Application of Geomatics Techniques for Cultural Heritage Mapping and Creation of an Unsafe Buildings' Cadastre

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Abstract: - Mapping of Cultural Heritage is a crucial process aiming at safeguarding and promoting the unique identity, history, and traditions of a particular community or region. This practice involves the documentation, conservation, and interpretation of various aspects of Cultural Heritage, which can be conducted through Geomatics techniques including the use of various tools and methods to collect, analyze, and visualize spatial data related to heritage sites. The same techniques can be used for the identification and subsequent cataloging of unsafe buildings thus creating a cadastre useful for authorities, urban planners, and building management organizations to identify, monitor and address unsafe structures. In this context, this paper presents an automatic, innovative, and experimental system through which it has been possible to map the Cultural Heritage in a fraction of the province of Reggio Calabria and, at the same time, to build a cadastre of unsafe structures. A prototype drone was programmed to acquire the images, subsequently pre-processed using commercial software and analyzed using Machine Learning techniques and dedicated software. An Open GIS (Geographic Information System), then, made it possible to view the archaeological heritage sites and the dangerous and damaged buildings, with identified and cataloged cracks. In relation to the monitoring of Cultural Heritage and old, unsafe buildings, several different technologies including Light Detection and Ranging (LiDAR) and high-resolution satellite imagery are being successfully used, which involve, however, data processing complexity and the need for specialized expertise. By overcoming the challenges of these traditional methods, this proposed approach holds promise in facilitating comprehensive Cultural Heritage monitoring and management even in smaller and less resource-rich areas. The use of drones for data acquisition and integration into a well-implemented GIS, in fact, could offer a potential solution to monitor Cultural Heritage and assess the condition of existing buildings, while saving time and costs in the process.

Key-Words: - UAV, Big Data, Machine Learning, Cultural Heritage, Digital Archaeology, Buildings, GIS

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1 Introduction

Mapping cultural heritage involves identifying, documenting, and spatially representing significant cultural sites, monuments, landscapes, and artifacts. The need to map Cultural Heritage arises from several reasons: preservation of cultural heritage that represents a community's history and identity; protection of cultural sites to identify those at risk and take protective measures to prevent their degradation; cultural and tourism promotion to support the local economy and raise community awareness. This process can be accomplished through various geomatics techniques, including Geographic Information Systems (GIS) that enable the collection, analysis, and visualization of spatial data related to Cultural Heritage allowing for the creation of maps displaying the distribution and characteristics of heritage sites and providing valuable information for planning and management purposes; aerial imagery techniques with advanced technologies such as Light Detection and Ranging (LiDAR) and high-resolution satellite imagery, that can capture high-resolution images of Cultural Heritage sites, aiding in the identification of archaeological remains, historical buildings, and cultural landscapes, [1], [2], [3]. These techniques offer an efficient and effective method to acquire and manage high-quality geospatial data while simultaneously creating a real register of unsafe buildings. These technologies can generate, in fact, detailed three-dimensional models of buildings and cultural sites and, at the same time, identify buildings that may present risks or be unsafe.

In the literature, many articles concern the application of Geomatics in the monitoring of Cultural Heritage and the acquisition and creation of three-dimensional models of unsafe or vulnerable buildings. Different remote sensing technologies are explored for Cultural Heritage monitoring, [4], along with the use of different geospatial data and methodologies for Cultural Heritage management and accurate models of objects and buildings, [5], [6]. As known, a commonly used approach is to combine accurate LiDAR elevation data with detailed visual information from satellite imagery. This process includes collecting LiDAR data from aircraft-mounted sensors to obtain precise three-dimensional points, processing the data to filter and classify terrain features, acquiring high-resolution satellite imagery to obtain detailed images of the Earth's surface, processing the images to improve their quality and alignment, and integrating LiDAR data and satellite imagery.

Such approaches are often limited by the complexity of the process or the lack of trained personnel to interpret the acquired images, not allowing the application of such methodologies to smaller and more limited case studies. Additionally, it should be noted that access to and processing of LiDAR/Satellite data can be costly, especially if frequent monitoring over time is desired. So, optical imaging and LIDAR solutions are certainly accurate and reliable tools, but costly and time-consuming, as well as computationally expensive to process. An alternative to these solutions could be Unmanned Automated Vehicles (UAVs): they make it possible to perform continuous visual inspections of buildings, overcoming the aforementioned problems and reducing the margin of error associated with human operators. However, this technological solution generates a large amount of data and information (Big Data), necessitating more effective and automated methods to evaluate only the information useful for analysis and discard the excess data, thus avoiding overloading the archives without risking increasing or decreasing the margin of error.

Despite various types of research in the literature on evaluating the stability conditions of buildings through drone data acquisition, [7], [8], creating high-resolution 3D models of structures, [9], and assessing the structural safety of buildings using UAV photogrammetry, [10], there are still few studies on using drones and machine learning techniques for automatically construct a cadastre displaying cultural heritage and creating a real catalog of unsafe buildings in a given area.

For this reason, the proposed research focuses on the study and development of an automatic system to monitor, inspect, and map the main archaeological sites of the area under study and subsequently identify the cracks in buildings to constantly update and obtain the safety status of buildings through a GIS platform. A new automated UAV system for monitoring and capturing large amounts of data (Big Data) is created: a prototype drone and an innovative recharging basis, called Smart Grid, are implemented through which images are collected and transmitted for elaboration. For the pre-processing phase, KNIME software was used to manage the amount of geo-referenced data acquired. Then, KNIME software and traditional machine learning techniques are applied to the images to recognize the presence of cracks. Three Convolutional Neural Networks are created for crack recognition, using the Support Vector Machine technique. Finally, on the GIS platform, open and updatable thematic cartography is obtained through which it is possible to represent the characteristic elements of building geometry, cracks’ status, their relevance, and interventions made in the most important historical buildings.

This paper differs from related ones published in the technical literature for several reasons: first, it presents a technological innovation through the implementation of an advanced, automated system that takes advantage of cutting-edge digital technologies. Furthermore, compared to the technologies listed above, the proposed system has a low economic impact while still maintaining good accuracy compared to traditional visual inspection methods conducted by human operators. Finally, an additional distinguishing feature is the joint use of different Geomatics methods, allowing multiple objectives in monitoring buildings and conserving Cultural Heritage to be achieved.

2 Materials and Methods

This work serves a dual purpose: the visualization and cataloging of Cultural Heritage and the identification of vulnerable and unsafe buildings and structures present in the study area. To achieve these goals, an automatic system for the acquisition of images of Cultural Heritage and buildings and subsequent visualization through GIS after appropriate treatment, elaboration, and analysis of the acquired data is created and implemented. The process involved distinct phases: the first consists of the acquisition of images by a drone also using an innovative recharging and experimental data transmission basis (Smart Grid); the second phase involves the processing of the acquired data through commercial software and machine learning algorithms and finally, the last phase consists of the visualization of the information obtained in an open-source GIS. The entire system is described in the flowchart in Fig. 1.

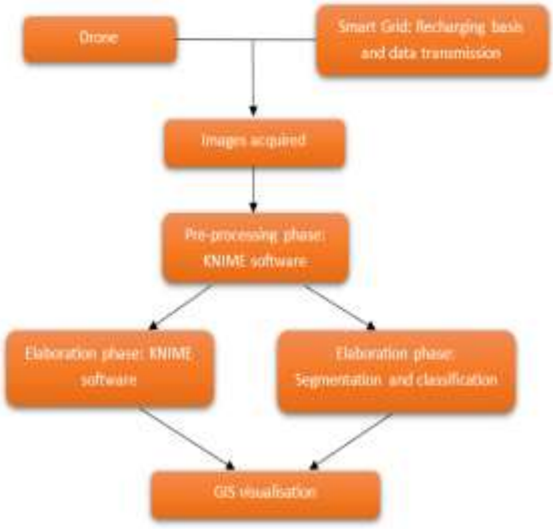

Fig. 1: Flowchart showing the proposed methodology.

The task of acquiring the images for the related processing and subsequent training of the neural networks was assigned to a remotely piloted drone, while to better test the transfer of the data acquired in flight to the Smart Grid it was decided to build a drone prototype. For the construction of the drone, the Raspberry Pi 3 model B was used to which the Navio 2 module was integrated, providing access to tools such as the gyroscope, barometer, and power management. Additionally, to ensure piloting capabilities, PX4 Autopilot was integrated and for the radio interface, the Service Set Identifier was directly connected to the Smart Grid to guarantee wireless access only to authorized devices. The prototype drone only lacks the flight-related module which was compensated by the commercial drone used to acquire the pre-established images from the flight plan set through the QGroundControll application, allowing for mission planning and management. The commercial drone used for image acquisition is the remotely piloted Mavic Air 2. The UAV used for image acquisition is presented in Fig. 2.

Fig. 2: UAV used for image acquisition.

The characteristics of this drone are well known. It is equipped with a high resolution enabling it to acquire video in 4K with 60 fps and capture images with a 48 Megapixel CMOS sensor ½”. Additionally, it also has sophisticated features like Active Track 3.0, Spotlight, and Point of Interest 3.0, [11], [12]. After the commercial drone completed its flight and collected the information, the data was transferred to the prototype drone to test the functionality of the drone-smart grid communication. The prototype drone sends all data to the Smart Grid via SSH protocol, and the data is transmitted to the server through the SFTP protocol for processing. The innovation of this research study also lies in the creation of the Smart Grid, i.e., a wireless charging base for drones. Besides recharging the drone’s battery to guarantee greater flight range, the Smart Grid also allows for considerable efficiency in transferring information from the platform drone and vice versa. The physical hardware used for the Smart Grid is PC Engines Alix. Furthermore, charging modules for the drone and all the components used for internet access were physically created. The drone is recharged via this platform through a magnetic coupling system allowing the connection between the charging module on the smart grid and the drone battery. The drone can recognize the location of the smart grid platform for the connection but also establish the point on which to land with an accuracy of the order of a millimeter: the drone will thus be able to recharge completely autonomously. This type of open communication was chosen for different reasons:

- To allow immediate communication once the drone gets close enough to the transmitting platform.
- To operate in a restricted area of action with a range of two meters.

The advantages of this innovative method of communication are numerous, including energy savings, greater efficiency, and the possibility of multiple connections.

Thus, a large amount of data was obtained. Big Data are primarily informational resources, i.e., organized data, [13], [14]. However, this data has such a large volume, speed, and variety that it requires data analytics techniques to transform it into actionable insights.

The second phase of the research, in fact, focused on the treatment and processing of Big Data (images). The pre-processing phase was conducted using commercial software called KNIME or Konstanz Information Miner. This is a free, open-source platform under the GPLv3 license used for data analysis, reporting, and integration [15], [16]. The advantages of this platform are various:

- It facilitates the creation of ETL and Data Preparation flows.
- It includes more than 200 configurable Machine Learning algorithms.
- It offers a user-friendly interface and immediate usability.
- It is designed for team collaboration.
- It integrates Python and R languages.

While KNIME is not a complete big data management system like Hadoop or Apache Spark, it can be used as a complementary big data management tool within a larger data analytics workflow, leveraging its data analysis, manipulation, and integration capabilities. Compared to other platforms KNIME has several features that make it stand out in analyzing and processing data. These features lie in the fact that KNIME has in its basic version more than 200 machine learning algorithms implemented and easily configured even by non-experts, it has an intuitive interface, and it allows teamwork by sharing programs and codes, configuring itself as a useful and versatile tool. For preprocessing big data in KNIME, a combination of standard KNIME nodes together with the KNIME Image Processing extension can be used. Some of the nodes used in the pre-treatment phase of the images acquired by drone are listed below:

- “Image Filter”: this node was used to improve the quality, reduce the noise and adjust the contrast. Additionally, it allowed the application of the Gaussian filter, the median filter, and the Sobel filter.

- “Image Compressor”: the images were reduced in size to optimize storage space.

"Image Deduplicator": duplicate images within the acquired dataset were removed.

Using KNIME, the images with characteristics not compliant with the requests of the research in question (blurry, duplicate, and redundant images) were deleted, leaving only the useful ones.

In the following phase, images are elaborated both with the KNIME software and traditional machine learning algorithms. For the study under consideration, images were subjected to machine learning techniques that the authors had tested in other publications, [17], [18], [19]. The acquired images were segmented using Edge Detector and Canny Filter and classified with the Support Vector Machine (SVM), [20], [21], [22]. As known, the Support Vector Machine (SVM) is a machine learning algorithm used for classification and regression. It is a supervised learning method that can be employed to solve binary or multiclass classification problems. This algorithm is appreciated for its ability to deal with non-linear data through the use of kernel functions, which allow transforming the data into a high-dimensional space where they can be separated by a hyperplane. This makes SVM very versatile and suitable for a wide range of classification problems. In fact, it has proven to be effective in various domains, such as image recognition, text classification, medical diagnostics, and many other machine-learning applications.

The SVM classification process involved two distinct phases: 1) SVM Training and 2) Performance testing. In the first phase, the geometric characteristics of the connected components assigned for SVM training were computed. These features were then normalized within a specific range. The Radial Basis Function (RBF) kernel was chosen as a kernel trick due to the moderate number of instances (connected regions) and the infinite size of the transformed space with RBF. Optimal training parameters for the SVM were determined using grid search. To ensure comprehensive learning of different types of cracks, a triple cross-validation approach was employed. The training set was divided into three equal subsets, and the trained classifier was tested on two subsets while using the remaining subset for validation. The aim was to identify the most effective parameters for predicting test data accurately. Once the optimal parameters were determined, SVM was trained using the "One Against All" approach with the assistance of the MATLAB LIBSVM library. In the second phase, the performance of the SVM classifier was evaluated on connected regions that were not used during the SVM training phase. In our experimentation, we used datasets consisting of approximately 250,000 images. Therefore, using Machine Learning techniques, we developed a model capable of automatically recognizing and identifying cracks in images. We have also successfully created an open-source GIS application that displays a map of buildings with identified cracks and Cultural Heritage, along with the trajectories of the drones. In this phase, the structuring of the GIS is of significant importance to effectively manage the acquired geospatial data and the attributes related to the cracks. The GIS database has been designed to be scalable and capable of handling a large amount of data. Moreover, spatial analyses have been conducted to identify potential patterns among the cracks of the buildings in the area, aiming to highlight high-risk areas. Additionally, by interacting with the GIS interface by means of layers, users can access all the acquired images by clicking on the drone trajectory and identify cracks and significant Cultural Heritage. The peculiarity of this GIS is the ability to overlay data about Cultural Heritage with data about unsafe buildings, allowing for the identification of areas with a high concentration of vulnerable cultural sites. This integration of data provides a comprehensive and interconnected view of cultural heritage and structural safety issues of buildings.

3 Case Study

The proposed system has been evaluated in Casignana, an Italian town of 710 inhabitants (Fig. 3) located in the metropolitan city of Reggio Calabria in Calabria, South Italy. It is situated in the Locride region and is part of the municipalities of the “Costa dei Gelsomini”. Casignana is a small center of the Jonico hinterland, situated on a hill at 342 m on the eastern side of Aspromonte, east of Reggio Calabria. Located between the mountain and the sea (in Palazzi, on the coast, the remains of the Roman Villa of Casignana arise), the village boasts almost untouched environmental landscapes, which have been made accessible through naturalistic paths that branch off from the coast inland.

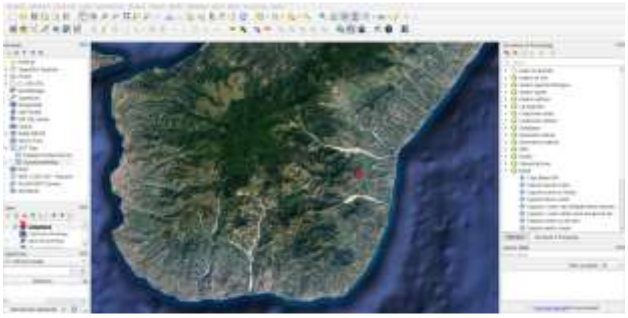

Fig. 3: Casignana (Reggio Calabria, Italy), case study.

Part of its territory is included in the Eastern Aspromonte Mountain Community. Due to its history, the hamlet has some religious buildings and an Archaeological area:

- The Chiesa Matrice, named after San Giovanni Battista, is accessed from a balcony with a ladder and has a high altar with a painting depicting the Blessed Virgin Mary.
- The Church of Santissima Annunziata, located at the entrance to the village, consists of a nave with a bell tower equipped with two bells.
- The Roman villa, located in the Palazzi district, is the most important archaeological park of the Roman age.

Fig. 4, Fig. 5, and Fig. 6 show some of the images captured by the drone once the autonomous plan flight has been established with the QGroundControll application. In this way, images of the Cultural/Archaeological sites of interest were imported into the GIS allowing the visualization of the Cultural Heritage of the region on a thematic and virtual map.

Fig. 4: Sanctuary Madonna Delle Grazie, Casignana (Reggio Calabria, Italy).

Fig. 5: Palazzo Barletta, Casignana (Reggio Calabria, Italy).

Fig. 6: Church of San Giovanni Battista di Casignana, Casignana (Reggio Calabria, Italy).

Particularly performing was the use of the Smart Grid charging and transmission station. Fig. 7 shows the image collection process: once the flight plan was established and transmitted, the images captured by the drone were sent to the charging station and then to the server via the aforementioned protocols.

Fig. 7: Images collection process.

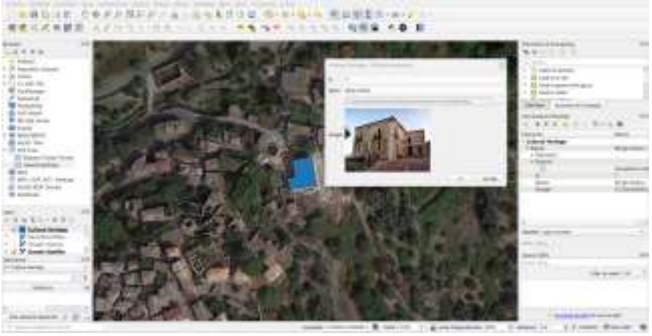

Fig. 8: GIS: Borgo Antico, Casignana (Reggio Calabria, Italy).

As for data exchange, a narrow range of coverage was chosen to avoid interference problems and especially to make sure that data exchange takes place close to the charging point. If data were transferred from large distances from the access point, the transmission energy would be greater than for a short-range transmission. Therefore, it was chosen that the data exchange would take place near a charging point to ensure a continuous power source for the drone and thus neglect the problem of battery consumption during charging. Short-range transfer via wifi technology, (in particular, 802.11g protocol was used, which allows a peak data rate of 54 Mbit/s), allows the maximum data rate to be achieved.

During the flight, the drone also acquired images related to the state of buildings around the hamlet. Fig. 9 displays some of the images acquired by the drone and then used for the creation of one of the three subsets used for the training and subsequently validation of the Neural Network. At this stage, it is of considerable importance to acquire a substantial number of images so that the neural network can be effectively trained to recognize the various types of cracks.

(a) (b)

Fig. 9 (a and b): Images highlighting buildings' cracks.

Therefore, the images are pre-elaborated, segmented, and classified according to the two methods proposed and described above to obtain and extrapolate the information we needed. Fig. 10 shows the methodology applied to the classification of building cracks, highlighting the detection of the cracks.

Fig. 10: Classification of the different types of cracks detected.

Three types of cracks were identified by the system:

- Type 1: structural cracks involving load-bearing components of the building, such as load-bearing walls, foundations, and beams.
- Type 2: horizontal and vertical cracks, of particular concern that may be indicative of lateral pressure or differential movement or uplift of the ground.
- Type 3: surface cracks, caused by shrinkage and uneven settlement.

Some of the key parameters for identifying the three crack types were extent, thickness, and location. In this way, this experimental system has allowed to create automatically, the first updated map on the GIS showing the network of buildings that need interventions. For the specific case study, a layer was created in QGIS (on satellite base map with reference system EPSG: 3857) related to unsafe buildings. Regular data acquisition can be conducted without the need for human operators, leading to streamlined operations, cost reductions, and time savings. The acquired data is stored in a database that includes the coordinates of the buildings, categorized based on the study area, type, and conditions. The database also provides geometric information, as well as details regarding the conservative and functional status of the buildings.

Fig. 11 shows the first results: blue polygons represent the principal Cultural Heritage of the area; red polygons represent buildings with cracks of Type1 (most dangerous buildings needing timely interventions); orange polygons represent buildings with cracks of Type2 (buildings that don't need timely interventions but must be monitored); and green polygons represent buildings with cracks of Type3 (buildings that are affected by minor injuries). Similarly, Fig. 8. shows, in particular, the open-source GIS interface highlighting the Cultural Heritage site in Borgo Antico (RC).

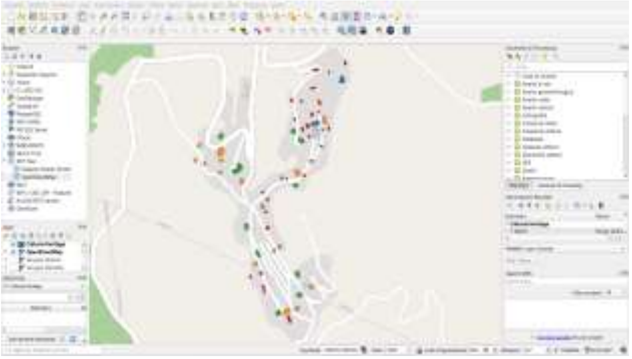

Fig. 11: GIS visualization: Cultural Heritage and three types of cracks detected.

The cataloging of cracks enables the visualization and management of valuable information about the structural stability and health of the buildings, allowing for the diagnosis of structural problems, assessment of building safety, monitoring of the evolution of cracks, and most importantly, planning maintenance or necessary repairs. In this way, it is possible to ensure, through a low-cost system, a comprehensive overview of small communities that can be enhanced and improved. The method also serves as a support for public managers and municipal agencies in visualizing and managing the cultural sites in the area, facilitating the scheduling of any timely maintenance work.

4 Conclusions

Digital and technological transformation plays a crucial role in enhancing the preservation of our cultural heritage while supporting the green transition. Our innovative monitoring system for cultural heritage, with low environmental impact, addresses territorial inequalities and safeguards cities, towns, and rural areas from the potential socio-economic consequences associated with the loss of cultural heritage. If designed to focus on prevention and maintenance functions, our experimental system can become an excellent tool for public administrations. These administrations can plan interventions based on the information provided within the GIS. The system identifies vulnerable buildings, those with significant damage caused by dangerous cracks or other structural problems. This information is crucial for public authorities, as it enables them to assess potential risks to the safety of people and structures. Through an accurate assessment of the state of buildings, authorities can prioritize interventions and allocate resources in a targeted manner to ensure the safety of people and preserve the building stock. Thus, based on the findings of our research, it can be concluded that digitalization plays a crucial role in the mapping and management of cultural heritage, enabling the preservation, understanding, and promotion of these valuable testimonies of the history and identity of a community or region.

With the advancement of technology and ongoing research and innovation, it is expected that new opportunities and solutions will emerge to preserve and enhance our cultural heritage. Some of these may include the development of timely alert systems and the implementation of algorithms and logic that enable drones to make decisions during flight. By leveraging data acquired by drones and developed analytical models, timely alert systems could be implemented to notify the relevant authorities in the event of imminent danger or significant changes in the conditions of hazardous buildings. This would enable a rapid and targeted response to mitigate risks.

Other future developments in this research could lead to increasingly sophisticated and effective systems for the preservation of cultural heritage, enabling the relevant authorities to plan targeted maintenance interventions and helping to safeguard historical evidence for future generations. These developments could include the implementation of advanced algorithms and logic that enable drones to make decisions while in flight and provide timely alerts to relevant authorities in case of imminent danger or significant changes in the condition of unsafe buildings. The system could be expanded to a territorial level allowing even more cultural heritage assets and vulnerable buildings to be monitored and preserved. Additionally, integration with other emerging technologies, such as augmented reality or virtual reality, could provide an even more immersive experience in the enjoyment and preservation of cultural heritage. Looking ahead to future experiments and studies, this research has developed an automatic and experimental system aimed at creating a thematic and virtual map in the GIS capable of visualizing Cultural Heritage and vulnerable buildings in need of interventions. The system not only documents the existing building heritage but also incorporates maintenance planning activities, such as identifying buildings with high levels of damage caused by dangerous cracks and scheduling interventions to enhance safety. The databases will be enriched with relevant additional information to support these objectives. Consequently, we are studying how to implement the building cadastre to facilitate maintenance planning and restoration interventions. Future developments will focus on improving automation systems to streamline processes further.

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