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Sensor network architecture for intelligent high-speed train on-board monitoring*

Xiao-fan WU†, Chun CHEN, Jia-jun BU, Gang CHEN
(*College of Computer Science, Zhejiang University, Hangzhou 310027, China*)
†E-mail: wuxf@zju.edu.cn

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Abstract: The China's high-speed railway is experiencing a rapid growth. Its operating mileage and the number of operating trains will exceed 45 000 km and 1500 trains by 2015, respectively. During the long range and constant high-speed operation, the high-speed trains have extremely complex and varied work conditions. Such a situation creates a huge demand for high-speed train on-board monitoring. In this paper, architecture for high-speed train on-board monitoring sensor network is proposed. This architecture is designed to achieve the goals of reliable sensing, scalable data transporting, and easy management. The three design goals are realized separately. The reliable sensing is achieved by deploying redundant sensor nodes in the same components. Then a hierarchal transporting scheme is involved to meet the second goal. Finally, an electronic-tag based addressing method is introduced to solve the management problem.

Key words: High-speed train, On-board monitoring, Sensor network, Network architecture
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1 Introduction

Since the zero serious high-speed train (HST) was put into operation on the Tokaido Shinkansen in Japan in 1964 (Wikipedia, 2011), the HST technology has experienced a rapid development all over the world. In China, the mileage of high-speed railway network will be beyond 45 000 km, and the number in the HST fleet will be more than 1500 trains by 2015. Due to the vast land area and the diverse geographic conditions in China, the HST operation is characterized as long continuous running time, high constant operation speed, and complex running conditions. Besides these operation characters, the HST operation status is influenced by the factors of wheel-track interaction, pantograph-contact line interaction, and aerodynamic effect. On-board monitoring is crucial to the safety of HST operations.

Taking advantages of the merge developed electronic technology, sensor network has been applied to the area of environment monitoring, event detection, and target positioning (Akyildiz *et al*., 2002). For the purpose of HST condition monitoring, an on-board sensor network is needed. This sensor network should be capable of reliably sensing the dynamic status of the travelling system, traction-and-breaking system, and carrier system of which an HST consists.

To build such a sensor network, some challenges must be considered. Firstly, this sensor network may work in alternative environment. Because some important parts of HST, such as the buggies, the traction transformers, the traction converters, are outside the vehicle body, the sensor nodes on these components will experience dramatically changing aerodynamics effects. The poor working conditions may cause sensor failure to work properly, and then reduces the monitoring reliability. Secondly, the HST vehicles are grouped in various forms. In China, the China

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Railway high-speed (CRH) trains are of 8-vehicle short groups and 16-vehicle long groups. And in other countries, much more grouping forms are used. The architecture of condition monitoring sensor network must be scalable to the different grouping form. The large number of HSTs in service brings the third challenge to the condition monitoring sensor network, the management and maintenance problem. Hundreds of sensor nodes need to be deployed on-board an HST to retrieve status parameters of the key components. It is impossible to assign addresses to each node manually considering the huge amount of the HSTs.

In this paper, a hybrid hierarchal architecture for HST condition monitoring sensor network is proposed. In this architecture, an electronic tag is attached to every key component which is covered by the monitoring sensor network. This tag can be read via a handheld reader by maintenance people or via a circuit by the sensor nodes around this component. When the sensing data is being reported, a hierarchal transporting scheme is introduced. The data packets are first gathered by the subnet level sinks (SLSs), then the SLSs report the sensing data to the vehicle level sinks (VLSs). Finally, the VLS handover the monitoring information to a train level sink (TLS).

In this architecture, the monitoring reliability is achieved by deploying redundant nodes on a single component. The transportation reliability is achieved by linking the VLS and TLS via a double ring network. The scalability is realized by the hierarchal transportation scheme. From the view of train level network, only a few VLSs are added or removed when they apply to HST with different grouping forms, and from the view of every vehicle, the network topology remains the same. The management problem is solved mainly by assigning addresses to sensor nodes via the electronic tag attached on the HST components.

2 Related works

In recent years, research on applying sensor network to railway condition monitoring has been undertaken. SENSORAIL (Flammini *et al*., 2010) has been presented as an early warning system. It is suitable for both structural health monitoring and infrastructure surveillance against natural hazards and intentional threats. SENSORAIL makes use of wireless sensor networks (WSN) for railway infrastructure monitoring. Fukuta (2008) discussed the possibility of applying sensor network for a railway signaling system, and the ability of multi-hop wireless communication of sensor networks is reliant upon as a solution for long range data link along the rail. Both SENSORAIL and Fukuta (2008)'s work applied sensor networks to monitoring railway systems. The sensor nodes were deployed along the track. Yan *et al*. (2010; 2011) demonstrated the optical sensor network solution for strain measurement and axle-counting. They made use of fiber-bragg-grating (FBG), a kind of emerging optical fiber sensors, as the sensing components.

An indirect approach for measuring vehicle operation speed by mounting inertia sensors on a bogie frame achieved better accuracy than the International Union of Railways (UIC) standard method (Mei and Li, 2008). Different wheel-sets of a single bogie may appear to have the same moving pattern with a time interval. This approach uses the time interval to derive the vehicle speed. Both Yan *et al*. (2010; 2011)'s work on fiber sensors and Mei and Li (2008)'s work on speed measuring focused on the sensors themselves and their uses, whilst the network architecture was not mainly considered.

For monitoring the performance of rail vehicles, a wireless communication based system was designed (Nejikovsky and Keller, 2000). This system consisted of Global Positioning System (GPS), embedded computer, sensors and satellite data link. The sensing data together with time and location tags report to a central station via the satellite data link. Nejikovsky and Keller (2000) discussed the top level design of a train remote monitoring system, but the on-board system was not detailed. Also, their system was designed for the normal speed locomotives.

3 Network architecture

3.1 Design goals

To meet the demand of intelligent HST on-board monitoring, our network architecture is mainly concerned three aspects.

The first goal is to enhance the reliability of sensing. Sensing network system is the key factor to keep on-board monitoring system to work well. However, the on-board monitoring network is required to handle high payload and to work under poor environment due to the high-speed, large-capacity, and long-distance characters of the HST operation. Thus, we consider the reliability to be the first point to consider.

The second design goal is to improve the scalability of the monitoring sensor network. All of the CRH1, CRH2, CRH3 and CRH5 have two different grouping forms, the 8-vehicle group and the 16-vehicle group. For the same CRH model, two 8-vehical groups can be hooked up to operate as a single train-set. As shown in Fig. 1, the environment monitoring sensor network usually adopts the ad-hoc multi-hop data reporting scheme (Shi *et al.*, 2008). Such a scheme is adaptive when the network shrinks. However, in the intelligent HST scenario, the network with hundreds of nodes may double the node amount due to the change of grouping form. As a result of the limitation in scalability of usual network architecture, a new data transporting scheme is needed.

The third design goal is to ease the management of this on-board monitoring sensor network. Assigning addresses to network nodes is the first and an important step in managing a sensor network. Due to the huge amount of sensor nodes on HSTs, it is almost impossible to configure the nodes with proper addresses. This raises the demand of an easy solution to manage the node addresses.

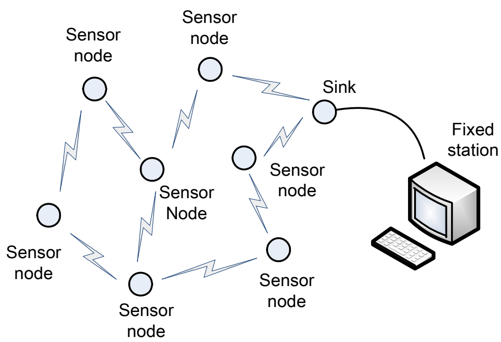

Fig. 1 A sensor network adopting ad-hoc multi-hop data reporting scheme

3.2 Hybrid hierarchal architecture

As shown in Fig. 2, the presented architecture consists of three layers, i.e., the sensing layer, the data transporting layer, and the on-board data center.

Positioned at the bottom, the sensing layer plays the role of data source of the complete monitoring system. The network nodes at this layer are hybrids of electronic tags and sensors. Taking advantage of this hybrid, the network management can be greatly eased (The benefits of hybrid nodes are detailed in Section 6). The other feature of nodes in this layer is the redundant deployment. The sensing reliability can be enhanced by this redundant deployment and proper data fusion at the data transporting layer.

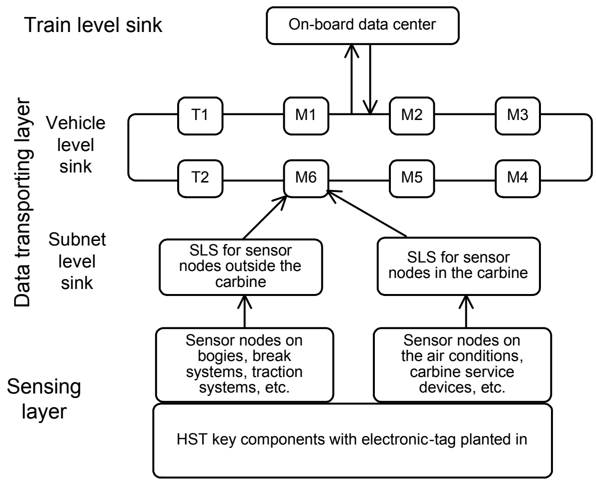

Fig. 2 Hybrid hierarchal architecture

At the middle of this architecture is the data transporting layer. Network nodes in this layer are SLSs and VLSs. In every vehicle, sensor nodes of the sensing layer are divided into two subnets, the one inside the carbine and the other outside. The subnet outside the carbine has an individual SLS located under the vehicle body. This SLS gathers the sensing data from the traction system, the break system, and the bogies. Splitting the sensing layer into two subnets enables linking the sensor nodes inside and outside the carbine at a single point. The single linking point reduces not only the network complex, but also the building cost.

After aggregating the sensing data, the SLSs report packets to the VLSs. VLSs have more powerful communication and computation capacity to exchange data with other VLSs and perform the advanced data fusion in order to reduce the workload over the sensor network. All of the VLSs on an HST are linked via a ring network. Using a ring network rather than a bus network is a result of reliability requirement. The bus network cannot suffer any link failure because of the serial link through the whole HST, while the ring style network can function normally even if a single link is down as shown in Fig. 3b. Note that the ring network linking the VLSs is independent from the existed train control network to prevent interference between the monitoring network and the control network.

An on-board data center sits on the top of this monitoring sensor network. The data center stores the data reported from the lower layers, and analyzes it in order to give on-board alarm for security risks and component faults. Discussion about the data center is beyond the scope of this paper, because the main focus here is the network architecture.

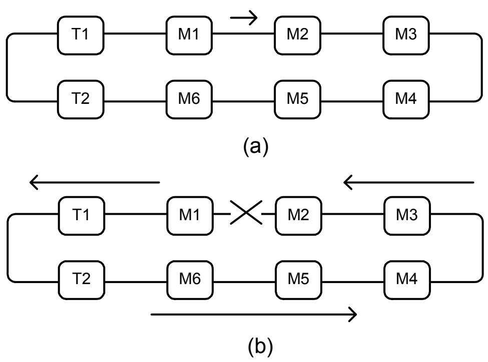

Fig. 3 VLSs linked via a ring network
Each box represents a vehicle of a CRH2 train. T1 and T2 are at the two ends of the train, M1 to M6 are the middle vehicles. In normal case, the VLS on M1 can talk with the VLS on M2 through the direct link as shown in (a). When the direct link is down for any reason, the VLS on M1 can still exchange data with VLS on M2 via the remaining links as shown in (b)

4 Reliable sensing

The sensing reliability comes from two aspects of the presented architecture. First is the redundant deployment of sensor nodes as shown in Fig. 4. Due to the poor working environment during the HST operation, a single sensor node may give an error data or go down completely. To solve this problem, involving redundant deployment is a rapid way to develop more robust sensors.

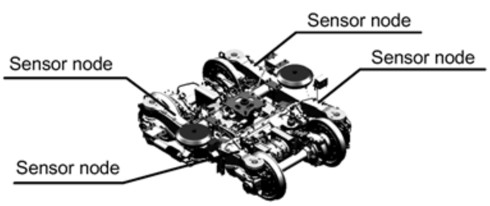

Fig. 4 Redundant deployed sensor nodes on a single bogie

Let $0 \leq R_0 < 1$ be the reliability of a single sensor, and n to be the total number of sensors around the same monitored component. Then the final reliability of this sensor groups R_g can be derived as follows:

$$R_g = 1 - (1 - R_0)^n.$$

From the above formula, the failure possibility of an n-sensor group, noted as $P_f=1-R_g$, is exponentially reduced when n increases.

To make use of this redundant deployment, data calibration and filtering should be performed on the SLS because of the limitations in computing and storage capacity of sensor nodes. A machine learning method or empirical model based method can be used to do this (Bychkovskiy *et al*., 2006).

5 Scalable data transporting

The sensor nodes in a usual sensor network report sensing data by sending a packet to the destination of the sink node. Although this packet may hop several times, the relay nodes in the middle of the handover path do not merge the payload with other packets even it is possible. Also, the sink node will process packets originating from any other nodes.

Under the scenario of HST on-board monitoring, hundreds of components are covered by a single sensor network. Considering the redundant deployment introduced to rising reliability, the number of sensor nodes may be more than 1000. Also, every node produces a constant data stream. These data streams jam the data link and occupy computing resource of the sink node.

To address this issue, a hierarchal data transporting layer is involved. Within this transporting layer, the data reporting procedure is divided into subnet level, vehicle level, and train level. Each level has its own sink node, and the sink node of a lower level is also the source node in an adjacent higher level. The sink node of a level aggregates the data stream from the source node, reduces the total data amount, and reports to a higher level sink.

By dividing into levels, a single sink needs to handle tens of data streams only. The workload is much reduced in comparison with a sink node in the usual sensor network.

This mechanism will work correctly on both 8-vehicle group and 16-vehicle group. The reason is that at the levels lower than the vehicle, everything remains the same, and at the train level, the on-board data center (plays a role of total sink) receives only eight more aggregated data streams.

The hierarchal data transporting layer prevents the network structure changing within the top level when the grouping form varies. Also, the sink nodes of lower levels reduce the total data amount by aggregation and compressing.

6 Manageability of the monitoring sensor network

To manage the monitoring sensor network on-board thousands of HSTs is a challenging task. Ill configured sensor nodes cannot communicate with other part of the network, and may even jam the data link by sending rubbish data.

Some automatic tools are developed to manage a data-centric sensor network (Lee *et al*., 2012). That kind of sensor network marks nodes through the sensing data, and the demand of indentifying a specific node is small. However, in the HST condition monitoring scenario due to the similarity of vehicles in an HST, the data-centric way of network management does not work.

This problem is addressed by using hybrid nodes that are described in Section 3. To enable the hybrid nodes, the monitored components should have an implanted electronic tag. Also, the tag stores information of the component, such as type, model, and serial number. During the sensor network booting procedure, the sensor part of the hybrid nodes reads the tag, and retrieves the network address based on the serial number information. By doing this, every sensor node has a different address, and the higher layer of sensor network can easily indentify the data source of each packet. The tags can be used not only to assign the address automatically, but also to help HST maintenance. The workers can read the tag through a handheld reader, which makes the service events paperless.

7 Conclusions

In this paper, a hybrid hierarchal sensor network architecture for HST on-board condition monitoring is presented. This architecture is designed for achieving reliable sensing, scalable data transporting, and easy management. To realize these three design goals, redundant sensor nodes are involved as a guarantee of reliability, a multi-level data reporting scheme is used to make the data transporting scalable, and a new kind of tag-sensor hybrid nodes is introduced to ease the network management.

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