Comparative study between the topographic method (classical) and photogrammetric method (by drone) for the monitoring and data acquisition of mining works: case of the SOMAÏR uranium mine (Arlit, North Niger)

ABSTRACT

The SOMAÏR open-pit uranium mine, commonly known as « Société des Mines de l'Aïr Aïr » (Arlit, Northern Niger), has been using the topographic method for several years to monitor and estimate mine production. However, the method has limitations and constraints in the implementation and reliability of the results. The company is considering the use of an innovative, more reliable and economical method. Thus, a pilot project using drones is being implemented. The objective of this work is to carry out a comparative study between the topographic method and the photogrammetric method for monitoring and acquiring data from mining operations. Thus, the data acquired by topometry using a total station, for the so-called classical method and by drone for the photogrammetric method, were analyzed and interpreted. These two (2) methods were used for the follow-up of the M4_Art North ore deposit and the G4_Taossa pit of the SOMAÏR mine. The results of the analysis and processing show that the data acquisition time by drone is relatively low (30 to 40 minutes) compared to that of the topographic surveys (21 to 60 minutes). However, data processing times for the photogrammetric method are relatively higher (50 to 60 minutes) than those for the conventional method (14 to 20 minutes). Nevertheless, this processing time of drone images can be improved with powerful computer equipment. In addition, the use of UAVs offers additional advantages in the monitoring of mining operations, particularly with regard to worker safety, precision in the calculation of dimensions, volumes and tonnages at the mining slice and at the overburden. Immediate analysis of the two methods shows the accuracy of the drone for the front survey and also shows all the details present on the ground, namely: the machines used, the purging products and other products or elements used. So, it would be wise to opt for the drone in downhole activities.

Keywords: SOMAÏR, topographic method, photogrammetric method, mine pit, ore pouring.

I. Introduction

The development of mining industries is one of the main factors of world economic growth. Increasing the yield of these mining activities necessarily requires the choice of more sophisticated and profitable methods of exploitation and estimation of reserves. The evaluation of reserves is therefore one of the main concerns of mining companies; it aims to determine the resource potential of a mining deposit **[1]**. It is important to evaluate the reserves because they allow determining the feasibility or not of a project or better still the choice of type of exploitation method to be applied. In addition, many techniques are available to estimate and quantify the available volume of a deposit **[2]**.

In Niger, one of the poorest countries in the world, mining and petroleum operations are one of the main sources of revenue for the state. One of the most active and oldest companies in the exploitation of uranium ore is the « Société des Mines de l'Aïr » (SOMAÏR). This company is a mining company whose main activities are the exploitation and processing of uranium ore in Arlit (Northern Niger). Like many mining companies, the evaluation and estimation of the tonnage of ore extracted and the quantity of ore processed remains a major concern. At Niger, SOMAÏR sets an annual objective to be reached, namely the quantity of ore to be extracted from the mine and the quantity to be processed by the plant. Thus, the mine evaluates its production on a monthly basis in order to position itself in relation to the required annual production. In order to achieve its objectives, SOMAÏR has three divisions monitor the mine's activities, namely the Geology Division, the Exploitation Division and the Mining Engineering and Planning Division. These divisions each use different methods to quantify the ore extracted from the mine. They produce different results from each other that are subject to discussion. However, among the evaluation methods used by the three (3) divisions, the one based on topographic surveys seems to be the most common.

The topographic method consists mainly of layout (pit contour, pre-cutting, overburden, mine slice, tracks); and also of surveying (ore and waste slopes, blasting faces, mine slice, rock overburden, leach stockpile and other projects) **[3]**. In surveying, layout is the art of moving from the plan, whether computerized or on paper, to the terrain. It consists in materializing on the ground the layout, the axis or the limits of a computer or paper project **[3]**. The coordinates of the points to be established can be calculated beforehand and transferred to a tacheometer or a differential GPS to facilitate the work in the field. In the SOMAÏR mine, the layout operations first concern the tracks, which are laid out at a certain angle. The track serves as a means of access to the work area. Then, the location of the mine holes that will be drilled. These operations are carried out at any stage of the mining work: pre-cutting, overburden shots to reach the mineralized zone, shots of the mining slice to extract the ore and drilling. As for the topographic survey, it designates a set of topographic operations intended to collect on the ground the elements necessary for the establishment of a plan or a map. A topographic survey is intended to define the exact location of the main physical characteristics of the land. The results of the survey allow the preparation of plans, topographic maps and to make the cubatures. In order to do this, it is necessary to establish a three-dimensional system in which the object or the land surveyed will be represented. The survey consists of two phases: the establishment of the geodetic grid (a set of known points in position serving as a framework for the realization of a topographic survey) and the surveys of the details.

Nowadays, mining is increasingly mechanised in the basic operations of extracting the substances used. Approaches to evaluation and monitoring of mining operations are becoming increasingly sophisticated in order to achieve more satisfactory results **[4], [5]**. It is in this order of idea that SOMAÏR wants to move from the evaluation of the production by topographic approach (Total Station) to the estimation by a more modern means using sophisticated technology (drones). Thus, the use of UAVs for the survey of ore deposits and for the survey of the mine's advancement fronts is adopted. The drone is a small remote-controlled aircraft or aircraft without a passenger or pilot on board, which can fly autonomously or be controlled remotely from the ground **[6], [7]**. It photographs the various ore bodies and mine faces, and shows all the details on the ground, including workers, mining equipment, blowdown products and other products or features dedicated to the mine **[8], [9], [10], [11].** The general objective of this work is to carry out a comparative study between the photogrammetric method and the topographic method in order to justify the deployment of drone in the monitoring and data acquisition of the mining operations of SOMAÏR. The goal is to provide more precision in the cubatures, to facilitate the "reconciliation" on the production data provided by the various directions, to provide quality work, to increase productivity thanks to the saving of time, but especially to ensure the safety of the workers while minimizing the risks of accident. This study will also focus on the estimation of tonnages, processing and data acquisition times.

Specifically, the drone is used to photograph the different mine advancement fronts and the different ore and waste rock piles. These photos are then processed under photogrammetric software (AGISOFT and/or SURPAC) which allow the estimation of the tonnage of ore produced **[12], [13], [14]**. However, before definitively adopting this method, it should be evaluated by making a comparison with the classically used method, the one using a total station to carry out topographic surveys and the SURPAC software for processing and cubature calculations.

II. Materials and methods

For the realization of the surveys of the ore slopes and the pit of the mine at SOMAÏR, two main methods are applied for comparison: the topographic method or the so-called classical method and the photogrammetric method or the so-called drone method.

II.1 Presentation of SOMAÏR

This study was carried out at the Société des Mines de l'AÏR (SOMAÏR), a mining company that exploits uranium deposits via an open pit mine with four pits currently being mined at different stages of completion. SOMAÏR is located in Niger, in the Agadez desert region, near the town of Arlit (**Figure 1**). It is located approximately 1250 km from the capital Niamey and 250 km northwest of Agadez, between latitudes 18°35'N and 18°43'N and longitudes 7°15'E and 7°20'E.

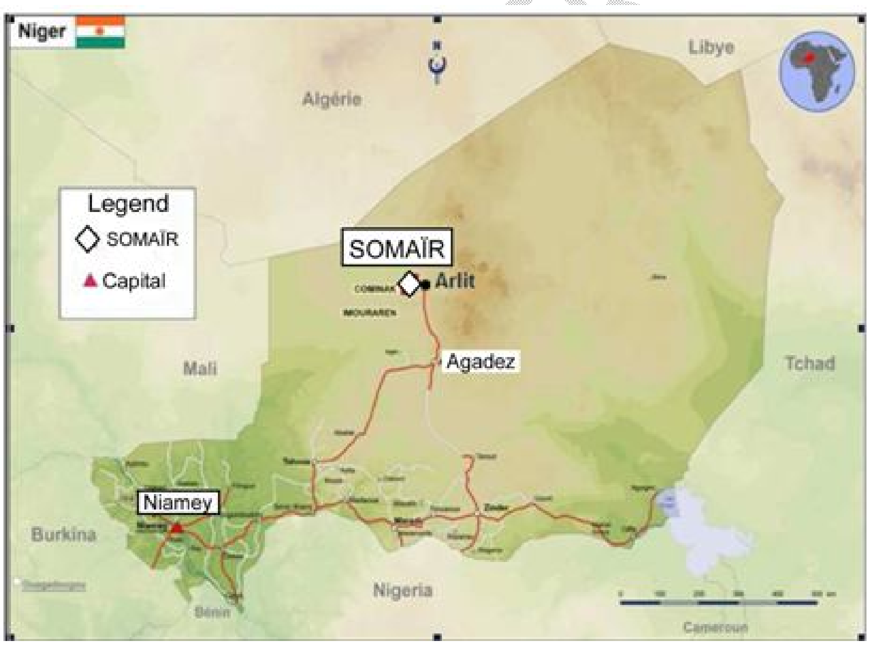

Figure 1: Location of the SOMAÏR mine **[15]**

Ore extraction at SOMAÏR is done in open pits with depths ranging from 40 to 80 m (**Figure 2**). The ore, which contains an average of 3 kg of uranium per ton, is processed in a plant located a few kilometers from the quarry. The deposit mined is sedimentary, consisting of alternating clay and sandstone layers. All the work carried out during the operation is divided into two stages:

- Stripping is all the work done to remove the overburden from the ground. In other words, it is the operation that consists in extracting the sterile layer before accessing the mineralized layer. At the overburden level, the steps are 20 m high with working platforms 60 m wide. The mine holes have a diameter ranging from 6" to 6"3/4. They are drilled up to 20 m in length with 1 m of over-drilling. The inclination of the holes can be 15°, 10°, 5° or 0° in relation to the vertical. The mesh varies according to the rock and the height of the step. The meshes currently used in overburden are 5x8m and 5x9m.
- The work of the mining slice is the whole of the work of extraction of the ore. SOMAÏR owns several pits, including four pits exploited by the simultaneous horizontal slice method. In the mining slice, the mining is characterized by shaking shots with a drilling angle not exceeding 15°, a depth of 6 m without over-drilling and a diameter of 3"1/2 and 3" in pre-cutting. The mesh size is 4x4m or 5x5m. The ramps are designed with 250 m length and 30 m width, and a slope of 8%.

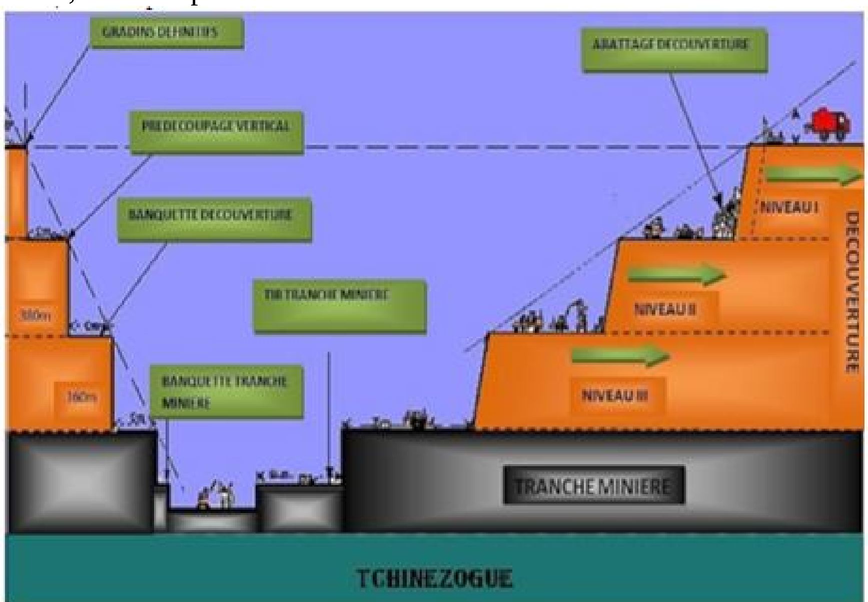

Figure 2: Schematic cross-section of mining at SOMAÏR **[16]**

II.2 Topographic or classical method

II.2.1. Data acquisition technique by the classical method

To conduct a conventional survey, **the** Trimble S3 or Trimble 5600 **total station (Figure 3A)** and the **differential GPS (Figure 3B)** are used. The total station, also known as a tacheometer, is a device that combines the functions of a theodolite and a distance meter. It allows the measurement of horizontal angles, vertical angles and distances. When using it, the total station is placed on a tripod. Before any measurement, the tacheometer must be "put in station". This operation consists in making the rotation axis of the instrument vertical by using shimming screws located on the base, until it enters the validity range of the bi-axial compensators. The rotation plane of the telescope is then vertical. Thanks to this setting in station, the angles measured on the two graduated circles are well horizontal and vertical angles. It will then be necessary to center the device. This operation makes it possible to place the principal axis of the total station at the vertical of a topographic point with known coordinates. By measuring the height of the device, the coordinates (X, Y, Z) of the center of the device are obtained. Finally, the device must be oriented by aiming at a point with known coordinates and thus determine the theoretical azimuth of the "zero" of the horizontal circle.

Once the device is centered and oriented, the detail points or targets are surveyed either by the sighting function of the total station or by aiming the reflector of the rod placed on the point to be surveyed. The next step is to select the point description code. To ensure that the survey is carried out properly, the total station is accompanied by a differential GPS. The GPS is equipped with a **notebook**, the **rod** and the **receiver (Figure 3B)**.

- The **GPS Logbook** allows you to fill in the file name, the references (dates, names of points) and the code according to the desired information;
- the **pole** is set at a fixed height. The rod carries the GPS and the receiver;
- the **receiver** allows to receive the radio and the satellites.

A relay is used to maintain the radio link between the base station and the GPS, when in a remote area or when there are obstacles between the base and the mobile. Before starting the survey, a file in which the survey data is recorded is created. The coordinates of the points are recorded using the laser function of the total station, which has a range that varies according to the type of equipment, or by aiming a sight placed on the point to be surveyed through the reflector (such as prisms). The coordinates of the various points representing the pile or pit are surveyed using a code. As an indication, code 15 materializes the top of a slope, code 16, the lower part of the inner and outer slope and code 17, inique the platform which is taken along two (2) or three (3) lines (in our case). The distance between the points of the same level is about eight (8) to ten (10) steps. Finally, the file created in the total station is transferred to the computer using a USB key for processing. The file in the Trimble S3 device has a CSV extension and the file in the Trimble 5600 has a JOB extension.

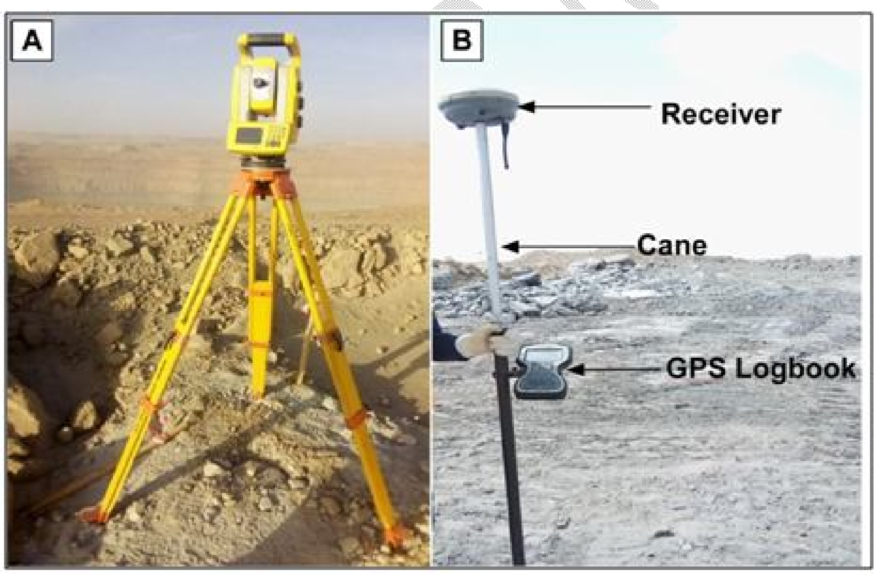

Figure 3: (A) Setting up of the Total Station (B) Illustrative photo of the mobile differential GPS .

II.2.2. Treatment of data from the classical method

The purpose of processing is to calculate the tonnage and volume of the ore pour. For the pit, it is a question of determining the volume and dimensions, at each stage of the progress of the extraction of the ore and the waste rock. The data from the topographic measurements is processed using SURPAC software. For data obtained with the Trimble S3, they are loaded and renamed with the STR extension (instead of CSV) in the SURPAC software. For files obtained from the Trimble 5600 total station, they require pre-processing to convert the "JOB" extension to "STR" to obtain a "string" file **(Figures 4A and 5A) from which** the

Digital Terrain Model (DTM) **(Figures 4B and 5B)** is generated. From the DTM file, the cubature calculations (tonnage, volume, dimensions) are automatically executed.

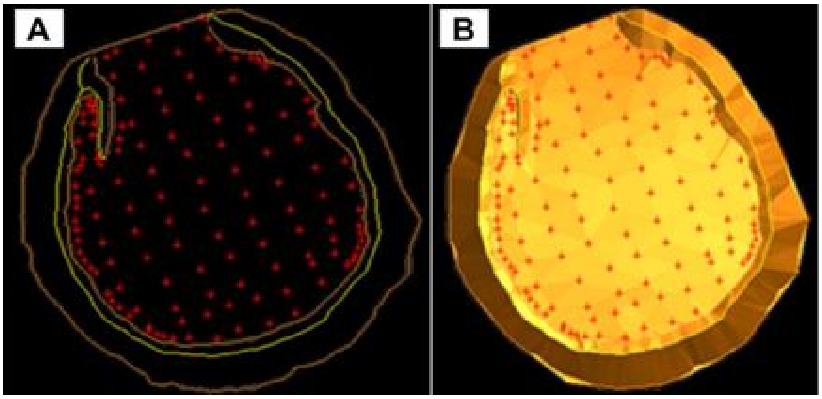

Figure 4: String (A) and DTM (B) files of the M4_Art North verse

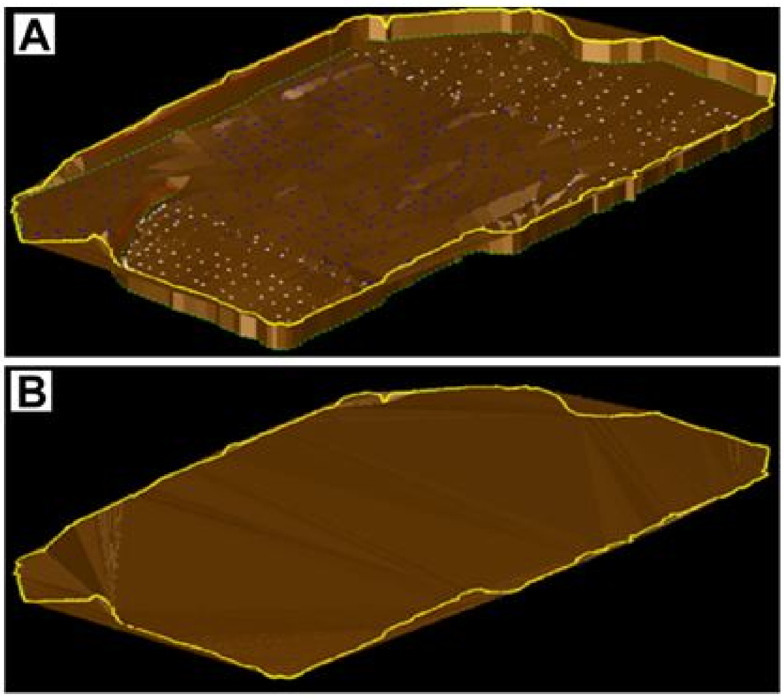

Figure 5: String (A) and DTM (B) images obtained by the classical method, from the Taossa pit at the G4 front

II.3 Photogrammetric or drone method

The drone method is a photogrammetry technique. It is a technique for determining the characteristics (dimensions, volume, tonnage, relief, etc.) of a given area from several aerial or terrestrial photographs of this area taken from different angles **[17], [18], [19]**. The photogrammetric method therefore consists of taking a multitude of aerial photographs which are then processed under the Agisoft software (Metashape) and generates a 3D terrain model **[20], [21], [22], [23]**. Using this technique, the cubatures of the ore slopes and the pit of the mine, are made.

II.3.1. Data acquisition by drone

SOMAÏR uses two types of UAVs for the photographs of the deposit or pit: the YUNEEC H520 UAV (**with six (6) wings**) **(Figure 6A)** and the DJI Matrix UAV (**with four (4) wings**) **(Figure 6B)**. The data acquisition is done by flying the drone over the ore dump or the pit of the mine to take several photographs under different English. To perform a drone flyover mission, it is necessary to:

- ➢ define the mission area: by integrating the coordinates of the polygon constituting the mission area or by drawing the area via the tablet connected to the radio control.
- ➢ gather the necessary material for the mission:
  - ✓ marker cones ;
  - ✓ the take-off and landing platform;
  - ✓ geo-referencing tarps;
  - ✓ the drone (the DJI Matrice 200 was used) **(Figures 6A and 6B)**;
  - ✓ batteries that need to be fully charged;
  - ✓ the radio control which must be fully charged **(Figure 6C)**;
  - ✓ the tablet which must be fully charged **(Figure 6D)**;
  - ✓ Backup batteries ;
  - ✓ the camera ;
  - ✓ a memory card in good condition for storing images;
  - ✓ the drone checklist ;
  - ✓ individual and collective protective equipment for remote pilots
  - ✓ GPS to lift the tarpaulins;

The data is stored on the memory card inserted in the drone. Once the mission is completed, it is removed and connected to a computer via an adapter for photo recovery.

Figure 6: (A) YUNEEC H250 Drone, (B) DJI Matrix 200 Drone, (C) Drone radio control, (D) Mission supervision tablet.

II.3.2. Data processing acquired by drone

At SOMAÏR, image processing is done with AGISOFT PHOTOGRAMMETRIC (Métashape) software. The SURPAC software is also used to make the cubature thanks to the file obtained on Métashape after treatment. The photos obtained are imported into AGISOFT and the processing is done automatically. The orthophoto (**Figure 7A)** (single photo of the study area obtained by mosaicing all the photos taken) resulting from the processing is generated in georeferenced form in a selected coordinate system. The images provided by the drone are by default in the "WGS 84" system (in longitude and latitude). A digital surface model (DTM) **(Figures 7B, 8A and 8B)** is finally obtained from the processing in AGISOFT. From the DTM file, cubature calculations (tonnage, volume, dimensions) are automatically performed.

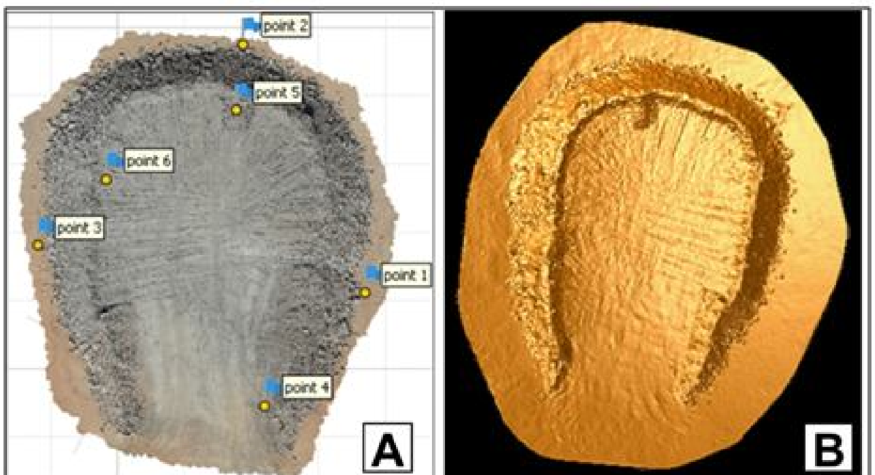

Figure 7: Orthophoto (A) of the M4_Art North layer obtained with AGISOFT and (B) DTM image of the M4_Art North layer obtained with SURPAC

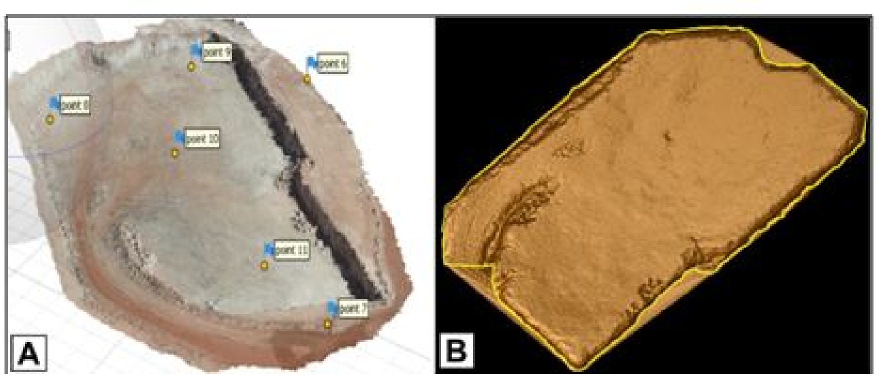

Figure 8: DTM image of the G4_Taossa pit obtained by photogrammetric processing (A) under Metashape and (B) under SURPAC

III. Results and Discussions

III.1 Results obtained by measurements on the ore deposit

The results of the acquisition and processing of data from the M4_Art North ore body surveys by both methods (topographic and photogrammetric) are summarized in Table I.

Table I: Results of the measurements and treatments carried out by the conventional method and by photogrammetry on the M4_Ar t North ore deposit

Verse M4_Art North			
Photogrammetric method			
Data acquisition time (minutes)	Processing time (minutes)	Calculated tonnage (tonnes)	Tonnage variance
30 minutes	50 minutes	23 600 t	0,8%
Topographical method			
Data acquisition time (minutes)	Processing time (minutes)	Calculated tonnage (tonnes)	
21 mn	14 mn	23 411 t	

The time of data acquisition by the drone method is a little higher (30 m) than that of the conventional method (21 m). Indeed, this survey is done on a single slope which does not allow to see the speed of the acquisition by drone. On the other hand, if several verses will have to be surveyed, the time saving with the drone would be considerable considering that it is possible to survey several verses with a single flight mission **[24], [25], [26]**. As for the processing time, that of the photogrammetric method is higher than that of the conventional method. This is due to the density of points taken by the drone unlike the classical method where points are taken at 8m steps. Indeed, the drone photographs the area at 0.5 m steps. In addition, the conventional method does not take into account the blocks of ore while the drone takes into account the large blocks in addition to the density of points that provides more detail. Hence the tonnage given by the drone, higher than the topographic survey.

III.2 Results obtained by measurements in the pit

The results of the acquisition and processing carried out by the conventional and photogrammetric methods of the G4_Taossa pit are given in Table 2.

Table II: Results of the G4_Taossa pit survey using photogrammetric and topographic methods and data processing

Pit G4_Taossa			
Photogrammetric method			
Data acquisition time (minutes)	Processing time (minutes)	Tonnage	Tonnage variance

40 minutes	60 minutes	547 765	4,2%
Topographical method			
Data acquisition time (minutes)	Processing time (minutes)	Tonnage	
60 minutes	20 minutes	571 757	

The analysis of this table shows that the time of data acquisition by the conventional method (60 minutes) is higher than that of the method using the drone (40 minutes). This is due to the constraint of the terrain during the topographic surveys. In addition, since the mining work is not in progress at the time of acquisition, there is co-activity with machines, workers, dust and other constraints that make the work difficult.

Moreover, we notice that the processing time of the photogrammetric method is twice as long (60 minutes) as the conventional method (20 minutes). This time difference is explained by the density of the points taken by the drone. Indeed, with the traditional method the points are taken with a step of 8 to 10 meters between two points or more depending on the state of the land. While with the drone, the distance between two points is 0.5 m. Also this long duration, is relative to the capacity of the computer used **(64 GB of RAM and 7.2 GHz of frequency)**.

In addition, the tonnage obtained by the drone method (**547,765 t)** is lower than that obtained by the conventional method (**571,757 t), which** gives us a difference of 4.20%. This difference can be justified by a much denser mesh of the study area by drone than by topographic measurements and the presence of the merlon. In order to visualize the difference between the two (2) methods, an intersection between the DTM images from the two methods (conventional and drone) was performed **(Figure 9)**.

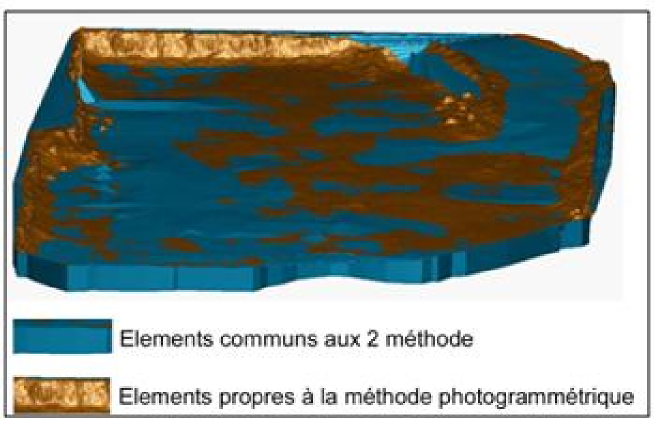

Figure 9: DTM image comparing topographic and photogrammetric methods

III.3. Discussions

The comparative analysis of the photogrammetric and topographic methods shows that the data acquisition times by drone **(30mn and 40mn)** are less than those of the topographic survey **(21mn and 60mn)** contrary to the data processing times which are much higher for the photogrammetric method **(50mn and 60mn)** than for the classical method **(14mn and 20mn)**. However, the photogrammetric processing time can still be improved by increasing the computer capacity **[27], [28], [29], [30]**. Also, there are many other advantages to using the drone **[7], [31], [32], [33]**. Indeed, the monitoring of the pits allowed the detection of anomalies that could cause pit instability such as a crack detected at Taossa pit G4 **(Figure 10)**. Specifically, the use of the drone in the pit allows to:

- facilitate mine planning;
- to facilitate the monitoring of the mine's advancement front;
- monitor the site remotely;
- optimize the cost and speed of execution (relatively simple operation to implement);
- to secure the site and respect the regulations: does not lead to the stopping of activities (in adequacy with the respect of the regulations), does not lead to the degradation of the site and allows a complete survey of the inaccessible or dangerous zones of access;
- reduce the risk of work-related accidents;
- make quick decisions to respond to an accident;
- facilitate data processing when the machines used are powerful;
- The photogrammetry made by the drone allows in addition to create topographic data but also geographical with the orthophoto.

Figure 10: Fissure detected in pit G4_Taossa monitored by the drone

However, the use of drone has constraints which, one must always take into account **[12] [30], [13], [34], [14]**:

- the drone is not RTk (Real Time Kinematic), which makes its use difficult (installation of several tarpaulins);
- it can't fly in the No Fly Zone; a zone forbidden by civil and military aviation;
- its use is conditioned by the weather conditions;
- a long time is needed for the break and the collection of the tarpaulins;
- the processing time is too long;
- a rapid depletion of the batteries.

To overcome these constraints, certain provisions are necessary for optimal operation of UAVs **[35], [36].** With this in mind, SOMAIR has already acquired a new model of drone with six (6) propellers (the YUNEEC H520) unlike the first prototype with four (4) propellers (the DJI Matrice 200). The "H520" also has a dual function tablet (radio control + tablet). This new model allows for a better mesh of the investigation area, resulting in high quality results **[37], [38], [39], [40] [41].** In particular, it is necessary to:

- set up direct geo-referencing (fixed tarpaulins to be used as a reference for surveys);
- increase the number of batteries ;
- consider the possibility of imaging in the infrared range (by lidar) **[42], [43], [44]** ;
- Use more powerful machines for image processing **[45], [46], [47], [48], [49] ;**
- Accelerate the empowerment of the rest of the team to meet expectations;
- Survey at the end of the shift to avoid interference with machinery and/or workers during data acquisition;

- ➢ survey the same area at different grid sizes and compare the results to determine the optimal grid size.

Table III shows the advantage matrix of the photogrammetric method over the topographic method.

Table III: Comparative table between the advantages and disadvantages of the drone method and the topographic method

<table>
<tr><th>CLASSICAL METHOD</th><th colspan="2">DRONE METHOD</th></tr>
<tr><td>Time consuming to implement</td><td colspan="2">Reduced implementation time</td></tr>
<tr><td>Limits production due to the time taken to use it</td><td colspan="2">Modern and sophisticated equipment</td></tr>
<tr><td>Hard work when surveying large slopes</td><td colspan="2">Increases production, as it allows for the surveying of several slices at a time</td></tr>
<tr><td>Is very unsafe (risk of accidents such as falls, stumbles, etc.)</td><td colspan="2">Convenient use</td></tr>
<tr><td>Has a high radiation exposure on the ore slopes</td><td colspan="2">Reduction of exposure time</td></tr>
<tr><td></td><td colspan="2">Provides security for workers</td></tr>
<tr><td></td><td colspan="2">Very precise (gives more details)</td></tr>
<tr><td></td><td colspan="2">Speed of data acquisition</td></tr>
<tr><td rowspan="2"></td><td rowspan="2">Provides more reliable production results</td><td>Quantitative (quantities of ore extracted and stored are estimated)</td></tr>
<tr><td>Qualitative</td></tr>
</table>

Conclusion

This study is related to the comparative analysis between the topographic method and the photogrammetric method for the monitoring and data acquisition of the mining works within the SOMAÏR uranium mine located in Arlit, North of Niger. The analyzed data were acquired by topometry using a total station, for the so-called classical method. For the photogrammetric method, measurements were carried out using drones. These two (2) methods were used to monitor the pouring of the M4_Art Nord ore and the G4_Taossa pit of the SOMAÏR mine. The results of the analysis and processing show that the data acquisition time per drome is relatively low compared to that of topographic surveys. However, the time of data processing by the photogrammetric method is relatively higher than that of the conventional method. Nevertheless, the processing time of drone images can be improved with powerful computer equipment. In addition, the use of UAVs offers additional advantages in the monitoring of mining operations, particularly with regard to the safety of workers and the mine, accuracy in the calculation of cubatures and the optimization of operating costs.

Bibliographic references

[1] Maminirina, R. L. (2015) Application Of Geostatistics In The Estimate Of The Antsirakambo Graphite Gisment Reserves.

[2] Alex, B. W. M., Patrick, I. L. D., & Roger, M. N. S. (2017). Optimization and Estimation of Reserves at the Lunsanu Mine in Upper Katanga, DR Congo.

[3] Milles S. and Lagofun J., 2007. Topography and modern topometry: Measurement and representation techniques.

[4] James M., Robson S., 2014. Mitigating systematic error in topographic models derived from UAV and ground-based image networks. ESPL [Wileyonlinelibrary.com]. no. 39. Available at: < www.onlinelibrary.wiley.com/doi/full/10.1002/esp.3609 >.

[5] Nex and Remondino, 2014. UAV for 3D mapping applications: A review, Applied Geomatics [https://link.springer.com/article/10.1007/s12518-013-0120-x].

[6] Brisset P. , 2004. Civilian drones: Perspectives and realities. ENAC Research, 44p.

[7] Eissenbeiss H. , 2009. UAV Photogrammetry. PhD Thesis (Sciences), ETH Zurich (Switzerland), 203 p.

[8] Wolf P., Dewitt B., 2000. Elements of Photogrammetry: with applications in GIS. Vol. 3. McGraw-Hill New York, NY, USA.

[9] Snavely N., Seitz S.M., Szeliski R., 2008. Modeling the world from internet photo collections. International Journal of Computer Vision 80 (2), 189-210. URL http://dx.doi.org/10.1007/s11263-007-0107-3.

[10] Zhang Y., Xiong J., Hao L., 2011. Photogrammetric processing of low-altitude images acquired by unpiloted aerial vehicles. The Photogrammetric Record 26 (134), 190-211. URL http://dx.doi.org/10.1111/j.1477-9730.2011. 00641.x.

[11] Turner D., Lucieer A., Watson C., 2012. An automated technique for generating georectied mosaics from ultra-high resolution unmanned aerial vehicle (UAV) imagery, based on structure from motion (SfM) point clouds. Remote Sensing 4 (5), 1392-1410. URL http://www.mdpi.com/2072-4292/4/5/1392.

[12] Tournadre V., 2015. Metrology by light airborne photogrammetry: application to the monitoring of dike evolution, PhD thesis, Speciality "Image processing", Université Paris-Est, 249p.

[13] Murtiyoso A. , 2016. Image acquisition and data processing protocol by drone, 3D modelling of remarkable buildings by photogrammetry, Mémoire de Ingénieur Spécialité " Topographie ", INSA de Strasbourg, 81 p. accessed in May 2020

[14] Vandenbroeck M. , 2018. Photogrammetry by drone of a small mountain glacier - Development and application of a protocol ensuring the reproducibility of repeated surveys at seasonal and interannual intervals, Master's thesis, Speciality "Geographic science, geomatics and geomorphology orientation", University of Liege (Belgium), 92p.

[15] AREVA, 2010. End of campaign report, Guezouman Flexure 2008-2009, 92p.

[16] Zabre B. , 2022. Deployment of the drone data acquisition system in the downhole activities of SOMAÏR. Mémoire d'Ingénieur en Mines et Environnement. School of Mines, Industry and Geology (EMIG) of Niamey, Niger.

[17] Slama C.C., Theurer C., Henriksen S. W., 1980. Manual of photogrammetry. Falls Church, Va. American Society of Photogrammetry.

[18] Damien R., Christian P., Nicolle M., Bruno R., Andres J., Jean A., Jean-Stephane B., 2005. Aerial photographs by drone and DEM: application to Draix observatory on badland erosion. Geomorphologie : relief, processus, environnement, 2005, n° 1, p. 7-20.

[19]Aber J.S., Marzol I., Ries J. B., 2010. Small-Format Aerial Photography: Principles, Techniques and Geoscience Applications. Elsevier Science & Technology Books.

[20] Jacome PA., 2010. Very high spatial resolution DTM for 3D representation of erosional gullies in mountains. PhD thesis. Institut des Sciences et Industries du Vivant et de l'Environnement, AgroParisTech, 260p.

[21] Nocerino et al. 2013. Accuracy and block deformation analysis in automatic UAV and terrestrial photogrammetry -Lesson learned-, ISPRS [www.ISPRS. org] No. XXIV. Available at: https://www.researchgate.net/publication/257486039.

[22] Dudka T. , 2015. Photogrammetry and 3D modeling from drone images within TPLM-3D. Master thesis, INSA Strasbourg.

[23] Breels, Nicolas, Marneffe, Stephan, 2020. River flow measurement using imaging techniques combining LSPIV and photogrammetry. Leuven Polytechnic, Catholic University of Leuven, 2020. Prom. : Soares Frazao, Sandra. http://hdl.handle.net/2078.1/thesis:25215

[24] Peipe J., Stephani M., 2011. Performance analysis of a pole and tree trunk detection method for mobile laser scanning data. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XXXVIII-5/W12, pp. 197-202, https://doi.org/10.5194/isprsarchives-XXXVIII-5-W12-197-2011.

[25] O'connor J., Smith M.J., James M.R., 2017. Cameras and settings for aerial surveys in the geosciences: Optimising image data. Progress in Physical Geography, 41(3), pp. 325-344. DOI:10.1177/0309133317703092.

[26] Rossini M., DiMauro B., Garzonio R., Baccoloa G., Cavallini G., Mattavelli M., De Amicis M., Roberto C. R. , 2018. Rapid melting dynamics of an alpine glacier with repeated UAV photogrammetry. Geomorphology, 304,pp. 159 - 172. DOI: 10.1016/j.geomorph.2017.12.039.

[27] Brown DC. 1966. Decentering distortion of lenses, Photometric Engineering, 32(3), pp. 444- 462.

[28] Jacome P.A., Puech C., Raclot D., Bailly J.-S., 2007. Extraction of a digital terrain model from drone photographs. Clermont-Ferrand, pp. 79-100.

[29] Eisenbeiss H., 2008. UAV photogrammetry in plant sciences and geology, In: 6th ARIDA Workshop on "Innovations in 3D Measurement, Modeling and Visualization, Povo (Trento), Italy.

[30] Dandois, PJ., Olano M. And Ellis EC., 2015. Optimal Altitude, Overlap, and Weather Conditions for Computer Vision UAV Estimates of Forest Structure. Remote Sensing, 23 October, Issue 7, pp. 13895-13920. DOI :10.3390/rs71013895.

[31] Finn R., Wright D., 2012. Unmanned aircraft systems: surveillance, ethics and privacy in civil applications. Computer Law and Security Review 28 (2), 184-194, cited By (since 1996) 0. URL http://www.scopus.com/inward/record.url.

[32] Fonstad M.A., Dietrich J.T., Courville B.C., Jensen J.L., Carbonneau P. E., 2013. Topographic structure from motion: a new development in photogrammetric measurement. Earth Surface Processes and Landforms 38 (4), 421-430. URL http://onlinelibrary.wiley.com/doi/10.1002/esp. 3366/abstract.

[33] Lisein J., Linchant J., Lejeune P., Bouché P., Vermeulen C., 2013. Aerial surveys using an unmanned aerial system (UAS) : Comparison of dierent methods for estimating the surface area of sampling strips. Tropical Conservation Science 6 (4), 506-520.

[34] Dandois et al, 2015. Optimal Altitude, Overlap and Weather Conditions for Computer Vision UAV Estimates of Forest Structure. Remote Sensing [www.mdpi.com/journal/remotesensing]. No. 7(10): 13895-13920.

[35] Gindraux et al, 2017. Accuracy Assessment of Digital Surface Models from Unmanned Aerial Vehicles Imagery on Glaciers. Remote Sensing [www.mdpi.com/journal/remotesensing]. No. 9(3): 186.

[36] Karara, H.M. and Faig W., 1980. An expose on photographic data acquisition systems in closerange photogrammetry. International Archives of Photogrammetry. 14(5). Hamburg, pp. 402 - 418.

[37] Kraus K. and Waldhäusl P., 1998. Handbook of Photogrammetry: Fundamental Principles and Procedures. Paris: Hermes.

[38] Kraus K., Karel W., Briese C., Mandlburger G., 2006. Local accuracy measures for digital terrain models. The Photogrammetric Record 21 (116), 342-354. URL http://onlinelibrary.wiley.com/doi/10.1111/j. 1477-9730.2006.00400.x/full.

[39] Honkavaara E., Arbiol R., Markelin L., Martinez L., Cramer M., Bovet S., Chandelier L., Ilves R., Klonus S., Marshal P., 2009. Digital airborne photogrammetry-a new tool for quantitative remote sensing, a state-of-the-art review on radiometric aspects of digital photogrammetric images. Remote Sensing 1 (3), 577-605. URL http://www.mdpi.com/2072-4292/1/3/577.

[40] Gruen A., 2012. Development and status of image matching in photogrammetry. Photogrammetric Record 27 (137), 36-57.

[41] Lindberg E., Hollaus M., 2012. Comparison of methods for estimation of stem volume, stem number and basal area from airborne laser scanning data in a hemi-boreal forest. Remote Sensing 4, 1004-1023. URL http://www.scopus.com/inward/record.url.

[42] Etten R.J.H., 2014. raster: Geographic analysis and modeling with raster data. R package version 2.2-31. URL http://CRAN.R-project.org/package=raster.

[43] Baltsavias E. P., Jul. , 1999. A comparison between photogrammetry and laser scanning. ISPRS Journal of Photogrammetry and Remote Sensing 54, 83-94. URL ://000081673900004.

[44] Baltsavias E., Gruen A., Eisenbeiss H., Zhang L., Waser L. T., 2008. High-quality image matching and automated generation of 3d tree models. International Journal of Remote Sensing 29 (5), 1243-1259. URL http://www.tandfonline.com/doi/abs/10.1080/01431160701736513.

[45] Aguilar F.J., Mills J.P., Delgado J., Aguilar M.A., Negreiros J.G., Perez J. L., Jan. , 2010. Modelling vertical error in LiDAR-derived digital elevation models. Isprs Journal of Photogrammetry and Remote Sensing 65, 103-110, 1. URL://000274448200010 American society for photogrammetry and remote sensing.

[46] Blaschke T., 2010. Object based image analysis for remote sensing. ISPRS journal of photogrammetry and remote sensing 65 (1), 2-16. URL http://www.sciencedirect.com/science/article/ pii/S0924271609000884.

[47] Burkholder A., Warner T., Culp M., Landenberger R., 2011. Seasonal trends in separability of leaf re- ectance spectra for ailanthus altissima and four other tree species. Photogrammetric Engineering and Remote Sensing 77 (8), 793-804.

[48] Colomina I., Molina P., Jun. , 2014. Unmanned aerial systems for photogrammetry and remote sensing: A review. ISPRS Journal of Photogrammetry and Remote Sensing 92, 79-97. URL http://www.sciencedirect.com/science/article/ pii/S0924271614000501.

[49] Rochat Matthias. 2018, Étude de la faisabilité de l'acquisition de données par drone dans l'application d'une délimitation foncière, Mémoire de Master, Spécialité " Identification, Aménagement et gestion du Foncier ", ESGT Le Mans, 63 p.