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Uncertainty-based information extraction in wireless sensor networks for control applications

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ABSTRACT

Design of control applications over wireless sensor networks (WSNs) is a challenging issue due to the bandwidth-limited communication medium, energy constraints and real-time data delivery requirements. This paper introduces a new information extraction method for WSN-based control applications, which reduces the number of required data transmissions to save energy and avoid data congestion. According to the proposed approach, control applications recognize when new data readings have to be collected and determine sensor nodes that have to be activated on the basis of uncertainty analysis. Processing of the selectively collected input data is based on definition of information granules that describe state of the controlled system as well as performance of particular control decisions. This method was implemented for object tracking in WSNs. The task is to control movement of a mobile sink, which has to reach a target in the shortest possible time. Extensive simulation experiments were performed to compare performance of the proposed approach against state-of-the-art methods. Results of the experiments show that the presented information extraction method allows for substantial reduction in the amount of transmitted data with no significant negative effect on tracking performance.

1. Introduction

Recent advances in wireless sensor networks (WSNs) have resulted in new possibilities of data collection for a wide range of control applications including home automation, environmental protection, precision agriculture, transportation systems, space exploration, industrial automation, military systems, etc. [1–4]. The WSNs offer numerous advantages, such as cost effectiveness, simple deployment, mobility, high monitoring precision and vast area coverage. However, the design of control applications over WSNs raise great challenges due to the bandwidth-limited communication medium, energy constraints, data congestion and transmission delays. These issues are particularly important when dealing with control tasks that require reliable real-time data delivery [5].

Current research efforts, that address the needs of timeline and accurate data collection in WSNs, fall into two main categories. The first category includes communication protocols that are designed to maximize the data transmission performance of WSNs. The second category comprises data collection methods aimed at minimization of the demand for data transmission. Such methods optimize the use of sensor nodes by selecting data readings that are necessary for extraction of needed information. These two approaches can work in tandem to fulfill requirements of a particular application. In the literature, much work has been done to develop communication protocols for control applications of WSNs, however, relatively little research has been focused on appropriate information extraction schemes.

The available methods of information extraction have been devised mainly for monitoring applications [6] that require the WSN to provide information describing monitored parameters with a defined, constant precision or to

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report a predetermined set of events. In case of control applications, the required scope and precision of the delivered information change during the control process. They depend on past and current state of the controlled system as well as on the available control actions that can be implemented at a given time. Therefore, the dynamically changing requirements on input information have to be taken into consideration when designing the information extraction procedures for control applications based on WSNs.

The main objective of the presented study is the development of a method which allows the WSN-based control applications to recognize situations when new data have to be collected as well as to determine sensor nodes that have to be activated. The originality of the proposed method lies in the uncertainty analysis used to extract information which is necessary and sufficient for making control decisions. The uncertainty of control decision was defined as an estimate of probability associated with cases where the control decision is not optimal. According to the proposed approach, input data are delivered from WSN if it is expected that such operation will result in decrease of the decision uncertainty. Selection of the activated sensor nodes is based on determination of a data set, which is necessary to confirm or exclude the possibility that the considered control decision is not optimal. Processing of the selectively collected input data is based on definition of information granules [7] that describe state of the controlled system as well as performance of particular control decisions. The concept of information granules provides convenient representation of the extracted information, the precision of which changes during execution of control tasks.

The paper is organized as follows: Section 2 includes review of related research and describes main contribution of this paper in the context of WSN literature. In Section 3, the method of uncertainty-based information extraction is introduced in details and an illustrative example is given to demonstrate the proposed approach. Section 4 contains results of an experimental study on information extraction in WSN for mobile object tracking. The task of the considered object tracking application is to control the movement of a mobile sink which has to reach the target in the shortest possible time. In this study, the performance of the proposed method was compared against results obtained for state-of-the-art algorithms. Finally, in Section 5, conclusions are presented and some future research directions are outlined.

2. Related work and proposed approach

A number of approaches have been introduced in the literature that deal with information extraction in wireless sensor networks. A survey and classification of these approaches can be found in [8]. This section provides a concise description of selected information extraction methods that are relevant for control applications and focus on reducing amounts of data transmitted by sensor nodes.

2.1. Data aggregation

One of the fundamental techniques is based on in-network data aggregation [9]. According to this approach each sensor node at a predetermined path aggregates data transferred from other nodes in communication range, and communicates only the aggregated information to the next node in the path. Depending on method, the data aggregation path can be created randomly or can be optimized for a given query. Selectivity of queries and spatial correlations in sensor readings are taken into account by the PDT algorithm [10], which creates a data aggregation tree that minimizes the use of non-selected sensor nodes. Main disadvantage of this type of methods is a delay in data transmission, which is a consequence of the time-consuming data aggregation operations executed by intermediate nodes.

2.2. Data suppression

Suppression based methods make use of the fact that different observed states of the monitored physical phenomena are temporally as well as spatially correlated [11]. Temporal suppression is the most basic method: sensor readings are transmitted only from those nodes where a change occurred since the last transmission [12]. Spatial suppression reduces redundant transmissions of sensor readings from neighboring nodes that have the same or similar values [13]. In [14] a combined spatio-temporal suppression algorithm was introduced that considers the sensor readings and their differences along transmission paths to suppress reports from individual nodes.

In case of model-based suppression methods the divergence between actual sensor readings and model predictions is analyzed to detect the necessity of data transfers [15]. This approach uses a pair of models of the monitored phenomenon. The first model is used at the sink and the second one is distributed in the sensor network. Both models predict the same values of sensor readings. Sensor node sends the data only if the divergence between predicted and measured value is above a predetermined error tolerance threshold. This technique guarantees that all values available at the sink are within a fixed error bound from the measured values.

2.3. Model-based querying

Another approach to the problem of information extraction in sensor networks is the model-based querying approach, in which sensor readings are complemented by a probabilistic model of the monitored process [16]. Sensors nodes are used to collect data only when confidence of information provided by the model is under a required level. The confidence bounds have to be defined by the user. Data collection plan is optimized to minimize sensing and transmission cost. During data collection only those sensor readings are transmitted that are necessary to deliver information with an acceptable confidence. This approach was applied to information extraction in sensor network for light control in buildings [17].