Design of Cyber-Physical Systems Architecture for Prognostics and Health Management of High-speed Railway Transportation Systems

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ABSTRACT

The high-speed railway (HSR) transportation system in China has been growing rapidly during the past decade. In 2016, the total length of HSR in China has reached to 22,000 kilometers, and there are over 2,000 pairs of high speed trains operating daily. With the advancement of design and manufacturing technologies, the reliability and construction costs have been improved significantly. However, there is still great need for reduction of their operation and maintenance costs. With such incentive, a pilot project has been launched in CRRC to develop a prognostics and health management system for rolling stock to transform the maintenance paradigm from preventive to predictive maintenance. Considering the high task variety and big data environment in HSR real-time monitoring system, a cyber-physical system (CPS) architecture is proposed as the framework for its PHM system. This paper reviews the needs of predictive maintenance for the HSR system, and then present a concept design of the CPS-enabled smart operation and maintenance system.

INTRODUCTON

The high-speed rail (HSR) system in China has been growing rapidly since 2007. In 2016, there were over 2,000 pairs of high speed trains operating daily with total ridership of 1.4 billion, making the HSR China most heavily used in the world. A recent survey conducted by Nomad Digital among rail operators shows that operation and maintenance costs have become the biggest concern [1, 2], and China is no exception. For example, the maintenance paradigms of HSR in China is mainly preventive maintenance with large safety margin due to the high safety standard, which has caused considerable cost burden and challenges of sustainable growth of China's HSR system; Meanwhile, many Europe countries such as Italy, France all have high safety requirements on their railway transportation systems and also encourage to reduce maintenance costs. Thus, it has attracted many attentions on new techniques for railway condition-based maintenance. These concerns have led to the development of Prognostics and Health Management (PHM) solutions in CRRC Group to transfer the condition monitoring data into desired information and knowledge to improve the life-cycle costs and service reliability [3].

The enabling technologies to develop a PHM system involve condition monitoring, information and communications technologies (ICT), and more importantly predictive analytics technologies. The primary goal is to transform the invisible patterns of component degradation and loss of efficiency into health insights [4]. A good example of PHM system practice in HSR is the TrainTracer™ [5] launched by ALSTOM in 2006 for real-time remote monitoring of trains. Another product named TrackTracer™ [6] has also been developed by ALSTOM that is complementary to and integrated with TrainTracer™ to further enable predictive maintenance service for track infrastructures.

The CRRC Qingdao Sifang Co. Ltd. has realized that manufacturing of rolling stocks solely has a predictable limit of market needs and profit margin. Therefore, predictive analytics and smart services have been introduced for enhancing the product competency and improving the sustainability of value chain. This paper discusses a framework design of predictive maintenance system based on the architecture of cyber-physical systems.

A PHM Framework designed based on Cyber-Physical Systems

The concept of cyber-physical systems (CPS) has been defined as an engineered system in which the nature and human made systems (physical space) are integrated with computation, communication, and control systems (cyber space) in all scales [7]. In 2013, Lee, et al. proposed an implementation framework of CPS for predictive maintenance which consists of five levels [8]. Inspired by the five-level architecture design of CPS, the CRRC Qingdao Sifang Co. Ltd has proposed a framework for rolling stock predictive maintenance, which consists of the following elements, as seen in Figure 1:

Data connection: There are various data sources from the rolling stock and the operating environment. Data sources related to operation conditions includes add-on sensors and controllers from critical subsystems, which include traction motor, power transmission systems, bogies and electronic systems. Railway infrastructure such as tracks, catenaries and point machines can also be sources of data that needs to be integrated in the onboard DAQ system.

From data to health features: After connecting various data sources in the train, the data will be further converted to health related features in the onboard processing system. Signal processing, feature extraction, health assessment & diagnosis algorithms (such as self-organizing map, logistics regression, support vector machines, etc.) and predictive analytics are integrated in a train-based analytical server; The health information is then used to support the decision of drivers to be aware of the condition and potential risks.

Data mining and modeling: The underlying features and selected raw data from fleets of trains are transferred to a data center at the CRRC Qingdong Sifang. With a big data environment created, data mining for knowledge discovery and model development will be performed with advanced algorithms. Peer-to-peer comparison, information sharing, collaborative modeling, and time machine records of utilization matrix and health condition history will also be developed. Models created or improved in the data center is able to be deployed and updated to multiple fleets.

Decision support Apps: In this level, the PHM analytics results of the railway system will be combined with the expert knowledge through their inputs for making optimal fleet management and maintenance decisions. The analytics results and decision support information will be shared in Web service APPs to different sectors, such as the HSR operators, OEMs, and service providers.

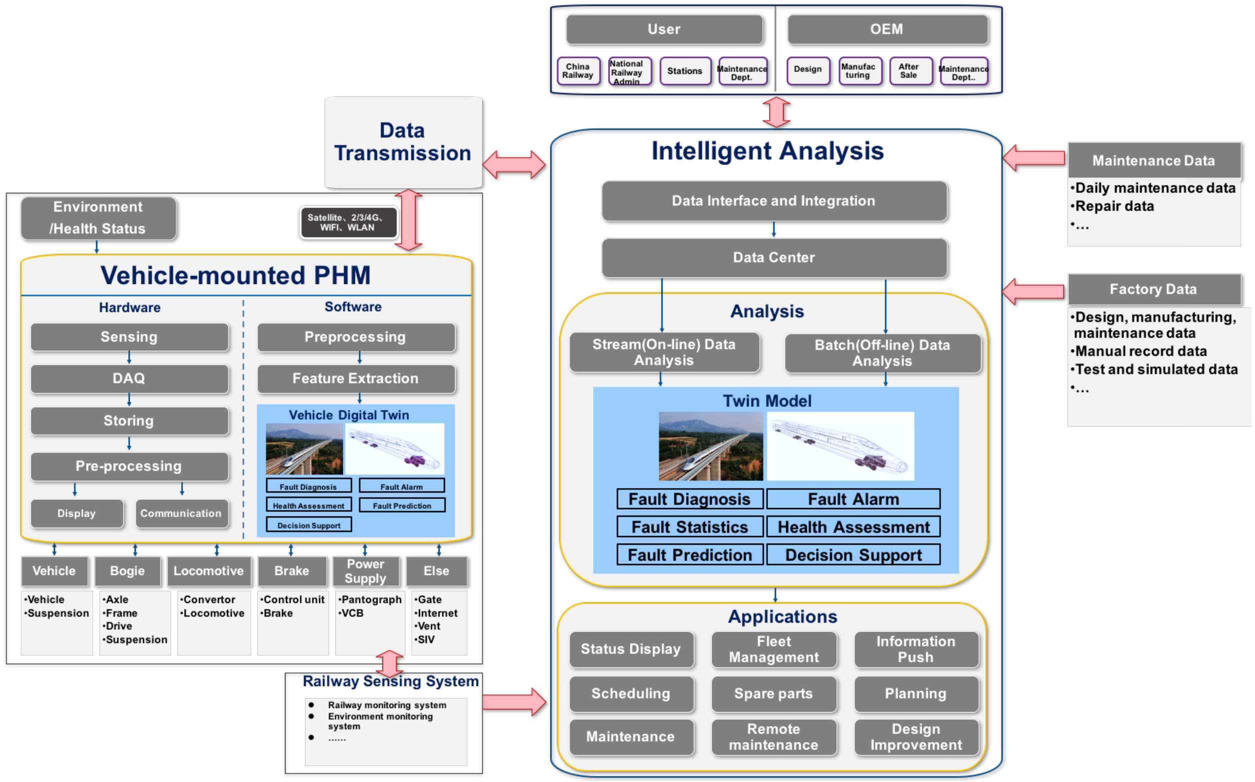

Figure 1: The PHM System Framework Design in CRRC Sifang Co. Ltd.

A Predictive Analytics Interface to Connect Physical Space and Cyber Space

For HSR systems, one could consider a variety of critical assets in the physical space, such as locomotive induction motor, bogies, wheelset bearings, and transmission gearbox. With various components and data sources, it urges to consider what hidden issues of the assets are of most concern, and what invisible information needs to be predicted and revealed in cyber space. For instance, the development of winding shortage is difficult to be measured directly, but could be monitored from sequence impedance features which are extracted from motor current and voltage signals. Therefore, appropriate features and analytical models need to be established in a cyber-physical interface to enable transparency of the hidden state in physical space as twin model representations in cyberspace, as indicated in Figure 2. The CPI introduces the concept of 'Time Machine' to convert the continuous and heterogeneous data source into structured data format for further computation. To improve data storage and computation efficiency, the snapshots of sensor data, controller data, and event data are all recorded instead of the raw time-series data. These snapshots are only taken in discrete time, and can be triggered by either fixed time intervals, or based on event such as change of operation regimes and health status. During the lifecycle of a machine, these snapshots will be accumulated to construct the 'time machine' history of condition changes of the assets. Each snapshot record can be used as a twin model of a particular condition for peer-to-peer comparison and causal relationship modeling between the assets.

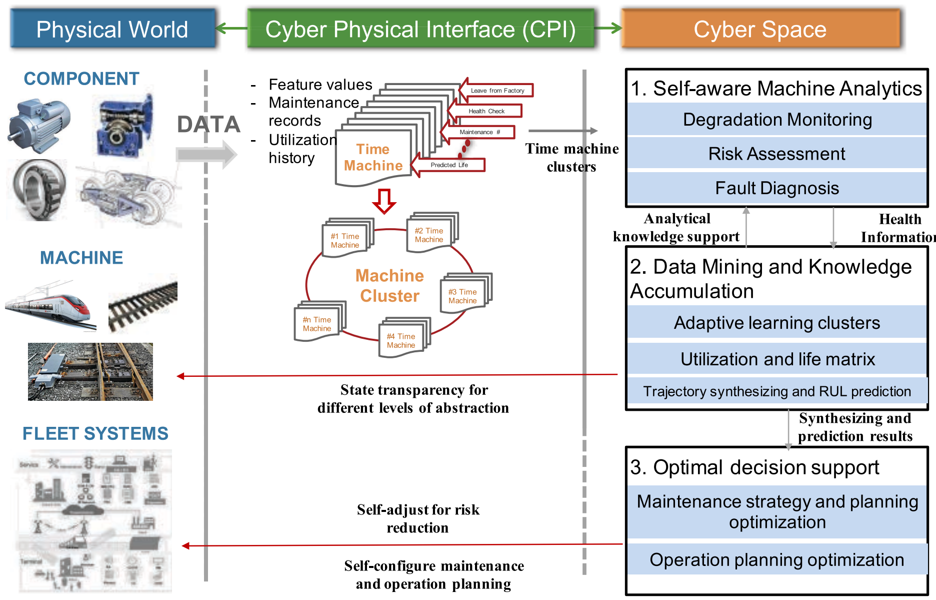

Figure 2: Cyber-Physical Interface Platform for HRS Applications

Summary

In this paper, the experience of HSR condition monitoring and concepts of CPS are combined to consider a framework of PHM system architecture and discuss the elements in the framework. The PHM system architecture proposed in this paper is designed to meet the requirements and challenges in large fleets and big data environment. A train-based agent with smart analytics algorithms is used to collect data and convert them to health related information. The underlying features and selected raw data are further transferred to the data center for knowledge discovery, model development, and decision support. The health insights and decision references can be further used by different sectors of the HSR industry through App services to improve collaborative optimization and synchronization.

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