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DYNAMIC SIMULATION OF WIRELESS STRUCTURAL MONITORING SYSTEM USING PETRI NETS

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Abstract

To certify the safety of existing buildings, more and more structural monitoring systems are installed, especially in the application of wireless sensors. However, the main weakness of wireless sensors is their short operative time due to limited battery life. Besides, the factors include the detective locations of wireless sensors and the effects by the various structural materials. For these reasons, this study proposes a dynamic information framework of the wireless structural monitoring system that applied the Petri Nets and Fuzzy rule-based reasoning theorem.

This dynamic simulated framework, called 4D-Fuzzy Petri Nets, considers the three-dimensional structural space as well as the duration of the wireless sensor. 4D-Petri Nets adapted the spaces to be the positions of wireless sensors in the structure, and the possible token carried the information from the wireless sensor. Moreover, different transitions were given by the different time conditions and weights. For the sake of sifting the wireless signals, the Fuzzy Petri Nets Model with database deals with the wrong situations. Under the 4D-Fuzzy Petri Nets, architects can quickly design the wireless structural monitoring system for different structures and extend the life of batteries at least two to five times.

INTRODUCTION

In the civil engineering field, many structural health monitoring (SHM) and damage detection develop variously and progress quickly, and include destructive and non-destructive evaluations [1][2]. For existing buildings, non-destructive evaluation is a valuable approach, and most structural information is gained by the sensors bonded on and/or embedded in a structure. However, the overall structural health monitoring needs various kinds of sensors which include accelerometers, strain gauges, displacement transducers, anemometers, temperature sensors, and weigh-in-motion sensors [3]. Besides the expensive cost itself, monitoring sensor networks require time spent on wire installation and consume power from outsides electric support. Fortunately, the advance in micro electronic systems and wireless communications improve low-power, small-volume, and stable-signal wireless sensors. In this scenario, the advantages of the application for wireless sensors in the civil engineering field are as follows:

1. Application to structures without electric power support. In some disaster areas caused by natural or man-made calamities, the majority of architecture has been damaged and lost outside electric support. If wireless structural monitoring can be performed efficiently and properly, governments can avoid critical conditions happening on the refuges from more calamities later on. Besides, the wireless sensors also can be manipulated on those temporal constructions or sites which do not use the electric wire.

2. Reduced time in the monitoring sensor assignment. Without wiring, wireless sensors can be distributed quickly among the all of the structure.

3. Economic Benefits. The wireless sensors install and remove easily. After recharging, wireless sensors can be set up again; moreover, some wireless sensors consist of a normal detective unit and a wireless transmitter unit.

Although there are many advantages for wireless SHM, it is not invincible. Regardless of the accuracy in the evaluation, the major weakness of the wireless sensors is the duration of the battery life. There are three directions to improve the wireless sensor node lifetime: reduction of the power consumption for the IC elements, extension on the battery life and capability, and network topology with effective communication among wireless sensors. In this study, we propose the 4D-Fuzzy Petri Nets to simulate the power consumptive states of wireless sensors and deploy the space location of wireless networks. In addition, the Fuzzy model is built by Fuzzy Petri Nets [4][5]. All related works will be discussed later.

4D-FUZZY PETRI NETS

Petri Nets was first proposed by Carl Petri in 1962 [6], and classic Petri Nets essentially contain four components --- places, transitions, arc, and tokens [7]. In recent decades, many extended Petri Nets apply to structural safety [8][9][10], sensor networks [11][12][13], and fuzzy theorems [14][15][16]. All existing buildings are in real world, 3D spacial installed positions of wireless sensors should be considered as a momentous issue for networks. Besides, the limited battery lifetime of a wireless sensor determines the operative duration of the monitoring system. Hence, for the architects, how to swiftly and effectively deploy the structural wireless monitoring system on existing damaged buildings becomes extremely significant. In this study, we propose a high-level hierarchical Petri Nets, 4D-Fuzzy Petri Nets which consist of three modules, to simulate the power consumption of a wireless sensor, wireless networks topology of structural monitoring system and fuzzy monitoring module by a fuzzy rule-based reasoning Petri Nets (Fig. 1).

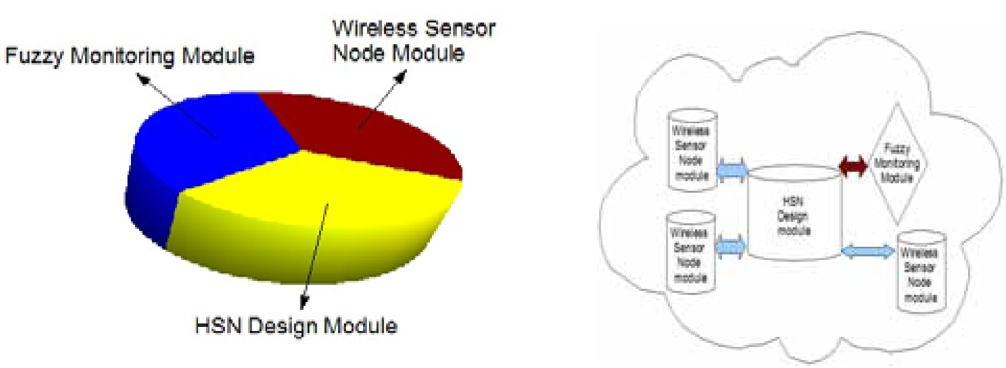

Figure 1: Triple Compositions for 4D-Fuzzy Petri Nets

WIRELESS SENSOR NODE MODULE

To effectively arrange the wireless sensors and network design, active wireless sensors becomes the major research objects. For the finite battery lifetime, active wireless sensors contain three major power-consumptive components: a sensor detector, processor, and transceiver (Fig.2). In this module, we depend on the power consumption to design three states: Dormant State, Sleeping State, and Active State. In [17], Rakhmatov specified the relationship between the power consumption and chemical change, and defined two battery-specific parameters for battery lifetime. Due to this concern, we set EP_1, EP_2, EP_3, as three states separately, and EP_4, EP_5 mean abstract places, which contain abstract tokens. Those abstract tokens show the assumed total power capacity, and the wireless sensor is out of power when EP_4 has no abstract token. Moreover, EW_1, EW_2, and EW_3 specified different weight values ($EW_1<EW_2<EW_3$). For example, only EP_3 active state could detect structure and launch wireless signal, but this state also consumed a lot of power (large value for EW_3). ET1, ET2, and ET3 could decide the delayed time reference to the wireless networks topology.

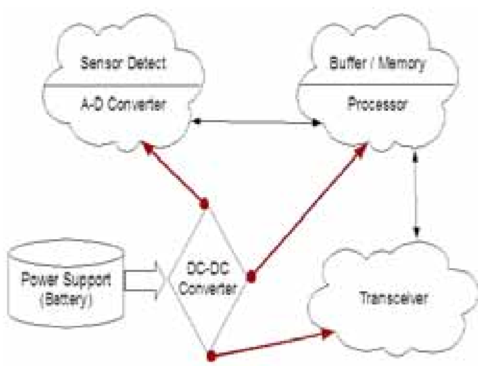

Figure 2. Basic Framework of Wireless Sensor

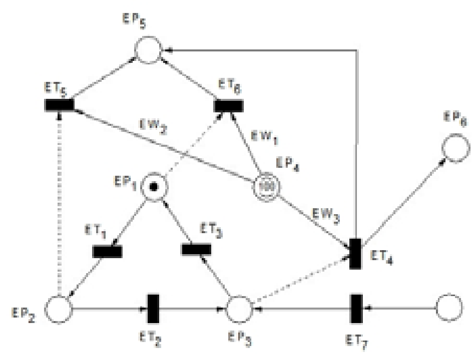

Figure 3. Power Consumption of Wireless Sensor

HIERARCHICAL SENSOR NETWORKS (HSN) DESIGN MODULE

In structural monitoring, all buildings are categorized spacial 3D objects. Due to the stationary monitoring sensors, the exact 3D spacial positions help architects to separate entire network into several small sub-networks. Therefore, we adopted the hierarchical sensor networks (HSN)[18] design module to simulate the wireless monitoring network. Under this module, every sub-network settled one area center to communicate with other wireless sensors in a sub-network. The area center collects structural data from wireless sensors one by one (called polling), and transmits this data to the information database by wire or wireless. In addition, an area center commands the wireless sensors to re-detect structural information when the wireless signals seem incorrect after being filtered by the fuzzy monitoring module. In Fig. 4, we assume that all sub-networks operate one by one (called polling) with the same period (ldc), which means remaining sub-networks remain in a sleeping state when one sub-network operates. For example, except for the active state, one wireless sensor of the second sub-network remains in a sleeping state when the second sub-network operates. Otherwise, it remains in a dormant state to save power consumption. In Fig. 4, we divide the three periods when one sub-network operates: Registration period, polling period, and Ending period. Moreover, one sensor works in three steps: ask, reaction, and set sleep time. In Fig.5, n means the numbers of sub-networks, and shows the setting sleep time formula.

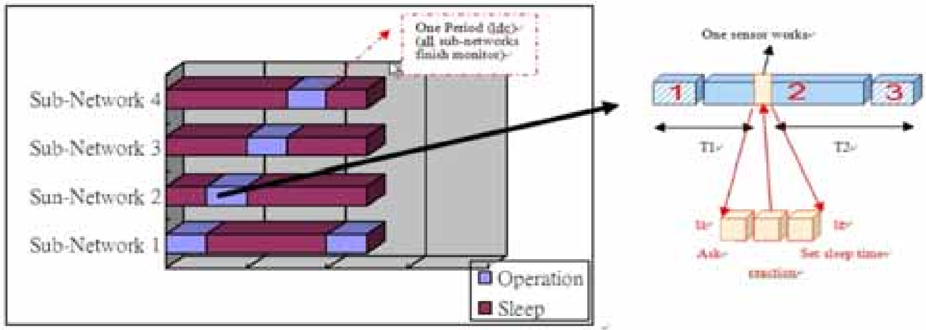

Figure 4: Polling period of sub-network and process in the sub-network

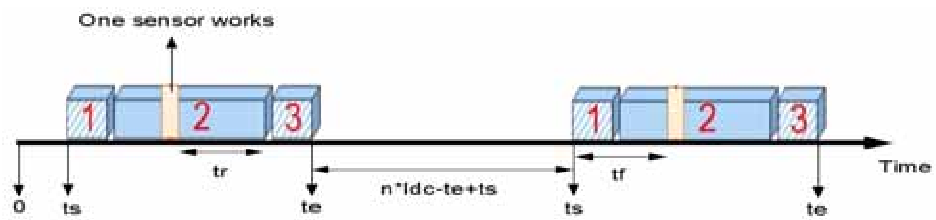

Figure 5: Sleep time for the wireless sensor

FUZZY MONITORING MODULE

Fuzzy Petri Nets are used for fuzzy reasoning modeling, based on the static logic rules [4][5][8][9]. In our study, all structural data of the wireless sensors is transmitted to the information database by the area center in the sub-network. The area center not only schedules the sub-network but also filters the wireless signal by fuzzy rule-based reasoning (Fig.6). Accordingly, we propose that the fuzzy Petri Nets avoid collecting the wrong structural information from wireless sensors since the unstable signal or wrong detection. The fuzzy monitoring Petri Nets are defined as 15-tuple: where; (Fig. 7)

(1) P = {p1, p2, p3…} – the finite set of places.
(2) PF = {pf1, pf2, pf3…} the finite set of fuzzy places.
(3) T = {t1, t2, t3…} the finite set of transitions, representing the filter for the wireless data.
(4) TF = {tf1, tf2…} the finite set of fuzzy transitions, and following the set of logical fuzzy rules R.
(5) TFF, a finite set of transition functions, which process actions of fuzzy inference.
(6) tff: TF -> F, the finite set of transition functions, which associated to the fuzzy rules modeled by transitions, function F describes the credibility degree $\mu = F(t)$ of the rule.
(7) D = {d1, d2, d3…} the finite set of logical propositions that defines the fuzzy rules R.
(8) I: T -> P, the input function of places.
(9) O: P -> T, the output function of places.
(10) R: {r1, r2, r3…} the set of fuzzy information rules.
(11) S: {s1, s2, s3…} the set of arc to transmit fault symptom token from wireless network.
(12) W: {w1, w2, w3…} the set different weight value to normalize the different wireless sensor data.
(13) PFD: PF -> D, the bijective function that maps a logic proposition d_i to each place p_i
(14) M: PF -> [0, 1], is the truth values of tokens (μ_i) for a place pf_i. The function with a fuzzy value μ_i of credibility for each place pf_i corresponding to the logic proposition $d_i \subset D$.
(15) TT: the finite set of fuzzy token (colored type). Each token carries the structural information from different wireless sensors.

According to the fuzzy parameters above, we represent the T transition as the watching dog to filter the structural data from the wireless sensor in the sub-network. When the T is enabled and fires, the color token TT with data assigns to the PF places. $M\ (pf_i) \in [0,1]$ indicates a token value in place $pf_i \in PF$. If $M(pf_i) = \mu_i$, $\mu_i \in [0,1]$, and $PFD(pf_i) = d_i$. When transition tf_i fires, a token moves from input place $I(tf_i)$ and deposits to output $O(tf_i)$, which has token value $p_k \in O(tf_i)$ using transition TFF_i, where $TFF_i = tff(tf_i)$. Finally, the output fuzzy place pf_4 has $\mu_4 = TFF(I(t_i))$, and the database gets the possible fault value to reset the fuzzy rules and sensor will restart to detect.

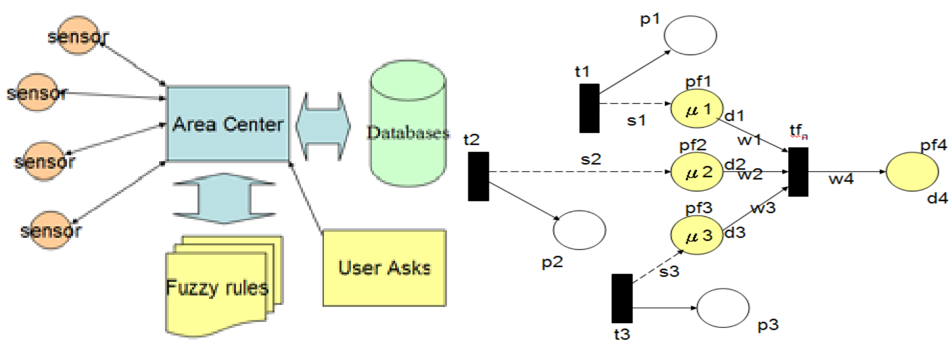

Figure 6. Flowchart of the Area Center

CONCLUSIONS

In this paper, we have proposed that 4D-Fuzzy Petri Nets which consist of three modules simulate dynamitic wireless monitoring systems. Due to space limitation, we didn’t canvass well and expound in detail in this paper. However, the power consumption of wireless sensors is obviously reduced by the wireless sensor node module. Furthermore, the polling process and sleep time set extend the battery lifetime by HSN design module. Under the fuzzy monitoring module, we can decrease to accumulate the incorrect data from wireless sensor. As a result, architects can simulate wireless networks by 4D-Fuzzy Petri Nets, and build efficient structural monitoring systems, especially for existing, damaged buildings the disaster power-destitute regions.

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