Application of UAV-based Photogrammetry in Monitoring Slope Deformations in Open Pit Mining Environments: A Systematic Review

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SUMMARY

Mine surveyors play a critical role in assessing and monitoring slope deformations in open pit mining environments. Monitoring the stability and deformation of open pit slopes is crucial to minimize hazards at mining sites. However, traditional survey methods for monitoring slope deformations, such as precise levelling, total station surveys, and GNSS surveys, can be limited in terms of coverage as the pit advances, accessibility, and safety of the survey crew. Unoccupied Aerial Vehicle (UAV) based photogrammetry is an emerging technology that is gaining prominence in monitoring open pit slope deformations. The review aims to summarise the current knowledge, perspectives and potential areas for future exploration of this emerging monitoring methodology for open pit mines. The research used "Preferred Reporting Items for Systematic Review and Meta-Analysis": the keywords used were "mine", "slope" and "photogrammetry") combined with the words "open pit", "temporal analysis", "UAV" and "deformation monitoring" and applied to the most appropriate databases. 47 records were initially identified; after applying exclusion criteria (such as year, document type, source type, language) and after an initial review of each study title, 30 articles were considered eligible. Records were examined in full text to obtain the required information, leaving only 24 records. Most studies utilized photogrammetric techniques (using unoccupied aerial vehicles) to monitor open pit slope deformations. There is need to conduct more research on the temporal problems that were identified in the review. Addressing this research gap will lead to effective and robust harnessing of UAV-based photogrammetry in monitoring slope deformations in open pit mining operations.

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1. INTRODUCTION

Slope collapses are triggered by factors such as local geological conditions and mining activities (Salvini *et al.*, 2018). Hazardous situations may arise when unfavourable sedimentological characteristics and geological discontinuities are made more critical by resource extraction (Zajc *et al.*, 2014). Morphological features like sharp cuts and steep slopes also play a crucial role in triggering rockfalls in mining areas (Zheng *et al.*, 2015). In order to assess the possibility of slope failures, it is crucial to understand the geometric links between geological discontinuities and slope morphology (Salvini *et al.*, 2018). Photogrammetry analyses images from multiple viewpoints, allowing for the calculation of the three-dimensional coordinates of the points (Poudel, 2023). This allows for the detection of any irregularities or changes in the surface of the object being measured (Ozhygen *et al.*, 2021).

The impact of mining and expansion of the mining area leads to the opening and formation of new rock joint blocks, which weakens the stability of the slopes (Ozyhygin *et al.*, 2021). Slope monitoring is a critical process for assessing the stability of natural and man-made slopes to ensure the safety of people and infrastructure located on or near them (Poudel, 2023). The accuracy, cost and convenience of monitoring are primarily determined by the monitoring method used (Li *et al.*, 2021). The above studies noted that traditional slope deformation monitoring mainly includes point monitoring and surface monitoring. Total stations, levels and Global Navigation Satellite System (GNSS) are commonly used in point monitoring (Li *et al.*, 2021). However, these point-based monitoring techniques provide limited spatial coverage and often require time consuming fieldwork for data collection (Li *et al.,* 2021; Bar *et al*, 2020). For example, Bar *et al.* (2020) noted that by utilising traverse procedures, traditional rock slope mapping techniques would normally require 30 to 180 minutes of field time to evaluate a 10-metre length of slope.

Giordan *et al*. (2020) noted that the use of unmanned aerial vehicles (UAVs) has grown rapidly, and it is now thought of as a standard research tool for the on-demand capture of images and other information over a given area of interest. UAV refers to an unmanned aerial vehicle that can fly autonomously with or without an engine, can be operated remotely, and can gather data (Giordon *et al.*, 2020). Coccia *et al.* (2022) agreed that a UAV is remotely operated, semi-autonomous, autonomous or a combination of these capabilities.

The foundation of photogrammetry technology is to capture an actual thing in a series of photographs taken from various perspectives and to analyse the images collected using specialized software that independently connects the images together to establish the framework for a three-dimensional object (Ozyhygin *et al.*, 2021). The last decade has witnessed unprecedented growth in the use of UAVs in open pit slope deformation monitoring

(Battulwar *et al.,* 2020). The study added that UAV technology is the ideal tool to use in these tasks, given the size of mines and their hazardous environment. By using overlapping photos captured by aerial cameras, photogrammetry reconstructs three-dimensional (3D) representations of slope surfaces (Poudel, 2023).

Using UAVs equipped with cameras, photogrammetry allows for the generation of dense 3D point clouds which can be used for change detection to monitor mining slope deformations from imagery (Poudel, 2023). The precise information about the surfaces that were stabilised and those that are continuously in danger of deformation may be obtained from an assessment of the spatial and temporal evolution of the displacements (Dobos *et al*., 2022). The study further noted that it was possible to forecast the spatial and temporal trends of the deformation.

During the last decade, open pit mines have embraced the use of UAV-based photogrammetry for slope deformation monitoring, and arguably it has proven to be more efficient than traditional surveying methods (Li *et al*., 2021; Bar *et al.,* 2020; Kolapo *et al.*, 2022; Battulwar *et al*., 2021). There appears to be a paucity of literature on the use of UAV-based photogrammetry in monitoring open pit slope deformations. There are few published references that deal with the research of rock slopes (Francioni *et al.*, 2015; Coggan *et al.*, 2007; Harbrink *etal.*, 2008; Niethammer *et al*., 2010). Furthermore, there is need to study the feasibility of using photogrammetry for monitoring lateral movement of slopes (Poudel, 2023). Further research is also needed to develop methods for optimizing the temporal frequency and timing of image acquisition for open pit slope deformation monitoring since available research publications point to slopes which are monitored on a monthly and quarterly basis (Francioni *et al*., 2015; Bar *et al.,* 2020; Kim *et al.,* 2023; Poudel, 2023; Coccia *et al.*, 2022; Vinielles *et al*., 2022).

The current study aims to analyse the research published on the use of photogrammetry for open pit slope deformation monitoring. The study searched the literature, which allowed the authors to understand the use of UAV-based photogrammetry to effectively monitor slope deformations in open pit mining environments. The literature also reviewed the methods used by past researchers to adopt UAV-based photogrammetry in open pit slope deformation monitoring. The literature was mapped to understand what lessons can be learned from the past and discuss a possible future scenario for monitoring slopes in open pit mines.

2. METHODS

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) was used in order to draw up the scoping review protocol for this study (Tricco *et al*., 2018), including the formulation of review questions, search strategy, study selection criteria, data extraction and synthesis.

2.1 Eligibility criteria

The scoping review included research articles, official reports, theses, and dissertations that examined the outcomes associated with utilising UAV-based photogrammetry for monitoring open pit slope deformation or similar tasks. Non-research articles (opinion articles, literature reviews) and studies that do not specify the use of UAV-based photogrammetry in open pit slope deformation monitoring were not considered.

2.2 Search strategy

A search of literature from 2014 to 2023 was performed. The research included some leading engineering databases: Scopus and Google Scholar. The keywords defined to conduct the study are mine, slope and deformation which were sequentially combined with open pit, UAV and temporal analysis. All of these keywords were separated by the boolean operator “AND”. The search was conducted in English. At the end of this process, the existence of potentially associated keywords related to the subject in the selected items was checked. If found, the new keywords were used in new search combinations with the keywords previously used.

2.3 Selection of sources of evidence

After applying the first set of exclusion criteria, the review process was divided into two levels of screening. A detailed review of titles and abstracts was used to exclude articles that fell out of scope. The second level involved full-text reviews. For the second level, some minimum inclusion criteria were applied in order to determine which papers were to be screened. The respective references of the selected articles were checked in order to find older articles not detected in the initial survey. In this process, the other works of the authors of the selected articles, as well as the respective research centres, were verified.

2.4 Data extraction

In the data extraction phase, 24 original articles, review and conference papers, published reports and case studies were selected and extracted. The articles were in English and from the fields of Photogrammetry, Mining and Rock Mechanics, Geotechnical Engineering. Figure 1 outlines the systematic literature review approach as adapted from Moher *et al*. (2009).

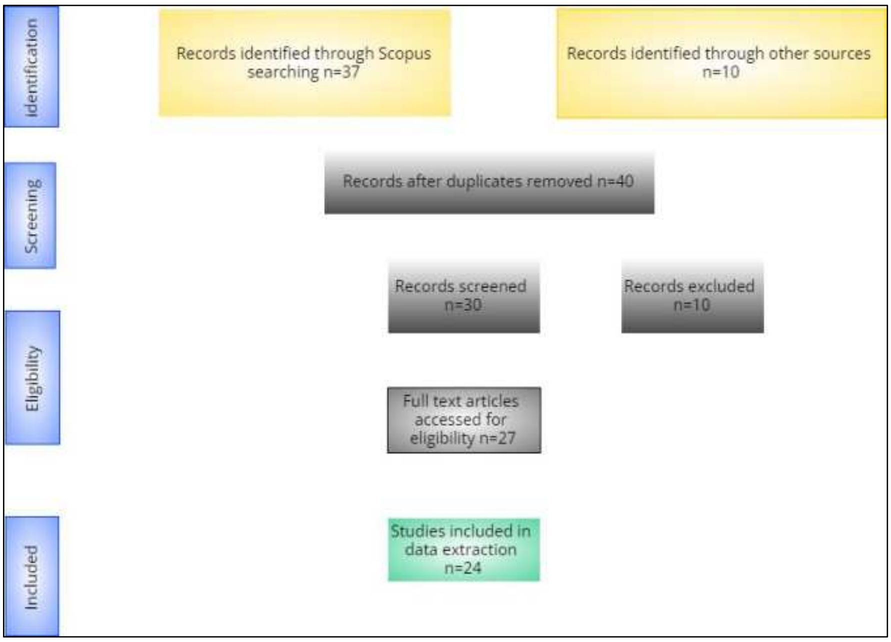

Figure 1: Structure and workflow of the scoping literature review (adapted from Moher et al., 2009)

3. Results and analysis

The search yielded a total of 47 studies. After screening the titles and abstracts, 30 studies were identified as potentially relevant. After a full-text review, 24 studies met the inclusion criteria and were included in the review (Figure 2).

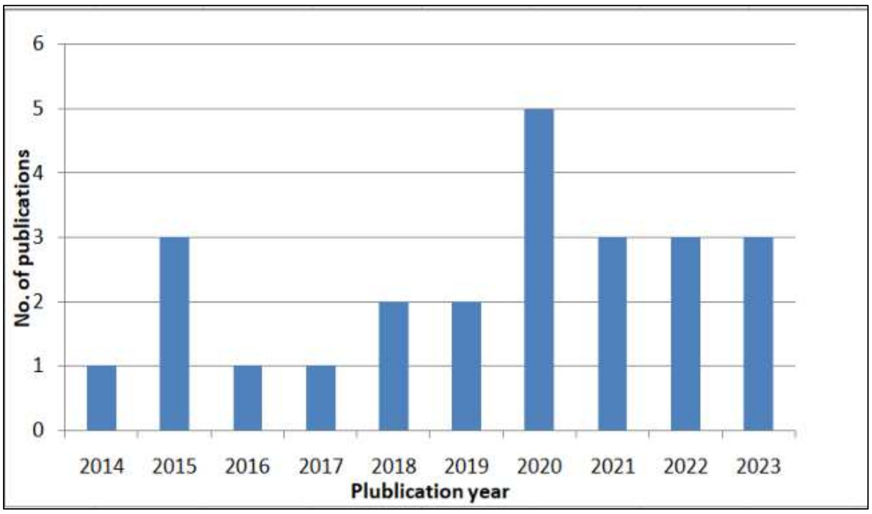

Figure 2: Publication year from the databases

Most of the reviewed publications focused on monitoring slope deformations and blasting operations in the mining sector. Other areas included safety inspections, stockpile inventories, exploration surveys, among others as indicated in Figure 3.

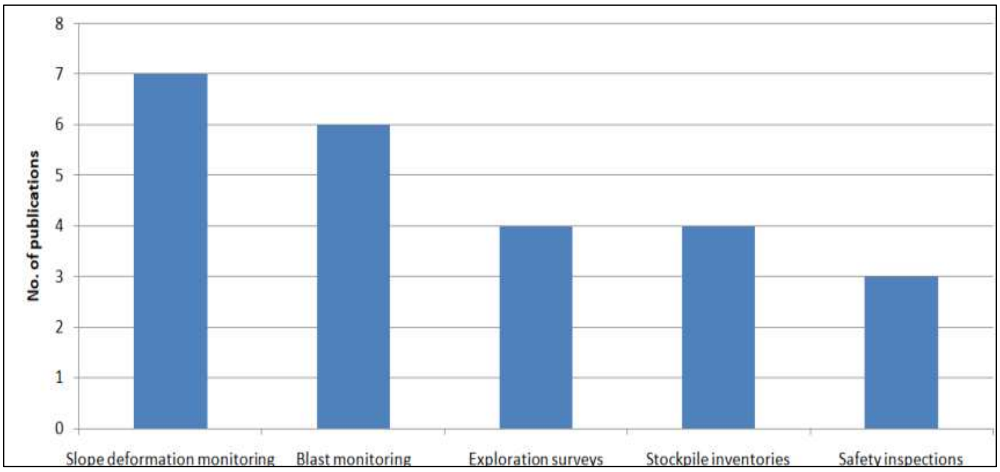

Figure 3: UAV application areas in open pit mining environments

A number of publications noted the increased use of quadcopter, fixed wing drone, octocopter platforms in aerial photogrammetry operations (Bar et al, 2020; Coccia *et al.*, 2022; Vinielles *et al.*, 2022). Figure 4 shows the types of UAV platforms which have gained prominence in recent times.

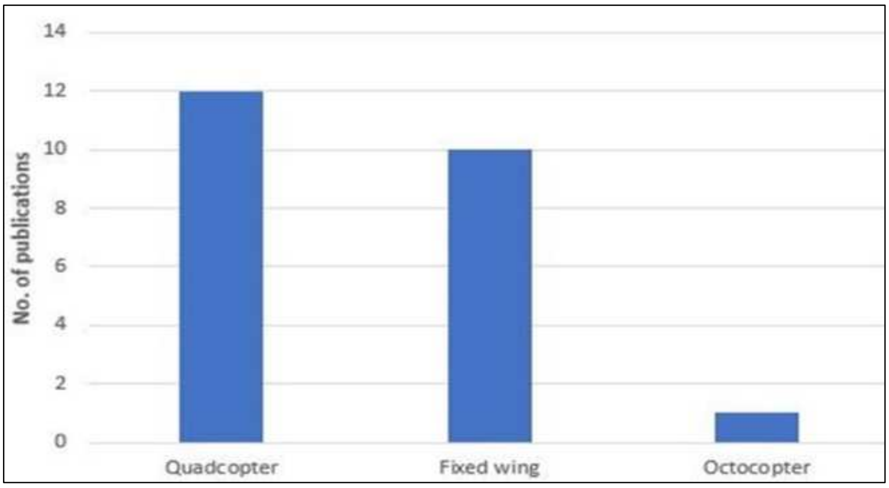

Figure 4: UAV platforms

The reviewed studies found that RGB sensors were the most commonly used sensors (Francioni *et al.*, 2015). Multispectral sensors were widely used in slope deformation monitoring due to their usefulness in mapping steep environments (Battulwar *et al.,* 2020), while the application of hyperspectral and thermal cameras was limited as shown in Figure 5.

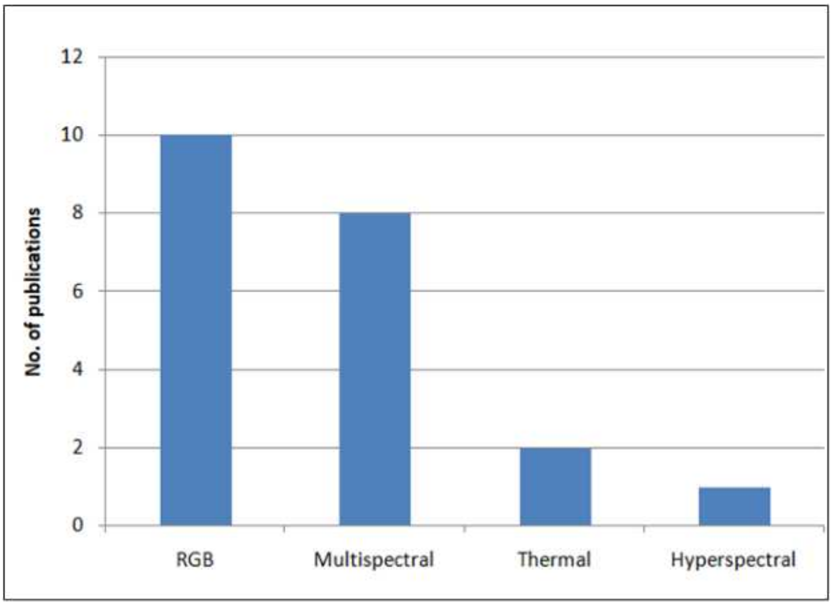

Figure 5: Common UAV Sensors

In recent studies, there has been a trend in the change of the acronym from unmanned aircraft vehicle UAV to unoccupied aircraft vehicle UAV. Giordan (*et al., 2020*) introduced the definition of the unoccupied aircraft vehicle, and subsequent studies, such as those by Kim *et al*. in 2023 and Vinielles *et al*. in 2022, have adopted this terminology.

Aerial photogrammetry requires ground control points (GCP) data to define the mapping datum and image scale and also to ensure a good image block geometry (Kim *et al*., 2023; Li *et al*., 2020). The reviewed studies utilized flight planning applications and processing software packages such as Pix4DCapture Map Pilot App, Autopilot for DJI, AgiSoft PhotoScan processing software, and Pix4DMapper (Francioni *et al*., 2015; Bar *et al*., 2020; Li *et al*., 2020; Kim *et al*., 2023).

The reviewed studies utilized UAV-based photogrammetry to monitor open pit slope deformations. The technology is becoming a powerful, accurate, cost effective and reliable tool for monitoring open pit slope deformations (Francioni *et al.*, 2015; Bar *et al.*, 2020; Kim *et al.*, 2023; Poudel, 2023; Coccia *et al*., 2022; Vinielles *et al.*, 2022). Furthermore, the reviewed studies utilized a range of softwares including Agisoft, Pix4D and ShapeMetriX for processing the 3D spatial data.

UAV-based photogrammetry and point cloud processing softwares determine surface displacements by comparing the variations between the 3D point cloud coordinates or digital elevation models obtained by periodic flights respectively (Francioni *et al.*, 2015; Bar *et al.*, 2020; Li *et al.*, 2020; Kim *et al.,* 2023; Poudel, 2023; Coccia *et al.*, 2022; Vinielles *et al*., 2022). Horizontal displacements can be investigated using orthoimages while DEMs are ideal for determining vertical displacement (Kim *et al.*, 2023; Li *et al*., 2020; Bar *et al.,* 2020). Kim *et* *al*. (2023) analysed both the vertical and horizontal displacements by using surface elevation change to a preset baseline surface. Bar *et al.* (2020) and Vinielles *et al*. (2022) used DEM elevation differences to analyse slope deformations in open pit mines. Some of the studies used visual inspections combined with the methods mentioned above to analyse slope deformations in open pit mines (Coccia *et al*., 2022; Li *et al* 2021).

Both advantages and limitations for the application of UAV-based photogrammetry have been identified in the reviewed studies. A sequence of processing procedures used in Structure from Motion enables the computation of a complete collection of 3D surface points that are then merged to create a surface description in a photo-realistic manner (Kim *et al*., 2023). Due to the availability of redundant information, lens distortion and other geometric deviations caused by the camera being utilized are taken into account while creating the 3D model (Bar *et al.,* 2020). This means that even inexpensive, off-the-shelf drones can be used to create 3D models with a high enough level of accuracy (Francioni *et al.,* 2015; Bar *et al.*, 2020; Li *et al.,* 2020; Kim *et al*, 2023). It should be noted, nevertheless, that a photogrammetry application on its own is still not fully capable of carrying out a ground characterization. for instance, utilising this method would necessitate spending physical time in the field when it is safe to do so in order to evaluate or estimate joint qualities like infilling and intact rock parameters like strength (Bar *et al*., 2020). Additionally, slope deformations may be far from perpendicular to the slope surface, and other complementary techniques could aid in interpreting the true slope displacement vectors (Kim *et al*., 2023; Francioni *et al.*, 2015).

4. TRENDS

4.1 Time lapse monitoring

Time lapse photogrammetry allows for continuous monitoring of slope deformations over extended periods (Francioni *et al.*, 2015). By capturing images at regular intervals, changes in slope morphology and deformation patterns can be detected, analysed and compared over time (Bar *et al.*, 2020). This approach provides valuable insights into the behaviour and stability of open pit slopes.

4.2 Integration with other monitoring techniques

Photogrammetry is being used in conjunction with other monitoring techniques such as Light Detection and Ranging and radar-based interferometry synthetic aperture radar to monitor open pit slope deformations (Kim *et al*., 2023; Li *et al*., 2020; Giordan *et al.,* 2020). These complementary methods provide different perspectives and data sources to enhance the understanding of slope deformations and improve the accuracy of deformation measurements (Li *et al.,* 2020). Francioni *et al.* (2015) used UAV photogrammetry and geographic information system (GIS) to effectively estimate the ground displacements of open pit slopes.

4.3 Real time kinematic and post processed kinematic

Installing and surveying ground control points (GCPs) can occasionally be expensive and time-consuming, especially in challenging terrain. Likewise, in a mining operation where workers might be exposed to interactions from a safety standpoint, GCPs may not be feasible with haul trucks and other mining machinery (Harbrink *et al.*,2008). In such scenarios, GNSS data collected while the photos were being taken can be used to scale and orient 3D models (Bar *et al.*, 2020). Utilising real-time kinematic (RTK) or post-processed kinematic (PPK) can further enhance pure GNSS reference by improving the 3D model's absolute geo-localisation without the need of GCPs (Poudel, 2023; Bat *et al.*, 2020).

5. RESEARCH GAPS

UAV based photogrammetry offers numerous advantages in monitoring slope deformations in open pit mining, however despite its potential, there are still research gaps that need to be addressed to maximize its reliability. One of the key research gap pertains to temporal monitoring.

Open pit slope deformation is a dynamic process that occurs over spatial scales ranging from centimetres to kilometres and temporal scales from hours to years (Chen *et al*., 2020). Effective monitoring of slope stability requires remote sensing data with high temporal resolutions to capture small deformations as they develop and progress. However, available studies monitored open pit slope deformations annually and bi-annually. These infrequent aerial surveys tend to miss multiple slope failure events occurring at short time scales (Francioni *et al*., 2015; Salvin *et al.,* 2018; Bar *et al.*, 2020; Li *et al*., 2020; Kim *et al.*, 2023; Poudel, 2023; Coccia *et al.,* 2022; Vinielles *et al*., 2022). Salvin *et al.* (2018) monitored slope deformations annually using UAV-based photogrammetry at an open pit mine in Apuan Alps marble district in Italy. Additionally, Vinielles *et al.* (2020) used UAV-based photogrammetry to monitor an active landslide bi-annually at an open pit mine called Las Cruces in Spain. Poudel (2023) concluded that the temporal resolution of the monitoring system was a limiting factor, as frequent monitoring was necessary to capture all of the changes that were occurring on the slopes. Further research is needed to develop methods for optimising temporal frequency of image acquisition for open pit slope deformation monitoring.

6. CONCLUSION

The systematic review examined the use of UAV-based photogrammetry for monitoring slope deformations in open pit mines. The findings underscored the significant potential and advantages of this technology for assessing and monitoring slope deformations. UAVs with high-resolution cameras can capture detailed imagery, enabling accurate 3D modelling and analysis. This approach offers a cost-effective and efficient alternative to ground-based surveying methods, facilitating regular and systematic monitoring of slope deformations. However, there is need for further research to address challenges such as the optimisation of image acquisition periods in the course of mining activities. By addressing this gap, UAV-based photogrammetry can be fully utilised for effective slope monitoring in open pit mining.

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BIOGRAPHICAL NOTES

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