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Drones and Real-Time Kinematic Base Station Integration for Documenting Inaccessible Ruins: A Case Study Approach

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Abstract: Ruins, marked by decay and abandonment, present challenges for digital documentation due to their varied conditions and remote locations. Surveying inaccessible ruins demands innovative approaches for safety and accuracy. Drones with high-resolution cameras enable the detailed aerial inspection and imaging of these inaccessible areas. This study investigated how surveying technologies, particularly Unmanned Aerial Vehicles (UAVs), are used to document inaccessible ruins. Integration with Real-Time Kinematic (RTK) technologies allows direct georeferencing in photogrammetric processing. A case study of the Castle of Terracorpo in Italy was used to demonstrate UAV-only surveying feasibility in inaccessible environments, testing two different scenarios. The first scenario involved the use of a DJI Matrice 300 RTK coupled with the D-RTK2 base station to survey the Castle; both direct and indirect georeferencing were exploited and compared through the photogrammetric process. This first scenario confirmed that this approach can lead to a centimetre-level accuracy (about three times the GSD value for indirect georeferencing and seven times the GSD value for direct georeferencing exploting RTK). The second scenario testing the integration of data from drones at varying resolutions enabled the comprehensive coverage of ruinous structures. In this case, the photogrammetric survey performed with the dji Mavic 3 Cine drone (indirect georeferencing) was integrated with the photogrammetric survey performed with the dji Matrice 300 RTK drone (direct georeferencing). This scenario showed that GCPs extracted from a direct georeferencing photogrammetric survey could be successfully used to georeference and integrate other drone data. However, challenges persist in surveying underground or enclosed spaces that are inaccessible to UAVs. Future research will explore integrating robotic LiDAR survey systems and advanced data fusion techniques to enhance documentation.

Keywords: UAV photogrammetry; RTK; direct georeferencing; data integration; cultural heritage; ruins

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1. Introduction

Ruins can be defined as the remains of man-made architectural structures, even if they can go beyond the merely destroyed architecture [1]. From the architectural point of view, they generally include a wide range of structures, including abandoned, historic, and crumbling buildings, showing obvious signs of decay, such as unstable walls, partially collapsed walls or roofs, with even entire rooms without roofs. Their geographic location can vary; they can be either in mountainous or lowland areas, or in lake or maritime areas. Generally, what makes them "ruins" is the poor state of preservation of the buildings themselves [2], including portions that have collapsed or are in a severe state of degradation and often abandoned (for various reasons).

The digital documentation of complex structures is challenging, and in many cases, the integration of Geomatic techniques, such as Terrestrial Laser Scanners (TLS), Global Navigation Satellite Systems (GNSS), photogrammetry, Unmanned Aerial Vehicles (UAV), Mobile Mapping Systems (MMS), and the implementation of a supporting topographic network comes into play [3–8]. Plus, surveying and documenting ruined structures can be extremely complex, as they are often located in remote or difficult-to-access areas and have severe damage and deterioration. The condition of the ruins can also include hazardous elements such as debris and piles of materials, making survey work not only complicated but also potentially dangerous for human operators. In this context, the use of drones has proven to be extremely useful, enabling detailed, high-resolution images of the ruins to be obtained from different perspectives and angles, even in areas that are difficult to access or dangerous.

To fully understand the crucial role of survey technology integration, the contribution of different components of the system needs to be explored in more detail. First, the use of different types of drones, each with specific capabilities, amplifies the scope and accuracy of the aerial photogrammetric survey. Drones with high-resolution cameras are used for the overall aerial inspection of ruins, while more compact and manoeuvrable drones can penetrate narrow, hard-to-reach spaces, allowing detailed views of interior areas and walls.

Depending on the conditions and characteristics of the ruins, some technological solutions may be more convenient than others. Alternatively, the circumstances and the survey context may constrain the choice of only certain types of instruments. For example, in the case where the ruins are difficult to reach or even not accessible for safety reasons, the choice of using Unmanned Aerial Vehicles (UAVs) seems to be feasible. In such a case, it becomes interesting to understand the most appropriate approaches on how to conduct the survey, which drone to prefer, and which methods to implement to integrate the data resulting from the different instruments. Certainly, the possibility of using a base GNSS receiver coupled with a UAV makes it possible to take georeferenced photographs, which then allows direct georeferencing to be performed within the photogrammetric process [9,10]. In addition, the use of drones coupled with a ground base station, exploiting Real-Time Kinematic (RTK) or Post-Processing Kinematic (PPK) technologies, would result in a greater accuracy of such data [11–13].

Given this context, it becomes interesting to understand what methods and strategies can be put in place for combining data from drones with different resolutions and flight capabilities. In this study, we investigated a specific working condition: the survey of a ruin under the assumption that the environmental and structural conditions do not allow access to it; so we examined the advantages and limitations of using only UAVs for surveying a ruin. We examined the effectiveness of data integration between UAVs with different resolutions by assuming the impossibility of using traditional topographic instruments, and we will discuss the deliverables that could be produced. In particular, the use of a UAV coupled with RTK technology was tested, and its integration with other UAV photogrammetric survey data will be evaluated and discussed.

This study exploited data obtained during the survey campaign of the castle of Terracorpo (province of Caserta, Italy); its geographical position is shown in Figure 1. The UNESCO Research Lab of the Mantua Campus of the Politecnico di Milano was assigned to carry out a project proposal for the conservation and enhancement of the Terracorpo Castle. To support the conservation project, the lab was also involved in carrying out an integrated survey of the building to extract 2D and 3D products typical for this type of project. The work described here was therefore part of a larger project. The case study was completely accessible at the moment of the survey, so it was documented using various survey techniques, including TLS and UAV photogrammetry, to reach all spaces of the building. For research purposes, instead, a subset of the data acquired was selected, and we decided to simulate a situation in which only UAVs were used because of the inaccessibility of spaces.

The rest of this paper is organised as follows. Section 2 presents related articles concerning the survey of complex architectures, including the integration of multi-platform and multi-sensor surveys, and the use of UAVs with RTK and PPK technologies. Section 3 describes the case study, its historical evolution, and the current state of the building; this section also describes the integrated survey conducted on the building. Section 4 is devoted to the description of the two scenarios put in place for our tests and their materials and methods, under the assumption of surveying using only UAVs. Scenario I analyses the differences between direct and indirect georeferencing using a UAV and a ground base to provide centimetric accuracies with RTK technology. Scenario II analyses the case of data integration between two UAVs with different characteristics and accuracies. Section 5 presents the results of the tests conducted under the two scenarios. It also presents some deliverables that can be produced using the presented approach. Section 6 presents a discussion, and Section 7 presents the conclusions.

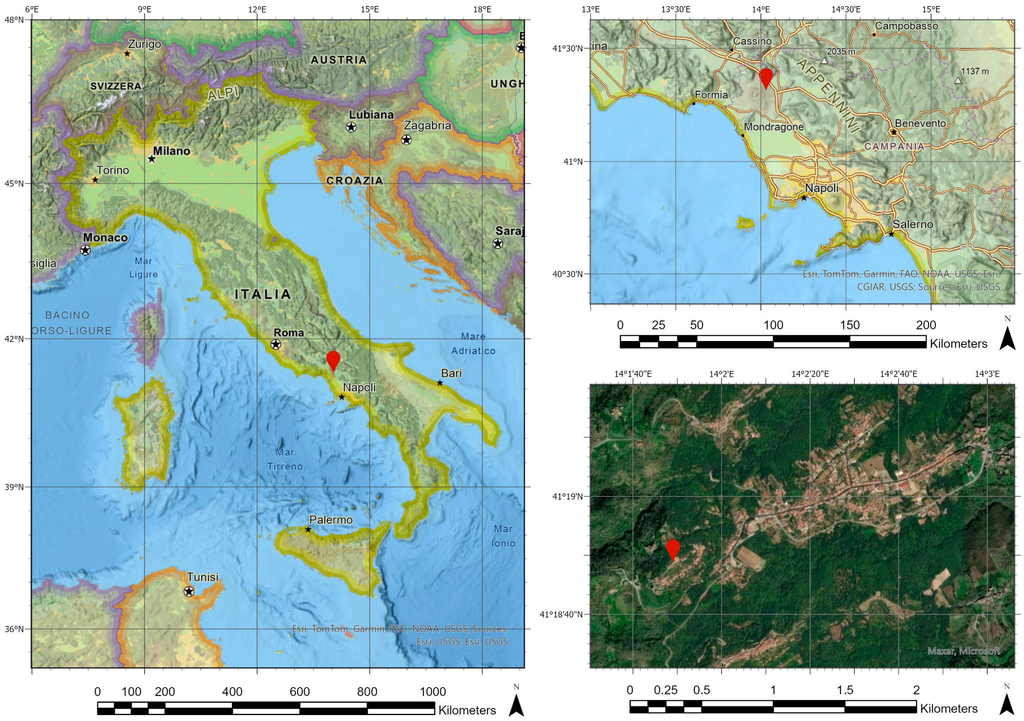

Figure 1. Geographical location of the case study, the Terracorpo Castle (Marzano Appio, Caserta, Italy). The red symbol indicates the position of the framed element at the Italian national, regional, and local scale.

2. Related Works

2.1. Digital Documentation of Ruins

Architectural ruins constitute a part of the existing building stock and can be traced back to both valuable and less valuable buildings. An important step in the management, conservation, and valorisation of these types of buildings is their documentation. The starting point for any intervention on ruins is certainly a historical analysis followed by a survey that allows us to know and correctly determine and interpret their shape, spatial organisation, materials, and degradation [14]. Articles dealing with the documentation of ruined buildings can be found in the scientific literature [14–21], especially when the buildings are of architectural significance.

The authors of [14] discussed the survey stages, which involve the survey campaign on-site, but also a large amount of reading and interpretation skills concerning the architectural spaces surveyed. They focused on fortified architectures in a state of ruin and used a combination of various survey techniques to reach the goal. In the case of reference [15], the authors investigated the ruins of Casa Ippolito, a typical 17th-century Maltese aristocratic country residence. They studied the ruins of the building as the primary source to reconstruct the building's architecture. They studied the materials, the historical evolution of the building, and the phases of the construction. Instead, to fill a gap due to a lack of documental sources, the authors of [16] carried out a survey supplemented by various sources to document the ruins of the castle of Assoro. Focusing instead on burial sites, the authors of [21] developed a 3D digital survey and the consequent high-precision burial model and contour map to enhance the protection of the burial site in Yaoheyuan, Ningxia, one of the top 10 archaeological discoveries in China in 2017.

On a different scale, the authors of [17] investigated an area that includes the ruins of 30 churches and villages in a territory covering Brazil, Argentina, and Paraguay. They then focused on the ruins of one church and carried out an integrated survey in order to produce a geographic database to assist its management. On a similar urban scale, the authors of [18] focused on various buildings in the urban centre of Navelli (L'Aquila, Italy), now in a state of ruin after an earthquake in 2009. The authors undertook a multi-scale and multi-sensor data acquisition–integration task to document these buildings.

Focusing on archaeological ruins, the authors of [19] carried out an integrated survey of the ruins of a Roman aqueduct in order to improve its documentation, but also to enhance its representation through the use of Historic Building Information Modeling (HBIM) and virtual and augmented reality technologies. Also, the authors of [20] focused their attention on HBIM, developing the modelling of a ruined building in a municipality in Umbria (Italy). They evaluated that digital documentation can be an excellent starting point for HBIM, which requires several compromises from a geometric point of view (especially in ruined buildings), but also allows for the better management and analysis of the information content, which leads to virtuous processes for the valorisation of the cultural asset.

What emerges is a particular category of ruins that has been investigated in the literature that concerns the ruins of fortified buildings and castles; this category of ruined buildings often plays an important role in the history of the geographical areas around them. In such cases, the objective is the documentation, also digital, of the building for its future redevelopment. It is also interesting to note that the condition and state of preservation of such objects make them very risky and difficult to access, making the surveys carried out similar to those performed for risk assessment [22–24].

2.2. Integrated Survey of Complex Architectures

Given the environmental complexities and the generally poor state of preservation of ruined buildings, it is often optimal to use a combination of several surveying techniques to fully document them. Various surveying tools and techniques could be used to achieve this goal, such as TLS, UAVs, GNSS receivers, MMS, a total station (TS), and techniques such as close-range photogrammetry. UAV photogrammetry and TLS surveying are prominent among the most widely used technologies. The data from these surveys can then be merged using various methods. Various data integration methods can be found in the literature [18,21,25–32], referring not only to the case of ruins but, in general, to complex buildings.

In general, regardless of the case study analysed, but still concerning integrated surveys of complex historical buildings, we can see that the most commonly used technologies are TLS and close-range photogrammetry (both from the ground and from drones), and through their integration, the creation of a topographic support network is widespread, measured with GNSS receivers [18,25,26] alone or in pairs with TS [16,27–32]. This topographic network is then used to formalise a reference system (local or georeferenced) to which the surveys carried out with the various instruments can be locked, measuring Ground Control Points (GCP) and targets with it. Alternatively, there are also cases where the authors have used different techniques for the integration of data from different sources, such as the use of GCPs identified in the TLS survey for integration with UAV data [16], or the use of point cloud co-registration algorithms such as the Iterative Closest Point (ICP) algorithm [21,32].

In taking a more specific look at the integration techniques employed, several examples of integration between UAV photogrammetry and TLS can be observed. For instance, the authors of [27] surveyed a church using TLS and close-range photogrammetry with images taken using a low-cost UAV; the integration was performed through two methods: measuring the GCP with a TS and retrieving them from a TLS survey. The results showed a slightly higher error when using TLS data. A similar approach was developed by the authors of [28], who developed a survey of a church using TLS, close-range photogrammetry with a DSLR camera, UAV platforms, and a multi-camera system. They used TS to materialise a topographic network to georeference all the data within the same reference system. Due to various reasons (e.g., no complete visibility of all points from TS), not all point clouds were registered using TS-measured GCPs, or using GCPs retrieved from one of the point clouds acquired with other systems. The TLS data were used as a geometric reference for the UAV photogrammetry. Leica register360 cloud-to-cloud was used to assemble all the point clouds.

In shifting the focus to urban areas, integration methods remain similar; for instance, the authors of [25] developed a multi-scale multi-sensor and multi-purpose survey. They used an integration between TLS, UAVs, DSLR cameras, and 360° cameras. GNSS and TLS technologies were used to create a reference network that was used as a standard reference coordinate system. Similarly, the authors of [18] surveyed a damaged area of a village. The survey was carried out using a mobile laser scanner based on SLAM technology and a drone for aerial photogrammetry. The integration of the two technologies was optimised through the placement of GCPs acquired with a GNSS receiver.

Focusing then on a building in ruins, the authors of [30] surveyed a highly degraded historical castle. The purpose of the work was to perform a structural analysis. The survey was performed using a low-cost drone, a DSLR camera, and a smartphone. Data were validated and integrated using TLS. While a GNSS receiver and TS were used to generate a Topographic Reference Network. Similarly, the authors of [26] analysed a castle and its surroundings by performing a multi-scale survey with UAV photogrammetry and a TLS survey. The data were integrated using a GNSS-measured reference topographic network.

2.3. RTK and PPK Technologies for UAVs

From the above, it can be deduced that among the most widely used technologies for surveying ruins and complex cultural heritage, the use of UAVs certainly stands out, often in combination with other technologies (e.g., GNSS, TLS, TS) for georeferencing the data and measuring GCPs. However, there is also the possibility of directly georeferencing the drone images using GNSS stations connected to the UAV system, which then exploits RTK or PPK technologies. In this way, the direct georeferencing of the data can be realised [12,13,33,34], i.e., reducing the need to acquire several GCPs on the ground.

The reliability of a UAV photogrammetric survey in RTK or PPK mode was investigated by the authors of [35], who developed several tests on a forest environment. They developed several tests using both UAVs with RTK and PPK and GCPs. They assessed that within their working conditions, the most accurate results for both horizontal and vertical accuracies were achieved using UAV RTK/PPK technology, even compared with the use of GCPs. Another evaluation was performed by the authors of [36], who tested a DJI Matrice 600 Pro and assessed that the direct georeferenced results of this drone with an onboard GNSS RTK unit can generate a photogrammetric product with decimeter accuracy. Another study, which focused on RTK-based UAV photogrammetry, in terms of interactions between GCP, direct georeferencing, and camera self-calibration, was performed by the authors of [37]. They investigated different case studies with different characteristics (a UAV test field, a moorland, and a building) and used different drones with various flight configurations. They found that the RTK option leads to sufficient results if at least 1 GCP is introduced. Flights without any GCPs lead to a significant height error in the order of up to 30 times the GSD value. Moreover, the authors of [38] aimed at improving the accuracy of UAV-RTK photogrammetric projects without the need to use oblique photographs or GCPs. They used multiple GNSS-fixed base stations correcting the geolocation data of the photographs simultaneously by averaging the differential corrections. The results showed that this methodology considerably reduces the altimetric errors, placing them in limits even below the GSD. Lastly, the authors of [12,39] demonstrated how the integration of a GNSS RTK/PPK module on low-cost commercial UAVs makes the system efficient for the reconstruction of a highly detailed and precise Digital Elevation Model without using GCPs, allowing them to make precision measurements in areas that are difficult to explore and investigate.

Finally, there are practical examples where UAV technologies combined with RTK and PPK technologies have been used to survey case studies of relevant interest, also integrating them with other survey technologies. For example, in reference [40], the authors analysed a small town centre. They integrated 360° videos and UAV image photogrammetry. They used GNSS data acquired by a UAV to perform GNSS-assisted image georeferencing to reduce or even avoid, in specific situations, the need for GCPs. Camera positions were computed either in RTK or PPK mode, with results similar to those using GCP. Another example is related to the survey of an archaeological site, where the authors [41] used aerial photogrammetry (exploiting PPK technology) and TLS data, which were integrated employing the ICP algorithm. Lastly, the authors of [42] surveyed historical defensive structures in mountainous areas. They used traditional photogrammetric solutions and novel methods based on Neural Radiance Fields (NeRFs). They performed direct georeferencing based on PPK and also used traditional GCPs placed on the ground, considering the difficulties in placing and measuring control points in such environments.

2.4. Synthesis and Outlook

Based on what has been presented, it can be seen that for the survey of complex architecture, including ruined areas, the integration of different surveying techniques is the rule, as it allows all areas of the surveyed building to be reached. The integration of such data is mainly realised through the use of topographic networks that measure GCP, either using TS or GNSS receivers. Cases of registration using ICP algorithms have also been presented. Of particular interest is also the possibility of integrated surveys in which the UAV data are coupled with technologies such as RTK or PPK, which allow direct georeferencing in the photogrammetric process.

In this study, we investigated the case of a survey conducted using only UAVs with the use of RTK technologies for direct georeferencing when other surveying technologies cannot be used and in the case where GCPs cannot be detected. Furthermore, in this study, the integration of two acquisitions—carried out with two UAVs of different resolutions, one of which uses an RTK system—without reference to GCPs was tested.

3. Terracorpo Castle: Case Study Description and Integrated Survey

3.1. Description of the Case Study

Terracorpo Castle (see Figure 1) is located in a small settlement that is apparently the original nucleus of the nearby town of Marzano Appio (Caserta, Italy). The earliest certain evidence of the existence of a castle near Marzano is from the Norman–Swabian period (11th and 12th centuries), while the first explicit mention of a castle dates back to 1278. The earliest form, like the layout of the village, was not dissimilar to that of other fortified settlements of the time, that is, with a fortress located in an apical and asymmetrical position with respect to the built-up area, which, together with a place of worship, was enclosed in a domain within descending walls. This assumption rests on the surviving remains of ancient walls on the northern slope of the present fortress and the surviving remains of a fragment of the original enclosure on the southern slope of Terracorpo Hill, where the village is located.

Aerial observations of the village reveal the existence of at least two city walls and the presence of two gateways. The main entrance is located at the western end, identified by a portal with an ogival arch in local Tufo, made in the Gothic style, and can be ascribed to the 14th century. Equally evident are the structural reinforcements, which occurred between 1500 and 1700, reinforcing and strengthening the pre-existing structural elements. The fortress encloses a large inner courtyard with a rectangular plan preceded by a large vestibule. The 1700–1800 appearance of the main layout following the last major transformations is the result of the logical structural evolution affecting all centuries-old structures.

The palace was then fully inhabited, equipped with prisons inside, the hub of all life in the surrounding area. Indeed, the political, commercial, and administrative life of the town took place there.

Although it originated as a fortification and for defensive use, the castle today has the appearance of an austere 18th-century palace that is firmly grafted into the natural scenery of the local area with its long, linear facade of Tufo stone. The castle is currently (see Figure 2) overgrown with weedy vegetation that inhibits its full fruition. It is also in very poor condition due to bombing during World War II, and following collapses due to the 1980s earthquake [43]. As of today, almost the entirety of the main floor no longer exists as the roofs and floors of the main floor have collapsed. Only a few rooms on the piano nobileremain, accessible only through the use of portable ladders to be placed at openings facing the ground floor. There are rooms with vaulted ceilings on the ground floor, corresponding to those on the main floor that still exist. The castle also has a water collection cistern, an underground room, and a room with access from the street level only.

Globally, the castle has five covered rooms (i.e., with roofing) on the ground floor and three covered rooms on the second floor, while eight rooms on the ground floor do not have covers and are at full height. Three of the rooms are on the first floor without roofs. The current conservation condition of the castle allowed a photogrammetric survey with drones, due in part to the absence of roofs in many of the rooms. To complete the survey in the underground rooms and rooms with roofing, a laser scanner survey was also carried out.

Figure 2. Pictures of the Castle of Terracorpo in its actual status.

3.2. Survey of the Case Study

Within this short section, we describe the integrated survey developed in the case study (see Figure 3 for some images of the survey processing). For the tests presented in the next sections, we used a subset of the actual data acquired on-site.

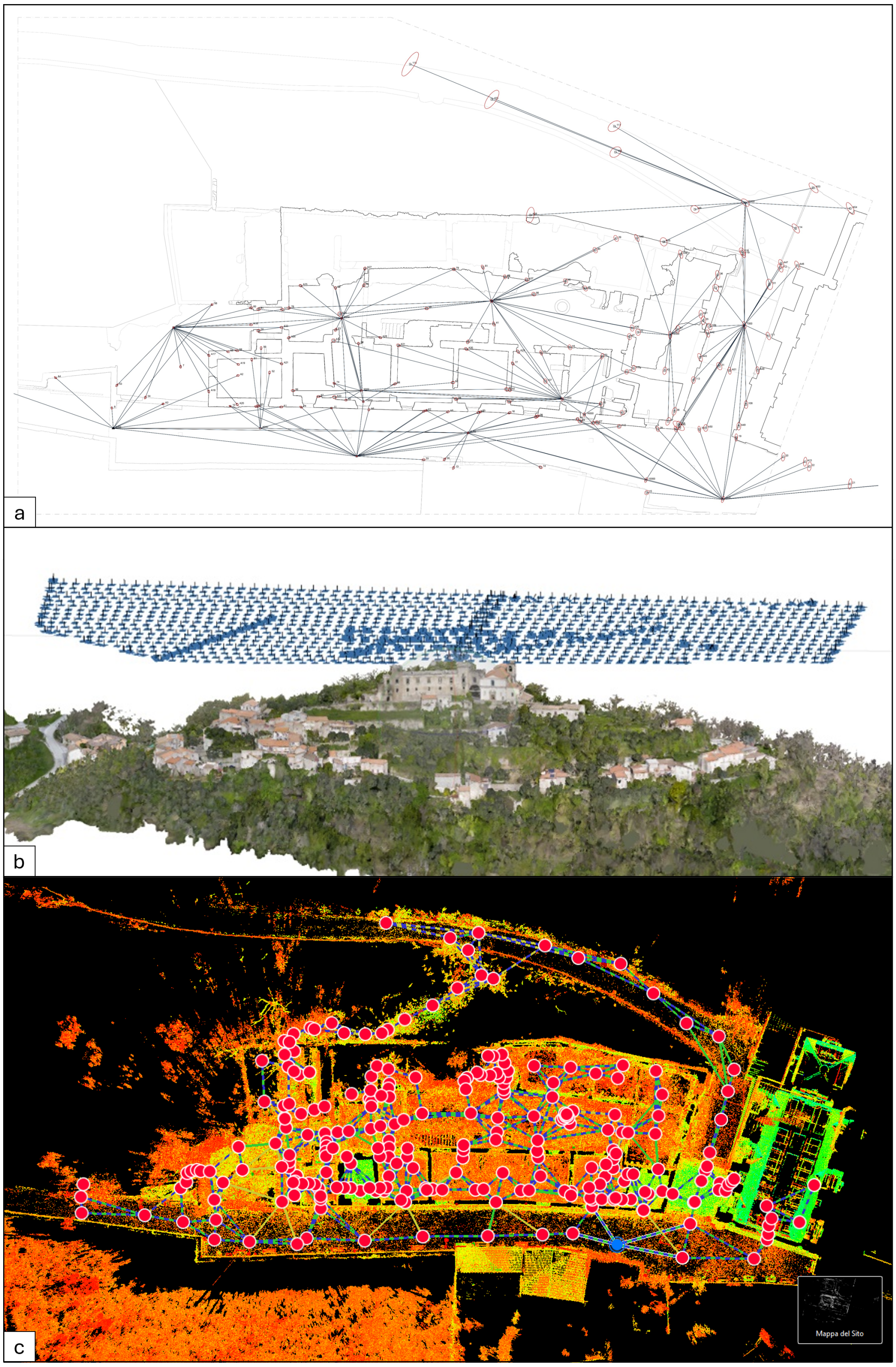

Figure 3. Screenshots of survey processing phases. (**a**) The topographic network developed during the survey to materialise a common reference system for all the data. (**b**) A screenshot of Agisoft Metashape Professional v. 2.0.0 with the reconstructed model of the castle. In blue is the position of the cameras. (**c**) A screenshot of the processing of TLS data with Leica Register 360 Plus (version 2023.0.2) software. Point cloud data are coloured in a false colour scale according to the intensity. The red circles represent the positions of the scanner along the survey execution.

As already mentioned, the purpose of the survey was to support a project for the conservation and enhancement of the castle (see Figure 4 as an example of a deliverable produced). Conducting conservation and restoration work on a historic building generally requires a solid and large amount of information and documentation about the building. In addition to a rich historical documentation of the building's evolution over time, information on the current state of the preservation (materials and state of decay) of the building's surfaces is needed. Therefore, in order to provide good support for the planning of the conservation of the castle, it was necessary to carry out a complete and highly detailed and informative survey of the building and its surroundings. The objective of this survey was, therefore, to provide drawings of plans at various heights and sections at various strategic points of the building, as well as orthophotos for the description of the state of the conservation of the wall surfaces. In order to achieve the appropriate accuracy (the scale of restitution required was 1:50, which admits a drawing error of 1 cm), it was decided to carry out an integrated survey, with laser scanner, photogrammetric techniques (from a drone and from the ground), with the support of a topographic network measured with a total station and GNSS receiver.

Figure 4. One of the project boards delivered by the UNESCO Research Lab as a result of the survey for the conservation and enhancement project of Terracorpo Castle. The picture shows a board with a plan of the castle.

The survey of Terracorpo Castle was developed by integrating different technologies. A TLS (Leica RTC360), a GNSS receiver (Leica GS-18), a TS (Leica TS30), a Digital Single-Lens Reflex (DSLR) camera (Canon EOS 5DS R), and two UAVs (DJI Matrice 300 RTK equipped with the DJI D-RTK2 base station and DJI Mavic 3 Cine) were used. The choice of the aforementioned surveying techniques and instruments was, first of all, possible because the current condition of the ruined castle left it almost completely accessible. Some rooms on the upper floors are currently not accessible from below (e.g., stairs no longer exist and ceilings closed during previous redevelopment work); therefore, they are only visible with a drone. In addition, due to the presence of underground areas and some rooms with low ceilings on the ground floor, it was also necessary to use TLS technology.

The TS was used for the creation of a topographic network to support the entire survey, while the GNSS receiver was used to measure some GCPs in order to georeference the topographic network in cartographic coordinates. The topographic network was materialised using sixteen points, inside and outside the perimeter of the building, from which the local reference system of the entire complex was generated. The Mean Squared Errors (MSEs) of the coordinates of the adjusted vertices were lower than 5 mm. The measurement operations were carried out with a Leica TS30 total station (declared accuracy of 2 mm + 2 ppm), with redundant measurements such as to allow statistically valid checks.

The calculation of the network was carried out with a least-squares data adjustment program. The topographic network points were also acquired with GNSS instrumentation (exploiting RTK and connected to HxGN SmartNet), to allow the georeferencing of the topographic network on a geographic reference system. The acquired measurements in terms of latitude, longitude, and altitude were then converted into plane geographical coordinates, referring to the WGS84/UTM-33N geographic coordinate system.

The data from the surveying instruments were integrated in various ways, depending also on the areas surveyed:

- The Leica RTC360 TLS was used to survey all areas that could be reached from it, including the underground areas and all accessible rooms of the castle, as well as the exterior fronts. The TLS data were registered based on targets measured using the TS and referred to the topographic network. A total of 256 scans were acquired between the interior, exterior, and underground spaces. It was also possible to detect and register with the rest of the data scans in the spaces of the cistern, accessible from the castle courtyard, and the underground space accessible from the rear of the building. From the latter room, it was possible to acquire information, albeit only a small and incomplete part, of a third underground space under the courtyard.
- The DJI Matrice 300 RTK drone was mainly used for surveying the castle and the urban village built around it. In using an automatic flight plan, 1350 images of the village were acquired in classical nadiral mode from an altitude of 40 m, ensuring a frontal and sidelap overlapping of 80%. A second flight was carried out at an altitude of 30 m from the road in front of the castle; it involved the acquisition of 885 nadiral and oblique images, ensuring a frontal and sidelap overlapping of 80%. Both nadiral and oblique photo flights were carried out using the RTK technology; 16 GCPs were also measured (using both the TS and GNSS receiver) along the area of the survey, to be used within the photogrammetric workflow. The photogrammetric process was performed using Agisoft Metashape Professional v. 2.0.0; images were aligned using "high" resolution on an intel i9 PC, with 256 GB of RAM and an NVIDIA RTX A6000 graphics card.
- The DJI Mavic 3 cine drone was mainly used for surveying the internal fronts of the rooms without ceilings (e.g., the ceilings that had collapsed) and for the external elevations of the castle and the internal elevations of the courtyard. A total of 8300 photographs were taken to describe all the vertical surfaces (interior and exterior) of the castle, ensuring a frontal and sidelap overlapping of 80%. The photogrammetric process was performed by splitting all images into various groups according to the surveyed areas (e.g., one project for each room and one project for each facade) using Agisoft Metashape Professional v. 2.0.0; images were aligned using "high" resolution on an intel i9 PC, with 256 GB of RAM and an NVIDIA RTX A6000 graphics card. The integration of these data with the global reference system was performed by measuring the coordinates of the GCPs with the TS. However, the environmental context of the building did not always allow a sufficient number of GCPs to be measured through the positions of the stations in the topographical network, so the coordinates of some of them were derived from the TLS survey.

4. Materials and Methods

This section and the following ones present two study scenarios (see Table 1), named I and II, developed under the assumption that these ruins were inaccessible and could be surveyed only using UAVs. Various tests were then carried out under these two scenarios. Both scenarios referred only to the use of UAVs, also exploiting the RTK mode for direct georeferencing, without having to refer to GCPs. The tests developed within scenario I had the purpose of assessing the accuracy of a survey performed only with a UAV and RTK technology. The tests of scenario II had the more operational aim of showing the integration of data from two UAVs with different characteristics. The features of the two UAVs used are provided in Table 2, while Figure 5 shows a diagram reporting the development of the tests for the two scenarios; we can note the phases of the photogrammetric process analysed through the various tests in scenario I, as well as the logical development of the test in scenario II. The data exploited for the scenarios were a subset of the data acquired during the survey of Terracorpo Castle.

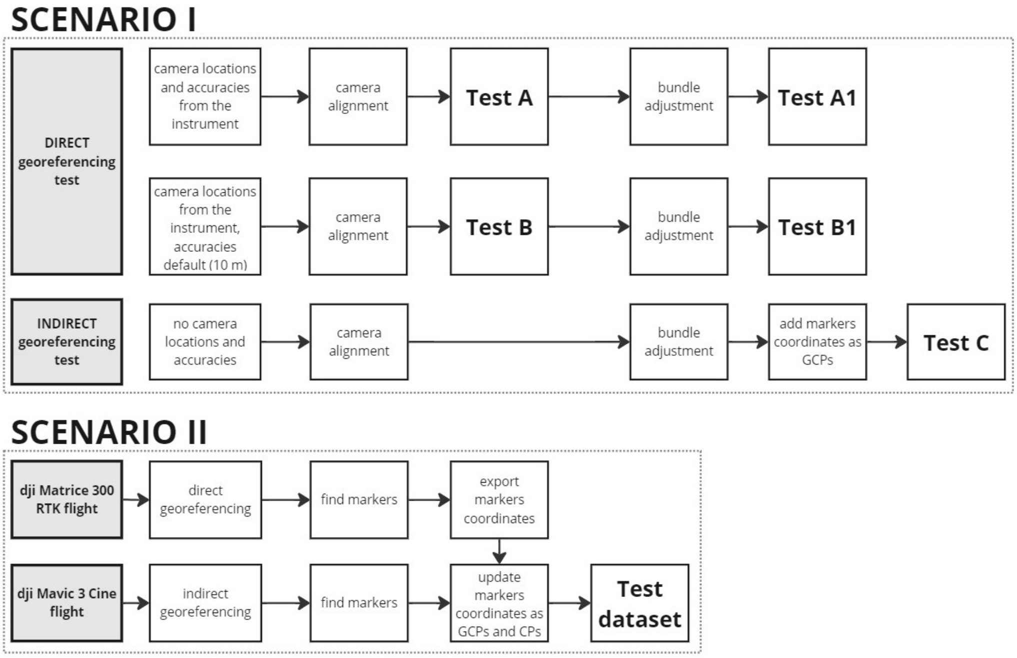

Figure 5. Schematic of the tests carried out in this study. Scenario I analyses the differences between direct and indirect georeferencing, and scenario II analyses the merging of datasets surveyed with two different drones. The steps of the photogrammetric process analysed with the various tests in scenario I and the logical development of the test in scenario II can be seen.

Table 1. Description of the two scenarios exploited in this study, with their purposes and instruments used. The tests designed within the two scenarios were developed under the assumption of using only UAVs to perform a survey of ruins, to assess the reachable reliability and accuracy.

Scenario	Instruments Used	Purpose
I	DJI Matrice 300 RTK (DJI Ltd., Shenzen, China), DJI D-RTK2 station (DJI Ltd., Shenzen, China), GNSS receiver Leica GS18 (Leica Geosystems, part of Hexagon AB, Stockholm, Sweden)	check the accuracy of the photogrammetric workflow using RTK station data to perform direct georeferencing in comparison with indirect georeferencing (checkpoints acquired with Leica GNSS receiver)
II	DJI Matrice 300 RTK (DJI Ltd., Shenzen, China), RTK station DJI D-RTK2 (DJI Ltd., Shenzen, China), DJI Mavic 3 Cine (DJI Ltd., Shenzen, China)	operative workflow followed to integrate data of two drones without other topographic support (one of the two UAV is operating in RTK positioning mode)

Table 2. Features of the UAVs used for the tests performed.

UAV	Camera, Lens	Camera Resolution
DJI Matrice 300 RTK (DJI Ltd., Shenzen, China)	Zenmuse P1 (DJI Ltd., Shenzen, China), 35 mm	45 MP, 8192 × 5460 px
DJI Mavic 3 cine (DJI Ltd., Shenzen, China)	Hasselblad (Hasselblad, Göteborg, Svezia), 12 mm	20 MP, 5280 × 3956 px

4.1. Scenario I: Direct Georeferencing with RTK vs. Indirect Georeferencing with GNSS Surveyed GCPs

To evaluate the effectiveness of RTK technology for a detailed UAV photogrammetric survey, the different stages of the photogrammetric process were analysed to verify the best alternatives according to the final results. The aim was to validate the feasibility of the complete photogrammetric survey of a ruin surveyed solely through the use of drones with RTK systems and to assess the achievable accuracy. In this case, the UAV DJI Matrice 300 RTK employed the RTK technology for accurate measurements of the camera locations and rotations (with accuracies) at the time of image shooting. These data, detected through the RTK approach, has a positioning accuracy, as stated by the manufacturer DJI, of 1 cm + 1 ppm (horizontal) and 1.5 cm + 1 ppm (vertical). The advantages of using RTK technology is related to a higher accuracy in the flight plan (especially in following the designed trajectories) and to the possibility of facilitating the photogrammetric process by having the coordinates of the perspective centre of the images.

The image acquisition procedure was fairly straightforward and well defined. In addition to all the necessary pre-flight checks, it is necessary to initialise the ground RTK station on a point of known geographic coordinates (e.g., using a point in the higher-order geodetic networks, or by performing a prior GNSS survey on the same point). After this preliminary step, the connection between the drone and the ground base station must be verified, thus activating the communication between the two systems.

Then, the operator can proceed to the flight, choosing between a flight plan conceived in advance and designed using special flight planning software, or performing a free flight, in which the experienced operator can freely operate the system. However, it is necessary to check the drone–base station distance to avoid signal loss and carefully choose the ground station location (generally in the open and possibly in a high place) to avoid obstacles between the two. At the end of the acquisition phase, the acquired images are obtained; thanks to the RTK technology, every image was acquired with the coordinates of its perspective centre, characterised by a specific planimetric and altimetric accuracy.

The processing phase, in contrast to the acquisition phase, provides several possibilities that could change the final result. The fact that commercial software (in this research, Agisoft Metashape Professional v. 2.0.0 was used) relies on processing algorithms that are not known to the public makes it advisable to carry out some tests to verify the behaviour of the photogrammetric software with images acquired in the manner described above, to identify the procedure that leads to better results.

The coordinates of the perspective centre constitute the approximate coordinates from which the image georeferencing starts. Still, the use of their accuracies, recorded by the RTK and stored within the XML image metadata file, can strongly constrain the calculation. If the RTK link has suffered signal losses or malfunctions, the accuracy value is over-estimated, and thus, the system is over-constrained. In fact, a very high accuracy value allows only minimal "shifts" of the perspective centre in the adjustment phase (within its range). For this reason, at first, we focused on the camera alignment stage. We tried to georeference the same set of nadiral photos using, firstly (Test A), the accuracy values provided by the system and, secondly (test B), a default value (set automatically by the Agisoft Metashape Professional v. 2.0.0 software equal to 10 m—so for test purposes, it was considered almost "unconstrained"). The two solutions were compared by checking the average residuals on image markers locations and on some Check Points (CPs).

Furthermore, the coordinates and accuracy of the image perspective centre coordinates can also affect the bundle adjustment process [44,45]. Again, overestimating the accuracy could constrain the system excessively (and incorrectly). In this case, the second group of tests involved starting from the same set of oriented photos and applying the bundle adjustment process by exploiting, firstly (test A1), the coordinates with accuracy from the RTK base and, secondly (test B1), the coordinates with a generic accuracy (as previously used, 10 m as pre-set by the software). Again, the result was evaluated based on the reprojection error on the image markers and Check Points.

After determining the effect of the RTK accuracy on image georeferencing, the direct and indirect georeferencing processes of the same set of photos were compared. In test C, the images were imported without the coordinates of the perspective centres, and then they were oriented, and later, the photogrammetric model was scaled and georeferenced through bundle adjustment, exploiting the GCPs acquired by the GNSS receiver Leica GS18.

4.2. Scenario II: Data Integration between UAV-RTK and UAV

The purpose of these tests was to evaluate the potential and integration of photogrammetric data from two UAVs with different characteristics. For this test, the data acquired by the DJI Matrice 300 RTK drone (DJI Ltd., Shenzen, China) (connected with the DJI D-RTK2 base for accurate corrections to the measured locations of the images) and the data acquired by the DJI Mavic 3 Cine were used.

The DJI Matrice 300 RTK was used to survey the entire building and surrounding area. For the photogrammetric process, direct georeferencing was used under the same conditions as the best of the tests performed in scenario I, and without the use of GCPs to preserve the assumption of working only with UAVs without ground support. The DJI Mavic 3 Cine was used to survey the castle fronts. In the context of this test, the flight of this UAV was carried out only for the survey of the castle's main exterior elevation.

This test was more operative and intended to evaluate the results achievable under the aforementioned conditions. It is difficult to analyse the behaviours only from a statistical point of view since many variables are running, for example, different image resolutions of the 2 diverse camera systems and different heights of flight (i.e., different distances from objects). For these reasons, this test was intended only to verify the feasibility of the entire survey.

For this test, the integration of the two data was tested. To do so, architectural points and targets were identified on the building facade to be used as GCPs. The coordinates of the GCPs were obtained from the survey data performed with the DJI Matrice 300 (georeferenced using the RTK system and in geographic coordinates) and were then used and entered as constraint coordinates in the photogrammetric process followed for the DJI Mavic 3 Cine. Some of these points were then used as GCPs and others as CPs, and the error values were verified. The two point clouds from the two drones were also imported into CloudCompare (v. 2.13.1) to verify their exact overlap using the C2C method and the M3C2 plug-in [46] that verifies the mutual distances of points on different point clouds.

5. Results

5.1. Scenario I: Direct Georeferencing with RTK vs. Indirect Georeferencing with GNSS Surveyed GCPs

The experimental tests were performed on a subset of images from a nadiral flight conducted by a Matrice 300 RTK equipped with a Zenmuse P1 camera. This subset was made of 560 images, each one with a dimension of 8192 $\times$ 5460 pixels. Figure 6 shows the distribution of GCPs and CPs on the surveyed area used within the tests of this scenario. For the purposes of this study, the processing time was neither analysed nor compared.

The first analysis, concerning the influence of the RTK accuracies of the perspective center coordinates within the georeferencing process, demonstrated that accuracy plays a role in the final results, even if the values are not so different. The error is slightly larger in Test case A, compared to B (see Table 3), but in looking at the coordinates and the average error, the use of accuracies in the camera locations leads to a lower error.

In the second case, Tests A1 and B1, we tried to evaluate the contribution of accuracies in the bundle adjustment process. The same sets of pictures, already used in the previous tests, were adjusted with a bundle adjustment process (the command "optimize" in Agisoft Metashape Professional v. 2.0.0, with all parameters selected) in two different cases: in test A1, the bundle adjustment was performed using camera locations and accuracies from an XML file, while in B1, the adjustment used only the default accuracy (set to the default value of 10 m). The comparison of A1 and B1 proved that accuracy affects the results positively, considering an average error from 0.0367 m (in B1) to 0.0320 m (in A1).

Table 3. Accuracy results for the sub-tests developed within scenario I.

Test ID	Georef.	Photogram. Process Stage	Cameras Location Accuracy	Average Pixel Error	Average E-Error	Average N-Error	Average Altitude Error	Average Error
A	direct	camera alignment	imported from XMP metadata	0.426 px	0.048 m	0.023 m	0.026 m	0.0323 m
A1	direct	bundle adjustment	imported from XMP metadata	0.374 px	0.048 m	0.023 m	0.025 m	0.0320 m
B	direct	camera alignment	10 m (default)	0.417 px	0.045 m	0.025 m	0.029 m	0.0330 m
B1	direct	bundle adjustment	10 m (default)	0.375 px	0.045 m	0.027 m	0.038 m	0.0367 m
C	indirect	with GCPs	imported without locations and accuracies	0.388 px	0.018 m	0.013 m	0.021 m	0.0173 m

Figure 6. (**a**) The dataset used for scenario I. In this image, the mesh model is visible on top of the image; it is possible to see the camera locations. (**b**) The GCPs and CPs used throughout the tests performed within scenario I, positioned around the castle area.

The third test compared the previous results (A, B, A1, B1) with the indirect georeferencing process. In test C, which was the case of indirect georeferencing, the accuracy was significantly higher, confirming what has already been shown in the literature. Still, in referring to the coordinates of the Check Points, the average error was about 0.032–0.033 m for RTK (in different conditions) and 0.017 m for the orientation based on the GCPs. Since the Ground Sample Distance was 0.005 mm within the project, we can say that in the indirect georeferencing process, the error was about three times the GSD value, while for the RTK approach (e.g., direct georeferencing), the average quality was about seven times the GSD value.

5.2. Scenario II: Data Integration between UAV-RTK and UAV

In this scenario, the possibility of data integration between photogrammetric models obtained from two different drones was analysed. The first flight (Figure 7a), performed with the DJI Matrice 300 RTK, obtained 885 photographs and covered the entire castle area, and was processed by performing direct georeferencing. The second flight (Figure 7b) was performed with the DJI Mavic 3 Cine, obtaining 8300 photographs of all the reachable vertical surfaces of the castle, of which 1300 photos (used in this scenario) covered the main facade of the castle (the one facing the small road leading to the castle). The photogrammetric process exploited for reconstructing this facade was performed through indirect georeferencing.

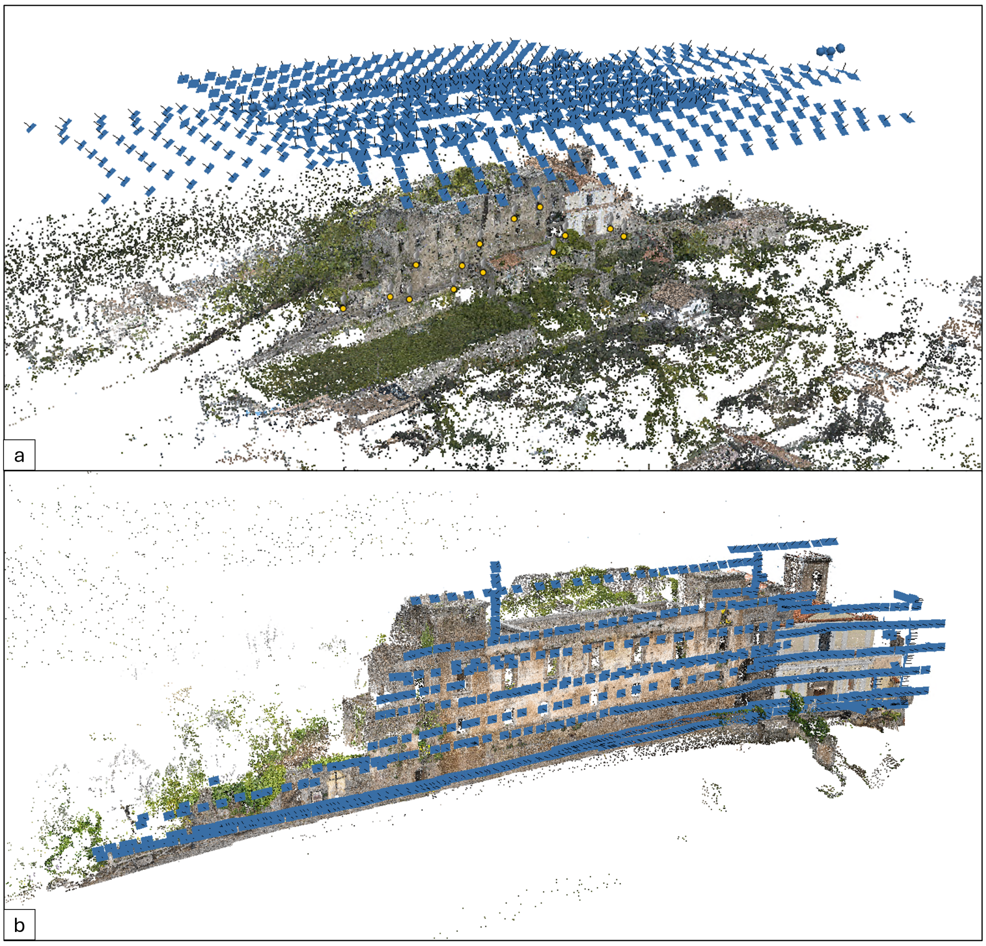

Figure 7. Screenshots of two photogrammetric projects for scenario II. Both figures show the positions of the cameras (in blue) and the tie points identified by the software. (**a**) Survey with DJI Matrice 300 RTK. (**b**) Survey with DJI Mavic 3 Cine.

For the test, the data obtained with the DJI Matrice 300 RTK were processed following direct georeferencing. From this, notable points and markers located on the facade of the building and in common with the flight performed with DJI Mavic 3 Cine were identified. The estimated coordinates of the notable points were then exported to be used as GCPs in the indirect georeferencing of the Mavic 3 Cine data. These estimated coordinates were then assigned an accuracy value of 2 cm, which is compatible with the technique used. From the results of the indirect georeferencing photogrammetric process, it was then possible to identify errors in the CPs, which were 0.0057 m in East, 0.0075 m in North, and 0.0071 m in Elevation. The distribution of errors for each GCP and CP, showed as error ellipses, are reported in Figure 8.

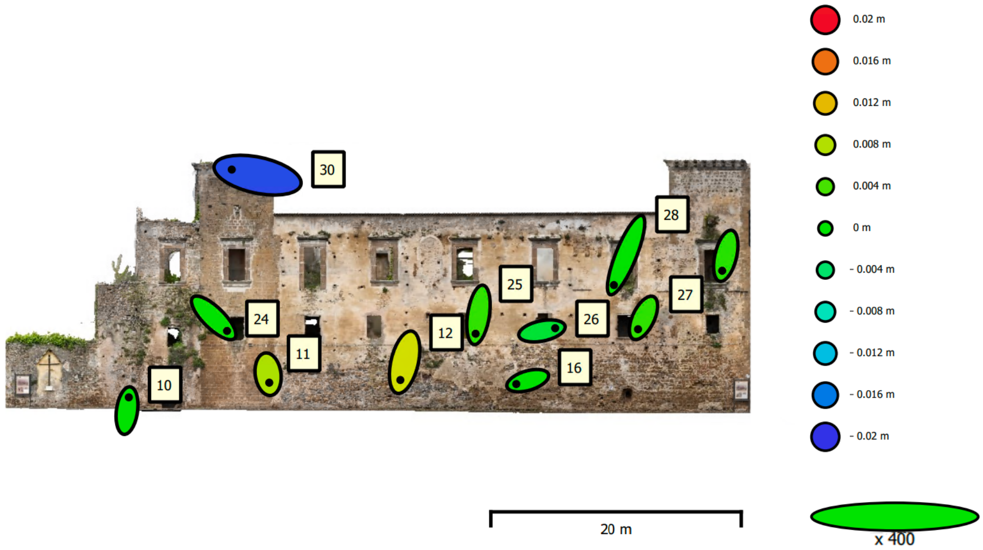

Figure 8. Position residuals represented as error ellipses based on GCP and CP positions for the analysed castle facade. Error ellipses are enlarged by a factor of 400.

In addition, for a further comparison of the two datasets, two algorithms available in the CloudCompare (v. 2.13.1) software were used. We used the M3C2 plug-in (Figure 9), which primarily allows the assessment of significant changes between two point clouds, and we used the Cloud2Cloud (C2C) algorithm (Figure 10), native to CloudCompare (v. 2.13.1), which allows the distance between two point clouds to be calculated. Figure 9 shows the results of the comparison made using the M3C2 method, which clearly (in red) shows the major differences between the two clouds. It can be noted that the most divergent elements are mainly related to some eaves overhanging and some spots horizontally aligned in the middle of the facade, which correspond to holes that were used for the construction of the building and the position of the scaffolding. As the two surveys were carried out from two different positions (one from above and one orthogonal to the facade), it can be observed that in the survey carried out with the Mavic 3 Cine and carried out orthogonally to the facade, these holes were photographed from more angles and better reconstructed. Other discrepancies can be attributed to the presence of weedy vegetation on the facade. Finally, for the rest of the points, the differences were not extensive and were mainly less than 2 centimetres, as it is also visible in the histogram shown in Figure 11 on the left. A similar trend was confirmed through the comparison made with the C2C method (see Figure 10), where a good fit between the two compared point clouds can be seen, with a greater deviation (although contained within 2 cm) in the upper left portion. It can be seen that the distribution of distances also conforms to the distribution of GCPs (see Figure 8) along the facade itself. The GCP to which a greater error corresponds is in fact located at the top left of the facade. Again, however, as can be seen from the distribution histogram of the distances (Figure 11 right), they are within 2 cm.

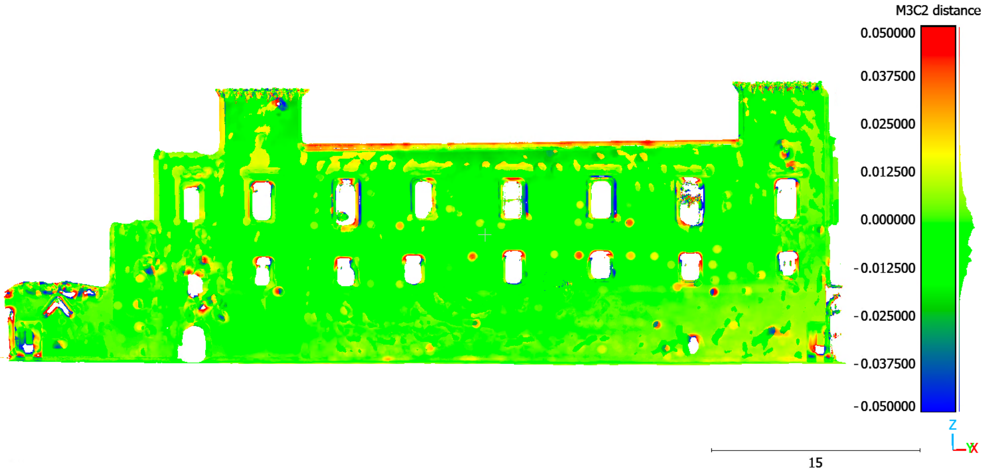

Figure 9. Comparison between the two point clouds of the castle's main facade, obtained through a photogrammetric process and using two drones: DJI Matrice 300 RTK and DJI Mavic 3 Cine. The two photogrammetric point clouds were compared in CloudCompare (v. 2.13.1) using the M3C2 algorithm. The scale bar goes from −0.05 (blue) m to +0.05 m (red).

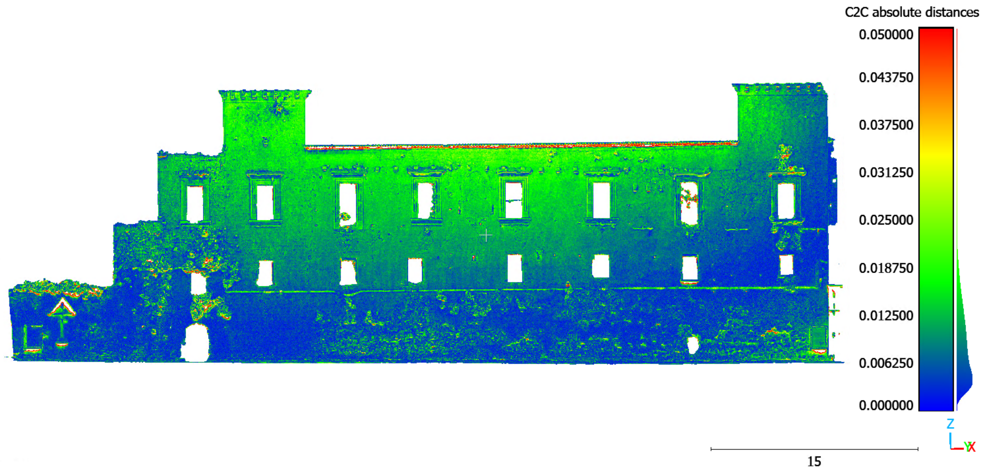

Figure 10. Comparison between the two point clouds of the castle's main facade obtained through a photogrammetric process and using two drones: DJI Matrice 300 RTK and DJI Mavic 3 Cine. The two photogrammetric point clouds were compared in CloudCompare (v. 2.13.1) using the C2C algorithm. The scale bar goes from −0.05 (blue) m to +0.05 m (red).

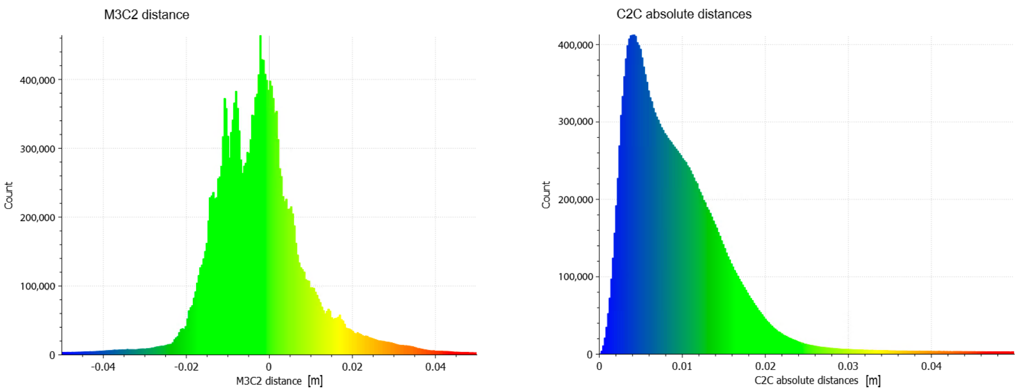

Figure 11. Histograms related to the previous figures (Figures 9 and 10), showing the distribution of distances between points in the two compared point clouds. It can be seen that both histograms, relating to the analyses with the M3C2 algorithm (**left**) and with the C2C algorithm (**right**), show a range tending to be within 2 cm.

5.3. 2D and 3D Deliverables

Continuing with the assumption that the ruins of Terracorpo Castle were only surveyed with UAVs, we describe in this section the products (2D and 3D) that could be obtained. Therefore, we proceed as in scenario II, i.e., assuming that the DJI Matrice 300 RTK drone was used to survey the castle and its surrounding village, and the DJI Mavic 3 Cine drone was used to survey all the interior faces. The subset of data was obtained directly from the survey actually carried out. With these data (RTK georeferenced images and non-georeferenced images), it is possible to develop the photogrammetric process, using direct georeferencing (for the Matrice 300) and indirect georeferencing (for the Mavic 3 Cine) as described in scenario II.

The results that can be obtained are the classic ones of a photogrammetric process, i.e., orthophotos of the area of interest both as a top view (as in a planimetry) or elevation view for facades. In addition, in using the photogrammetric point cloud, it is also possible to create sections of the building, showing the front of the inner rooms in perspective. In using the textured mesh, it could also be possible to realise three-dimensional visualisations (to create renders, walkthrough videos, and Virtual Reality experiences) for the dissemination of the current state of the building or design hypotheses. Figure 12 shows various images of the deliverables.

Figure 12. Examples of deliverables obtained through the photogrammetric process in the case study exploiting UAV data. (**a**) Orthophoto of the castle and its surroundings. (**b**) Ortophoto of the facade of the castle. (**c**) Three-dimensional model (texturised mesh) of the castle.

6. Discussion

The first scenario demonstrated that RTK data allow centimetric accuracies to be obtained while ensuring UAV operator safety. From the tests performed, the values of the accuracies are relevant, especially in the bundle adjustment step of the optimisation. A fundamental condition for the use of RTK data (especially location accuracies) is, in a way, the quality of the data, because overestimated accuracies do not bring real advantages to the final results. On the other hand, if there is a possibility, indirect orientation with ground-based GCPs has shown better effectiveness in terms of achievable accuracy (about three times the GSD value compared to seven times the GSD value of the RTK approach) as also observed in the literature.

As is always the case, it is not possible to define a single, specific scope, as the results obtained, at least in terms of quality and accuracy, must be verified according to the purposes of the survey and the scale of representation.

The test of scenario II demonstrated the possibility of surveying even the most difficult areas (even those accessible by UAV such as narrow rooms) by structuring the survey into two phases: a first UAV survey with RTK to determine, in addition to the general documentation from the top, the reference system to be used, and a second survey that relies on the previous one for the georeferencing stage.

With regard to the products realised from the data generated only with UAVs, several elements can be realised: orthophotos of the building area and its fronts, 2D drawings based on the photogrammetric point cloud, and textured 3D models for dissemination. The realised products suffer from the fact that only the surfaces actually visible from the UAVs are present in the final product. Vegetation with very large canopies can affect the visibility of the instrument and, consequently, the completeness of the final data. The same reasoning applies to all areas that are underground or in closed and/or dark rooms, which are difficult to reach using such instruments.

In general, however, the products that can be realised are compatible with the needs of a preservation project and the digital documentation of a ruined building. Thus, if site conditions do not allow it, a survey performed only with UAVs can still generate documentation of significant use.

Therefore, one advantage of drone-only surveying for areas that are not easily accessible is that it is still possible to carry out a survey with good accuracy (at the centimetre level) despite not being able to inspect the area with other surveying technologies. The execution of the survey requires a good scheduling of the flight plan, as well as the execution of the entire survey, but this still allows for good results while keeping both the survey time in the field and the number of people required limited. The disadvantages are certainly linked to the dependence (at the moment) on the presence of an RTK station positioned on the ground, which must always be in connection with the drone and must therefore be positioned either at a point of known coordinates or must be able to connect to a network of permanent stations to receive corrections. In addition, it should be pointed out that this methodology does not allow for reaching and surveying closed, underground, or generally non-illuminated areas. Finally, it should be noted that integrating a GNSS system to measure a few Ground Control Points (GCPs) greatly enhances accuracy, as demonstrated by various studies cited in the literature and the state-of-the-art reviews.

7. Conclusions

Ruined buildings constitute an important part of built heritage. To ensure the proper management, maintenance, and regeneration of such buildings, it is necessary to carry out adequate documentation of them. The survey of ruins is often characterised by the use of various survey technologies and tools that are integrated using various methods. Among the most widespread techniques, there is the use of TLS and close-range photogrammetry from UAVs or from the ground, integrated using topographic networks surveyed with TS or GNSS receivers.

In this study, we decided to analyse a particular case study, the survey of a ruined building when it is not fully accessible (e.g., for security reasons or due to the environmental conditions surrounding it). In such conditions, the use of UAVs has only been identified as the most suitable survey method. Indeed, such systems make it possible to reach all parts of the ruined building without endangering the survey operator. In addition, if the UAV system is used in combination with RTK technologies, the photogrammetric processing of the survey performed can be carried out using direct georeferencing by exploiting the locations of the images.

The DJI Matrice 300 RTK ground-based D-RTK2 drone and the DJI Mavic 3 Cine drone were used in this study. Two specific scenarios were set up with distinct purposes. The first scenario (I) was aimed at identifying the possible accuracies achievable by a drone used with RTK technology using direct georeferencing following the photogrammetric process. The tests performed showed that this approach allows centimetric accuracies to be achieved. The second scenario (II) tested the integration of two sets of photogrammetric data collected with drones at different resolutions and for different purposes. One drone was used to survey the entire building and its surroundings, georeferencing the data with RTK technology. And a second drone was used to closely survey the building fronts, and the data were georeferenced by deducing GCPs from the data taken with the first drone. This second test showed that the integration of data from drones at different resolutions is possible and optimal for working conditions where survey areas are not easily accessible. These tests also confirmed that underground areas or enclosed rooms are difficult to survey using UAVs alone. In such cases, different surveying technologies must be used, such that they allow the operator to enter these rooms, thus making it necessary to set up security conditions to make the building accessible.

This work demonstrates that the surveying of inaccessible ruins is possible through the use of various UAVs with varying resolutions and technologies in which the use of RTK systems makes it possible to not materialise a topographical network in situ, without the need to use other surveying instruments but inevitably achieving lower accuracies. This research is a first step in analysing survey modes for the digital documentation of areas or buildings that are not easily accessible (i.e., at risk of collapse, in locations that are not easily accessible, or in areas that are dangerous to humans). The use of direct georeferencing with RTK technology has been shown to be effective, but it is important to identify and test methodologies that can achieve higher accuracies, such as the use of PPK or others. In addition, the use of RTK technologies requires the presence of a telephone network to connect to the permanent stations with the GNSS receiver. Such conditions are not always guaranteed. Future research, therefore, may investigate the coupled use of other technologies that, while allowing the user not to enter hazardous (or otherwise unreachable) areas, allow surveys with high accuracy. As an example, integration with robotic LiDAR (Light Detection and Ranging) survey systems could be interesting for the inclusion of underground areas not visible through the drone, without requiring the operator to approach inaccessible areas.

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Abbreviations

The following abbreviations are used in this manuscript:

CP	Check Point;
GCP	Ground Control Point;
GNSS	Global Navigation Satellite System;
MMS	Mobile Mapping System;
MSE	Mean Squared Errors;
PPK	Post-Processing Kinematic;
RTK	Real-Time Kinematic;
TLS	Terrestrial Laser Scanner;
TS	Total Station;
UAS	Unmanned Aerial System;
UAV	Unmanned Aerial Vehicle.

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