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Proposal of an integrated 3D architectural survey method for application in historic agri-food building analysis and representation

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Abstract

In Italy, historic agri-food buildings can be considered a relevant material expression and testimony of century-old agriculture and food processing practices handed down by generations. Recently they have gained ever-growing importance as a part of the wider architectural heritage. As such, they deserve dedicated general surveys to build a thorough knowledge of their distinctive characteristics and investigate their current condition, setting the basis for the implementation of planning and management actions for their sustainable valorisation. To this end, building information modelling can be considered an efficient strategy to preserve construction information by creating 3D models based on surveys of the built heritage. To acquire in a fast and accurate way geometric, reflectance, and colour data of rural buildings as a 3D point cloud, the terrestrial laser scanner (TLS) represents a powerful tool. The traditional TLS-based survey methods, in the context of historic agricultural buildings, have several limitations, mainly due to the presence of inaccessible parts and bulky machinery once used for processing and storage. In the present research, to overcome these issues and thus have a complete survey, we describe a proposal of an integrated methodology for obtaining 3D point-cloud data of existing rural agri-food buildings based on the integrated use of TLS, hand-held scanner, and unmanned aerial vehicles instruments. The proposed methodology was tested in surveying three historic agri-food buildings, and the accuracy of the obtained 3D point cloud was calculated using the root mean square error (RMSE) on the X, Y, and Z alignment of the two different 3D point clouds in correspondence of the used B/W target. Moreover, a measure of the distance between two merged 3D point clouds in their overlap area has been performed using the multi-scale model to model cloud comparison (M3C2). RMSE analysis always shows values lesser than 1 cm, and M3C2 shows values between 0 and about 6 cm.

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Introduction

Historic buildings for processing and storing agricultural products represent a large and important part of the rural architectural heritage. They are today recognised as worthy of protection since they represent: an essential expression of the built vernacular heritage (ICOMOS, 1999); a testimony of the way of life and of the building tradition of past generations; a distinctive and characteristic component of the historic landscapes documenting the agricultural practices of a given region (Di Fazio and Modica, 2018); an important material heritage documenting the evolution of the technical knowledge and of the specific technology, machinery, methods, and tools applied over time to food processing activities (Di Fazio, 1999).

Among the historic buildings for agri-food production in the South of Italy, flour mills, wineries, and olive-oil production facilities are the building types most represented. They often show formal and functional organisations inherited from the ancient Greek and Roman civilisations (Adam, 1999; Di Fazio *et al*., 1999) and have had a centuries-old continuity of use, thus becoming a precious document of the production techniques' evolution from ancient times to the present. Moreover, since wheat flour, wine, and olive oil have always had an essential role in the food culture and diet of the Mediterranean peoples, the buildings that supported their production present relevant sizes and thoroughly studied functional characteristics as a consequence of the economic relevance assumed (Cascone *et al*., 1997; Di Fazio *et al*., 1999).

Despite the wide recognition of their importance, historic buildings for agri-food production have not yet received as much consideration as they deserve. Several studies describe and help interpret them from many points of view. However, in many regions, it still lacks comprehensive knowledge based on extensive surveys of this heritage, enabling to produce material, geometric surveys offering metric data, and a detailed description of the building materials and the constructional systems used at different times, often stratified and overlaying in the same building. Because of the considerable number of historic agri-food buildings deserving such kind of surveys, their widespread presence in large parts of the countryside, and the redundancy and neglection now threatening them, it is necessary to define innovative surveying methods coupling expeditiousness and precision, good detailing and economic affordability, advanced techniques and ease of application. Many of the historic building facilities for agri-food products processing show a close relationship between the buildings themselves and the machinery housed, often requiring a very complex architectural plan-altimetric organisation. This, depending on functional reasons related to the processing needs and the energy sources used to drive the machinery, move the products through the processing areas and assure satisfactory indoor environmental conditions. In historic buildings such as wineries or olive oil mills, for example, the need to transfer the product by gravity and the clarification phase required the altimetric articulation of the building into different floor levels, thus taking great advantage of sloping sites. In other cases, the use of water-driven machinery required an altimetric building and site organization, coupled with complex systems of water caption from the near streams and channelling works, thus producing sufficient kinetic energy from the positional potential (Cascone *et al*., 1997; Di Fazio *et al*., 1999).

For this kind of building the conventional surveying methods, based on the adoption of only one surveying tool to detect the whole area, show significant limitations depending on the difficult accessibility and steepness of the building sites, often invaded by wild vegetation; the complex stepping articulation of the indoor space; the presence of historic and bulky machinery making the survey of building parts difficult and deserving themselves accurate detailed-surveying operations (Di Fazio *et al*., 2016).

In many Mediterranean countries, several historic agro-industrial buildings still are or can be effectively used either for the original function or other alternative uses. Sustainability strategies encourage prolonging the functional life of the current building stock and the recovery and reuse of redundant farm buildings. In Italy, these often-present characters corresponding to the application of the architectural sustainability principles: use of local natural materials; use of passive systems for indoor microclimate control; visual integration with the agricultural landscape; adaptation to the site landform; architectural forms corresponding to the local cultural tradition; *etc*. Moreover, today there is an ever-growing interest in recovering traditional rural buildings for cultural purposes (Picuno, 2012). Their role in promoting the touristic attractiveness of rural landscape is well recognized (Leanza *et al*., 2016), and the recovery of traditional buildings is to be preferred to new constructions because, especially in rural areas, these last are seen as one of the leading causes of landscape degradation (Garcìa and Ayuga, 2007).

For many historic agri-food building facilities, the continuity of use for production purposes, on the one hand, has favoured their permanence, but on the other hand, it has required continuous adaptation over time to meet the changing food processing and storage requirements (Barreca *et al*., 2017). Also, in these cases, accurate architectural surveys are needed to adequately address the reuse and conversion interventions according to compatibility and suitability criteria.

Based on metric survey documentation, thorough knowledge of the rural architectural heritage's current condition is fundamental for understanding its development and is a prerequisite for implementing planning and management actions for sustainable valorisation (Poloprutský, 2018; Ruggiero *et al*., 2019). To this end, building information modelling (BIM) can be considered an efficient strategy to preserve the construction information by creating 3D models based on surveys of the building as a whole and its constituent parts (Osello *et al*., 2018; Ivanov, 2020). BIM is a computer-based process that, through 3D models, digitally represents and manages the main functional and physical characteristics of a building facility. The main feature of a BIM is the 3D geometry of the object to be represented (as-built or in-design), which is the basis for 3D modelling and storing the information associated with it (Borrmann *et al*., 2018). Creating an as-built BIM parametric model is fundamental not only to engage in any type of new design (Volk *et al*., 2014), but also for developing detected building facilities management (Pärn *et al*., 2017). Therefore, a building is represented by a set of information describing different characteristics (geometry and dimensions, functional distribution, functional, constructional, and technical elements, *etc*.), which, if well managed, can improve its performance (Chen *et al*., 2015). BIM strategy is mainly applied to under-construction buildings but is increasingly used nowadays for conserving existing ones (Pocobelli *et al*., 2018). Arayici (2008) proposed adopting the BIM approach to refurbish a building in East Manchester. Since 2009, a specific methodology has been developed for applying BIM in historic buildings, usually referred to as HBIM (historic building information modelling) (Murphy *et al*., 2009). Its potential application to a wide range of buildings and site of cultural heritage (Dore and Murphy, 2012; Oreni *et al*., 2014; Logothetis *et al*., 2015; Moyano *et al*., 2021; Bastem and Cekmis, 2022) encouraged specific research worldwide (Zhao, 2017) and since the middle 2010s opened way to the development of HBIM open-source software, tools and cloud-based technologies (Logothetis and Stylianidis, 2016; Diara and Rinaudo, 2018; Diara, 2022). This determined a radical change in the approach to historic buildings' surveying, documentation, data storage, and management, also in view of future interventions and with the advantage of better data accessibility and shareability (Diara, 2022).

One of the main inputs into the flowchart for obtaining an as-built BIM is data providing geometric information about the building (or object) of interest. For this purpose, in the last two decades, there has been a wide use of 3D point clouds obtained from various sources. The ever-increasing application of this approach to historic buildings is documented by a recent scientometric survey by Yang *et al*. (2022), considering all the scientific articles in English present in the Web of Science database and concerning 3D point-cloud used in the cultural heritage field. It observed that since 2006 – the first year when the type of articles under consideration was detected (only 2) – the number of articles published per year shows an increasing trend, particularly remarkable in the period between 2016 (16 articles published in that year) and 2021 (68 articles) for which a total of 256 articles were found. The study, through a term co-occurrence and cluster analysis, also shows a major importance assumed by the term cluster "historic building information" and helps reveal that 3D point-cloud data is the main source of BIM and HBIM. The growing scientific interest in 3D point cloud shows a trend that in some ways corresponds to technological progress, which in recent years has offered scientists and professionals a wide range of new devices, easy to use and able to generate this kind of data at a relatively low cost. Application to surveying buildings and sites with complex geometry or irregular shapes can benefit greatly from the integrated use of different 3D point-cloud data sources, both terrestrial and aerial. To acquire in a fast and accurate way geometric, reflectance, and colour data of rural buildings, the terrestrial laser scanner (TLS) technology represents a powerful tool. TLS allows the massive acquisition of 3D point clouds with a high measurement accuracy (typically in the order of mm). Beyond 3D coordinates (X, Y, Z), TLS technology allows the acquisition of surface reflectance and, using integrated or external red, green, and blue colour space (RGB) digital cameras, colour values are useful in obtaining texture information. In this way, for each surveyed point of the 3D point cloud, it is possible to obtain and store up to 7 different parameters (X, Y, and Z coordinates, reflectivity value, and RGB colour values). This TLS-based 3D point cloud is gaining attention from scholars interested in conserving and managing cultural heritage buildings and sites (Di Angelo *et al*., 2018; Jo and Hong, 2019). In the broad context of the survey of historical monuments, many studies use TLS for 3D surveys (Moyano *et al*., 2022). Quattrini *et al*. (2015) adopted a TLS-based 3D point-cloud approach to survey the Romanesque period church of Santa Maria in Portonovo (Italy), which is considered a high-quality Italian heritage monument. Santagati *et al*. (2019) performed a TLS-based survey to obtain the BIM of St. John Cathedral in Nicosia (Cyprus).

Unlike the mentioned cases applied to historical monuments, all the historic agri-food buildings often house bulky machinery, plants, and furniture once used for food processing and storage. Furthermore, they usually present a complex spatial organisation where the geometry and topological succession of spaces immediately descends from the processing flow scheme and closely relate to the site's landform and energy use. In the case of these complex objects, several scans from different station points (SPs) are generally required to survey their entire architectural envelope, obtaining a complete 3D point cloud. Nevertheless, processing machinery and furniture in the surveyed space generates occlusions (*i.e*., shadow areas that determine missing data) and clutter of background surfaces that should be considered since the early stages of the survey design and planning.

TLS-instrument's limitations are mainly due to the indoor space's complexity and the occlusions and clutter of surfaces placed behind (Adan and Huber, 2011), which determine the data loss in the generated 3D point cloud. A simple way to create complete surveys, trying to avoid or reduce data loss, can be pursued with the intensification of the number of TLS SPs, increasing survey time and data redundancy. Several algorithms and techniques have been implemented to fill holes in the post-processing-phase as analysed by several scholars in recent years (Adan and Huber, 2011; Salamanca and Cerrada, 2012; Dumitru *et al*., 2013), but it is worth observing that the resulting 3D point-cloud can be still incomplete.

A way to obtain a complete survey without increasing the number of SPs is to integrate the TLS data with 3D point clouds derived from other surveying instruments (Mill *et al*., 2013), such as hand-held scanner (HS) systems. HS is a portable 3D scan system using photogrammetry to obtain a 3D point-cloud reconstruction of the investigated scene (Givi *et al*., 2019). HS tools have been used, in several research fields, for the detection of details of small objects, such as jars (Kaneda *et al*., 2022) or human bones (Probst *et al*., 2022) and parts of bodies (Xia *et al*., 2019). Saptari *et al*. (2022) proposed combining TLS and HS to survey a temple in Bali. They performed a TLS survey of the inner areas of the temple and used HS to scan the details of one of the statues at the temple's entrance. As a portable solution, HS can be used in agri-food environments to survey the surfaces not detected by TLS because of obstacles on the scene. HS can also help survey the machinery present on the scene.

A further limitation of the traditional agri-food buildings survey with TLS is the difficulty in obtaining an accurate survey of the roof, highest-faced parts, and other inaccessible areas of the detected building (Yang *et al*., 2022). To address this issue, integrated surveying solutions based on TLS and unmanned aerial vehicles (UAVs) are proposed mainly in the literature (Cheng *et al*., 2013; Xu *et al*., 2014; Achille *et al*., 2015; Chiabrando *et al*., 2016; Chatzistamatis *et al*., 2018; Rocha *et al*., 2020; Ursini *et al*., 2022). UAVs are remotely piloted platforms used for several applications like precision agriculture (Messina *et al*., 2021; Modica *et al*., 2021), forestry (De Luca *et al*., 2019; Solano *et al*., 2022), protected landscapes (Cucchiaro *et al*., 2020), soil erosion (Meinen and Robinson, 2020), including surveying of cultural heritage and rural buildings (Vacca *et al*., 2017; Bakirman *et al*., 2020; Martínez-Carricondo *et al*., 2020;). UAVs use a photogrammetric technique based on structure from motion (SfM) algorithms (Westoby *et al*., 2012) to obtain a 3D point cloud starting from aerial pictures.

Integrating data from different sources and collecting with different techniques, *i.e.*, a data fusion process, allows for more detailed and valuable information on the object of the survey (Lawrence, 2012). In the present research, we propose an integrated methodology for obtaining 3D data models of existing rural agri-food buildings based on advanced geomatics techniques and the contextual use of TLS, HS, and UAV instruments. The integration of three geomatics techniques allows scholars to analyse in detail the complex geometry of hardly accessible rural buildings. The raw data are suitable for creating a parametric 3D model of the surveyed buildings. Based on a parametric library of objects (Murphy *et al*., 2013), this information constitutes the first stage in implementing a 3D HBIM (Murphy *et al*., 2009; Poloprutský, 2019). Moreover, the proposed methodology is dedicated explicitly to historic agri-food buildings that maintain their original function or convert to alternative uses. Unlike the different solutions proposed by scholars, fundamentally based on the use of software algorithms to generate the missing data model (Müller *et al*., 2006; Thomson and Boehm, 2015), the method here proposed and presented does not entail that TLS point clouds are integrated with UAV-derived point-clouds to detect the roof and to avoid occluded and clutter surfaces. TLS SPs are instead integrated with HS surveys since the survey project phase. Moreover, HS led to surveying tight spaces with a different technology capable of generating a 3D point cloud, merged with the TLS one. The main aim is to obtain a complete 3D point cloud, which can be used as a basis for constructing BIM for the technical documentation and management of agri-food buildings.

Materials and Methods

The acquisition of dimensional data of historic agri-food buildings needs careful planning of the *in-situ* surveys. To this end, the pre-survey project is a crucial part of the whole process since it affects the fieldwork duration and the accuracy and completeness of collected datasets. Our proposed method, synthesised in the workflow shown in Figure 1, pays much attention to the survey project phase regarding both instruments' setting and positioning and target typology and placement.

Case studies

The proposed method was tested in three historic olive oil mills (B1, B2, B3) located in the Province of Reggio Calabria (Calabria Region - Southern Italy). They are particularly representative of the rural architectural heritage of the area and are an essential material document of the technological transition that

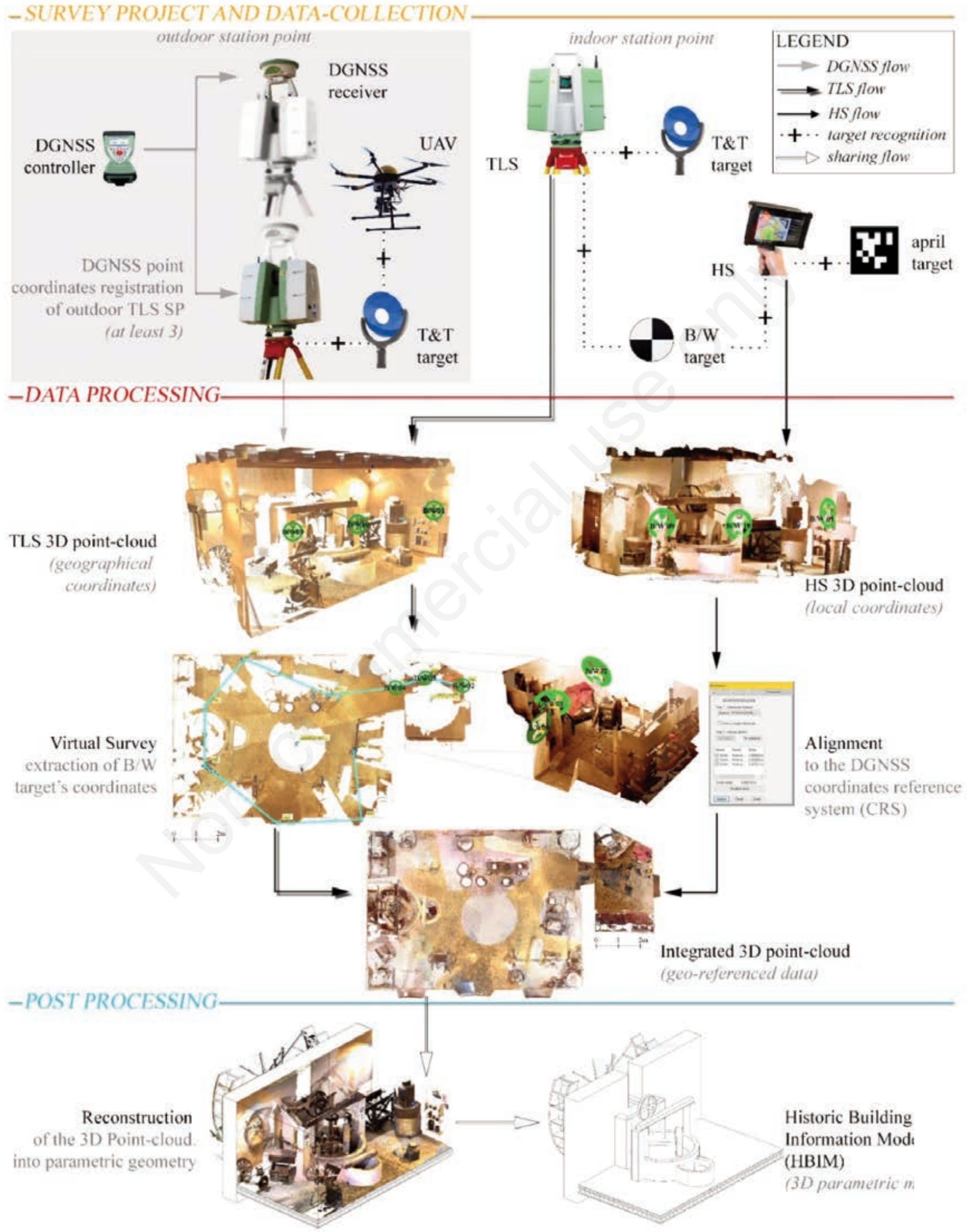

Figure 1. Flowchart of the proposed integrated 3D Survey method. Three main steps are singled out: survey project and data collection, based on terrestrial laser scanner and hand-held scanner surveys coupled with differential global navigation satellite system surveys; data processing, mainly dealing with registration, alignment, and co-registration of terrestrial laser scanner and hand-held scanner 3D point-clouds; post-processing, devoted to obtaining a 3D parametric model.

occurred between the late 18th and early 19th centuries (Mazzotti, 2004; Di Fazio, 2008) when the primary power source driving the machinery used in these agri-food buildings passed from human/animal power to water kinetic energy (Figure 2). Moreover, these buildings represent three different present conditions of use: continuity of use for the original function with adequation of the building and the machinery to present functional requirements; conversion to cultural uses and services related to the promotion of olive-oil production and rural tourism in the region; redundancy and partial disuse, only some parts of the building complex being used as storage areas for various materials.

The first building surveyed (B1) is located in the "Modi" district in the municipality of Gerace. It was built in the 19th century and shows typological and constructional characteristics coherent with the local tradition. The building envelope presents rubble masonry load-bearing walls, a longitudinal timber roof structure supported by masonry arches, and a pitched roof covered by pantiles. Various spatial remodelling and constructional transformations interested the building over time. In particular, the indoor space was modified to ensure the correct layout of the new olive oil machinery. The second building (B2), today housing an olive oil museum and a restaurant, is located in the municipality of

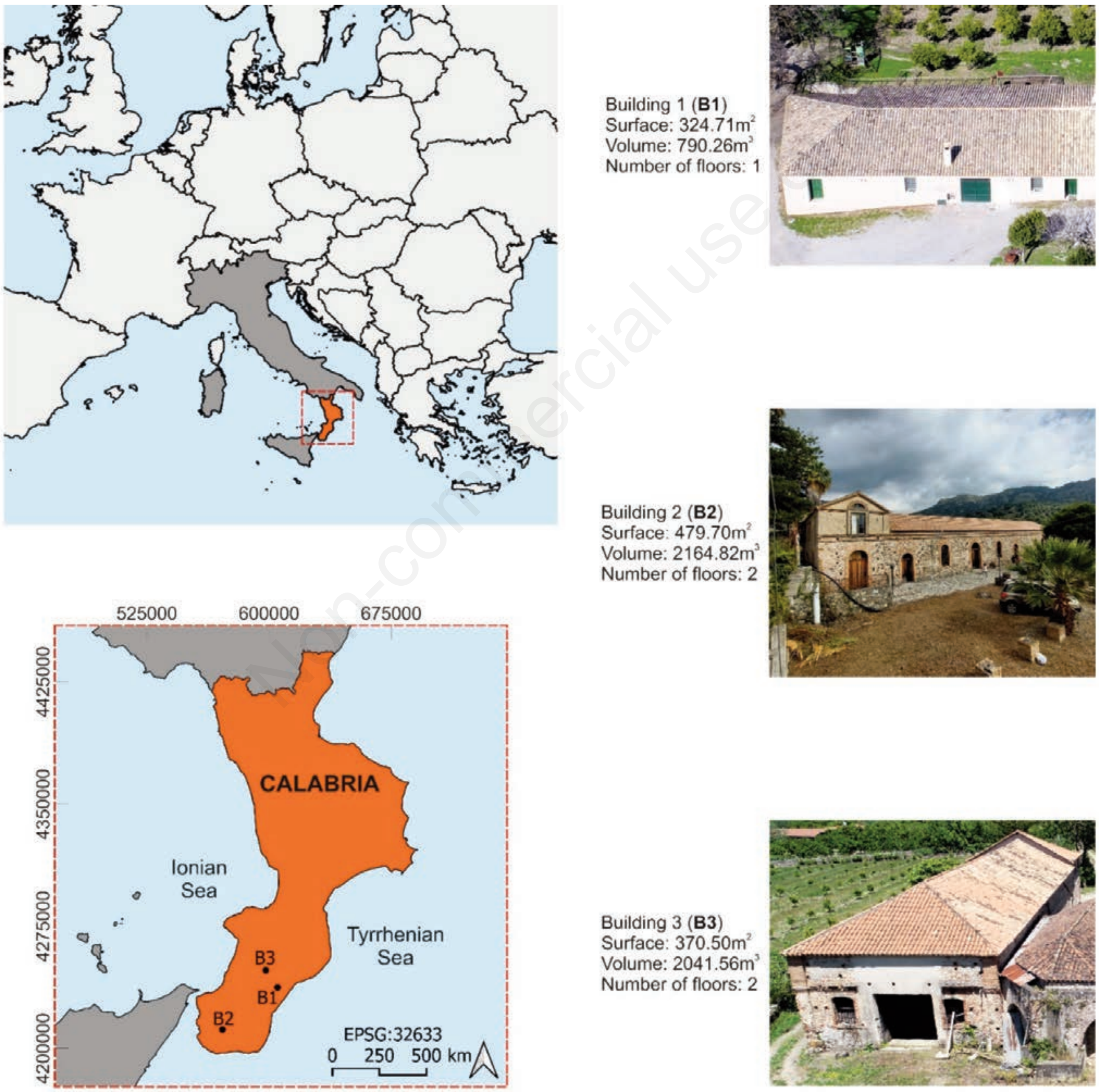

Figure 2. The geographical location of the three investigated historic olive oil mills.

Bagaladi. It has a built volume of about 2000 m^3 distributed over 2 floors. On the ground floor are office rooms, toilets, a restaurant with kitchens, and a conference room; on the basement is a museum of ancient agricultural instruments. An artificial canal conveys the water of a river towards the centre of the building. With a diameter of 5 metres, a wooden wheel moves two stone millstones that lie, one on the ground floor and the second in the basement. The third building (B3) dates back to the first half of the 19th century and is located in the countryside of San Giorgio Morgeto. Its spatial and functional organisation follows the proposals presented by Marquis Domenico Grimaldi in a book published in 1773 to promote the rationalisation and innovation of the olive oil industry in Calabria (Grimaldi, 1773). This olive oil mill is characterised by a huge rectangular processing space that houses at different levels: water-driven olive crushers, a battery of presses so-called “alla Genovese” (with a single central screw), and a series of stepping clarification tanks.

Data collection

Terrestrial laser scanner point-cloud

TLS 3D point cloud was obtained using a Leica ScanStation C10, a short-range time of flight TLS with a 360° (horizontally) ×270° (vertically) field of view (FoV), a maximum scanning speed up to 50,000 points per second and characterised by high positional accuracy. For distances up to 100 m, the systematic error of C10 does not exceed 3.7 mm (Antanavičiūtė *et al*., 2013). C10 uses a green pulsed laser (532 nm of wavelength) for point coordinates detection and an integrated 4-megapixel RGB camera to acquire colour information for each point.

The instrument needs different SPs that must be connected to each other by tilt and turn (T&T) targets. It is also possible to detect the relative and/or absolute positions of black-and-white (B/W) targets in the software environment.

TLS surveys were conducted by combining 3D points data with RGB information derived from the integrated camera. For each SP, before starting the points’ acquisition, the instrument was perfectly levelled, and a topographic nail was applied on the ground to allow the replicability of the survey. After this, a complete 360°×270° scan window was surveyed at the maximum resolution, which takes about 20 minutes to collect points and images. Moving from an SP to the following one, we ensured that at least three common T&T targets were detectable from both SPs. After each acquisition, the collected data was visually checked directly on the scan station screen for a quick look at the survey quality. At the end of the surveying campaign, all surveyed 3D point clouds were combined in a single cloud through T&T targets. Moreover, to improve the repeatability of measures in multitemporal surveys, for each outdoor SP, the absolute coordinates were acquired using the Leica GS12 as Real-Time Kinematic (RTK) GNSS, and a survey point nail was used as a permanent marker.

Hand-held scanner point-cloud

The Trimble portable HS DPI-8 was used to scan all those areas occluded in the TLS surveys. DPI-8 captures 3D colour data in a 5 to 60 cm distance range with a horizontal FOV of 57.5°. This HS permits real-time feedback on data quality, thanks to the Phi.3D software that shows in green the most accurate points detected, in yellow the points with lower accuracy, and in grey all the other areas of the detected scene. According to Trimble specifications, it has an operational range spanning between 0.6m and 5.0m. The measuring procedure is based on a structured light speckle pattern provided by an infrared (IR) and RGB PrimeSense sensor integrated with a powerful Android 8” tablet that allows having a scanning system in just one hand. The user must manually move the HS between tasks and pick up where it left off, moving through its own target, the April target. During a typical HS survey, scans are pre-registered via an iterative closest point (ICP) algorithm (Besl and McKay, 1992).

HS surveys were conducted to integrate those areas that were difficult to reach with the TLS. Moreover, HS was used to survey detail of the historic machinery present in the scene (*e.g*., olive stone-mill crushers, old presses, water-driven motion wheels, *etc*.). Before each HS survey, the instrument needs time to calibrate the sensors. Once it is ready to scan, for each detected scene, the operator moves slowly, ensuring to acquire all data with the highest accuracy and collecting several April targets needed to reconstruct the acquired geometry and several B/W targets that will be used in the following co-registration step. After each survey, the collected data are pre-processed and visualised as 3D reconstruction directly on the tablet to quickly check the survey’s quality.

3D point clouds generated by HS surveys were combined with those obtained from TLS surveys. This process requires linear environmental conditions, as the photographic sensor’s characteristics work directly on a digital output signal and are more noise-sensitive.

Unmanned aerial vehicle point-cloud

For the UAV-based aerial survey was used a DJI Phantom 4 Pro+, a quadcopter multirotor solution with an integrated RGB camera. The equipped sensor is a 20-megapixel 1” CMOS global shutter with a field of view (FoV) of 84° (DJI, Shenzhen, China). UAV-based surveys were conducted using the flight planning app Pix4Dcapture (Pix4D SA, Prilly, Switzerland) to plan the nadir acquisition according to a double grid drone path at a mean altitude of 50m above ground level. To ensure a high-resolution survey, an overlap area of 80% and a speed of 2.5 m/s were set during the planning step. As far as oblique acquisitions are concerned, however, a freehand flight was carried out. A professional UAV pilot performed each mission, and to ensure safety, the detected area was fenced, avoiding other people’s presence. The pilot has performed the take-off and landing operations with manual UAV control for both planned and freehand flights. In order to improve the georeferencing of the acquired images, a set of easily detectable 50×50 cm B/W panels distributed all along the surveyed areas were used as ground control points (GCPs). For each GCPs, the absolute coordinates were acquired using the same RTK-GNSS system for the outdoor TLS SP. The entire post-flight processes needed to obtain the 3D point cloud from the UAV pictures were conducted in Pix4Dmapper Pro 4.3 (Pix4D SA, Switzerland). This software allowed, through SfM algorithms, to obtain a 3D point cloud and an orthophoto starting from the UAV aerial images. The 3D point cloud was finally exported in *.las format and co-registered with the TLS and HS ones.

Data-processing: registration, co-registration, and georeferencing of 3D point-clouds

Registration (only terrestrial laser scanner)

The registration process involves only the TLS surveys and refers to fitting all 3D point clouds obtained from different SPs to a single 3D point cloud. Before their registration, raw 3D point clouds were filtered using a distance criterion approach fixing a threshold of 50m to remove the points extraneous to the scan scenery. TLS 3D point-cloud registration is typically performed using one of the following methods (Abellán *et al.*, 2014): point-to-point, feature-based and target-based. Currently, the most common registration practice in TLS surveying refers to the target-based method (Fan *et al.*, 2015). This method needs a precise detection and survey of several targets, at least three for each SP. It is a time-consuming method, but better final accuracy is ensured than the other two. In the proposed workflow, a target-based method was chosen for registering TLS 3D point clouds using a T&T target. Different 3D point clouds with at least 3 T&T targets in common were merged using these targets as snapping points.

Co-registration

The co-registration, *i.e.*, the registration of different data sources outputs (Granshaw, 2016), is the process of merging all surveyed data of the same scenery captured from different sources, using a surveyed 3D point cloud as reference. The co-registration process is a prerequisite to ensure the quality of all following 3D modelling and analyses.

A sufficient overlap among different scans (*i.e.*, an overlapping surface between the different surveys) is needed to perform the co-registration. The 3D point-cloud co-registration has been investigated for more than 20 years; several solutions have been proposed, which can be classified mainly into two macro-groups: on the one hand, the *sparse methodology* that operates on significant points of the surveyed scene to unite different surveys; on the other hand, the *dense methodology* that operates, instead, on the entire survey (Serafin and Grisetti, 2017). The ICP technique is used for 3D point-cloud registration in the sparse approach. In order to apply the ICP technique, a superposition of homologous and recognisable surfaces is required. Using the ICP approach to merge the 3D point cloud from TLS with that from HS and UAV is a challenging operation, as the surveyed surface portions to be merged offer limited areas of overlap. Unlike other experiences in which TLS and 3D point cloud co-registered through the ICP algorithm (Mandelli *et al.*, 2017), we propose an approach based on targets to improve the obtained accuracy. A modified target-based registration is adopted in our methodology to co-register different 3D point clouds, introducing a simple way to reduce the time survey. The adopted methodology allows the co-registration of the different 3D point clouds using common targets, detectable at least by two different surveying tools. To this end, two target types (Figure 3) are used: circular 6-inch blue and white T&T target with high reflectivity, detectable both by TLS and UAV, and squared 6-inch B/W target detectable both by TLS and by HS. At the end of this step, a global co-registered 3D point cloud has been produced, merging the different 3D point clouds obtained by TLS, HS, and UAV surveys.

Georeferencing

The georeferencing step transforms the obtained global 3D point cloud from a local coordinate system (CS) into an absolute one. Typically, the conversion from a local (Cartesian) to an absolute CS involves a translation (*i.e.*, shift in X, Y, and Z measurements) and a rotation (separate rotations around X, Y, and Z axes could be necessary) (Heritage and Large, 2009) with respect to reference points and a defined coordinate system.

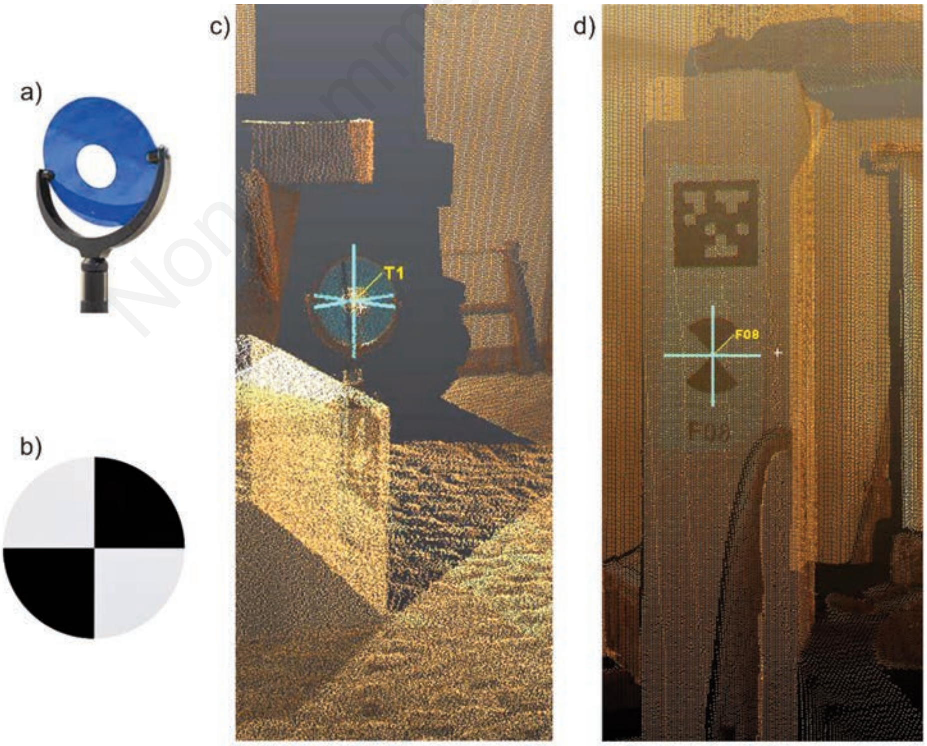

Figure 3. a) 6-inch tilt and turn (T&T) target used to integrate terrestrial laser scanner (TLS) and unmanned aerial vehicle (UAV); **b**) 6-inch black and white (B/W) target used to integrate TLS and hand-held scanner (HS); **c**) 6-inch T&T target into the detected scene; **d**) 6-inch B/W target into the detected scene.

The global 3D point cloud was georeferenced using the coordinates acquired with Leica GS12 RTK GNSS employing GCPs and outdoor SPs positioning, respectively. The GNSS antenna was directly mounted on top of the TLS to obtain the SPs' X, Y, and Z coordinates. The coordinates were acquired in WGS84/ETRF1989 UTM33N (EPSG:32633) as a coordinate reference system (CRS) with a planimetric accuracy of ±2.5 cm and a ±5 cm accuracy for the elevation. According to our proposed flowchart, at least the position of three SPs of known coordinates and four GCPs are required to transform the coordinates of the 3D point cloud from the local CS to the absolute one.

Accuracy assessment

To evaluate the goodness of the co-registration process, the accuracy was calculated on the one hand, using the root mean square error (RMSE) on the X, Y, and Z alignment of the different 3D point-cloud in correspondence of the used B/W target and on the other hand, measuring the distance between the merged 3D point cloud, in several overlap areas. This approach, known as cloud to cloud (C2C) method, preserves the geometry of the 3D point cloud, measuring changes along directions that are unique for each point, avoiding computing distance just along an axis (Williams *et al*., 2021). In our proposed method, we used the multi-scale model to model cloud comparison (M3C2) (Lague *et al*., 2013) to compute differences in distance between different sources of 3D point-cloud. M3C2 is often used to compute differences between 3DCPs of the same object surveyed at different times. It mainly monitors natural hazards like landslides (Stumpf *et al*., 2015) or cliff erosion (Warrick *et al*., 2017). It operates directly on a 3D point cloud, highlighting a set of core points (Brodu and Lague, 2012) on which calculate their distances along normal direction, so no point gridding is needed (Schürch *et al*., 2011). At the end of the process, the distance between the points of the two investigated clouds is indicated. This analysis was con-

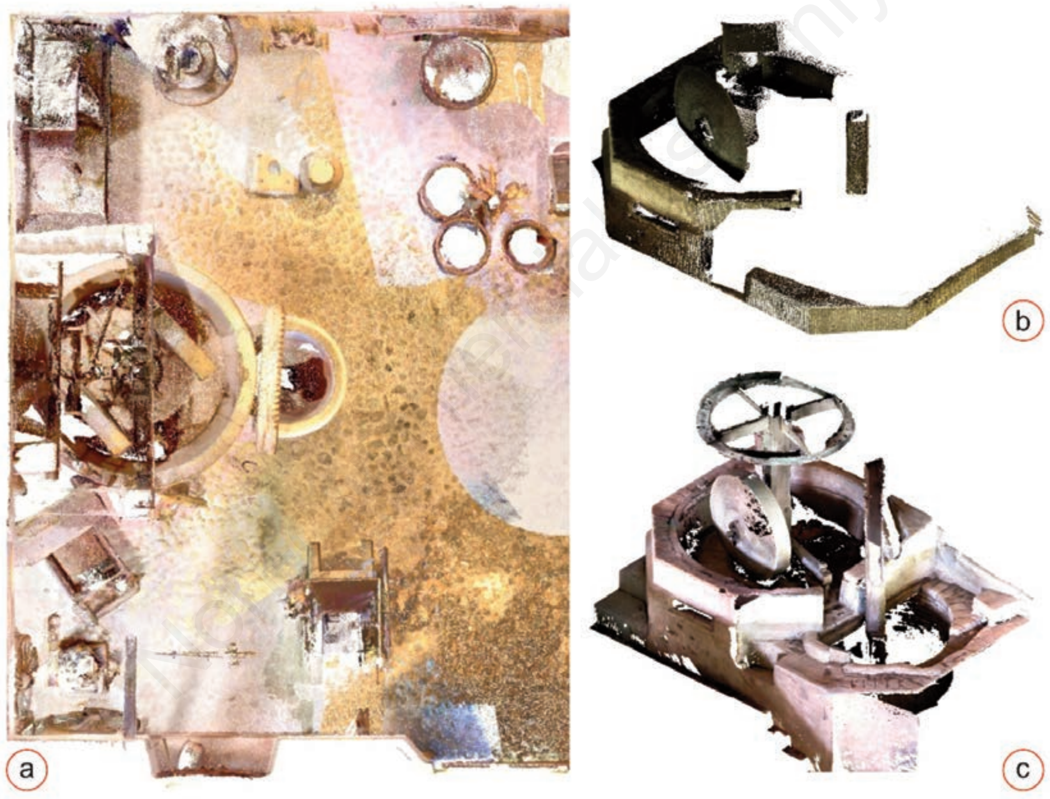

Figure 4. a) Example of merged 3D pointcloud provided concerning building 2; **b**) 3D point clouds (3D point cloud) of a water-driven olive millstone surveyed with the terrestrial laser scanner (TLS); **c**) 3D point-cloud of the millstone after integrating TLS and hand-held scanner 3D point-cloud.

Table 1. Main characteristics of 3D point-cloud obtained from the surveys for each instrument adopted and each building surveyed.

	TLS survey		HS survey	UAV survey	
ID	No. of SPs	No. of points	No. of points	No. of images	No. of points
B1	17	40,244,976	172,008,044	224	2,624,128
B2	49	426,381,327	219,691,685	252	2,352,781
B3	21	153,677,377	171,928,478	280	2,081,434

TLS, terrestrial laser scanner; HS, hand-held scanner; UAV, unmanned aerial vehicle, B, building; SPs, station points.

ducted for each investigated building through the M3C2 algorithm implemented into the free software CloudCompare (https://www.danielgm.net/cc/ – last access 05/10/2022). In performing this analysis, we chose the 3D point cloud derived from the TLS survey as a reference because of its widely recognised reliability (Rodríguez-Martín *et al*., 2019; Russhakim *et al*., 2019).

3D modelling

At the end of the proposed method, once the obtained accuracy of the global 3D point cloud was tested, 3D modelling of surveyed data was performed to test the applicability of the obtained 3D point cloud as a geometry basis for elaborating the BIM/HBIM. The 3D point cloud was imported into Autodesk Recap® software

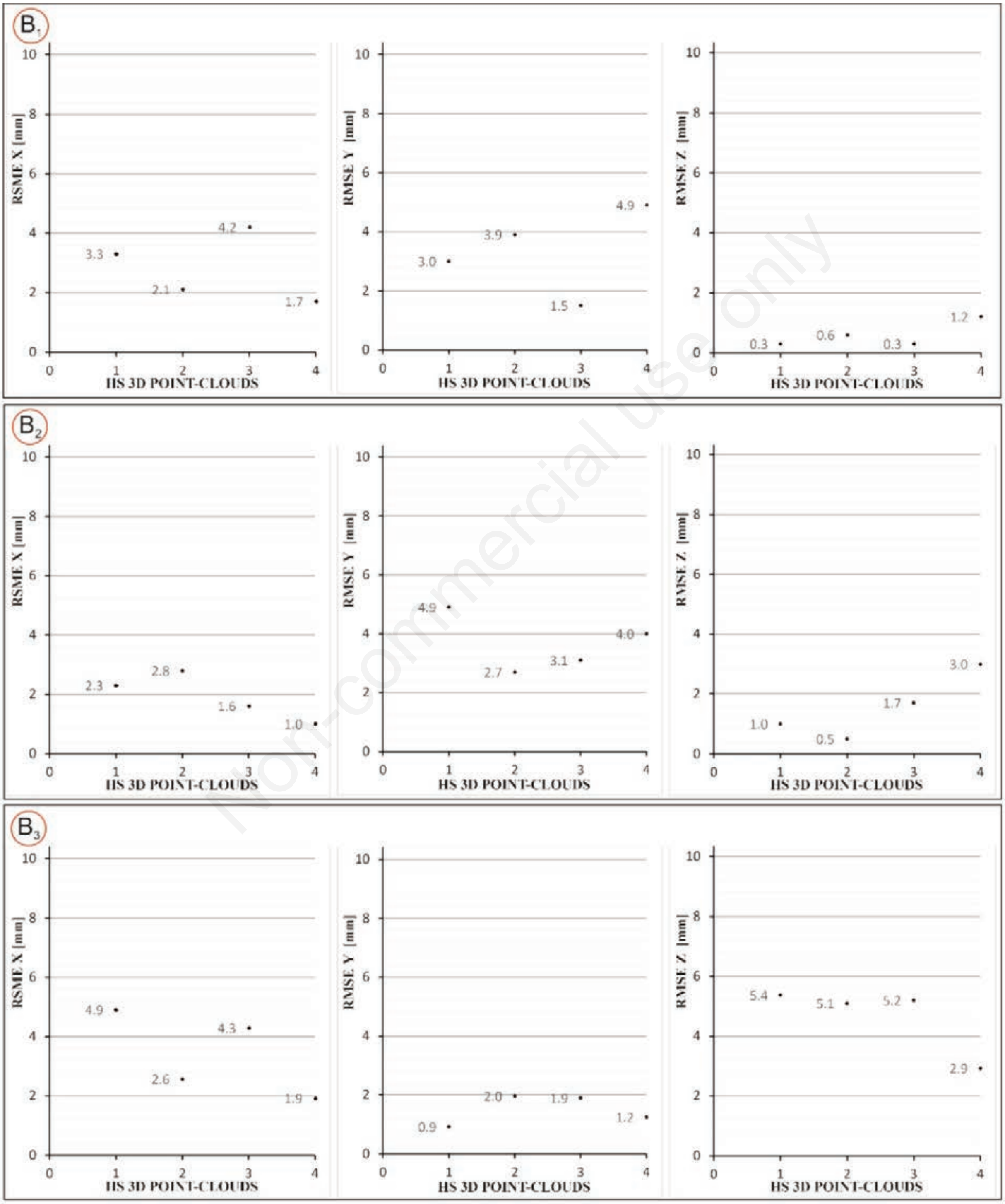

Figure 5. Root mean square error (RMSE) of X, Y, and Z positions of the hand-held scanner (HS) 3D point-cloud against terrestrial laser scanner (TLS) 3D point-cloud alignment in correspondence of 4 black and white targets for each of the surveyed building

and converted into *.rcp file format to be processed in the Revit® environment. Autodesk Revit is a BIM software supporting 3D point-cloud, commonly used for BIM/HBIM *as-built* production (Murphy *et al*., 2013; Fryskowska and Stachelek, 2018). It is possible to create the most commonly used parametric objects in the Revit environment, like windows, walls, doors, *etc*. (Banfi, 2019). In this work, Autodesk Revit was used to create 3D parametric models of the surveyed geometry.

Results and Discussion

The proposed method allowed us to obtain, for each study case, two main results: i) an integrated 3D point cloud derived by merging the data obtained by the different used sources (*i.e*., TLS, UAV, and HS) and ii) a 3D reconstruction of the 3D point-cloud into parametric geometry that can be implemented by information (*e.g*., thermal or energy) which can serve as bases for BIM/HBIM processing. The characteristics of each 3D point cloud, obtained from different surveys, are synthesized in Table 1.

Figure 4 shows the result of the interaction between TLS- and HS-surveyed 3D point clouds. On the left side of the picture (Figure 4a), the darkest 3D point cloud refers to the TLS survey, and the lightest one to the HS survey. As can be noticed, the HS 3D point cloud covers all parts not surveyed by TLS, having a complete 3D point cloud of the entire area. On the right side of the picture, we can see the 3D point cloud of a millstone surveyed with the TLS (Figure 4b) and the 3D point cloud of the same millstone after the integration between the TLS and the HS 3D point-cloud (Figure 4c), highlighting how the merging of different 3D point-cloud is useful to obtain a complete survey of machinery in order to perform their parametric reconstruction. For each integrated 3D point cloud, the differences between the TLS 3D point-cloud, used as a reference because of its widely recognised reliability (Ingman *et al*., 2020), and the HS 3D point-cloud alignment have been evaluated. RMSE values fall in a range between 0.3 and 5.4 mm. Figure 5 reports the RMSE values in X, Y, and Z for the three analysed buildings.

The RMSE values highlight a good alignment between TLS and HS 3D point cloud. The obtained values are comprised in a sub-centimetre range. These errors, although acceptable, may be due to micro-movements that the TLS may undergo during the surveying operations due to the flooring of the buildings surveyed, which in this kind of historic rural productive buildings, is often irregular. Also, fast movements of HS during the acquisition process can lead to the misregistration of scanned points, thus affecting the data quality.

The accuracy was also analysed in the overlap area between the TLS 3DCP and the HS 3DCP, and the respective distances were calculated by adopting the M3C2 algorithm. The analysis has been conducted in a sample zone for each investigated building in an area characterised by integrating the two clouds. Figures 6-8 show the result of the analysis. The distance between the TLS 3D point cloud and HS 3D point cloud ranges between 0, which means a perfect correspondence, and 18 cm in the most marginal parts of the merged cloud. This could be due to the HS FOV, which does not allow precise acquisition of objects falling in the outer areas of the frames. These marginal areas are not the main objective of the integration because they are present in the TLS cloud, so they cannot be considered. Considering the central part of the integration (*i.e*., those areas connecting the overlapping clouds with the solely HS 3D point cloud), it can be noticed as the distance between the two surveys ranges from a maximum value of 0.06m in B1 and B2 buildings, and sub-centimetre values in B3. These values represent a good compromise between the accuracy and expeditiousness of the survey considering that to have a complete survey using only the TLS, a congruous number of SP is required, and often, they will not be sufficient to cover all areas and/or to survey the roof of the buildings. Moreover, in this way, it is possible to have a detailed survey of the productive machinery on the scene, characterising these historic agri-food buildings.

The analyses of the obtained results, jointly with a trial-and-

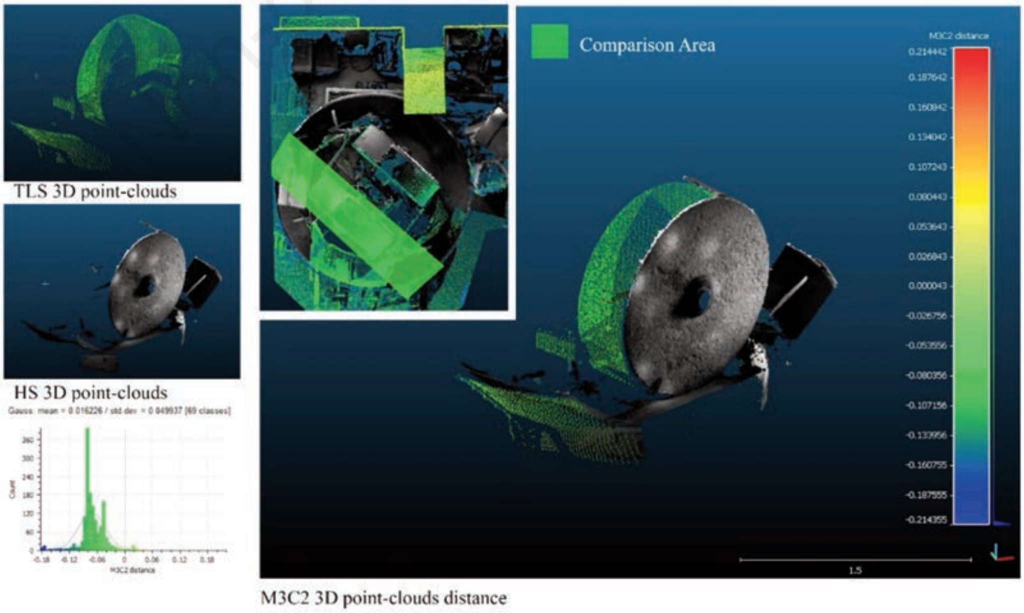

Figure 6. Multi-scale model to model cloud comparison result for building 1 sample. HS, hand-held scanner; TLS, terrestrial laser scanner, M3C2, multi-scale model to model cloud.

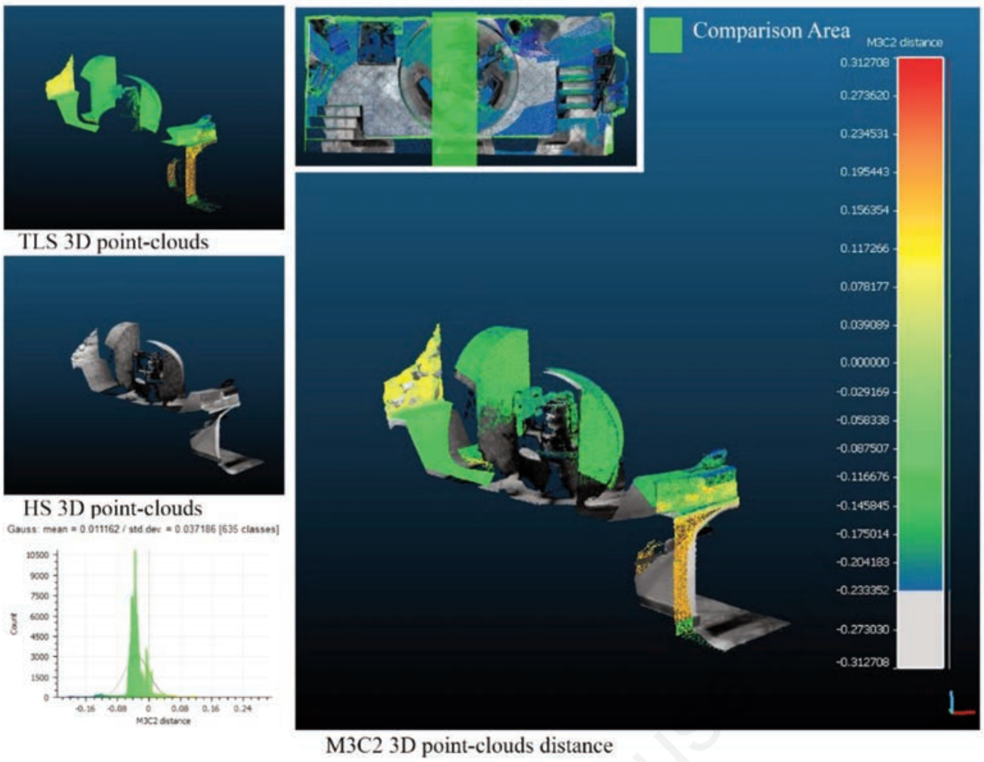

Figure 7. Multi-scale model to model cloud comparison result for building 2 sample. HS, hand-held scanner; TLS, terrestrial laser scanner; M3C2, multi-scale model to model cloud.

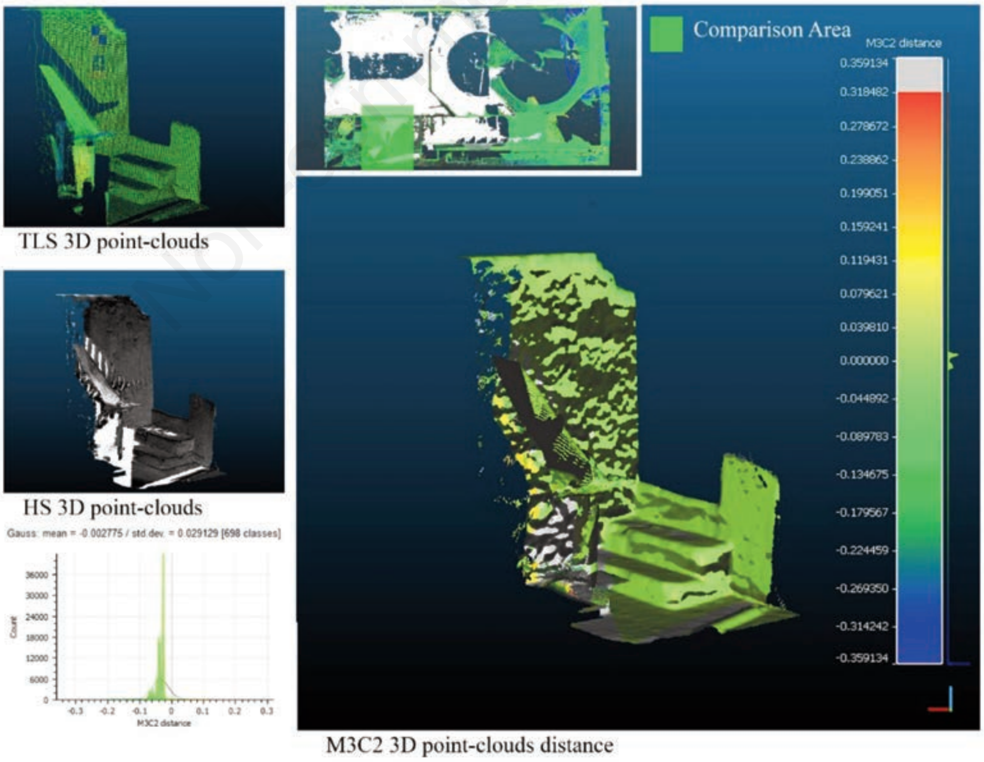

Figure 8. Multi-scale model to model cloud comparison result for building 3 sample. HS, hand-held scanner; TLS, terrestrial laser scanner; M3C2, multi-scale model to model cloud.

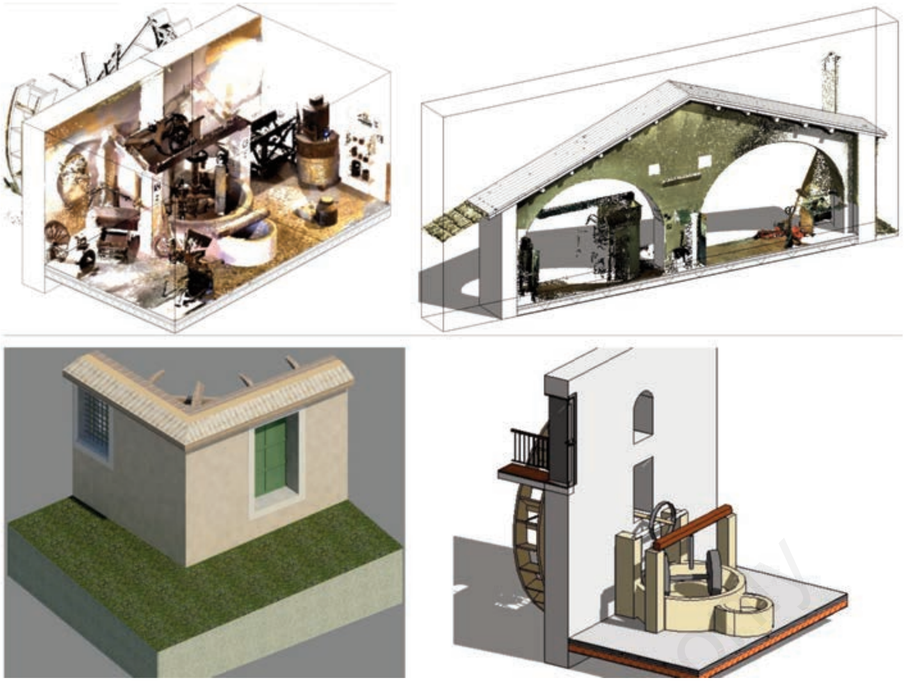

Figure 9. Top: 3D point clouds modelled into Autodesk Revit® environment; bottom: example of parametric objects obtained from modelled 3D point cloud.

error approach during the surveying process, highlighted a similar behaviour of the HS 3D point cloud with local coordinates. A more homogeneous distribution of points was shown for those located short distances from the operator. In contrast, a more significant error in the distribution was shown in the more distant areas. This allowed us to define an optimal HS distance for the acquisition, which falls between 0.3m and 1.5m.

Concerning the modelling step, the highly accurate survey, performed with the proposed method, allows obtaining a database to develop a re-modelling and a subsequent project, as well as operating the management of the building manufacturing and machinery present in it (Figure 9).

Conclusions

The presented research aimed to obtain a complete 3D point cloud capable of serving as a geometric basis to obtain an as-built HBIM/BIM of historic agri-food buildings, integrating the 3D point clouds obtained from three different surveying tools: TLS, HS, and UAV. Portable scan solutions, like HS, can represent an optimal supplement to TLS provided that the survey, to ensure a good quality of the obtained 3D point cloud, is performed by experienced users with slow and homogenous movements. The HS and UAV integrations to the TLS 3D point cloud offer a complete and reliable dimensional datum that allows obtaining a complete 3D point cloud, even in those areas difficult to reach with a traditional TLS survey.

The surveying method proposed for agri-food buildings allows obtaining important information otherwise unavailable and other categories of rural buildings, particularly for the vernacular ones for which historical documentation and metric drawings (plans, sections, elevations) often lack. For these kinds of buildings, many of which are threatened and risk disappearance, a complete, accurate, and expeditious architectural survey – as proposed in our research with integrated geomatic techniques – allows for preserving their memory better. Moreover, for the whole stock of historic agricultural buildings, it helps to adequately address their management as a part of comprehensive strategies for the protection and creative valorisation of the rural built heritage.

The proposed method provided complete geometrical and georeferenced data, which are very important for future analysis. The modelling phase can represent a point of weakness. Once imported into Revit, the obtained 3D point cloud behaves like a tracing sheet, so the modelling accuracy depends solely on the precision and attention of the operator.

Moreover, more focused analyses with specific tools allow obtaining data helpful in elaborating the so-called Building Energy Model (BEM) by adding the thermal behaviour of building components. This model allows for carrying out dynamic simulations of the thermal conductivity of the building envelope and energy analyses.

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