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Optimal wireless sensors' location for monitoring of structures in randomly disturbed environment

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In the paper we present the specific conditions that appear in structures' monitoring by means of Wireless Sensor Networks (WSN). First, we introduce the problem of optimal sensors' location for structures monitoring and its specific constraints if one uses WSN. We formulate the conditions that must be taken into account during optimization. Then, we give an example of temperature measurements and formulate the procedure that leads to finding optimal wireless sensors locations. Finally, we present the experimental observations of wireless sensors in the network that strongly affect on the temperature estimation on a basis of the collected measurements. We conclude with remarks concerning WSN practical design for permanent structures' monitoring to obtain exact and reliable results.

1. Introduction: Wireless Sensor Networks

Permanent structures' and their surrounding monitoring enables immediate and effective detection of failures and possible threats. It is especially important for safety and proper functioning of intelligent structures and mechanisms. Application of WSN for environmental and structural monitoring not only makes possible permanent observation of working structures but also increases functionality of the monitoring system and decreases its overall cost. However, designing WSN-based monitoring system one must take into account additionally (except of usual engineering constraints) specific restrictions connected with the low energy broadcasting. Thus, in such a case the optimal location of sensors should take into account both conditions connected with structure's behaviour (finding the most "informative" measurement points, [1]) and random disturbances of the measured signal transmission depending on external fields and structural barriers. In this paper we formulate a novel problem of optimization of finding placements of wireless sensors of WSN (Fig. 1) to simultaneously obtain the best measured data for the assumed mechanical purposes and the required communication conditions determined, e.g., by maximal possible distances between sensors and random disturbances of environmental conditions.

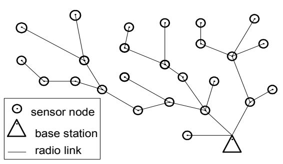

Fig. 1 Sample sensor network

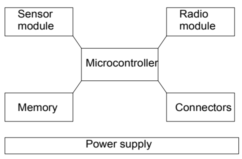

Fig. 2 Node architecture

Fig. 3 Sensor MICAz Crossbow

Fig. 4 Base station

Fig. 5 WSN used in experiments

Similarly to other sensor networks, the WSN nodes fulfil a measuring function, yet WSN specifies that the nodes are responsible for communication using a wireless media and come under strongly influential restrictions due to battery power supply, exchange of which is usually implausible (Fig. 2). Though, it would be more convenient to make use of an universal network model, one has to take into consideration, already in the design phase, what the system based on WSN would be applied for as well as consider the possible working structure [2]. As far as WSN are concerned even the best localization which enables an optimal measurement of the very quantity seems to be meaningless, if the communication specification of the network will not be taken into account. Sensors are so deployed in a given area that they ensure the coverage of all parts of the terrain, though first of all communication [3].

2. Optimal measurements with WSN

A specific problem of estimation of temperature at point x inside domain Ω on a basis of measurements at points b_i on the boundary can be formulated as an initial-boundary problem of heat equation and solved by Green method [4]. For this

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purpose we include the measured temperatures θ_i, i=1, 2,…,n to the boundary condition in the initial-boundary problem. The boundary condition function is then the sum of pulses $\delta(\xi - b_i)\theta_i(t)$, concentrated at points $b_i \in \partial\Omega$. Thus, to estimate the value of temperature, one should measure continuously (or at quantified instant of time) the temperature and deliver the measurements to a computation centre to obtain estimates. In a case of wired sensors, the measurements are of the form:

$$\Theta(b_i,t) = \theta(b_i,t) + \varepsilon(b_i,t), \tag{1}$$

where $\theta(b_i,t)$ is the exact value of the temperature and $\varepsilon(b_i,t)$ is the measurement error. To obtain the best estimate, one should optimize the sensor's location to minimize errors, using, e.g., a method of paper [5]. In a case of WSN and wireless sensors, the measurements obtained by the calculation centre are additionally disturbed by the additional errors $\eta(b_i,t)$:

$$\Theta(b_i,t) = \theta(b_i,t) + \varepsilon(b_i,t) + \eta(b_i,t), \tag{2}$$

which are caused by inaccuracies of sensors' functioning and random disturbances of transmission in WSN (routing delay, temporal connection loss, etc.). In such a case finding optimal locations of sensors must take into account both the criterion of temperature measurements and the criterion of transmission in WSN, what leads to multi-criteria optimization [3].

3. Experiments of temperature measurements with WSN

The stochastic characteristic of many factors influencing the WSN activity is illustrated by the carried out experiments. One has to consider the following factors: battery discharge level, data (from network parts) loads of certain nodes, random disturbances and distortions in transmission, in order to obtain optimal effects regarding the network.

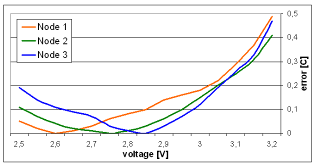

Fig. 6 The measured temperature's systematic error vs. voltage of discharging battery

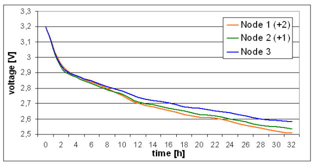

Fig. 7 Battery voltage vs. WSN's time of operation

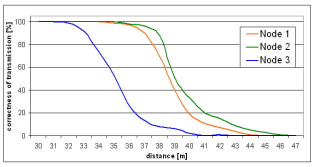

Fig. 8 The nodes' work on the transmission boundary

Fig. 9 Correctness of transmission vs. number of disturbances

Performing experiments, we observed the operating WSN's behavior, essential for its functioning. The biggest systematic errors resulting from discharging the battery appear in initial (relatively short) and final (more elongated) lifespan of the network (the smallest systematic deviation is falling for the voltage of 2.9 – 2.6 V, see Fig. 6). The power consumption of the most loaded node is a little bigger than the power consumption of the least loaded node. However, in a network where one node forwards information from other nodes will be rather significant for the lifetime of the network, Fig. 7. (Placing of the nodes for this experiment was planned in a way which the path of the data transfer could not change since it was the only available track). After exceeding the nominal range of nodes' transmission, the performance of the WSN rapidly decreases (Fig. 8), so for the proper functioning of WSN the nodes must be closely located. Effects of random disturbances of the environment strongly reflect on the quality of transmission (the number of packets lost), see Fig. 9. The nodes of WSN must be located so dense that in a case of intensive stochastic disturbances an alternative path between nodes is possible.

4. Conclusions

The initial (quasi-optimal) locations of wireless sensors can be calculated with the information-theoretic criterion with the additional constraint connected with sensors' radio range. The locations taking into account practical conditions of sensors' functioning can be fixed according to the cross-validation and multi-criteria optimization. More effective criteria of optimality need additional studies. Although the large number of criteria complicates the search for optimal disposition of the WSN sensors, the benefits resulting from using the very modern technology compensate in many applications of interest.

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