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3D SURVEY AND MONITORING OF ONGOING ARCHAEOLOGICAL EXCAVATIONS VIA TERRESTRIAL AND DRONE LIDAR

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ABSTRACT:

In recent years, LiDAR has seen an increased application in the field of archaeological documentation, as it allows for rapid acquisition of spatially dense and accurate point clouds. The three-dimensional survey and monitoring of ongoing excavations is a topic of particular interest for archaeological documentation, due to the importance of recording stratigraphy during the destructive and irreversible process of the excavation, and the challenges of obtaining complete photorealistic digital representations of the archaeological terrain. In this paper, we investigate the feasibility of obtaining in real time high-quality digital models and maps of the stratigraphy via laser scanning, aiming to establish a replicable methodology for archaeological practice. Optimal acquisition and processing scenarios are explored for both terrestrial and drone-mounted LiDAR. The application concerns two different case studies of archaeological interest with different topography. The presented research is part of the project ARCHAEORAMA–“Advanced system for multimodal Recording, Documentation and Promotion of Archaeological Work”.

1. INTRODUCTION

1.1 LiDAR and Archaeology

LiDAR (Light Detection And Ranging)—implementing ToF (Time of Flight) active laser sensors—is a contemporary geomatics technology adopted in the field of virtual archaeology, which can significantly reduce digital recording times, without sacrificing the quality and spatial resolution of the recorded data (Haddad, 2011). Therefore, LiDAR-based scanners find wide application in digital three-dimensional (3D) recording of excavation sites and archaeological remains (Moser et al., 2010; Usami et al., 2017), where density and accuracy of the collected data is of high significance. The recording of archaeological stratigraphy, as one of the most important documentation products of the excavation process of historic sites, is significantly assisted by the use of laser scanners which in effect gives new possibilities to the visualization and management of the generated archaeological information (Croix et al., 2019; Previtali and Valente, 2019).

1.2 Terrestrial Digital Recording

The surveying of excavations and, in general, archaeological sites with terrestrial LiDAR, is characterized by flexible and fast data acquisition, but is nonetheless accompanied by restrictions caused by the geometric arrangement of the recording procedure (Doneus and Neubauer, 2005). A common problem regarding terrestrial laser scanning is the occlusion of areas out of the instrument’s field of view, which can be observed on the collected point clouds, a result of either the archaeological site’s topography, the excavated architectural remains, or other natural and artificial obstacles. Tackling these occlusions often requires the execution and subsequent merging of multiple overlapping scans (Ebolese et al., 2018; Torres et al., 2014). The optimal design of the network of scans requires careful planning of the individual laser scanner positions in order to acquire a complete and homogeneous point cloud (Stamnas et al., 2021). Usually, the integration of terrestrial laser scanning with structure-from-motion multi-image digital photogrammetry is preferred over performing a very large number of scans, not only because of the greater ease of covering the occlusions, but also for the reason that this combination produces better quality of texture attributed to the resulting point clouds and photorealistic models (Galeazzi, 2016; Siebke et al., 2018).

Digital recording of ongoing archaeological excavations via laser scanning is a current topic, seldom addressed with state-of-the-art LiDAR technologies and scarcely found in literature, not only due to the difficulty of fully scaning an excavation, but also due to legal and time-related restrictions often involved when publishing information from excavations in progress. The multi-temporal scanning of an ongoing excavation process helps monitor changes in the pit topography, making it possible to generate reliable geospatial information independent of the work platform (e.g., geographical information systems, 3D modeling or analysis programs) (Martínez-Fernández et al., 2020). Real-time excavation laser scanning offers the possibility of digitally reconstructing the excavation process, mapping the state of excavated surfaces, documenting the level of preservation and stability of surfaces such as stratigraphic walls, even when immediate and irreversible interventions are imposed to secure them (Schreiber et al., 2012).

1.3 Low-Altitude Digital Recording

The continuous miniaturization of sensors and electronic components has enabled the integration of LiDAR into unmanned aerial platforms, allowing low-altitude laser scanning for digital mapping of sites of archaeological interest. The availability of compact LiDAR sensors for drones is growing rapidly, as the latest technological developments have allowed a

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progressive increase on the quality of the collected point clouds, and the precision of their georeferencing. This situation creates fertile ground for the replacement of high-altitude LiDAR data collection (by manned aircrafts), with LiDAR-equipped drones, as point cloud acquisition becomes gradually more flexible and therefore more comprehensive (Adamopoulos and Rinaudo, 2020). The performance limitations of LiDAR instruments for drones regarding measurement density—occurring due to reduced sensor sizes and lower intended costs—can be compensated by collecting data from lower flight altitudes, i.e., with a shorter distance between the laser sensor and the ground.

Contemporary applications of drone LiDAR for archaeology are mainly focused on digitization and visualization of the terrain morphology for large archaeological sites, land surveys to investigate the possible existence of buried archaeological remains, and landscape archaeology (Casana et al., 2021; Kadhim and Abed, 2021; Murtha et al., 2019; Risbøl and Gustavsen, 2018; Saunaluoma et al., 2019; Zhou et al., 2020). Multitemporal digitization of excavations by means of drones has successfully been addressed with low-altitude aerial photogrammetry (Papadopoulou et al., 2020; Waagen, 2019). Therefore, drone LiDAR also presents an exciting prospect as a means for documenting ongoing excavations, considering that the production of 3D models from LiDAR scans is, generally, less time-consuming comparing to structure-from-motion multi-image photogrammetry.

1.4 Scope and Aims

The main scope of this research is to investigate multitemporal documentation of ongoing archaeological excavations via terrestrial and low-altitude aerial LiDAR. We aim to propose a well-defined mapping approach for 3D survey and monitoring, highlighting strengths and weaknesses of this technique for archaeological use. We also intend to address special challenges occurring from the ongoing excavation process.

2. METHODOLOGY

2.1 Data Collection

The purpose of surveying and monitoring an archaeological excavation site with geomatic tools is obtaining digital records of the ongoing excavation process at different stages, while minimizing the manual work required to generate drawings, maps, and photorealistic representations. Personnel allocation and time consumption are critical parameters for the excavation, which requires careful management of available resources and, at the same time, thorough recording of the stratigraphy that can be irreversibly altered through the destructive excavation work. A workflow for multitemporal documentation of excavation sites, not only has to consider the management of available resources, but also has to take into account the specific circumstances that arise from the ongoing excavation procedure, delivering the required accuracy and quality of results. Due to the prevailing time restrictions and topographical constraints of the excavation, a digital recording strategy needs to be flexible and adjustable for varying terrains. The scanning configuration as well as scanner specifications are key attributes for defining an efficient approach for excavation monitoring via LiDAR.

2.1.1 Excavation Surveying with Terrestrial LiDAR: The ToF operating principle of a terrestrial LiDAR means that obstacles along the laser sensor's line-of-sight create occlusions on individual scans, leading to lack of data on the acquired 3D point cloud. Therefore, the optimization of the laser scanning configuration—which is formed by a network of terrestrial LiDAR positions spread throughout the archaeological excavation site—during acquisition is essential to ensure the point cloud's completeness. In particular, planning the layout of the scanning process is required to avoid holes occurring on the point cloud due to the geometry of the pits, unearthed immoveable finds, and natural obstacles, simultaneously minimizing the number of required scans. As the occlusions are directly related to the excavation pit's depth, the progression of the excavation directly affects the occlusions and subsequently the number of scans necessary to acquire a complete point cloud (Figure 1; o=d*r/h where o: occlusion, d: excavation pit depth, r: horizontal distance from the pit, and h instrument height). The pattern of occlusions is also affected by the terrestrial LiDAR's relative location to the excavation pit (Figure 2). A large-scale systematic archaeological excavation, consisting of a grid of square pits with unexcavated balks between them, has significant occlusions (due to the existence of the balks), which progress as the pits deepen (Figure 3). Consequently, while the excavation advances the number of required scans increases. It should be highlighted that the network of the terrestrial LiDAR positions has to be even denser after architectural remains are unearthed, in order to tackle additional occlusions. The number of scans also increases depending on the topography of the site as it may not allow placing the scanner in certain positions. Considering the above, the laser scanning configuration is optimized to collect a complete and homogeneous point cloud.

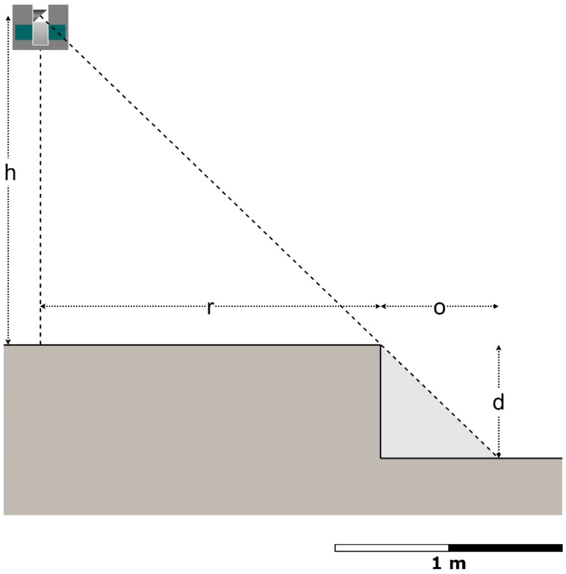


Figure 1. Relation between LiDAR instrument position and excavation pit occlusion for a single scan.

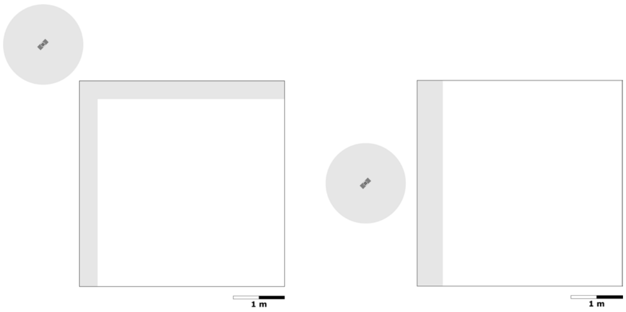


Figure 2. Occlusion diagram for one station of the 3D laser scanner (nadiral view) for a pit depth of 0.75 m—the occlusions due to the line-of-site of the instrument are highlighted in grey.

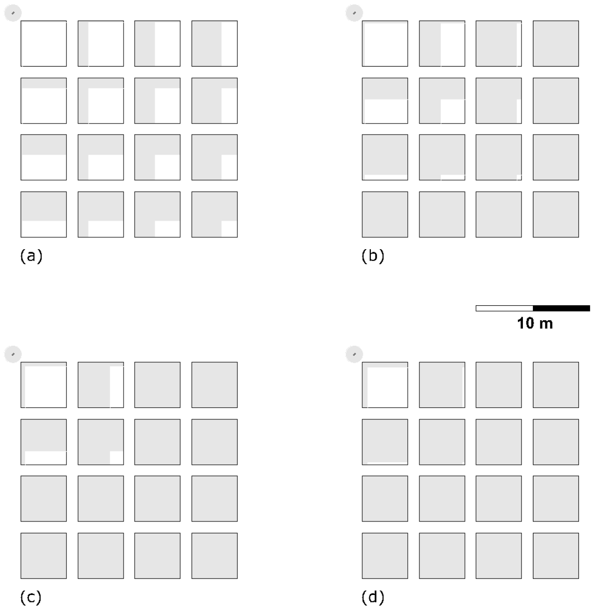


Figure 3. Occlusion diagram for one station of the 3D laser scanner (nadiral view) for pit depths of (a) 0.25 m, (b) 0.50 m, (c) 0.75 m, and (d) 1.00 m— the occlusions due to the line-of-site of the instrument and the excavation balks are highlighted in grey.

LiDAR technical specifications and scan parameters are important for optimizing the scanning process while reducing acquisition time. Scan density (the distance between individual 3D point measurements) affects the quality of the results, and should always be higher than the required resolution, however higher density values mean longer scanning duration. At the same time, the resolution should not be lower than the ranging accuracy (or the ranging noise value), as the collected point cloud may contain a significant amount of noise which cannot be filtered out at a later processing stage. Hence, the density value should be selected so that it does not produce unnecessarily dense, sparse or noisy 3D point clouds. Limiting scanning angles to only capture the area of interest within the excavation site also reduces recording times significantly.

Image capturing with an integrated camera can produce true color texture for point clouds and photorealistic models, but is another factor increasing the scanning duration, depending on the selected capturing features. When terrestrial LiDAR is used as a standalone solution for excavation surveying, the only source of color texture is the integrated digital camera, and therefore the imaging parameters required to obtain good fidelity texture should be selected in accordance with the lighting conditions of the excavation site. High dynamic range (HDR) imaging and weighted color balancing are capturing options that can allow better quality color to be captured. When terrestrial LiDAR is used in combination with photogrammetry, color capturing with the integrated camera can be avoided to reduce the data capturing duration. Alternatively, low quality color capturing can be selected if the texture is deemed essential to identify artificial targets for the registration process.

The scan registration and georeferencing methods are other important parameters that should be taken into consideration while planning the scanning procedure. Registration targets should be visible in multiple scans, which affects both the geometry of the scanning layout and the placing of the targets. Targets should be spread throughout the excavation. Each pair of scans needs at least three common targets to perform the registration. Having targets visible between multiple scan pairs ensures more accurate registration. 2D targets can replace sphere targets when weather or terrain conditions make their placement difficult. An important consideration for good coverage is to ensure that there is a significant amount of overlap between scans, especially if the survey is heavily reliant on cloud-to-cloud registration. Determining and measuring a control network allows georeferencing to the national grid or a site-wide system, and ensures successful merging when target-to-target or cloud-to-cloud registration may fail.

2.1.2 Excavation Surveying with Drone LiDAR: Low-altitude airborne LiDAR tackles a significant number of problems occurring from data collection with terrestrial laser scanning. Drone-mounted LiDAR, which operates with the same line-of-sight principle as terrestrial LiDAR, leads to less occlusions on the scans, due to the incidence angles of the laser beam and the continuous acquisition from the moving laser sensor. Although longer distances from the target and flight time restrictions usually lead to sparser 3D point clouds, this can be compensated by multiple passings over the excavation and planning the flight height accordingly.

Scans acquired from multiple flights can be registered following the same methods as for terrestrial LiDAR. However, it should be highlighted that georeferencing using data from an integrated positioning system onboard the unmanned aerial platform facilitates the registration procedure. Direct georeferencing to the national grid using data from the onboard sensors may be sufficient in terms of required accuracy (depending on the type of archaeological application) meaning that measurements with a terrestrial positioning sensor may not be necessary.

A drone-mounted LiDAR instrument can be often coupled with a camera sensor, that being the case the flight path can be planned as a photogrammetric flight, thus acquiring both dense scans and a photogrammetric block of images, which is used to apply true color texture on the point cloud.

2.1.3 Excavation-Parallel Monitoring: Monitoring an ongoing excavation requires multitemporal 3D surveying and can take place at set time intervals, every time a stratigraphic layer has been excavated, or a group of archaeological findings has been unearthed. For excavation-parallel monitoring to take place, the control network should be unchanging, so that point clouds, meshes and terrain models produced over time can be comparable. This needs favors georeferencing to the national grid with a GNSS sensor over a site-wide reference system, due to the continuously changing terrain of an excavation site. Point cloud acquisition intended for monitoring should be consistent regarding density, accuracy, noise levels and color fidelity.

2.2 Data Processing

Unprocessed point clouds can be useful for undemanding visualization purposes, providing a swift and useful perspective of the archaeological excavation through cross sections and static scenes, however, further analyses require in most circumstances processing of the scan data. Processing steps providing documentation deliverables include: registration, denoising, subsampling, segmentation, classification, meshing, texturing, vectorization, and visualization.

3. APPLICATION AND RESULTS

3.1 Description of the Equipment

Terrestrial digital recording of the archaeological excavations was performed with the FARO Focus^{M} 70 laser scanner (ranging error: 3 mm), while the coordinate measurement for geo-referencing the collected 3D point clouds was performed with the Leica GS07 antenna (XY error: 10 mm + 0.5 ppm, Z error: 20 mm + 0.5 ppm using kinematic RTK positioning). The low-altitude aerial digital surveys were carried out by means of the DJI Zenmuse L1 LiDAR of the Matrice 300 drone (ranging error: 3 cm at 100 m distance), while the precise control of the position of the drone was done with the DJI D-RTK 2 sensor (XY error: 10 mm + 1 ppm, Z error: 20 mm + 1 ppm with kinematic RTK positioning). 2D targets were used instead of sphere targets, as the weather conditions prevented their use.

3.2 Case Study at Paleokastro Hill (Mykonos)

The Paleokastro, or Gizi Castle, of Mykonos is built on the top of the homonymous hill which rises about 150 m from the surface of the sea, in the middle of the island near the current settlement of Ano Mera, overseeing the surrounding fertile lands and the bay of Ftelia. Today it is preserved in a dilapidated state, while around the hill lay archaeological remains of, probably, retaining walls and other constructions. It is dated to the 7th century AD. and it was probably built atop of a more ancient fortification, given that under the Byzantine castle remains of the ancient fortification of the area can be clearly seen. The strategic position of the hill of Paleokastro and the relevant findings of surficial 1 investigations reveal the uninterrupted habitation of the area from antiquity to the present day and lead to the opinion that it is one of the most important archaeological sites of the island (Figure 4). More specifically, the use of the location already during the Prehistoric period is confirmed by archaeological remains of settlements and burials of the Geometric period, which have been identified on the slopes of the hill.

Figure 4. Marking of the excavation grid at Paleokastro hill, Mykonos.

3.2.1 Terrestrial LiDAR: Multitemporal recording via terrestrial LiDAR at the Paleokastro hill excavation site was carried out during five successive days of the excavation process, recording clusters of overlapping scans, aiming to collect complete point clouds, and subsequently to generate photorealistic models of each phase of the excavation. The surveying was performed following the approach described in Section 2, adjusting the scanning layout depending on the natural and artificial obstacles, the depth of the excavation, and the geometry of excavated architectural remains. The required scale of the final products was 1 cm and therefore a lower resolution (point spacing of 6.1 mm at 10 m) was selected. Furthermore, the placement of 2D targets for the control network measurement was completed avoiding their collinearity and coplanarity, in order to achieve precise registration between scans and small georeferencing residuals.

Figure 5. Photo of the excavation pit after the last day's excavation work at Paleokastro hill, Mykonos.

The required number of scans to acquire a complete point cloud was increasing each day, while the depth of the excavation pit was also increasing to a final 0.8 m (Figure 5). Four scans were required the first day when the pilot scanning application started, and then five, five, six and seven the following days successively, also increasing the recording time from fifteen minutes to approximately an hour. The time required to plan the scanning layout also increased day by day due to the complexity of the acquisition. Figure 6 shows the scanning layout of the excavation during the first and last day of the recording with terrestrial LiDAR.

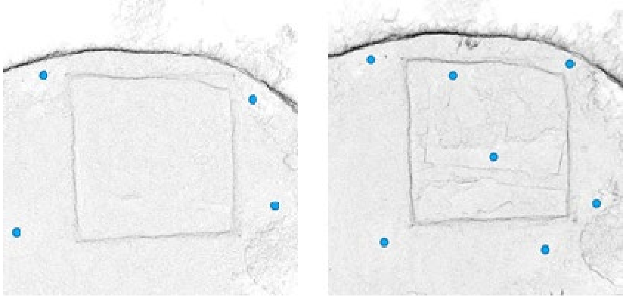


Figure 6. Scanning layout for the first and fifth scan clusters collected at Paleokastro hill, Mykonos.

The workflow for producing 3D photorealistic models from the clusters of scans followed specific and replicable steps. The same processing parameters were applied for all clusters of scans, from the initial phase of generating point clouds from the scans until the final production of the textured mehes:

A. Point Cloud Generation from Scans (FARO Scene)
  1. Point cloud creation
     - Create scan point clouds
  2. Point cloud colorization
     - Colorize scans from photos
  3. Point cloud registration and merging
     - Manual point-based registration (artificial targets)
     - Cloud-to-cloud registration optimization
  4. Production of final merged point clouds
     - Distance filter: Maximum distance 7.5 m

  - Stray point filter: Grid size 3px, Distance threshold 0.0061 m
  - Edge artifact filter: No
  - Denoising: Medium denoising, Resampling distance 6.1 mm

B. Point Cloud Post-Processing (Cloud Compare)
1. Noise removal
   - Clean\Noise filter
2. Subsampling
   - Subsample: 6 mm
3. Georeferencing
   - Registration\Align (Point pairs picking)
4. Triangulation
   - Delaunay

C. Photorealistic 3D Model Generation (MeshLab)
1. Normals generation
   - Compute normals for point sets
2. Phototexture production
   - Parametrization: Trivial Per-Triangle
   - Transfer: Vertex Attributes to Texture

Figure 7. 3D model from the fifth day of scanning at Paleokastro hill, Mykonos.

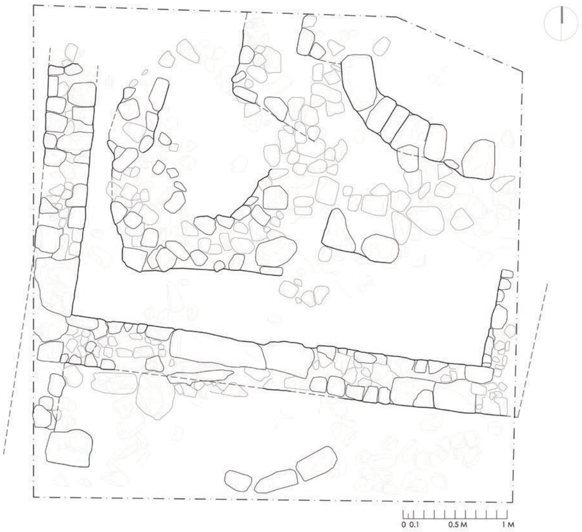
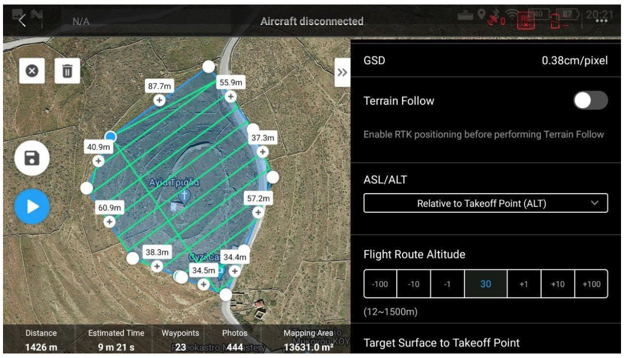


Figure 8. Drawing of the unearthed architectural remains at Paleokastro hill, Mykonos.

The point cloud registration residuals in each scan cluster were approximately 2 mm, while the georeferencing residuals were in all cases approximately 10 mm. There were no occlusions in the final merged point clouds and thus no holes or discolorations were observed on produced 3D meshes (Figure 7). The point clouds were also used to produce 2D drawings of the architectural remains (Figure 8).

3.2.2 Drone LiDAR: Recording at the Paleokastro hill excavation site via drone LiDAR was carried out during three successive days of the excavation process, performing each day one flight obtaining a complete point cloud and one acquiring a photogrammetric block (Figures 9 and 10). The scans had a density of approximately 40,000 pts/m^2 and the images a resolution of 4 mm.



GSD 0.38cm/pixel

Terrain Follow

ASL/ALT: Relative to Takeoff Point (ALT)

Flight Route Altitude: 30

Target Surface to Takeoff Point

Distance 1426 m

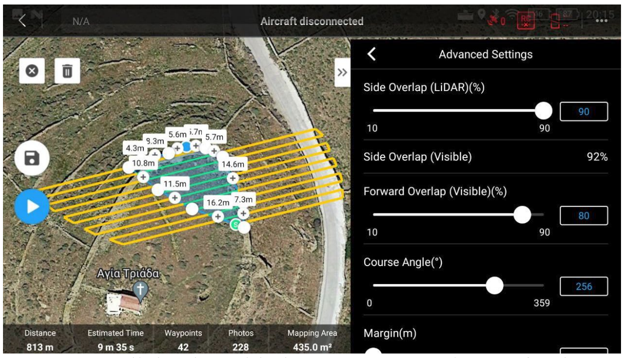
Estimated Time 9 m 21 s

Waypoints 23

Photos 444

Mapping Area 13631.0 m²

Figure 9. Flight plan with the Zenmuse P1 camera, for the 3D surveying of Paleokastro hill.



Side Overlap (LiDAR)(%) 90

Side Overlap (Visible) 92%

Forward Overlap (Visible)(%) 80

Course Angle(°) 256

Margin(m)

Distance 813 m

Estimated Time 9 m 35 s

Waypoints 42

Photos 228

Mapping Area 435.0 m²

Figure 10. Flight plan with the Zenmuse L1 LiDAR, for the 3D surveying of Paleokastro hill.

Point cloud generation from the scans, and georeferencing were performed in DJI Terra. The orientation of the photogrammetric block of images and the dense point cloud reconstruction were executed in Agisoft Metashape. Then the photogrammetric and LiDAR point clouds were registered in Metashape so that the mesh produced after triangulation could be textured with true color. The georeferencing residuals were in all cases approximately 17 mm. The point clouds (Figure 11) and 3D models (Figure 12) had lower density but higher texture fidelity than those produced by terrestrial LiDAR.

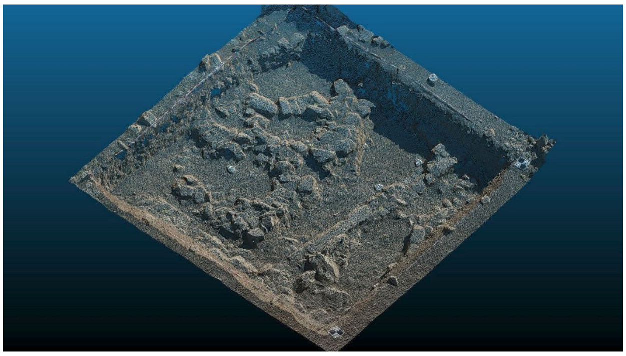


Figure 11. 3D point cloud of the excavation site at Paleokastro hill from LiDAR data in Cloud Compare.

Figure 12. 3D model of the excavation site at Paleokastro hill from LiDAR data in Cloud Compare.

3.3 Case Study at the basilica of Agios Kirykos (Delos)

The archaeological remains of the Early Christian basilica of Agios Kirykos, built in the 5th century AD., are located in the northwestern part of Delos, close to the port. More specifically, against the southeast corner of the Agora of Delion, 8 m south of the Tritopatorus Monument. It is a three-aisled basilica with a narthex and a large prominent arch (Figure 13).

Figure 13. Basilica of Agios Kirykos, Delos: central and south aisle.

Recording with LiDAR and photogrammetric 3D modeling were carried out for three small scale excavations taking part at the Basilica of Agios Kirykos, one at the south aisle, one at the narthex and one at the bema, in order to acquire complete phototextured 3D models on the initial and final phases of the excavations. Figures 14 and 15 show examples of the scanning layout and the registration process for the point cloud of the narthex excavation.

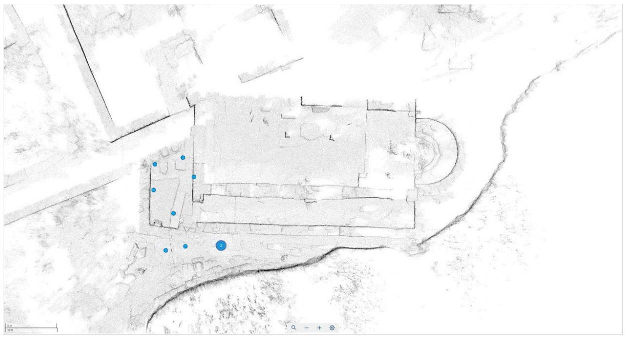


Figure 14. Layout of scan cluster for the excavation at the narthex of the Basilica of Agios Kirykos, Delos.

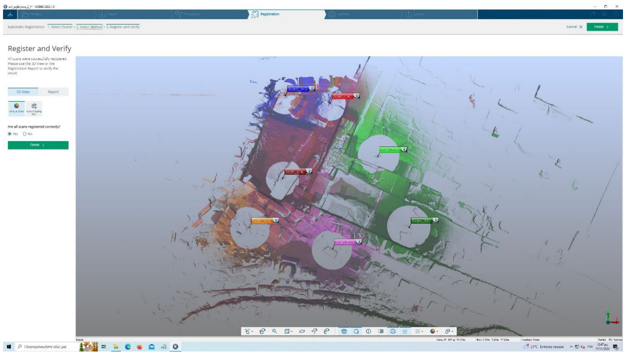


Figure 15. Registration of scans for the excavation at the narthex of the Basilica of Agios Kirykos, Delos.

For these excavations the post processing of the LiDAR data followed steps A and B of the process described in 3.2.1., while the texturing took place in Metashape after blocks of approximately 200 images for each excavation were aligned, and densely reconstructed and registered to the LiDAR point clouds. Registration errors were approximately 3 mm and georeferencing errors ranges between 1 – 2 cm. Images 16 – 20 showcase orthophotomaps produces for the final excavation stages and maps of the terrain change between the start and finish of the excavations.

Figure 16. Orthomosaic - excavation at the south aisle of the Basilica of Agios Kirykos, Delos.

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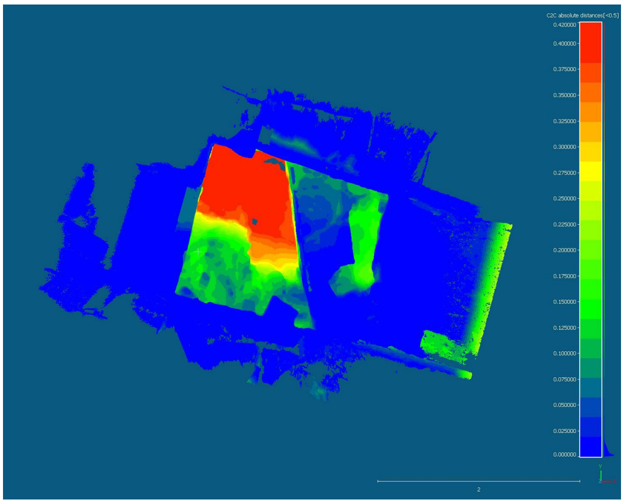

Figure 17. Change map - excavation at the south aisle of the Basilica of Agios Kirykos, Delos.

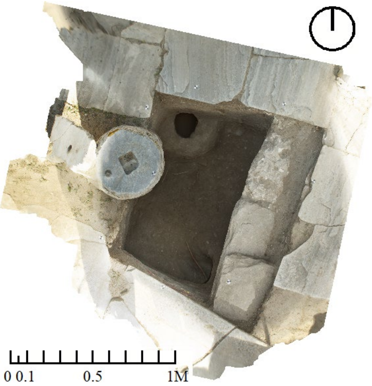

Figure 18. Orthomosaic - excavation at the altar of the Basilica of Agios Kirykos, Delos.

Figure 19. Orthomosaic - excavation at the narthex of the Basilica of Agios Kirykos, Delos.

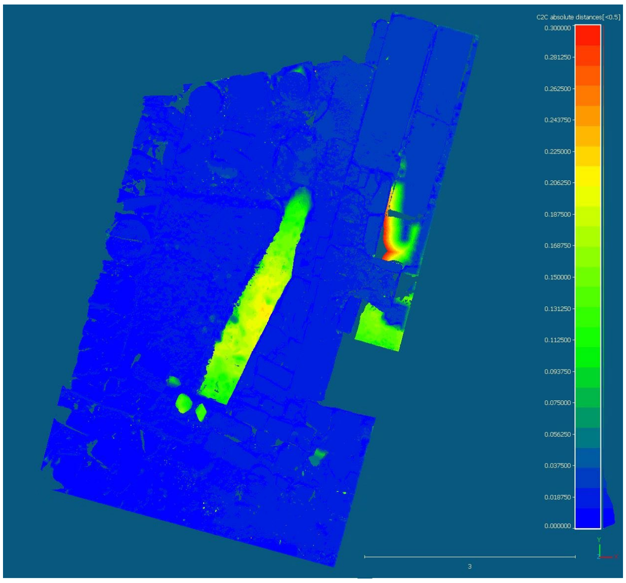

Figure 20. Change map - excavation at the narthex of the Basilica of Agios Kirykos, Delos.

4. CONCLUSIONS

Monitoring ongoing archaeological excavations with digital tools is a challenging task that has to tackle problems regarding resources, instrumentation and terrain topography. In this paper, the feasibility of recording the excavation process via LiDAR as a standalone solution was examined, explaining in detail the parameters of data collection and the steps of processing collected point clouds. Given the necessary equipment is available, recording with terrestrial laser scanners can be optimized to minimize acquisition times and produce accurate 3D models of the excavation process thus acquiring records of each excavation phase and of the changes of the archeological terrain without delaying the excavation. Usually, this method does not produce good quality phototexture and as a result terrestrial LiDAR has to be combined with photogrammetry to collect the necessary true color information for producing textured models and orthophotomosaics. However, such combined solutions increase significantly the data recording and data processing times and cost, suggesting that photogrammetry may be a more appropriate solution when texture is more important that the geometric accuracy of the models. Optimizing the parameters of color capturing with the integrated camera sensor of a terrestrial LiDAR instrument and collecting very dense data can be a compromising solution, which avoids the additional use of photogrammetric methods, but, however, increases significantly recording times. In this acquisition scenario the lighting conditions and color balancing methods would have to be taken into consideration while scanning. Finally, it should be mentioned that drone LiDAR increases significantly the cost of surveying for archaeological purposes, but decreases the recording times, tackling most of the problems caused by the difficult terrain of excavation sites and thus offering an exciting prospect for heritage documentation.

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