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Collaborative fusion estimation over wireless sensor networks for monitoring CO_2 concentration in a greenhouse[☆]

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A R T I C L E I N F O

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A B S T R A C T

This paper investigates the data fusion problem over wireless sensor networks (WSNs) for monitoring the carbon dioxide (CO_2) concentration in a greenhouse. CO_2 concentration is an important environmental parameter in the greenhouse, and adequate regulation of CO_2 concentration is certainly beneficial to the improvement of the crop growth efficiency in the greenhouse. Since the measurement of CO_2 concentration is unavoidably subject to environmental interferences (e.g. noises), it is vitally important to estimate the true CO_2 concentration through available sensor measurements over a WSN with given topology. In this paper, based on the Consensus–Kalman filter, the distributed estimation scheme is presented to improve the state estimation accuracy. After the distributed consensus estimation, the head node can conduct the fusion estimation on the data from the available sensor nodes. The packet loss phenomenon brought by unreliable communication links is reflected by the proportion of the faulty sensors. To further alleviate the effects from the packet losses, we propose a modified estimation scheme for the head node that combines the estimates from sensor node at both the previous and current time points, thereby enhancing the accuracy of data fusion. Simulation analysis is carried out on the collected information of CO_2 concentration in the greenhouse in order to demonstrate the effectiveness of the proposed scheme.

1. Introduction

The greenhouse system is regarded as the innovation of modern agriculture that provides crops with the favorable environmental conditions [11]. A greenhouse is a closed environment that can be actively controlled to improve the crop yields [17]. Like temperature and humidity, the carbon dioxide (CO_2) concentration is another important environment parameter in the greenhouse. During the photosynthesis process, CO_2 and sunlight are used to generate carbohydrates required by crop growth [15]. A typical change curve of CO_2 concentration gathered in the greenhouse is shown in Fig. 1, from which we can observe that the change of CO_2 concentration is relatively large in one-day time. During the time period from 10:30 to 16:00, the CO_2 consumption is quite large and this is obviously due to the crop photosynthesis. Reasonable regulation of CO_2 concentration could supply sufficient CO_2 for the crop photosynthesis, enhance the efficiency of crop growth [14] and further improve the crop quality in the greenhouse [21].

There has been a rich literature focusing on the monitor and control problem on CO_2 concentration in the greenhouse [5,15,23,24]. In [5], the change rule of CO_2 concentration in the greenhouse has been investigated and two conclusions have been drawn: 1) there are obvious seasonal and diurnal variations of CO_2 concentration in the greenhouse, and 2) adjusting the CO_2 concentration reasonably could increase production and also improve the quality of crops. In [23], the variations of CO_2 concentration have been studied for the overwintering tomato cultivation in the solar greenhouse with sand land. It has been suggested that CO_2 enrichment would be needed during the cultivation process in the greenhouse. In [24], two quantitative models have been established by using the back-propagation (BP) neural networks and the radial basis function (RBF) neural networks, respectively, where the crop photosynthetic rate and CO_2 concentration in the greenhouse have been analyzed for reliable action on the CO_2 enrichment. In [15], a prediction model has been built for the single leaf photosynthetic rate on the BP neural network, which could be used to the quantitative management of CO_2 concentration for the tomato cultivation in the

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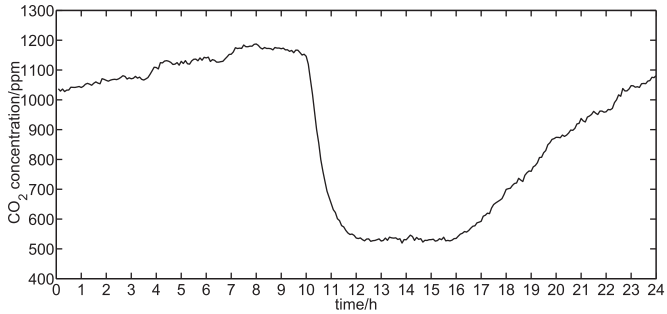

Fig. 1. Change curve of CO_2 concentration in the greenhouse.

greenhouse environment. It can be seen from the aforementioned literature that the estimation/control of CO_2 concentration is a practically significant topic of research for efficient growth of crops in the greenhouse. Unfortunately, the greenhouse system is a complex time-varying system and it is difficult to accurately predict the CO_2 concentration for the control over the CO_2 enrichment in the greenhouse. As such, the real-time monitoring of CO_2 concentration could help the control of CO_2 concentration changes in the greenhouse. The recently popular wireless sensor network (WSN) [13] is very propitious to the distributed environment monitoring due to its great advantages including easy deployment, self-organization, less demand for cables and network extendibility, etc. [17]. With a deployed WSN, the CO_2 concentration could be monitored efficiently in the greenhouse, and this would help facilitate the reliable control over CO_2 content with hope to create the best conditions for the crop growth.

Despite the capability of WSNs in acquiring the CO_2 concentration information in the greenhouse, there is a gap between the information gathered by distributed sensor nodes and the understanding of the CO_2 concentration state in the greenhouse. Such a gap is mainly due to the unavoidable internal and external disturbances as well as communication constraints of the WSNs. For example, the sensor measurements could be subject to various types of noises, packet dropouts and communication delays that result typically from random fluctuations of the network conditions and inherent limits of the network bandwidth. Therefore, a vitally important issue is to estimate the true CO_2 concentration in the greenhouse from imperfect sensor measurements for the benefits of CO_2 enrichment for the crop growth. It has been discovered in [27] that the data fusion estimation of WSNs in the greenhouse monitor system can enhance the sensory ability of the greenhouse environmental state. In [22], the estimation process has combined the observed data with the spatial or temporal correlation according to certain rules to get the accurate description of the monitored object. In [27], a weighted fusion algorithm with optimized grouping has been proposed which could improve the optimal estimation of the greenhouse environmental state. In [22], the Kalman filter algorithm has been introduced into the greenhouse environment monitor system by using an improved distribution map method. It should be pointed out that the fusion algorithm can improve the monitor accuracy only under the condition of stable operation of the greenhouse system. In [6], the measured values of sensor nodes in each group have been assumed to be tested for the consistency to exclude outliers, which may throw away the data caused by the dynamic fluctuations of the system and reduce the information integrity for the accurate estimation.

As is well known, the greenhouse system is a complicated system with chemical, biological and physical reactions [19], and it is rather challenging to grasp the changing law of the dynamic process. In order to obtain a satisfactory state estimation for CO_2 concentration over WSNs with network-induced phenomena, the data fusion scheme should take into account both the dynamic changes of the CO_2 concentration in the greenhouse and the inherent characteristics of WSNs. It is, therefore, the focus of this paper to investigate the fusion estimation problem over WSNs for monitoring the CO_2 concentration in a greenhouse where the possible packet dropouts with the communication links and the combined utilization of current and past estimates are taken into account. Motivated by the discussions made so far, in this paper, the data fusion scheme for estimating CO_2 concentration in the greenhouse over WSNs is investigated. Since the distribution of CO_2 concentration has characteristics of regional consistency in the modern greenhouse with large scale size, the cluster-based WSNs is adopted for efficient monitoring of CO_2 concentration in the greenhouse. Considering the facts that the measurement of CO_2 concentration is easily subject to environmental interferences, the distributed estimation scheme via Consensus–Kalman filtering approach is proposed to improve the estimation accuracy of CO_2 concentration where the sensory data are transmitted to the head node by the distributed data dissemination in WSNs. The head node of the cluster carries out the weighted data fusion of the data from the available nodes in the same cluster within hierarchical networks.

The main contributions of this paper are summarized as follows: 1) the distributed Consensus–Kalman filter algorithm is proposed to estimate the CO_2 concentration in order to improve the estimation accuracy; 2) the distributed transmission of sensory data is allowed to conduct on the dynamic route in WSNs so as to reduce the communication conflict and increase the transmission efficiency from sensor nodes to the head node; 3) the proportion of the faulty sensors is used to reflect the packet loss phenomenon resulting from the unreliable communication links; and 4) a modified estimation strategy is put forward that combines the estimates from sensor node at both the previous and current time points, thereby improving the accuracy of data fusion.

The remainder of this paper is organized as follows. Section 2 introduces the network model and system model of WSNs for CO_2 concentration monitoring in the greenhouse. The problem formulation is presented for the distributed estimation and transmission in WSNs. In Section 3, the detailed schemes for distributed data estimation and transmission are proposed. In addition, the reliable data fusion scheme at the cluster head node is presented. The simulation and performance evaluations are presented in Section 4 to demonstrate the effectiveness of our proposed scheme. Finally, we conclude the paper and point out possible future research topics in Section 5.

2. System description and problem formulation

2.1. Network model

WSNs are composed of wireless sensors of small size and low cost, which have potentials for ubiquitous monitoring of the smart greenhouse. In Fig. 2(a), the WSN with single layer network structure is presented for the greenhouse monitoring, which is suitable for the small-scale greenhouse. Sensor nodes can transmit the collected information to the sink node for the reliable control over the CO_2 concentration in the greenhouse. If the greenhouse space is relatively large, the distribution of CO_2 concentration is often not uniform. In order to improve the accuracy of data fusion and perform the reliable distributed control, the cluster-based WSN is a good choice. As shown in Fig. 2(b), sensor nodes scattered in the field are divided into several clusters. Each cluster has a head node with superior power, computational and communication capabilities as compared to other sensor nodes. The cluster-based topology of the WSNs scales effectively in accordance with the regional variations of CO_2 concentration in the greenhouse with a larger space. Sensor nodes have limited communication capability, and they are responsible for collecting and sending data to the corresponding head node by multihop transmissions. The head nodes fuse the data and send them to the sink node of WSNs for further processing. Head nodes can be integrated with actuators for the distributed control over the state change in the greenhouse.

The topology of the network is modelled as a fixed directed graph