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D-SITE

Drones - Systems of Information on Cultural Heritage for a spatial and social investigation

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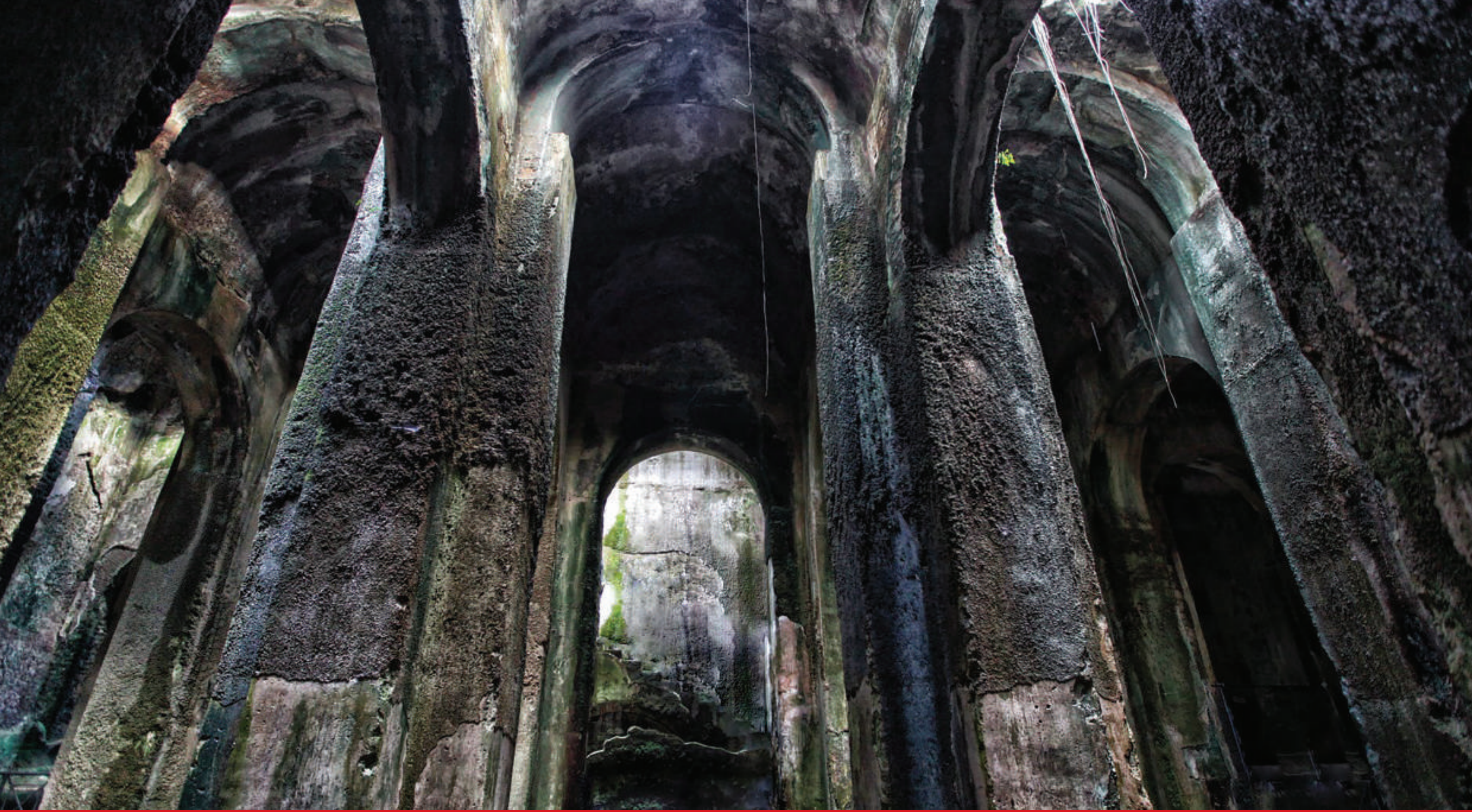

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ABSTRACT

The aim of the present research is to test an integrated framework between the data obtained from the Unmanned Aerial Vehicle (UAV), a handheld thermographic camera (Infrared thermography) and the Terrestrial Laser Scanner (TLS).

Piscina Mirabilis, in the city of Naples, becomes the benchmark to generate a comprehensive database, including a clear geometrical definition of the thermal variations of the wall surfaces by texturing the IR images directly on the RGB mesh surfaces. To measure the performance of mapping, the present research compared the quality of information by using 3D processing algorithms to optimise final the result.

MULTI-SOURCE DATA FRAMEWORK: INTEGRATED SURVEY FOR 3D TEXTURE MAPPING ON ARCHAEOLOGICAL SITES

1. INTRODUCTION

1.1. LITERATURE REVIEW: 3D THERMAL MAPPING AND UAV IN THE CULTURAL HERITAGE FIELD

Infrared thermography (IRT) is a widely used non-destructive method for energy audits.

However, considerable research indicates that the performance of thermography is influenced by the method of data acquisition (Hou et al., 2019).

The use of IRT images is playing an important role because heat loss from buildings can be easily detected and visualized by thermal cameras. In fact, for detailed inspections of small areas, terrestrial images can be taken manually, while for surveys of larger areas mounting IR cameras on an unmanned aerial vehicle (UAV) is an alternative option. Terrestrial image acquisition methods can provide detailed information on the smallest areas (Lin et al., 2018).

Unmanned aerial vehicles (UAVs) have been successfully employed to perform RGB photogrammetry to reduce the time and complexity of data collection.

But the data collected by an infrared thermal camera and an optical camera differ from each other in terms of the level of resolution: the data collected by the optical camera are considered to have a higher resolution.

On the other hand, the infrared thermal camera usually has a lower display resolution, is more likely to be influenced by environmental conditions and is limited by the distance between the camera and the objects (Mayer et al., 2021). Thermal texture mapping, which maps thermal images onto existing 3D geometric data, allows thermal images to be spatially referenced and thermal patterns to be accurately interpreted.

Due to large image overlaps, each face of a building model often corresponds to several thermal images.

Researchers are exploring different thermal texture mapping approaches focusing on the automation of texture selection: (Wang, 2008) combined object incident angle and visibility analysis to select textures from oblique images.

To differentiate components' semantic information (semantic segmentation) and to delineate each distinct object (instance segmentation), many computer vision algorithms - especially deep learning approaches - have been developed, such as Mask R-CNN (He, et al., 2020), the YOLO family (Wong et al., 2019), and the DeepLabfamily (Chen, et al., 2018). Finally, Chizhova and Korovin (Chizhova et al., 2017) improved the geometric matching accuracy of their model-to-image registration method by taking uncertainties of the 3D building model and image features into consideration.

Therefore, thermal radiant characteristics are taken into consideration. To measure the performance of texture mapping, this research compared the quality of images generated from a 3D point cloud model constructed by UAV and TLS acquired data with images acquired directly from a handheld thermal camera.

The comparisons were based on quality and efficiency in the data acquisition phase, and different factors' influences.

The following sections will present the goals and case of study, materials, research methods, discussion of the results and final conclusions.

1.2. AIMS OF THE PROPOSAL AND CASE OF STUDY

The present work seeks to determine a workflow to map the IR images with TLS and UAV data.

For this reason, it was considered necessary to integrate different techniques and sources of information in order to optimise the results and reduce the margin of error.

The main issue is that thermal camera resolution is not as high as the optical camera's resolution resulting in a lower quality 3D model generated by photogrammetry mapping.

The benchmark of the experimentation is the Piscina Mirabilis (Figure 1), the final reservoir of the "Serino aqueduct" in the city of Naples. (De Feo, 2007).

The aqueduct filled several points in the Campi Flegrei area to finally reach the end of the path: the Piscina Mirabilis.

This building is a gigantic water reservoir of 72 m long and 27 m wide with a height of 15 m., which operated through a series of gates that opened and closed along with the vaults in the central nave; the water was lifted by hydraulic machines over the opening terrace of the covered cistern. (De Feo, 2010)

Forty-eight pillars, presented in four rows supporting the barrel vaults, divide the space into five main naves on the long sides and thirteen secondary naves on the short sides, giving it the majestic appearance of a cathedral, hence its name, "The cathedral of water".

Today, the building is in a visible state of degradation and the creation of an integrative database could be considered a solution to manage the monitoring and restoration activities.

Based on these assumptions the subsequent sections of the manuscript are specifically aimed at proving the research procedure adopted.

Figure 1. Internal view of the Piscina Mirabilis in the current state. Source: Fondo Ambiente Italiano, Piscina Mirabilis, https://fondoambiente.it/luoghi/piscina-mirabilis.

2. MATERIALS

2.1. FARO Focus 3D X330

Faro Focus 3D X330 is a stationary laser scanner with integrated digital color camera.

The range-based modelling method employs techniques based on active sensors, using laser scanners that emit electromagnetic signals recorded by a sensor in order to derive a distance (range) measurement.

This solution guarantees an accuracy of +-2 mm in a range of 0.6 m up to 130 m.

2.2. DJI Phantom 4

The UAV has an approximate weight of 1.4 kg Its camera is equipped with a 12 MP Sony Exmor sensor and a wide-angle lens with a 4 mm focal length and FOV (Field of View) of 94°.

With a flight autonomy of almost 30 minutes the drone can fly at a maximum speed of 70 km/h.

The camera is integrated in a gimbal to maximize the stability of the images during the movements, being able to acquire videos in 4K definition.

2.3. Flir E40bx

This Thermal Camera has a 160x120-pixel resolution providing thermal images that clearly display building conditions.

The advanced MSX imaging feature adds even more texture and detail to these images, allowing quicker fault location.

With a low thermal sensitivity capable of detecting temperature differences as low as 0.045°C, the FLIR E40bx enables users to accurately diagnose anomalies.

The camera is in fact equipped with two separate optical systems for acquiring the thermal image and the corresponding image in real colors.

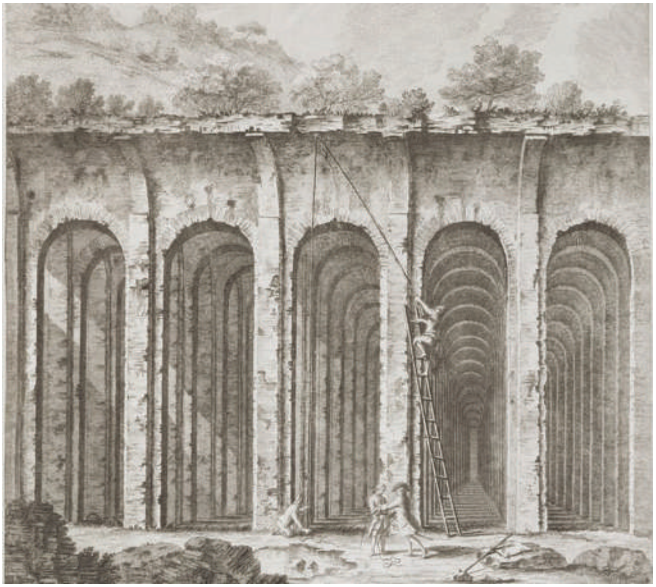

Figure 2. Design of a vertical section. Source: Avanzi della Antichita esistenti a Pozzuoli, Cuma, e Baia by Paulo Antonio Paoli, by Giovanni Volpato (1735-1803).

3. RESEARCH METHODS

3.1.Survey design and data collection

3.1.1.TLS

A survey design should first define TLS station locations to ensure complete coverage of the object at the required spatial resolution.

Considering the main dimensions of the interior space of the Piscina Mirabilis (on the horizontal plane the maximum extensions are 72 m x 25 m, and the internal height is 15 m) (Figure 2) with a total of 48 columns distributed in 4 rows of 12 columns, the instrument was set to have a resolution of 6 mm in 10 m. Basically, in order to avoid areas of occlusion generated by the number of pillars, as a general criterion, it was decided to make one scan for each bay. In the outside, the resolution was changed to 10 mm in 10 m, placing the

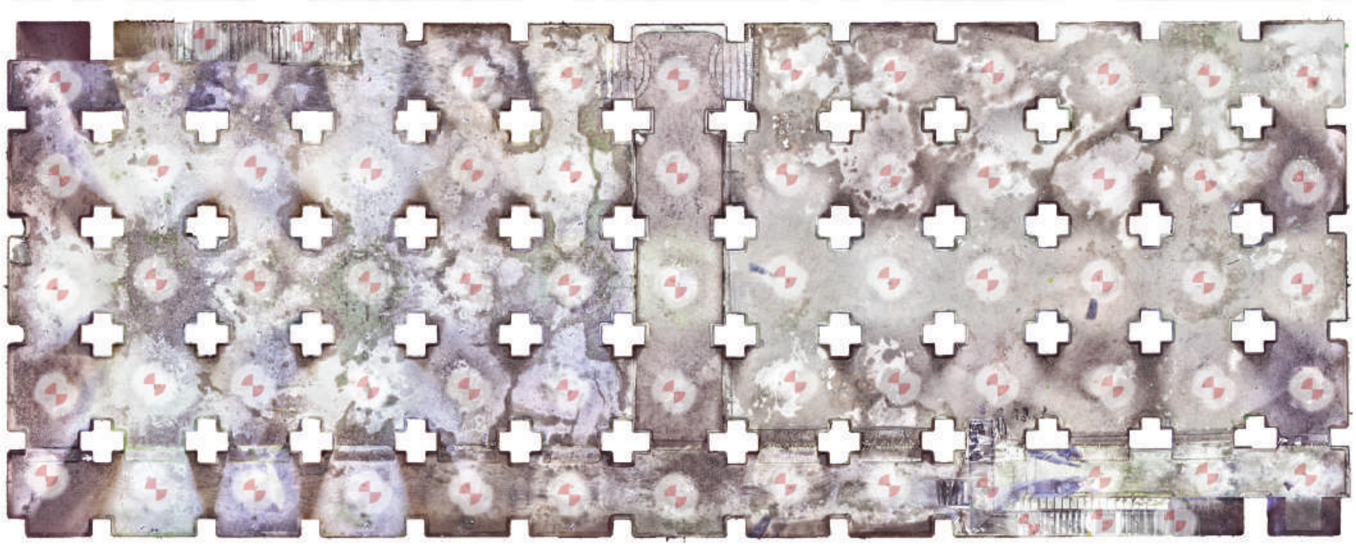

Figure 3. Floor plan extracted from the point cloud processed, with the interior TLS stations.

stations on the external street with a distance of 5 m. defined by the spacing between columns.

Finally, In the entrance sector, it was necessary to make 3 stations that allowed linking the data acquired on the inside and outside of the building.

With a total of 75 internal scans and 17 external scans, the TLS acquisition campaign has taken almost 10 hours, with a single-scan time of approximately 6 minutes and 30 seconds (Figure 3).

3.1.2.UAV

Due to the high elevation of Piscina Mirabilis (15 m), it was necessary to integrate the data acquired with the laser scanner. The geometrical acquisition of the upper vaults was not optimal because the insufficient illumination inside the environment did not allow an optimal acquisition of the color deducible from the projection of the panoramic image obtained with the laser scanner camera. Therefore, it was decided to merge the data using aerial photogrammetry, which, although less precise than the techniques based on active sensors, allows to control the parameters related to the exposure and the position of the shooting point. Considering that the study site to be treated is located at the underground level, it was already anticipated to carry out a manual flight because it would be impossible to connect the UAV to the GPS network. Consequently, the study area was reduced to the vaults adjacent to the side walls of the Piscina Mirabilis (Figure 4) in order to merge the information with infrared data to be acquired.

For the acquisition of the internal frames, two types of manual flights were designed: a first one for the acquisition of nadir photogrammetric images and a second one, with the optical axis tilted about 45°, to survey any shadow cones.

As expected, the quality of the data taken was not optimal since the drone presented stabilisation problems due to the missing connection to the GPS network and it was not able to fly at the expected height.

A total of 180 images were taken at 90°, while 235 images were taken at 45°, with a grand total of 415

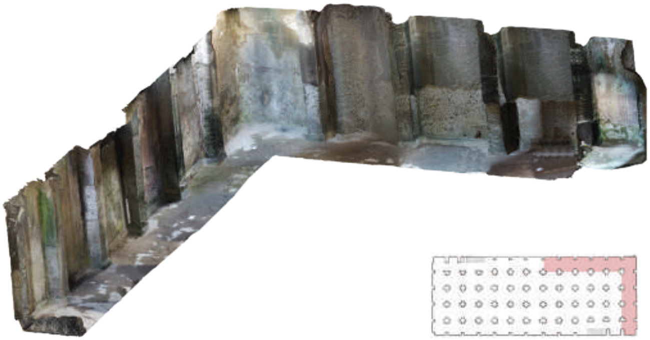

Figure 4. Axonometric view as a result of the photogrammetric process, with the study area highlighted in color.

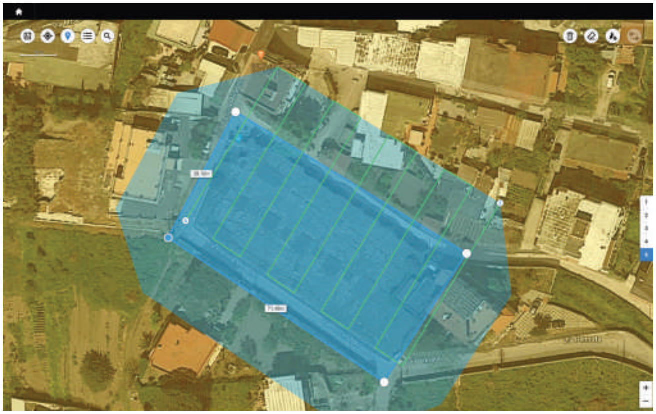

Figure 5. Oblique flight mission setup in DJI Terra software.

internal images and an overlapping of 80% in the first case and 70% in the second case. On the other hand, for the external data acquisition, the instrumentation worked correctly, allowing the loading of the flight plan previously designed in the DJI Terra software (Figure 5).
Another two flights missions are programmed: a first nadir flight and a second oblique flight, both having an image overlap of 70% as well as sidelap of 70% in a total area of 2550 m^2 approximately.
In the nadir flight, 74 images were acquired for the first grid, at a flight route distance of 353 meters and a flight time of 4 min and 35 s. After that, an oblique flight with the camera tilted at 45° on the horizontal plan, was carried out acquiring 143 photos in 5 minutes and 26 seconds.

3.2. INFRARED THERMOGRAPHY

In order to obtain a comprehensive representation of the anomalies present in the Piscina Mirabilis, thermographic data have been acquired through relevant instruments that have to investigate the reflective and emissive response of the surface examined in different bands of the integrated spectrum, providing auxiliary instructions compared to traditional methods.
The goal, as mentioned before, is to incorporate the differences in temperature obtained with the infrared camera.
For this reason, it was decided to continue working with the lateral zone of the monument, which presented a greater amount of masonry mass and therefore, a greater level of degradation to analyze.
A total of 182 images with a 160x120-pixel resolution were taken inside the building (Figure 6), obtaining as a result the IR and its corresponding RGB image.
Since this is a largely underground area, the temperature of the lateral walls varies between 5 and 9 degrees Celsius (41 and 48.2 Fahrenheit), increasing proportionally according to the amount of wall mass or the proximity to the outside, where the temperature is higher. However, despite the proximity of the user to the object of study (2 m), it was not possible to reproduce the degradation pathologies with an optimal level of detail.

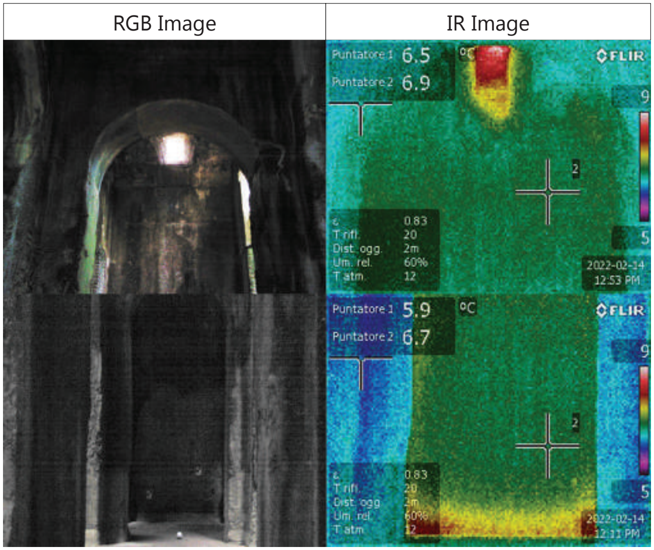

Figure 6. Comparison between the RGB image and the corresponding IR image, where the temperature is higher on the side walls.

3.3 Data processing: point cloud registration

3.3.1 TLS scan registration

These data were, indispensable to align the photogrammetric data. The clouds are characterized by a high degree of overlap (60%) and for this reason are registered employing a global bundle adjustment procedure, accomplished after a top view-based and cloud-to-cloud preregistration (Figure 7).

Given the set of scans, the algorithm searches for all the possible connections between the pairs of point clouds with overlap.

For each connection, a pairwise ICP is performed and the best matching point pairs between the two scans are saved. A final non-linear minimization is run only among these matching point pairs of all the connections. The global registration error of these point pairs is minimized, having as unknown variables the scan poses (Barba et al., 2021).

The RMSE on the registration is about 1,2 mm and the maximum value is 2,2 mm.

3.3.2 UAV orthoimages registration

Agisoft Metashape software was used for the photogrammetric data processing phase. Initially, all frames were grouped into a single chunk. Due to the similar geometrical characteristics of the building, it was necessary to add makers as control points for an easier recognition of homologous points in the different images.

The operations performed by the software are based on Structure from Motion (SfM) using algorithms such as SIFT (Scale-invariant feature transform) and SURF (Speeded Up Robust Features) that extract the significant points or tie points, homologues in different frames and identify the internal and external orientation parameters (Lowe, 2004).

With the data calculated by triangulation, the software created a first sparse point cloud. In the next step, Dense Image Matching (DSM) algorithms build a Triangulated Irregular Network (TIN) and a B-Rep (Boundary Representation) model is obtained.

Finally, it was possible to combine the photogrammetric data with that obtained by the laser scanner resulting in an integrated point cloud of the exterior and interior of the Piscina Mirabilis.

3.4 Data analysis: 3D texture mapping

To calculate the differences and errors between merged two images (IR and RGB), two mathematical approaches were used being Mean Squared Error (MSE) and Structural Similarity Measure (SSM). Shown in equation (1) and equation (2) (Hou et al., 2019).

$$MSE = \frac{1}{mn} \sum_{i=0}^{m-1} \sum_{j=0}^{n-1} \left[I(i,j) - K(i,j) \right]^2 \quad (1)$$

$$SSIM = \frac{\left(2\mu_x \mu_y + c_1\right)\left(2\sigma_{xy} + c_2\right)}{\left(\mu_x^2 + \mu_y^2 + c1\right)\left(\sigma_x^2 + \sigma_y^2 + c_2\right)} \quad (2)$$

Figure 7. Partial cross-section showing the central part of the Piscina Mirabilis, as a result of TLS data processing in FARO Scene software.

MSE checks difference of every two relative pixels in two images. It squares these differences, sums them up and divide the sum of squares by the total number of pixels in the images. An MSE of value 0 indicates that two pictures are perfectly identical. The greater the value of MSE is, the more errors rendered pictures create. On the other hand, SSIM method can perceive changes in small sub-samples, whereas MSE estimates the perceived errors in the entire images. In equation two, (*x*, *y*) indicates the $N\times N$ sub-window in each image, and SSIM can be calculated on various windows of an image. The SSIM value can range between -1 and 1, where 1 represents perfect identicality. With the basis on these assumptions, in the present research the criterion of comparison was to calculate the differences and errors between RGB and IR images in 2 different scenarios presented in Table 1: First, with images taken at 90 degrees and second with images at 45 degrees. Different factors were tested: Flight grid, angle in the UAV flight pattern, overlap of images, number of aligned images, distance of the camera from the object under study and finally the height of the IR camera held by the user.

4. RESULTS AND DISCUSSION

Two comparison cases were tested, as presented in Table 1. In scenario 1, the flight was developed with the UAV camera angle at 90° with respect to the side walls (Figure 8). The image on the left presents the IR image and the picture on the right shows the RGB data as a result of integrated point cloud reconstruction.

To test the color rendering performance and structure similarity performance in the texture mapping process, the MSE and SSIM values are calculated (Fig 9.). Mapping process in images of a model with a flight camera angle of 90° (scenario 1) was better than rendering images of a model with a flight camera angle of 45° in terms of capturing color information, since scenario 1 had a lower MSE score. The MSE value in scenario 2 was

Scenario Number	Flight Grid	Camera Angle	Image Overlap	Number of aligned images	Mean Reprojection Error [pixels]	IR Camera Distance	IR Camera Height
Scenario 1	Complete Grid	90°	80%	180 of 180	0.198	2 m	1.7 m
Scenario 2	Complete Grid	45°	70%	213 of 235	0.203	4 m	1.7 m

Table 1. Summary of different factors to be tested in both cases.

5.25941 which can be considered an outlier, since the MSE values varied from 0 to 1.

Factors influencing the higher MSE value for scenario 2 is the distance and different angulation between the image taken by the UAV and that taken with the handheld thermal camera, obviously determined by the height of the user. Also, although the number of photos was higher, the overlap between images was lower than in scenario 2: because of this, Metashape software was not able to align all the images and therefore they were not processed.

5. Conclusions

Thermography has been introduced in a number of research fields, most notably, it has been used to capture the energy loss of a single building. However, creating a 3D thermal model with high resolution for asset restoration remains a challenge in terms of efficiency and performance.

Regarding the UAV flight, a camera angle of 90 degrees could capture more details on the internal walls or exterior flat roof system, while a camera flight angle of 45 degrees is more suitable for capturing details of the internal vaulted system, which presents a complex geometry.

In terms of image overlap, a larger number of thermal images could introduce more potential outliers. In addition, the quality of the images taken must be taken into account. Using a handheld camera, where the

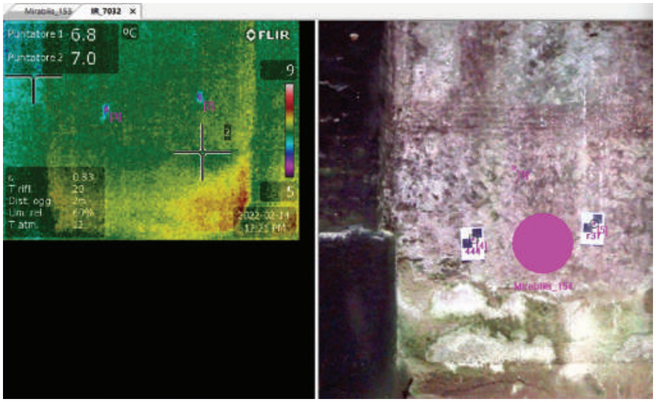

Figure 8. Comparison both images (IR and RGB) in the case 1.

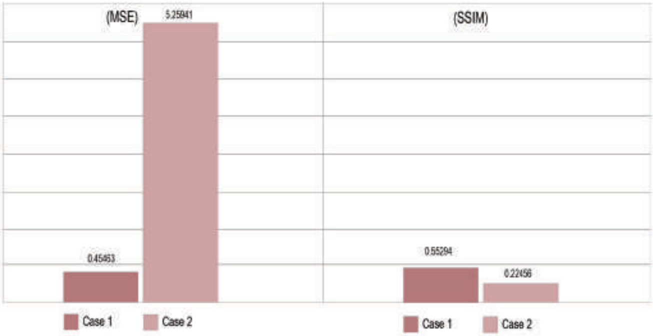

Figure 9. Statistics of MSE, and SSIM for both scenarios.

images are taken by the user, it is impossible to achieve a match between the angles of the images acquired by the UAV. If both RGB and IR images can be captured from the same angles and altitudes, a detailed 3D model can be created using high resolution RGB images, and then thermal textures can be projected onto the 3D model achieving a higher final accuracy.

Future prospects include the acquisition of data using UAVs with a thermal camera included to eliminate the problem of the angle difference between photos, which is a main factor influencing the efficiency and performance of 3D thermal mapping. In addition, it is also expected to face the problem of stabilization of the drone in areas without GPS signal, thus being able to optimize the data processing phase by applying automatic processing algorithms.

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