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# Preliminary study on a novel Optimal Placed Sensors method based on Genetic Algorithm.

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# Preliminary study on a novel Optimal Placed Sensors method based on Genetic Algorithm.

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**Abstract**. The safeguarding of the historical and cultural heritage is one of the main research topics that has been addressed in recent years. Particular attention was given to the development of structural health monitoring systems that allowed the real time acquisition of different physical quantities that are stored in a cloud and compared with the health limit values of the structures obtained from numerical analysis previously carried out. One of the major problems highlighted by the use of these systems is related to the position and quantity of smart sensors to be used within the structure to be monitored. To avoid this, in this paper an Optimal Sensors Placement method was applied to a case study located in China. In particular, the positioning of the sensors was identified through an optimization workflow that adopt a Multi Objective Optimization engine called "Octopus" in Grasshopper3D. The identified optimal solutions have made it possible to detect the areas of the structure that will be subject to collapse during a seismic event.

## 1. Introduction

The world historical cultural heritage is subject to precarious security and could collapse due to external actions that afflict it such as: earthquakes [1], strong winds, heavy rains, fires, water infiltrations, floods [2], effects of atmospheric agents that cause the degradation of the material [3], factors related to environmental conditions, concentration of bacteria and fungi [4], protective treatment, corrosion and prolonged solar radiation. Examples of this precariousness in historical constructions are different, in Italy, in 1989 a bell tower of the fourteenth century collapsed in Pavia, while in 2017, the collapse of a portion of masonry in the Basilica of Santa Croce in Florence killed a person. Regions also affected by this problem are the Asian ones, in 2018 a minaret at the entrance of the Taj Mahal in Agra, India, collapsed due to heavy rain and winds with no apparent warning sign [5]. One of the main reasons that generates this degradation is linked to the lack of knowledge of these structures located in these Asian countries. Recently, several architectural surveys and campaigns on structural behaviors have been conducted on buildings that characterize the Chinese territory, the Pagodas [6][7]. These studies have shown that the structural performance and aesthetics of these historic buildings have decreased over time due to the degradation of the material leading to the formation of cracks, humidity, atmospheric agents, environmental degradation, dust deposition and other factors such as vandalism by tourists [8]. In order to preserve the historical cultural heritage, many governments have increased the monitoring of structural health (SHM) of buildings through systems that make use of Smart Objects (SO) [9]-[11]. This makes it possible to start maintenance at the beginning of the problem, avoiding unnecessary expenditure for countries to rehabilitate and maintain heritage structures through the implementation of appropriate retrofit strategies. In fact, the classic approach based on extraordinary last minute maintenance leads to high repair costs and considerable investments in the damaged building. In light of this, the prediction of structural health in real time has attracted considerable interest in recent decades because it allows to come in only when necessary, reducing the risk of collapses and excessive expenses. The main purpose of this work is to expose a preliminary model to optimize the positioning of the SOs within a structure to be monitored. Specifically, the chosen case study is the Longhu Pagoda located in China in the Sichuan province.

## 2. Case study

Longhu pagoda (Figure 1) which was built in 1342 A.D. is located in Sichuan province, China. It has a square plan with 13 layers of eaves outside it, and is roughly 33 meters tall which contains 2 meters of stylobate and 31 meters of body. On May 12, 2008, a 8.0 magnitude Richter earthquake occurred in Wenchuan. The pagoda, which has been subjected to a huge earthquake load, suffered great damage during the Wenchuan earthquake, but it did not collapse. From the bottom to the top of the pagoda, a north-south crack appeared. The crack developed along the height, and the higher the position, the wider the crack width (Figure 2). With the aim to analyze the seismic vulnerability of the pagoda and to study how the damage spread within the structure, several numerical simulations are performed by means of FE-based software Abaqus [12][13]. A different spread of the damage can be noticed from the pushover along the W-E ($X^+$) direction. Indeed, the first crack occurs on the East facade where the presence of the stairs represent a weakness of the structure (Figure 3). On the North facade the crack is pretty similar with the one obtained in the previous analysis but involving more the upper part of the structure. Even on the South façade it is noticeable a difference. In place of a vertical crack, a more diffused damage characterizes the center of the structure.

**Figure 1.** Longhu Pagoda

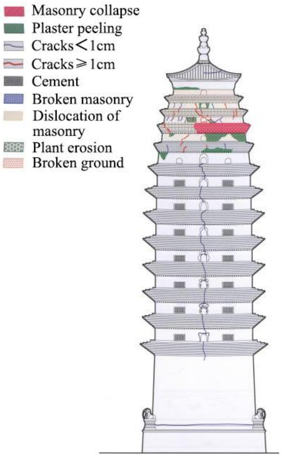


**Figure 2.** Cracks on the Longhu pagoda

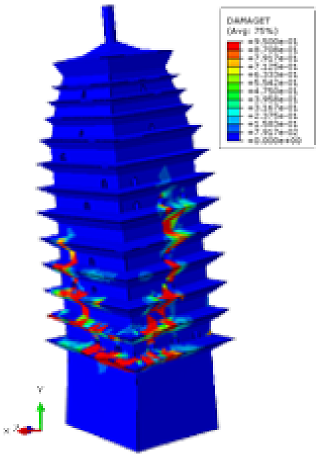


**Figure 3.** Results of pushover analysis in $X^+$ direction

## 3. SHM system based on Optimal Sensors Placement (OSP) method.

The Structural Health Monitoring systems (SHM) are introduced in the monitoring of different types of buildings to lower costs of maintenance and protect human safety. The principal aims of SHM are

connected to the storage of information about the alterations in the structures brought about by materials aging, action of the environment, earthquakes, or accidental events [14][15]. SHMs systems not only collect and measure physical quantities, but are able to process them and share information via the internet with other devices. The latest generation of SHM is composed of several Intelligent Smart Objects (SOs) that act as sensors and are based on the Internet of Things (IoT) paradigm[16]-[21].
In order to guarantee a minimum number of sensors to satisfy the sensitivity required by the SHM, methods of OSP have become widespread in the last years [22]. They minimize costs, reduce energy consumption and system invasiveness, increase system effectiveness and optimize acquired data. The design of the monitoring system is simplified in a reduction of the number of degrees of freedom by searching for the optimal point at the constrained extremes [23]. The solution obtained is unique and is identified only when the positioning of the sensors does not coincide and the requirements chosen by the designer are guaranteed [24]. The main purpose of this work is to identify a preliminary method for evaluating the multi-objective OSP problem that allows to monitor the portion of the structure that will most likely be involved and subject to damage during the earthquake. This analysis will take place, identifying a pareto optimal set that contains all the most probable collapse configurations, obtained through an algorithm that solves multi-objective functions.
The preliminary physical part of the SHM system designed is composed by: Smart Object (SO), gateway, Remote Control and Service Room (RCSR) and Open Platform Communications (OPC) server. In particular, the position of The SOs was identified by the analysis conducted on the Numerical model with the Genetic Algorithm (GM). The SOs chosen are piezoelectric accelerometric sensors characterizing and identifying a wired Sensor network (Integrated Electronic Piezoelectric—IEPE): KS48C-MMF with voltage sensitivity of 1 V/g and measurement range of ± 6 g; KB12VD-MMF with voltage sensitivity if 10 V/g and measurement range of ± 0.6 g. This type of sensors transmits in quasi real time, with delays of a few hundredths of a second, information concerning the movement and acceleration of the structure during a seismic event, placing the sensors in areas where the formation of cracks patterns is expected. This allows to act quickly to safeguard the building, avoiding major damage and loss of human life.

## 4. Genetic Algorithms

Multi-objective optimization aims to identify a vector of decision variables that optimize a vector function whose elements represent a multi-objective function. This is due to the need to reach a decision-making compromise in a problem of many conflicting objectives. The purpose of the optimal research is to explore a subspace of optimal solutions, where each solution presents a different level of objective satisfaction, and not in order to find a single optimal solution.

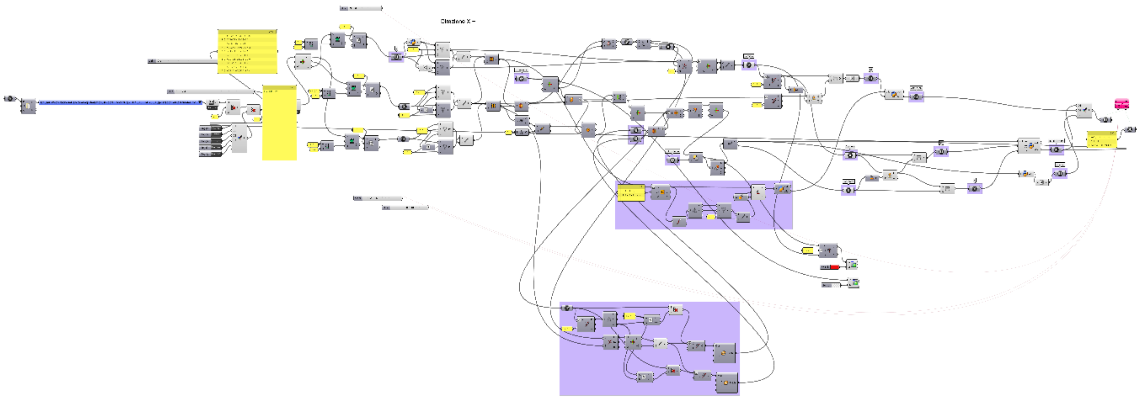


**Figure 4.** Visual script

A typical multi-objective optimization problem which uses algorithms inspired by biological evolution is called Evolutionary Multi-Objective Optimization (EMO) [25]. In particular, the approach based on

Genetic Algorithms (GA), is a method inspired by natural selection, which has found widespread use in recent years in various fields [26].

This conference paper is based on the development of a workflow of an optimization tools consisting in the integration of two components: simulation tools and genetic algorithm. The fulcrum of this workflow is the multi-objective optimization engine Octopus able to applying the evolutionary algorithm at the model of Pagoda created in Rhinoceros and analysed in the plug-in Grasshopper3D.

In order to identify a graphic tool capable of predicting the portion of the structure that most likely collapses during a seismic event, the visual script shown in figure 4 has been created. The problem has been optimized by imposing the research for three objectives: minimize the collapse multiplier ($\alpha$), identify the cutting plane characterized by the lowest frictional force and maximize the mass involved in the kinematics expressed in terms of Volum Fraction (VF).

The geometric complexity of the Pagoda model caused an "overflow" of the simulation. In order to avoid this, the model has been separated into two parts, the external casing (Figure 5) and the internal void system (Figure 6). By doing this, in each step the computational burden decreased because once the cutting plane was identified, the software calculated the portion of the structure involved in the kinematism, by performing a Boolean difference subtracting from the external casing the staircases voids system.

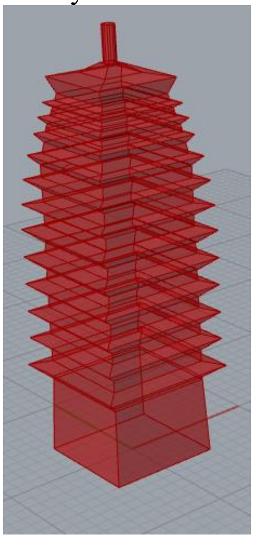


**Figure 5.** Model External casing

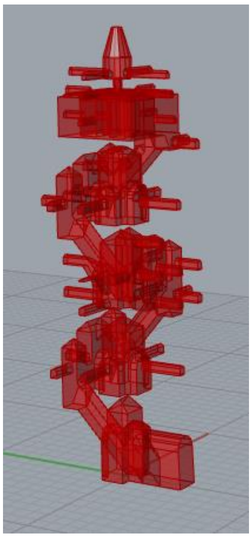


**Figure 6.** Voids staircase system

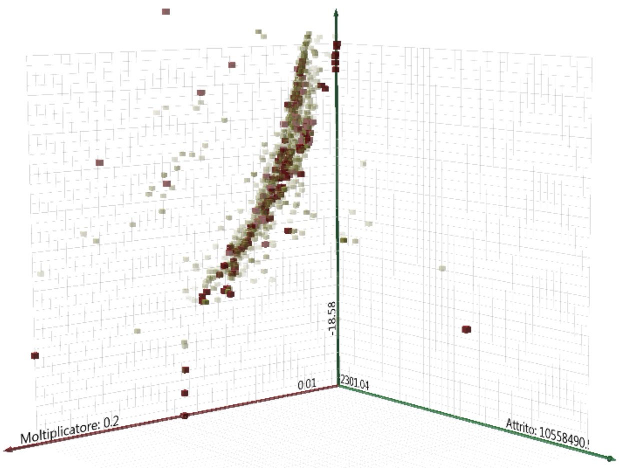


**Figure 7.** Pareto Optimal Set

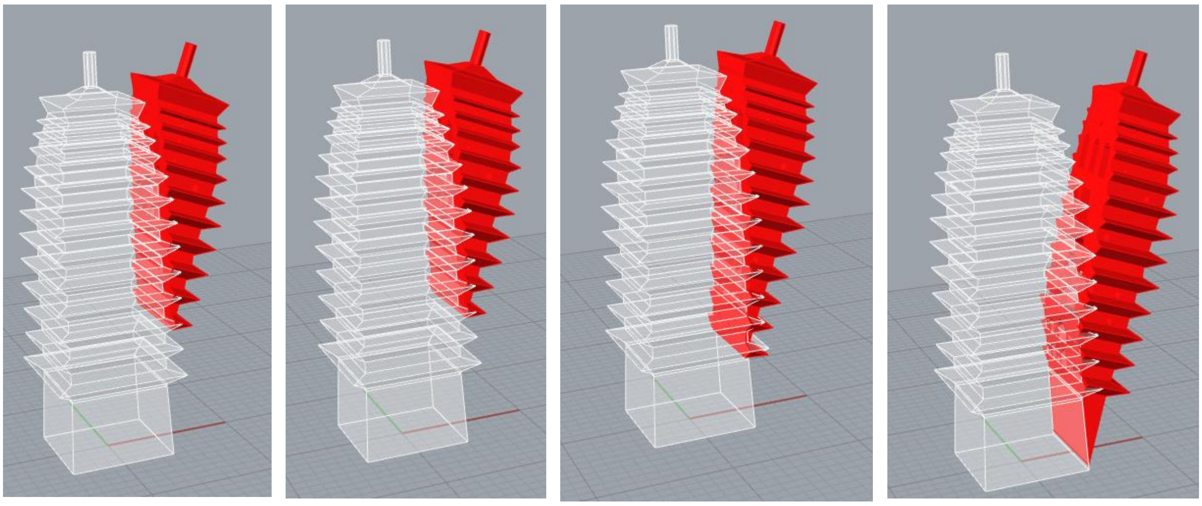
The collapse multiplier was calculated in according to the Italian technical standards relating to the overturning of a monolithic wall [27].

In order to identify the sliding plane, associated with the overturning characterized by a lower collapse multiplier, the friction force calculated with the following equation [28] was minimized:

$$F = \frac{(hs * tg\vartheta + 2b - s) * hs}{2} * \gamma * f * tb \qquad \textbf{(1)}$$

In the equation 1, *hs* is the height of the cutting plane, $\theta$ is the angle formed between the cutting plane and the vertical, *b* is the horizontal projection of the cutting plane, *s* the length of the brick (.50 m), $\gamma$ is the specific weight of the masonry, *f* is the coefficient of friction and is equal to 0.4, *tb* is the average thickness of the wall.

Figure 7 represents the pareto optimal set in the space of objectives reported as values in the three axes. The position of the solution in space is representative of the level of satisfaction of each objective. The individuals in red are the optimum identified by the last generation, while those in green are the individuals discarded during the analysis.



α=0.21
VF=22.8 %
F=4937 N

α=0.22
VF =27.0 %
F=15515 N

α=0.19
VF = 28.2%
F= 6537 N

α=0.15
VF =46.0 %
F=14530 N

**Figure 8.** Optimal solutions represented as phenotypes

Figure 8 shows some Pareto optimum phenotypes, characterized by the values of the objectives reported under each figure. The results identified with the simplified geometric analysis, along the x + direction, are in agreement with those illustrated in paragraph 2 through the numerical model in ABAQUS and with the crack pattern detected on the structure.

The preliminary study conducted, therefore, allows to reduce the computational burden of calculation and to identify the critical areas to be monitored.

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## References

[1] Lombardi, G. (2021). Irpinia Earthquake and History: A Nexus as a Problem. Geosciences, 11(2), 50.
[2] Alcoforado, M. J., Silva, L. P., Amorim, I., Fragoso, M., & Garcia, J. C. (2021). Historical floods of the Douro River in Porto, Portugal (1727–1799). Climatic Change, 165(1), 1-20.
[3] Ginjupalli, K., Shavi, G. V., Averineni, R. K., Bhat, M., Udupa, N., & Upadhya, P. N. (2017). Poly (α-hydroxy acid) based polymers: A review on material and degradation aspects. Polymer Degradation and Stability, 144, 520-535.
[4] Raghav, N., Shrivastava, J. N., Satsangi, G. P., & Kumar, R. (2020). Enumeration and characterization of airborne microbial communities in an outdoor environment of the city of Taj, India. Urban Climate, 32, 100596.
[5] Mishra, Mayank. "Machine learning techniques for structural health monitoring of heritage buildings: A state-of-the-art review and case studies." Journal of Cultural Heritage (2020).
[6] Wang, P., Scacco, J., Milani, G., & Li, S. (2021, March). Seismic vulnerability assessment of Longhu Pagoda, Sichuan, China. In AIP Conference Proceedings (Vol. 2343, No. 1, p. 080012). AIP Publishing LLC.
[7] Wang, P., Scacco, J., Milani, G., & Li, S. (2020). Seismic vulnerability evaluation of longhu pagoda, sichuan, prc. In 11th International Conference on Structural Dynamics, EURODYN 2020 (Vol. 2, pp. 4226-4242). European Association for Structural Dynamics.

[8] De Masi, F., & Porrini, D. (2020). Cultural Heritage and natural disasters: the insurance choice of the Italian Cathedrals. Journal of Cultural Economics, 1-25.

[9] Dousse, O., Mannersalo, P., & Thiran, P. (2004, May). Latency of wireless sensor networks with uncoordinated power saving mechanisms. In Proceedings of the 5th ACM international symposium on Mobile ad hoc networking and computing (pp. 109-120).

[10] Ye, W., Heidemann, J., & Estrin, D. (2002, June). An energy-efficient MAC protocol for wireless sensor networks. In Proceedings. Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies (Vol. 3, pp. 1567-1576). IEEE.

[11] García-Macías, E., Ierimonti, L., Venanzi, I., & Ubertini, F. (2019). An innovative methodology for online surrogate-based model updating of historic buildings using monitoring data. International Journal of Architectural Heritage, 1-21.

[12] Tiberti, S., Scuro, C., Codispoti, R., Olivito, R. S., & Milani, G. (2019). Experimental and numerical analysis of historical aseismic construction system. In Structural Analysis of Historical Constructions (pp. 910-918). Springer, Cham.

[13] Tiberti, S., Scuro, C., Codispoti, R., Olivito, R. S., & Milani, G. (2017, November). Masonry structures built with fictile tubules: Experimental and numerical analyses. In AIP Conference Proceedings (Vol. 1906, No. 1, p. 090010). AIP Publishing LLC.

[14] Lamonaca, F., Scuro, C., Sciammarella, P. F., Olivito, R. S., Grimaldi, D., & Carnì, D. L. (2019). A layered IoT-based architecture for a distributed structural health monitoring system. Acta Imeko, 8(2), 45-52.

[15] Scuro, C., Lamonaca, F., Porzio, S., Milani, G., & Olivito, R. S. (2021). Internet of Things (IoT) for masonry structural health monitoring (SHM): Overview and examples of innovative systems. Construction and Building Materials, 290, 123092.

[16] Cho, M. Y., Kim, S., Kim, I. S., Kim, E. S., Wang, Z. J., Kim, N. Y., ... & Oh, J. M. (2020). Perovskite-Induced Ultrasensitive and Highly Stable Humidity Sensor Systems Prepared by Aerosol Deposition at Room Temperature. Advanced Functional Materials, 30(3), 1907449.-708.

[17] Lamonaca, F., Balestrieri, E., Tudosa, I., Picariello, F., Carnì, D. L., Scuro, C., ... & Colaprico, A. (2019, June). An overview on Internet of medical things in blood pressure monitoring. In 2019 IEEE International Symposium on Medical Measurements and Applications (MeMeA) (pp. 1-6). IEEE.

[18] Li, J. X., Tong, Z. R., Jing, L., Zhang, W. H., Qin, J., & Liu, J. W. (2020). Fiber temperature and humidity sensor based on photonic crystal fiber coated with graphene oxide. Optics Communications, 467, 125707.

[19] Yang, J., Guan, C., Yu, Z., Yang, M., Shi, J., Wang, P., ... & Yuan, L. (2020). High sensitivity humidity sensor based on gelatin coated side-polished in-fiber directional coupler. Sensors and Actuators B: Chemical, 305, 127555.

[20] Lamonaca, F., Sciammarella, P. F., Scuro, C., Carnì, D. L., & Olivito, R. S. (2018, April). Synchronization of IoT layers for structural health monitoring. In 2018 Workshop on Metrology for Industry 4.0 and IoT (pp. 89-94). IEEE.

[21] Tudosa, I., Picariello, F., Balestrieri, E., Carnì, D. L., & Lamonaca, F. (2019, June). A Flexible DAQ Hardware Architecture using SoCs for IoT based Structural Health Monitoring Systems.

[22] Song, J. H., Lee, E. T., & Eun, H. C. (2021). Optimal sensor placement through expansion of static strain measurements to static displacements. International Journal of Distributed Sensor Networks, 17(1), 1550147721991712.

[23] Li, Y., He, B., & Wang, Y. (2021). Optimal Sensor Placement for Underground Tunnel Monitoring via Wireless Sensor Networks. Wireless Communications and Mobile Computing, 2021.

[24] Zhou, G. D., Yi, T. H., Xie, M. X., Li, H. N., & Xu, J. H. (2021). Optimal Wireless Sensor Placement in Structural Health Monitoring Emphasizing Information Effectiveness and Network Performance. Journal of Aerospace Engineering, 34(2), 04020112.

[25] Bentley, P. J., & Kumar, S. (1999, July). Three ways to grow designs: A comparison of embryogenies for an evolutionary design problem. In GECCO (Vol. 99, pp. 35-43).

[26] Frazer, J. (2016). Parametric computation: history and future. Architectural Design, 86(2), 18-23.

[27] Sarhosis, V., Milani, G., Formisano, A., & Fabbrocino, F. (2018). Evaluation of different approaches for the estimation of the seismic vulnerability of masonry towers. Bulletin of Earthquake Engineering, 16(3), 1511-1545.

[28] Casapulla, C., & D'Ayala, D. (2006, November). In-plane collapse behaviour of masonry walls with frictional resistances and openings. In Structural analysis of historical constructions. Possibilities of numerical and experimental techniques. Proceedings of the 5th International Conference, Macmillan India Ltd, New Delhi (pp. 1153-1160).