# A State-of-the-Art Review of Nature-Inspired Systems for Smart Structures

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**Abstract.** Since the dawn of humanity, nature has been a source of inspiration for developing engineering systems, referred to as "nature-inspired systems". With respect to smart structures instrumented with smart structural health monitoring (SHM) systems, nature-inspired systems may provide promising advancements, for example, by executing self-healing or self-diagnosing processes. However, for developing optimum strategies towards deploying nature-inspired systems to smart structures, the plenitude of nature-inspired systems in SHM need to be classified. This paper aims at reviewing the potential of nature-inspired systems to advance the performance of smart structures. Upon a brief introduction to smart structures and nature-inspired systems, a state-of-the-art review of nature-inspired systems that exhibit potential to advance smart structures is presented, providing decision support on how to advantageously apply the benefits of nature-inspired systems to smart structures.

**Keywords:** Structural health monitoring (SHM) · Smart monitoring · Smart structures · Nature-inspired systems · Biologically inspired systems

## 1 Introduction

Since the beginning of humanity, nature has been a source of inspiration for developing engineering systems, such as airplanes or submarines, leading to an area of research, referred to as "nature-inspired systems", operating across the border between living and non-living systems [1]. In the last decades, the field of structural health monitoring (SHM) has been adapting the advantages of nature-inspired systems, also known as "biomimicry", e.g. for optimal sensor placement or for identifying and localizing damage in structures [2]. The naturally optimized performance keeps on inspiring the development of nature-inspired systems that may potentially outperform conventional systems. Also, for adaptive or "smart" structures instrumented with smart SHM systems, nature-inspired systems have provided advancements, for example, by autonomous, self-managing SHM systems that are capable of self-configuration, self-healing, self-optimization, and self-protection [3].


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Smart structures present a novel engineering approach that integrates sensors and actuators into systems able to dynamically respond to environmental changes. In this regard, self-healing, self-diagnosis, and self-control are some of the characteristics anticipated to be features of smart systems and technologies [4].

Although considerable advancements of nature-inspired systems for smart structures have been made [5], smart monitoring processes still suffer from several limitations, e.g. related to sensory overload, data compression, data transmission, or energy consumption [6]. To overcome current limitations and to effectively drive new scientific and technological breakthroughs in nature-inspired smart structures, the variety of nature-inspired systems in smart monitoring needs to be reviewed and classified.

This paper, based on a classification of SHM processes relevant to smart monitoring and nature-inspired systems, presents a review of nature-inspired systems for smart structures. Due to the large number of reviews on artificial intelligence in SHM, neural networks are not considered in this paper. In what follows, an overview of the SHM processes relevant to smart monitoring and a broad classification of nature-inspired systems, including nature-inspired algorithms, is provided. Subsequently, work on nature-inspired systems in the field of smart structures is reviewed. Finally, the results of the review and possible future trends of nature-inspired systems for smart structures are discussed, and main conclusions of the work are summarized.

## 2 Smart Monitoring

Smart monitoring is a paradigm essential to smart structures, which is materialized through smart SHM systems, representing an integral tool for assessment and quality assurance of structures throughout the lifecycle. The long-term, systematic use of reliable sensor and measurement techniques, as well as appropriate data analysis methods, helps significantly (i) evaluate and ensure the health and safety of structures, (ii) repair damage duly, and (iii) calculate the financial expenses for structural and building maintenance due to aging, changes in use, or cumulative environmental influence. Smart SHM systems should support the following SHM processes.

i. *Data acquisition* employs data acquisition units, e.g. data loggers or wireless sensing units, for recording data through sensors, while accomplishing pre-processing sub-processes, such as fault diagnosis or plausibility checks.
ii. *Data communication* refers to wireless or cable-based transmission of the (pre-processed) data recorded by the data acquisition units or wireless sensor nodes through one or more base stations to a central computing unit.
iii. *Data processing* includes extracting, transforming, and loading (ETL) the heterogeneous sensor data, probably applying normalizing, cleansing and compressing techniques, to prepare the data for data storage.
iv. *Data storage* denotes persistent storage of the data, applying data archival and data management sub-processes.
v. *Data analysis*, representing one of the most relevant processes in SHM, is devised for interpreting the data and transforming the data into information, in an attempt to accomplish, e.g., condition assessment, damage diagnosis and prognosis, or life-cycle management.

vi. *Data and information retrieval* allows retrieving data and information gained in the previous process for further processing and analysis.

The recent technological advancements have enabled smart SHM systems carrying out the SHM processes mentioned above (largely) autonomously. Most smart monitoring approaches are based on data acquisition units that embody wireless communication and dedicated computing components on board, thus providing relatively inexpensive sensor platforms with distributed and autonomous data acquisition nodes not physically linked [7]. Despite the benefits, several challenges mainly associated with wireless telemetry still remain unsolved, e.g., the power consumption of batteries, time synchronization of sensors, long-range communication, lossless data compression, and reliable transmission [8].

To overcome the challenges in smart SHM systems, nature-inspired systems are increasingly deployed to accomplish the SHM processes. In the following section, the SHM processes described above are taken as a conceptual basis to elucidate recent developments in nature-inspired systems relevant to smart structures equipped with smart SHM systems.

# 3 Nature-Inspired Systems for Smart Structures

To review nature-inspired systems for smart structures, a categorization of nature-inspired systems is presented in the following subsections. The categorization of nature-inspired systems is then used to review state-of-the-art applications of nature-inspired systems, following the SHM processes presented above.

## 3.1 Categorization of Nature-Inspired Systems

Nature-inspired computing involves extracting ideas from nature to develop artificial systems. Research on nature-inspired systems entails efficient computational tools with enhanced flexibility, robustness, and scalability, as compared to traditional tools. Nature-inspired computing is divided into the three categories listed below [9, 10]. In the remainder of this paper, the categories are used as a basis for the review.

i. *Computing inspired by nature (CIN)* uses natural phenomena to develop computational algorithms for designing problem-solving techniques and is categorized into neurocomputing, evolutionary computing, computing inspired by swarm intelligence, and immune computing.
ii. *Simulating and emulating nature through computing (SENC)* describes a synthetic process that aims at creating patterns, forms, behaviors, and organisms to mimic natural phenomena. SENC includes artificial life techniques and tools for studying the fractal geometry of nature.
iii. *Computing with natural materials (CNM)* is a nature-inspired computing category that takes advantage of phenomena observed in natural materials to create new concepts for computational processes, e.g. deoxyribonucleic acid (DNA) computing and quantum computing.

### 3.2 Nature-Inspired Systems for Smart Monitoring

For smart structures, nature-inspired systems may provide significant advancements, e.g. by executing self-healing or self-diagnosing processes. The nature-inspired systems are reviewed according to the SHM processes presented in the previous section.

**Nature-Inspired Systems for Data Acquisition.** Several nature-inspired systems have been proposed for determining optimal sensor placements, which is an integral part of data acquisition. For example, evolutionary algorithms have successfully been applied [11]. Moreover, multi-level intelligence [12] and combinations of optimization methods for sensor placement have been studied, e.g. employing multi-agent technology [13] or quantum genetic algorithms [14].

Nature has also been an inspiration for sensor design. In-situ triboluminescent optical fiber (ITOF) sensors for SHM of composite and concrete structures have been proposed in [15]. The design of ITOF sensors has been inspired by the biomimetics of the human nervous system. The ITOF concept allows converting energy from damage events into optical signals indicating the magnitude of the damage. To overcome limitations with respect to energy consumption, a biologically inspired poly (3-hexylthiophene)-based sensor has been developed that allows generating electric current due to lighting [16].

Based on the inspiration of natural species, such as geckos that may move in vertical walls by exploiting negative pressure, a mobile, flexible sensing system has been proposed, able move on vertical surfaces based on piezoelectric wafers [17]. Another approach, studied in [18], has been taking inspiration from the sensitivity of the inner ear of fish to perceive feeble and low-frequency motion; for designing ultra-sensitive, low-frequency sensors deployed to monitor civil structures and establish early-warning systems, the mechanical-electricity transduction of hair cells has been simulated.

For SHM of composite materials, physically inspired, embedded quantum-resistant sensors (QRS) have been proposed that monitor strain and damage [19]. The resistance drift of the QRS occurs during structural loading and is related to the damage initiation of a structure. In [20], the memory effect of the resistance of embedded QRS has been used to quantify damage accumulation in glass-fiber-reinforced polymers.

For developing smart structures, attention has recently been drawn on material able to autonomously sense the material state and to report damage [21]. So-called "self-sensing" (or "self-reporting") material transfers the damage-sensing concepts known from nature to materials sciences. Damage and deformation of polymeric material, in analogy to the warning signals of bleeding wounds, can be visualized by changes in color, in fluorescence, or in the production of luminescence. A review of self-reporting composites may be found in [22]. Facilitating damage detection in materials, so-called quantum dot (QD) material has been proposed. QD material is surface-modified, i.e. the QD surface becomes compatible with cement-like material made from a water-based component. QD solutions have been tested for crack monitoring in cement-based materials [23]. Also inspired by quantum properties, a sensor that records mechanical stress has been proposed in [24], able to visualize changes in mechanical stress by changing based on changes in the photoluminescence of the quantum dots.

**Nature-Inspired Systems for Data Communication.** The primary challenge in data communication, besides ensuring reliable data transmission, is the aggregation of data to reduce the quantities to be transferred. Regarding wireless systems, for efficiently utilizing the power sources of wireless sensor nodes, biologically inspired systems have been proposed in [25] for sensor node localization and for grouping of sensor nodes to advance collaborative processing within sensor networks depending on the energy level of the sensor nodes.

By exploiting ant colony behavior, a clustering strategy for data communication in wireless sensor networks has been proposed in [26]. Through adapting swarm behaviors, precisely separation and alignment, it has been demonstrated that energy consumption in data communication in monitoring applications may be reduced. Also situated in the area of swarm intelligence, multi-agent technology and dynamic code migration has been proposed to facilitate wireless SHM [27]: By collective intelligence entailing emergent group behavior, an agent-based wireless SHM system allows distributed information processing and agent cooperation, resulting in a decrease of wireless data transmission and memory consumption of the wireless sensor nodes.

**Nature-Inspired Systems for Data Processing.** Implementing advanced ETL techniques for intelligent data processing, multi-agent technology has been proposed in [28] to automate SHM processes in a smart SHM system of a wind turbine. To solve the data processing in a distributed-collaborative manner, the software agents communicate strictly in compliance with speech act theory, mimicking human communication. Nature-inspired data processing based on multi-agent technology has also been reported in [29], in which automated diagnostics of sensor faults in a smart SHM system are conducted by software agents. Serving as “personal assistants” to the human individuals involved in SHM, the software agents autonomously create safety reports summarizing the data processing results, to be sent to the human individuals by email or by text messages.

**Nature-Inspired Systems for Data Storage.** To overcome data storage bottlenecks in long-term SHM systems, a memory model embedded with causality reasoning functions for structural fault location has been presented in [30]. The memory model has been inspired by the (temporal) human memory and the causal relationships observed in structural fault processes. Moreover, a mechanism of causality reasoning has been developed for locating faults in SHM systems. Similarly, a memory model has been developed following the human recognition function to identify and to discard redundant SHM data [31]. Furthermore, the model utilizes the recall function of the human memory to restore monitoring data that has mistakenly not been recorded, e.g. due to faulty sensors. For autonomous intelligent mining of SHM data, a memory model with short-term and long-term memory has been reported in [32]. In the memory model, abnormal signals go into the short-term memory for real-time assessment, while normal signals go into the long-term memory, serving as a basis for information on the structural state

**Nature-Inspired Systems for Data Analysis.** For damage detection, which is among the most important data analysis goals, the concept of gene expression monitoring has been applied [33]. Following this study, the naïve Bayes (NB) algorithm has been proposed in [34] to identify and classify the DNA array of cells. By employing array expression data, a biologically inspired two-mode SHM system has been developed in

[35]. Based on the type of vibration, either strong ground excitation or ambient vibration, the array has been analyzed using the NB classification method to detect damage. Also, in combination with self-healing materials for SHM, researchers have developed damage detectors that, applying nature-inspired data analysis, may autonomously trigger healing. In [36], multi-cycle-triggered healing of nanocomposites through an external alternating magnetic field (AMF) has been proposed. The AMF triggers the heating of magnetic nanoparticles filler, entailing shape recovery and subsequent healing. A biologically inspired microvascular healing network has been studied in [37], which senses structural damage before initiating a triggered healing response to damage formation in composite material.

In [38], two biologically inspired optimization methods, the artificial bee colony and the firefly algorithm, have been employed and compared with respect to the damage detection performance. Drawing from current trends in quantum-inspired methods, [39] have proposed a mobile impact testing method for structural flexibility identification. Optimization is accomplished by a quantum-inspired genetic algorithm (QIGA), a probabilistic evolutionary algorithm that embeds quantum computation into the genetic algorithm. A quantum genetic algorithm has also been used in [40] to optimize parameters of a least square support vector machine aiming to detect damage in glass fiber structures. Moreover, an inverse damage detection problem has been set up as an optimization problem and solved by a quantum particle swarm algorithm [41].

Finite element (FE) model updating is an SHM practice well-established since decades and continuously being enhanced, which ensures, based on SHM data, keeping the FE model in compliance with the real structural condition [42]. For model updating, nature-inspired algorithms have been used, e.g. particle swarm optimization and genetic algorithms [43]. Also, a firefly algorithm has been proposed in [44] to solve the model updating problem. The algorithm has been inspired by the flashing characteristics of fireflies, with each firefly representing a randomly generated solution. Individual brightness is assigned to each solution according to the value of the objective function.

**Nature-Inspired Systems for Data Retrieval.** A variety of nature-inspired systems for data and information retrieval applications have been applied, e.g. for text summarization, data classification (clustering), data scaling, and data representation. While nature-inspired systems for data and information retrieval applications in smart monitoring have received little attention so far, a general overview of nature-inspired systems for data and information retrieval may be found in [45].

## 4 Results and Future Trends

The results of the review are summarized in Fig. 1, which provides an overview of nature-inspired systems for smart structures. As can be seen from Fig. 1, the nature-inspired systems are assigned to the SHM processes, with the thickness of the lines connecting a nature-inspired system with an SHM process denoting the quantity of papers. In summary, for *data acquisition*, including sensing, particular focus of the community has been put on nature-inspired systems for optimal sensor placement and sensor design (specifically sensor design for damage detection). To advance energy consumption in *data communication* and *data processing*, swarm intelligence and combinations with multi-agent technology have been proposed. For *data storage*, comprehensive memory models inspired by the human memory have been presented. Most nature-inspired research aiming to improve the SHM processes has been devoted to *data analysis*, and, besides optimization techniques, nature-inspired systems for damage detection, damage diagnosis, as well as self-healing materials have been proposed. Last, but not least, nature-inspired systems for *data retrieval* have been studied, with limited focus, however, on SHM processes or smart structures in particular.

In conclusion, current and emerging application areas of nature-inspired systems for smart structures may be found in

i. Smart materials (e.g. applying self-healing and self-reporting processes of humans/animals, or artificial immune systems),
ii. Smart sensors (e.g. using swarm intelligence, quantum computing, behavior of natural species, or neurocomputing), and
iii. Smart data processing and data storage (e.g. based on memory models, human speech acts, or swarm intelligence).

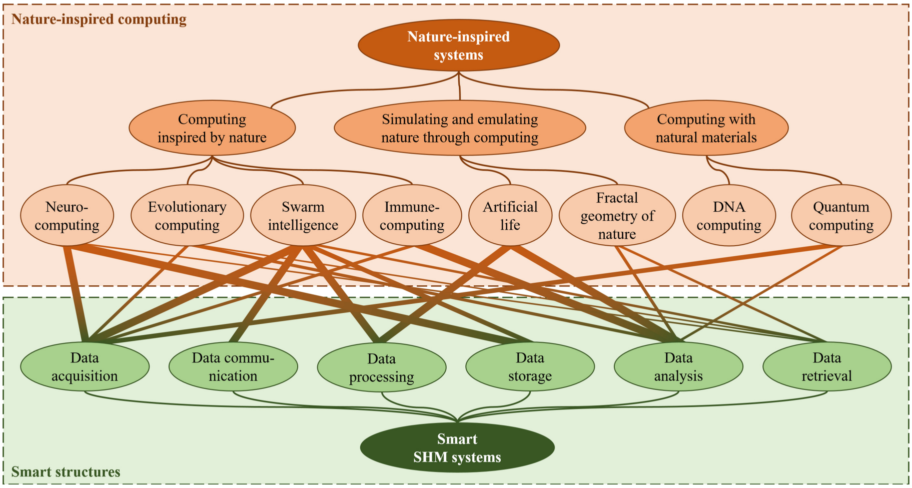


**Fig. 1.** Nature-inspired systems for smart structures.

## 5 Summary

Engineering systems are inspired by the diversity of natural processes, referred to as "nature-inspired systems". The inherent limitations of current SHM technologies have encouraged the civil engineering community to explore new SHM paradigms in an attempt to advance to the current state-of-the-art technologies applied for executing the SHM processes. This paper has summarized the state of the art in nature-inspired systems showing potential to be deployed to smart structures. Based on the review presented in this paper, prospects of nature-inspired systems for smart structures and trends in research have been presented, providing an overview of how to advantageously apply the benefits of nature-inspired systems to smart structures. As can be concluded from the state-of-the-art review, nature-inspired systems may provide significant benefits to smart structures in all SHM processes, i.e. data acquisition, data communication, data processing, data storage, data analysis as well as data and information retrieval. Promising nature-inspired approaches and techniques to advance smart structure include, e.g., self-healing processes of humans and animals, swarm intelligence, quantum computing, artificial immune systems, central nervous systems, and artificial memories. It is expected that future smart structures implement the vision of self-configuring, self-healing, self-optimizing, and self-protecting structures.

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