REMOTE SENSING IN ARCHAEOLOGY. THE STATE OF THE ART AND PRESENTATION OF METAdAtA RESEARCH PROJECT’S PRELIMINARY RESULTS

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Résumé

Depuis la genèse des techniques modernes de télédétection au moyen de drones, les applications se multiplient dans tous les domaines pour parfois devenir des outils indispensables de la recherche et de l’industrie actuelle. Cependant, dans le domaine des Sciences Humaines et tout particulièrement en archéologie ancienne (Préhistoire, Protohistoire), malgré un dynamisme indéniable, certaines techniques dites « classiques » ne cèdent pas véritablement le pas aux techniques plus modernes, pourtant plus efficaces et sources d’innovations. Certaines techniques intermédiaires, comme l’usage de théodolites ou plus récemment de GPS RTK associé aux Systèmes d’Information Géographique, se sont pourtant relativement bien implantées dans les problématiques de relevés topographiques, d’architectures et de structures archéologiques de divers types. L’incroyable progrès que constituent les drones équipés de LiDAR, de matériel photogrammétrique et thermique, tout comme celui des techniques de photogrammétrie opérées depuis le sol, n’a pourtant pas encore détrôné les techniques « séculaires » de dessin et de documentation des sites en cours de fouille et de leurs contextes. Si ce sont, dans un premier temps, des contextes très spécifiques qui ont généré l’application de nouvelles technologies en Archéologie, notamment dans des cas d’accès difficile aux vestiges (archéologie sous-marine, reliefs difficilement accessibles) ou bien des sites exceptionnels (grottes ornées du Paléolithique), les tendances actuelles montrent que ces technologies sont encore au stade expérimental dans d’autres contextes et que le plus souvent seules des solutions mixtes entre les procédures classiques et modernes sont appliquées.
Le présent article a pour objectif premier de définir, dans le cadre d’un état des lieux spécifique à la discipline archéologique, les problématiques et les contextes dans lesquels interviennent déjà les nouvelles techniques de relevés photogrammétriques depuis le sol et depuis les airs. Cet état des lieux ne peut être complètement exhaustif au vu de la quantité d’information disponible sur le sujet, parfois très répétitive, mais cherche à couvrir toute l’amplitude des applications passées et actuelles et de réfléchir aux applications futures. Il permet également de pointer du doigt et de mieux comprendre les réticences passées et actuelles vis-à-vis de supposés problèmes de précision et de problèmes d’éthique liés à la documentation automatisée de certains vestiges des sociétés anciennes. L’archéologue aura toujours, du moins faut-il l’espérer, le besoin d’être en contact avec son sujet, de l’analyser de ses propres yeux et de le tester de ses propres mains. L’on se demande désormais pourquoi il apparaît encore fréquemment si délicat d’abandonner un peu plus le papier et le crayon en faveur de procédés de télédétection et de relevé offrant un gain de temps, une meilleure qualité de documentation et un archivage de données exploitables sur le long terme. Ces « réticences » liées au passage à une pleine mise en œuvre de ces nouveaux moyens démontre aujourd'hui qu’un peu de recul est nécessaire afin d'obtenir une vue d'ensemble des résultats et des applications potentielles, afin de redéfinir les pratiques et les enjeux de la recherche archéologique de terrain. L’objectif second de cet article est de présenter le projet de recherche « METAdAtA » (« METAdAtA : sviluppo MEtodologico, Tecnico e sperimentale del volo Autonomo di Aeromobili senza pilota a bordo nell'ambito Archeologico sardo »), financé par les fonds européens de la Région Sardaigne et impliquant l’utilisation de drones pour la documentation de sites archéologiques néolithiques et de l’âge du Bronze en Sardaigne (Italie), sous divers de ses aspects : problématiques, objectifs, cas d’étude et résultats préliminaires. Ce projet de recherche a notamment permis de mettre au point des procédés et protocoles types pour la documentation de sites archéologiques assistée par drone mais également de démontrer que les nouvelles technologies constituent un facteur essentiel de l’apparition et du développement de nouvelles problématiques scientifiques, de nouveaux besoins auxquels la discipline tarde peut être un peu trop à donner libre cours.

Mots-clés : archéologie, documentation archéologique, photogrammétrie, drones, état des lieux, projet, Sardaigne, Italie.

Abstract

The application of modern remote sensing technologies in archaeology is not yet widespread in all procedures. Current trends show that such technologies are still at the experimental stage and mixed solutions between classical and modern procedures are applied. The “reluctance” to move to a full implementation of these technologies demonstrates that today a step back is necessary in order to get a broader overview. In addition to these modern technologies, new technical means are being tested, such as the increasing use of drones. This article aims firstly at presenting the state of the art of such new technologies in archaeology and secondly at evaluating technical and methodological protocols through the research project “METAdAtA” and its preliminary results.

Keywords: *archaeology, archaeological recording, photogrammetry, drones, state of art, project, Sardinia, Italy.*

1. Introduction

Archaeology is a discipline that requires the development of accurate technical drawings and various types of documentation during fieldwork research, whether undertaking archaeological excavations or surveys for mapping known sites, or geo-environmental mapping and research for unknown sites.

Conventional documentation on an archaeological excavation is generally implemented using very basic materials such as a pencil, gum, tape, plumb line and graph paper to manually draw the structures and stratigraphic evidence within an orthogonal grid framework (conventionally 1 m squared). These field documents are then processed by computer operations and supplemented by various photographic views of the discovered structures or the excavation itself. This phase of the documentation of the excavated deposit is essential and requires a very significant investment of time in relation to the total duration of an excavation. Performing an archaeological excavation certainly means discovering and collecting new information, sometimes directly crucial to the understanding of ancient societies, but the archaeologist is also aware that this means irreparably destroying the context of these remains. Ideally, the archaeologist manages to collect and document all the information that the archaeological deposit has preserved through the centuries and millennia.

The work that the archaeologist implements on a larger scale is mostly related to the completion of the mapping of the natural and archaeological environment. The ground surveys are also an essential aspect of archaeological field research because they help highlight deposits of different natures being excavated in a same archaeological complex (e.g. settlements, burials, monuments). These surveys allow a more in-depth evaluation and analysis of the organization and history of the landscapes and thus a better understanding of the position and role of the more thoroughly studied site.

Conventional sensing techniques related to archaeological and environmental surveys are the use of maps (e.g. OS in England, IGN in France, IGM in Italy), a mobile handheld GPS, a good sense of direction and paper documents. In recent years, such conventional techniques have been partially enhanced by the use of GIS software (Geographical Information Systems, e.g. ESRI ArcGIS or the open-source solution Quantum GIS) that allows the use of the same cartographic resources but in a geo-referenced computing environment and possessing powerful elaboration and analysis tools. The evolution of GPS technology has joined this computing progress (differential GPS or RTK - Real Time Kinematic), and is now relatively well established in the archaeological discipline. During fieldwork, the archaeologist, frequently associated with a topographer, is now implementing such new technical means that have already revolutionized their approach to his/her field of research. This revolution should be the first of a long series of advances in spatial modelling and remote sensing.

Although these technological advances are strongly rooted in the discipline, especially with the use of GIS and related technical means (Total Station, RTK-GPS), the archaeological discipline is still partially characterized by a strong spirit of conservatism when it comes to considering the full introduction of the most modern techniques such as photogrammetry surveys, laser-scanners, LiDAR and the direct use of GIS.

This is particularly the case of the emergency archaeology, where this conservatism is very strong, especially because of the time and economic constraints dedicated to rescue operations. These constraints, much stronger in the emergency archaeology than in the programmed one, do not always make it possible to proceed to the data acquisition but especially do not coincide with the time necessary for the verification and the data processing. It is certainly remarkable that the data acquisition can now be very fast in the field, but the archaeologist needs to have the result of the documentation thus produced before irreparably destroy the remains. This is essential in particular in order to add essential information such as the characterization of specific elements or the addition of information, which it fears not to be able to observe on the documentation produced by means of these new techniques. Paradoxically, this is both a fear of strong *clichés* with regard to these techniques but also a sense of incompleteness and loss of information sometimes well founded because some observations are made - and will remain so in the future - only on the field. In spite of these strong time constraints, the emergency archaeology constitutes since along time a privileged field of experimentation for these new techniques because, at least for certain aspects such as architectures, representing a saving of time and a gain of quality in the documentation. Various contributions of the emergency archaeology have thus been developed in the use of these new technologies (e.g. Delevoie et al., 2012; Belarbi et al., 2014; Samaan, 2016, Seguin and Breuil, 2017). However, their application in emergency archaeology is still not systematic, probably because of the still too long data processing times but also because of the rare presence of specialized figures within organizations and teams.

In addition to the logistical difficulties of computerizing the whole chain of fieldwork operations and the issues of material costs, some of this reluctance is mainly due to the problems of accuracy of automated sensing and possible distortions, especially those related to photogrammetric sensing. Archaeologists are also concerned about both the ethical aspects and the technical opportunity to permanently abandon certain types of conventional and therefore traditional recording and sensing in favour of emerging technologies that are already massively applied in other fields (e.g., architecture, urbanism, geology, and geomorphology).

Beyond the still high cost of these technologies, these concerns are entirely legitimate when one considers the responsibility that the archaeologist undertakes in the precise documentation of archaeological remains, that are systematically endangered or even totally destroyed by the very act of scientific excavation (“The unrepeatable experiment”, Barker, 2003:1-2). Distrust of these new technologies is due to the fact that it is impossible to document most of the discoveries after their excavation, unless fully reliable assessment of the findings is obtained during the excavation activity. The archaeologist has theoretically no room for error when he/she documents and conducts surveys of remains that have a truly scientific value only in their stratigraphic and structural context.

This mistrust is increased by the existing difficulties in the production of archaeological documentation in both objective and subjective ways because "*the new survey techniques tend to produce images that are more faithful to the object – that we can think of them as more "objective" – but could get away from their initial analytical vocation: if the manual drawing was organizing the data while recording it, the partial automation of technologies does not allow to operate the first selection of information. It is therefore interesting to question ourselves about their relevance according to different contexts and programs*" (Laroze, 2011). This is indeed one of the main reasons for the archaeologists' reluctance to fully accept the introduction of new technologies because the eye of the researcher and his/her sense of observation and experience are based on visual as well as "tactile" contact with the object, structure or archaeological deposit. Nonetheless, this automation of modern techniques can still allow the partial organization of data when collected, especially with the use of RTK-GPS and GIS environments.

The two groups of documentation techniques (classical and modern) are inherently different in terms of scientific results (D'Agostino et al., 2013). Another major aspect of manual field drawing procedures is that, firstly, the result can be checked in real time and possibly corrected or modified immediately. On the other hand, the time the archaeologist does not spend in the field manually documenting his discoveries is spent in the laboratory processing photogrammetric or other types of data. If an error occurs or any issues arise about the data, he/she is no longer able to remedy it and the information is lost or loses at least part of its scientific value.

The current trend is to proceed with the implementation of mixed survey techniques (classical and modern) and double or even triple the documentation produced, while maintaining the traditional manual drawings: so we see the use of such mixed solutions that can integrate manual drawing using total stations, differential GPS, laser scanner or LiDAR technology, classic photography and experimental photogrammetry (e.g., airborne, ladder, mechanical lift, telescopic handle, mini-balloon, kite). The current demands for the applicability of such new technologies, in particular the requirement for reliable high level accuracy and specific cheaper solutions, act as strongly dissuasive forces against the choice of finally making this shift towards modern sensing technologies, even though these may allow considerable time saving during fieldwork.

This paper provides an update on the various objectives and applications of the new multi-sensory remote sensing technologies in archaeology and crucial issues for archaeologists: What is their actual scientific utility? Can we go beyond the simple documentation purposes of illustration or representation? How can these new technologies help to respond to scientific matters? How can they be better adapted and when should they be preferred, compared to classical techniques? Such questions require the review of relatively broad state-of-the-art developments, from the origins of remote sensing techniques to their past and current applications in archaeology.

Subsequently, this paper proposes the presentation of an ongoing research project on remote sensing techniques and their objectives, in particular concerning the experimentation with the accuracy of these modern technologies implemented with drones and experimental sensors in the archaeological discipline, and the feasibility of replacing the more conventional techniques still largely used in archaeological fieldwork.

This research project, entitled METAdAtA, "*Methodological, technical and experimental development of airmobile autonomous unmanned aerial vehicle flight in the Sardinian archaeological context*" was financed by the European Fund of the Autonomous Region of Sardinia[1] and joins the Oben srl spin-off global project entitled "*Innovative control for autonomous unmanned aerial vehicles*" (www.oben.it). This research project proposes, in particular, to apply these new technologies to archaeological contexts within surveys characterized by conditions of difficult access and extreme logistics contexts (cliffs, canyons, narrow valleys, remote places) and "prior to excavations" the mapping of archaeological complexes (sensing of stone structures and monuments; reconstruction of topography or even monument reconstruction, for example in different conditions of vegetation cover). Some preliminary results obtained from these experiments are presented at the end of this paper in order to illustrate the potentialities of photogrammetric remote sensing in archaeology fieldwork.

2. State of the art: origins and actual applications

The modern remote sensing technologies (e.g., LiDAR, infrared, photogrammetry, radiometry) involving in particular the use of satellites, aircraft and drones originally developed in the context of military projects (Fig. 1.a-b) and spatial projects (Fig. 1.c) (Brisset, 2004; Watts et al., 2012; McBride, 2013) have, more recently, been implemented and developed in civil applications (Brisset, 2004) and environmental or urban disciplines (Sanli et al., 2008) such as geography, biogeography, topography and land analyses (Gomarasca et al., 2001; Bonarz and Rinaudo, 2002; Gilabert et al., 2002; Camacho-De Coca et al., 2004; Jiao and Liu, 2012; Atzberger et al., 2014a; Capaldo et al., 2014; Gianinetto et al., 2014; Giardino et al., 2016; Szantoi et al., 2016) (Fig. 1.d); geology, geomorphology and geophysics (Zribi et al., 2011; Oleire-Oltmanns et al., 2012; Di Salvo et al., 2014; Scaioni et al., 2014); urbanism and architecture (Rosnell and Honkavaara, 2012; Skoglar et al., 2012); volcanology (Amici et al., 2013); forest studies (Schlerf and Atzberger, 2006; Lingua et al., 2008; D'Agostino, 2012; Esposito et al., 2012;. Jakubowski et al., 2013; Maselli et al., 2013 ; Fassnacht et al., 2014; Bottalico et al., 2014 ; Lisein et al., 2014 ; Waser et al., 2014; Chirici et al., 2016); or even precision agriculture (Bachmann et al., 2013; Paloscia et al., 2014).

These parallel developments are intrinsically linked to modern needs for better representations of the two-dimensional and three-dimensional aspects of our spaces (DSM, DEM, DTM) and manage them within computer environments, especially in order to include the implementation of analytical calculations and predictive models.

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[1] European research resources *P.O.R. SARDEGNA F.S.E. 2007-2013 - Obiettivo competitività regionale e occupazione, Asse IV Capitale umano, Linee di Attività l.1.1. e l.3.*

The technical means used are numerous in terms of both the sensors (laser scanner or LiDAR, radiometry, photogrammetry, infrared, thermal cameras, video cameras, etc.) and airborne or ground based techniques permitting the carrying of these sensors in the space (satellites, different tonnages aircraft, different sized balloons, kites, raised platforms, most recently drones, cars or even totally manual means).
The recent use of drones in many aspects of remote sensing is in itself a transfer of military and spatial technologies into the context of civilian research and now provides low-cost solutions that should still be considered as experimental and thus in the development stage. In fact, direct technology transfer from military and spatial applications is unlikely due to secrecy and economic reasons, but many software products have been emerging in recent years, especially for the treatment of photogrammetric data (PhotoModeler, Agisoft PhotoScan, IGN MicMac, Pix4d, etc.) and the processing of LiDAR or laser scanner point clouds as complete suites of tools or LiDAR classification algorithms (ENVI, MCC-LIDAR, Rapidlasso LAStools, QCoherent LP360, ESRI ArcGIS, LiVT, etc.).

a. Predator USA fleet since 1995

b. EAD Harfang, Europe- Israel fleet since 2008

Boeing X-37B, USA spatial drone

d. Gatewing X100, civil topographic sensing drone

Figure 1 : examples of military, spatial and civil drones (Source: Wikipedia).

A whole category of scientific literature presents results of new classification algorithms for LiDAR point clouds (Lodha et al., 2007; Tinkham et al., 2011; Hesse, 2014; Ming and Chen, 2013) (Fig. 2.a). Although most of these algorithms supply the current software, some of them are unfortunately not yet really accessible to non-specialists in the field. However, their diversity offers sufficiently wide choices to reach satisfactory results.
This kind of application concerns three separate general aspects: the realization of archaeological surveys and the planning of preliminary surveys prior to archaeological excavation; onsite sensing of archaeological excavations or complex monuments and 2D and 3D documentation of archaeological objects.
This last aspect is not directly linked to contextual scientific matters but in most cases to reconstruction, illustration and specific analytical needs (Mélard, 2010; Pitzalis, 2007; Samaan et al., 2013). It is not the major focus of the "METAdAtA" research project because it should be considered as one of the least problematic applications.
The bibliography on various aspects of this subject is generally extremely abundant and this review cannot reasonably claim to address the complete list. Rather, the main aim is to highlight a non-exhaustive but representative range of applications in archaeology.
An important application of such techniques has been on buildings and ancient monuments (e.g. Roman, Medieval), which should be considered as purely architectural applications aiming at the illustration, reconstruction and monitoring of the state of conservation or even the restoration of this kind of cultural heritage (Fig. 2.b). We also find in these contexts applications based solely on laser-scanner or LiDAR sensing (Albery et al., 2006), solely on photogrammetric sensing (Fallavollita et al., 2002; Almagro, 2011; Favre-Brun and De Luca, 2011; Bouet et al., 2011; Lo Brutto and Spera, 2011; D'Agostino et al., 2013) or on remote sensing based on the combination of the two techniques (Nex and Rinaudo, 2010; Alby et al., 2011; Laroze, 2011; Borel, 2013; Di Salvo, 2014). The latter is generally considered to be the most satisfactory in terms of the quality of the results.
These modern technologies have proven to be indispensable for archaeological excavations in extreme conditions, especially for underwater excavations (Bass and Rosencrantz, 1973; Long, 1998; Lianos and Patias, 1999; Drap, 2012) or the documentation and analysis of decorated caves (Fritz et al., 2010; Pinçon and Geneste, 2010; Pinçon et al., 2010; Maumont, 2010; Azéma al., 2010; Feruglio et al., 2010; Lacanette, 2010). Such early applications should be considered as

the ones to truly have given birth to remote sensing techniques assisted by photogrammetric and laser analysis in the archaeological discipline.

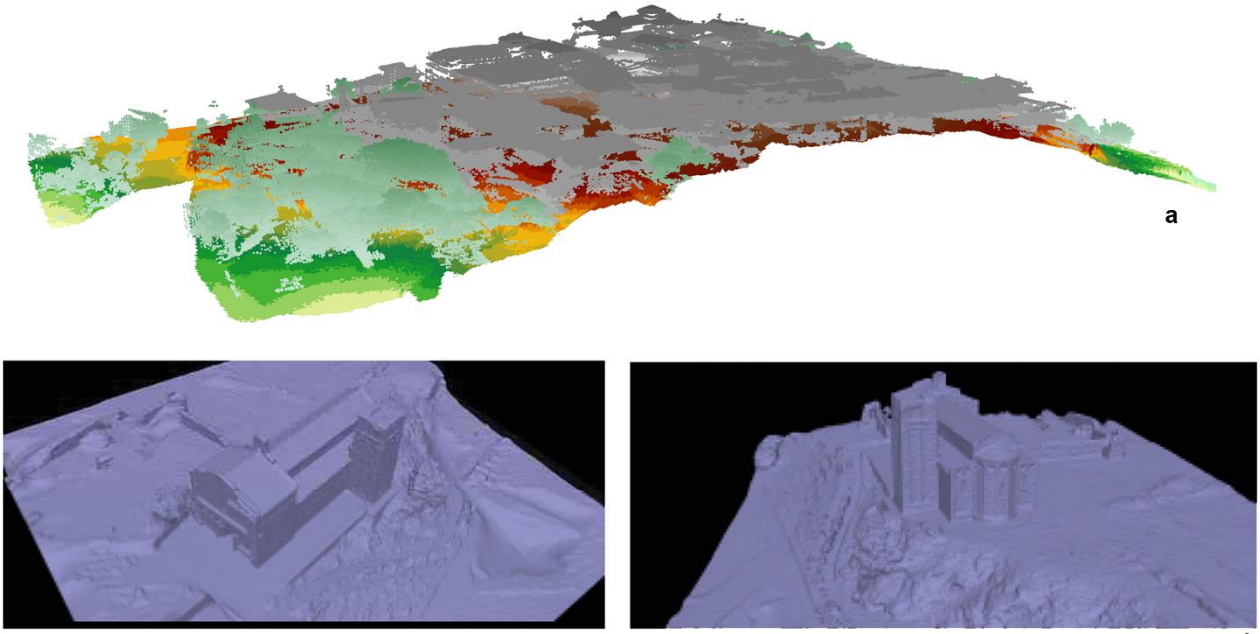

Figure 2 : example of LiDAR points cloud classification, Forconese case study (Molise region, Italy, Oben's data, elaboration F. Soula); b. example of 3D reconstruction of an architectural monument, Bisarcio church (Sardinia, Italy) (Fallavollita et al., 2002).

2.1. Archaeological surveys and preliminary cartography

The implementation of the photogrammetric remote sensing technique in archaeology as part of surveys and archaeological complex mapping is becoming more frequent due to the recent development of powerful and increasingly easy to use software solutions (PhotoModeler, Agisoft PhotoScan, IGN MiMac, Pix4d, etc.). Although there are various technical means implemented to produce photogrammetric surveys (plane, kite, mini balloon, etc.), the use of drones is under development and should within a few years become one of the best solutions – if not the best – as it provides data usually of better quality (owing to low altitude and low flight speed, and higher resolution) but still on more limited areas compared to high altitude means.
Some types of sensors (radiometry) are still airborne by airplanes (Briese et al., 2013; Atzberger et al., 2014b) while drones or even balloons are increasingly used for conventional photogrammetric sensing (various types of cameras, video recordings) (Fallavollita et al., 2002; Chiabrando et al., 2010, 2011; Lo Brutto et al., 2012; Rinaudo et al., 2012; Esposito et al., 2013). The photogrammetric sensors are frequently associated with high efficiency thermal applications for the detection of buried archaeological structures (Haley et al. 2002; Corrie 2011; Orlando and Villa 2011; Poirier et al. 2013).
The quality of these results is constantly improving and nowadays the most important limits are related to the need to use very powerful computers (x64 systems, dual or quadruple Intel Xeon processors, a large amount of new generation RAM and graphic gear with high GPU potential) for the treatment of large datasets.
The identification of entities or ground anomalies on a photogrammetric base can be improved through various types of image processing algorithms. However, although the photogrammetric technique provides 2D and 3D reconstruction possibilities, it is still only rarely used over large areas, at least in archaeology, and is most often used for limited areas like parts or whole small archaeological sites.
The application of the LiDAR remote sensing technique in archaeology, generally operated from airborne platforms, is a major aspect of current research. Although aircraft of various tonnages are the most used way to operate this kind of sensing, the use of drones is developing gradually with the onset of miniature LiDAR prototypes. Implementation of LiDAR technology (laser pulse with multiple returns) has proven particularly useful in the research in forest environments, for exploration and identification of archaeological structures covered by vegetal mass (Devereux et al., 2005; Georges-Leroy et al., 2011, 2014) or for archaeological surveys of large areas characterized by various types of natural contexts (Bofinger and Hesse, 2010).
As for archaeological excavations contexts (see next part), the implementation of ground control points (GCPs) is fully part of the data acquisition process, both in order to verify the absolute and relative accuracy of the data and to ensure the interoperability between remote sensing or close-range sensing and GIS platforms. There are several techniques for verification of scale and connection to geographic systems, where the use of sensors integrating geographical coordinates for each acquired element (photographs, laser points,

and thermal images), the integration of scales and control surfaces, the correlation to pre-existing geographic databases or the use of geo-referenced targets using RTK GPS or total stations measurements. This latter technique is the most reliable and widely used for photogrammetry. However, it should be associated with the integration of scales and control surfaces.
The aim of mapping archaeological complexes or sites and their environment is also a fully-fledged research axis (Hesse, 2010, 2012) leading to the realization of topographic mapping (extraction of DTM) allowing for both a better characterization of the context of archaeological sites or complexes and the identification of ancient anomalies or entities.
LiDAR surveys in archaeology are frequently implemented by aircraft, which carry out surveys over large areas. Ground verification of indicators detected by LiDAR is in any case necessary to guarantee the reliability of the survey.
It is widely recognized that the multi-sensor surveys along with laser sensing (most frequently by means of LiDAR or ground-based laser scanning) is a multi-sensory and more effective solution (Nex and Rinaudo, 2010), because it creates a 3D photogrammetric spine on which photogrammetric data is superimposed with better accuracy.
This association is truly essential in the context of caves or rock shelter art (engravings and paintings) because it offers the possibility to produce 2D and 3D models of works inexorably destroyed by the passing of time (Grenier et al., 2013) without altering the integrity of the remains. Through these models, cave paintings can be best observed through a variety of software solutions to increase contrast, the light or the colour levels; and thereby reveal elements that are too sparse, or altogether invisible, to the naked eye. These are not however the only possible applications of this combination of sensing techniques. In the context of caves with rock art, these models are useful for the analysis of paintings and engravings, offering the possibility of eliminating potential later graffiti or separating various phases of implementation. By isolating artworks, it is possible to better understand and reconstruct the painted or engraved panels such as they could have been at some point in their history. From there, restoration processes or conservation may be planned or highly accurate copies produced for exhibition to the general public, thus avoiding endangering the original works (Fritz et al., 2010; Pinçon and Geneste, 2010; Pinçon et al., 2010; Maumont 2010; Azéma et al., 2010; Feruglio et al., 2010; Lacanette, 2010). Some of these applications can also be implemented as part of mining archaeology (Arles et al., 2013) or even for the study of moveable objects such as usually small works of art (Mélard, 2010; Luglié and Pinna, 2012).

2.2. Archaeological excavations

The application of photogrammetric techniques during archaeological excavations is an increasingly frequent practice. At this smaller scale, the use of heavy airborne means (airplanes) or even lighter airborne means (UAV, drones) is not really essential. There are lighter means such as ladders, raised platforms or telescopic sleeves which are handled from the ground. Implementing photogrammetric recording of excavations (specific structures, stratigraphy, general plans) does not require reaching great heights. In the case of large excavated areas, drone flight implementation could, however, be preferable.
In such contexts, it is frequently details of the archaeological structures on a human scale that are sought (Samaan et al., 2014; Soula and Manca dir., 2014) or general records of the current excavation (Cléry et al., 2011; Gianolio et al., 2014; Soula and Manca dir., 2014).
The objectives of these procedures carried out during archaeological excavations can be many:

- The creation of additional documentation that provides 2D and 3D views of structures, conventionally recorded contexts (manual drawing) or stratigraphic units viewed in planimetry before their destruction by the excavation. This especially allows the observation of particular entities reconstituted by this means during various phases of excavation while providing more elaborate documentation than simple photography (Fallavollita et al., 2002; Wulff, 2010; Ardissone et al., 2013; Gianolio et al., 2014; Soula et Manca dir., 2014). Some authors have proposed procedures to accelerate the phases of documentation of archaeological site during excavation through the use of photogrammetric sensing (Chiabrando et al., 2010; Spanò et al., 2011).
- The general recording of monuments or excavations during fieldwork (Melis and al., 2013; Soula and Manca dir., 2014).
- The acquisition of accurate geo-referenced documentation allowing measurements and observations even after the excavation has finished (Wulff, 2010).
- The virtual reconstruction of archaeological monuments (Cassen, 2008; Chiabrando et al., 2011; Bryan et al., 2013).
- The presentation of alternative illustrations that are not fixed on a single angle (Wulff, 2010; Soula and Manca dir., 2014).

The excavation of the Bronze Age megalithic monument of Vaccil Vecchiu (Grossa, South Corsica. - Soula and Manca dir., 2014) provides examples of a mixed application of traditional and modern techniques. Photogrammetric documentation experiments have been developed there in a complementary manner. Photogrammetric documentation is based on RTK-GPS sensing operated by the research engineer Guy André from the LAMPEA laboratory (CNRS UMR 7269, Aix-en-Provence) to operate the excavation and documentation in a geo-referenced framework.
During this archaeological excavation, part of the planimetric documentation was produced directly by the photogrammetric technique (Fig. 3.a). This choice was made when the site's conservation status (pretty bad in some sectors) did not contain well-preserved structures. In this case, the rapid recording of those sectors most damaged by mechanical work done over the last century was at stake.
Another part of the recording was carried out using conventional surveys coupled to photogrammetric documentation (Fig. 3.b). The challenge here was to compare the results from the two types of drawings: classical and photogrammetric, and to plan research for future improvement of these results.
A third case of the application of photogrammetric technology in this Corsican case study is the detailed documentation of some uncovered structures in order

to complete the manual drawings and conventional photographic shots (Fig. 3.c). The challenge in this case is the illustration and establishment of a 3D mesh model for better post-excavation observation.

The application of such techniques used during archaeological excavations, however, involves some limitations that are apparent to the archaeologists but are less clear for other specialists. The photogrammetric survey is not yet seen as a unique means of archaeological documentation of sites during excavation. Many archaeologists remain sceptical of highly automated means that could detach them from their direct vision of the excavation in the field. Many scientific observations can be made only with the human eye and contact in the field. It is very likely that these techniques will never become a truly unique solution in archaeology but that they will rather tend to become alternative means that provide additional documentation to classical methods. The quality of the modern documentation means that it is not always considered as such to be optimal and can still hamper their widespread application. For example, the presence of “holes” meaning the absence of correlated photogrammetric data is quite common, especially in 3D models created with photogrammetric textures (Chiabrando et al., 2010). These imperfections could also be associated with an exaggerated “polygonisation” of 3D models treated in medium quality renderings (Chiabrando et al., 2011). It is therefore necessary to assess the acceptability of a rendering that is sometimes still imperfect but which offers significant time saving in the field. Nevertheless, such issues are often due to incorrect sensing parameters such as the taking of too few pictures, points of view that are too partial and of too low quality for the elaboration of the 3D models. The continuous improvement of software and algorithms also tends to limit these inaccuracies.

Regarding the application of the LiDAR sensing technique in archaeological excavations, it is not yet documented because it is a technical means rather intended for the survey of large areas with the goal of environmental and general landscape reconstruction. The archaeological excavation requires no such technology, at least on a smaller scale. These are usually the laser-scanners that are used to make accurate readings with a unique return of laser beams (Bouillon and Cassen, 2008) like in the architectural case studies.

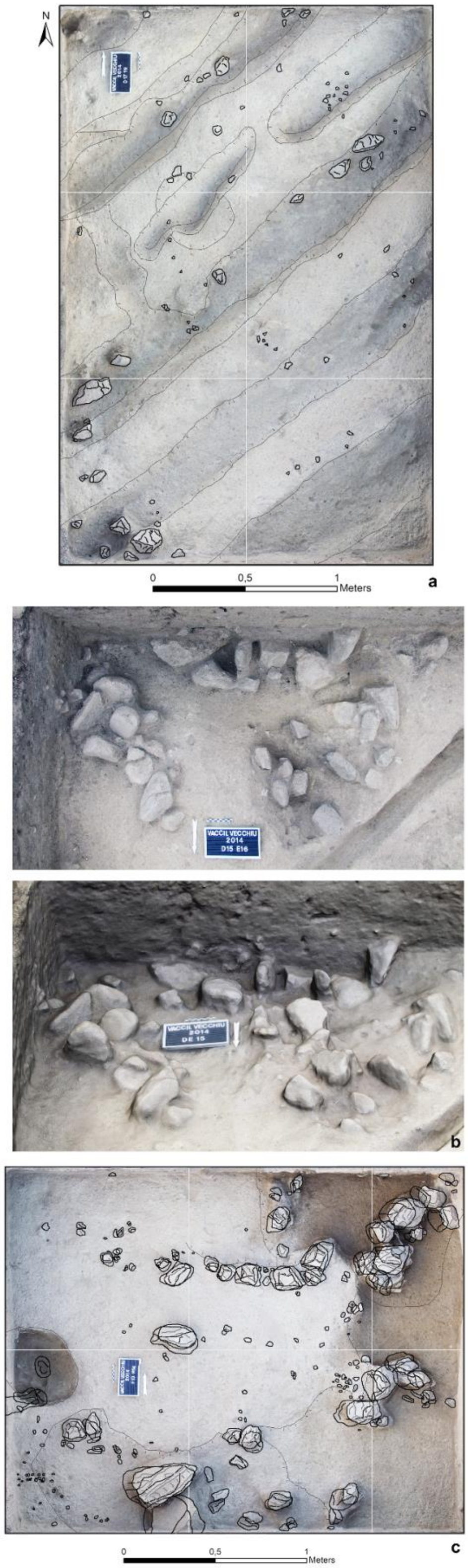

Figure 3: examples of application of new sensing technologies in archaeology, Vaccil Vecchiu (Grossa, South Corsica; Soula and Manca, 2014), a. archaeological drawing on photogrammetric reconstruction; b. photogrammetric documentation and classical manual drawing comparison; c. classical photography and 3D photogrammetric reconstruction comparison (Photos and computing by F. Soula).

2.3. Focus on the use of drones

The research project presented in the third part of this article is mainly directed towards the use of drones for multi-sensory remote sensing in archaeology. It is therefore necessary to present a brief state of the knowledge specific to this aspect of the current research, although the involvement of drones has already been partially documented previously.
Drones (excluding any use of a balloon or kite) are still little used as part of the archaeological discipline. However, this situation is gradually changing, suggesting that in a few years drones will become a major asset for all archaeologists. Their use will therefore be gradually integrated everywhere as part of archaeological surveys and archaeo-environmental mapping.
Current developments derived from research in military and spatial contexts are increasingly present in the civil context (Watts et al., 2012; Bosak, 2013). While drones are expected to be mobilized in various disciplines such as volcanology (Amici et al., 2013; Di Salvo et al., 2014), geomorphology (D'Oleire-Oltmanns et al., 2012), modern architecture or ancient cultural heritage (Barazzetti et al., 2010; Chiabrando et al., 2011, 2013; Rinaudo et al., 2012), urbanism (Rosnell and Honkavaara, 2012; Skoglar et al., 2012; Brucas et al., 2013) or even precision agriculture (Bachmann et al., 2013), the archaeological applications are still relatively rare and still very experimental (Fallavollita et al 2002; Lo Brutto et al., 2012;. D'Oleire-Oltmanns et al., 2012; Melis et al., 2013). However, numerous worldwide and European projects are ongoing on this specific subject (e.g. www.arcland.eu) and a lot of laboratories equip themselves with drones.
At present, the most popular remote sensing technique using drones is photogrammetry because it does not require very expensive equipment and matches very easily with the intrinsic weight limits that drones can carry (usually 500g to 4kg of lift for about 10-30 minutes of flight). The implementation of the most imposing drones that are able to carry more weight and therefore other types of sensors is in the early stages in civilian applications. The first generation of miniaturized LiDAR specifically intended for drones is beginning to emerge (e.g. YellowScan, Riegl, 3D Robotics, Velodyne) and be experimented with in various contexts and disciplines (www.oben.it). The use of drones is therefore clearly one of the most important future technological advances in all disciplines, and archaeology is already one of the testing grounds, among the most stringent in terms of accuracy.

3. The METAdAtA project: presentation of case studies and primary objectives

3.1. Research project framework and technical context

This biannual research project, funded by European funds dedicated to the Autonomous Region of Sardinia (Italy, www.regione.sardegna.it), was developed with Oben srl, a spin-off of the University of Sassari and partner of "La Sapienza" University of Rome. Oben develops various research projects in the field of remote sensing using drones and also works in areas such as engineering, humanitarian demining, forest studies, urban planning, architecture, archaeology and even precision agriculture. The main experimented sensors are photogrammetry and LiDAR (YellowScan - Fig. 4.a) integrated in a general context of research in the field of Unmanned Aerial Vehicle navigation and obstacle avoidance. Oben has a relatively wide fleet of multi-rotor drones (Fig. 4.b-c) supplemented by fixed-wing UAVs and a 10m. long airship (Fig. 4.d). The METAdAtA project is part of this research program, specifically in the field of archaeology, with the long-term objective of providing procedures and protocols for all disciplines.

3.2. Research project objectives

The METAdAtA project's overall objective is to contribute to the realization of methodological and technical protocols and procedures for the remote sensing and more or less automated processing of obtained information through drone flights mainly in archaeological and environmental disciplines. The research project was organized around three specific objectives that incorporate various sub-objectives of implementation of remote sensing techniques using drones. The first main objective includes:

- the development of methodological and technical protocols for remote sensing using drones: this sub-objective was intended to work on the analysis of the methodological and technical criteria still to be resolved in order to create smooth, fast and efficient procedures for data processing and analysis;
- the articulation of the preparation phase and the results processing phase in a GIS environment (Geographic Information Systems) to optimize the data taken through the UAV flights.

The second main objective concerns the implementation of experiments and tests carried out to validate the techniques and procedures so developed. Of all the possible fields of application, archaeology is a privileged sector because it integrates various geographic scales and required precision levels. This variability allows the realization of photogrammetry and LiDAR sensing of different surface areas and levels of precisions in very diverse environmental contexts. It also helps to cope with various interpretative parameters of LiDAR data.

Finally, the third main objective was to exceed the experimental framework of the implementation of these new technologies in archaeology and develop multidisciplinary procedures and technical protocols. These protocols and procedures were meant to be calibrated according to the expectations of other disciplines such as environmental, architectural, urban and agricultural.

Figure 4 : Oben's material and fleet examples (www.oben.it), a. first prototype of YellowScan LiDAR (www.lavionjaune.fr); b. Multi-rotor drone OB-I; c. Multi-rotor drone OB-II with YellowScan LiDAR onboard; d. 10 m length dirigible (Photos by Oben srl).

3.3. Experimental cases study

The METAdAtA research project was oriented towards the application of photogrammetric remote sensing on various Sardinian archaeological case studies that can be classified into two main categories: general surveys of medium to large areas, particularly in contexts characterized by strong constraints of accessibility; and mapping of archaeological complexes from medium to low surface areas. These experimental applications mainly concerned the central and north-west of Sardinia (Fig. 5.a).

From a purely technical and methodological point of view, the experiments were designed to test and evaluate the potential of the photogrammetry – and to push it to its limits – for the analysis of archaeological complexes of different types and within various natural environments.

Implementing remote sensing using drones is an excellent field of application within more or less inaccessible spaces such as limestone cliffs and narrow valleys.

All the study cases implemented in this project were geo-referenced using a GPS station correlated to regional geographic databases, thus integrating the setting of physical targets in the field before the survey and the verification of consistency with these databases. While taking photogrammetric data, a minimum overlap of 60% to 80% between each photograph was favoured to ensure the correct superposition of data and to avoid peripheral deformations.

Experimentation of remote sensing in such contexts was implemented on a first example with the hypogeal burial ground of Calancoi - Sos Saltos (Sassari, Sardinia, Italy). This late Neolithic burial ground, composed of seven rock-cut tombs (Melis, 2009), opens in the top part of a limestone cliff about 70 meters high, and has alternating vertical rock walls and large areas of low benches and slope deposits (Fig. 5.a). The main objective of this experiment consists in the characterization of the potential of photogrammetric sensing of hypogeal graves in this context but also in the implementation of a precise topographic reconstruction of the environment of the burial ground through the software removal of vegetation. UAV flights have been scheduled with photogrammetric sensors in a window of 225 by 125 meters, to cover both the hypogeal graves and the whole limestone cliff (from top to bottom) (Fig. 5.b, c and d). The flight was scheduled at an altitude of 50 m above the ground and a speed of about 6 meters per second with equidistant passes of 25 m.

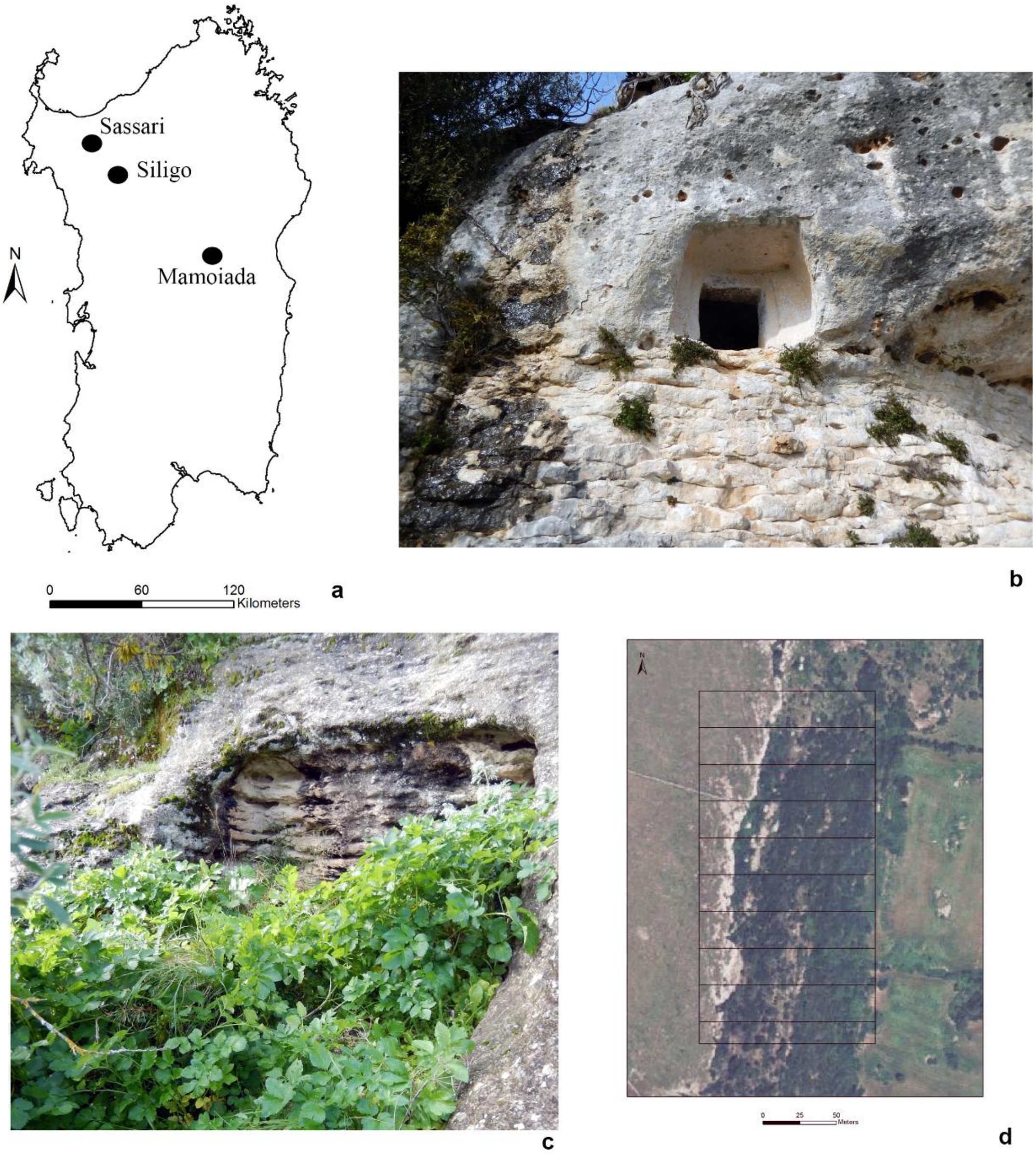

Figure 5 : a. location of experimental case study of Mamoiada, Siligo and Sassari, Sardinia; b. hypogeal grave, Calancoi – Sos Saltos I, Sassari; c. hypogeal grave, Calancoi – Sos Saltos II, Sassari; d. Remote sensing area planned on the hypogeal burial ground of Calancoi – Sos Saltos (Sassari, Sardinia, Italy) and flight planning (Photos and computing by F. Soula).

Three other experimental projects on the photogrammetric surveying and documentation of archaeological complexes have been implemented in Sardinia in the Mamoiada and Siligo territories.

The experimental drone flights operated in Siligo, in north-western Sardinia, aimed at proceeding with the photogrammetric remote sensing of the Conzattu *nuraghe* (Bronze Age tower monument) and its surrounding area (Fig. 6.a). The main objective was to assess the ability and quality of reconstruction and analysis of the main tower and realize the DEM (Digital Elevation Model) and DTM (Digital Terrain Model) of the sector. The survey window is a square of 150 m on which the drone crossing points have been previously positioned to perform autonomous flights (Fig. 6.b). The flight was scheduled at an altitude of 50 m above the ground and a speed of about 6 meters per second with equidistant passes of 25 m.

The last remote sensing experimental drone flights were located at Mamoiada in the centre of Sardinia, and divided into two windows with variable objectives.

The Bronze Age deposit of Orgurù (dated to the second millennium B.C.) is constituted of the remains of a tower located on a granitic outcrop and a settlement (walls, stone structures, houses, etc.) underneath a sparse oak forest (Fig. 6.c ; Fig. 7.a and 7.b). The objective of this experiment (120 m by 100 m wide) is the photogrammetric remote sensing of the tower monument and its associated settlement structures in an attempt to undertake preliminary planar documentation of visible or less visible structures on the ground.

The nearby Neolithic hypogeal burial ground of Orgurù (fourth millennium B.C.) is constituted of four tombs carved into a granite outcrop (Fig. 7.c and d). The objective there is to proceed with remote sensing recording of the outcrop and its immediate surroundings (DEM and DTM; 100 m by 100 m wide) and the evaluation of detection, and therefore of the digital signal of this type of burial in a granitic environment composed of large blocky and rocky outcrops of medium size. This last experiment has been conducted with manual means at about 30 meters above ground level and elliptic flights at various altitudes, and with an oblique view of the more or less vertical surfaces of the granitic outcrop (oblique position of camera) in order to obtain better documentation of the burial ground.

Figure 6 : a. Conzattu Bronze Age tower remains (Siligo, Sardinia, Italy); b. Remote sensing area planned on the Conzattu Bronze Age tower (Siligo, Sardinia, Italy) and flight planning in 2D; c. Remote sensing area planned on the Bronze Age tower and settlement of Orgurù (Mamoiada, Sardinia, Italy) and flight planning in 2D (Photos and computing by F. Soula).

Figure 7 : Remains of the Bronze Age tower of Orgurù (Mamoiada, Sardinia, Italy); b. Remains of the Bronze Age settlement of Orgurù (Mamoiada, Sardinia, Italy); c. Remote sensing area planned on the Neolithic hypogeal burial ground of Orgurù (Mamoiada, Sardinia, Italy) and flight planning in 2D; d. Example of hypogeal grave of Orgurù (Mamoiada, Sardinia, Italy) (Photos and computing by F. Soula).

4. Preliminary results of the photogrammetric remote sensing experiments

The preliminary results of two case studies are presented in this paper: the Bronze Age tower of Conzattu in Siligo and the Neolithic hypogeal burial ground of Orgurù in Mamoiada (Fig.8 and 9). With the description of these results, we also propose more detail about the actual state of data reconstruction.

The photogrammetric data from remote sensing experiments were elaborated through the use of Agisoft Photoscan software with the following parameters: high quality photo alignment, medium quality dense cloud generation, and high quality 3D model reconstruction.

These first experiments allowed the production of various kinds of data and recording of the archaeological sites including orthophotography, DEM, DTM and 3D illustration renderings.

The reconstruction of the Conzattu Bronze Age tower (Fig.8) is based on 510 high quality pictures (12-14 megabytes each) that allow the reconstruction of a dense point cloud of 41 366 407 points (medium quality) and a 3D model of 8 328 035 faces (high quality). This model led to the production of precise orthophotography and DEM recording the tower and its immediate environment. In a second attempt, a dense cloud of higher quality (high parameter) was reconstructed in order to provide a best quality points cloud for classification of ground, building and vegetation entities. The orthophotography has also been useful during the classification of the dense points cloud extracted from the 3D model. The automatic and manual classification of this very dense points cloud (166 539 943 points) led to the DTM reconstruction of the area. In this specific case study, LAStools classification has been used in a first phase and ArcGIS manual classification revealed itself essential in a second phase because of the presence of too many classification errors (these algorithms are made for LiDAR data). Other classification experiments showed that it will be preferable in the future to use the MCC-Lidar classification tool despite the long time needed to complete the calculation task (depending on the density of the points cloud). Other experiments are actually underway on this aspect in order to assess the feasibility of quicker classification through sampling a

dense cloud parameter to create a lower density cloud parameter.
The actual result enabled the reconstruction of a LAS dataset including 118 576 926 ground points (71.2% of the total). In addition to auto-piloted horizontal sensing, this case highlighted the need to include a manually piloted drone flight with an oblique orientation of the camera in order to obtain a coherent reconstruction of vertical and sub-vertical elements. This kind of procedure could have other applications, not only archaeological ones, such as for the 3D reconstruction and monitoring of trees.
The production of the local photogrammetric DEM and DTM permitted the clear identification of various anthropic structures: in addition to the presence of modern structures like the walls of land divisions, these results strongly highlight the digital signature of stepped terraces from an unknown period. It is very probable that these terraces are linked to the modern or sub-modern agricultural and pastoral use of these lands. Finally, if the Bronze Age tower is very visible in this kind of data, this is also the case of other structures such as the megalithic terrace visible south of the tower, an anthropic mound at the base of these structures and a partially conserved defensive megalithic enclosure of the hill, frequently hidden by actual vegetation.
The DEM and DTM profiles extraction permitted the completion of these observations and illustrate how much these lands have been transformed by the building of the Bronze Age tower. The position of the Conzattu tower is clearly the result of the choice of the most dominant point of this plateau border. By raising a small natural hill, an artificial mound was created from which the tower could have had a very dominant position over the whole valley. These first observations enhance the known or largely supposed role of territorial surveillance of this kind of Bronze Age towers.

The Orgurù Neolithic hypogeal burial ground case study was fully recorded through a manual drone flight. Some photographs were also taken directly from the ground with the aim of integrating detailed views of the hypogeal tombs into the reconstruction of a 3D model. This manual procedure helped to better understand the necessities for good 3D reconstruction of complex elements. It allowed the assessment of manual flights and showed how ground based photography could also be very important to the general output quality. The main difficulty of this complementary aspect remains in the protocols of taking each photograph in order that the software successfully aligned it with drone sensing data.
The Orgurù Neolithic hypogeal burial ground reconstruction (Fig. 9) is based on a selection of 1 091 high quality pictures that permitted the reconstruction of a dense cloud of 35 444 604 points (medium quality), and a 3D model of 7 131 323 faces (high quality). This model also led to the production of a precise orthophoto and DEM documenting the granitic outcrop and its immediate environment. The automatic and manual points cloud classification offers a LAS dataset including 19 897 236 ground points from which the local DTM was extracted.
The extraction of profiles from both DEM and DTM permit the underlining of the global morphology of the ground. They also provide some elements to confirm the hypotheses about the orientation of hypogeal tombs towards open spaces because rock-cut tombs are frequently dominating wide landscapes, in this case globally between south and south-east.

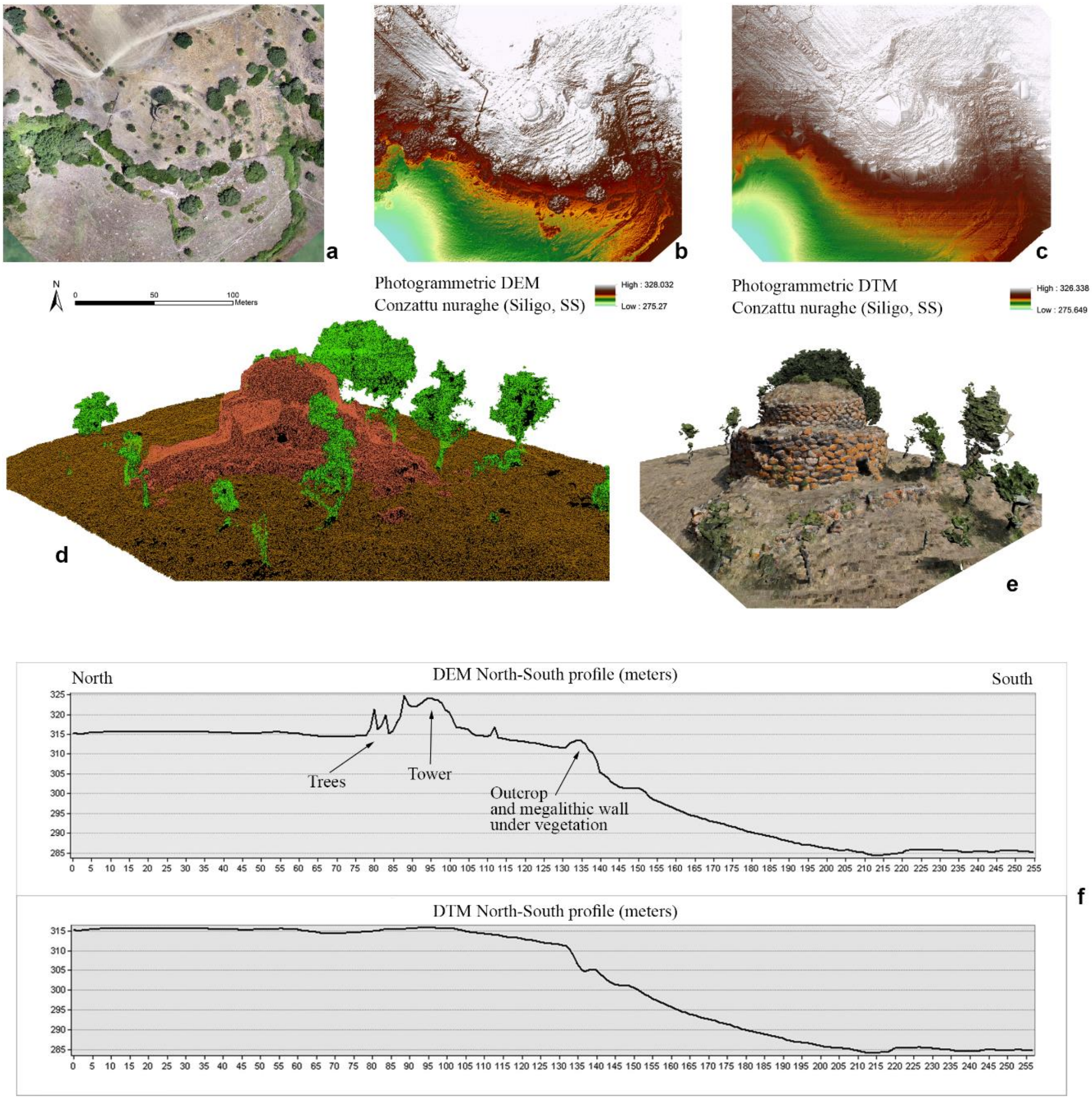

Figure 8 : Photogrammetric preliminary results, the case study of a Bronze Age tower at Conzattu (Siligo, SS), a. Orthophotography, b. DEM, c. DTM, d. Points cloud classification (green for vegetation, red for structures, brown for ground), e. OpenCL rendering; f. North-South DEM and DTM profiles (Computing by F. Soula).

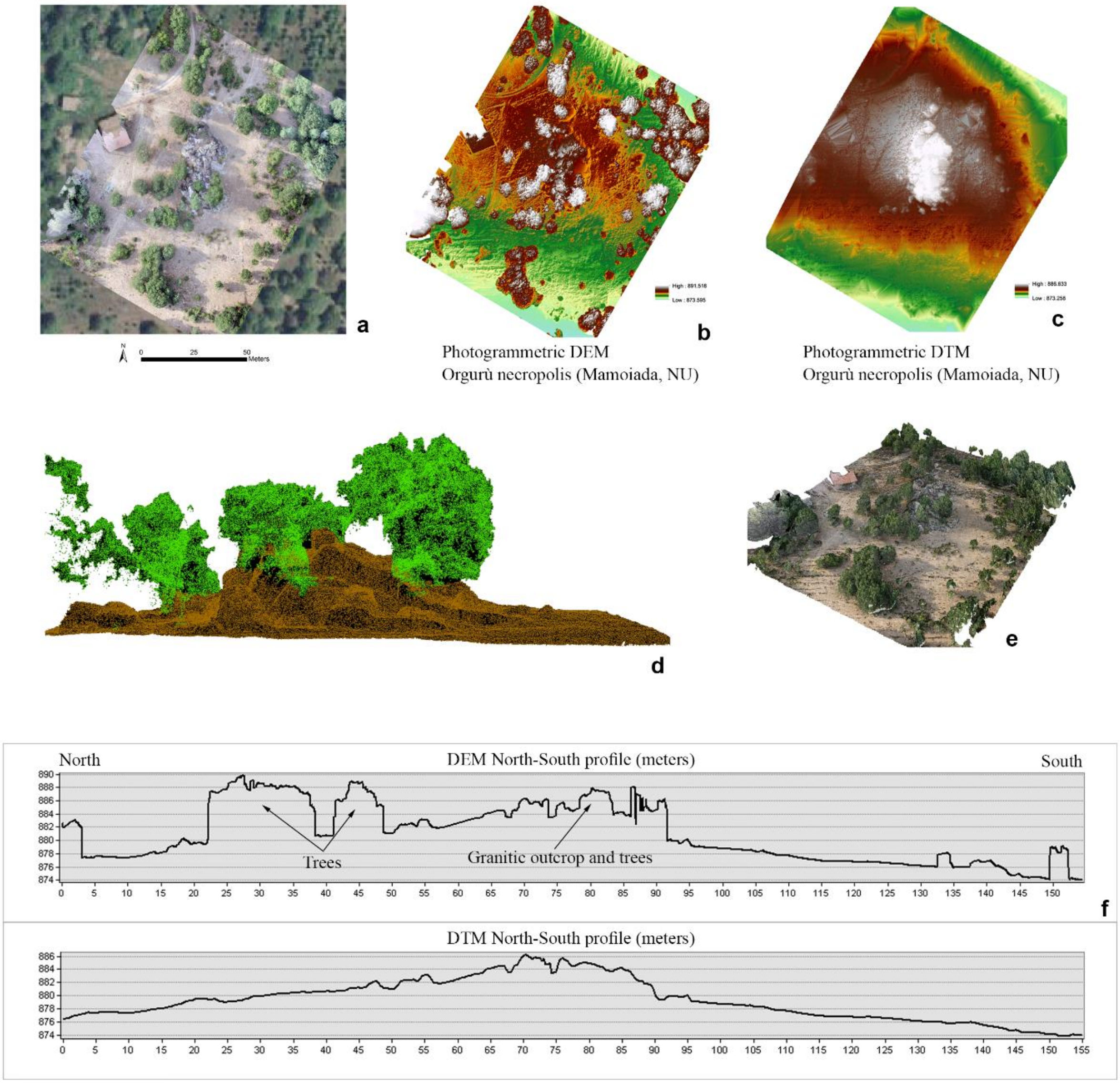

Figure 9 : Photogrammetric preliminary results, Orgurù Neolithic hypogeal burial ground (Mamoiada, NU)), a. Orthophotography, b. DEM, c. DTM, d. Points cloud classification (green for vegetation, brown for ground), e. OpenCL rendering; f. North-South DEM and DTM profiles (Computing by F. Soula).

5. Conclusions and perspectives

The broader developments in these state of the art technologies and the METAdAtA results allow us to assess the high potential of photogrammetric remote sensing in the preliminary documentation and analysis of archaeological deposits or monuments. It is especially interesting to note that photogrammetry is expected to offer good results for accurate DTM extraction insofar as the vegetation present on the ground does not exceed a certain level of density. Another result is linked to the observations made on the usefulness of crossed autonomous and manual remote sensing, allowing the multiplication of the points of view and easily adapting procedures to the specific needs of each case study.
At the dawn of a more direct transition to the application of new remote sensing technologies in archaeology, the METAdAtA research project aimed at the evaluation and adoption of a new way to approach archaeological field studies. There is no doubt that we are at a stage of new technical and technological conception of archaeological research. Drones and various types of remote sensing technologies will develop and rapidly become essential, especially by providing improvements in the quality of scientific documentation as well as faster data acquisition in the field. Multisensory remote sensing should therefore be considered as a new technical approach, although it may in any case be considered as a methodological framework to replace existing methods. This new approach to fieldwork is susceptible to go beyond the purposes of documentation, illustration or representation because it already allows the archaeologist to respond to scientific questions posed by the detection of hitherto unknown archaeological sites by such surveys.
Experimental research projects such as those under actual development enable the testing of these new remote sensing technologies in archaeology and the development of IT protocols and procedures to

characterize the quality and the accuracy of the obtained results. They are therefore a major key to undergoing this transition that is already taking place in other disciplines. The questions common to many archaeologists concern the real scientific and technical utility in the application of these new technologies. This utility is probably set to become a necessity in the near future as these questions are met with positive answers by the ongoing developments in these technologies.

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