UAV-BASED ARCHAEOLOGICAL 3D MONITORING: A RURALSCAPE CASE IN IRAQI KURDISTAN

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ABSTRACT:

Recently rapid mapping techniques based on UAV photogrammetry increasingly help on-site archaeological documentation works. Multi-temporal data are specifically crucial in diachronic investigation research, and for this purpose the data co-registration and integration can support the accurate 3D digitization of excavation phases and make coherent topological relation among them and phases-related stratigraphic units' data. In this framework, the level of automation and accuracy control are challenging aspects to streamline the documentation process during excavation activities, however all experimentation phases must be tested and validated in the actual archaeological context, where the boundary conditions are typically demanding. This research is developed during the collaboration project with Cà Foscari University of Venice, started in 2022 campaign, in the excavation site of Tell Zeyd, in Iraqi Kurdistan, The Tell Zeyd Archaeological Project (ZAP) aims to study the rural landscape of the hinterland of Mosul in the long Islamic period, from the Arab conquest in the 7th century to the disintegration of the Ottoman Empire with the First World War, as an ideal observatory on the characteristics of the settlement in its spatial organisation, places of worship, production installations and facilities for storing foodstuffs. The research aims to present the preliminary test and results on an experimental documentation activity based on multi-scale UAV mapping strategy and training with the archaeological expert group, and particularly for automatic co-registration of multi-temporal data, considering different images datasets epochs belonging to subsequent excavation phases.

1. INTRODUCTION

The archaeological survey is a continuously evolving fieldwork in which the use of efficient Geomatics technologies have widely mastered documentation projects since long time (Forte & Campana, 2016; Patias, 2006). Integrated 3D approaches for digital recording and 3D dissemination proved to be extremely powerful in the contribution to the study, interpretation and management of heritage contexts, as broadly investigated since beginning of 2000's and declared in (London Charter, 2009). The archaeological spatial analysis based on geographical scale approach and geographic information system (GIS) benefits from the use of geospatial data, combining both image- and range-based methods, especially for the multi-scale nature of this winning approach (Al-Ruzouq, 2022). The perspective shifting from terrestrial to aerial acquisition had its turning point in geosciences supporting archaeological investigation with the use of aerial remote sensing and the introduction of digital approaches and digital products ad othoimages and Digital Surface Models (DSM) (Lambers et al., 2007). Recently rapid mapping and integrated techniques based on the remote control of drones for UAV photogrammetry (Colomina & Molina, 2014; Sauerbier & Eisenbeiß, 2010), together with ground-based low cost and newly portable systems increasingly help on-site documentation works (Themistocleous, 2020; Spanò, 2019). Particularly, in the last 10 years, the breakthrough in drone technology has also brought its disruptive effect also into the archaeology fieldwork assisting experts in documentation, with countless experimental instances, with various imaging sensors and spectrum acquisitions and in different application contexts (Abate et al., 2021; Campana, 2017; Brumana et al, 2013; Rinaudo et al., 2012).

In archaeological photogrammetric survey, usually the challenging context conditions (light-shadows, temperature etc.), accessibility (wideness, time schedules, topography, etc.) and excavation routines (layers phases for stratigraphic units approach, topographic levels control, etc), require strategically designed survey plans, especially for multiple images datasets acquisition, considering operator involvement, devices performances, data acquisition timing and on-site processing workflows. Here, the use of uncrewed devices with both fix wing or multi-rotors engines, equipped with performing digital cameras, allow efficient 3D multi-temporal mapping and modelling of terrain and emerging structure and supporting advanced analysis, continuously assisting archaeological activities in their progression (Chiabrando et al., 2018). Specifically for multi-temporal data, that are crucial in diachronic investigation processes as archaeological research, the data co-registration and integration can support the accurate 3D digitization of excavation phases and make topological relation among them and phases-related stratigraphic units' data, increasing availability and sharing solutions (González Ballesteros et al, 2023; Previtali & Valente, 2019).

This research presents the preliminary tests and results about multi-scale UAV mapping strategy for multi-temporal 3D modelling and monitoring applied to ongoing archaeological site. The data acquisition has been shared with archaeologist practice during a training activity period. The first tests have been presented, considering different images datasets epochs belonging to subsequent excavation phases. The proposed study aims to develop, test, optimize a linear methodological workflow for automatic co-registration of multi-temporal photogrammetric datasets, that try to surpass the only unsupervised almost-automated software-based processing, but

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that can also support the daily activity of archaeologists in the field. The research is based on the multi-disciplinary collaboration, started in the 2022 mission, in the framework of a research project with Cà Foscari University of Venice in the excavation site of Tell Zeyd, in Iraqi Kurdistan, the Tell Zeyd Archaeological Project (ZAP) (Figure 1).


(a)


(b)


(c)

Figure 1. (a) The Tell Zeyd and the area of the expected settlement; (b) the team at work in the area, establishing the extension of the survey’s areas and stable system of control points; (c) a moment of the training activity.

1.1 The Tell Zeyd Archaeological Project

The Tell Zeyd Archaeological Project (ZAP) started with a first field campaign in 2022. ZAP aims to study the rural landscape of the hinterland of Mosul in the long Islamic period, from the Arab conquest in the 7th century to the disintegration of the Ottoman Empire with the First World War. This area played a major role in the supply of the caliphate, particularly with regard to cereal products (Tonghini & Usta 2021; Tonghini 2022). The site of Tell Zeyd constitutes an ideal observatory on the settlement, production, material culture and society of this territory from the time it became part of the Islamic Caliphate.
With the excavation of Tell Zeyd, the project aims to document the characteristics of the settlement (spatial organisation, places of worship, production installations and facilities for storing foodstuffs) and to shed light on its material culture and on the palaeo-environment, with specialised archaeo-botany and archaeo-zoology studies. ZAP promotes the knowledge, protection and enhancement of the cultural heritage of the rural world; it also aims to identify innovative policies capable of reinserting rural culture into today's identity, and to enable the community to re-appropriate it and take an active part in its protection.

1.2 Related works

Managing multiple and multitemporal datatests is a crucial task in monitoring application in case of dynamic scenarios (Gülk, 2011). Among the various application for change detection in disaster scenarios, or for construction site monitoring, in case of the site excavation, multitemporal documentation strategies are necessary to track and support the daily routine of the excavation phases for the archaeologist team (Masini & Lasaponara, 2015).
Focusing on the data acquisition issues, on the one hand the automation in flight planning and the choice of high-performance sensors and efficient drones really streamline the capturing operation on large and topographically complex areas, compared to the use of terrestrial close-range photogrammetry by tripod, poles, kites, of more expensive terrestrial Lidar sensors, with a more limited applicability in ordinary recovery operations. Conversely, the standard topographic measurements pipelines to support the metric control of the models and traditional bundle block adjustment (BBA), often takes on a different connotation in terms of time-costs adaptability in the context of archaeological sites. In UAV photogrammetric extensive mapping application direct GNSS positioning solutions have been recently developed for *on-the-fligh* of post-processing estimation of camera geotag position, thanks to RTK (Real Time Kinematic) and PPK (Post Processing Kinematic) solution for positional accuracy, efficiently reducing or avoiding redundant topographic measurement on ground (Sammartano et al., 2020; Teppati Losè et al., 2020; Chiabrando et al., 2013). Particularly for monitoring application, parallelly to cameras direct georeferencing, also automated image-based co-registration approaches have been investigated (Aicardi et al., 2016) as promising strategy to streamline integration and correlation of multi-temporal images blocks, without the use of Ground Control Points (GCPs) or limited to one reference block of anchor images.
The automatic procedures can concern both the image blocks ex-ante, in the orientation phase (Aicardi et al., 2016) or, ex-post, by exploiting direct georeferencing of photogrammetric blocks after BBA, and can concern a refinement of the co-registration of the final products such as orthophoto and DSM, based on features matching. In this paper, the authors propose an automatic solution for co-registration of final products, as described in the following paragraphs.

2. DATA & METHODOLOGY

The UAV photogrammetric tests, as introduced, aim at experimenting a multi-scale and multi-temporal mapping approach based on multiple epochs datasets co-registration. Different solutions have been tested and in next paragraphs some operational problems of datasets collected in the fieldwork and some bottlenecks will be discussed, beyond the design strategy expected beforehand, causing the strategy to evolve seeking for alternative solutions.
Particularly, the research plans to verify the applicability of a semi-automated methodology for image alignment and co-registration workflow with controlled accuracy for multiple images datasets related to specific sondages areas for site fieldwork, following the excavation activities during a couple of months. In this sense the proven strategy aims to

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operationalizing a workflow, that support archaeologists' daily/weekly excavation routine.
The AUTEL EVO II PRO Enterprise RTK Rugged Bundle equipped with RGB camera and RTK module. The GSNN onboard sensor allows a centimetres-level high-precision positioning system using real time kinematic positioning (RTK) and support post-processing kinematic positioning (PPK) (See Par. 3 for further discussion). For each data acquisition session, it has been used the camera XT705 (10.1424 mm) equipping the AUTEL EVO II PRO with the following characteristics: lens focal length 10.14 mm, sensor resolution 5472 x 3648 px, pixel Size 2.4 x 2.4 μm.

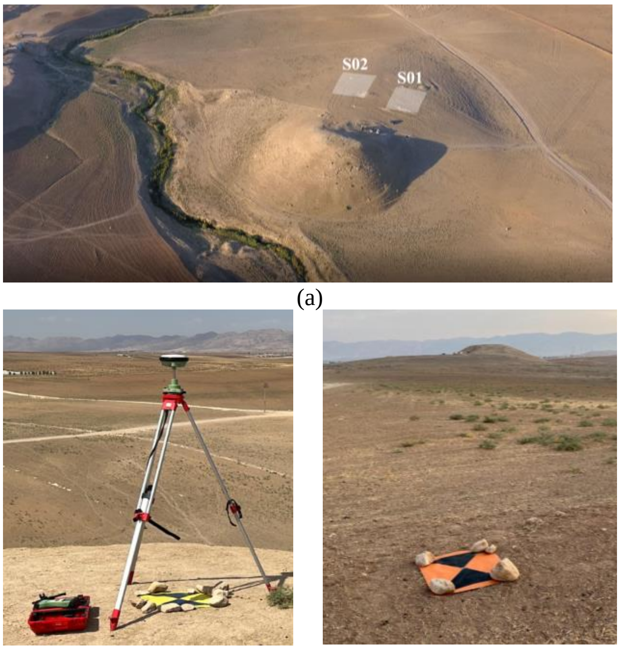

Figure 2. (a) Aerial view of Tell Zeyd by UAV with indication of excavation areas planned by archaeologists. (b) GNSS receiver (c) contrast marker as photogrammetric GCPs.

The planned data acquisition refers to three main general photogrammetric goals:

I. A general wide-scale mapping of the area (Figure 3;Figure 6). This is normally performed with high altitudes and large overlap, which ensure a large-scale documentation of the topography at the beginning of the excavation work in the new site, as in the case of Tell Zeyd. (Accuracy in Table 1).
II. A reference acquisition, with medium-high scale
III. Figure 5), comparable to the scale of the site excavation datasets, related to T0 (time zero), that will be named Epoch 0 [E0], all-encompassing and focused on the work area at the base of the hill named Tell Zeyd (Figure 2a). In this case it refers to the area of sondages. (Accuracy in Table 1).
IV. A series of multi-temporal dataset with a very close-range flight plan (Figure 3), whose result is reported in Figure 7 and Table 2. See Par.2.1.

The topographic approach has been a crucial phase at the beginning of the mission, and generally at the starting point of the new site investigation project. (Figure 2b, c).

A procedural topographic phase has been conducted for two main goals:

- the measurement of a reference vertices network
- the positioning GCPs measurement both contrast markers for (I) wide scale mapping, and stable system of markers for (II) and (III).

The survey of n°5 vertexes have been realized using two GNSS Geodetic Receivers by LEICA Geosystem (Figure 2b) for measuring 3D baselines by means of statical operative method with over 1h of each baseline observation (Figure 4). Considering a high redundant reliable schema with 9 baselines for a total number of 27 observations, the GNSS network has been adjusted with a very high accuracy, and the results show accuracies of few mm in directions.
The ellipsoidal heights estimated for the GNSS vertexes have been converted in Ortho heights (on sea level) using a mean value of Geoid Height (+17.65 m on WGS84 surface) extracted by the most recent global geoid grid, the Earth Geoid Model of 2008 (EGM2008-5) with Geoid Height Calculator by UNAVCO (Cassie Hanagan & Brooks Mershon).
After that, n°23 GCPs (M) (Figure 2c) have been distributed on ground with plastic contrast markers considering a very large area of interest around the *tell*, and measured with Total Station using Leica Circular Prism in infrared mode.
Together with that, a set of n°16 permanent CPs (P) have been distributed in the smaller area of sondages excavation (S01, S02, Figure 2a in aerial view and located in the orthophoto Figure 4), following a 10m*10m network. In this case, the position of the vertices is expected to be stable and continuous for the entire duration of the excavation of the mission. The research focusses on S01.

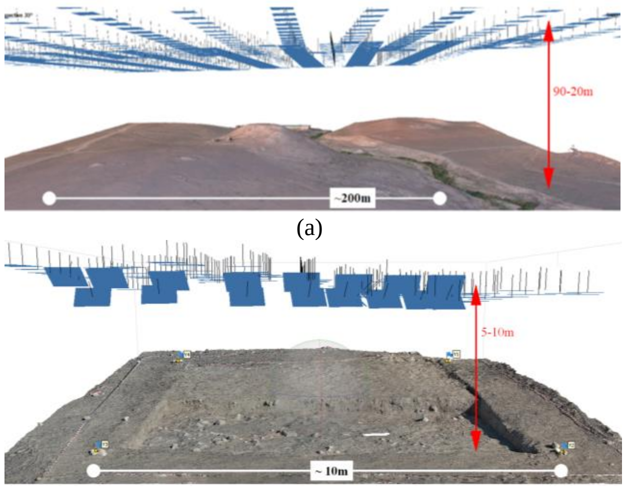

Figure 3. Two photogrammetric blocks configuration: (a) the large-scale flight on the whole site area (I) and (b) the very close-range on S02 soundings excavation area (III).

A large-scale dataset (I) of almost n°1400 images (Figure 3a) have been acquired for mapping the entire area of the tell (Figure 4 ortho; Figure 6, DSM) and its topography for a covered area of almost 0.5 km^2 with a flight height of 65m. This acquisition distance ensures an estimated GSD (Ground Sample Distance) of 1.8 cm/px. For this case, (M) markers are used in the BBA. A reduced coverage dataset (II) of 640 images have been collected, covering the excavation areas of 300m^2 before the sondage opening, with a flight height of 20m and an estimated GSD of 5 cm/px. For this case, (M) markers are used in the BBA (Accuracies of both dataset processing in Table 1).

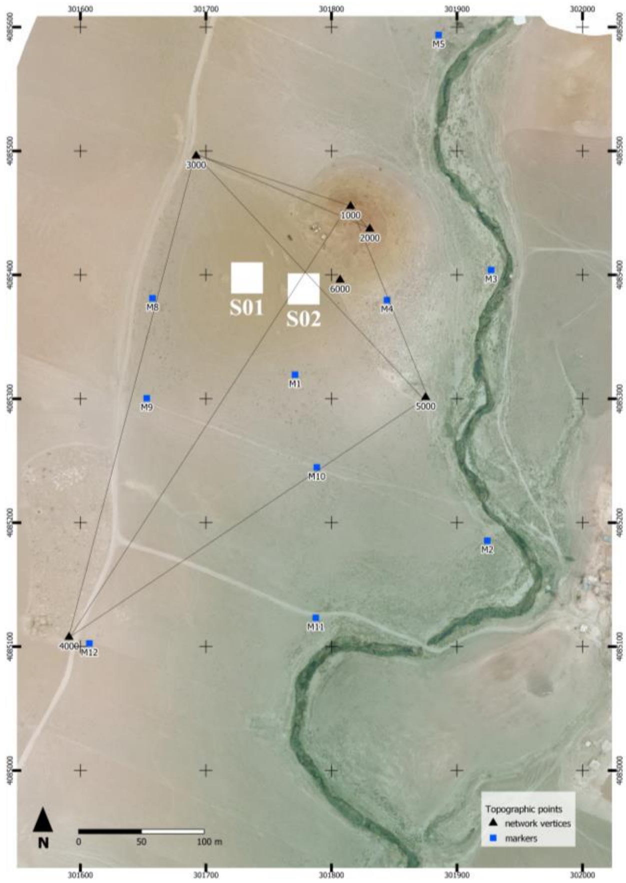

Figure 4. The orthoimage generated from the UAV flight, dataset (I), covering almost 0.5 km^2 with a flight height of 65m. Resolution 2cm/px, with the indication of excavation areas, network vertices and GCPs.

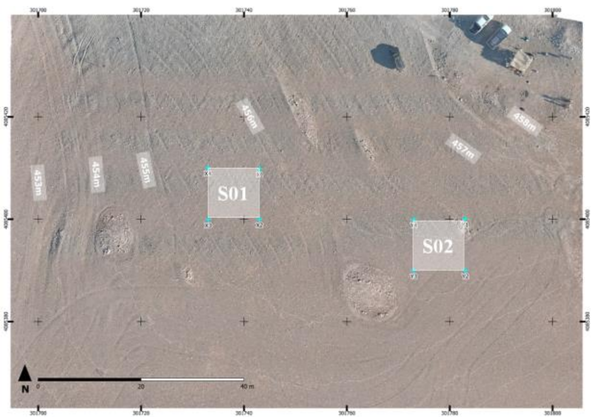

Figure 5. The orthoimage generated from the UAV flight, dataset (II), as the reference Epoch [E0] with the indication of the CPs grid reference system of the two excavation areas.

Table 1. Accuracy results.

(I)	RMSE		
	X (m)	Y (m)	Z (m)
GCPs	0.022	0.013	0.028
CPs	0.031	0.025	0.032
(II)	RMSE		
	X (m)	Y (m)	Z (m)
GCPs	0.015	0.014	0.008
CPs	0.019	0.020	0.012

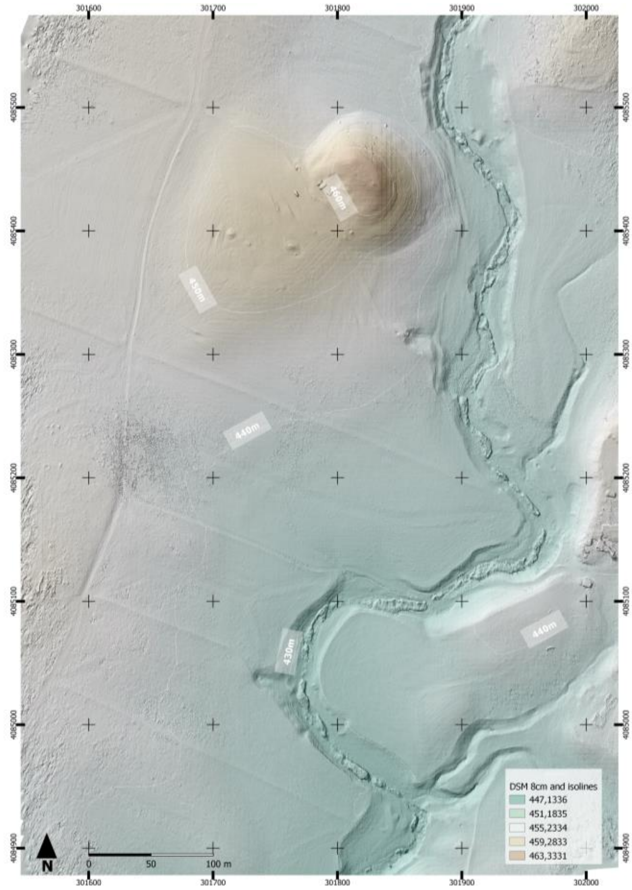

Figure 6. The DSM generated from (I) dataset, with 8cm/px.

Parallelly to that and during the following fieldwork month, different test datasets named epochs [E1], [E2,] etc… have been collected at greater scale in different day epochs, to recurrently record the excavation progress, as reported in Table 2 and Figure 7. Within this approach, the multiple datasets acquired, even at different scales, are planned to contain in their coverage areas (P) points, the permanent CPs.

Table 2. Epochs datasets

Epochs		Images n°	height	GSD mean	Valid
[E1]	25.09.22	245	17	5mm/px	X
[E2]	27.09.22	70	10	4mm/px	
[E3]	01.10.22	230	5	3mm/px	X
[E4]	03.10.22	245	5	3mm/px	
[E5]	10.10.22	260	5	3mm/px	X
[E6]	13.10.22	130	10	4mm/px	
[E7]	16.10.22	125	5	3mm/px	

2.1 Proposed workflow & challenges

As introduced, the research approach aims to propose an alternative solution to the standard GCPs-based BBA of excavation area datasets, based on georeferencing approaches exploiting real-time coarse GNSS georeferencing solution, dependant on the quality of the onboard sensor equipping the drones, in absence of PPK and RTK solutions. It is delivering final metric products (Ortho and DEM) generated within an assisted workflow into commercial software interface (e.g., Agisoft Metashape in this tests), and then a co-registration using the pipeline as in Figure 8 is applied.

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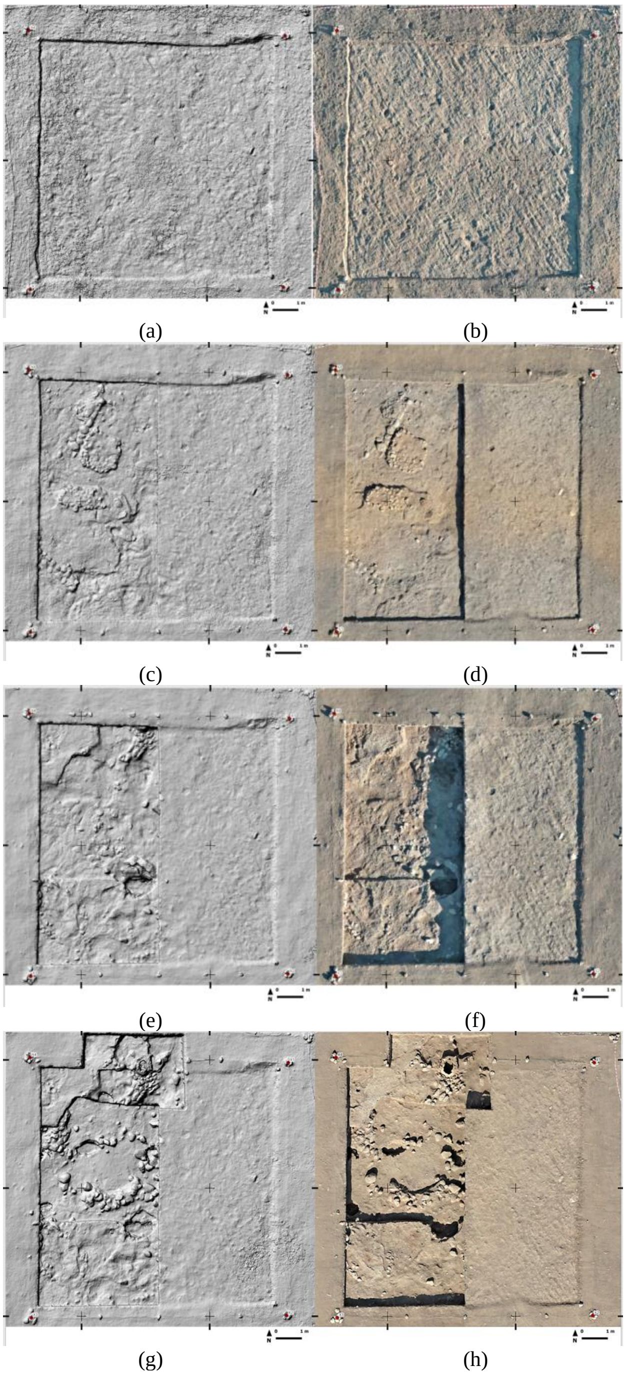


Figure 7. A sample of epochs results, DSM, left and ortho, right: (a) and (b) for 25/09; (a) and (b) for 26/09; (c) and (d) for 01/10; (e) and (f) for 10/10; (g) and (h) for 16/10.

Finally, the methods plan to analyse positional accuracy of the proposed solution results. The test results are compared to the ground-truth photogrammetric model, that considers the use of the GCPs-based BBA. The validation tests refer in detail to the position accuracy (XYZ) with different georeferencing solutions and make use of: [E0] as reference epoch dataset, and [E1], [E2], etc… as co-registered dataset based on input orthophoto and input DSM, with the use of (P) and without them, only exploiting real time GNSS data associated to images *exif* data.
The Figure 8 show a schematic synthesis of the proposed workflow and implemented into MATLAB®.

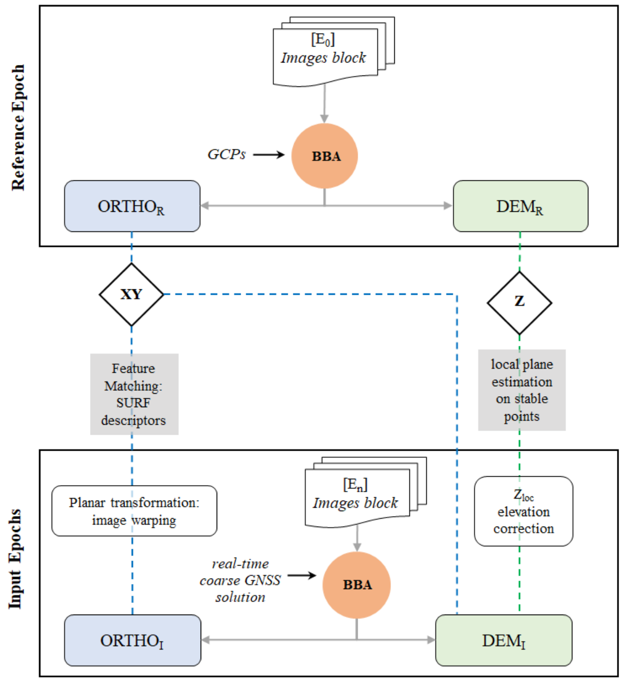
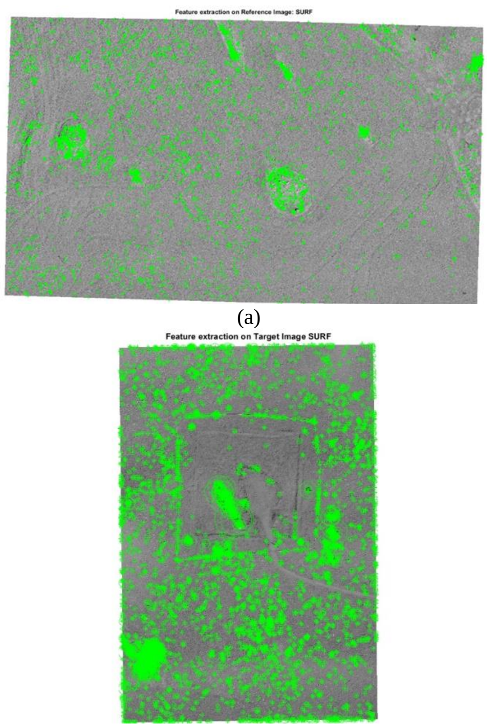


Figure 8. The proposed workflow, from the reference epoch to the input epoch

Th algorithm realizes the coregistration between 2 orthophotos [Ex] and [Ey] using a well-known feature extraction and matching approach. Both scale-invariant feature transform - SIFT (Lowe, 2004; Lingua et al., 2009;) and Speeded Up Robust Feature - SURF (Bay et al., 2008) have been tested. The SURF is the one that delivers optimal matching results with this specific environment conditions (lack of extensive image details). An adaptive local histogram equaliser has been applied to orthophotos enhancing the radiometric contrast before the SURF feature extraction.
A feature matching has been applied to the two sets of points extracted from the orthophotos [Ex] and [Ey], defining a list of multi-temporal homologous points used for the robust estimation of a 2D roto-translation with homogeneous scale factor. In this phase, the orthophoto [Ex] must be georeferenced to realize the coregistration of the orthophoto [Ey].
Finally, the orthophoto [Ey] has been resampled according to the estimated 2d roto-translation obtaining a new georeferenced image.

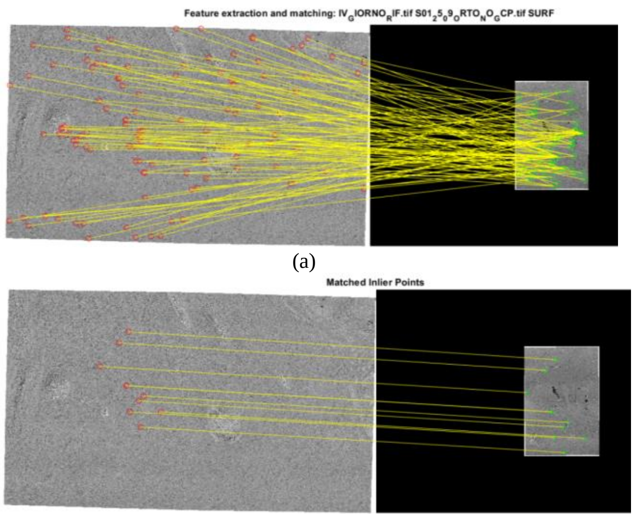
2.1.1 *Results of planar co-registration*

The co-registration tests have been conducted between all the consecutive epochs pairs, according to Table 2.
Both reference and input orthoimages have been processed with a GSD of 1 cm. The first successful coregistration is the one regarding [E0] and [E1].
The feature extraction Figure 9 have been performed without contrast enhancement (ContrastType=A).
In Figure 10 the matched points results.
The results of the coregistration approach have been compared (Table 3) with the initial location of the orthophoto derived from the automatic BBA based on real-time coarse GNSS georeferencing solution: the accuracy of proposed solution has been estimated using a set of 4 CPs surveyed using a total station (sqm = 5 mm) and completely indipendent from the points used for the coregistration.



(a)
(b)

Figure 9. The epochs [E0-E1] co-registration test: feature extraction

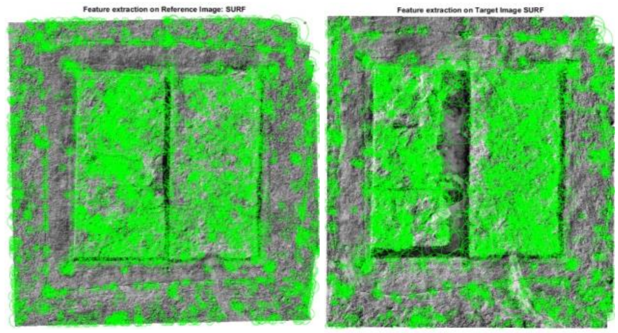


(a)
(b)

Figure 10. [E0]-[E1] feature matching

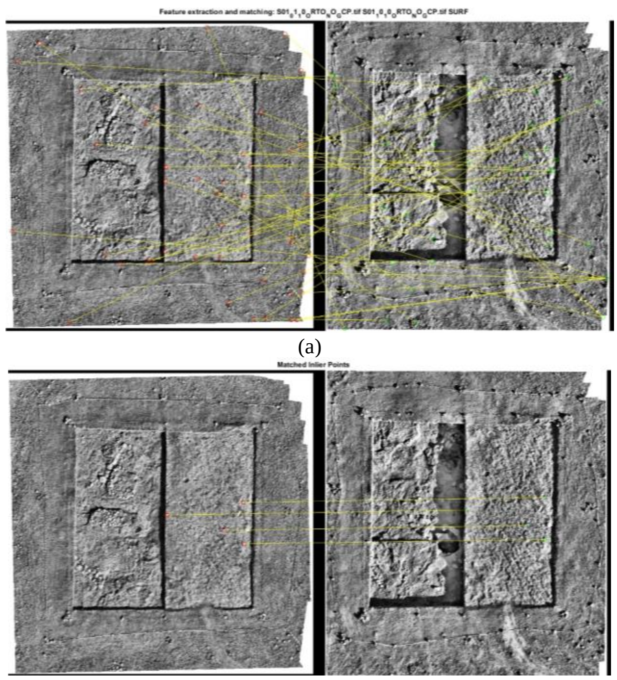
Table 3. Accuracy results for [E0]-[E1] co-registration

CPs	Before Co-registration (real-time coarse GNSS solution)		After Co-registration	
	X (m)	Y (m)	X (m)	Y (m)
X1	0.808	2.033	0.021	0.067
X2	1.137	1.717	0.003	0.053
X3	0.850	1.456	0.033	0.003
X4	0.485	1.795	0.011	0.012
Mean error	**0.820**	**1.750**	**0.017**	**0.034**



(a) (b)

Figure 11. The epochs [E3]-[E5] co-registration test: feature extraction.



(a)
(b)

Figure 12. [E3]-[E5] feature matching

With the same approach, a second successful coregistration regards [E3] and [E5]: after the SURF feature extraction (Figure 11), the matched points are shown in Figure 12, while Table 4 shows the comparison between accuracy results for [E3]-[E5] co-registration.

Table 4. Accuracy results for [E3]-[E5] co-registration

CPs	Before Co-registration (real-time coarse GNSS solution)		After Co-registration	
	X (m)	Y (m)	X (m)	Y (m)
X1	1.549	0.660	0.026	0.019
X2	1.558	0.935	0.079	0.075
X3	1.845	0.917	0.025	0.123
X4	1.851	0.619	0.096	0.010
Mean error	**1.701**	**0.783**	**0.056**	**0.057**

2.1.2 *Vertical co-registration.* To obtain a co-registration of the DEM coherent with the orthophoto (Figure 8), the same 2D roto-translation with scale factor has been applied generating a new georeferenced DEM.

In the epoch [E_1], the georeferenced DEM has been compared with the original DEM of epoch [E_0] using a set of 12 points located near the excavations but within an area potentially not affected by the excavation activities and therefore unmodified.

Albeit correct planar (horizontal) location of the DEM, the discrepancies in Z direction (Table 5), depict very high errors (about 18 m), due to the inadequate real time solution of the on board GNSS receiver. The sqm of these Z discrepancies (about 1.2 m) denotes that it is not possible to apply a simple vertical translation to obtain a correct DEM: a specific correction must be thus defined to solve these errors. The proposed solution uses a robust estimation of a local plane (Z_{loc} correction) based on the 3D coordinates of the set of 12 stable points. If the points considered stable for the estimation of Z_{loc} correction are partially affected by local topographic terrain variations due to work activities (e.g., moved stones, etc.), their rejection can be applied using a robust estimation technique. The results of this approach for [E1] are shown in Table 5 (right column) in comparison with the uncorrected ones. This method has been applied to the other epochs obtaining similar results.

Table 5. Accuracy results for [E0]-[E1] co-registration

Local points	Before Coreg. (real-time coarse GNSS solution)	After Z_{loc} correction (Points used for the estimation)	After Z_{loc} correction (Independent points)
	Z (m)	Z (m)	Z (m)
Mean Error	18.02	0.045	0.063
St. dev	1.23	0.015	0.018

3. RESULTS & DISCUSSION

As introduced, the demanding context conditions and the excavation routines were the most challenging aspects in the experimentation of the workflow, and in the optimal exploitation of the multi-temporal datasets.These considerations must certainly be taken into account in the planning of subsequent tests and in the improvement and refinement of the methodology. Furthermore, the aspect related to direct positioning of images block potentially contributes to the workflow streamline. Nevertheless, in foreign archaeological areas, especially in complex geopolitical situations such as Iraqi Kurdistan, the availability of an effective and continuous GNSS signal is not an aspect to be taken for granted. This is the reason why the plan to exploit RTK direct georeferencing was not possible indeed, and therefore the starting dataset on which to experiment the proposed pipeline was based on real-time coarse GNSS solution. It must be emphasized also that the results in terms of accuracy of the positioning in the proposed co-registration strategy, especially Z, are not yet optimal for the accuracies required by the measurements of the excavation levels and for the definition of the phases-related stratigraphic units’ in the archaeological research.

3.1 Bottlenecks & limitation

The main problematic aspects evident from the experimental datasets are thus summarized as:

- Epochs dataset features: uneven distribution of images between epochs; outmost height difference between the reference epoch and the dataset belonging to the following epochs
- GNSS signal continuity and reliability
- Ensure adequate coverage area over unchanged boundary surfaces, strictly dependent on the global coverage area itself.

Initially, some tests were also conducted to co-register the multitemporal datasets in the BBA phase using the principle of anchor-images blocks in the adjacent unchanged areas, but the datasets proved to be too close together and with too little area of overlap. Furthermore, this area was subject to localized modifications due to excavation operations.

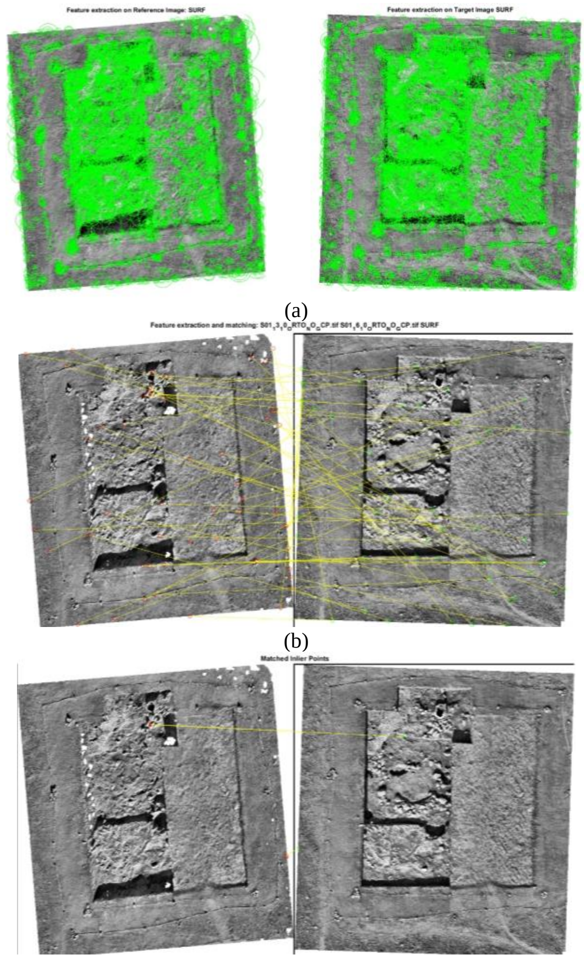


Figure 13. [E6]-[E7] feature extraction (a) and failed matching (b) without valid inlier points (c).

The example in Figure 13, shows one of the failed epochs pair matchings, [E6]-[E7], with similar results even using other types of 2D transformation (e.g., projective, affine). These problems may be due to different aspects: some local deformations in the orthophotos, caused by an incorrect image alignment given the GNSS errors; the inability for the descriptors used in the transformation to detect the correct extracted points for the image matching and the significative radiometric variation between the images, due to the different times of acquisition (affecting shadow projections and color saturation).

4. CONCLUSIONS & PERSPECTIVES

The initial phase results of Geomatics investigation within ZAP project aims to optimize UAV photogrammetric workflow for sustainability of multi-temporal survey in archaeological mapping, improving automation and developing, testing and validating direct georeferencing. In the research perspectives, following the campaign progression in 2023 and with

archaeologist fieldwork and stratigraphic excavation, the perspectives are oriented toward tree main goals:
- the streamline of the multi-temporal data co-registration approach, optimizing the proposed strategies, focusing improving of lighting conditions, capturing more regular datasets according to number and flight height, according to broader areas ensuring wider unchanged areas
- the possibility of acquiring visible and non-visible data, useful for identifying potential archaeological evidence present in the area in order to orientate detailed archaeological investigations towards interesting objectives
- the construction of a 3D/2D data geodatabase for interdisciplinary workflows and dissemination of results and knowledge developments about the site, specifically for spatial organization of historical settlements.

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