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UAV for monitoring the settlement of a landfill

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ABSTRACT

Remote-pilot aircraft are developing very rapidly and their potential in the various fields is often still to be fully investigated. The possibility to fly over the areas to be surveyed without the need to access the areas themselves makes the use of UAVs in some cases certainly preferable for safety reasons, as has already been tested for the management of post-disaster areas. Waste landfills are small sites where contact with waste itself must be limited and scientific experimentation on surveying this specific type of site is currently limited. The results obtained in other types of sites or infrastructures are not automatically applied to waste landfills due to the specific geometrical characteristics and texture of the images that can be obtained at sites like these. In this work, a test on an exhausted landfill has been carried out with attention to the accurate survey of a large number of control points necessary for a correct assessment of the final geometric accuracy. The use of ground control points and checkpoints has allowed the separate evaluation of precision and accuracy, which are very close to those obtained with the most common methods for these sites, such as laser scanning and total stations.

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Introduction

European Directive 1999/31/EC and the resulting national and local rules require that landfills be located in geologically appropriate areas and designed according to criteria that ensure the protection of the environment in which they are located, preventing their potential contact with any contaminants present or arising from the waste disposal. It is therefore essential that the integrity of the protection systems present in it is guaranteed over time (leachate drainage system, biogas collection system, barrier systems, capping). While the stability of the ground on which the landfill is located is an easily verifiable task and for which the instruments and models are consolidated by geotechnical discipline, the stability of the waste body and its settlement, however, is still being studied for the difficulties involved in determining accurately the geotechnical properties of solid urban waste. In fact, settlement in landfilled waste occurs due to loading and other processes as chemical and microbial actions. These processes are controlled by factors such as leachate composition, pH, temperature and moisture (both as a reactant and as a vector for species transport). For these reasons, settlement in landfilled waste is complex and difficult to predict in both magnitude and timing (University of Southampton, 2019).

To this purpose, numerical models for the prediction of solid waste landfill settlement were developed as they are an important support for landfill design and rehabilitation (Chen, Chen, & Liu, 2012). Other authors introduced a model based on unsaturated consolidation theory and considering the biodegradation process to simulate the landfill settlement behaviour (Zhao, Chen, Shi, & Huang, 2001). Special attention has been paid to the study of long-term settlement estimation and its application to postclosure maintenance and development plans (Sharma & De, 2007)

The determination of accurate geotechnical parameters of waste are strongly influenced by several factors including:

- the heterogeneous composition of waste;
- the difficulty of collecting representative samples;
- the lack of widely standardized sampling procedures;
- the variability of waste properties over time, also depending on the layering methodologies, the pre-treatments and the presence of daily coverage layer.

Monitoring the morphology of closed or active lots at established time intervals would make it possible to promptly and effectively manage the effects of settlement. At the same time, it is therefore an important

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indicator of the quality of the system in both environmental and economic terms. The use of UAVs for waste settlement monitoring potentially has very useful features for this specific application.

The aim of this work is to evaluate the effectiveness of UAVs survey for monitoring landfill settlement in a real post-closure scenario, by comparing two models obtained through the acquisition of UAV imagery from two separate flights, repeated after about 6 months.

State of the art

The literature on UAVs and the modelling of their images are starting to be very extensive, both in terms of papers describing general, methodological and photogrammetric aspects of this new technology (Colomina & Molina, 2014; Nex & Remondino, 2014; Watts, Ambrosia, & Hinkley, 2012; Kendoul, 2012;) and in terms of specific applications.

In a way, what differs most between "classic" aerial photogrammetry and UAV photogrammetry are the models used. The possibility to acquire a lot of images without the storage limits typical of analogical supports, together with the ever increasing calculation capacities available, have suggested to experiment the use of algorithms already known and adopted in the field of computer vision (Ullman, 1979; Westoby, Brasington, Glasser, Hambrey, & Reynolds, 2012).

The classic photogrammetric approach is based on collinearity equations and describe the imagery acquisition considering geometrical and camera characteristic. Collinearity, as illustrated in Figure 1, is the condition in which the exposure station of any photograph, an object point, and its photo image all lie on a straight line. The equations expressing this condition are called the collinearity condition equations. They are perhaps the most useful of all equations to the photogrammetrist (Wolf, Dewitt, & Wilkinson, 2014) and they relate

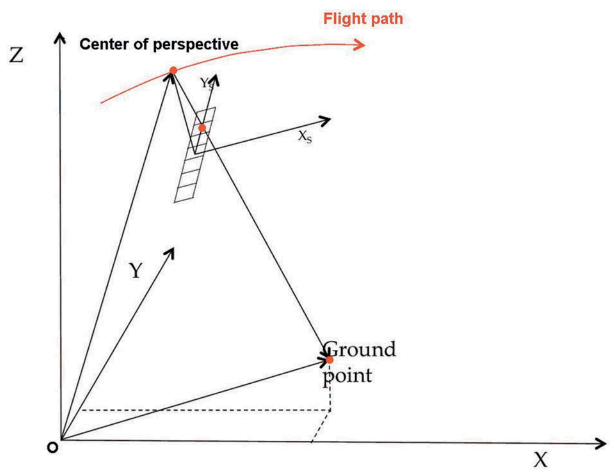

Figure 1. The collinearity condition.

the position of a point in the image space to the corresponding point in the object space, according to a central projection (Kraus, 2000). The reconstruction of the image acquisition geometry is obtained studying acquisition mode, sensor features, camera position and attitude (Figure 1).

The initial position and attitude parameters must be corrected by a least square estimation based on a suitable number of Ground Control Points (GCPs), a set of points with object coordinates computed through a direct survey as a GNSS differential survey.

The Computer Vision algorithms use several methods of automation (i.e. Structure from Motion "SfM") that estimate the interior orientation parameters and the camera attitude and position in a relative image-space coordinate system. Using SfM, in fact these are extracted automatically, with high redundancy, using an iterative bundle adjustment (Triggs, Zisserman, & Szeliski, 2000) on a set of images (multi-image approach). The SfM algorithms are currently implemented in several software packages available for the 3D reconstruction of DSM, combining SfM and bundle adjustment, between them: Agisoft Photoscan (2019), Pix4D (2019), Context capture (Topcon Positioning, 2019).

Models from UAV images are automatically dimensioned and geo-referenced using the positions of the GPS/GNSS receiver and the onboard navigation system. Despite the latest developments in mobile GNSS chips (Robustelli, Baiocchi, & Pugliano, 2019) in most cases GPS/GNSS receivers mounted on UAVs still work in point positioning so with insufficient accuracy. The correct georeferencing and sizing are still operations that are performed on the basis of manual collimation of GCPs surveyed on the ground generally with differential GNSS receivers in static mode.

The images acquired by the drone can then be processed with SfM and the bundle adjustment (Snavely, Seitz, & Szeliski, 2007). Usually, the first phase is the identification of the keypoints, or feature points, in every image (Snavely et al., 2007) through the use of so-called detectors, i.e. operators who scan for 2D positions in images (Remondino, 2006). In accordance with the key points found in every image, multi-image matching is performed to obtain the match between them. In this phase, an outlier analysis is important to avoid mismatches then key points are used to match images and then to identify the tie points among images (Apollonio, Ballabeni, Gaiani, & Remondino, 2014; Mikolajczyk & Schmid, 2005; Remondino, 2006).

The bundle adjustment estimates the camera position for every image and its internal orientation allowing the creation of 3D point clouds.

Due to the high number of tie-points on which statistical adjustment is applied, the calibration parameters of the camera can be obtained automatically by considering them as unknown, during collinearity equations resolution (Figure1) this strategy is usually referred as “autocalibration” (Fraser, 1997). As already mentioned, the GCPs provide georeferencing and dimensioning of the 3D models still obtainable through the bundle adjustment. At this stage models with scattered points can be improved by dense matching algorithms to obtain dense point cloud models. Matching models are generally classified as stereomatching (Hirschmuller, 2008) and multi-stereo matching (Furukawa & Ponce, 2010; Pierrot-Deseilligny & Paparoditis, 2006). The three-dimensional accuracies that can be obtained at the end of the described process are influenced by various parameters and are the subject of a wide debate in the literature (Ahmadabadian et al., 2013; Apollonio et al., 2014; Caroti, Martinez-Espejo Zaragoza, & Piemonte, 2012; Kersten & Lindstaedt, 2012; Kung et al., 2011; Remondino, Del Pizzo, Kersten, & Troisi, 2012).

From the above, we can in general deduce the importance of ground control points since the results obtained with automatic approaches are not as certifiable as those of traditional photogrammetry. Moreover, for the specific application of the monitoring of the settlement of landfills, we can deduce that the often homogeneous texture of the upper surface of landfills could make it difficult for algorithms to search for key points and subsequently tie points. Therefore, it is necessary to carry out specific experiments on these particular sites to verify the feasibility of a three-dimensional survey using UAV images with SfM approach.

In literature, papers on the various possible applications of UAVs as a support to various disciplines are being diffused. To do a complete overview would require a review work probably more suitable for other contexts. Below we will quickly illustrate some of the applications in various disciplines and then focus on the few available for the specific field.

Applications in agriculture focus mainly on the identification of early-stage plant suffering with multispectral sensors (Gago et al., 2013) and secondly also on the possibilities of using UAVs for the treatments of the plants themselves (Xue, Lan, Sun, Chang, & Hoffmann, 2016)

Another application that has been heavily investigated is post-disaster management, as in the case of a seismic event, where it is necessary to be able to intervene immediately and produce an immediate damage estimate (Baiocchi, Dominici, Milone, & Mormile, 2014 & Alicandro, Dominici, & Buscema, 2018).

A difficult environment for accessibility problems and for its specific very homogenous texture was the reconstruction of a Himalayan glacier using ground GPS control points (GCPs) and obtaining an accuracy of about 0.2 m. (Immerzeel et al., 2014). The texture of a glacier can be very homogeneous even more than that of a landfill and this research can, therefore, be considered as a guideline for our experimentation.

Infrastructures that are similar to landfills, although with some differences in texture, are the areas undergoing quarrying activities which, in addition, at the end of their activity are often converted into landfills. Even on these infrastructures the bibliography is not very extensive but there are more examples than on landfills, as for example Chen, Li, Chang, Sofia, & Tarolli (2015); Vinci, Todisco, Brigante, Mannocchi, & Radicioni (2017) & González-Aguilera, Fernández-Hernández, Mancera-Taboada, Gozalo-Sanz, & Arias-Perez (2012)

With regard to applications in the specific field of waste, we can see that in (Gasperini, Allemand, Delacourt, & Grandjean, 2014) the drones were used to assess the volumes and monitor the subsidence zones of a lot of landfill, at Rosignano Marittimo (Italy), obtaining a digital surface model with a horizontal resolution of 0.028 m and vertical resolution of less than 0.05 m, that are declared fully comparable with traditional scanning techniques, both total station and Lidar. Unfortunately, this study does not provide data on the actual geometric accuracy but only on the presumed accuracy of the GPS receiver estimated at about 0.5 m. Similar results have recently been achieved by Grünner and Dudáš (2017) & Daugela, Visockiene, and Aksamitauskas (2018) but still there is no a proper estimation of actual geometric accuracy, while Yoo, Lee, Chi, Hwang, and Kim (2017) have applied UAV techniques to the detection of a post-disaster landfill site for the estimation of displaced volumes. More recently Incekara, Delen, Seker, and Goksel (2019) studied the volume variations in an active landfill they properly estimated the precision of the model, but no CPs were used; thus it was possible to survey points only around the landfill and not inside.

The latter contributions are among the few applications concerning waste landfill UAVs applications and have therefore been used as a starting point for the development of this research.

Materials and methods

The chosen area is a completed lot of the urban waste landfill of Borgo Montello (Latina, Italy); the activity having ended it is equipped with all the necessary protection devices (capping, biogas wells, and leachate drainage) (Figure2).

In particular, the object of our survey is the raised area with a trapezoidal shape (still Figure2) whose upper area is almost flat, limited by very steep slopes up to about 30-m high. The study area is near the city of Borgo Montello that is near the city of Latina in the southern part of Lazio Region. Lazio is the region of

Figure 2. The study area with the surveyed point, CPs are in red circle.

Rome and is in the centre of Italy along its West coast on the Tyrrhenian Sea. The approximate WGS84 coordinate of the site are 41°28' N, 12°46' E.

For this research, 46 photogrammetric markers have been installed on the top of 46 tubes in the upper part of the landfill body (Figure 3), arranged along a regular grid (Figure1) on the landfill body, on the area under study, with an extension of about 400 m in an east-west and 270 in a north-south direction (Figure 2). The markers, 40 cm by 40 cm in size, were surveyed by the GPS considering the plane of the marker itself as a reference for the height. It has been verified that on point clouds the difference in height between the marker plane and the ground is always detected correctly by the matching algorithms and therefore has not caused problems in the reconstruction of the surfaces. On the other hand, it should be noted that the matching algorithms certainly work better on the markers than on the rest of the landfill surface, because the markers are better recognizable and this can lead to an overestimation of the accuracy of the method, but unfortunately there is no other solution because on the surface of the landfill is not possible to identify natural points that are guaranteed to remain unchanged over time. The markers were installed to follow the planoaltimetric modifications of the landfill itself, at the same time a number ranging from 6 to 10 external natural points were surveyed for each flight, these points ensure the correct correlation between the various flights as they are considered not to be affected by the settlement movements of the landfill.

Figure 3. One of the photogrammetric markers.

All this has been prepared so that the site can be used as a test site to verify different procedures to study the settlement of the landfill and at the same time estimate the accuracy obtainable.

Extract an accurate and repeatable digital model of the site at fixed time intervals, from which it is possible to assess the amount of settlement, it is certainly a more complete way of documenting the evolution of landfill if compared to Total stations and GPS surveys (Baiocchi, Fabiani, Liso, & Mascia, 2005). Whole surface information can be provided also by a terrestrial laser scanning survey (TLS) but for a complete survey of a landfill, it is almost always necessary to access the landfill itself which can be a disadvantage. In addition, TLS equipment is generally less easy to transport and certainly more expensive than a UAV.

The optical images used for the generation of the digital model and of the orthophoto of the landfill lot were processed by two softwares: the widely diffused Agisoft Photoscan software (version 1.4.1) for the first flight and ContextCapture 2018 for the second flight. During the first flight also a thermal camera was used to experiment if its images can be used to extrapolate temperature data, potentially useful for the study of the landfill. The results in terms of geometric accuracy of thermal images are currently not satisfactory mainly due to the difficulty of identifying GCPs on the thermal images themselves; for more details see Baiocchi et al. (2018).

The acquisition flights for the first campaign were carried out on 20/10/2017, between 14:00 and 16:00 using a hexacopter (six motors) FlyNovex Flytop series (Figure 4)

The flight of this first campaign was conducted by equipping the drone with a digital camera SONY ILCE a6000 with a focal length of 16 mm and sensor size 23.5 × 15.6 mm operating in the visible (Figure 5) with which 153 photos were taken of the area at a flight height of about 120 m. whit a mean ground sample distance (GSD) of 2.2 cm. For the planning of the flight an along track overlap of 80% and an across track overlap of 45% were respected; these overlap values are suggested by the planning software (Pix4D Ctrl+) and have been successfully tested in previous experiments.

Figure 4. The FlyNovex hexacopter.

Figure 5. The Sony ILCE camera.

Before the flights, the points were surveyed by a GPS/GNSS differential RTK (Real Time Kinematic) receiver TOPCON Legacy E; the coordinates of the GCPs were determined by differentiating the data considering the permanent station of the city of Latina (LTNA) framed in the reference system RDN2008 (EPSG: 6708) (Regione Lazio, 2019). According to GNSS measurements, average accuracy of the topographic survey was 1.6 cm for planimetric coordinates and 2.0 cm for height (Root Mean Square Error (RMSE)).

The second campaign was carried out with an Intel Falcon Plus 8 eightcopter (Figure 6), with a Sony Alpha 7r v. 3.10 that is a full-frame photo camera with an image resolution of 7360 × 4192 pixels, focal length 35 mm., it features 36 MP ISO 100–25.600 with a 35 mm sensor. The images acquired in this case were 262 from an average flight altitude of 70 m and with a mean ground sample distance 1.8 cm. An along-track overlap of 80% and an across track overlap 45% were respected for consistency with previous flight.

The change of UAV between the first and second flight was a mandatory choice because the first drone was no longer available, at first we thought of this as a big drawback (and in part it is) but from a certain point of view we think it is also an opportunity of actual experimentation because it is a situation that in the real world of applications can happen often given the short operational life of the UAVs.

The dataset available is completed by point measurements made by differential GNSS receivers on topographic markers monthly and, referring to the same permanent station (LTNA) (Figure 7).

Experimentation

The optical imagery, obtained from the first campaign, has been processed using the software Agisoft Photoscan v.1.3.5, based on the algorithm SfM that allows, the fully automatic reconstruction of the 3D model of the site chosen, from the 153 images available. The import and processing parameters of the images have been left at their default values (Figure 8) to make the procedure as standardized and comparable as possible.

A scattered point cloud was obtained first and then the dense one; only in the latter case, in the "build mesh", the number of reconstructed faces has been limited to 200,000 in order to optimize the calculation time (Figure 9).

As reported in Table 1, planimetric RMS error was 2.7 cm, altimetric RMS error was 2.7 cm on GCPs, whereas it was 3.6 cm and 6.0 on CPs. These values are close to those reported in the literature and in particular for experiments with Agisoft (Masiero et al., 2019)

The images acquired in the second campaign were processed with the *Context capture 2018* software

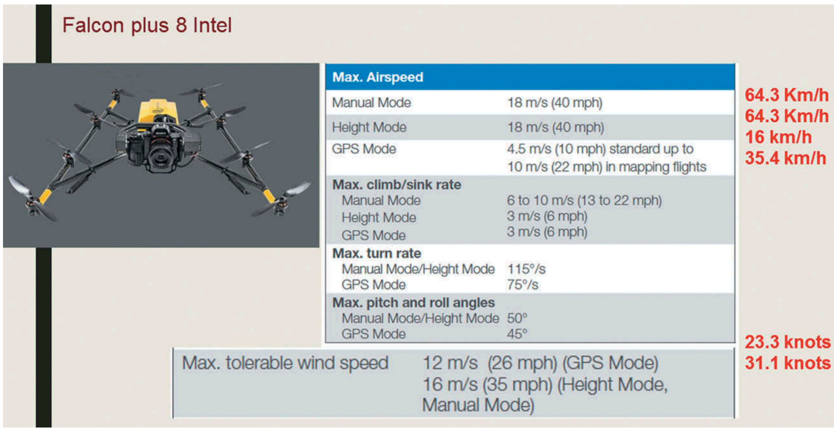

Figure 6. The Intel Falcon eightcopter and its main characteristics.

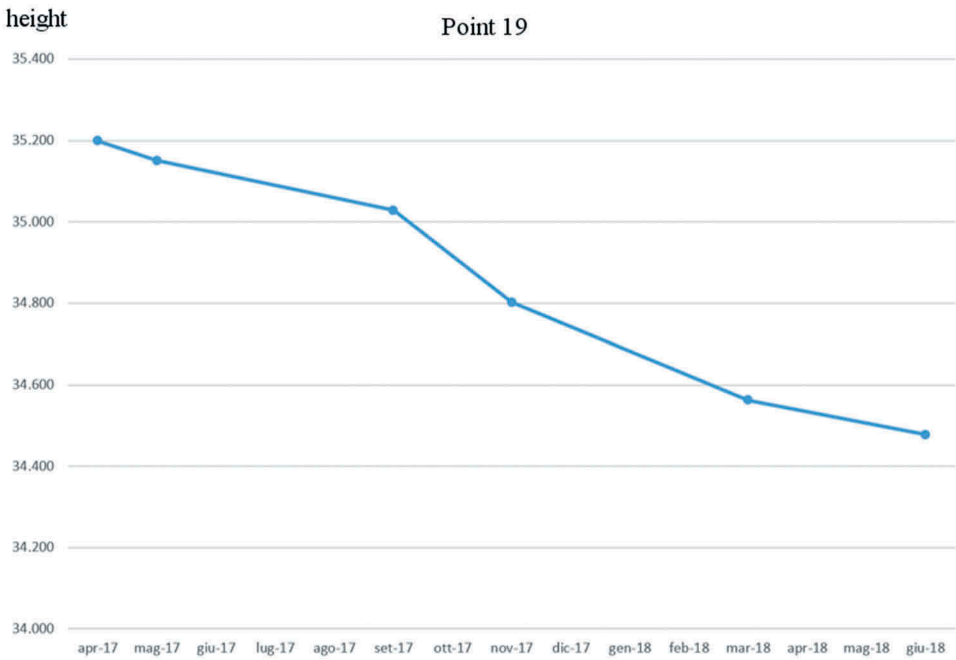

Figure 7. Height variations on one of the points during the observation period.

because it was developed by the same vendor of the drone and so it already contained the parameters of the specific camera and therefore it was not necessary to self calibrate the camera. These information make the least square estimation certainly more robust because the parameters to be estimated are less and should provide more accurate results, anyway we have chosen to use the default options (Figure 10) for all other parameters to obtain a procedure as standardized as possible that we think can be the more comparable with the one used for the Agisoft model.

As reported in Table 1, planimetric RMS error was 2.0 cm, altimetric RMS error was 1.7 cm on GCPs, whereas they were 3.0 cm and 3.4 on CPs. The results are very close to those of Agisoft on the same GCPs and CPs, the slightly better results could be attributed to the calibration of the camera available in Contextcapture and not in Agisoft as already mentioned. The model obtained with Context capture 2018, with its camera-specific parameters and all the other parameters left to default value is visible in Figure 11.

To compare the two models, we used Cloud Compare (v. 2.6.3), open-source software widely used for this type of analysis (CloudCompare, 2019). With regard to the settings in *Distance computation*, we decided to use the option *Split X, Y, Z* components to obtain the distance between clouds as a function of the three components of the difference vector and not only the absolute distance between them. In this case the option allows us to focus our processing on the vertical direction which is the most significant for this type of sites.

For local modelling, there are currently three types of algorithm models, all three models are based on the least square fit: the least square best fitting plane, or a 2D1/2 Delaunay triangulation, or a quadratic height function (the latter being the more precise but also the

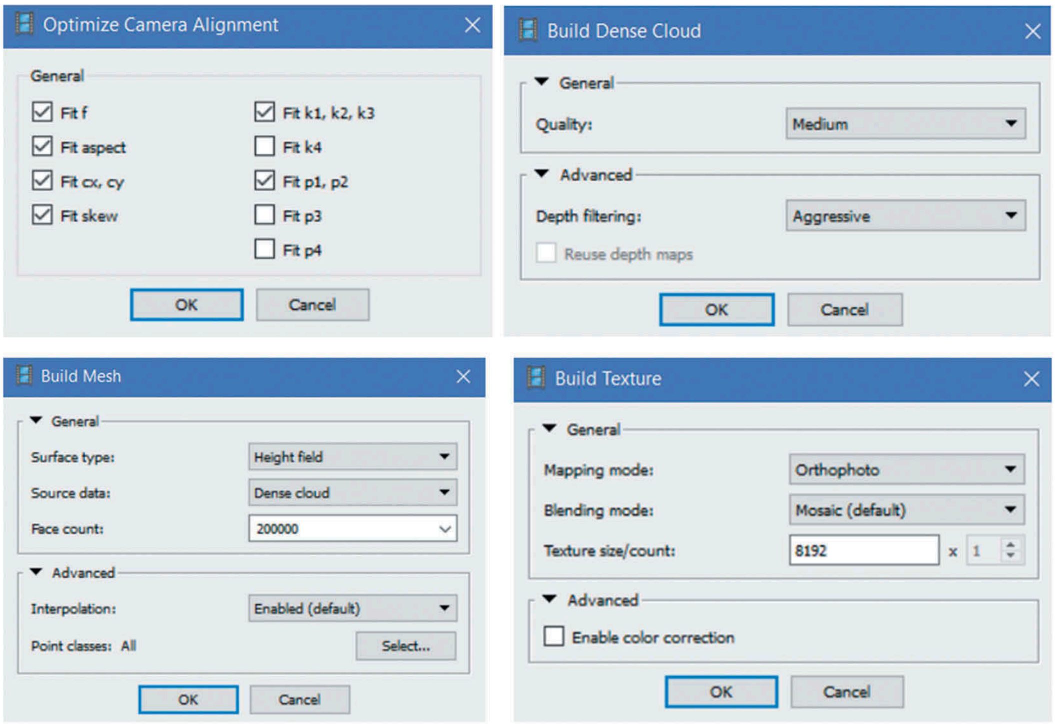

Figure 8. Default values used for main parameters in AgiSoft.

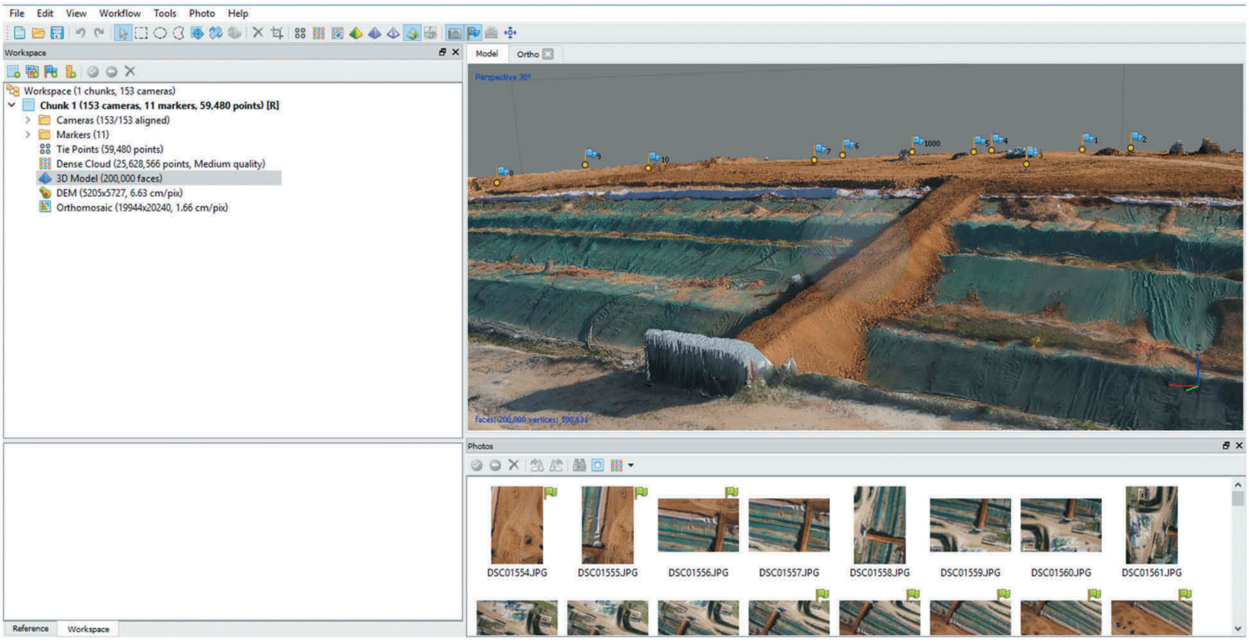

Figure 9. Detail of the reconstruction of landfill morphology with first campaign images.

Table 1. Precision and accuracy for first and second campaign models.

	First flight (Agisoft)	Second Flight (context capture)
Precision (45 GCPs) XY metres	0.027	0.02
Precision (45 GCPs) Z metres	0.027	0.017
Accuracy (5 CPs) XY metres	0.036	0.03
Accuracy (5 CPs) Z metres	0.06	0.034

longer to compute). In 2D1/2 triangulation, the projection of the points on the plane is used to calculate the triangulation of Delaunay (the original 3D points are used as vertices of a mesh in order to obtain a 2.5D mesh) or the quadratic function: based on a quadratic function with six parameters (1).

$$z = ax^2 + bx + cxy + dy + ey^2 + f \quad (1)$$

Since Delaunay's triangulation is the only model that can theoretically represent sharp edges for this specific field of application, the 2D1/2 triangulation model was chosen.

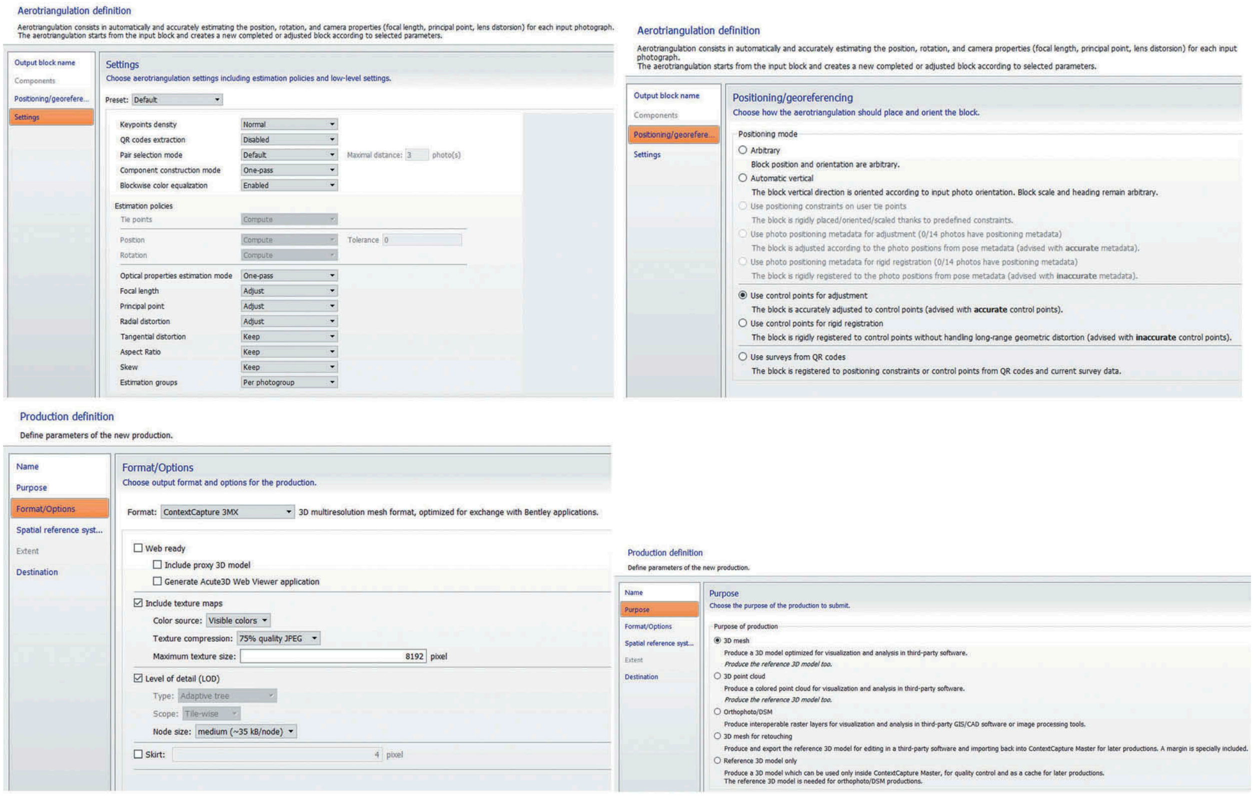

Figure 10. Default values used for main parameters in ContextCapture.

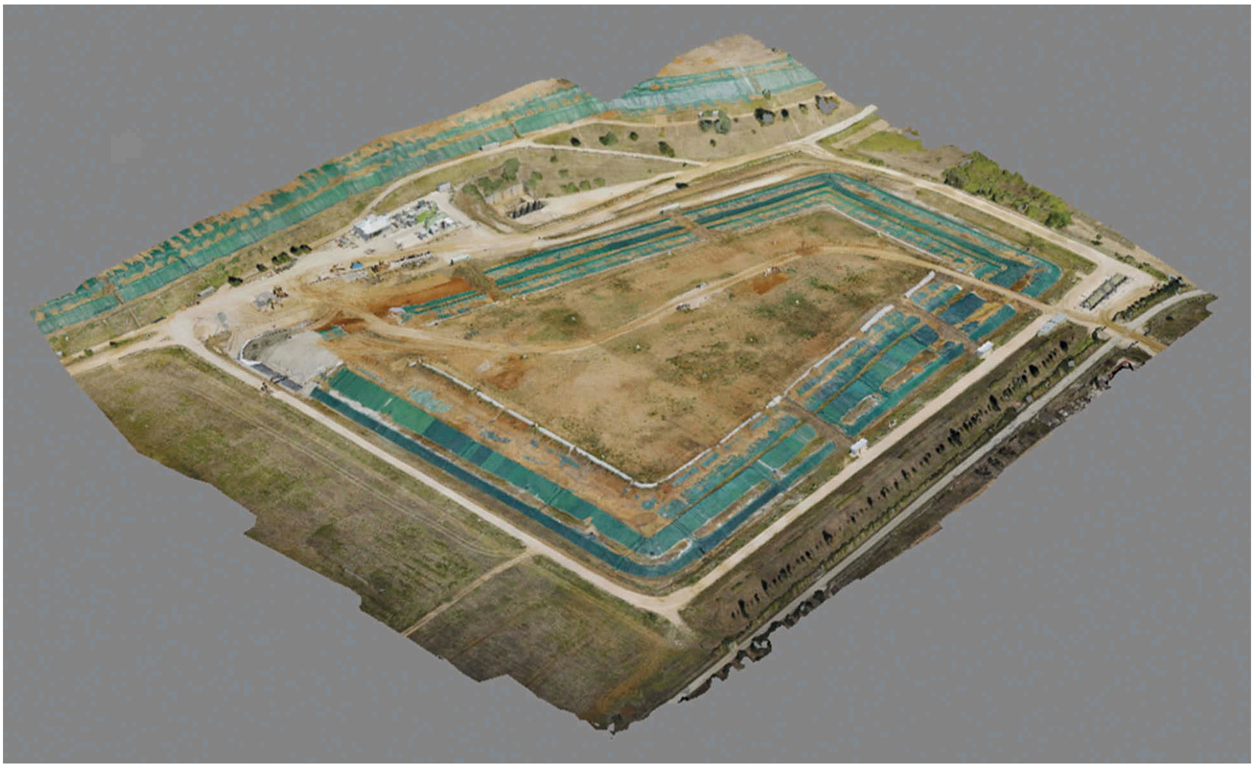

Figure 11. Obtained landfill morphology from second campaign images.

Discussion

The first results obtained allowed to observe numerical values of the difference between the two models very close to those surveyed with GPS survey proving that the accuracy that can be obtained is comparable with that of classic topographic surveys. At the same time, the comparison between the two-point clouds allowed

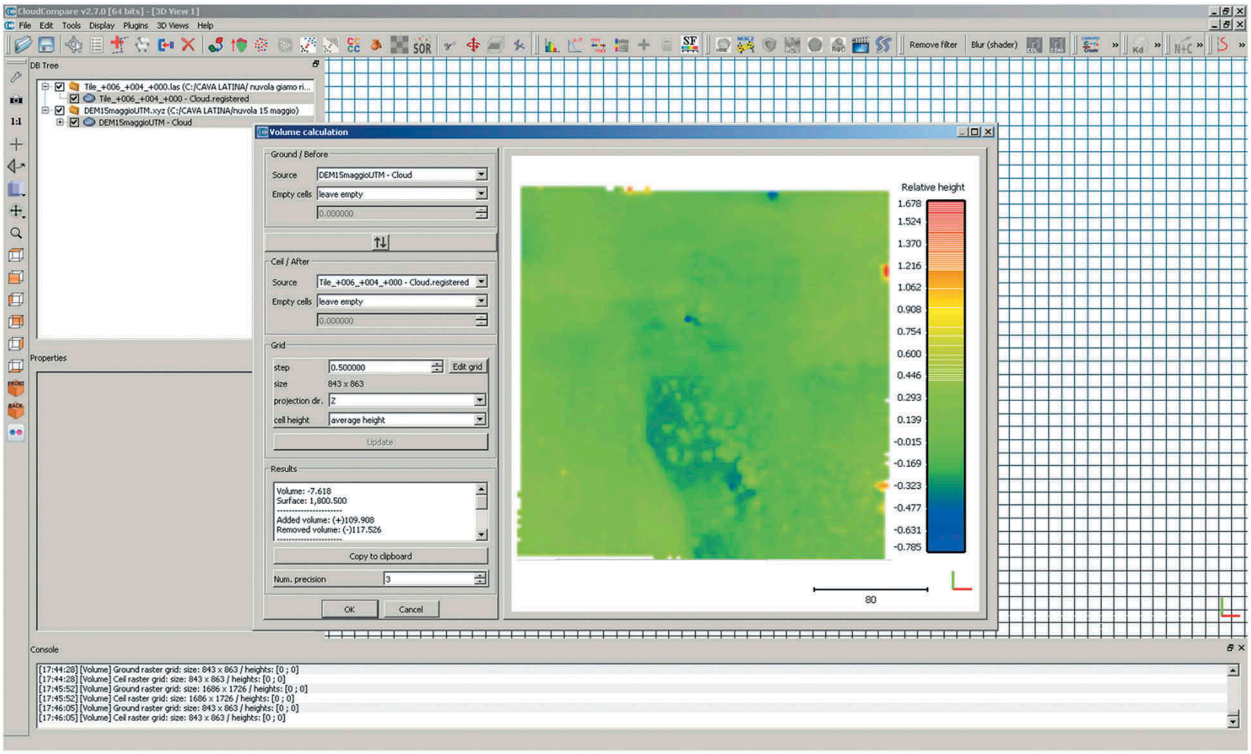

Figure 12. CloudCompare difference between first and second campaign models.

to observe local discontinuities that it would not have been possible to observe using only topographic measurements on individual points (Figure 12). This is certainly a strong point of the use of UAV DSMs in these applications because it would not have been possible to detect such changes with a classic topographic or GPS survey on single points since the interpolation can only be done linearly between a point and those adjacent.

Figure 12, therefore, shows the graphic representation of the distance values obtained on the Z-axis, which is the one we are more interested in for these specific applications. In the legend of the figure, we can observe both positive and negative values: positives can be read as “rising“ while negatives can be read as “lowering”.

Observing the legend of the values present on the right of the figure it is possible to notice how the landfill has undergone some localized big changes (blue areas) if compared to the rest of the variations that are contained in a range which order of magnitude is the expected. The variations closest to zero are those spanning the colour green and blue and we find them on the slopes with capping and on the roads outside the area. The internal road system is made up of incoherent materials, so it is possible that in a season it have undergone alternating phases of compaction and leaching due to weather events, rain, and wind and to the mechanical action of the vehicles or to their combination. The red areas, also located in a few areas, are due to rare positive variations, which are also some of the largest numerically, not compatible with those observed topographically and with the expected behaviour of the body of landfill; they are probably attributable to the effects of the interpolation on edges and to differences due to the presence of objects and vehicles not present at the time of the first survey.

Table 2. Height differences between surveyed points and corresponding differences between UAV DSM on the same planimetric positions.

GPS ΔH	UAV ΔH
0.145	0.197
0.128	0.177
1.19	0.234
0.43	0.451
0.475	0.476

The validity of the differences between the two models obtained from UAVs have also been correlated with the corresponding topographic measurements, for this purpose the absolute dimensions on the two models have been calculated on the same planimetric coordinates of the points detected by the plug-in “point sampling” of QGIS 2.18. The differences in height obtained were compared with the differences measured topographically in the two surveys closest in time: the deviations between the differences thus obtained were contained in maximum values of 8 cm (Table 2).To better assess the significance of these differences the correlation between the differences obtained by the survey and those obtained by photogrammetry, was calculated obtaining the value of 0.91235.

Conclusions and future developments

In the present work, the degree of reliability of the treatment of optical images has been investigated in order to monitor the morphological variations, especially vertical, that may occur in such a plant. The quantitative data, extrapolated from the optical images, have values comparable with the traditional techniques of survey. The accuracy obtained in the 3D reconstruction of the landfill survey showed values of less than ±10 cm, which are certainly more than enough for monitoring during the activity, it was also shown that the accuracy obtained were compatible with the most delicate phase of monitoring the settlement after the activity where the requests for accuracy are centimetres.

This specific application of UAVs can interest many actors, from the landfill operator himself to carry out the periodical survey according to the rules and to make more efficient the activities, to the public agency responsible for control.

In general, the results obtained can be considered positive both compared to specific landfill that compared to other types of conventional ground survey. The scientific literature available, as mentioned, is still lacking enough data for a more thorough comparison in a way this result is the first actual accuracy evaluation in this specific field. What can be said is that in general the use of UAVs for photogrammetric purposes in landfills can be further engineered and standardized. For example, the presence of permanent target on the ground, certain, allow the repeatability of the survey, which, as thought of in this study, is a necessary feature for accurate monitoring of the changes that the landfill body may undergo. Using a network of points such as the one used in this experiment, it is possible to obtain metrically correct results that are absolutely correlated with those of a traditional survey, but also areally representative of the dynamics of settlement, otherwise invisible with more traditional techniques. It is important to underline that a network of points such as the one realized here cannot be used for areas still in activity for obvious reasons of compatibility with the landfill operations.

However, it has been possible to make a rigorous assessment of the accuracy and precision of which few or no examples have been found in the literature. The differences of a few centimetres between the differences obtained from the two models acquired from different UAVs and processed with different software compared to the same differences measured with more accurate instruments confirm the validity of the approach. This is also confirmed by the calculation of the correlation between the two sets of data.

It is believed that the study and application of UAVs in the monitoring of landfills will develop in the coming years for its advantages, which are mainly the speed, cost-effectiveness and the ability to survey without having to access the site itself.

Disclosure statement

No potential conflict of interest was reported by the authors.

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