Contribution Title: Exploring UAVs for Structural Health Monitoring

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The preservation and maintenance of architectural heritage on a large scale deserve the design, development, and exploitation of innovative methodologies and tools for sustainable Structural Heritage Monitoring (SHM).

In the framework of the Moscardo Project (https://www.moscardo.it/), the role of Unmanned Aerial Vehicles (UAVs) in conjunction with a broader IoT platform for SHM has been investigated. UAVs resulted in significant aid for a safe, fast and routinely operated inspection of buildings in synergy with data collected in situ thanks to a network of pervasive wireless sensors (Bacco et al. 2020). The main idea has been to deploy an acquisition layer made of a network of low power sensors capable of collecting environmental parameters and building vibration modes. This layer has been connected to a service layer through gateways capable of performing data analysis and presenting aggregated results thanks to an integrated dashboard. In this architecture, the UAV has emerged as a particular network node for extending the acquisition layer by adding several imaging capabilities.

Applicability of the proposed architecture has been demonstrated in real case studies in Tuscany, among which the Torre Grossa in San Gimignano and the Fortezza Vecchia, an ancient fortress complex in Leghorn.

Fig. 1 – Panoramic view of San Gimignano and Torre Grossa, a case study of Moscardo project.

Fig. 2 – The operator pilots the UAV around Mastio di Matilde, a tower in the Fortezza Vecchia complex in Leghorn, which has been considered as a case study in the framework of the Moscardo project.

Indeed, in the San Gimignano case, the UAV has been relevant for photogrammetric reconstruction and visual inspection of the towers and surrounding structures which are very difficult to be reached and inspected by other means. The second case study of the Fortezza Vecchia has an additional interesting feature: it presents several critical crack patterns. Since the sea partially surrounds such a Tuscan historical building, monitoring its ancient walls is very hard by manual methods. Besides, the sides of most of the cracks along the fortress walls are quite far from each other and don't lie on the same plane. Therefore, using standard methods (e.g. those based on planar crack gauges) may not allow for obtaining an absolute and accurate measurement of the separation of the sides. With the aim to monitor such complex crack patterns over time, an ad hoc image processing pipeline has been identified and tested in a controlled environment (Germanese et al 2018a) and then applied for long-term monitoring on-site (Germanese et al 2019), where measurements accuracies are reported. In brief, the proposed method is a marked-based approach for extracting quantitative information about the absolute value and displacement over time of a set of predefined targets around a crack pattern to be studied. In this way, for instance, a crack enlargement can be detected as well as shear displacements.

At first, under the suggestion and guidance of an expert such as a civil engineer or architect, a configuration of planar markers is installed around the crack pattern or damage to be monitored. Notice that this is the only step, which, at the moment, requires physical access to the damaged part, while the actual monitoring can be executed remotely, thanks to the use of the UAV.

Fig. 3 – Bastione della Capitana. This area of the Fortezza Vecchia complex has been considered for long-term monitoring of cracks and damages in the building by UAV inspection. A configuration of markers has been placed around a crack to perform quantitative 3D measurements.

At each inspection time, either following a predefined mission or in manual flight mode, the UAV can reach waypoints nearby a crack and capture a set of pictures using a standard camera (in our case, an RGB camera). Collected images are then transmitted to the service layer and there processed for extraction of a matrix of distances among the various planar markers as well as their orientation. Tests have allowed demonstrating that the results are reproducible. A UAV can obtain that acceptable images under normal operating conditions (no further requirements on wind speed and weather have been required) during daylight. It has been possible to perform routine analysis of cracks and to understand possible seasonal changes in a way that is safe for operators since it is not required to reach damaged and critical areas. Further capabilities of the UAVs might be considered in the future, such as adding infrared vision to analyse defects and other onboard intelligent systems to detect faults (Jalil et al, 2019).

The first flights executed in the case studies also allowed to acquire image surveys for performing a 3D photogrammetric reconstruction of the monitored structures, which has been used to provide a Virtual Reality (VR) system (Germanese et al 2018b). Such a VR system aims at enriching the historical building monitoring and providing support to the UAV operator during inspections. For each monitored zone, a detailed photogrammetric reconstruction has been realised and placed inside a 3D scene. The scene also contains all the sensors in the acquisition layer of the IoT platform for SHM. The VR system can retrieve and display the raw data measured by each sensor as well as the output of data processing.

The VR system can be experienced in several ways: (i) freely exploring it and interacting with displayed sensors; (ii) accessing past UAV inspections and retracing UAV flights performed during a selected inspection; (iii) live during a UAV inspection by following live movements. During the UAV flight, the user has no control of camera movement and orientation; indeed, camera movements reproduce actual UAV movements estimated using SLAM algorithm ORB-SLAM (Mur-Artal et al, 2015). Thanks to this solution and the high fidelity of the 3D model, UAV operators can rely on this tool to plan the drone's route and have a quick look at the sensor position relative to the UAV and possible obstacles surrounding the vehicle. In this modality, the interface is composed of three parts:

- The central and main one is devoted to showing the subjective 3D scene from the vehicle. From here, it is possible to view near sensors and acquired measurements;
- The upper right side displays the direct view of the UAV acquired by the onboard camera;
- The lower right portion shows a perspective view of the entire scene with the actual position of the UAV.

The Moscardo solution has proved to be feasible, minimally invasive and customisable depending on the peculiarity of the architectural asset. From a technical point of view, the use of such a system, based on the use of a net of sensors and UAVs, can be quite effective in acquiring a rich set of data for long-term monitoring of ancient structures. Indeed, the local authorities demonstrated a strong interest in collecting data beyond the end of the project, and research scientists, including the authors, are still collaborating on planning future actions to exploit and further improve the Moscardo system.

Fig. 4 – The VR interface is composed of three elements: (i) the central part shows a reconstructed virtual scene with installed sensors and their gathered values; (ii) on the upper right side of the screen, the video recorded by the UAV during the inspection operations is shown; (iii) in the lower right side, a panoramic view of the virtual scene is displayed reporting also UAV actual position (yellow pyramid) and travelled path (represented as a set of smaller red pyramids). Please, see http://moscardo.isti.cnr.it/ for an interactive demo.

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