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# Bio-inspired self powered nervous system for civil structures

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**Abstract.** Globally, civil infrastructures are deteriorating at an alarming rate caused by overuse, overloading, aging, damage or failure due to natural or man-made hazards. With such a vast network of deteriorating infrastructure, there is a growing interest in *continuous monitoring* technologies. In order to provide a true distributed sensor and control system for civil structures, we are developing a Structural Nervous System that mimics key attributes of a human nervous system. This nervous system is made up of building blocks that are designed based on mechanoreceptors as a fundamentally new approach for the development of a structural health monitoring and diagnostic system that utilizes the recently developed piezo-fibers capable of sensing and actuation. In particular, our research has been focused on producing a sensory nervous system for civil structures by using piezo-fibers as sensory receptors, nerve fibers, neuronal pools, and spinocervical tract to the nodal and central processing units. This paper presents up to date results of our research, including the design and analysis of the structural nervous system.

**Keywords:** bio-inspired systems; structural nervous system; neuro-fuzzy inference engine; structural health monitoring.

## 1. Introduction

New civil engineering construction is the largest industry in the world, accounting for more than 10% of the world's gross domestic product (GDP). Civil infrastructure systems are generally the most expensive investment and assets in any country. In the USA, this asset is estimated to be about $20 trillion. Over the last century, the United States has invested a significant amount of capital into developing and maintaining the nation's infrastructure in the form of roadways and bridges. However, this infrastructure is deteriorating at an alarming rate due to material or system deterioration caused by overuse, overloading, aging, damage or failure caused by external loads such as natural or man-made hazards (Lim, *et al.* 2003).

The National Bridge Inventory indicates that more than 104,000 bridges are rated as structurally deficient (Liu, *et al.* 1993) and even greater numbers have damage patterns that are yet undetected and pose a mounting risk to public safety (Small and Cooper 1998). The recent collapse of the Minneapolis Bridge is a great example of the degree of urgency of this matter. With such a vast network of deteriorating infrastructure, there is a growing interest in continuous monitoring technologies. The

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importance of understanding and predicting damage in civil structures is underscored by the economic losses incurred by recent seismic events: 2005 hurricane that devastated the Golf Coast states of US, the destructions caused by the 2004 Sonoma in South East Asia, the 2002 Bam earthquake with thousands of loss of life and millions of dollars of damage; the 1994 Northridge earthquake with over $20B damage; and the 1995 Kobe earthquake with over $100B damage. What is even more ambiguous is that presently, there are no effective techniques to assess the safety of an infrastructure after it has experienced seismic events, tornados, fire, etc.

Although significant progress has been achieved in the area of Structural Health Monitoring (SHM) (Shoureshi 2004), there is yet to develop a robust, effective, self-contained and reliable monitoring system for civil structures. For example, after an earthquake is detected, then for safety reasons city and state regulations require electric power to be shutdown. Thus, until a self-powered monitoring system is developed, no reliable diagnostic and prognostic techniques would be effective for the emergency situations.

This paper is the result of our on-going research that has introduced a new and innovative idea for the design of a self-powered infrastructure monitoring and diagnostic system that mimics the sensory nerve system of a human body, and utilizes the topology of information processing in a human body and piezo-fibers as a building block for this nervous system. We believe that this innovative system will revolutionize the area of structural health monitoring.

## 2. State of structural health monitoring

Damage in structures can be defined as a decrease of the structural bearing capacity during their service period. This decrease is usually caused by degradation and deterioration of structural components and/or connections. Load-carrying structures such as buildings, bridges and offshore platforms continuously accumulate damage during their service life. Undetected damage may lead to structural failure and loss of human lives. It is, therefore, essential to detect damage within a structure and make appropriate repair as early as possible. The field of structural health monitoring (SHM) has experienced significant progress during the past decade (Shoureshi 2004, Straser and Kiremidjian 1996, Mal, *et al.* 2004, Casciati and Faravelli 2004, Kim, *et al.* 2004, Kurata and Spencer 2004, Ou and Li 2004, Shinozuka, *et al.* 2004).

Visual inspection is the most common method for structural damage detection, which is unreliable for complex structures because certain critical damage may occur in inaccessible areas or may be covered by paint or skin. Visual inspection cannot provide a quantitative value for the remaining strength of the structure. Other non-destructive evaluation (NDE) methods includes: radiographic, fiber optics, X-ray, acoustic emission, and ultrasonic techniques. These traditional NDE methods, however, only give the effective deterioration state of local areas and tend to be impractical for large complicated structures. Finally, none of these approaches provide a quantitative assessment of the damage magnitude.

Vibration measurements have been used for NDE. Change in structural properties due to damage subsequently affects the dynamic behavior of structures. It is, therefore, natural to use the measured changes in dynamic behavior for the identification of structural damage. By using the vibration-based methods, damage can be detected in a global sense even when the location of damage is inaccessible (Straser and Kiremidjian 1996). Although successful applications have been developed recently, the damage assessment of complex structures such as buildings and bridges remains a challenging task for civil engineers.

As the development of wireless sensors becomes more rapid and the price of this technology is decreasing, most of the structural health monitoring architecture is now geared toward the utilization of distributed wireless sensor. Lynch (2004) describes the concept of intelligent wireless sensors that can be further extended to include actuation capabilities. In his research, the design of a wireless sensing unit that has the capability to command active sensors and actuators is applied for structural monitoring applications. With high-order vibration modes of structural elements exhibiting greater sensitivity to damage than global structural modes, wireless active sensors can play a major role in a structural health monitoring system because they are capable of exciting high-order modes. Han (2004) has developed an infrastructure monitoring technique that addresses the specific issue of incorporating internet-technology into structural health monitoring. Han's approach has been applied to several case studies, including two bridges and a statue.

On the sensors side, applications of fiber optic and micro-electromechanical systems are the current state of the art for SHM. Gheorghiu (2004) has studied the application of fiber optic sensor (FOS) for SHM. FOS capability of reading various parameters is a promising candidate for life-long health monitoring of these structures. Rivera (Han 2004) introduced the term Civionics, which involves the application of electronics to civil structures and aims to assist engineers in realizing the full benefits of structural health monitoring (SHM).

MEMS (micro-electromechanical systems) research on inertial sensors has focused primarily on accelerometers and gyroscopes (Rivera 2004). The lightweight and miniature size of MEMS-based sensors has advantage in the power consumption, survivability, and cost reduction of a SHM system. Iwasaki (2004) has developed a new statistical diagnostic method for structural damage detection. In his work, system identification using a response surface is performed and damage is diagnosed by testing the change of this identified system by statistical test.

### *2.1. Technical background*

The autonomous state awareness of biological systems can be attributed directly to the inherited nervous system, which is built into the materials at cell level. Neurological system consists of networks of millions of neurons for sensing (sensory neuron) and actuation (motor neuron) along with locally distributed as well as centralized units for signal processing to provide the first defense through sensing to recognition. The state awareness of biological system depends upon the effectiveness of the neurological network to sense, detect and recognize external stimuli or threats or the changes of environment and to adjust the physiological state in a timely manner. Millions of Mechanoreceptors, built in a human skin, are able to detect exogenous thermal and mechanical excitations and inform the human nervous system about such external inputs. In comparison, current structural materials do not have any capabilities close to what the biological systems have and are capable of doing. For this research, we have examined and attempted to understand some of the intricacies of the human sensory and nervous system. The Human Body contains an incredible sensory system, information transfer mechanism, and sensory information processing unit (brain). Sensations in the human body occur when external stimuli interact with sensory receptors. Sensory information is conveyed to the brain as trains of action potentials traveling along individual sensory neurons, with pools of neurons acting together. To savor the richness and diversity of perception, the central nervous system must integrate the activity of an entire sensory population. Among five basic types of sensory receptors in the human body, mechanoreceptors detect mechanical compression and stretching of the receptor, or of tissues adjacent to the receptor.

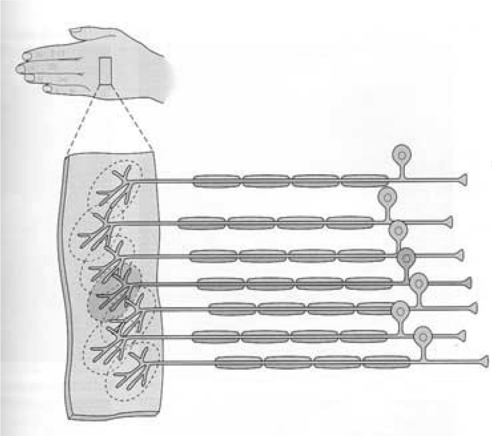


Fig. 1 Structural basis of receptive field of mechanoreceptors (Kandel, *et al*. 2000)

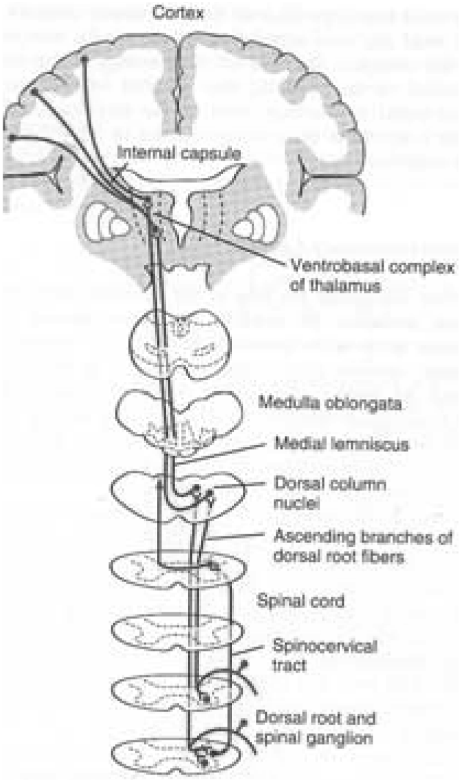


Fig. 2 Medial lemniscal pathway for transmitting critical types of tactile signals to brain (Guyton and Hall 2000)

Consider the receptive field of touch-sensitive neurons that is composed of sensory transduction apparatus in the nerve terminals, as shown in Fig. 1 When a field is externally excited, pulses are initiated at the nodes and conduct the signal to the cell body (located in the dorsal root ganglion), thereafter to the synthetic terminals in the spinal cord, and eventually to the brain, as shown in Fig. 2. What is fascinating in a biological system is its integrated and distributed sensing, data processing, and actuation mechanisms. In order to develop building blocks analogous to those of natural systems, two alternatives were considered: biologically-based Forisomes, and flexible piezo-fibers.

With the discovery of the plant-protein forisomes (Knoblauch, *et al.* 2003, Pickard, *et al.* 2005, Shen, *et al.* 2005), a novel, non-living, smart, ATP-independent biological material capable of sensing and actuating has become available. Forisomes underlie the stopcock blockade of pressure-driven mass flow in the phloem of higher plants and act as "wound healers" of the plant world. The in-vitro studies of forisomes show that, by the application of a pH and calcium concentration shift, forisomes (1-3 μm wide and 10-30 μm long) can be repeatedly stimulated to contract and expand anisotropically and swiftly (on the order of ms) by some 30% strain along its longitudinal axis while its radial axis increases by more than 200% strain. Forisomes exert similar mechanical forces in expansion and contraction with a minimum of 0.10 N. Further, no functional metabolic apparatus is required for forisome-based smart actuation. While these features make forisomes a prime candidate for the building blocks for sensors, and actuators in structures, there have been difficulties associated with their stability and operation in ambient conditions. Fig. 3 delineates Forisomes during expansion and contraction modes.

The second alternative for our building blocks of the structural nervous system is flexible piezo-fibers. The curiosity research of the last decades of the 19th century created landmarks in the evolution of Modern technologies. In 1880, Jacques and Pierre Curie discovered an unusual phenomenon in certain crystals that exhibit output voltage when exposed to mechanical tension and compression, and experience mechanical strain if exposed to an electric field. Over the last century, especially during the past twenty years, the field of peizo-electric materials has experienced a tremendous growth, expansion and advancement to the point that now peizo-ceramics come in variety shapes, configurations, in terms of an electromechanical coupler for both sensing and actuation applications. Fig. 4 illustrates this variety.

One of the more recent advancement in piezo-ceramic materials has been the development and fabrication of Ceramic Fiber Reinforced Piezo (CFRP) materials (Bent, *et al.* 1995). Based on this

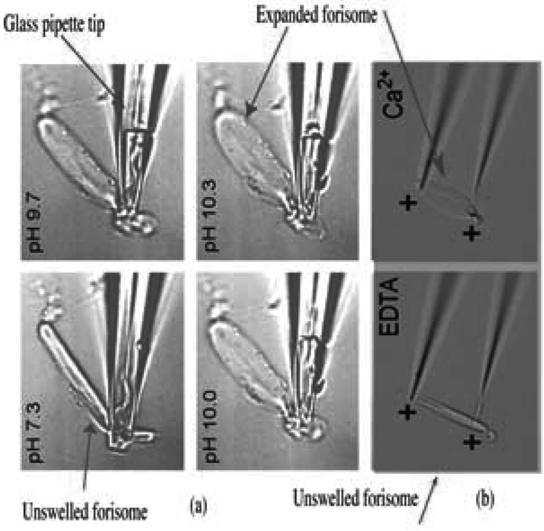


Fig. 3 Operation of a 30 μm long forisome after pH or $Ca^{2+}$ (Shoureshi and Shen 2007)

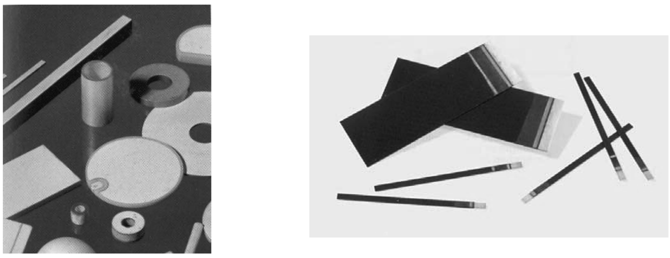


Fig. 4 Different configurations of piezo-ceramics as sensors and actuators (Henderson 2002)

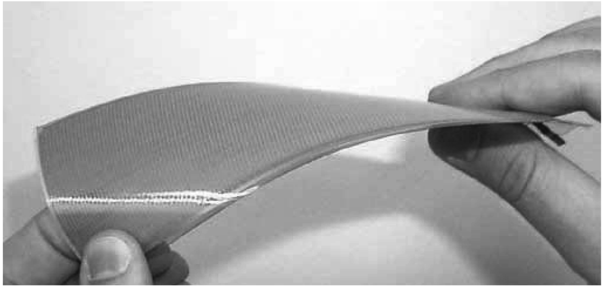


Fig. 5 Robust flexibility in piezo fiber composites (“new ceramix fiber...” 2005)

research, CFRP can be in a very thin film form composed of fibers which are transversely aligned in a polymer matrix, resulting in gain of larger strains along the fiber axis. Development of piezo fibers has opened new frontiers in acoustics, vibration control, and structural health monitoring. Given that piezo fibers are now manufactured in flexible shapes, as shown in Fig. 5, then they can be bent, flexed even over 200 million cycles without degradation in their properties.

### 2.2. Structural nervous system design

Very small size sensory layer composed of thousands of piezo fibers would be patched to the columns and beams of structures to act as both mechanoreceptors and the information nerve system of the structure, as shown in Fig. 6. Due to structural vibrations, the deformation of structural elements will excite the piezo fibers, causing them to release an electric current which in turn would stimulate the structural nerve fibers. These nerve fibers will then perform the sensation and data transfer and eventually reach the nodal processing cells (neuronal pools). This monitoring and diagnostic system will be able to operate without external power and will provide features such as fault location, severity, and spatial distribution of the damage.

This synergistic integration of piezo fibers and the nerve fibers acting as sensors/actuators, create an information architecture similar to that of the human nervous system, and the concepts from the control theory, forms the foundation of this innovative structural monitoring system. Consider a structural deformation due to a heavy load or an earthquake. With the piezo fiber-based sensory nerve system embedded within the structure (see Fig. 6), the following sequence of events would take place:

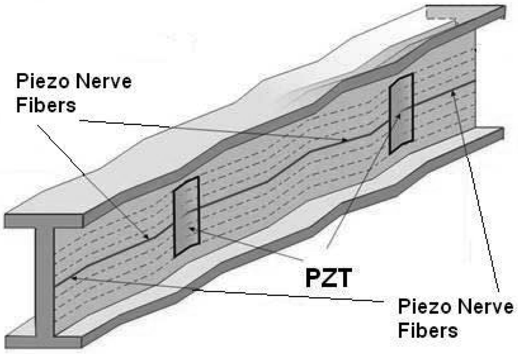
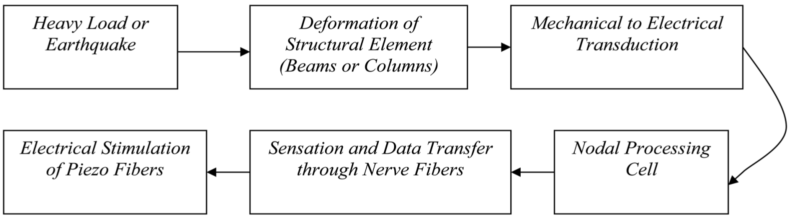
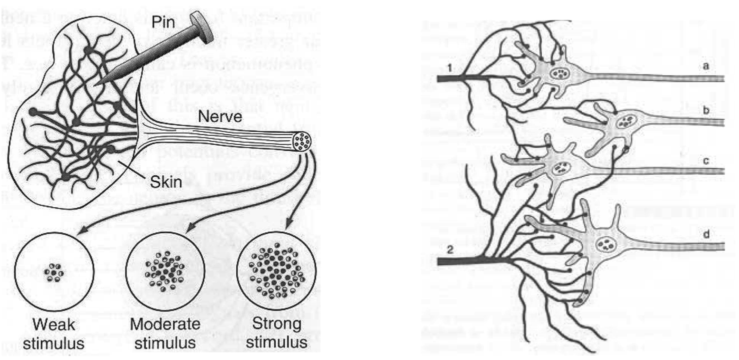


Fig. 6 Piezo fiber-based nervous system for self-powered structural diagnosis



Depending on the severity of the initial deformation of the structural element, either a few or hundreds of nerve fibers would get excited and cause further stimulation. Fig. 7 (left) illustrates the analogy of this concept with mechanorecptors of the human skin. Our structural nerve fiber will be composed of hundreds of piezo fibers placed sequentially and the degree of the excitation can be sensed by the number of the activated nerve fibers.

Following our understanding of the human nerve system, the piezo-based nerve fibers will lead into a Neuronal Pool. Fig. 7(right) depicts the neuronal pool of the human nervous system. The central nervous system is composed of hundreds, thousands, or even millions of neuronal pools. The entire cerebral cortex could be considered a single large neuronal pool. Each pool has its own special characteristics for



**(a)** **(b)**

Fig. 7 (a)-Pattern of stimulation of pain fibers in a nervetrunk due to skin pricked by a pin; (b)-Right, basic organization of human neuronal pool of central nerwous system (Guyton and Hall 2000)

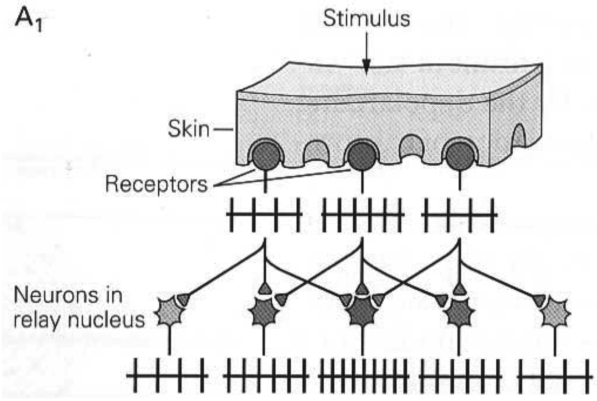


Fig. 8 Convergence of nerve fibers into smaller output fibers (Kandel, *et al.* 2000)

processing signals, thus allowing the total consortium of pools to achieve the multitude of functions of a nervous system. Each neuronal pool is composed of input fibers (left side), output fibers (right side), and a central processing unit. Our piezo-based neuronal pool is composed of a summing junction of an artificial neural network with hundreds of input piezo nerve fibers bringing in their input signals. Depending on the severity of failure or deformation, output of the artificial neuron may turn on or off, signaling the next neuronal pool about its state. This design forms the central processing unit of our piezo neuronal pool. Similar to a synaptic function of a human neuron, by selecting an appropriate clearance between each nerve fiber, and the output excitation firing function of an artificial neuron, we can define the threshold for the excitation (firing) of the neuronal pool. Therefore, going back to the initial stimulus, namely damage caused by heavy loading or earthquake on a structural component, the excitation intensity can be sensed (measured) by the degree of the firing of the neuronal pool that would be translated into the number of stimulated piezo output fibers. This approach to the development piezo-based nervous system can be converged from multiple tracks (multiple neuronal pads) into smaller and smaller output fiber nerves that eventually lead into one output fiber nerve going to the central data processing unit, very analogous to the human nervous system, as shown in Fig. 8.

### 2.3. Neural based data processing and diagnostics

Successful results of the proposed piezo fiber-based sensory nervous system will provide us signals that are correlated to the structural acceleration. The next task is to map these signals onto acceleration values that dcan be used to identify any structural damages. Given that this is an inverse nonlinear problem with some level of uncertainty due to the finite resolution of our sensory system, we propose to use a mix of neural network and fuzzy logic inference for this mapping.

Our previous research efforts (Shoureshi 2004) has resulted in a multilayer feedforward neural network which uses Tsukamoto's fuzzy reasoning to generate membership functions in both fuzzification and defuzzification layers. This neuron-fuzzy network is used as the central processing element of the proposed structural nervous system. This neuro-fuzzy inference engine has five layers and can be used for any number of inputs and outputs (MIMO). It employs the gradient descent method and the least square estimation (LSE) algorithms to train the network. Fig. 9 shows the architecture of this engine.

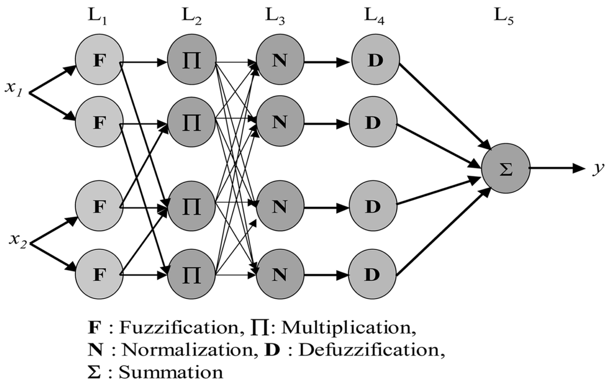


Fig. 9 Structure of neuro-fuzzy inference engine

**Layer 1:** (Fuzzification layer) Each node generates a membership degree of a linguistic value. The *k*th node in this layer performs the following operation, where *j*=2:

$$O_k^1 = \mu_{Aij}(x_i) = \frac{1}{1 + \left(\frac{x_i - a_{ij}}{b_{ij}}\right)^2} \tag{1}$$

**Layer 2:** (Multiplication Layer) Each node calculates the firing strength of each rule by using multiplication operation, where *j*=2.

$$O_k^2 = \prod_1 O_{ij}^1(x_i) \qquad (1 \le k \le 4) \tag{2}$$

**Layer 3:** (Normalization layer) The number of nodes in this layer is the same as the first layer, where the output of layer two is determined according to:

$$O_k^3 = \frac{O_k^2}{\sum_k O_k^2} \qquad (1 \le k < 4) \tag{3}$$

**Layer 4:** (Defuzzification layer) The number of nodes in this layer is equal to the number of nodes in layer one times the number of outputs. The defuzzified value for the *k*th node is:

$$y_k = \left\{ \begin{array}{ll} c_k - d_k\sqrt{\frac{1}{O_k^3} - 1} & \text{if } k = odd \\ c_k + d_k\sqrt{\frac{1}{O_k^3} - 1} & \text{if } k = even \end{array} \right\} \qquad (1 \le k \le 4) \tag{4}$$

where $\{c_k, d_k\}$ are consequent parameters and are used to adjust the shape of the membership tunction of the consequent part. Then, the output of this layer becones:

$$O_k^4 = O_k^3 \cdot y = \left\{ \begin{array}{ll} O_k^3 \cdot \left(c_k - d_k\sqrt{\frac{1}{O_k^3} - 1}\right) & \text{if } k = odd \\ O_k^3 \cdot \left(c_k + d_k\sqrt{\frac{1}{O_k^3} - 1}\right) & \text{if } k = even \end{array} \right\} \qquad (1 \le k \le 4) \tag{5}$$

**Layer 5:** (Summation layer) Here, the number of nodes is equal to the number of outputs. There is only one connection between each node in layer three and a node in the output layer:

$$O_1^5 = \sum_k O_k^4 \qquad (1 \le k \le 4) \tag{6}$$

In the training process, it tries to find the minimizing error function between target value and the network output. For a given training data set with $P$ entries, the error function is defined as:

$$E = \sum_{p=1}^{p} E_p = \frac{1}{2}\sum_{p=1}^{p}(T_p - O_{1,p}^5)\ , \qquad (1 \le p \le P) \tag{7}$$

where $O_{1,p}^5$ is the $p^{th}$ output of the network $T_p$ and is the $p^{th}$ desired target. The premise parameters $\{a_{ij}, b_{ij}\}$ are updated according to a gradient descent and the consequent parameters $\{c_k, d_k\}$ are updated using a LMS algorithm.

There are several key attributes of this neuro-fuzzy inference engine that would make it well suited for this application. These include:

- This network is a combination of a fuzzy inference engine and an adaptive neural network
- It uses Tsukamoto-type fuzzy reasoning for both fuzzification and defuzzification, that is, the membership functions are half of a bell-shape function called monotonic nonlinear functions.
- It can be applicable to Multi-input and Multi-output (MIMO) system
- It uses associated hybrid learning algorithm to tune the parameters of membership functions: Feed forward Process; Least Square Estimation; Backward Process; Gradient Descent method
- Optimal learning rate is updated after each learning process
- This network has the least number of coefficient to learn, has a fast convergence rate, and thus suitable for real-time applications.

As we have demonstrated, this inference engine can be used in modeling and mapping of uncertain systems whose mathematical representation (e.g. differential equations) is not available to predict its future behavior (Shoureshi 2000). It integrates the best features of a fuzzy system (fuzzy reasoning) and neural networks (learning). Neuro-fuzzy inference technique provides a means for the fuzzy modeling to learn information about a data set, which will compute and generate the membership function parameters, so that the associated fuzzy inference system can track the given input and output pattern. Its learning method works similarly to that of neural networks. This network can be used to find out system parameters and unknown factors through the training process, which means it achieves the goal of system identification. Further more, it is applied to fault detection and system diagnosis.

This neuro-fuzzy network will map the output of our self-powered piezo sensory system into accelerations. Thus, it would eliminate the need for accelerometers and power supplies.

### 2.4. Experimental analysis

To verify our approach, we have attempted to implement the proposed architecture on a 1/150 scaled-down model of an actual cable-stayed bridge, shown in Fig. 10. This implementation is at its first phase and requires extensive design and analysis. Thus, we have only reported here our preliminary results. In this phase of implementation, our goal has been to demonstrate peizo-fibers

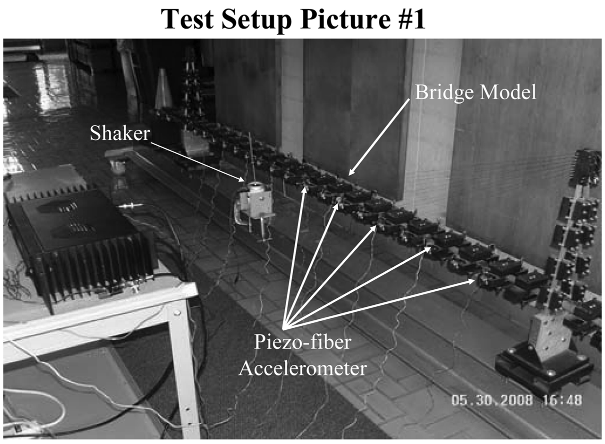


Fig. 10 Scaled model of a cable stayed bridge

Fig. 11 Sample of piezo-fibers used for self-powered sensory system

can be used as self-powered building blocks for the structural nerve system, using excitation energy, and can identify a structural fault. Fig. 11 shows these peizo elements, and Fig. 12. shows how these elements have been incorporated in the bridge model. By using earthquake data and a shaker, the bridge of Fig. 10 was excited. In addition to our self-powered sensory system, we also have used accelerometers for performance verification. Fig. 13 shows a comparison of acceleration data from a regular accelerometer and a self-powered piezo element, used as the bridge nerve system. As shown, we get excellent results and compatibility between these two sensors. Thus, these piezo elements are confirmed to be the right building blocks of the nerve system. In order to assess the ability of this piezo-based nervous system in detecting faults, we have attached a series of piezo elements on the model bridge and excited the bridge by an earthquake signal, using a shaker. By inducing a crack failure near piezo element #6, we have

Fig. 12 Piezo-elements on model bridge as vibration sensors

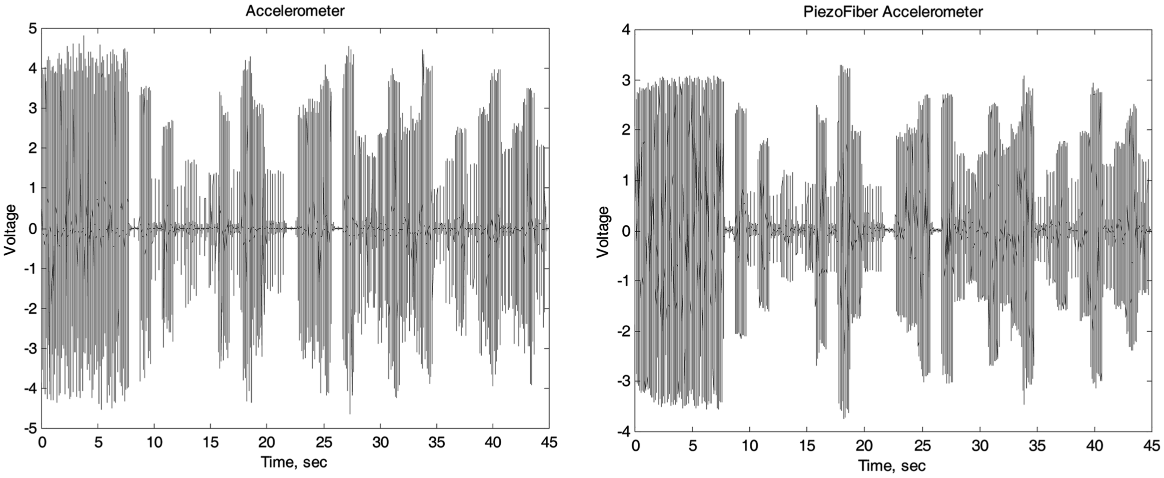


Fig. 13 Bridge response piezo-fiber sensory system with earthquake excitation

Table 1 Output of peizo elements with largest value at element #6

| Test Number | With usingonly Low-pass Filter | Combining with Low-pass and Ayerage Filters |
|---|---|---|
| #1 | **6**, 8, 7, 5 | **6**, 5, 8, 7 |
| #2 | **6**, 8, 5, 7 | **6**, 8, 7, 5 |
| #3 | **6**, 5, 8, 7 | **6**, 8, 7, 5 |
| #4 | **6**, 5, 8, 7 | **6**, 8, 5, 7 |
| #5 | 5, 8, **6**, 7 | **6**, 8, 5, 7 |
| #6 | **6**, 8, 5, 7 | **6**, 8, 7, 5 |
| #7 | 8, 5, **6**, 7 | 8, **6**, 5, 7 |
| #8 | 8, 5, **6**, 7 | **6**, 8, 7, 4 |

investigated the outcome of this failure diagnostics. This experiment was repeated several times. Table 1 shows the results from these self-powered piezo elements. As shown, the proposed nervous system was able to detect failure near the nerve element #6 in 7 out of the 8 experiments.

## 3. Conclusions

This paper described a new approach to monitoring and failure detection in civil structures. By studying the human nervous systems, we have inspired to create a structural nerve system. To achieve this goal, we have employed self-powered piezo fibers that can harvest energy from structural vibrations due to such exogenous inputs as earthquake or wind. By using a cable-stayed model bridge, we have been able to implement the proposed structural nervous system concept. It has been demonstrated that self-powered piezo fibers can be a good candidate for the development of structural nervous system. Furthermore, through a developed neuro-fuzzy inference engine, we have demonstrated that the output of these piezo nerve elements can be used to detect structural failures. The next phase of our research will focus on the design and implementation of optimal senor topology and information architecture, as inspired by the human nervous system.

## Acknowledgment

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