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Abstract

This paper presents the use of an Unmanned Aerial Vehicle (UAV) platform for the inspection and documentation of historical buried structures, starting from the landscape scale up to the local and detailed scale. The combined use of RGB and thermal images acquired from this kind of platforms, along with algorithms and procedures for data registration, can be a quick and powerful contact-less methodology to discover hidden structures. In this case study, the identification of buried remains needed the implementation of new algorithms able to register thermal images with the geometrical survey from RGB data. The georeferenced images (thermal orthophotos) were then used to inspect the ground and discover buried features.

1. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) are very common tools in different projects in the archaeological field and in the heritage sector. UAV platforms can be extremely useful in high risk situations without endangering the position of the researchers. Moreover, they can reach places that are inaccessible for men or that cannot be reached by manned systems. UAVs are also able to present real-time capability and fast data acquisition, which is becoming increasingly important in the current heritage sector. Several algorithmic implementations allow the user to process the acquired data in a fully automated way. In addition, their considerable small size, weight and operating system are a great advantage for conservation projects in case of transport, steering, processing of data, and economic considerations [1-3].

In the archaeological and heritage sectors their application is mainly focused on inspection, surveillance, mapping and 3D modeling, delivering data that can also be applied in other fields such as agriculture, environmental and landscape surveying, traffic monitoring, the real estate sector and 3D reconstruction.

The metric documentation of archaeological areas with UAV platforms is becoming more and more important. Particular attention is paid to the creation of three-dimensional models or more advanced Building Information Modeling (BIM) systems in order to obtain a comprehensive management structure and perform further analysis (e.g. the derivation of two-dimensional drawings and plans, vertical sections, etc., queries or the remote exploration of archaeological sites [4]).

The application of a UAV technology in documentation, observation and discovery of heritage sites has shown considerable results, opening up the field not only to aerial photography, but also laser scanning technology, thermal, and ultraviolet imagery. Nowadays the generation of RGB orthophotos, Digital Elevation Models (DEMs) and 3D models is mainly used for the inspection of sites or the documentation of archaeological excavations [5-10].

The scope of this research is to study the value and potential of a UAV as an instrument for documenting and analyzing a heritage site on both the detailed scale and the wider territorial scale by using both RGB and thermal images. The aim was not only the metric reconstruction from digital images, but also the inspection of georeferenced thermal images and their interpretation in order to discover buried structures. UAV technology provides new powerful instruments, especially if compared to satellite and aerial images: the metric resolution of UAV thermal data can reach sub-decimeter level, i.e. a value much better than that obtainable from satellite thermal images. In addition, the data acquisition campaign can be planned according to the local characteristics of the area, at different hours to inspect the ground without unwanted effects (such as shadows) by exploiting the best heating time, which may vary in different portions of the object depending on changes in its composition or exposure to sunlight. This is not feasible with satellite data that are, on the other hand, periodically available. This means that the analysis can be concentrated in small areas, starting from a territorial survey up to the single object following a cascade approach.

As thermal infrared cameras work in the bandwidth 3.5 μm < λ < 14 μm (Long Wave IR), they provide a visualization of thermal differences on the ground. The use of thermal images can be a new effective tool in this field of research that is still insufficiently explored but has a remarkable potential. Small thermal cameras are today available on the commercial market and allow the visualization of the temperature (or a quantity that depends on the temperature) and could provide more information than visible RGB photographic cameras. UAV thermography can be therefore intended as a contact-less investigation tool, where buried structures could be discovered by analyzing the local change of the measured temperature. This means that the work must combine the analysis of the radiometric information and the georeferencing of all the data to obtain a reliable estimate of the position where further and more detailed inspections should be carried out.

This paper focuses on the application of an UAV platform (Falcon 8) on Comacina Isle (Isola Comacina) in the Como Lake (Italy). The research considers the advantage of different scales and the possibilities of both RGB and thermal imagery to be up taken by a heritage information model. A detailed analysis with thermal images was carried out on areas of interest where some buried objects (supportive and defensive walls) were found, avoiding direct inspection techniques or other destructive tests

2. THE CASE STUDY

Comacina Isle (Fig. 1) is an island located in the Como Lake (Lombardy, Italy). Over the centuries, it had a pole position in the religious, politic and economic history of the region with remains dating back to the Roman and early Christian times until the Middle Ages, when it became a small fortified town on Como Lake. It is assumed that in the 12th century destruction struck the island and thus the island lost its dominant position [18]. However, remains of the later period indicate that the island was never totally deserted.

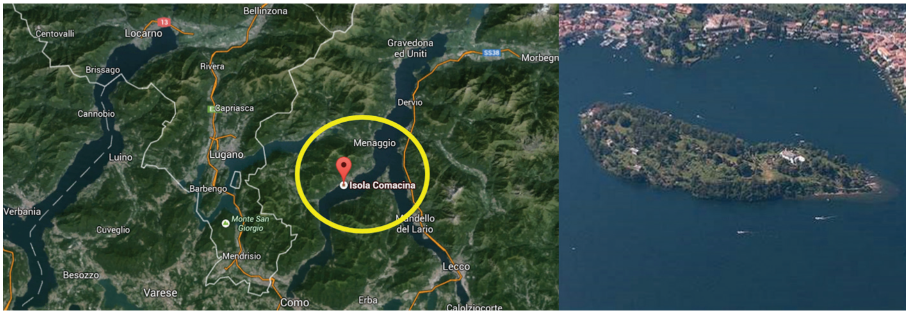


Figure 1. An overview of the archeological site of Isola Comacina

Comacina Isle takes an important position in the art-historical history of the area and of Italy, being claimed to be the birthplace of the 'Comacina art' that has influenced the Lombard and Romanesque art and building style of the 12th century. Especially interesting for such a small island is the position of an impressive amount of religious architecture, elaborated frescos and stuccos. In the 20th century the island came into the hands of a Belgian king, who passed it back to the Italian authorities and to the Brera Art Academy that has planned to make as island resort for artists. Today the island is a location for tourists with both historical and natural or environmental interests. The archaeological sites on the island are mainly religious remains; the complex of St. Faustino and St. Giovita,(parts of a Benedictine monastery), the church of St. Pietro in Castello, the church of St. Maria con Portico, the remains of the basilica of St. Eufemia with a beautiful arcade and a baptistery close to the contemporary church of St. Giovanni. The original church of St. Giovanni was destroyed in the 12th century and a new church was built in the same place in the 17th century. During the survey, the interest was focused on the archaeological remains of St. Pietro in Castello, the basilica of St. Eufemia (next to the church of St. Giovanni) and a small hilltop to the north of the church of St. Giovanni. The potential of the employment of the UAV devices (with the collection of both RGB imagery and thermal imagery) was to study the importance of different metric scales and the implementation of an integrated approach that combines several surveys and documentation techniques.

3. DATA ACQUISITION AND PROCESSING

The photogrammetric survey of the site was carried out with the UAV platform AscTec Falcon 8. The system is equipped with an RGB camera Sony NEX-5N and a thermal camera FLIR TAU 640, photogrammetrically calibrated. The Falcon 8 (70 cm x 60 cm, weight 2 kg) is equipped with 8 motors and is able to fly up to 20 minutes with a single battery. The electronic equipment includes a GPS antenna and a system of accelerometers determining the system roll, pitch and yaw. The communication system allows the ground station to receive telemetry data and video signals from the onboard sensors. Image acquisition for the site St. Eufemia was divided in different phases in order to optimize flight time (Fig. 2): a larger area corresponding to the remains of the church of St. Eufemia (Site A - about 40x70 m) and another one (about 25x60 m) that includes the remains of the baptistery (Site B). RGB image acquisition was carried out by using different heights above ground. The first flight had a height of about 30 m and provides ground coverage of about 30x45 m. The second flight (height ca. 50 m) had the primary aim to strengthen network geometry. The planned image overlap was about 80%, while overlap between consecutive strips was 60%. A total number of 50 images were taken for the first site, 42 for the second one. Before flying, 24 targets were materialized on the ground by using rigid black and white marks homogeneously distributed in the area. They were used as Ground Control Points (GCPs) and check points (CPs) to register the photogrammetric project [11-16].

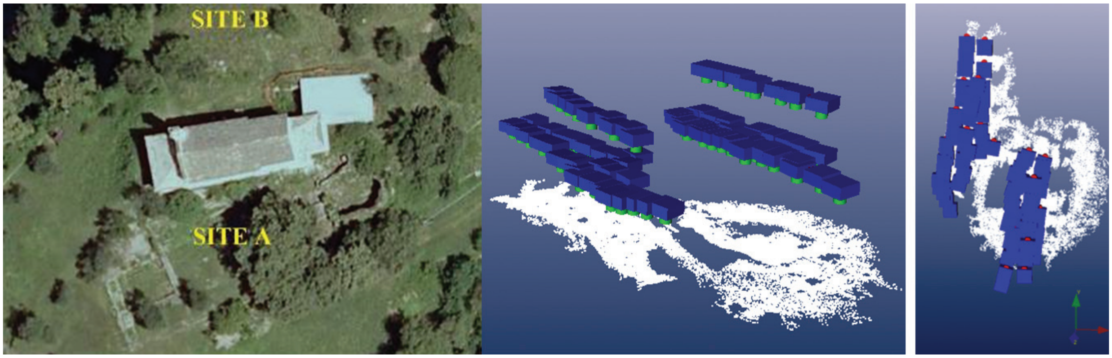


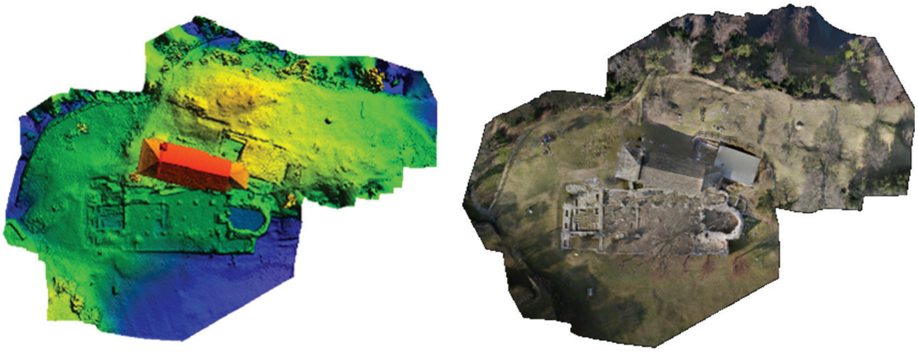
Figure 2. Sites and 3D visualization of orientation results (camera positions)

Automated triangulation of UAV images (bundle adjustment) is today a topic of great interest. In our work we integrated two commercial software: PhotoModeler 2012 for image orientation and Agisoft PhotoScan for Digital Elevation Model (DEM) and orthophoto generation. Two distinct packages were employed as they offer the same functionalities (image orientation, DEM extraction, etc.). Initially, images were oriented with PhotoScan but results were not satisfactory. The software allows a fully automatic image orientation in an arbitrary reference system and scale. Once images are oriented, GCPs can be manually measured and their coordinates in the ground reference system assigned. In this way the photogrammetric block is referenced in the ground reference system.

On the other hand, the obtained RMS values of GCPs were 29.8 mm, 26.9 cm and 55.1 mm in the X, Y and Z directions. These large values are also probably due to the limited overlap between both blocks (site A and B) and a residual network deformation. It should be mentioned that GCPs are not only useful to fix a reference system, but they can control network deformations.

Image orientation was therefore repeated with PhotoModeler 2012 and its automated triangulation routine termed SmartMatch. Image orientation was firstly performed with a free-network adjustment by using more than 128,000 tie points identified by SIFT algorithm. Then, some additional tie points were measured in the overlap area between the Sites A and B. Finally the exterior orientation parameters were computed by using the GCPs, reorienting all the images. Here, bundle adjustment was intended as orientation process where GCPs are included as pseudo-observations, weighted according to geodetic network precision (not only a 7-parameter transformation). GCP image coordinates were measured in a semi-automated way by using the Least Squares Matching (LSM) algorithm. The new LS adjustment gave a sigma-naught of 0.51 pixels and residuals on 12 check point coordinates (Root Mean Square Deviation- RMSE - values) of 4.7 mm, 5.6 mm, and 8.7 mm, X-Y-Z respectively.

Figure 3. DEM and RGB orthophoto



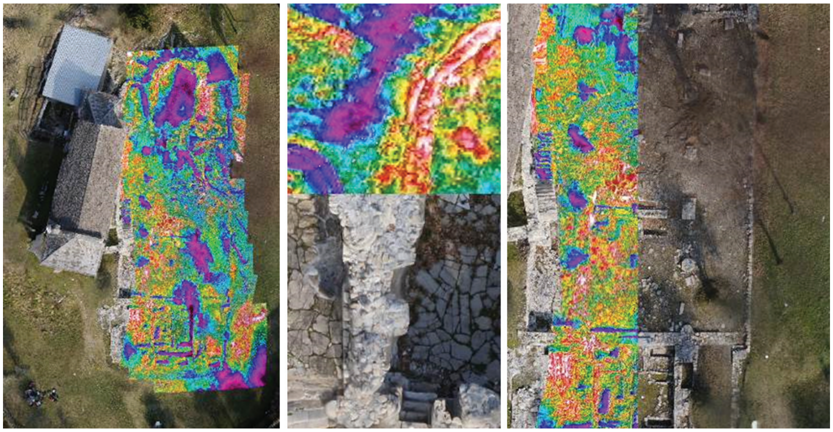
Starting from the estimated exterior orientation parameters a DEM was generated. External Orientation (EO) parameters were transferred to PhotoScan to run its multi-view reconstruction algorithm in order to obtain high quality 3D models. The parameters for geometry generation were set by fixing a maximum number of 5 million faces. Once the 3D triangulated model was generated, the DEM was obtained by setting a grid size of 3 cm (Fig. 3). Finally the orthophoto of the entire area was derived with a resolution of 9 mm.

4. THERMAL DATA REGISTRATION: FINDING BURRIED STRUCTURES

As mentioned, the study not only focuses on single objects within the site (or parts of the site), but it includes wider geological and topographic aspects. A part of the research considered the use of thermal imagery. For example, this type of imagery can help to discover rock formations partially buried. It is well-known that the inhabitants of the Comacina Island needed to interfere with the topography of the island and cut out their houses in the slopes of the rock-hard local stone called 'moltrasio'. Remnants of these activities can be found all over the island, as well as buried remains of the fortification system (http://www.isola-comacina.it).

In this work thermal images were turned into georeferenced products (orthorectification) in order to combine radiometry (temperature) and metric data. Different levels of thermal data processing (image orientation and thermal texture mapping) were employed. The first level (said level 1) provides accurate thermal orthophotos by means of a combined bundle adjustment of RGB and thermal images. This procedure is feasible because the thermal camera was photogrammetrically calibrated beforehand (Internal Orientation and additional parameters). The methodology here described uses both thermal and RGB images in a global photogrammetric bundle adjustment. The procedure is derived from an implementation for IR thermography of buildings [17] and it starts with the acquisition of a preliminary set of RGB images with a calibrated camera, where it is necessary to consider the overlap between consecutive images. RGB images are then oriented with standard photogrammetric methods from a set of image correspondences (tie points and ground control points to remove the rank deficiency: 7 parameters). Tie points should guarantee not only a good distribution in the images in order to provide reliable orientation results, but also the possibility to orient all thermal images in a new adjustment project. This means that tie points should be measured in correspondence of elements that are visible in thermal data. In addition, as thermal images have a limited field of view, the manual measurement of many tie points is highly recommended, even though this can lead to a longer processing time. The method can be therefore intended as a first project with RGB images only. Then thermal data are added by measuring the image points already available in 3D. A final bundle adjustment including all data is finally carried out to obtain the exterior orientation parameters of all images. There are some considerations to better understand the potential of this bundle formulation. First of all, the linearized model can be solved via Least Squares, and its solution is rigorous in a functional and stochastic sense. Then, thermal and RGB are employed together in order to obtain more precise and reliable results.

Figure 4. Thermal and RGM orthophotos derived from rigorous UAV image triangulation (RGB+thermal - level 1) for the site St. Eufemia



The main limit remains the manual measurement of many tie points, more than those strictly necessary for a standard photogrammetric project. In addition, the object must have a good texture where distinctive elements are visible in both thermal and RGB data. On the other hand, this combined orientation strategy has the main advantage to strengthen the network geometry and allows an estimation of orientation parameters much better than those obtainable with standard space resection techniques. In this adjustment the target coordinates (surveyed with a total station) were used as Ground Control Points (visible in both categories of images) in combination with some tie points extracted from both RGB and thermal images. Sigma-naught was about ±0.8 pixels and allowed to obtain a detailed thermal orthophoto for the church of St. Eufemia (Fig. 4 shows global overview and a detail).

An alternative approach (level 2) was used for the sites St. Pietro and Hilltop 1. As the terrain is relatively flat, the resolution of thermal images is quite limited, and other external information was not available (e.g. 3D target coordinates measured by total station or GPS) a solution based on a 2D independent model adjustment was implemented by using a multi-image affine as geometric transformation. A color orthophoto was derived from a block of RGB images acquired with the Falcon 8. Then, georeferencing of thermal imagery was based on both artificial targets and natural points measured on the high resolution RGB orthophoto. Points were used to estimate transformation parameters from which a georeferenced thermal mosaic was generated (Fig. 5).

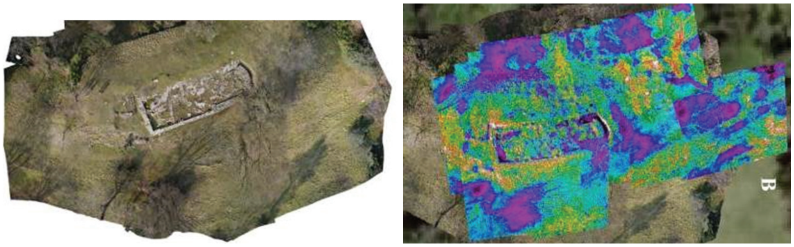


Figure 5. RGB and thermal orthophotos for St. Pietro in Castello derived from an multi-image affine-based Least Squares adjustment (level 2)

The combined inspection of both thermal and RGB images in a GIS allowed one to (re)discover buried traces. In particular, for the site of St. Pietro in Castello, the IR imagery helped to better outline a defensive or supportive wall running parallel with the longitudinal axis of the former church (Fig. 6). On the site Hilltop 1, it was confirmed by literature that several wall structures were uncovered during previous excavation campaigns, but they were not visible because of a new vegetation layer and they were 'forgotten' (Fig. 6). The use of thermal images from UAVs could be a valid support to determine the location and layout of these structures.

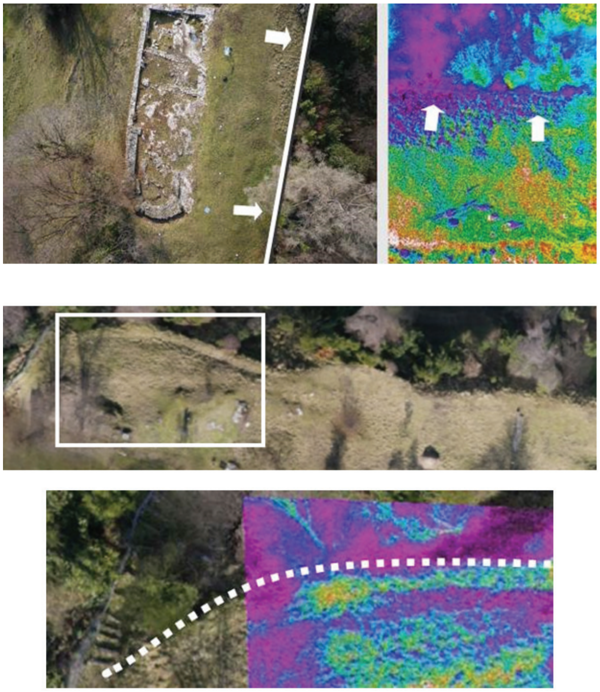


Figure 6. Remains of a (supportive/defensive) wall for the site St. Pietro in Castello (top) and remains of a (supportive /defensive) wall for the site Hilltop 1 (bottom).

Finally, the last level (level 3) is simply based on a rapid and approximate georeferencing based on the extraction of corresponding points directly on thermal images and the estimation of an affine transform for each image. Data processing is supported by the low quality GPS path to obtain georeferenced results. This methodology has some limitations in terms of metric accuracy but it was necessary for the inspection of the site when the area was inaccessible.

5. CONCLUSIONS

This paper presents the use of Unmanned Aerial Vehicle (UAV) images for the documentation of the site of Isola Comacina and the inspection of structures buried in the ground. The images depict not only standard RGB data, but also thermal ones acquired with a compact sensor for IR thermography. Thanks to these additional UAV data, more research can be done regarding the topographic situation and location of the whole island and its sites, the connection with the mainland (harbor areas) and of course the (re)location of known and unknown sites still buried (the whole island used to be a vivid city). Different solutions for the orientation of thermal data were illustrated and discussed. These different methodologies were needed because of the different local characteristics of the island. For this reason, the proposed algorithms rely on rigorous photogrammetric approaches (photogrammetric bundle adjustment incorporating RGB and thermal images), independent model registration based on an affine transformation or fast georeferencing from UAV trajectory parameters including some corresponding feature points, i.e. rigorous and reliable methodologies or quick and 'quasi real-time' solutions. The use of UAV images allows identifying the position of some remains buried in the ground. This result is extremely important and opens the scenario of additional UAV thermal inspections including the implementation of ad-hoc algorithms not only for the registration phase (like those presented in this work), but also for the automated analysis of the radiometric value stored inside thermal data. Integration with other data sources (such as satellite and aerial thermal and optical data) will be considered in future work in order to find and establish a robust processing workflow between data captured on-site and those periodically available. New analysis will be carried out and include the comparison and accuracy evaluation of these new observations with historical, thematic and other material data in order to validate the historical and stratigraphic interpretation along with new thermal inspections from both UAV and at ground level.

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