[11] Carabassa V., Montero P., Crespo M., Padró J. C., Pons X., Balagué J., Brotons L., Alcañiz J. M., "Unmanned aerial system protocol for quarry restoration and mineral extraction monitoring," Journal of Environmental Management, Volume 270, 2020, 110717, https://doi.org/10.1016/j.jenvman.2020.110717
[12] Zapico, I.; Laronne, J.B.; Sánchez Castillo, L.; Martín Duque, J.F., "Improvement of Workflow for Topographic Surveys in Long Highwalls of Open Pit Mines with an Unmanned Aerial Vehicle and Structure from Motion," Remote Sensing, 2021, 13, 3353. https://doi.org/10.3390/rs13173353
[13] Kim, D.-P., Kim, S.-B., Back, K. S., "Analysis of Mine Change Using 3D Spatial Information Based on Drone Image," Sustainability, 2022, 14, 3433. https://doi.org/10.3390/su14063433
[14] Tong, X., Liu, X., Chen, P., Liu, S., Luan, K., Li, L., Liu, S., Liu, X., Xie, H., Jin, Y., et al., "Integration of UAV-Based Photogrammetry and Terrestrial Laser Scanning for the Three-Dimensional Mapping and Monitoring of Open-Pit Mine Areas," Remote Sensing, 2015, 7, 6635-6662. https://doi.org/10.3390/rs70606635
[15] Sturzenegger M., Stead D., "Close-range terrestrial digital photogrammetry and terrestrial laser scanning for discontinuity characterization on rock cuts," Engineering Geology, Volume 106, Issues 3–4, 2009, Pages 163-182, https://doi.org/10.1016/j.enggeo.2009.03.004
[16] Wójcik A., Klapa P., Mitka B., Piech I., "The use of TLS and UAV methods for measurement of the repose angle of granular materials in terrain conditions," Measurement, Volume 146, 2019, Pages 780-791, https://doi.org/10.1016/j.measurement.2019.07.015
[17] Ismail A., Safuan A. R. A., Sa'ari R., Rasib A. W., Mustaffar M., Abdullah R. A., Kassim A., Yusof N M., Rahaman N. A., Kalatehjari R., "Application of combined terrestrial laser scanning and unmanned aerial vehicle digital photogrammetry method in high rock slope stability analysis: A case study," Measurement, Volume 195, 2022, 111161, https://doi.org/10.1016/j.measurement.2022.111161
[18] Vassena, G. and Clerici, A., "Open pit mine 3D mapping by TLS and digital photogrammetry: 3D model update thanks to a SLAM based approach," Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-2, 1145–1148, 2018, https://doi.org/10.5194/isprs-archives-XLII-2-1145-2018
[19] Kovanič, Ľ.; Peťovský, P.; Topitzer, B.; Blišťan, P., "Spatial Analysis of Point Clouds Obtained by SfM Photogrammetry and the TLS Method—Study in Quarry Environment," Land 2024, 13, 614, https://doi.org/10.3390/land13050614
[20] Nikolakopoulos K. and Kyriou A., "Creation of 3D infrastructure model from UAV and TLS data in the frame of PROION project," Proc. SPIE 12786, Ninth International Conference on Remote Sensing and Geoinformation of the Environment (RSCy2023), 127860R (21 September 2023); https://doi.org/10.1117/12.2680706
[21] Son, S.W., Kim, D.W., Sung, W.G., Yu, J.J., "Integrating UAV and TLS Approaches for Environmental Management: A Case Study of a Waste Stockpile Area," Remote Sensing 2020, 12, 1615, https://doi.org/10.3390/rs12101615
[22] Török, Á.; Bögöly, G.; Somogyi, Á.; Lovas, T., "Application of UAV in Topographic Modelling and Structural Geological Mapping of Quarries and Their Surroundings—Delineation of Fault-Bordered Raw Material Reserves," Sensors, 2020, 20, 489. https://doi.org/10.3390/s20020489
[23] Karagiannidi, T., Papaefthymiou, H. & Papatheodorou, G., "Radioactive impact of a bauxite beneficiation plant in the Itea Gulf (Gulf of Corinth, Greece)," J Radioanal Nucl Chem 279, 923–934 2009, https://doi.org/10.1007/s10967-008-7412-3
[24] Micheletti, N., Chandler, J., Lane, S.N., "Chapter 2—Structure from motion (SFM) photogrammetry," In Geomorphological Techniques; Section 2.2; British Society for Geomorphology: London, UK (2015).
[25] Smith, M. W., Carrivick, J. L., Quincey, D. J., "Structure from motion photogrammetry in physical geography," Progress in Physical Geography: Earth and Environment, 40(2), 247–275 (2016).
[26] Westoby, M., Brasington, J., Glasser, N., Hambrey, M., Reynolds, J., "Structure-from-Motion' photogrammetry: A low-cost, effective tool for geoscience applications," Geomorphology, 179, 300–314 (2012).
[27] Kyriou A., Nikolakopoulos K., and Koukouvelas I., "Synergistic use of UAV and TLS data for precise rockfall monitoring over a hanging monastery," Proc. SPIE 12268, Earth Resources and Environmental Remote Sensing/GIS Applications XIII, 122680A (26 October 2022); https://doi.org/10.1117/12.2636150
[28] Kyriou A., Filippa T., Pappas C., Nikolakopoulos K. G., and Koukouvelas I., "Generation of high quality 3D models of a monastery located in Western Greece," Proc. SPIE 12734, Earth Resources and Environmental Remote Sensing/GIS Applications XIV, 127340B (19 October 2023); https://doi.org/10.1117/12.2679804