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Combination of UAV-Borne Lidar and UAV-Borne Photogrammetry to Assess Slope Stability

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***Abstract* -** Monitoring and assessing slope stability quickly and accurately over large areas is a technical challenge. In this study, we investigated the combination of two UAV/UAS (Unmanned Aerial Vehicle or System) techniques to compensate for the limitations of each remote sensing technique, in the context of the Belchatow lignite mine (central Poland).
The test site is one of the largest open-pit mines in Europe. It is characterized by complex geological and mining conditions (Rybicki, 1996) and has experienced numerous slope failures. Its western slope, located near the Debina salt dome, requires specific mine design to ensure safe and effective lignite exploitation.
In this experiment, which is a first on this scale, two UAV-borne LiDAR and UAV-borne photogrammetry surveys were performed, the first in November 2016 and the second in March 2017. The occurrence of a landslide between these two campaigns allowed to precisely identify and study the impacted zone in terms of surface displacements, slip surfaces and fractures changes. It allowed also confirming previous results about the mine stability issues in the covered area, where a geotechnical monitoring was installed just before the first UAV-borne LiDAR and UAV-borne photogrammetry. Conclusions regarding the complementary approaches set-up were also brought, along with practical recommendations for monitoring and rapidly asses slope stability, particularly for inaccessible areas.

***Keywords*:** UAV borne LiDAR, UAV borne Photogrammetry, Open-pit mines, risk assessment, Landslides

1. Introduction

Understanding the mechanisms of slope instability is essential in order to predict the timing of slope failure (Rosser et al., 2007). This understanding is possible through slope monitoring, that can be conducted on the surface or sub-surface. Traditionally, observational techniques include simple human observations, geotechnical and geodetic measurements, photographic imaging, and optical surveying techniques.

In the open-pit mine context, slope stability is key question for maintaining production, safety and efficiency. It is therefore necessary to accurately identify zones where displacements and deformations develop and to understand the connection with changes in the geometry and steepening of the mine workings (Ren et al. 2019). In this context, and thanks to continual progress of monitoring devices and technologies, the mining industry is now interested in combining local real-time high- resolution monitoring sensors, such as differential GPS, robotic total stations with global techniques like terrestrial and airborne laser scanning (LiDAR). These technologies, which enable to cover large areas, are proven to be efficient, reliable and accurate. They are used to complement traditional visual/human inspections. The choice of one or more of these methods depends on site conditions, accessibility and cost-benefit balance.

Previous works have therefore explored the use of UAVs in open pit mining environments (Mcleod et al., 2013; Salvini et al., 2015, Xiang et al. 2018). Salvini et al. (2015) proposed to use both images obtained with a UAV and terrestrial laser scanning to identify potential instability in a quarry wall. Mcleod et al. (2013) established a method of using a UAV to obtain discontinuity orientations of the rock mass. Xiang et al. (2018) carried out two UAV photogrammetry surveys to assess geomorphic changes related to mining activities basing on a real case study. Other applications include the use of UAV imagery for monitoring landslides (Haas et al. 2016; Francioni et al. 2015; Salvini et al. 2018).

UAV can be defined as a vehicle that is remotely controlled, semi-autonomous, autonomous or a combination of these capabilities. It must be noted that UAV provides only the flight platform: for monitoring issues it has to be equipped with specific sensors. Different types of monitoring mission can be undertaken depending on the UAV equipment and one can see that the improvement of UAV encourages the development of new sensors. Modern UAVs can indeed be fitted with high-resolution cameras, laser scanners (LiDAR) and other equipment to complete airborne remote monitoring of soil or rock slopes. The LiDAR technique is common in the mining industry to design and monitor the exploitation, for example to calculate the real volumes of deposits, and to obtain geometrical information such as the Digital Surface Model (DSM), this represents the earth's surface and includes all objects on it or the Digital Terrain Model (DTM). This last can be described as a three – dimensional representation of a terrain surface consisting of X, Y, Z coordinates stored in digital form. It includes not only heights and elevations but other geographical elements and natural features such as rivers, ridge lines, etc. Furthermore, the periodic LiDAR investigations can indicate over the time the potential ground movement.

Generally, Aerial Laser (AL) systems can operate from two categories of UAV: a fixed wing aircraft and multi-copter. Fundamentally, the systems comprise several major components: a laser scanner sensor, a control system, containing a Global Navigation Satellite System (GNSS, i.e. Global Positioning System, GPS), a flight management system and an Inertial Measuring Unit (IMU) (Vosselman and Mass, 2010). Distance measurements are taken using laser measurement technology where a laser light pulse is transmitted through a telescope to strike a surface, the pulse reflects off the object and returns to the instrument. The time taken for the round trip is accurately determined and converted into a distance using the speed of. In order to obtain accurately the position of each point of reflection, the movement of the scanner (UAV) must be taken into consideration, this is achieved through the use of an IMU and GPS system. The integration of the position and attitude measurements from these sensors enables an accurate trajectory and altitude of the laser. Having a position and altitude of the start of the laser pulse plus the range to the point of reflection enables to determine the coordinates of the point of reflection.

The obtained coordinates of points form a DSM of the mine. The quality of the coordinates of the DSM depends on numerous factors including the measurement system itself, the atmosphere and the nature of the surface being measured. Furthermore, the quality of the DSM to represent the details of the surface depends on the resolution (density) of the points forming the DSM. The best accuracy of current AL solutions is between 5 and 10 cm for altimeter, which is directly related to the on-board GPS unit. To improve accuracy, several solutions could be used, such as local specific geo-referencing systems or some new light LIDAR with Applanix solution

This article provides a focus on the simultaneous use of UAV for AL and aerial photogrammetry for slopes monitoring which was performed in the Polish Belchatow open pit mine (Fig. 1). This lignite mine (12.5km in length and 3km wide) is one of the largest excavations in Europe. The choice of Belchatow as test site is rather related to the development of horizontal displacements and slope instabilities during the life of the mine. Landslides have occurred at Belchatow mine, above all in its western slope, over the years and have forced the installation of a geotechnical monitoring (Bednarczyk, 2018).

The results are presented and discussed to define the best methodology for monitoring slope stability. The limitations and advantages of this kind of remote sensing technologies are also discussed in this paper.

2. Materials And Results

Two UAV borne LiDAR and photogrammetric simultaneous surveys have been carried out on the western slope of the Belchatow mine (Area Of Interest, AOI, Fig. 1). The weather being a challenging factor over the winter period (wind, fog and snow cover), the field mission has been re-scheduled and delayed few times. Finally, the good weather windows for the multi-temporal survey were: on the 23rd November of 2016 and on the 31st March 2017. The campaigns were performed using a YellowScan Surveyor, which was at that moment one of the lightest (less than 1.6 kg) and most accurate LiDAR sensor solutions available on the market. The interesting aspects of this sensor was its accurate position and orientation direct georeferencing. In this project the YellowScan Surveyor was mounted on quad copter with a combo RGB camera.

The outline of the multi-temporal survey site is displayed in the following figure (Fig.1).

A total of 11 Ground Control Points (GCP) were picked up in the field in 2016 within the AOI (Fig.1). These GCP can be considered as targets with surface of 50cmx50cm. They had two purposes:

- for the LiDAR dataset, the GCP are used as validation of ground truth points. This enables to estimate accuracy,
- for the orthophoto (photogrammetry), the GCP are used during the ortho-rectification process and therefore are considered as control point rather than validation points.

Fig. 1: Belchatow lignite open-mine (Poland) with the outline of the UAV LiDAR and UAV photogrammetry survey (about 800m wide and 1000m long).

6 LiDAR flights were realized in about 6 hours, with a UAV flight autonomy of about 15 minutes. The area covered by LiDAR points represented about 55ha. In total, the LiDAR dataset collected captured 150M points for 4.70Gb of data. In comparison, 1045 photos were collected for the 4.5 flights, generating 25.1Gb of raster data. Because of a technical problem with the RGB camera (setup on the LiDAR frame) it was not possible to complete the 6 UAV photogrammetry flights in 2016. Flight altitude being about 50m, in order to achieve 50 to 70% LiDAR flight line overlap (Standard LiDAR Operation) the line spacing had to be about 50m. The table 1 summarizes all information about the first UAV flight, used as reference survey.

Table 1: 23rd of November Belchatow flight log book.

	Flight 1	Flight 2	Flight 3	Flight 4	Flight 5	Flight 6
Speed	5 m/s	5 m/s	5 m/s	5 m/s	5 m/s	5 m/s
Altitude	50 m (adaptative to the terrain)	50 m (adaptative to the terrain)	50 m (adaptative to the terrain)	50m (adaptative to the terrain)	50 m (adaptative to the terrain)	50 m (adaptative to the terrain)
Flight lines	5.5 incl. 1 transect	5 lines incl. 1 transect	5 lines incl. 1 transect	7 lines incl. 3 transect	6 lines incl. 1 transect	6 lines incl. 1 transect
Flight duration	12 min	13 min	12 min	14 min	16 min	15 min
Overlap	60%	60%	60%	60%	60%	60%
Start time (UTC)	07:53am	08:19am	09:27am	09:56am	11:09am	01:11pm
End time (UTC)	08:10am	08:32am	09:39am	10:10am	11:25am	01:26pm
LiDAR performance	Ok	Ok	Ok	Ok	Ok	Ok
Camera performance	Ok	Ok	Ok	Ok	50% ok	Trigger issue

2. Results

The final LiDAR results (a comprehensive dense point cloud of AOI) were obtained after the post processing treatment. Data processing was conducted in three steps. First, LiDAR data were collected and copied to a ground station computer in the field, after the flight to verify the point cloud and identify missing patches or weak overlap. This permit to determine if additional flights are needed. Second, back to the office, the trajectory post-processing the post processed Kinematic (PPk) was run. In this way the point clouds corresponding to the flight lines can be re-generated based on the corrected trajectory. Third, several processes were achieved to improve the quality of the LiDAR results, such as noise filtering, flight line matching and classification

In parallel, the geotagged photos were taken through a routine process (aero-triangulation, 3D mesh and orthophoto creation) generating the orthophoto of the AOI. Both LiDAR and photo processes were then merged to provide a colorized (with the RGB value of the orthophoto) point cloud (Fig.2).

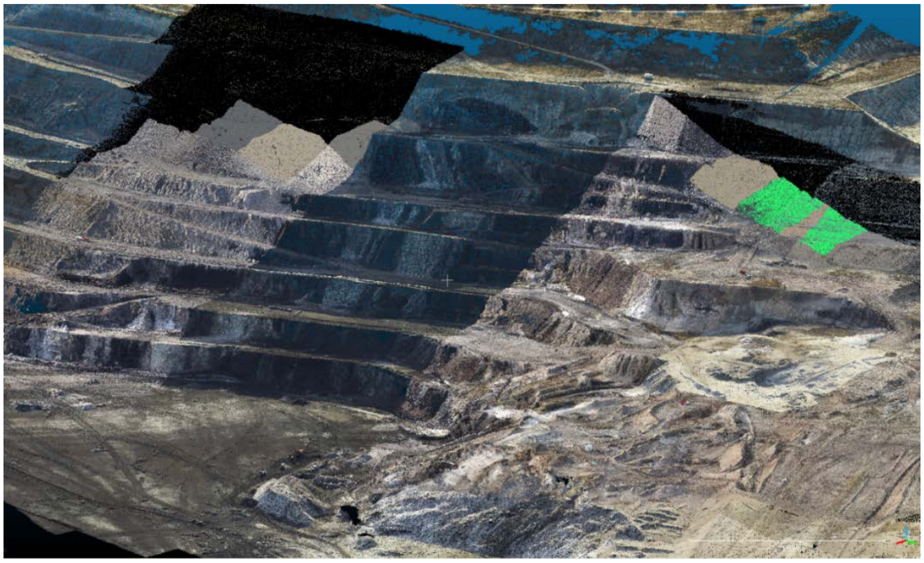

Fig. 2: Combination of orthophoto and LiDAR data in the same view

The resolution of the two remote sensing technologies is given in term of point density. The point density gives the amount of measurements per area at which the surface of the earth is sampled, it is similar to the photo resolution. An extremely dense point cloud (>10 pts/ m^2) is needed to capture all the details. The average resolution value for the two remote sensing technologies are similar, between 200 and 500pts/m^2. The produced point cloud from the LiDAR survey has a density of 250 to 300 pts/m^2 in most areas. Over dark soil cover (coal sands) the point density is affected and can be reduced to under 10 pts/m^2 - this has been noted on less than 3% of the overall AOI. The impact of dark soil on the LiDAR is clearly exposed and does not seem to affect the photogrammetric point density.

The accuracy assessment completed for the Belchatow mission considers the elevation only (Z). To achieve XY and Z accuracy assessments implies the need of 3D targets such as building corners or recognisable 3D features laser intensity based. This was not the case at Belchatow. However, the fact that we used table-like structures for GCP enabled to assess the accuracy in X and Y within a certain degree – if the laser points were out by more than 25 cm in X or Y, the points would be out in Z as they would not 'lie in on the table' structure anymore. Comparing the laser points and the GCP the average shift is about 20mm, while the RMSE is about 30mm. Finally, the LiDAR point clouds were also coloured according their height (Fig.3).

Then, the two point clouds obtained during the 2 UAV flights (November 2016-and Merch 2017) were compared to investigate potential ground movement and the resulting map is shown in figure 4. The comparison shows a landslide (red circle on the Fig. 4) magnitude closed to hundreds of metres. This landslide is also seen when comparing the two orthophotos of the 2 flights. These orthophotos show the changes that occurred on the slopes and the different fractures (Fig.4). The presence of 2 different data set is very important in term of information for the monitoring project as the mine faced other instabilities in the past. In fact, to manage the mine instabilities, a geotechnical monitoring system was installed from 2005 to 2013. For the western slope geotechnical monitoring showed that the horizontal displacements are strongly associated with the complex geological structure and intensive tectonic deformations in the area of the Belchatow mining field. The analysis of measurement results revealed that fault zones are more prone to formation of slip surfaces. Moreover, the potential slip surfaces were mainly registered in coal, coal-bearing clay and clay layers (Cala et al., 2016).

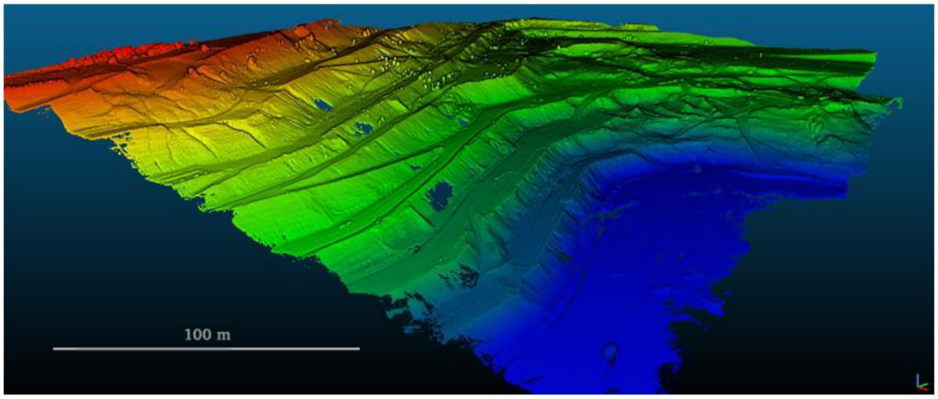

Fig. 3: height-colorized point cloud from the LiDAR acquisition (red 200m altitude and blue -30m altitude).

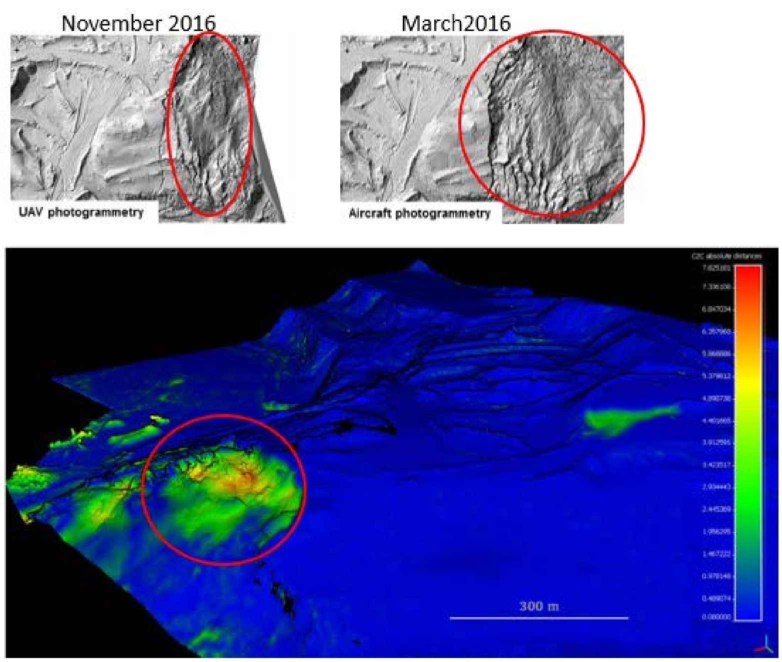

Fig. 4: The two different orthophotos (November 2016 and March 2017) of the western slope (above) and cloud to cloud comparison (down) between two different DEM (November 2016 and March 2017). Red circle indicates the ground movement in m occurred over 3 months.

For the AOI, before the landslide occurrence in December 2016, a continuous local inclinometer system, 100m depth, was also installed to monitor the western slope. This system recorded the largest displacement in Jan/Feb 2017, about 60mm, the depth of observed ground displacements varied 45-100m. The geotechnical monitoring confirms that instability has occurred post the first UAV fight in November 2016 and before the last UAV flight in March 2017.

Once a robust methodology for the UAV LiDAR and photogrammetry deployment had been established for mine slopes assessment, periodic flights can be undertaken to identify areas of potential instability. These flights complete and confirm information obtained with other kind of traditional monitoring

3. Field Issues Encountered

The Belchatow case study faced some issues during the remote sensing acquisition missions. Above all the weather for UAV flights was a challenging factor over the winter period. In fact, the field mission was re-scheduled and delayed a few times. In addition, the processing of the LiDAR datasets has allowed to confirm some known limitations of this remote sensing technology, such as reflectivity gaps. The combination of the LiDAR and photogrammetry technologies permits to overcome such problems, and sometimes this is the only way to obtain a complete geometrical information of the AIO. In detail, we present here the encountered issues:

- Reflectivity gaps – lignite related: multiple gaps of "no data" were found in the LiDAR dataset and over the southern portion of the AOI. These gaps appear to correspond to dark rock most probably related to their high lignite content (Fig.5). The alignment, location and size of the gaps occurring in the LiDAR dataset appear to depict the coal complex horizon. The point density over such rock falls down to about 3 ppsm. The LiDAR beam is completely absorbed. The impact of dark soil on the LiDAR is clearly exposed and does not seem to be affecting the photogrammetric point density.

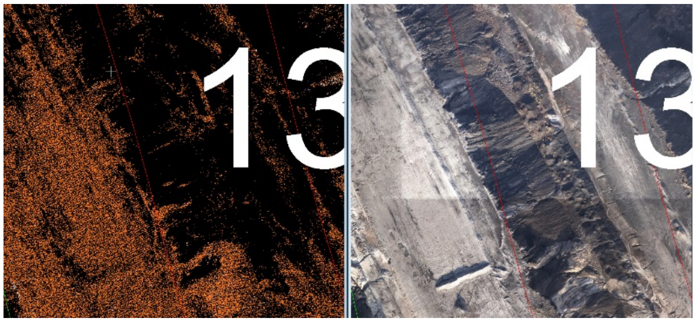

Fig. 5: to the left point density variation related to material nature (coal) shown on the orthophoto to the right.

- Reflectivity gaps – water related: water bodies are depicted by areas of "no data" in the LiDAR dataset (Fig.6). The water reflects the beam as a mirror and hence the sensor never collects the return.
- Reflectivity gaps – pipe related: just like coal material, black plastic pipe will not show on the LiDAR and will create "holes" in the dataset (Fig.6).

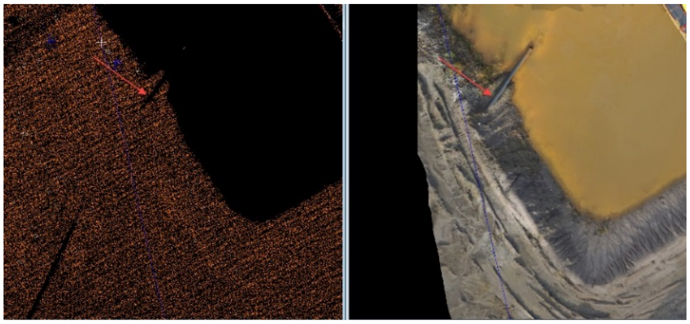

Fig. 6: to the left point density variation related to the material nature (water and dark pipes) shown on the orthophoto to the right.

- Scanner glitch: there seem to have been a 7 sec scanner outage on line 5 of flight 6 (eastern most line) corresponding to 40m of flight line. Short vibrations could have affected the scanner and produced a gap of data. However, with the overlap considered at this location the loss of data was kept to a minimum.

4. Discussion

Based on present experience and the work done by Vanneschi et al. (2017), we were able to provide some guidelines to end-users (table 2) allowing to compare the UAV solutions with terrestrial technologies, considering the most representative elements: costs, measurement duration, the measurement deployment, data processing and environmental conditions that can influence and perturb the measures. The choice of one or the combination of these technologies depend on the site accessibility, the budget and the aim of our monitoring project.

Table 2: Guideline for the choice of a best cost-effective remote sensing technology in open pit context.

		Terrestrial LiDAR (mid and long range)	**Aerial LiDAR (rotor UAV)**	**Aerial Photogrammetry (rotor UAV)**
Cost	Equipment cost	medium	medium	low
	Measurements cost *with external sub-contractor*	medium	high	low
	Measurements cost *with own equipment*	Depending on the scanner range	low	low
Time	Measurement duration	medium	long	medium
Implementation	optimum extent for the tool	10- 100 ha	< 100 ha	< 100 ha
	Range of sensors measurement	cm - 4 km	50 – 100 m.	n.o.
	Regulation/ Legislation	none	EASA / FAA rules	EASA / FAA rules
	Site accessibility	Depending on the scanner range	not required	not required
	Control points	recommended	recommended	required
Data	Points cloud density	medium	medium	high
	Time of post processing	medium	medium	long
Ground Cover Influences	Soil/Rocks	limited influence	limited influence	no influence
	Coal	limited influence	influence	no influence
	Water	influence	influence	no influence
	Vegetation	limited influence	limited influence	influence
Atmospheric Conditions Influences on Measurement	Wind	influence	limited influence	limited influence
	Rain/Snow	limited influence	influence	influence
	Fog/Dust	limited influence	limited influence	influence
	Brightness/Shadow	no influence	no influence	influence

5. Conclusion

In order to monitor a large slope instability, such as in an open pit mine context, several surveying technologies are generally applied separately: terrestrial laser scan, aerial laser scan, conventional surveying methodologies, terrestrial photogrammetric solutions, UAV based solutions, etc. The choice of one or more of these techniques depends on multiple factors: geology, geometry, weather, costs, etc. The mining industry faces a large surface that should be monitor. UAV surveys start to become popular for many applications even of some limitations. The principal reason is the quick and easy access to dangerous and inaccessible areas, and the possibility to observe ground from different angles of view. The paper suggests the combination of two techniques: LiDAR and photogrammetry. The current study described the first application in an open pit mine of combination of two remote sensing techniques: UAV borne LiDAR and UAV borne photogrammetry. Two surveys (6 flights) were carried out at the Belchatow western slope mine and the results are valuables and encouraged to continue the development and the implementation.

The results have showed that the combining data from different remote sensing technologies can be used to overcome the technical problems and allowed to obtain the complete geometrical information of the AIO. The multitemporal analysis between different AL flight campaigns at the Belchatow western slope mine has allowed to identify ground movement related to slope instability and confirm by geotechnical monitoring. This deformation is probably due to a fault and the slip surfaces are mainly registered in coal, coal-bearing clay and clay layers. Those results improved the management of the largest mine in Europe. Therefore, UAV can be considered as a good support, in complement of traditional monitoring systems, for large ground movements monitoring in open pit mine context. The trend of UAV technologies is an increase in the duration of flight of drone, so flights are longer and farther. It will become even more promising with the improvement of LiDAR sensors and algorithms of calculations for photogrammetry.

Acknowledgements

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