UAVs Photogrammetry for Inner Areas Documentation. Strategies for Close-Range and Fast Acquisition of a Traditional Historic Center in the Montagna Materana

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Italy's small historic centers in inland regions face significant fragility due to administrative challenges, depopulation, and geomorphological risks that threaten their long-term stability. As part of the EU-funded Next Generation EU PRIN 2022 project, this research initiates an experimental action aimed at developing a replicable methodological protocol for the rapid and integrated digital documentation of the historic center of Stigliano (Matera, Basilicata). The objective is to generate a detailed, reality-based 3D model of the urban fabric—encompassing both buildings and open spaces—to serve as the foundation for a digital information system dedicated to the preservation and enhancement of the site. The initial phase of the project focuses on data acquisition through photogrammetric techniques using mini-UAVs combined with mobile laser-scanning systems. This integrated approach, particularly well-suited for sites at high conservation risk, provides speed, flexibility, and comprehensive data capture. The challenging morphology of Stigliano, characterized by substantial elevation differences, a dense and irregular urban layout, and numerous narrow, inaccessible pathways, required a carefully structured close-range acquisition strategy. Additional terrestrial laser-scanning technologies, both static and mobile, were used to fill remaining data gaps. This paper presents the first results of the drone-based survey campaigns and discusses the methodological challenges encountered, along with the subdivision strategies adopted to produce a high-resolution 3D model of the historic center.

Keywords:
UAVs, close-range photogrammetry, fast survey, reality-based model, Inner areas.

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1. UAVS PLATFORMS FOR CLOSE-RANGE DOCUMENTATION

To represent the complexity of the cultural heritage, both at the architectural and urban scale, operators generally use tools capable of overcoming the gap between the use of "traditional" aerial photogrammetry and terrestrial survey tools as topographic, photogrammetric or laser scanner (Lo Brutto et al. 2014). The definition of increasingly specific and reliable photogrammetric acquisition procedures, also thanks to the widespread use of small drones (micro- and mini-UAVs), has produced significant experiments and interesting results in some fields (Picchio 2020).

The common objective of these research activities is to gain an effective configuration of integrated, verified, and discretized data, from which to structure valid multiscale and multilevel representation systems.

UAVs gives the possibility to obtain information of many inaccessible contexts with advantages of fast and very high resolution of the images obtainable. This makes possible to integrate photographic data and photogrammetric point clouds of surfaces that cannot be acquired with terrestrial instruments, as well as to inspect inaccessible architectural elements (Fig. 1), document them, and provide a comprehensive analytical overview of the conservation status of the wall surfaces. In fact, the development of documentation and monitoring strategies over time will make it possible to establish which priority interventions and enhancement actions will be necessary for the physical and cultural maintenance of the historical heritage.

Figure 1: Inaccessible fronts and roofs of Stigliano heritage captured by mini-UAV (picture by authors).

The application of specific UAVs is conditioned, of course, by objective of the research project, but it is also due by the limits of the use of drones in different contexts. For example, for the possibility or not of overflight areas or buildings according to specific legislative restrictions. The situation pushed the operator to prefer the use of no-offensive micro-RPAS5 in critical contexts, a choice that brings with it disadvantages related to the more frequent possibility of signal loss with the drone in flight, as well as the stability of the drone itself or the impossibility of making flight plans.

Another aspect that influenced the chose of a specific UAV is related to the performance of the instrument considering the extension to be covered. This is due to the height and the maximum distance it can reach (or minimum distance from a surface); the possibility of control of each shooting position and image resolution; the battery issues. These aspects contribute significantly to the planning of the operations, especially as a function of the complete and exhaustive SfM photogrammetric coverage of each subsystem into which the object has been semantically divided.

In this sense, the use of portable UAVs in the photogrammetric survey, as illustrated here, aims to demonstrate the potential of mini-UAV platforms in rapidly documenting Cultural Heritage and to establish methodological protocols for the acquisition phase (La Placa and Doria 2024).

2. STIGLIANO HERITAGE AND ITS DIGITIZATION PROJECT

With the goal of start policies for the protecting and enhancing of fragile settlements at risk of depopulation, abandonment, degradation, and loss of historical memory such as small towns of the Montagna Materana, the GO-IN! project proposes the creation of a replicable protocol for constructing digital twins of defined areas.

Figure 2: "Rione Terra" satellite image (source google maps).

The project involves the interdisciplinary collaboration of three research units - the University of Pavia (lead institution), the University of Basilicata, and the University of Parma — with the support of the Municipality of Stigliano and other local territorial agencies. Stigliano serves as the leading municipality of the inner area designated as SNAI "Montagna Materana", where SNAI refers to Italy's National Strategy for Inner Areas, a governmental program aimed at revitalizing remote, rural, and shrinking communities. The town is also included in regional development initiatives connected to the PNRR, Italy's National Recovery and Resilience Plan, funded through the European Union's post-pandemic recovery framework.

Stigliano exhibits several characteristics that make it an emblematic case study for this project: its geomorphological configuration, geographic position, traditional building techniques, and its network relationships with other small towns in the surrounding territory (Conte et al. 2023). At the same time, significant depopulation in recent decades has led to reduced maintenance of housing and public spaces in the historic center, creating risks of structural degradation and the potential loss of the town's cultural identity. Addressing these issues requires targeted and comprehensive interventions. The two-year funded project (October 2023–October 2025) focuses specifically on the original core of Stigliano's historic center, known as the "Rione Terra" (Fig. 2).

Figure 3: Images from Stigliano Rione Terra town center (pictures by A. Dell'Amico).

Planned activities include digital documentation, assessment of the conservation state of buildings, analysis of territorial resources, and evaluation of geomorphological vulnerabilities. The resulting information will be integrated into digital models accessible through a 3D GIS—allowing technical operators to manage and update data over time for strategic planning (Caselli et al. 2022; Parrinello et al. 2017)—and through an interactive virtual platform designed for multiple types of users at different scales (Wang et al. 2018; Galasso et al. 2021; Verdiani et al. 2019). These platforms will support interaction with digital spaces, virtual content, and other users, helping to reestablish connections with the collective memory of the place (Fig. 3).

First survey campaign has been conducted from 8th to 13th of July 2024, in an International Summer School, aimed to train students from the master's degree courses in Building Engineering-Architecture and in Architecture from the three universities involved in the project. The research groups engaged in field experimentation with different methodologies and technologies for digital documentation and fast surveying of existing heritage at multi-scales analysis. TLS, MLS, UAVs techniques, – in addition to GIS-based collaborative data collection systems for open areas, buildings, and facades – were employed, to build a heterogeneous and comprehensive digital database of the "Rione Terra" urban fabric. In particular, the digital photogrammetric survey strategy was dedicated to test:

- the application of fast and low-cost survey techniques (MLS and mini-UAVs) to an extended area (Rione Terra is almost 140.000 sqm);
- the geometric correspondence between the data obtained from the different tools and the possibility of their effective integration in a unique database;
- the possibility of considering mini-UAVs acquisition as the main tool for a performative survey campaign from which to build a reliable geometric 3D model.

To verify these methodological/procedural objectives, specific plans for the mini-UAVs campaign were developed, as illustrated in the following paragraph.

3. DECOMPOSING THE URBAN LANDSCAPE FOR MINI UAVS DATA ACQUISITION

The urban core of Stigliano town center has been acquired with UAVs photogrammetric acquisition dividing the complexity of the urban fabric in sub-systems (Fig. 4):

- *Areas.* Different areas have been classified thanks to the joint work between researchers from the three universities involved. In particular, the division has considered the geological and morphometrical characteristic of the urban fabric. Streets, density and historical sub-divisions have been the constraints by which the space was divided into areas. The subdivision also considered the subsequent classification and informatization of the model on a GIS environment. Therefore, the division was not made based exclusively on the performance of the UAV instrument chosen for the documentation campaign.
- *Blocks.* Inside each area, a further decomposition has been developed: several blocks, defined by homogeneous density or structural connections between buildings walls, constitute new sub-system to be acquired thanks to SfM technology. The semantic classification of the blocks thus respects the geometric and morphological constraint of the urban fabric, but also the drone's potential to move around it according to a convergent axis acquisition strategy.
- *Elements.* A further classification was necessary for isolated elements, such as monumental buildings or large complexes. These are elements, like blocks, which, due to their architectural importance or spatial conformation, have provided for specific acquisition as individual elements.

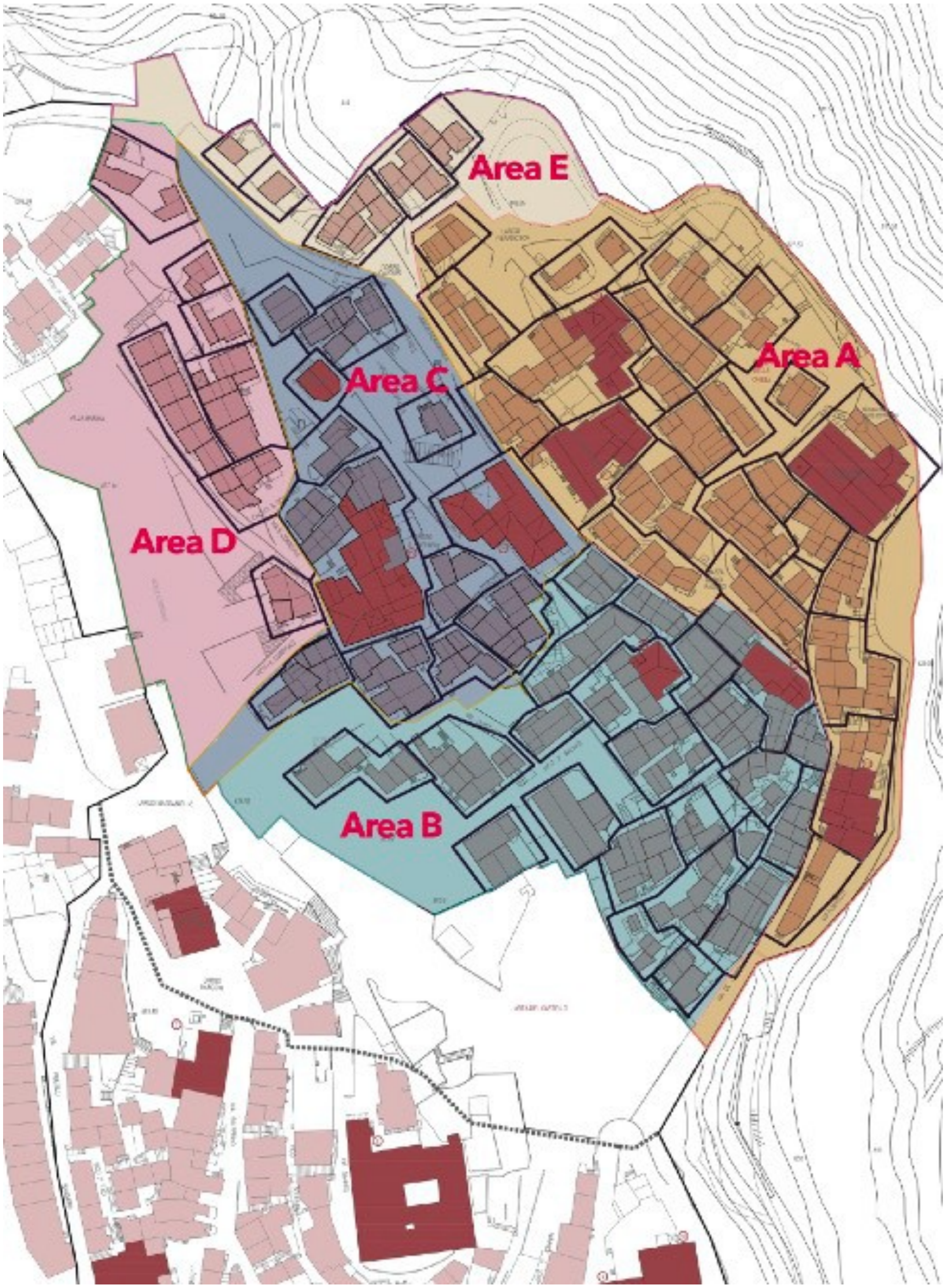

Figure 4: Division in areas (A,B,C,D,E) due to the morphometric aspects of the site. Division in blocks (black) for the mini-UAV data acquisition.

To perform an SfM photo campaign from UAVs, a DJI Mavic mini has been used as the main UAS for the definition of each element, block, area. The survey campaign has been planned during the morning time, (from 9 to 11 am), for a total of 3 days and 2 pilot operators. The choice to operate at that time was defined by the north-eastern exposure of the Rione Terra slope. In this way, a good self-balancing of the drone's camera could be achieved within 2 hours, with not too sharp shadows in the dark parts, and unburnt surfaces in the lit parts (Fig. 5).

Figure 5: Image quality of the pictures from mini UAVs (DJI mavic mini 2. Image resolution: Ground Sample Distance (GSD) = 2 cm/pix. (picture by authors).

The alternative would have been to opt for a more homogeneous exposure in the afternoon, before the sunset. However, it was decided to emphasize the three-dimensionality of the morphology of the urban fabric, highlighting precisely in the photographic image the light/shadow relationship of the surfaces for a greater visual and expressive contrast of the volumes. This aspect will be advantageous in the virtual or digital fruition of the photogrammetric textured model via immersive platform.

4. STRATEGIES FOR SFM ACQUISITION AND POST-PRODUCTION

To strengthen the image network geometry but also to better cover hidden parts (Murtiyoso and Grussenmeyer 2017), each subsystem is acquired following a manual flight with converging axes, maintaining as much as possible the same altitude and distance from the object acquired. Each mission has been evaluated to ensure total coverage of the blocks and elements within a time period of time that allows uniform exposure of the surfaces (essential for image texture homogeneity during the alignment phase by the software) (Parrinello and Picchio 2019).

Due to the layout of the area and the elevation difference along the west-east axis (approximately 60 meters in height), it was decided to first acquire the areas and blocks at higher elevations and then move downwards. This method allows for better control of the drone and visibility of the area to be acquired, which is much more difficult when done from the bottom up (Fig. 6).

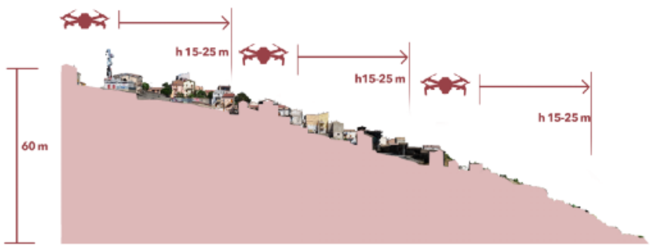

Figure 6: UAV data acquisition from top to down at different high levels (elaboration by authors).

However, the density of the buildings, narrow alleys, and numerous elevation changes within the same area required the operators to change the takeoff and control positions multiple times within the same flight mission to acquire a single block (Fig. 7).

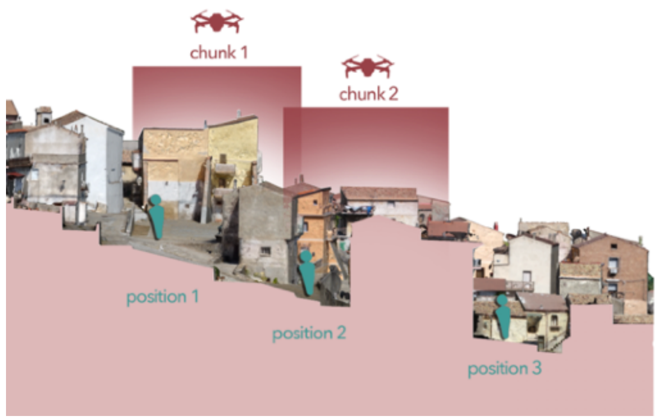

Figure 7: Position change for each set of data acquisition (chunk), corresponding approximately to block (elaboration by authors).

This factor involved significant problems with orientation and recognition of the surfaces to be acquired. In fact, each block needed to be re-acquired for 20% of its surfaces in the subsequent acquisition campaign to allow for the automatic alignment phase by the software. This re-orientation relative to the just-acquired block proved particularly challenging for the pilots during the drone's landing and takeoff for battery changes (approximately every 15-20 minutes). To conduct the block acquisition campaign effectively and avoid getting "lost" in screen recognition, the operators highlighted the recently acquired block on the map each time. This ensured that they had fully covered the area before moving on to the next one.

Each block was acquired by attempting to rotate around its ideal geometric axis (when the block was concentrically developed) and parallel to a line (when the block extended along a longitudinal axis). The drone altitude was maintained between 15 and 25 meters maximum, trying to maintain the same resolution of the image (GSD 2 cm/pix), depending on the complexity and morphology of the block. Shooting has maintained the 70-80% of overlapping between pairs pictures. In some cases, blocks extended over different ground levels or next to an obstacle, around which it was not possible to fly at a constant altitude. In these situations, operators tried to cover as much of the surfaces as possible with images from converging angles, simulating a semi- spherical or semi-cylindrical movement around the object, by rotating the gimbal as needed (Fig. 8).

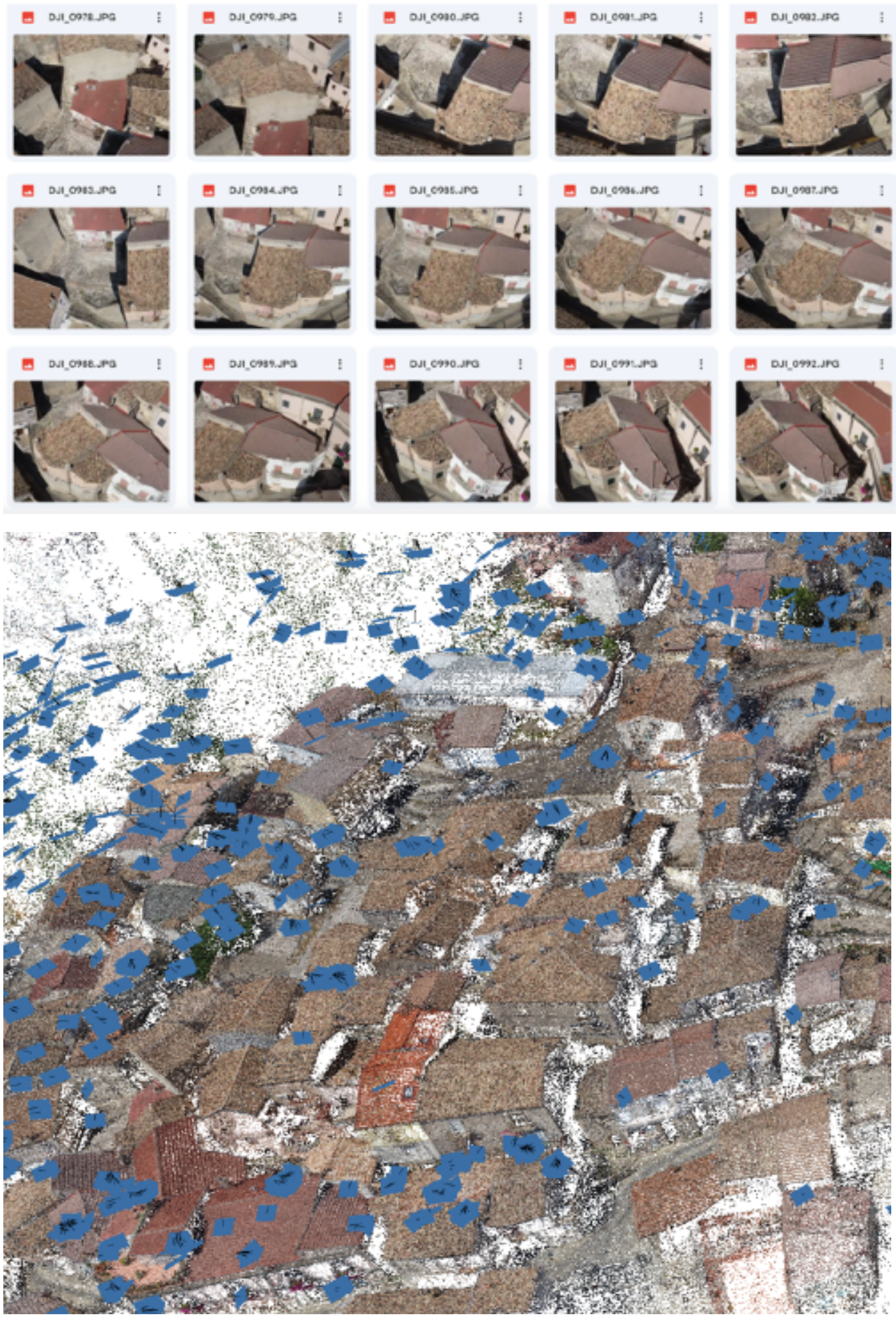

Figure 8: Sequence typologies of pictures related to a portion of a specific chunk. Below, position of cameras of two following chunks (pictures by authors).

On a portion of area A, corresponding to the monumental area of the Church of Santa Maria Maggiore and the square in front of it, an automatic flight plan with DJI Phantom RTK (h from the ground approx. 30 m and GSD = 2cm/pix) was also tested, in order to compare acquisition times and 3D restitution quality (Fig. 9).

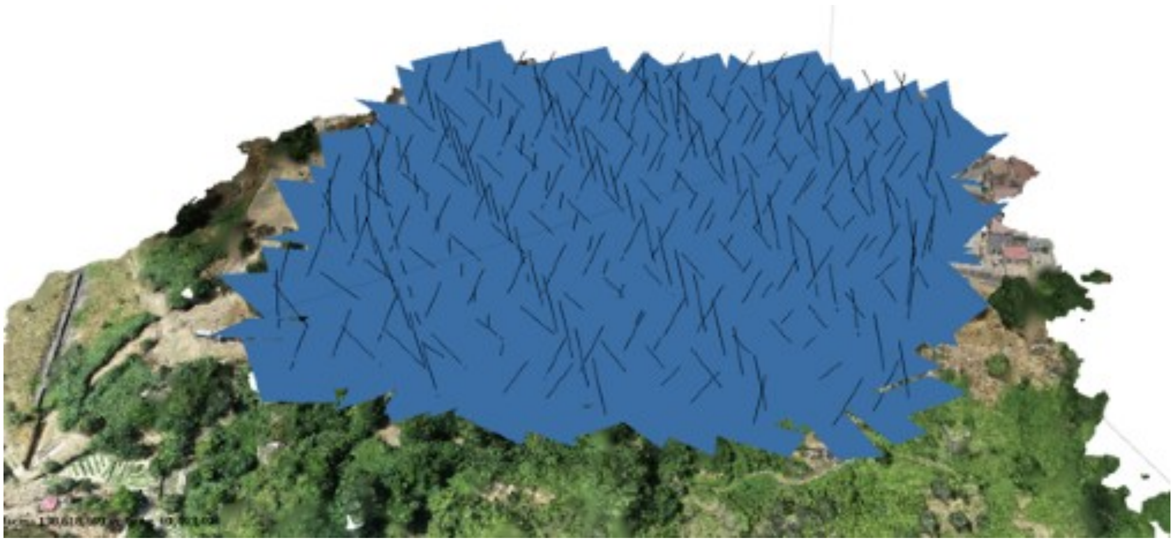

Figure 9: Flight plan of monumental area of Area A (pictures by authors).

Approximately, about 50-60 images were taken for each block, around 500 to 2000 for each area (based on areas with varying homogeneity and density), resulting in a total of 6815 images.

4.1 Construction of an accurate photogrammetric point cloud

The post-processing phase for aligning individual blocks, areas, and the complete photogrammetric database from UAVs was carried out using Agisoft Metashape software. To verify the effectiveness of the developed acquisition method, several verification block datasets were pre-aligned (at low data quality) during the summer school period on the days when the operators were in the field. Once the alignment of the single block and several contiguous blocks together had been verified, data post-production continued by processing the data from a stationary computer at the DAda-LAB research laboratory of the University of Pavia, which is responsible for the digital survey actions within GO-IN! project. The alignment followed the division into 6 portions, dictated by the subdivision of the areas, within which the chunks are processed all together with the logic of minimizing the alignment error between several groups.

Area A6 was the first to be processed. The set of photos comprises 529 taken with DJI mavic mini. For this alignment, a generic preselection and a reference preselection set to source was used (this model, as in the processing of the other areas, is based on the EXIF data linked to the photograph and recorded by the drone - data detected via the drone's IMU and GNSS system). Key point limit and Tie Point Limit were set to 100,000. the weight of the initial dataset is 4.21GB and the weight of the photogrammetric file on Agisoft Metashape is 9.73GB.

The A5 area was the second. The photo dataset comprises 1000 photographs taken with DJI Mavic mini. A generic preselection and a reference preselection set to source was used for this alignment. Key point limit and Tie Point Limit were both set to 100,000. The weight of the initial dataset is 3.87 GB and the weight of the photogrammetric file on Agisoft Metashape is 7.56 GB.

Area A4 was the third to be processed to proceed in logical order. The dataset comprises 2046 photos taken with DJI Mavic mini. A generic preselection and a reference preselection set to source was used for this alignment. Key point limit and Tie Point Limit were both set to 100,000. The alignment of this project with the previous settings failed; changing the settings of the Key point limit and the Tie Point Limit were both set to 120,000 and reference preselection was also changed to Estimated. The weight of the initial dataset is 7.91 GB and the weight of the final Agisoft Metashape photogrammetric file is 24.6 GB.

Area A3 was the fourth to be processed. The processing of the low-resolution dataset did not give any problems in the field, and the high-resolution alignment was carried out on a fixed PC. The dataset comprises 2205 photos taken with DJI Mavic mini. A generic preselection and a reference preselection set to source was used for this alignment. The Key point limit and the Tie Point Limit were both set to 120,000 to avoid the problems that occurred when processing the A4 area. the weight of the initial dataset is 8.57 GB and the weight of the final Agisoft Metashape photogrammetric file is 14 GB.

Area A2 was the fifth. The photo dataset comprised 747 photos taken with DJI Mavic mini. A generic preselection and a reference preselection set to source was used for this alignment. The Key point limit and the Tie Point Limit were both set to 120,000 to avoid the problems that occurred when processing area A4. The weight of the initial dataset is 2.88 GB and the weight of the photogrammetric file on Agisoft Metashape is 5.20 GB.

Area A1 was the sixth and last to be processed to proceed in logical order. The processing of the low-resolution dataset did not give any problems in the field, and the high-resolution alignment was carried out on a fixed PC. The photo dataset comprises 288 photos taken with DJI Phantom RTK in a n automatic flight plan. A generic preselection and a reference preselection set to source was used for this alignment. The Key point limit and the Tie Point Limit were both set to 120,000 to avoid the problems that occurred when processing area A4. This is the only flight that was set to manual. The weight of the initial dataset is 2.27 GB and the weight of the photogrammetric file on Agisoft Metashape is 7.21 GB.

In the final stage, the photogrammetric point clouds generated for the different areas were aligned within a single reference system by identifying common tie points across the various subsets (Fig. 10). The resulting unified database was then georeferenced and validated against the TLS and MLS point clouds acquired across the entire historic center.

Overall, the survey produced 6,815 images, collected during approximately 20 hours of fieldwork and covering an area of 140,000 m². The subsequent post-processing, comprising image alignment, point-cloud generation, and integration of the various datasets, required about 43 hours of computation and data refinement.

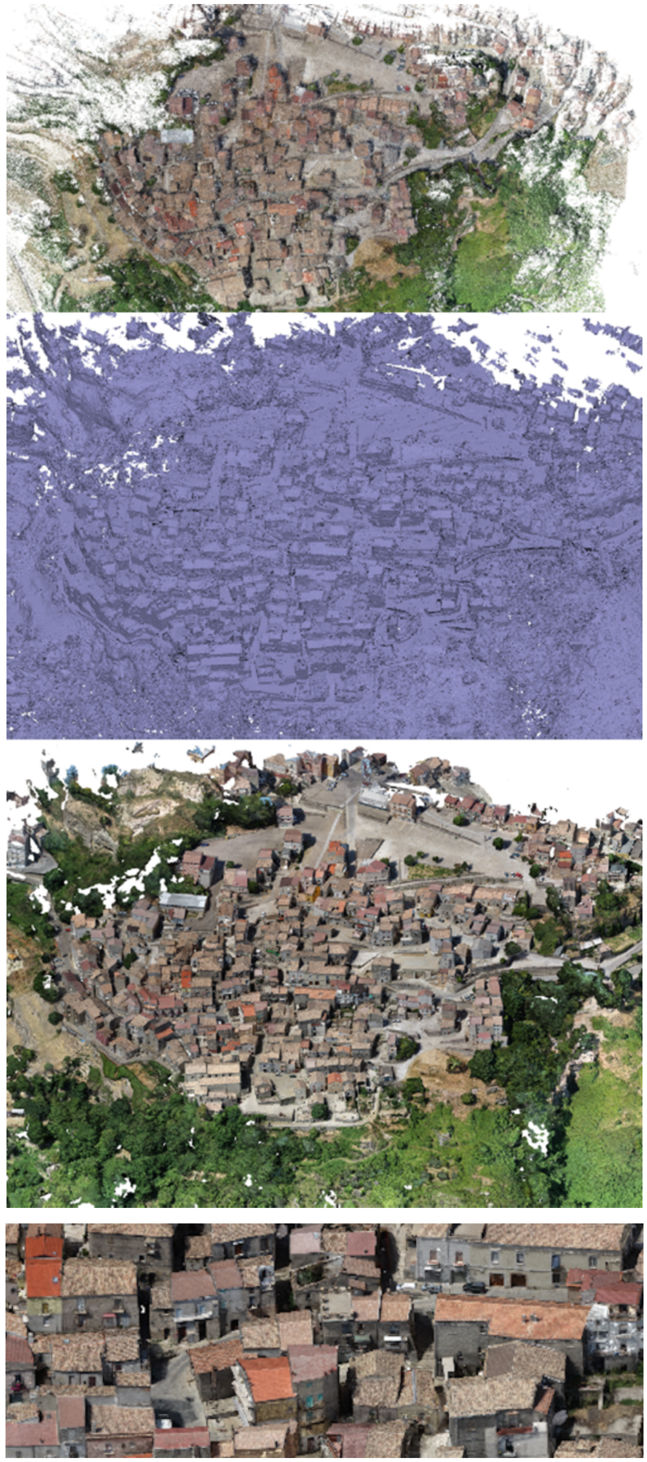

Figure 10: General photogrammetric database of the acquired Rione Terra site. From above, point cloud, mesh model and textured model (elaboration by authors).

4.2 From point cloud to 3D semantic model

The representation of architectural complexity is essential for developing analytical considerations, as it allows for the organization of meaningful relationships within a specific urban context. This process requires attention to both relationships and background, especially when dealing with a fragile architectural heritage at risk of preservation. Simplifying the characteristics of a place is a delicate operation, which risks causing the operator/ drawer to omit significant information. This is particularly relevant in the transition to digital, where critical synthesis and narrative models are transformed into containers of meaning, increasing the potential of documentation aspects.

The digital twin of a space, such as a townscape of an inner area, burden of memory and intangible values, allows the construction of an informative and semantic 3D model descriptive of spatial qualities. Thanks to the infographic information that will be appropriately associated with volumes, surfaces and elements of the model, it will be possible to guarantee a programmatic management of the architectural heritage over time (Tenedório et al. 2016), but also the possibility for the user to immerse himself into a reconstructed scenario, interacting with contents that, in some cases, exceed the interactive possibilities given by the real experience.

The modelling workflow adopted to transfer the database into a semantic 3D model followed a semi-automatic procedure. First, a macro-modelling phase (LoD 2), still work in progress for the GO-IN!. This phase was aimed at identifying the general structures and volumes of the built-up area and the morphology of the public space, in a first level of mesh-surfaces representation. The macro-modelling activity was carried out by extracting the virtual reference planes, from the photogrammetric point cloud, for each architectural surface (fronts and roofs) (Fig. 11).

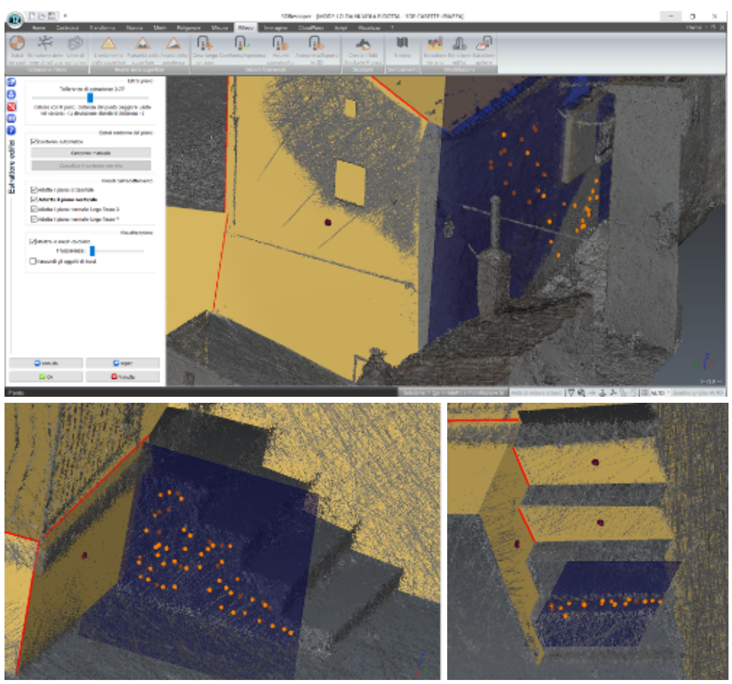

Figure 11: Macro-modeling phase with extraction of reference plans (elaboration by authors).

This operation was carried out using 3D Reshaper (Leica Cyclone), which in the first phase enables the creation of general models of the volumes, composed of interconnected mesh surfaces without discontinuities between buildings and terrain (a multi-block model) (De Marco 2020). This step is followed by the semantic segmentation of the blocks into classified surfaces, in which each plane is selected and linked to its corresponding informational attributes (Galasso 2020).

At this stage of the project, the research team tested the feasibility of the macro-modelling workflow with a view to the subsequent import of the 3D model into a GIS environment (ArcGIS Pro). Thus far, the tests indicate that the resulting base model is both georeferenced and metrically reliable, as it derives from accurate, integrated surveying data (a reality-based model). This general model is now prepared to support the next phase of micro-modelling, aimed at reconstructing the architectural elements on the façades and enriching the representation of the built environment with detailed formal components (Fig. 12).

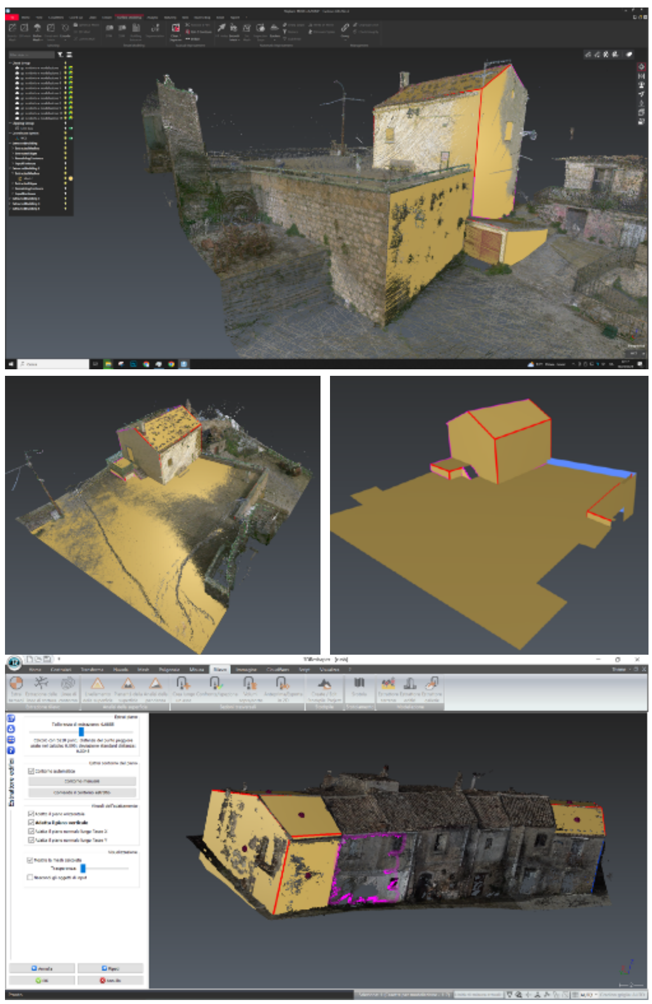

Figure 12: Macro-modeling phase and level sub-division for micro-modeling processing (elaboration by authors).

5. CONCLUSIONS

This contribution examines a specific component of a broader research project on the digital documentation of cultural heritage in inner, rural areas. In this context, we addressed two interconnected aspects related to close-range UAV photogrammetry. First, we tested a manual acquisition strategy on an exceptionally complex case study—both in form and density—to produce a complete and reliable database with strong geometric and qualitative consistency. Second, ongoing work focuses on translating this photogrammetric database into a 3D model that can be semantically structured into informational layers, enabling interaction with municipal authorities and supporting urban heritage management practices (Pettineo et al. 2023).

With regard to the first objective, the use of low-cost, fast, and easily deployable tools has shown that, when acquisition is carefully planned and the complexity of the site is broken down into manageable areas and sub-areas, it is possible to document even very large and heterogeneous environments. The survey campaigns carried out in this study demonstrate how commercial UAVs can effectively complement laser-based acquisition methods, integrating both metric accuracy and high-quality photographic data (Verdiani et al. 2021). The choice of UAV must be based on the site's morphological characteristics and on practical considerations of operational performance and regulatory constraints. When employed with a convergent-axis acquisition strategy, mini-UAVs can generate very high-density point clouds that fully meet the documentation requirements typical of cultural heritage work, positioning these low-cost tools as valuable options for rapid and reliable surveying.

The second aspect follows directly from the first. To develop a reality-based 3D model suitable for long-term management and virtual use, the workflow must rely on an extremely detailed and trustworthy photogrammetric database. The high density of images collected in this study facilitates semi-automatic surface recognition on reference planes, significantly improving the efficiency and precision of the modeling process.

In conclusion, this work demonstrates that, unlike TLS and MLS systems, whose contributions to the final geometric database are inherently constrained by their acquisition logic, the quality of close-range photogrammetric data is largely determined by the operator. Through careful planning and methodical execution, the operator directly shapes the characteristics and accuracy of the final dataset, effectively defining the quality of the resulting 3D model from the earliest stages of the survey.

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