

The use of RPAS – Remotely Piloted Aircraft Systems in the topographic mapping for mining

<http://dx.doi.org/10.1590/0370-44672017710120>

Rodrigo Pereira Lima

Engenheiro-Agrimensor da Vale S.A.
Gerência de Exploração Mineral e Geologia
Nova Lima – Minas Gerais - Brasil
rodrigo.pereira.lima@vale.com

Cleiton Coelho

Técnico em Geoprocessamento da Vale S.A.
Gerência Desenvolvimento e Planejamento de Mina
São Gonçalo do Rio Abaixo – Minas Gerais - Brasil
cleiton.coelho@vale.com

Germán Vinuesa

Geólogo da Hidrogeotécnica Ltda
Belo Horizonte – Minas Gerais - Brasil
hidrogeotecnica@gmail.com

Jean Thiago Grassi

Engenheiro Cartógrafo da Tetra Tech Coffey
Belo Horizonte – Minas Gerais - Brasil
jean.grassi@tetratech.com

Luiz Henrique Guimaraes Castiglione

<http://orcid.org/0000-0002-9771-5998>
Professor
Universidade do Estado do Rio de Janeiro - UERJ
Faculdade de Engenharia
Departamento de Engenharia Cartográfica
Rio de Janeiro - Rio de Janeiro - Brasil
castiglione.luiz@gmail.com, lhgc57@gmail.com

1. Introduction

Mining activity in an open-pit area imposes a recurring topographic survey of mined and service areas that require volume evaluation, as in the case of disposal piles of waste and temporary storage of ore for shipment.

Traditionally, the volume survey uses topographic methods, especially with the use of Total Stations and determination of all the several points that are necessary for the volumetric characterization of the bodies of interest. This activity is laborious and has results that in general are not sufficient

Abstract

In the light of the technological transformations that have been occurring in the field of Remote Sensing, the objective of this study was to evaluate the feasibility and the quality of the results that could be achieved in the topographic modeling of the terrain with a Remotely Piloted Aircraft Systems (RPAS) survey in open-pit mines. The mining activity imposes the recurring topographic survey of mined and service areas that require volume evaluation in an interval of at least one month. In this context, the expectation of adopting traditional remote sensing methods for surveying, instead of land surveys, has always been great. The restrictions on the adoption of the conventional photogrammetric or airborne laser scanning (ALS) methods were related to the need for recurring surveys, which are never simple with the use of manned aerial platforms. In this context, the RPAS opens a window of opportunity that should not be ignored, being the main reason for the case study reported here. The essential data set of the research results from the direct confrontation between two digital terrain models: the first obtained with the RPAS survey executed in 2016 and another one of the same area obtained by a laser aerial survey performed in 2012, which was considered as a quality benchmark. The results recommended that the implementation of mapping solutions with RPAS consider the quality constraints of the photogrammetry in order to improve final results with the theoretical and operational knowledge that underpin the photogrammetric process.

Keywords: Remotely Piloted Aircraft System (RPAS); Digital Terrain Model (DTM); topographical survey; open-pit mine.

for the precise volumetric characterization because of the short time available for execution and the operational difficulties of the detailed measurement, that are almost impossible to be done. Besides, there are risks for operators in the midst of the circulation of machinery and large open-pit mining equipment.

In this context, the expectation of adopting traditional remote sensing methods for surveying, instead of land surveys, has always been great. The restrictions on the adoption of the pho-

togrammetric or ALS methods based on manned aircraft, however, were related to the need for recurring surveys, which are never simple with the use of aerial platforms, not to mention the economic feasibility, hard to find when covering small areas with these methods, which are relatively more expensive in cases like this. Photogrammetric aerial surveys with conventional aircraft, satellite imagery and even the generation of huge cloud points from airborne laser scanning were viable technical alternatives, but with no

operational effect because of the following difficulties: find a day when the demand for surveying coincides with the appropriate meteorological time (sky clear from clouds and fog); high cost in recurring activities (airplane and crew always available for frequent measurements – at least once a month); and, response time of the processing of the resulting products. Terrestrial laser surveys, however, with the use of laser scanner stations or even vehicles equipped with these stations, seems to make real the possibility of a precise and fast measurement, combining the advantages of direct measurement (topographic survey) and remote sensing surveys (terrestrial laser). The operational contextualization of the terrestrial laser surveys, however, still faces some problems related to immersion in the operational areas, like conventional surveys, either by the installation of the equipment and the consequent movement of surveyors in the area, or by the circulation of the measuring vehicles by the mining fronts, circulation that, in some cases, is even unfeasible.

Considering these circumstances, the technological evolution that made the topographic aerial surveys available through Remotely Piloted Aircraft Systems (RPAS) opens a window of opportunity that should not be ignored. In fact, there is a shift of paradigm when we consider the use of Remote Sensing in this case. Topographic mapping with these systems is suitable for small areas, requires almost no movement of people in the operational areas and does not compromise either the safety of mine personnel or the operation of mining equipment (Acosta, 2014; Coyne, 2015). In addition, it

has a short processing time to make its products available, and is much less weather-dependent than airborne manned aircraft, because remotely piloted aircraft fly at low altitude, so the cloudy weather is not an obstacle to operation. The main unknown to evaluate, in this case, since this is a method that does not involve significant costs, concerns on the accuracy of the topographic modeling that results from it.

The objective of this study was to evaluate the feasibility and the quality of the results that could be achieved in the topographic modeling of the terrain with a RPAS aerial survey, in the same way as those that would be executed daily in open-pit mines, for evaluation of extracted or arranged volumes. It is not, therefore, a study that tried to minimize the influential factors of error in the result. The research option was to carry on the execution of the work as similar as possible to the daily operational process, so that its results reflect the best possible results that should be achieved daily by the mine measurement teams. In general, since the RPAS technology is very new and has its theoretical principles associated with the photogrammetric technique, the teams involved in regular work are not specialized in aerial surveys, but mining or surveying technicians specifically trained for this execution. This article aims to highlight both the weaknesses and the potentialities of the RPAS operational solution, focusing not only on the technical issues associated with its accuracy, but also on day-to-day practices, operating and usage constraints that have the potential to degrade final results, considering the actual circumstances of their use,

by technicians not yet specialized.

The team that performed the experiment was trained at the time of the acquisition of the system and carried out the aerial survey for this research according to the knowledge learned and the previous experiences that they had during some months of training and practice in the company. It was done that way precisely to evaluate the inconsistencies and eventual fragilities that result from the lack of specific technical knowledge of photogrammetry, leaving more evident the reasons and possibilities for future improvements. This is in line with the idea behind the development of RPAS, which has been developed to be used directly by users and not necessarily by experts, such as conventional aerial surveys (Küng *et al.*, 2011).

The RPAS aerial survey that is in the core of this research essentially deals with the generation of the digital terrain model (DTM) of an open-pit mining area named *Timbopeba* and located in the region of *Quadrilátero Ferrífero*, in the state of *Minas Gerais*, Brazil, that can be observed in Figure 1. The essential data set of the research results from the direct confrontation between two DTM: the first obtained with the RPAS aerial survey executed in 2016 and an another one of the same area obtained by an airborne laser scanning performed in 2012, which was considered as a quality benchmark, or the so-called ground truth, as suggested by Küng *et al.* (2011). The point clouds of the two aerial surveys are quite dense and make feasible the direct comparison between the altitudes in the two DTM, almost point by point, in several positions chosen by the analysts.

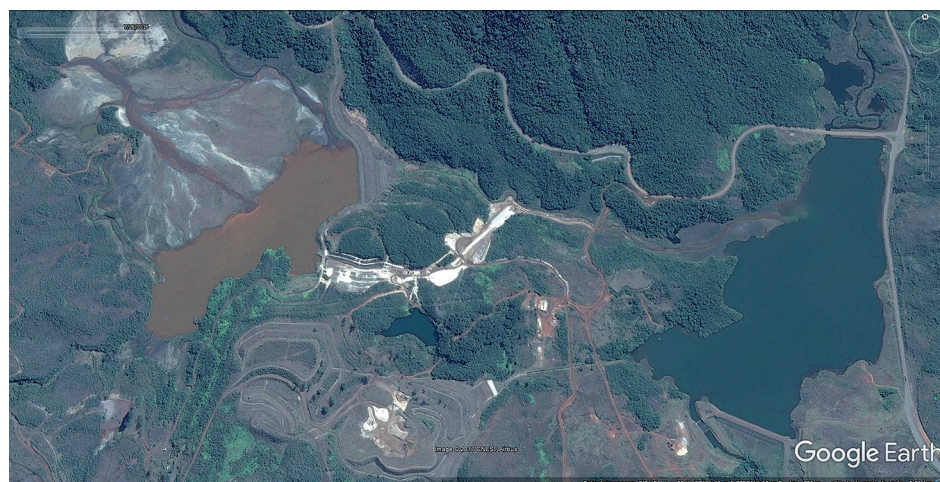


Figure 1
Image of the Timbopeba area.

2. Materials and methods

In order to carry out the experimental survey in the widest possible range of scenarios to be mapped, the chosen area included open-pit mining sites (deactivated) and natural forested land. Consequently, the defined area had expressive dimensions, which forced the execution of the RPAS mission in sections, since it was impossible for the total area to be mapped in a single photographic flight mission. This subdivision stems from operational factors such as limiting the autonomy of the RPA, the availability of spare batteries and the limitations of data recording by the various on-board systems. Considering yet that, the higher the aircraft flies, the poorer is the quality of the resulting images. Also, planning issues require subdivision to prevent significant degradation of the quality of results by means of a lower resolution images. Küng *et al.* (2011) demonstrate the importance of this decision about image resolution (smallest element of the image – pixel size on the terrain or ground sample dimension (GSD)) and flight height on the accuracy of the final products of photogrammetric processing, which is considered by these authors as the key stage of production. The eventual attempt to make the whole area in a single flight would degrade the resolution of the image too much, compromising the final accuracy of the DTM to be produced.

The reference point cloud originates from a ALS survey, with pulse density of 1 (one) pulse per square meter (1 ppsm). In its quality tests for DTM validation, this aerial survey presented a root mean square error – RMS less than 0.30 meters in altitude, in the vegetation-free areas. In this case, validation tests for ALS point clouds were done by determining field control points (ground truth) on exposed terrain areas that are compared to the altitude of the DTM ALS in that position.

For all the quality tests that have been done with the various ALS made by Vale Company over the past ten years, it is reasonable to consider that the generated point clouds are very consistent and precise internally. This is, therefore, one of the main reasons for using a ALS point cloud as a reference, in order to evaluate if this internal consistency and precision are also present in the generation of point clouds by RPAS in the areas without vegetation cover, as the main areas of open-pit mines.

Considering that the method of the producing digital terrain model and

ortho-image data used by RPAS that is essentially photogrammetric, the methodology chosen for the comparative tests between the RPAS and ALS DTM took into account the precision factors that influence the production of data by Photogrammetry. Essentially, these factors can be classified as intrinsic and extrinsic to the photogrammetric method itself, being the first associated to the pure application of the photogrammetric technique and the extrinsic ones to the contextualization of the application in areas with different characteristics. It should be noted that, for the purposes of this study, the main concern refers to intrinsic factors, since in typical areas of interest, such as open-pit mining areas, there is no expectation of significant extrinsic factors such as vegetation cover, for example. Another relevant extrinsic factor, slope and relief variation, in the case of tillage and disposal areas which have no vertical slopes, does not offer relevant degradation in clouds of extremely dense points such as the DTM clouds from RPAS and ALS, since the high density of points favors the modeling.

In fact, the first activity to be performed in this work contemplates the selection of specific and suitable locations – sites – for the confrontation tests between the RPAS DTM and the ALS DTM. This selection sought to identify flat and no vegetation sites, which are suitable for confrontation because, in this situation, the most relevant extrinsic factors, related mainly to the existence of vegetation cover and slope of the relief, would be non-relevant. The reason for this methodological solution of attenuation of the extrinsic factors relies on the focus of this analysis to the essential comparison between the DTM generated by ALS, as a ground truth, and the DTM produced by RPAS.

Once the possible sites were identified, the sequential operation was the choice of those sites that would be representative of the entire area, that is, that were distributed evenly throughout the test region of Timbopeba. The selected sites make up a total amount of 14 (fourteen). Of these sites, 12 (twelve) fall within the premise of being flat and devoid of vegetation; the remaining two sites have been chosen in forested places, just as control sites that would be able to confirm the degradation imposed by the vegetation cover on the results of a DTM from RPAS.

The research decision about ground control points (GCP) for RPAS was for its full use, considering its importance in the accuracy of the final results, as a georeferencing element. To choose the position of these points, the choice was for the areas of overlap between the subareas or blocks of photographs that composed each subdivision of the total RPAS flight area. This solution was aimed to ensure that the connection between the blocks of photos (subareas) was as rigorous as possible. In the places chosen for positioning of the GCP, the standard cross-shaped signals were placed, that when being photographed by the RPA during its flight, would be used as reference points – GCP to the georeferencing of the entire RPAS aerial survey.

The definition of the quantity and position of the GCP is made so that each flight is tied by at least five points. In the present study, the coordinates and altitudes of the seventeen control points were surveyed using the GNSS receiver Trimble R8 RTK and the TSC2 - Trimble Survey Controller.

The RPAS aircraft used is produced by the Swedish SmartPlanes, model SmartOne that was a small RPA. The complete system incorporates the aircraft, composed of three mountable parts, which allows its transport in a small suitcase. The aircraft has a wingspan of 120 cm, a take-off weight of 1.2 kg and a maximum flight time of 45 minutes. Its launch is manual, as well as landing, by landslide. The digital camera transported is the Canon PowerShot S100, with a maximum resolution of 12.1 MP and a wide-angle lens with a fixed focal length of 5.2 mm, to take the images that are necessary for the production of the DTM by the photogrammetric processing system.

Regarding the execution of the aerial survey with RPAS, the work began with the planning of the flight, which is of great relevance for the success of the work. Circumstantial factors, such as location of the region, boundaries of the area to be mapped, flight height, altitude of the terrain, local wind regime and existence of obstacles to the flight should be considered. Technical factors related to photogrammetric mapping, such as overlap between photos and tracks, flight direction, technical characteristics of the camera and the sensor storage unit instruct the planning, which is done based on specialized

RPAS software. The resolution of images, which refers to quality and sharpness, is a function of the type of camera and its distance from the ground, that is, the height of flight. The pixel is the smallest image forming element and is technically defined as ground sample dimension (GSD), expressed in centimeters. A balance between resolution – small GSD – and flight height is decisive for the success of the mapping, because low flights imply high resolution – small GSD – but with excessive photos and longer flight time and data processing. Very high flights, on the other hand, may imply low resolution images – large GSD – and insufficient accuracy. It should also be considered that the radio link for communication between the ground control base and the aircraft is limited to a radius of 600 m. Regarding the photogrammetric parameters of lateral and longitudinal overlap between the photos,

they should be conservative because the image processing uses these overlapping areas to make the necessary geometric connection between images, which ensures that the photogrammetric mapping method can be applied in a precise way. In order to put in line the research with the accuracy demands of the surveys used in the open-pit mines, the RPAS aerial survey was parameterized according to the experimental use that has been adopted in the works done in the mining areas. The GSD adopted was 12 cm; the lateral and longitudinal overlaps of the flight were set at 60%; and the average flight height at 300 meters. The specifications used were optimized to the limit in order to reduce the generation time of the DTM, since this is the normal operating condition for this type of mine survey.

The effective evaluation of the most accurate correlation among the DTM in

these areas was made through the direct comparison between points of both point clouds – RPAS and ALS, which were practically coincident in their horizontal position. The large density of the two clouds allowed this solution, which is as direct as possible, in terms of comparison, since it avoids the DTM surface modeling process by triangulated irregular network (TIN), that could have inserted additional errors in this case.

The point coincidence positions were chosen by decision of the analysis team and were distributed homogeneously by each of the 14 sites. Thirty coincidence positions were evaluated in each site, where the altitude of the DTM ALS was ground reference for the determination of the difference of the DTM RPAS in relation to the ALS, by subtracting the altitude of the ALS from the altitude of the RPAS. The results are presented in the next section.

3. Results

The objective results found in the fourteen evaluated sites are presented in Table 1, in which the Site context column reports the execution condition of the analysis. All sites obeyed the conditions of being cleared of vegetation and flat, except for sites 6 and 11, which are covered by forest. These two sites were included, as a control, only to confirm the effect of degradation of the results that is caused by relevant extrinsic factors, as vegetation. Sites 3a and 4 were excluded from the analysis because land movements in these areas were identified and confirmed in the time period between aerial surveys

ALS (2012) and RPAS (2016).

As a consequence, of the fourteen initially chosen sites only twelve remained for the comparison between the DTM RPAS and ALS. In Table 1, the "Quantity of positions for direct comparison" column refers to the number of direct comparison point positions between RPAS and ALS altitudes. The "Mean" column refers to the average of the direct difference of altitude points between the DTM RPAS and the ALS in each site. In the last column, in order to have an evaluation of the data dispersion, the calculated standard deviation for the sample of each

site is presented.

The sites 1, 2, 3, 5, 7, 8, 8a, 9, 10 and 12, which were not compromised by any extrinsic factors, present the mean unified differences by about -0.30 m (thirty centimeters negative). It means that the DTM of the RPAS is, on average, 30 cm below the DTM of the ALS. It is worth noting that the standard deviations for these sites present an approximate average value of 15 cm, which, given the circumstances of the test, can be considered a low dispersion of the differences between the clouds of points.

Sites	Site context	Quantity of positions for direct comparison	Comparison: RPAS height – ALS height	
			Mean [m]	Standard deviation [m]
1	Bare Earth	30	-0.17	0.19
2	Bare Earth	30	-0.58	0.06
3	Bare Earth	30	-0.57	0.14
3a	Altered Earth	30	-3.73	0.46
4	Alterad Earth	30	+0.64	0.15
5	Bare Earth	30	-0.41	0.15
6	Forest	30	+10.60	2.09
7	Bare Earth	30	-0.18	0.10
8	Bare Earth	30	+0.09	0.14
8a	Bare Earth	20	-0.08	0.11
9	Bare Earth	30	-0.34	0.16
10	Bare Earth	30	-0.30	0.12
11	Forest	30	+5.18	5.10
12	Bare Earth	30	-0.45	0.08

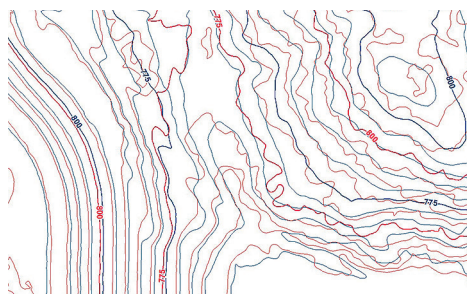
Table 1
Summary table for comparative analysis between altitudes from RPAS and ALS.

In sites 6 and 11 the difference between DTM reaches 10.60 and 5.18 meters, i.e., the DTM RPAS is more than five meters above the DTM ALS. The commitment of the RPAS method for the terrain modeling under these conditions becomes clear when the points of the RPAS modeling are returned and verified from the forest canopy. Vallet *et al.* (2011)

also evidence this intrinsic restriction to the photogrammetric mapping process of the RPAS, that could be illustrated by the Figure 2. It could be observed that where the terrain is clear from vegetation the contour lines generated by laser (blue) are parallel to the contours produced by DTM RPAS (red). It may mean that the internal consistency of the two DTM

is almost the same in clear areas. In the forested area, contrarily, the contours have different delineation. It results from the fact that automatic generation from photogrammetric process (RPAS) works with points that came from digital surface model (DSM), while laser model were generated with points returned from the terrain (DTM).

Figure 2
On the left, contour lines generated by DTM ALS (blue) and by RPAS (red); on the right, the ortho-image of the same local, so as to allow a view of the different contexts.



In terms of time consuming, the results showed that it takes fifteen minutes to plan each flight and that each flight lasts for twenty minutes. In terms of processing the

data, it takes about five hours of work, in a medium accuracy way, with the use of Agisoft Photoscan photogrammetry software. This means that if well planned and opera-

tionalized, including the adoption of fixed ground control points in sites of recurring surveys, the entire production of the DTM can be completed in less than 48 hours.

4. Discussion

Considering that the DTM ALS is very consistent internally, the average standard deviation of 15 cm that was found gives the DTM RPAS almost the same presumption of consistency that was made for the DTM ALS. This is one of the best results of this research, because the relative internal consistency of a survey method, the so-called precision of the method, is one of the first questions to consider when assessing its potential to produce good results. Identifying this coherence in the RPAS, even in an experimental survey like this one, is an excellent observation in operational terms, which is in line with other experiments such as those presented in Küng *et al.* (2011), Neitzel & Klonowsky (2011) and Vallet *et al.* (2011).

The accuracy demands in terms of recurring topographical surveys in open-pit mines could be adopted in values that vary from 30 to 40 centimeters, in the best cases. The potential of RPAS should be understood in the light of the almost 15 centimeters found in the standard deviation, as long as the average difference of 30 centimeters could be input to several systematic factors as small georeferencing differences between ALS and RPAS, GPS errors and others. As long as RPAS is as coherent as ALS, we may affirm that RPAS could be used to solve the problem of recurring surveys (every month or less) in open-pit mines, in light of the almost 40

centimeters demand on accuracy.

In spite of the good results found, this means that the internal consistency of the DTM generated by the RPAS is equivalent to DTM generated by the ALS, there is a significant variation between the location with the highest mean difference between the RPAS and ALS points cloud (area 2 with -0.58 m) and the one with the smallest difference (area 8 with +0.09 m). This seems to contain strong signaling that a more rigorous application of photogrammetric project assumptions in the workflow of aerial surveying with RPAS is lacking. By project assumptions, in this case, it is understood the more judicious and technical choice of the position for the GCP, the form of materialization and determination of these points, the way of connecting between different blocks of photographs, the process of data with greater precision, and the visibility of the images, among other factors. As long as this significant variation in the mean difference is not found in the standard deviation, being the worst result with 19 cm, the presumption of internal consistency for RPAS survey remains valid and reinforces the recommendation for a careful set of photogrammetric project assumptions, especially in terms of the georeferencing – GCP – process.

One of the problems found in the processing of the survey done for this

research, the visibility of the signals that materialized the GCP has already been reported by Remondino *et al.* (2011). In fact, the signals that are made available to use have a standard size, whose visibility in the images varies with flight height and GSD or pixel size on the ground. The signals were not clearly visible to the target in the images obtained, just like the problem identified by Remondino *et al.* (2011), which undoubtedly degrades the accuracy of the process as a whole. The control points (GCP), the georeferencing in the broadest sense of a photogrammetric process, accounts for an expressive part of the final result. It is not without reason that Nex & Remondino (2014) consider them an important issue in the formation of the RPAS image blocks. As the authors point out, the inconsistencies of the ground control points degrade all subsequent stages of the photogrammetric process, even in the context of processes as automated as those of processing RPAS.

Colomina and Molina (2014) are correct in stating that in the case of robotic RPAS, computer vision and geomatics technologies have established the new paradigm, as well as the decisive contribution of techniques, rooted in computer vision (Küng *et al.*, 2011), which have been developed specifically for the treatment of this type of data and make all the difference in relation to conventional

photogrammetry techniques. However, these same authors point out at the end of their work that "the accuracy figures presented here could be further improved by following a traditional photogrammetric work-flow" (Küng *et al.*, 2011). Tong *et al.* (2015) when dealing with critical factors to investigate, observe that it is very important to devise a specific workflow for the

photogrammetric mapping when applied to an open-pit mine. Colomina and Molina (2014) point out that the contributions the research in computational vision have given to the generation of point clouds by these systems are significant. However, it is important to consider that much of the quality depends on the photogrammetric bases on which the process is sustained.

The main reason to leave this experiment free to non-specialized user parameterization was precisely to try to identify the importance of technical care, specialized or not, that should involve the production of topographic mappings by RPAS. One of these cautions, as can be seen from this and other experiments, is the need to see it as essentially a photogrammetric process.

5. Conclusions

The main conclusion deriving from the tests carried out is based on the good internal precision and consistency presented by the DTM RPAS and the feasibility to produce the DTM of open-pit mines in a short time schedule – almost 48 hours, with great potential for replacement of the conventional topography in conditions of bare earth. As observed by Nex & Remondino (2014), these systems have great ability to rapidly provide geo-information at appropriate spatial and temporal resolutions, which allow for rapid response to open-pit mine operations in a number of critical situations. In this case, it is impor-

tant to note that this technology is already sufficiently mature for the production of geo-information, which, in the specific case of the experiment reported here, is the generation of topographic mapping of open-pit mining areas.

This work was guided by the idea of executing the field test exactly as the daily operation that has been applied in the mining areas, by the Vale team. It is recommended, however, that the implementation of these mapping solutions with RPAS consider the quality constraints of the photogrammetric aerial survey, in order to improve the workflow

and final results of the RPAS survey, with the theoretical and operational knowledge that underpin the photogrammetric process. This can be done through a more careful choice and determination of the position of the ground control points (GCP), in a more rigorous connection solution between blocks of photos of different flights, in the maintenance of overlaps between images in the order of at least 60%, in the choice of high resolution images (GSD) and the use of powerful computers for data processing, so that results can be obtained quickly and at high levels of accuracy.

Acknowledgments

Special thanks to Vale for making the data available and encouraging the execution of the research presented here.

References

- ACOSTA, T. NMSU Physical Science Lab tests unmanned aircraft over active mine. *News Center*, New Mexico, ago. 2014. Seção All About Discovery! Disponível em: <<https://newscenter.nmsu.edu/Articles/view/10673/nmsu-physical-science-lab-tests-unmanned-aircraft-over-active-mine>>. Acesso em: 10 jun. 2017.
- COLOMINA, I., MOLINA, P. Unmanned aerial systems for photogrammetry and remote sensing: a review. *Journal of Photogrammetry and Remote Sensing*, Hannover, v. 92, p. 79-97, jun. 2014.
- COYNE, A. Rio Tinto to lean more heavily on drones. ItNews, Australia, set. 2015. Disponível em: <<http://www.itnews.com.au/news/rio-tinto-to-lean-more-heavily-on-drones-408740>>. Acesso em: 10 jun. 2017.
- KÜNG, O., STRECHA, C., BEYELER, A., ZUFFEREY, J.-C., FLOREANO, D., FUA, P., GERVAIX, F. The accuracy of automatic photogrammetric techniques on ultra-light UAV imagery. In: UAV-g 2011, CONFERENCE ON UNMANNED AERIAL VEHICLE IN GEOMATICS. Zürich, 2011.
- NEITZEL, F., KLONOWSKI, J. Mobile 3D mapping with a low-cost UAV system. In: UAV-g 2011, CONFERENCE ON UNMANNED AERIAL VEHICLE IN GEOMATICS, Zürich, 2011.
- NEX F., REMONDINO, F. UAV for 3D mapping applications: a review. *Appl Geomat*, Berlim, v. 6, n.1, p. 1-15, mar. 2014.
- REMONDINO, F., BARAZZETTI, L., NEX, F., SCAIONI, M., SARAZZI, D. UAV photogrammetry for mapping and 3D modeling: current status and future perspectives. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. Zürich, v. XXXVIII-1/C2, set. 2011.
- TONG, X., LIU, X., CHEN, P., LIU, S., LUAN, K., LI, L., LIU, S., LIU, X., XIE, H., JIN, Y., HONG, Z. Integration of UAV-based photogrammetry and terrestrial laser scanning for the three-dimensional mapping and monitoring

of open-pit mine areas. *Remote Sensing*, Basel, v. 7, n. 6, p. 6635-6662, mai. 2015.

VALLET, J., PANISSOD, F., STRECHA, C., TRACOL, M. Photogrammetric performance of an ultra light weight swinglet “UAV”. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. Zürich, v. XXXVIII-1/C2, set. 2011.

Received: 19 July 2017 - Accepted: 4 January 2018.