Gathering GPR Inspections and UAV Survey in Cultural Heritage Documentation Context

Alessandro Arato[2], Flora Garofalo[2], Giulia Sammartano[1] and Antonia Spanò[1]
[1](DAD) Department of Architecture and Design, Politecnico di Torino, Torino, Italy
[2](DIATI) Department of Environment, Land and Infrastructure Engineering, Politecnico di Torino, Torino, Italy

Keywords: UAV Photogrammetry, Ground Penetrating Radar (GPR), Historical Maps, GIS, Cultural Heritage.

Abstract: The archaeological researches and more generally the Cultural Heritage (CH) documentation and conservation activities have been favourably disposed to the use of new technologies, with renewed and increasing interest in the use of integrated techniques.

In the field of Geomatics the advent of advanced technologies has allowed and facilitated multidisciplinary studies as well as combined approaches to the documentation in various contexts. The production of spatially located data (e.g. from active or passive sensors placed in different system segments, from terrestrial to aerial to satellite position) and their interoperability from different source, with the help of Geographic Information Systems (GIS), were then made easier.

The work has the aim of investigating the integration of multiple data derived from aerial photogrammetry products through Unmanned Aerial Vehicles (UAV) survey, from geophysical Ground Penetrating Radar (GPR) prospection technique and analysis of historical maps. An archaeological area in the south of Piedmont (Italy), next to the ancient Roman settlement of *Pollentia*, has been the test case. The present fulfilled test was objected to exclude ancient presences, although this type of workflow is generally aimed to analyse and compare results in order to formulate some hypothesis about the potential presence of submerged elements or built substructures in the investigated area.

1 INTRODUCTION

Adding to the widening of cultural assets typologies subject to the safeguard aims, ranging from ancient to modern heritage, from architectural to landscape, and from mobile assets to intangible cultural heritage, the increasing challenges of CH conservation has given rise to an incessant specialization of methods involved in the protection projects. This trend has become visible in data collecting and survey, data archiving and structuring, and finally in communication and dissemination processes. Some features are increasingly requested to acquisition techniques: mainly 3D nature of data, quick acquiring and low cost solutions, keeping high accuracies and overall quality. On these bases, the present paper wish to investigate the integration of strengthened techniques as Ground Penetrating Radar purposed to search possible submerged archaeological remains, with emergent methods for quick large-scale mapping, generated from UAV photogrammetry. Moreover the examination of historical maps, generally highly significant in this kind of project, have been compared and commented by GIS tools in final results.

2 METHODS

2.1 UAV Photogrammetry

The UAV photogrammetry has developed very rapidly whereas it is able to fulfil successfully the large-scale maps updating in many fields such as environmental, CH applications. (Haala et al., 2011)

One relevant strong point of UAV systems for photogrammetry is the nadiral point of view connected with the ability to choose the height of flight depending on the requested scale of survey. The low cost, the high handily with contained playloads, and the ability to perform autonomous flights starting from a predefined flight plan, are other decisive advantages. Navigation sensors such as GNSS receivers (Global Navigation Satellite System)

Arato, A., Garofalo, F., Sammartano, G. and Spanò, A.
Gathering GPR Inspections and UAV Survey in Cultural Heritage Documentation Context.
In *Proceedings of the 2nd International Conference on Geographical Information Systems Theory, Applications and Management (GISTAM 2016)*, pages 85-91
ISBN: 978-989-758-188-5

and inertial sensors (IMU, Inertial Measurement Unit) are conveniently integrated; the effectiveness of the whole system depends from the balance of their accuracy and reliability with the *Flight control* device. (Rinaudo et al., 2012)

The product of UAV photogrammetry consists in a set of images from which it is possible to extract point clouds, 3D textured models, Digital Surface Model (DSM) and Orthophoto the processes are mainly automated by an image matching technique, so it's clear the reasons of increase.

In the next experience the only ortophoto will be used, which is absolutely the most automated product that is possible to derive, and this is one of the main reason of the method choice.

Structure-from-Motion (SFM) systems allow estimating the 3D position of points represented in multiple images, reconstructing the geometry of the represented object (*structure*) and the acquisitions position (*motion*), even when are not available the defined camera calibration parameters. The characteristic elements (*tie-features*) of images are automatically preliminarily extracted; in particular they are extracted objects (*points*) recognizable by the software thanks to the radiometric contrast in different directions, which identifies unambiguously the pixel. One of the most common algorithms for features identification and description for the association and the consequent orientation of images in photogrammetric software and computer vision is SIFT (Scale-Invariant Feature Transform). (Lowe, 2004; Szeliski, 2011)

In the next step of *feature matching*, points with more similar descriptors (recognized by the software as homologous) are aligned to make the next step of triangulation - *bundle adjustment*.

In SFM processes the orientation parameters are not necessarily known; so, using the rules of the epipolar geometry, which regulates relations between the *tie points* (TP), the acquisition centers and the point 3D position, to direct acquisitions and estimate internal and external orientation.

Figure 1: Two example of unmanned vehicles, the ones used in the further test: hexacopter by Mikrokopter and Ebee by Sensfly.

2.2 GPR (Ground Penetrating Radar) Survey

GPR method is based on the generation of an electromagnetic (EM) impulse through a signal generator, connected to a transmitting antenna (Tx) and a receiving antenna (Rx). The GPR systems work in the frequency range between 10 MHz and 3 GHz. The choice of the system frequency is essential and has to be made according to the scope of the survey. In fact, being the frequency inversely proportional to the wavelength, lower frequencies imply deeper signal penetration but lower resolution, while higher frequency allow the increase the resolution but reducing the signal penetration.

In archaeological researches, GPR survey is used in order to correlate electromagnetic impedance contrasts to possible submerged remains.

The electromagnetic discontinuities (or dielectric interfaces), act as signal reflectors, refractors and diffractors, via multiple mechanisms (e.g. Davis and Annan, 1989; Reynolds, 1997). Soil specific characteristics, like structure and texture, mineral composition, pore-fluid distribution and chemistry, influence the signal penetration as well (e.g. Sen et al., 1981; Friedman, 1998; Cosenza et al., 2003). Each reflection implies an energy loss, and the received signal is strongly attenuated with respect to the constant transmitted signal. Common GPR surveys are carried out along profiles, with the aim of obtaining 2-dimensional (2-D) sections of the subsoil. A radar profile is a composition of all the recorded signals, called traces, and allows to understand the subsoil inhomogeneity, or dielectric interfaces. In archaeological context, the analysis of a single profile is not sufficient, and a 3-D survey must be done to map the lateral discontinuities. The results are usually presented in the form of time-slices, horizontal maps at constant time (or depth).

2.3 Historical Maps Contribution and Their Spatial Reference

The success of the GPR survey is highly affected by the prevision of searched remains. The shape of possible submerged building elements related with the period of construction and especially the depth at whom they are expected to be found are very relevant in order to correctly plan the parameters of GPR survey. Then a panoramic examination of historical cartography is usually highly advisable.

The geometric and projective characteristics and properties of early cartographic representations have been largely studied when digital technologies have spread new perspectives for the visualization in the same spatial reference of recent maps. (e.g. Livieratos, 2006; Balletti, 2006).

Many research projects has directed efforts towards the use of GIS techniques of calibration, georeferencing and transformation of projection, for enabling the comparison among historical and actual maps.

In brief, the relation among the points coordinates of historical maps that have been transformed in image coordinates and the homologous coordinates in recent reference system are searched by Ground control points, derived by GPS survey or digital recent maps.

3 THE EXPERIENCE ON THE ARCHAEOLOGICAL AREA

The site under investigation is a plot of about 200 x 200 m; the area is flat, with some irregularities and some obstacles but the key point is the proximity to the ancient Roman settlement of *Pollentia*, the most ancient city of Tanaro Valley in South Piedmont. Archaeological researches lightened that the roman village was extended south to the roman amphitheatre, currently visible because of the village developed upon it. (Figure 2, 3). (Spanò et al., 2007)

Since the plot is placed close to the road for *Alba Pompeia*, some funerary remains or burials were the only ancient elements that were reasonably expectable to be found.

Figure 2: Excerpt from the orthophoto IT 2000 - Piedmont Region and highlighting the involved lot.

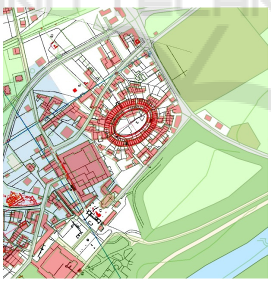


Figure 3: The Pollentia large-scale archaeological map superimposed on the regional digital map.

The site presents a plantation of walnut trees, arranged in the 1960s, so the usually desirable maps or aerial photograms recognition aimed to search crop-marks was in this case to be discarded. Therefore, the GPR survey, spatially located by the UAV photogrammetrical application, was performed according to the next report and after results some historical maps have been useful to complete the reading.

3.1 Photogrammetric Survey of Lot 2076 in Pollenzo by Drones

The first purpose of the photogrammetric flight on the Pollenzo 2076 lot was exactly the fast generation of a high resolution ortophoto, using aerial photos acquired contemporary to GPS survey in order to keep easily the spatial reference of GPR profiles. Actually two flights have been fulfilled by two different systems: a fix wing drone performing a 120 m height flight (*Ebee SenseFly)* and a hexacopter drone (by Mikrokopter) for a lower flight ensuring higher resolution. Provided that the two aircrafts are featured by different maximum altitude, maximum flight time, radio link range etc. they share important abilities for mapping purposes. Mainly it is the automated plan flight that is based on waypoints: that enable to foresee all parameters in order to acquire perfectly planned photogrammetric strips, including the desired overlapping and ground sampling distance.

The setting up of a topographic network and the measure of control points by GPS/GNSS techniques preceded the flights, guaranteed the processing of the orthophoto in the reference system of regional maps (WGS84-ETRF2000) and ensured the required accuracies.

The digital camera Sony Nex 5 acquired the large amount of aerial photos, reduced to 104 through a automated selection procedure; those photos with an overlap between consecutive frames of more than 90% are very suitable for a SfM approache.

Photogrammetric orientation and ortophoto generation results:

- 104 photograms
- ground resolution: 0.03 m/pix,
- Camera stations: 104,
- Tie-points: 21122,
- Medium error on GCP: 0.06 m,
- Medium error on CP: 0.13 m

3.2 GPR Data Acquisition and Signal Processing on Lot 2076

The survey was conducted along parallel lines, keeping at least 1 m of distance from the trees. The tree roots have a significant influence on signal penetration, as they act as diffractors and tend to scatter the signal in several directions. The site was almost plain, with obstacles (trunks, branches, soil accumulations) and some irregularities. A muddy upper soil layer (5 cm) was present over all the area.

GPR data were acquired along 84 parallel profiles, covering a total area of 2000 m^2 (Figure 4). 50 profiles, having 66.5 m length, were acquired along NW-SE direction, while the remaining 34 profiles, along SW-NE direction, were 40 m long.

The inter-profile distance was 0.6 m (except 3 m gaps in correspondence of the tree rows), in order to guarantee a spatial coverage, adequate to expected size of the remains.

Figure 4: Acquisition profiles on orthophoto: blue and red lines indicate, respectively, NW-SE and SW-NE profiles.

GPR survey was conducted by using IDS K2-MCH radar system, with 70 MHz and 200 MHz antennae, and an integrated survey wheel encoder. Each trace was sampled in-time, over a sampling window of 120 ns, with 1024 samples. A single radar trace was acquired every 3.5 cm along the profiles.

An example rawdata profile (acquired along NW-SE direction, y=0 m), is shown in Figure 5.

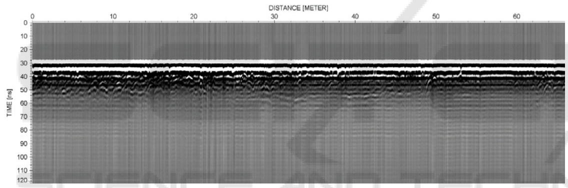


Figure 5: Example of raw GPR profile, (NW-SE direction, y=0 m).

Following a preliminary rawdata analysis, we decided to process only the data acquired with the 200 MHz, which were more focused on the target depths (down to 1.4 m) and had the necessary resolution to discriminate possible targets.

The example profile shows the main bang (main reflection at ground-antenna interface), several diffraction hyperbolae (10-20 ns), and some continuous reflections (25.30 ns, at distance between 0-20 m and 30-50 m). At higher times, ringing signals mask the presence of other possible reflectors.

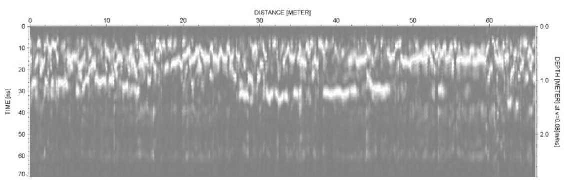


Figure 6: Example of resulting GPR profile, (NW-SE direction, y=0 m).

Each profile has been processed for reducing the noise and extracting the significant signal features. Low-frequency noise filter, move start-time, trace migration and band-pass filter have been applied to extract the resulting profiles. An example is shown in Figure 6. White features correspond to the stronger amplitudes of reflections, which can be associated to the anomalies present at the site.

Time-to-depth conversion, for each profile, has been done by imposing a wave velocity of 0.08 m/ns. This value is a reasonable approximation of GPR wave velocity in sedimentary soils, (fine sands with high water content, silty sands, silts, etc.). The Italian Geological Survey identifies the soil at Pollenzo site as clayey-sandy alluvial sediments (Carta Geologica d'Italia, Foglio n° 68, Carmagnola, 1:10000).

3.3 Results and Comparison

The processed profiles have been combined in 3D volumes of amplitude of reflection of the GPR signals, and several horizontal time-slices have been extracted. From the analysis of data, the following considerations can be made:

- Incoherent reflections and diffractions are present the depth range between 0 and 0.8 m, caused by coarse gravel, blocks and the roots;
- In the depth range between 0.9-1.3 m, a high-amplitude area is present; marked with *white* lines. It is referred to as "Anomaly 1".
- Two continuous reflections, located along WNW-ESE direction (*black* line), and SW-NE direction (*red* line) can be identified. These two anomalies are referred to, respectively, as "Anomaly 2" and "Anomaly 3".
- At higher depths, below 1.5 m from the surface, no significant anomalies can be identified. This is caused by the limited signal penetration in this particular context.

The spatial reference of time-slice was related during the analysis phase to a local coordinate system, with the origin is located at the top left corner of the area. Since the time-slice can be displayed ad a tiff image format, the cartographic reference has been assigned by a simple rototraslation function, easily manageable and imposed in *tfw* file. (Figure 7).

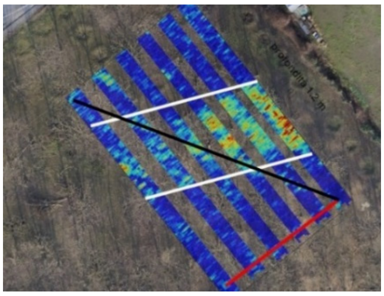


Figure 7: Superimposition of time-slice at 1.2 m of depth on orthophoto, with main anomalies derived from geophisical prospections highlighted.

3.3.1 Historical Cadastral Map

The more significant historical maps of new era for Piedmont territory is the “Carta Generale de’ Stati di S.A.R.” di G. T. Borgonio (1680). This map represent the beginning of a systematic knowledge course of estates by means of cartography. It correspond to a renewed will of administrative and military control of the land (Ricci, Carassi, 1986), but certainly the map scale is not proper for parcels positioning. In the political framework of strengthening of Savoy State, starting from the beginning of the XVIIIth century, the territorial fiscal control has been launched by the cadastral registry and maps.

The “*Catasto antico sabaudo*” achieved during the XVIIIth century underwent a precise enhancement with the French real estate Registry of 1802-1814. This new map had to be harmonized to the new French map of Cassini, having the same scale.

Figure 8: French particles calastral map (1810), *Section Xx de la Comune de Brà, portion A*.

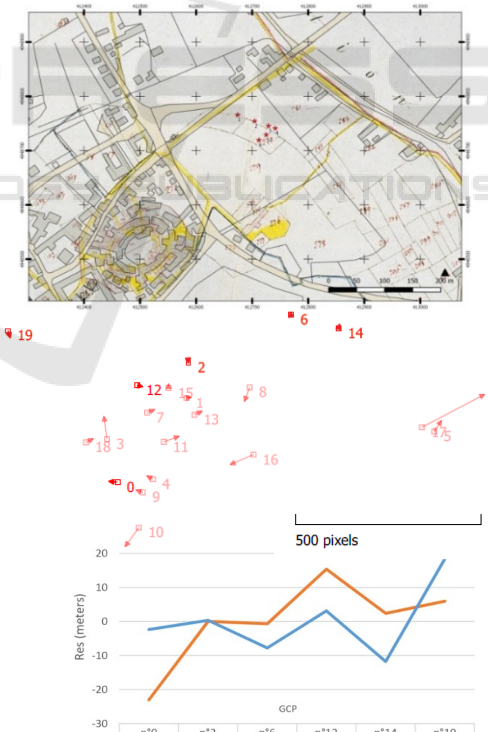
It’s not possible to know many information on map accuracy; we know that during the XVIIIth century the Snellius triangulation has been largely adopted and near the 60’s of the XVIIIth century the studies aimed to the ellipsoid determination started within the astronomical observatory of Turin in order to calculate the degree (*Gradus taurinensis Augustæ Taurinorum,* cited in (Frasca, 2004)). Moreover, as fundamental basis of the whole Piedmont topographical triangulation, the straight royal road connecting Torino with Rivoli has been chosen.

The interesting aspect represented in the French map is a different parcels partitioning as compared to the current situation.

A seven parameters Helmert transformation (1) has been used in order to provide a spatial reference to the French map and compare the position of GPR anomalies with the position of the no longer existed parcels.

$$X_p = T\ 1R\,(a_1,\ a_2,\ a_3)\,u_P \qquad (1)$$

Figure 9: Time-slice and related anomalies referenced to UAV ortophoto, superimposing regional orthomap.



	n°0	n°2	n°6	n°12	n°14	n°19
Res X	-23.0239	0.0276	-0.6915	15.3614	2.3927	5.9337
Res Y	-2.3404	0.3268	-7.7426	3.1216	-11.7433	18.3778
Spatial vector	23.1425	0.3279	7.7734	15.6753	11.9846	19.3120

Figure 10: (upward) Transformation of French map using points selected from regional medium scale map. (center) Directions of residual vectors, in red, and (bottom) least square residuals on points.

The best dozen of points selected on historical map and most probably still existing, have been used to perform the transformation. The least square residuals calculation provide an uncertainty of points coordinates near to 20 meters, which is exactly the distance between anomalies and historical parcels division. (Figure 10 and graph)

4 CONCLUSIONS

Spatial location and GIS tools have accomplished the complete comparison among geophysical and historical data.

The geophysical survey permitted to locate some GPR anomalies that could have possibly been attributed to archaeological remains. The joint geomatic-geophysical survey, with the help of historical maps recognition and analysis, permitted to locate and geo-refer the geophysical anomalies, and to describe their nature more reliably. A successive excavation activity confirmed that the different anomalies are attributable to geological and sedimentological discontinuities. Anomalies at point 2 and 3 are then to be linked to a paleo-channel of Tanaro River, which had a high flow velocity and could transport gravel particles and blocks. Anomalies at point 1, 4, 5 and 6 are attributable to sand and fine gravel accumulations due to natural flow patterns or to anthropic channeled flows within small irrigation channels, which served at that time to partialize the different soil plots. This last seem to be perfectly confirmed by historical map.

Many times the use of GPS/GNNS survey and polynomial transformations enable to reduce the effects of deformation of sheet maps and those due to the different systems of representation and measurement (Baiocchi and Lelo, 2010). Furthermore, on these basis many project of accessibility of historical cartographic heritage through the web have been fulfilled enabling the visualization from Web services. (e.g. Brovelli et al., 2012).

The enhancement of points residuals after historical maps transformation is surely achievable by ground measures, but this is profitable if the historical maps are recent and drawn by systems which are comparable with modern methods.

Some considerations upon methods can be underlined: now the image standard formats are highly interoperable, since geophysical, historical maps, and UAV products can be visualized in the same reference system. UAVs related to SfM technique provide 3D spatial data remarkably improved in the large scale environment and their products fit a very large set of needs.

ACKNOWLEDGEMENTS

Diego Franco from ENGEL-Environmental-Engineering Geophysics Laboratory took part to the field GPR survey. The UAV flights have been performed by the DiRecT Team (Disaster Recovery Team), involving Aicardi, I. Boccardo, P. Chiabrando, F. Donadio, E. Lingua, A. Maschio, P. Noardo, G. Sammartano, F. Spanò.

REFERENCES

Balletti, C., 2006. *Georeference in the analysis of the geometric content of early maps*. *e-Perimetron* 1(1), pp. 32-42.

Baiocchi ,V., Lelo, K., *Accuracy of 1908 high to medium scale cartography of rome and its surroundings and related georeferencing problems*,Acta Geodaetica et Geophysica Hungarica, 2010, 45,1, 97-104.

Brovelli, M. A. Minghini, M. Zamboni, G. 2012. *Valorisation of Como historical cadastral maps through modern web geoservices*. ISPRS Annals, I-4, pp. 287-292

Frasca F., 2004, *Le attività degli ingegneri geografi francesi nei territori italiani in età napoleonica*, Informazioni della Difesa, I.

Haala, N., Cramer, M., Weimer, F., Trittler, M., 2011. *Performance test on UAV-based photogrammetric data collection*. ISPRS Archives, *Vol. XXXVIII-1/C22*.

Livieratos, E., 2006. *On the study of the geometric properties of historical cartographic representation. Cartographica* 41(2), pp. 165-175.

Lowe, D., 2004. *Distinctive Image Features from Scale-Invariant Keypoints*, Int. Journal of Computer Vision, Vol. 60, pp. 91-110.

Cosenza, P., Camerlynck, P., Tabbagh, A., 2003. *Differential effective medium schemes for investigating the relationship between HF relative dielectric permittivity and water content of soils.* Water Resources Research 39, 1230.

Davis, J.L., Annan, A.P., 1989. *Ground-penetrating radar for high resolution mapping of soil and rock stratigraphy.* Geophysical Prospecting 37, 531–551.

Friedman, S.P., 1998. *A saturation degree-dependent composite spheres model for describing the effective dielectric constant of unsaturated porous media.* Water Resources Research 34, 2949–2961.

Reynolds, J.M., 1997. *An Introduction to Applied and Environmental Geophysics*. John Wiley & Sons, NY.

Ricci Massabò, I, Carassi M., 1986, *Amministrazione dello spazio statale e cartografia nello stato sabaudo*, in MIBAC, Uff. Beni Archivistici, (ed), Cartografie e Istituzioni di età moderna, Genova.

F. Rinaudo, F. Chiabrando, A. Lingua, A.T. Spanò. 2012. *Archaeological site monitoring: UAV photogrammetry can be an answer.* In: ISPRS, vol. XXXIX n. B5, pp. 583-588.

Sen, P.N., Scala, C., Cohen, M.H., 1981. *Relation of certain geometrical features to the dielectric anomaly of rock*s. Geophysics 46 (12), 1714–1720.

Spano' A.; Bonora V.; M.C. Preacco, 2007, *Geomatic contributions to archaeological investigations.The case of Torrione of Pollenzo (Piedmont – Italy)*, ISPRS Archives, Vol. XXXVI-5/C53.

Szeliski R., 2011. *Computer Vision: Algorithms and Applications*, Springer, London. pp. 181-207, 303-332.