An Investigation Of The Benefits Of Adopting Global Navigation Satellite Systems (GNSS) And Unmanned Aerial Vehicles (Uavs) In Mining Operations

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Abstract - The use of Unmanned Aerial Vehicles (UAVs) is expanding rapidly across multiple sectors due to advancements in efficiency, reliability, and accuracy. These technologies are increasingly applied in mining, agriculture, construction, surveillance, and emergency response, offering capabilities such as high-resolution mapping, precision monitoring, and access to hard-to-reach areas. This study investigates the benefits and challenges associated with the adoption of Global Navigation Satellite Systems (GNSS) and UAVs in mining operations, with a specific focus on FQM Trident Ltd in Zambia. A qualitative case study approach was employed, utilizing open-ended questionnaires administered to personnel within the Technical Services department at FQM Trident Mine. The findings reveal that GNSS and UAV technologies enhance time efficiency in surveying, support effective decision-making, and contribute to resource optimization through improved accuracy and operational continuity. However, several challenges were identified, including high acquisition costs, a shortage of skilled operators, resistance to technological change, and regulatory constraints. Despite these barriers, the study concludes that the integration of GNSS and UAVs presents significant operational advantages for mining firms. It recommends increased investment in these technologies, capacity-building for operators, and policy reforms to facilitate wider adoption. Future research may explore the application of GNSS and UAVs in the agricultural sector to evaluate their broader impact and potential benefits.

Index Terms - Global Navigation Satellite Systems (GNSS), Unmanned Aerial Vehicles (UAVs), Mining Operations.

I. INTRODUCTION

The use of UAVs is expanding rapidly and gaining popularity for various purposes [10]. UAVs have become more cost-efficient, reliable, and accurate, which has driven their adoption in areas such as mining, agriculture, construction, search and rescue, and surveillance. Additionally, their enhanced capabilities such as high-resolution mapping, precision agriculture, and even delivery of goods in hard-to-reach areas are now being utilized in both commercial and military sectors [20]. This study therefore investigated the benefits of adopting GNSS and UAVs in mining operations in mining, specifically at FQM Trident Ltd, a mining company in Zambia. According to Smith & Turner [17], by integrating these technologies, mining operations can achieve greater precision in mapping, enhanced safety, and increased operational efficiency which translates to optimized resource extraction, improved monitoring processes, and minimized environmental impacts, making it a critical area of research for modern mining practices. Hence this paper looks at the significance of GNSS and UAVs in mining operations to determine its applicability in the Zambian mining sector.

II. LITERATURE REVIEW

SURVEY STAKEHOLDER PERSPECTIVES ON THE BENEFITS OF ADOPTING GLOBAL NAVIGATION SATELLITE SYSTEMS (GNSS) AND UNMANNED AERIAL VEHICLES (UAVS) IN MINING OPERATIONS

The integration of GNSS and UAVs in mining operations has attracted global attention due to their potential to improve safety, efficiency, and productivity. Leading mining companies such as Rio Tinto and BHP Billiton in Australia have reported enhanced operational efficiency through GNSS-enabled mapping and UAV assisted automated drilling. Similarly, Mpofu et al. [12] found that UAVs improved underground mining safety at Anglo

American Platinum's Mogalakwena Mine by minimizing human exposure to unstable geological formations.

In Zambia, adoption has been slower due to infrastructural and regulatory challenges, though notable progress is being made. At Kalumbila Mine, GNSS and UAV technologies have proven effective for tailings dam monitoring, volumetric assessments, and mineral stockpile management [9]. Phiri et al. [15] observed a 25% improvement in surveying accuracy and a 15% reduction in fuel usage in drilling operations, attributing these gains to more efficient planning derived from UAV and GNSS data.

Safety benefits have also been emphasized. At Newmont Goldcorp's Akyem Mine in Ghana, UAVs reduced the number of personnel required in high-risk zones, thereby lowering accident rates [14]. These findings align with the International Council on Mining and Metals, which highlights how GNSS and UAV integration supports real-time monitoring and reduces exposure to hazardous environments [6].

Despite the advantages, significant barriers remain. High acquisition costs, a shortage of skilled personnel, and restricted airspace usage limit broader adoption, especially in underdeveloped regions such as Zambia [18,16]. Stakeholders emphasize the importance of collaboration among government agencies, mining firms, and technology developers to address these challenges and fully leverage the benefits of GNSS and UAV technologies in mining.

Safety and Efficiency Gains of Using GNSS and UAVs in Mining Operations.

The adoption of GNSS and UAV technologies in mining operations has significantly improved safety, operational efficiency, and decision-making processes, according to mining companies and regulatory bodies globally [6]. Real-time data acquisition tools such as robotic total stations and scanners connected to corporate networks have complemented GNSS and UAVs by enhancing safety protocols and streamlining operations. These technologies have also reduced the need for human presence in high-risk zones, thereby minimizing accidents and improving resource management.

One key application of UAVs is the surveying and monitoring of hazardous areas, including steep pit walls, shafts, and unstable tailings dams. At Debswana's Jwaneng Mine in Botswana, UAVs were used for slope stability monitoring, leading to a 30% reduction in monitoring man-hours and a corresponding decrease in accident risks [10]. Similarly, in South Africa, UAVs were employed to resolve rock fall incidents and provide real-time imaging for underground inspections [4].

The efficiency gains brought by GNSS and UAVs are evident in multiple mining functions, from exploration to fleet management. At Barrick Gold's Pueblo Viejo Mine in the Dominican Republic, the integration of GNSS led to a 25% improvement in ore recovery and a 15% reduction in fuel consumption by optimizing haulage and drilling patterns [1]. GNSS was also integrated into fleet dispatch systems, further enhancing productivity by reducing cycle times.

UAVs have proven highly effective for volumetric assessments and site condition monitoring. At FQM Trident Mine in Zambia, UAV usage for volumetric analysis reduced survey time by 250% and significantly improved the accuracy of volume estimations [2]. The rapid data acquisition facilitated quicker managerial decisions and minimized operational downtime.

Environmental monitoring is another area where UAVs have made a substantial impact. At Kansanshi Mine, UAVs enabled regular environmental assessments that supported regulatory compliance and prevented costly fines [13]. These capabilities make UAVs critical tools for sustainable mining.

However, challenges persist. High initial equipment costs, a shortage of skilled personnel, and regulatory limitations continue to hinder widespread adoption [8]. Despite these barriers, the potential for GNSS and UAV technologies to become standard practice in mining remains strong, with growing industry support pointing toward future widespread integration [5].

Accuracy and Reliability of Data Collected Using GNSS and UAVs in Mining Operations.

Recent developments in mining operations have highlighted the integration of GNSS technology and UAVs as a transformative approach to improving the accuracy and reliability of data collection. Equinox Drones [5] noted that the implementation of these technologies has facilitated more accurate geological mapping, infrastructure monitoring, and resource estimation. In both Africa and Zambia, case studies have shown an increasing trend toward adoption, driven by consistent accuracy in survey outputs.

GNSS provides high-precision positioning data, which is particularly crucial for mining applications. Groundhog Apps [7] emphasized the ability of GNSS to achieve centimetre-level spatial accuracy, which far surpasses traditional land surveying methods. At Indonesia's Grasberg Mine, Zhang et al. [19] reported that 98% of drill holes were accurately placed within optimal ore zones, resulting in reduced secondary blasting and increased extraction efficiency.

UAVs contribute to enhanced spatial data acquisition through high-definition imaging and LiDAR sensors. Mwenda et al. [13], in a study at Kibali Mine in Congo, observed that UAV-based surveys achieved horizontal accuracies of ±3 cm and vertical accuracies of ±5 cm. This improvement led to a 70% reduction in the time required for topographic surveys compared to traditional ground-based techniques.

The resilience of GNSS and UAV data in challenging environments has also been confirmed. Banda and Sichinga [2] documented how RTK-GNSS at FQM Trident Mine in Zambia successfully mitigated signal disruptions caused by complex terrain, making it a dependable choice for both open-pit and underground mining. Similarly, Mpofu et al. [12] noted that at Mogalakwena Mine in South Africa, UAVs achieved over 95% consistency in repeat slope stability surveys, removing the need for on-ground survey teams and avoiding operational disruptions.

The integration of GNSS-equipped UAVs has also improved mapping precision. Phiri et al. [15], studying operations at Kansanshi Mine, highlighted that GNSS-enabled UAV flights achieved spatial accuracies within 10 cm for digital terrain models and orthophotos, significantly aiding volumetric stockpile analysis and site condition monitoring.

Despite these advantages, some limitations remain. Weather conditions such as strong winds and rainfall can impact UAV flight performance and image quality, while GNSS systems are susceptible to multipath errors, especially in vegetated or built-up environments. However, advancements such as multi-layer antenna GNSS receivers and improved UAV designs are addressing these challenges and enhancing data reliability.

Challenges and Barriers to the Adoption of GNSS and UAVs in the Mining Sector

Lack of trained personnel is another factor that hinders mining firms from embracing GNSS and UAV technologies. To use these technologies effectively trained personnel are required to operate the GNSS receivers, fly the UAVs, and process the spatial data using GIS software. A survey reported by Mpofu et al. [12] in South Africa found that only 35% of the mining companies studied had employees with the necessary skills to effectively use GNSS and UAV systems. This skills mismatch leads to underutilization of the technologies, increased downtime, and more expenses on a consultancy due to outsourcing. The survey suggests that there should be more funding for capacity building and training activities to address this skills-related issue and enhance the adoption of the technologies.

Similarly, the regulatory burden becomes quite an obstacle to the implementation of GNSS and UAV technologies in the mining industry. In Zambia for example, the use of UAVs is subject to regulations from aviation authorities, and it may take a long time and involve a lot of processes to get the relevant approvals to use UAVs over mining regions. The Zambian Civil Aviation Authority (ZCAA) requires mining companies to obtain grants for the use of UAVs in aerial surveying stating that the operations have several restrictive conditions regarding safety and privacy. The approval stages sometimes last for a few months, and what is more, there are more requirements to be satisfied which then discourages some players from adopting UAV systems. In addition, it is common for aerial vehicles to be banned in many areas that are restricted or have high levels of security, such as areas neighbouring national frontiers or important facilities.

Scepticism about the capacity of new technologies and resistance to change are also serious impediments within the mining industry. It has been observed in many conventional mining activities that situational operations are subordinating the use of established methods of surveying, exploration, and monitoring. Such resistance, in any case, is usually influenced by inadequate information about the advantages of GNSS and UAV technologies. Banda & Sichinga [2] conducted a study on the adoption of technology in the Zambian mines. In their study, the availability of financial resources to such companies that were not utilizing the GNSS and UAV technologies due to ignorance of the capabilities of such technology by senior management was highlighted as one of the main factors for low adoption rates. The study encouraged greater awareness campaigns and pilot projects aimed at shaming and demonstrating the tangible benefits of these technologies in enhancing mining activities.

Furthermore, operational and environmental factors inhibit the use of GNSS and UAV technologies in mining. An example is the GNSS technology in underground or heavily vegetated areas where the signal is blocked leading to loss of data integrity. Weather-related aspects such as strong winds, rain, and dust are also some of the adverse conditions that are likely to compromise the functionality of UAVs. Research by Mhone et al. [11] at Kansanshi Mine, Zambia, showed that UAVs could not be applied properly during the rainy seasons, and this reduced their effectiveness in the monitoring and data collection throughout the year. The study proposed that some heavy-duty UAV platforms and GNSS systems that can endure extreme weather conditions be availed to solve this problem.

Along with the increased application of UAVs, data security and privacy issues become even greater obstacles. High-resolution imagery of mine sites is one of the data that UAVs gather, which can be misused or accessed without any proper authority in case suitable measures for data protection are not properly instituted. It is

paramount for mining companies to protect data that has been acquired using UAVs and GNSS systems in accordance with applicable local laws and regulations on data protection. Regarding data management in the mining industry in Ghana, Osei et al. [14] also defined the concern over data privacy as an important factor that hinders the adoption of UAVs for aerial surveys, as representatives of stakeholders were concerned that exposing UAVs to airborne operations would potentially disclose sensitive operational information.

III. METHODOLOGY

Research Approach & Design

This study adopted a qualitative research approach, emphasizing the interpretation of participant experiences and contextual understanding, as recommended by Creswell ,2014 [3]. A case study design was employed to explore the benefits of GNSS and UAV adoption in mining operations, focusing on real-world settings with complex interactions.

The target population comprised 81 employees from the Mining Technical Services (MTS) department at FQM Trident Mine. A purposive sample of 25 participants from Geology, Hydrogeology, Mining Engineering, Survey and Rock Mechanics sections was selected to ensure rich, relevant data. Sampling was guided by the principle of data saturation.

Data was collected using open-ended questionnaires, allowing participants to express detailed perspectives. Thematic analysis was used to analyse responses, with data coded and grouped into emerging themes. Interpretation involved comparing findings with theoretical constructs to establish relevance and context. Finally, the methodology adhered to key ethical principles, protecting participant identity and autonomy throughout the research process.

IV. RESULTS

Based on the data collected and analyzed, the three research questions were answered.

Efficiency gains of using GNSS and UAVs in mining operations

Surveying has been one of the more prominent tasks that the participants pointed out, and participants consistently emphasized that GNSS and UAV technologies have cut down on processes that took time and resources that were extensive in the past. Such technologies improve the overall process by eliminating repetitive data entry and giving up-to-date information which guarantees decisions are made in an effective swift manner.

By optimizing resource use, GNSS and UAV technologies can improve efficiency although it was pointed out that this technology is focused on the workforce who have been able to reorganize and focus on strategic activities instead of physically demanding or dangerous ones. This aspect relates to the transitions that occur when archaic systems are replaced with technologically advanced systems that increase productivity in the workforce.

The achievements in efficiency accruing from the adoption of GNSS and UAV technologies are a function of the accuracy and precision of operations. Several participants spoke about how these technologies reduce errors in surveying and data collection which then require fewer iterations.

As a result of accurate and consistent information provided by these technologies, there are no disruptions during operations.

The use of GNSS and UAV technologies during construction activities has led to improvement in productivity and output performance. Participants ents noted that these technologies enable them to finish tasks much quicker, hence ensuring that project out-turns are greatly enhanced.

Using these insights, it is possible to appreciate how these technologies assist in growing mining projects without affecting their grade.

The up-to-date information enhances the efficiency and flexibility of mining operations significantly.

Cost reductions resulting from GNSS and UAVs grossed efficiency emerged as a recurring theme. Participants needed to explain how the technologies help save both direct and indirect costs. With GNSS and UAVs, material wastage and exceeding expenses is minimized and therefore operations are cheaper.

The use of GNSS and UAV technologies reflects noticeable efficiency gains with GNSS reported to have limited implications on safety. Several participants highlighted that these technologies minimize human exposure to hazardous environments. This enhanced safety allows operations to be running concurrently and unbroken thus enhancing efficiency. This improved incident rate enables mining operations to respond promptly to different operational demands thereby increasing efficiency in many activities.

Another major theme was the flexibility and scalability that is provided due to the use of GNSS and UAV technologies. Participants remarked on the ability of such tools to be used for a variety of purposes with different operational scales.

GNSS and UAV technologies in environmental issues and operational efficiency management also overlap. This integration of environmental protection with business objectives minimizes disturbances and is consistent with environmentally sound development.

The long-term strategic dynamics that GNSS and UAV technology adoption affords were accented by the participants. These views underscore the fact that the acquisition of a particular technology has wider consequences for maintaining competitiveness and enhancing operational flexibility.

Accuracy and reliability of data collected using GNSS and UAVs in mining operations

The infinite value that GNSS and UAV bring in terms of data collection, especially in mining activities prompted participants to stress the accuracy of the technology. This accuracy decreases the planning and execution errors thereby increasing the quality of decisions made using the information. The significance of such reliability is in environments where precision has a direct correlation to the success of operation.

One of the notable points raised in the responses was the role of GNSS and UAVs in facilitating accurate geological and topographical mapping. These technologies allow for a level of detail that is difficult to achieve using conventional means which greatly enhances the mapping process.

Another factor that participants raised was the reliability of monitoring and surveillance. UAVs with advanced sensors and cameras are much better at providing unchanging and retrievable information. This capability helps with the activities and scope management of resources and risks. Such capability renders competence in preventing resource mismanagement, and risk exposure.

Concerning UAV images and GNSS, participants mentioned their advantages in volumetric modelling. High-resolution images from UAVs can do a volume calculation as they can locate stockpiles. These accurately taken measurements assist in the efficient use of resources and minimization of the materials.

Another issue that was common among most of the participants was the reproducibility of GNSS and UAV data in different surveys. They stressed that such technologies guarantee a participatory manner irrespective of the degree of complication or the size of the task. This level of consistency is vital in projects which might be planned for a longer time and comparison of data is the main concern.

Taking into consideration the current statistics, safety, and accuracy are much needed where UAV (drones) or advanced location capture is required, and the current methods are not sufficient.

Using UAVs, good data can be obtained from places that are highly risky for human surveyors such as at high steep slopes and other places with risky terrains. GNSS has the advantage of providing exact position determination of locations where it would be impractical for manual methods due to sensitivity to time and errors. This feature improves greatly the safety side, and the quality of data captured.

Access to real-time data was also among the mentioned advantages of GNSS and UAV accuracy. GNSS and UAV's capabilities ensure that there is enough data, ready at the user's disposal, which is necessary for fast and accurate decision making. This type of accuracy enables an environment where decision-making and execution solely depend on the data feedback from the system.

Another area These technologies, GNSS and UAV in this case, are noted to be flexible to the demands of the environment.

It is clear that the information highlighted contributes towards efficient output in the future which is more reliable.

Challenges in adopting GNSS and UAVs in mining operations

A recurring theme in the responses was the overall cost of acquiring GNSS and UAV technologies. Limitations related to finances were mentioned by the participants as one of the barriers to GNSS integration. These financial aspects always discourage adoption of such technologies. Another challenge in the adoption of GNSS and UAV systems is the shortage of qualified personnel. Training and capacity-building measures to fill the skills gap require considerable expenditure, time, and other resources.

Regulatory constraints were another constraint highlighted by participants. The participants pointed out the intricacies involved in getting authorizations to use UAVs and the stringent constraints applied to their use. These regulations can in some cases inhibit mining companies from fully embracing these technologies.

Resistance to change, particularly among senior management and employees who had been in service for a considerable amount of time was also reported. Participants submitted that cultural resistance in organizations acts as a bottleneck in the technology adoption process in that it elongates the timeline of when a new technology can be rolled out.

Furthermore, the operating environment presents challenges that negatively affect GNSS and the use of UAVs. This limits the reliability and effectiveness of technologies in some mining situations. Reservations about the security of data and privacy have been expressed as one of the deterrents to UAVs and GNSS usage. These issues require stringent data management processes which makes adoption even more cumbersome.

It was stated that GNSS and UAV technologies have maintenance as well as operational costs after the initial investment. Those recurrent costs also make it difficult for firms to continue applying these technologies in a longer time frame.

The insufficient infrastructure to enable the functions of GNSS and UAV systems was yet another recurrent theme. Such infrastructural deficiencies curtail the full exploitation of the technologies. This Edition includes the limited battery life of UAVs as one of the practical challenges because it restricts the operational time. This factor restricts the applicability of UAVs in large-scale mining activities.

Two participants referred to integration challenges of GNSS and UAV technologies with other technologies as issues inhibiting the effectiveness of the new technologies. The challenges related to integration cause delays and other such inefficiencies.

The participants overwhelmingly recognized the transformative potential of GNSS and UAV technologies in mining operations. These technologies are seen as game-changers, providing significant efficiency, accuracy, and reliability. This broad acknowledgment of benefits underscores their growing acceptance and integration in the industry.

A common perspective is that GNSS and UAV technologies have drastically improved operational efficiency. participants noted that these tools save time, optimize resource utilization, and reduce errors. These insights highlight the role of these technologies in fostering sustainable and efficient mining practices.

Participants emphasized the indirect yet significant impact of GNSS and UAV technologies on safety and environmental management. By minimizing human exposure to hazardous areas and providing tools for effective monitoring, these technologies enhance workplace safety and environmental compliance.

While acknowledging the challenges, many participants viewed GNSS and UAV technologies as opportunities for growth and innovation. This optimistic outlook reflects a readiness to address current obstacles and adapt to the demands of technological advancement.

Looking ahead, participants expressed confidence in the growing integration of GNSS and UAV technologies across all aspects of mining operations. This forward-looking perspective underscores the belief that these technologies will become even more integral to mining in the future.

A recurring theme in the discussions about future use is the potential integration of GNSS and UAV technologies with automation and artificial intelligence (AI). These possibilities highlight the trajectory of mining towards smarter, more automated practices.

Participants noted that as adoption grows, industry-wide standards for GNSS and UAV technologies will be necessary to ensure consistency and interoperability. Such standardization is seen as a critical step toward broader and more effective utilization.

The potential of GNSS and UAV technologies to enhance sustainability efforts was also highlighted. This focus on sustainability aligns with global trends in mining towards greener and more ethical practices.

Participants expressed optimism that the cost barriers currently limiting adoption would decrease over time as technology becomes more accessible. This expectation of reduced costs suggests a future where these tools are widely accessible.

Finally, participants emphasized the importance of collaboration and knowledge sharing for maximizing the benefits of GNSS and UAV technologies. Such cooperative efforts are seen as essential for unlocking the full potential of GNSS and UAVs in mining.

V. CONCLUSIONS

This study at FQM Trident Ltd. found that the integration of GNSS and UAVs in mining operations delivers significant benefits, including improved time efficiency, better decision-making, optimized resource use, and enhanced accuracy and productivity. Real-time data enabled quicker operational decisions, reduced material wastage, and minimized costs, particularly in fast-paced mining environments. UAVs further contributed to environmental monitoring and compliance, aligning business goals with sustainable practices.

The findings affirm that these technologies improve cost efficiency and operational speed through precise data collection, reducing the need for repetitive measurements. UAVs equipped with advanced sensors provided consistent and retrievable data for topographic and geological mapping. Despite these advantages, the high cost of acquisition, limited technical expertise, and restrictive regulations remain barriers to widespread adoption. The study recommends strategic investment in equipment and training, alongside regulatory reforms, to support broader implementation of GNSS and UAV technologies in the mining sector.

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