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A Proposal to Extend Agility of Wireless Sensor Network using Multi-Agent System for Structural Health Monitoring Application

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Abstract

The rapid and widespread construction of structures calls for rigorous structural health monitoring (SHM) programs throughout the construction, operation and maintenance phases. Thus, much of a structure's success or failure depends upon efficient SHM programs. The basic technology underlying the SHM program's ability to detect cracks and failures can be incorporated with Wireless Sensor Network technology for more robust SHM. The agility of the WSN is, therefore, a prominent factor for a successful SHM program. Unpredictable external events, such as earthquakes or serious impacts are an inevitable fact of life. During such an event, the WSN should continue to be active and efficient enough to perform the assigned tasks without failure. The never miss an opportunity scheme (NMAOS) model, which is a prototype based on multi-agent technology, is proposed in this paper to provide agility to the Wireless Sensor Network.

Keywords: *Multi-agent system, Agility, Structural health monitoring, Wireless sensor networks*

1. Introduction

The majority of structural health monitoring (SHM) related research completed to date has focused exclusively on the surface of structures such as bridges and buildings and seems to have attained some level of maturity [1-5]. On-structure long-term monitoring systems are increasingly being employed, and have been implemented, to some degree of success, on bridges in Europe [6-9], the United States [10-11], Canada [12-13], Japan [14-15], Korea [16-17], China [18-20], and other countries [21-23]. A successful and robust SHM program relies on efficient and active Wireless Sensor Network performance. Agility is defined as the capability of a WSN to timely capture the event response of the monitored structure, process the measured data, extract the relevant features, and interpret the results. According to Liang and Pakzad [24], the importance of WSN agility in the context of earthquake monitoring of bridges is described by two important aspects, as discussed below.

First, the need for an agile WSN to capture a bridge's response to earthquakes. In May 2006, a group of researchers from the University of California, Berkeley, installed a WSN on the main-span and on a tower of the Golden Gate Bridge (GGB), consisting of 256 accelerometers. After the initial installation phase, the network operated on the bridge from June to September 2006, periodically collecting acceleration and temperature data and transmitting them to a base-station located inside the south tower. During this period, at least three earthquakes occurred in Northern California, with the Glen Ellen on August 2, 2006, at a magnitude of 4.4, being the largest amongst them. The sensor network on the bridge did not

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collect data during any of these earthquakes [25] because it was not alert at their occurrences; the network was either asleep or transmitting ambient vibration data collected prior to the occurrence of the earthquake.

Second, the need for an agile WSN to process the sensor data for bridge modal identification, to extract important features from the data and to interpret the results. During an earthquake, bridges exhibit significant non-linear behavior and many of their extreme-condition design provisions are reached. Bridge owners and engineers, as well as the general public, are interested in knowing how each element of the bridge performs during strong motions, so that they can take that information into consideration when responding to the event, and when remedying the possible failures in future retrofit/design of this and other bridges. This can be done by relating the structural condition of the bridge to features of the response data, and monitoring the changes in those features.

Wardhana and Hadipriono of Ohio State University [26] studied 503 bridges in the U.S. that had failed between 1989 and 2000. The failed bridges included everything from spans designed to carry pedestrians over roadways to floating pontoon bridges across lakes. "Failure" was defined as anything from collapse to damage so serious that the bridge had to be closed down. Overall, they found that 53% of the failures occurred during floods, when raging waters undermine bridge footings or batter the structures with debris. The great floods of 1993 were particularly hard on bridges across the Midwest. A collision with a car or a boat was the second leading cause of bridge failure, bringing down about 12% of bridges. Fourteen bridges were collapsed by a collision with a car or truck, while ships and barges toppled ten bridges, and another three bridges failed after collisions with trains. "Overloading" took third place in the survey. Roughly, 10% of the bridges failed after too many people or cars crowded onto the span. The study notes that 107 people were injured after a walkway collapsed at an auto racetrack in North Carolina. Deterioration and design flaws, and potential factors in the collapse of the Interstate 35 West Bridge in Minnesota were responsible for about 9% of the failures. Twenty bridges, for instance, failed due to corroded steel or related deterioration. Earthquakes brought down another 3% of the bridges.

If carefully observed, it will be noticed that in most cases, the collapse was sudden, occurring within a fraction of a second. Furthermore, various sources state that it is a fact that the incidence of collapse is unpredictable and mostly happens suddenly, causing disaster [27]. Consequently, when relying on WSN technology for SHM of bridges, there should be maximum reliability, so that no loss of human life results due to a passive state of the monitoring system. In order to ensure such reliability, this study proposes a model based on multi-agent technology for an agile wireless sensor network.

2. Previous Work

Over the past few years, multi-agent technology has come to be perceived as crucial technology, not only for effectively exploiting the increasing availability of diverse, heterogeneous, distributed on-line information sources, but also as a framework for building large, complex and robust distributed information processing systems that exploit the efficiencies of organized behavior. Given the general benefits of multi-agents, researchers have explored the possibility for sensor network applications [28-30].

A design method for a multi-agent system (MAS) based on the SHM system has been presented by Yuan *et al.*, [31]. They presented a new parallel-distributed structural health monitoring technology based on a smart wireless sensor network and multi-agent system for large-scale engineering structures. Using this technology, the health monitoring system becomes a distributed parallel system instead of a serial system. Wu *et al.*, [32] presented a multi-agent design method and system evaluation for wireless sensor network based structural health monitoring to validate the efficiency of the multi-agent technology. Through the cooperation of six different agents for SHM applications, the distributed wireless sensor network demonstrated the ability to automatically allocate SHM tasks, self-organize the sensor network and aggregate different sensor information.

The basic idea of MAS technology proposed in the prototype for this study is similar to earlier models except that the aspect of WSN agility is given prime importance so that the SHM program should not miss a single opportunity, which could otherwise result in failure or non-capture of data at the time of an unpredicted calamity.

3. Never Miss an Opportunity Scheme (NMAOS)

The never miss an opportunity scheme (NMAOS) is a prototype based on multi-agent technology for an agile wireless sensor network. A multi-agent system (MAS) is a system composed of multiple interacting intelligent agents. In order to apply multi-agent technology to a distributed structural health monitoring system, each component or subsystem in the structural health monitoring system should be changed to an agent. According to the subsystem's functions, six kinds of agents are defined as follows for the purpose of attaining an agile wireless sensor network for a structural health monitoring system. The basic concept of pulse-based media access control (PB-MAC) from Liang and Pakzad [24] has been utilized as the theme of the model.

The experience gained from the Golden Gate Bridge (GGB) project shows that existing non-preemptive MAC without priority support has failed to capture earthquake signals in practice. Furthermore, using a reset message flooding based on the existing MAC protocols will take a long time to propagate throughout a large WSN due to hidden terminals, which may also lead to the loss of opportunity to capture earthquake signals by the WSN [33].

PB-MAC is an out-of-band MAC, in which the control channel only carries pulses and the data channel only carries packets, such as trigger-messages, time-sync and data packets. A regular pulse consists of an active part of a coded length in a single-tone wave and a random pause part in two sub-parts, *i.e.*, a contention window of a fixed size and a residual pause of a random length, where the contention window is cut into equal size contention sub-windows. A node transmits regular pulses in the control channel when it is transmitting a packet in the data channel. The active part of a pulse signals a busy data channel, while the pause part is mainly for collision detection. Any transmitting node hearing a pulse aborts its transmission. The length L of the active part of the pulse indicates the priority level P of the data packet in transmission; a longer active part indicates a higher level of priority for the data packet [34-35].

3.1. Comparison Logic

When a node detects a pulse in the control channel, it measures the length of the pulse's active part. If the active length is a valid coding length for priority level information, the information L is decoded. Thus, every receiver of the pulse has the knowledge of the priority level of the packet in transmission Lr. When a packet source Si detects a busy control channel but finds that the priority levels Li of its packet is higher than the priority level Lr of the packet in transmission, the source Si starts a random back-off timer as soon as the pulse in the control channel pauses. A packet source with a lower priority packet will defer and check the control channel status later. The random back-off delay di of the source i is drawn in a contention sub-window that is determined by the priority level Li of the source's packet. A higher level of priority acquires a smaller sub-window and thus a shorter delay. The source with the shortest back-off delay (*i.e.*, of the highest level of priority, such as the trigger message's priority level) acquires the medium before other sources do, and this source becomes the winner source Sv in this round of contention. When the back-off timer of the winner source Sv expires, Sv starts to transmit pulses in the control channel. The packet source So, then owning the channels, is still in its pause in the control channel because its random back-off delay di is of a larger value due to the relatively lower packet priority. Therefore, can detect the pulse of Sv and releases both channels. In the PB-MAC design, a relay scheme of pulses by the intended packet receiver is also designed to suppress hidden terminals [34-35]. The MAS prototype model for an agile WSN is shown in Figure 1.

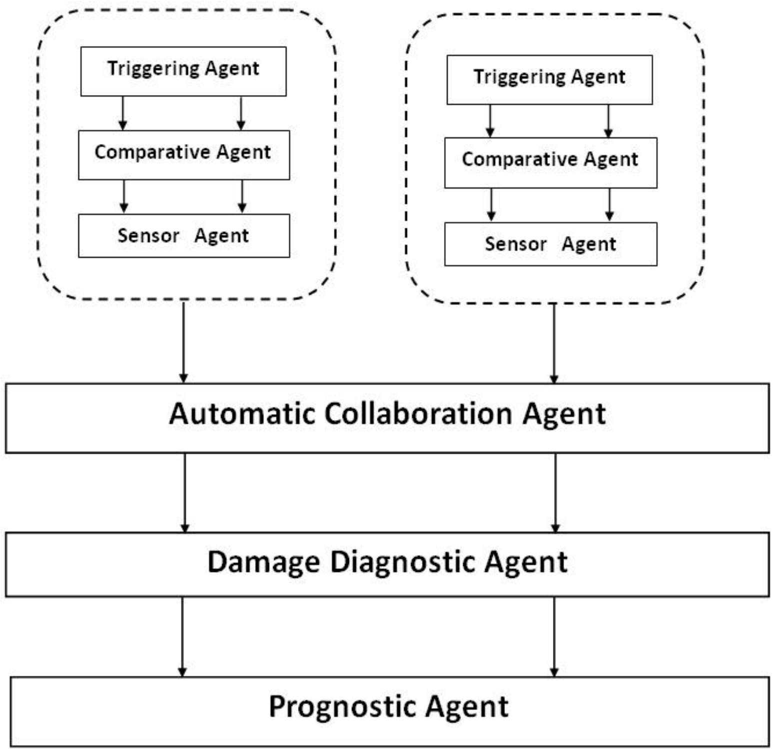

Figure 1. Proposed Multi-agent Architecture for an Agile WSN

3.1.1. Triggering Agent: Triggering agent: The successful dissemination of trigger messages in a WSN can make a difference between capturing a bridge's response to an event (earthquake/high impact) and missing the opportunity to do so. In order to achieve this goal and to enable a WSN to capture critical information, trigger message dissemination needs timely and lossless medium access within the WSN. A trigger message from a nearby observation site can be timely propagated across a WSN to preempt current tasks, such as energy-saving sleep and scheduled data transmissions, so that the sensor network can be forced into a record-ready state before the earthquake waves reach the monitored bridge. A self-learning intelligent-based software system that predicts the maximum peak load on the structure (bridge), for example, at some particular time may trigger more priority messages to an active monitoring system.

3.1.2. Comparative Agent: The comparative logic is embedded in the comparative agent, which accomplishes the task of preempting current tasks, such as energy-saving sleep and scheduled data transmissions and allows trigger pulses to activate the whole system to monitor the structure during any disastrous event.

3.1.3. Sensor Agent: The sensor agent is responsible for sensing parameters, such as stress, strain, displacement, acoustics, pressure, and temperature. Sensing agents can be implemented through smart sensors with an on-board microprocessor. There are sub-agents in the sensor agent to accomplish many tasks such as data processing and disseminating.

3.1.4. Automatic Collaborating Agent: It is implemented by software in the powerful desktop workstation that has wireless links to the sensor nodes and communicates with the cluster heads to a cluster-star framework, which can completely support low-power, multi-point, and heterogeneous operations with a distributed synchronization mechanism. It takes care of clustering, fusing and communicating data exchange between different agent entities.

3.1.5. Damage Diagnostic Agent: It comprises a real-time automated reasoning and decision-making integrated software system. Several models and techniques [36] are available that can be used for the accurate assessment of cracks and disorders in the infrastructure constituting the damage as a whole. A model's principal purpose is to predict, from first principles, the measurement system's response to specific anomalies in a given material or structure, (*e.g.*, cracks, voids, distributed damage, corrosion, deviations in material properties from specifications, and others). Thus, a measurement model includes the configuration of the probe and component being inspected, as well as a description of the generation, propagation and reception of the interrogating energy. Numerical results based on a reliable model are very helpful in the design and optimization of efficient testing configurations. A measurement model is also indispensable in the interpretation of experimental data and the recognition of characteristic signal features. The relative ease of parametrical studies based on a measurement model facilitates an assessment of the probability of detection of anomalies. A measurement model is a virtual requirement for the development of an inverse technique based on quantitative data. Last, but not least, a measurement model whose accuracy has been tested by comparison with experimental data provides a practical way of generating a training set for a neural network or a knowledge base for an expert system. The overall goal of the agent in structure diagnostics is the emulation of natural intelligence by incorporating declarative actions involving expert decision-making, the incorporation of system modeling, and completeness in contextual information identification.

3.1.6. Prognostic Agent: The task of the prognostic agent is to evaluate the remaining lifetime of the structure at a given state of damage and future loading. These future load spectra can be either damage tolerance or safe-life philosophy. The results of the damage diagnostic agent provide information on the current state of the structure for prognostics. Material-level modeling of constitutive properties, supported by experimental results, provides the input for damage growth law. A damage growth law together with a multi-scale structural model forms the input to a module on probabilistic prognosis, which in turn provides information on damage evolution and remaining life. Depending on its magnitude, the resulting statement of failure probability may result either in a recommendation for repair or replacement of a structural component, or, when the probability is low, for an additional cycle in the diagnostics/prognostics loop of the structural health management system. Accordingly, the strategy of the integrated system is that after damage diagnosis by the active damage agent the current health status of the structure is submitted to the prognostic agent to achieve certain prognostic information. Prognostic models [37-38] are widely available for predicting damage growth and estimating residual strength and remaining useful lifetime (RUL) of structures made of metals or composites. In order to yield accurate predictions of damage growth and residual strength, one key issue is to create a proper link between the diagnostic outputs and prognostic inputs.

4. Conclusion

Agility of a WSN is an important factor contributing to reliable and successful SHM programs. The prototype NMAOS (never miss an opportunity scheme) based on multi-agent technology proposed in this study uses the PB-MAC based technique of triggering a message of high priority to preempt the current passive state of the WSN and make it active for sensing and capturing data at the time of an unpredicted event of high impact on the structure, such as an earthquake. Further studies could be focused on evaluating the effectiveness and validating this cognitive multi-agent based prototype in real-time situations with a view to develop an agile wireless network system to monitor the health of structures.

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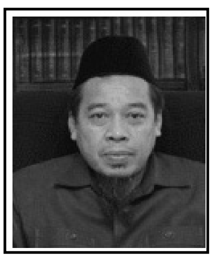

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