Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 199 (2017) 3320–3325

Procedia Engineering

www.elsevier.com/locate/procedia

X International Conference on Structural Dynamics, EURODYN 2017

# An overview on nature-inspired optimization algorithms for Structural Health Monitoring of historical buildings

Alberto Barontini[a]*, Maria-Giovanna Masciotta[a], Luís F. Ramos[a], Paulo Amado-Mendes[b], Paulo B. Lourenço[a]

[a]ISISE, University of Minho, Department of Civil Engineering, Guimarães, Portugal
[b]ISISE, University of Coimbra, Department of Civil Engineering, Coimbra, Portugal

**Abstract**

Structural Health Monitoring (SHM) of historical building is an emerging field of research aimed at the development of strategies for on-line assessment of structural condition and identification of damage in the earliest stage. Built heritage is weak against operational and environmental condition and preservation must guarantee minimum repair and non-intrusiveness. SHM provides a cost-effective management and maintenance allowing prevention and prioritization of the interventions. Recently, in computer science, mimicking nature to address complex problems is becoming more frequent. Nature-inspired approaches turn out to be extremely efficient in facing optimization, commonly used to analyze engineering processes in SHM, providing interesting advantages when compared with classic methods. This paper begins with an introduction to Natural Computing. Then, focusing on its applications to SHM, possible improvements in built heritage conservation are shown and discussed suggesting a general framework for safety assessment and damage identification of existing structures.


Peer-review under responsibility of the organizing committee of EURODYN 2017.

*Keywords:* Historical building conservation; structural health monitoring; damage identification; optimal sensor placement; nature-inspired algorithm

* Corresponding author. Tel.: +351 917099832; fax: +351 253510217.
*E-mail address:* albe.barontini@gmail.com

1877-7058 © 2017 The Authors. Published by Elsevier Ltd.
Peer-review under responsibility of the organizing committee of EURODYN 2017.
10.1016/j.proeng.2017.09.439

## 1. Introduction

The definition of immovable cultural heritage encompasses a wide range of monuments, buildings and sites from ancient time up to the XXth century. Experience demonstrates how they are weak against operational and environmental condition [1]. Although the variety of such conditions and the peculiarities of each structure make the assessment and the conservation hard to accomplish and very problem specific, Structural Health Monitoring (SHM) of historical building is an emerging field of research aimed at the development of easily adaptable strategies for on-line assessment of structural condition and identification of damage in the earliest stage. The aim of this paper is discussing the contribution of nature-inspired optimization algorithms, collecting the few applications which pertain specifically to heritage preservation and analyzing promising achievements and drawbacks to formulate a general framework which relies on a single algorithm to achieve more tasks of SHM only changing the inputs.

## 2. Natural computing for optimization problems

Natural Computing indicates a multidisciplinary field of research focused on the exploration of new paradigms of computation within natural processes [2]. Several applications in Civil Engineering can be formulated as optimization problems. Metaheuristics are global methods, commonly nature-inspired, able to address nonlinear optimization, handling black box objective functions for which an unambiguous formulation is not possible. Each metaheuristic is a set of strategies: specific operators and guidelines used to update the tentative solutions in an iterative process [3].

## 3. Natural computing in SHM

SHM consists of the implementation of strategies aimed at the assessment of the characteristics and the health condition of a system. One of the main open issues in monitoring consists of automating the processes, from the sensor network design to the diagnosis of the structure, to overcome errors due to human decision. The following sections focus especially on two tasks, providing an overview on nature-inspired optimization algorithms applied to the Optimal Sensor Placement (OSP) and the model-based Damage Identification (DI). These algorithms outperform many traditional methods in terms of robustness and solution quality, but their performance is strongly affected by two main aspects: (1) parameters tuning and (2) sensitivity of the features to errors. Each metaheuristic requires a fine setting of several parameters (e.g. the rate of the specific operators, the number of candidate solutions in population-based method, the length of the vector solution in binary coding, the termination criteria), but no general rules for setting exists. The quality of the numerical or analytical model, the accuracy of the sensors and their location are sources of error in SHM, whose effect is summed to the errors due to the algorithm and the sensitivity to its parameters and the unknown properties to update. Therefore, a problem specific statistical analysis should be done, carrying out more runs with the same parameter setting and a sensitivity analysis to parameters, noise and incomplete information. The effect of errors becomes relevant in real world applications. Improvement of robustness and quality of solution can come from the simultaneous use of more objective functions dependent on parameters less sensitive to the sources of error. Multi-objective optimization aims at providing a set of alternative optimal solutions [4,5]. Population based Nature Inspired optimization algorithms, analyzing simultaneously more candidate solutions, are particularly suitable, being able to generate the set in a single run. Applications showed other drawbacks. Nature-inspired algorithms, in fact, tend to converge quickly in the neighbor of the best solution but then oscillate around, sometimes without reaching it or failing to escape local optima. Also, special attention should be paid to the suitability of the solutions in constraint problems as OSP and DI. Such drawbacks are usually solved introducing novel or modified operators and hybridizing the algorithms.

### *3.1. Optimal sensor placement*

OSP consists of locating the minimum number and type of sensors in order to improve the Network Architecture (minimum invasiveness, costs and energy consumption, maximum system lifetime, robustness and network coverage) and improve the Signal Processing (maximum quality of information, minimum amount of data collected).

OSP is a combinatorial discrete constraint black box optimization problem. Given the monitored system, discretized in $N$ degrees of freedom, and the SHM system, OSP consists of finding, among $n \leq N$ candidates, $m < n$ non-duplicate locations and directions for the sensors. Usually, the only design variable is the set of locations, which assume discrete values. Using a binary coding, each bit represents a candidate location: 1 means that the sensor is placed whereas 0 means that the location is not measured. Alternative real-value coding uses a vector whose elements are the identification code of the measurement DOF. Any solution must satisfy constraints given by the list of $n$ candidates, the absence of duplicate locations and the number $m$ of sensors available. Further constraints about coverage and data transmission efficiency can be introduced. In literature, different criteria are commonly used to assess the suitability of the placement. Each of them stresses a specific aspect, but the identification of the more excited DOFs in the target modes is the main objective, through a proper norm of Fisher Information Matrix (FIX), the Modal Assurance Criterion (MAC), the Singular Value Decomposition Ratio (SVDR) of the mode shape matrix or the measured kinetic or strain energy per mode. Other criteria were developed to avoid redundant information [6,7] or specifically for wireless sensor network's requirements [8]. Nature-inspired algorithms, like genetic algorithms, particle swarm optimization, simulating annealing, monkey algorithm, ant colony optimization, firefly algorithm, artificial bee colony, harmony search algorithm and wolf algorithm were successfully applied [6,9-12]. Applications to large structures, like bridges [9], dam [13], high-rise buildings [10], prove their quality. Despite most of the methods developed analyze the best placement of single axis and single type of sensors, proper adjustment allows the OSP for multi-axial [13,14] and multiple type [15].

### *3.2. Damage Identification*

DI strategies can be summarized in five main goals of increasing complexity [16]: (1) detection of existence, (2) location, (3) classification of the type, (4) quantification of the extent, (5) prognosis. To achieve the higher goals, it is necessary to formulate and solve an inverse problem to calculate the damage parameters from changes in properties. Vibration-based methods allow an early identification of the damage through the measurement of the dynamic properties. Since the damage changes mass, damping and stiffness of the system, it has to be detectable through the consequent changes in modal properties (natural frequencies, modal damping and mode shapes). Features extracted from vibration measurements in structures are used in model-based DI to update the model. Model-based damage identification can be formulated as a continue constraint black box optimization problem. Nature-inspired optimization techniques are commonly used to calibrate the numerical model, analyzing in parallel more possible solutions. Each of them is a vector representing the extent of damage, usually in terms of stiffness loss (a real number between 0 and 1), in each candidate damage location. The features used to identify the damage strongly affect the quality of the results. For a review of the most popular criteria see [17]. Genetic algorithms and particle swarm algorithms were largely used, but, many other metaheuristics were applied to damage identification problem and, in general, all the nature inspired optimization algorithms developed so far are suitable for this task. Applications showed promising results, even though, most of them resort to models with small number of elements, synthetic target data or small scale laboratory tests, leaving some doubts regarding the scalability. Analyzing real complex buildings requires robust methods tested on large scale case studies. An interesting solution for large structures consists of dividing the system in substructures and introducing a multistage approach: a first step, to find the damaged area, through a coarse mesh, refined, in the second step, only in that neighborhood [5]. Robustness is further increased through multi-objective optimization reducing the sensibility to the sources of error [5,18].

## 4. SHM of historical buildings

Cost-effective management and maintenance of built heritage are essential tasks due to many factors as historical interest, cultural identity, environmental and economic benefits. Minimum repair and non-intrusiveness are widely shared keynotes of conservation of built heritage, adopted in a step-by-step procedure of structural assessment, whose main aspects are collecting information on geometry and materials, identifying extent and causes of the damage and designing remedial measures. As it is common in Civil Engineering, safety evaluation mostly relies on numerical analysis, such as Finite Element models, but historical buildings are usually composed of different structural techniques and materials strongly inhomogeneous with non-linear behavior. They have complex geometry and suffered several unknown events and interventions along the time. Therefore, the modelling of such structures is extremely challenging, leaving a high degree of uncertainty, and model validation is still an open issue, which strongly affects the reliability of extremely refined and non-linear models allowed by the improvement of computational power [1].

SHM techniques are easily integrated in this process as non-destructive approaches to the diagnosis and control of buildings. A review of SHM of historical building appears in [19]. Several SHM frameworks for historical buildings are proposed by different authors and applications led to successful results, as in the case of the Church of Monastery of Jerónimos in Lisbon [20]. Operational Modal Analysis (OMA) not only has a minimum incidence on preservation and intervention costs but also it allows a better organization of these activities through prevention and prioritization. Furthermore, exploiting output-only measurement, it fulfills the main requirements of conservation having a minimum interference with the use of the monitored system and its safety [21]. Modal properties, extracted from vibration measurement, provide an effective way to achieve model validation through calibration, as it was recently performed in the analysis of the tower of the University of Coimbra [22]. Such optimization process requires the development of a mock-up numerical model able to represent the building, providing a structural response close to the experimental one. Several parameters can be selected as design variables. The distance between measured and predicted features' values is the objective function whose global minimum corresponds to the best tuning of the variables. It is always essential to evaluate the physical meaning of the outcomes since optimization is only a numerical procedure without a physical interpretation and comprehension of the real problem faced, except for the definition of a reasonable design variable domain. Damage identification is based on the same model updating process, where the damage is introduced as a reduction of the properties (mass, section or stiffness). Among the nature-inspired methods, genetic algorithms were successfully applied to model updating of complex case studies as a group of historical buildings in Cadiz [23] or the church of Anime Sante in L'Aquila, which includes collapsed and damaged areas, as part of a sensitivity-based approach to calibrate different properties in different zones of the building [24]. Historical structures, in fact, are often composed of flexible (towers, vaults, arches) and stiff bodies (massive walls) which interact in a complex way and, in some cases, extremely damaged and/or collapsed parts coexist with healthy or even strengthened parts [24]. In these situations, the performance of the monitoring system largely depends on the quality of the network design, in terms of density, distribution or sensor placement and hardware sensitivity. As stated above, network design can be improved through optimization techniques and application of genetic algorithms to OSP exist [21,25,26,27]. Genetic algorithms usually outperform traditional methods, as confirmed by a comparison on a historic swing bridge in [21]. The network can be further improved by optimizing the identification of modal characteristics under different damage-scenarios. This strategy, adopted in the case of the Hall C of Turin Exhibition Centre, allows an early and clean identification of emerging damage, adding sensors to a basic setup or organizing in a more rational way the instruments available [25]. Damage in historical structures, especially in masonry, can occur as localized cracking or diffuse material deterioration. Model-based techniques demonstrate to be reliable for discrete, localized damages but diffuse effect of aging or plasticity is hard to identify, especially when global low frequency modes are used as target. Therefore, the methodologies introduced in the previous section are not common in preservation yet. Even though, there exist typical situations of localized cracks in built heritage, like in masonry arches [28]. Genetic algorithms demonstrated to be able to identify critical load condition and real damage scenario, in terms of hinge location, in a masonry bridge [29] and weakest parts and connections in monuments subdivided in macro-elements [26]. Despite the small number of papers devoted to the topic, the advantages of nature-inspired optimization algorithms showed in the previous sections recommend a successful application to historical building conservation. In order to achieve that, a general framework for safety assessment of building is suggested (fig. 1). The same multi-objective nature-inspired optimization algorithm is applied to more sequential problems only changing inputs and definition of the objective functions. First, the OPS is solved using a preliminary model which is then updated minimizing the differences between experimental and numerical response. Therefore, safety assessment of the building can be carried out through a complete structural analysis using the validated model. Finally, combining the data from a continuous monitoring and the model based approach damage is identified in real time. When a sudden change in the data provided by the SHM system emerges, the model updating process explores numerically possible damage scenarios (variations in the design variables) to locate and quantify the damage in the structure. Model updated with the damage scenario can be used again for structural analysis.

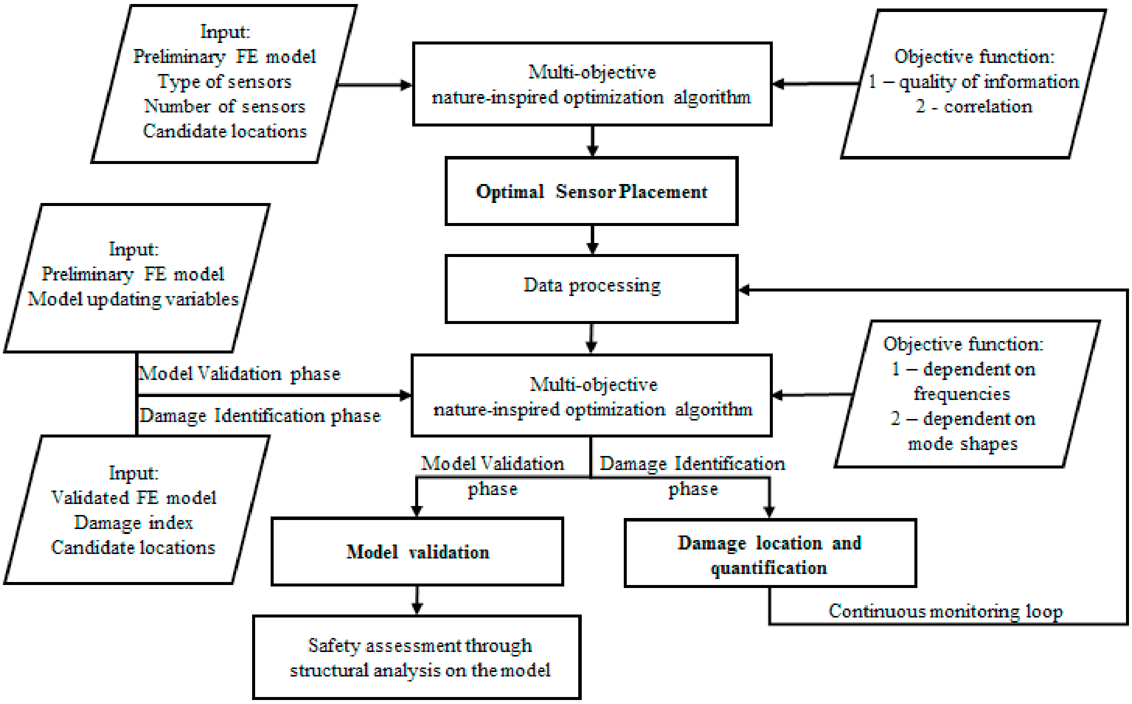


Fig. 1. Framework for SHM of existing structures through multi-objective optimization algorithm.

## 5. Conclusion

The paper has investigated the application of Natural Computing Optimization Algorithms to Optimal Sensor Placement (OSP), model updating and Damage Identification (DI) for historical buildings preservation. Promising outcomes of such techniques are summarized as well as shortcomings are highlighted and discussed.

Nature-Inspired Metaheuristics are global optimization methods suitable to OSP, model updating and Model-Based DI, all constraint black box problems, even of complex large historical buildings like monuments, with reduced information affected by different sources of error, thanks to multi-objectives formulation and decomposition in sub-structures. Model Based DI is reliable in locating and quantifying localized discrete damages, but characterizing a general diffuse deterioration is still an open issue. Despite that, the few applications existing in literature showed promising results in the identification of weakest macro-elements and localized cracks.

Finally, a framework for SHM which uses a single multi-objective optimization algorithm in a continuous process of safety assessment and DI for existing buildings is suggested. Such framework, still under development and analysis, combines more sequential problems, from the sensor network design to the diagnosis of the structure, only changing inputs and definition of the objective functions, providing a useful tool for automating the preservation of historical buildings.

## Acknowledgements

This work was financed by FEDER funds through the Competitiveness Factors Operational Programme - COMPETE and by national funds through FCT – Foundation for Science and Technology within the scope of the project POCI-01-0145-FEDER-007633.

## References

[1] P. B. Lourenço, L. F. Ramos, Recent developments in vibration analysis of historic and masonry structures: damage detection and wireless sensor networks, in EVACES'11: experimental vibration analysis for civil engineering structures (2011).
[2] L. N. de Castro, Fundamentals of natural computing: an overview, Physics of Life Reviews 4 (2007) 1-36.
[3] K. Sörensen, Metaheuristics—the metaphor exposed, International Transactions in Operational Research 22 (2015) 3-18.
[4] R. Perera, S.E. Fang, A. Ruiz, Application of particle swarm optimization and genetic algorithms to multiobjective damage identification inverse problems with modelling errors, Meccanica 45.5 (2010) 723-734.
[5] R. Perera, A. Ruiz, A multistage FE updating procedure for damage identification in large scale structures based on multiobjective evolutionary optimization, Mechanical Systems and Signal Processing 22.4 (2008) 970-991.
[6] T.H. Yi, H.N. Li, Methodology Developments in Sensor Placement for Health Monitoring of Civil Infrastructures, International Journal of Distributed Sensor Networks 2012 (2012).
[7] J. Lian, L. He, B. Ma, H. Li, W. Peng, Optimal sensor placement for large structures using the nearest neighbour index and hybrid swarm intelligence algorithm, Smart Materials and Structures 22.9 (2013).
[8] T. You, H. Jin, P. Li, Optimal Placement of Wireless Sensor Nodes for Bridge Dynamic Monitoring Based on Improved Particle Swarm Algorithm, International Journal of Distributed Sensor Networks 2013 (2013).
[9] G.-D. Zhou, T.H. Yi, H.N. Li, Sensor Placement Optimization in Structural Health Monitoring Using Cluster-in-Cluster Firefly Algorithm, Advances in Structural Engineering 17.8 (2014) 1103-1115.
[10] H. Sun, O. Büyüköztürk, Optimal sensor placement in structural health monitoring using discrete optimization, Smart Materials and Structures 24 (2015).
[11] H. Jin, J. Xia, Y.Q. Wang, Optimal sensor placement for space modal identification of crane structures based on an improved harmony search algorithm, Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering) 16.6 (2015) 464-477.
[12] T.-H. Yi, H.N. Li, C.W. Wang, Multiaxial sensor placement optimization in structural health monitoring using distributed wolf algorithm, Structural Control Health Monitoring 23 (2016) 719-734.
[13] L. He, J. Lian, B. Ma, H. Wang, Optimal multiaxial sensor placement for modal identification of large structures, Structural Control and Health Monitoring 21.1 (2014) 71-79.
[14] J. Jia, S. Feng, W. Liu, A triaxial accelerometer monkey algorithm for optimal sensor placement in structural health monitoring, Measurement Science and Technology 26 (2015).
[15] X.-H. Zhang, Y.-L. Xu, S. Zhu, S. Zhan, Dual-type sensor placement for multi-scale response reconstruction, Mechatronics 24.4 (2014) 376-384.
[16] C. R. Farrar, K. Worden, An introduction to structural health monitoring, Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences 365.1851 (2007) 303-315.
[17] W. M. Ostachowicz, M. Krawczuk, M. P. Cartmell, Genetic algorithms in health monitoring of structures, Lecture Notes-AMAS (2001).
[18] S. Jung, S. Ok and J. Song, Robust structural damage identification based on multi-objective optimization, International Journal for Numerical Methods in Engineering 81.6 (2010) 786-804.
[19] F. Ubertini, G. Comanducci, N. Cavalagli, A. L. Pisello, A. L. Materazzi, F. Cotana, Environmental effects on natural frequencies of the San Pietro bell tower in Perugia, Italy, and their removal for structural performance assessment, Mechanical Systems and Signal Processing 82 (2016) 307-322.
[20] M.G. Masciotta, J. C. Roque, L. F. Ramos, P. B. Lourenço, A multidisciplinary approach to assess the health state of heritage structures: The case study of the Church of Monastery of Jerónimos in Lisbon, Construction and Building Materials 116 (2016) 169-187.
[21] G. Quaranta, G. C. Marano, F. Trentadue, G. Monti, Numerical study on the optimal sensor placement for historic swing bridge dynamic monitoring, Structure and Infrastructure Engineering, 10.1 (2014), 57-68.
[22] E. Júlio, C. Rebelo, D. Dias-da-Costa, Structural assessment of the tower of the University of Coimbra by modal identification, Engineering Structures, 30.12 (2008) 3468–3477.
[23] P. Pachón, V. Compán, E. Rodríguez-Mayorga, A. Sáez, Control of structural intervention in the area of the roman theatre of Cadiz (Spain) by using non-destructive techniques, Construction and Building Materials 101 (2015), 572-583.
[24] G. Boscato, S. Russo, R. Ceravolo, L. Z. Fragonara, Global sensitivity-based model updating for heritage structures, Computer-Aided Civil and Infrastructure Engineering 30.8 (2015), 620-635
[25] E. Lenticchia, R. Ceravolo, C. Chiorino, Damage scenario-driven strategies for the seismic monitoring of XX century spatial structures with application to Pier Luigi Nervi's Turin Exhibition Centre, Engineering Structures, 137 (2017) 256-267.
[26] R. Ceravolo, G. Pistone, L. Zanotti Fragonara, S. Massetto, G. Abbiati, Vibration-Based Monitoring and Diagnosis of Cultural Heritage: A Methodological Discussion in Three Examples, International Journal of Architectural Heritage, 10.4 (2016) 375-395.
[27] R. Ceravolo, G. De Lucia, M. Pecorelli, L. Zanotti Fragonara, Monitoring of historical buildings: project of a dynamic monitoring system for the world's largest elliptical dome, in IEEE Workshop on Energy and Structural Monitoring Systems (EESMS) (2015).
[28] L. F. Ramos, G. De Roeck, P. B. Lourenço, A. Campos-Costa, Damage identification on arched masonry structures using ambient and random impact vibrations, Engineering Structures 32.1 (2010) 146-162.
[29] B. Conde, G. Drosopoulos, G. Stavroulakis, B. Riveiro, M. Stavroulaki, Inverse analysis of masonry arch bridges for damaged condition investigation: Application on Kakodiki bridge, Engineering Structures 127 (2016) 388-401.