Technology Innovation in Developing the Health Monitoring Cloud Platform for Maglev Vehicle-Suspension-Guideway Coupling System

SU-MEI WANG, YANG LU, YI-QING NI and YOU-WU WANG

ABSTRACT

The maglev transport system, which has the advantages of a wide speed range, smaller turning radius, and higher climbing ability, has currently been constructed and developed in China. Currently, one high-speed maglev business line and two low-speed maglev business lines are in operation, while many more maglev lines are in construction in China. For monitoring the operation condition of the maglev system, a health monitoring (HM) system based on the cloud platform has been designed for the whole maglev vehicle-suspension-guideway system. The study presented in this paper summarizes the innovative technology on design and the implementation of this HM cloud platform. In this paper, the modular design of the HM cloud platform is introduced first. The integration of on-board and way-side monitoring, and the application of the Big Data technologies, cloud computing, and artificial intelligence algorithms in the HM cloud platform are the focus of this paper and followed by the introduction of the special function of the presented HM cloud platform. The latter is used to verify and evaluate the effectiveness of the suspension control system.

INTRODUCTION

The maglev train, which uses non-contact and non-wearing levitation, guidance, and propulsion technologies, is a new type of transport and has been widely noted in recent years [1]. The main difference between the Maglev railway and the traditional wheel-rail railway is that the wheel-rail passive support force in the wheel-rail railway is replaced by the electromagnetic force of the active suspension control [2]. Two kinds

Su-Mei Wang, Yang Lu, Yi-Qing Ni, and You-Wu Wang, Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong; the Hong Kong Branch of National Rail Transit Electrification and Automation Engineering Technology Research Center, The Hong Kong Polytechnic University, Hong Kong

of maglev technologies, electrodynamic suspensions (EDS) with repulsive mode and electromagnetic suspensions (EMS) with attractive mode have been developed for practical applications [3]. As a new type of urban transport, the EMS technology has achieved great success in both low-speed (100 km/h) and high-speed (450 km/h) maglev trains [4].

Railway safety and reliability are critical factors for developing a new type of transportation as they are highly relevant to national development, and the lives and property of people. As the Maglev train is a new type of railway vehicle, it is difficult to analyze its safety performance, due to the lack of its experience on long-term operations [5]. Furthermore, the suspension control system in the maglev train indirectly controls the electromagnetic attraction force to neutralize the gravity of the train, which, in turn, causes special vibration problems [6, 7]. The dynamic characteristics and running safety and comfort of the maglev system are not only affected by the suspension control system but also by the coupling interaction of the vehicle and guideway. On the one hand, the electromagnetic forces produced by a constant current are inversely proportional to the square of the levitation gap, which makes the electromagnetic levitation system inherently unstable [6]. Hence, a reliable suspension control system is essential to stabilize the levitation system around a desired suspension gap. As the suspension gap is actively controlled by the electromagnetic suspension system, the dynamic interaction between the electromagnet and the guideway occasionally causes resonance or instability [8]. The electromagnet and the guideway will be significantly amplified once resonance occurs. In addition, it has been observed that the self-excited vibration occurs when the vehicle is suspended upon the guideway or moving at a very slow speed [7], which degrades the safety and durability of the guideway and the stability of the suspension control system [9]. Additionally, the vibrational characteristics of the guideway also play an important role in the dynamics of maglev vehicles. Since the gap between the guideway surface and vehicle electromagnet is only about 8 mm, the guideway status such as irregularity and faults in any part of the guideway could have a huge influence on the vehicle safety performance [10]. In practice, it is found that track irregularity can affect suspension control and ride comfort stability [11]. Moreover, railway conditions such as curvature radius of the track, climbing slope, and irregularity also largely affect the dynamic load on the levitation bogie which is the key subsystem for maglev train security [12]. As the levitation bogie is operated under levitation force, restoring force, and propulsion, the fatigue load is easily caused by repetitive levitation and landing during service. If abnormal loads including a lateral skid, torsion, propulsion motor, brake, adhesion of electromagnet, and vertical drop load occur [12], the levitation bogie may become unstable, leading to a failure of the suspension control system to suspend the vehicle. Under these circumstances, there is growing attention on the development of a systematic health monitoring (HM) system for a maglev vehicle-suspension-guideway coupling system for condition assessment, fault diagnosis, and preventive maintenance purposes. Information on maglev health conditions is important, not only for the stability and safety of maglev systems but also for the design of new maglev systems.

In this paper, a sophisticated online HM platform based on a cloud platform has been designed and implemented by the Hong Kong Polytechnic University to monitor a maglev vehicle-suspension-guideway coupling system. The HM cloud platform consists of more than 200 sensors being installed on the maglev train, track, and bridge. The key technological issues in the development and implementation of the HM cloud platform and the special function of that platform are described. Finally, some representative results from monitoring data are presented and discussed.

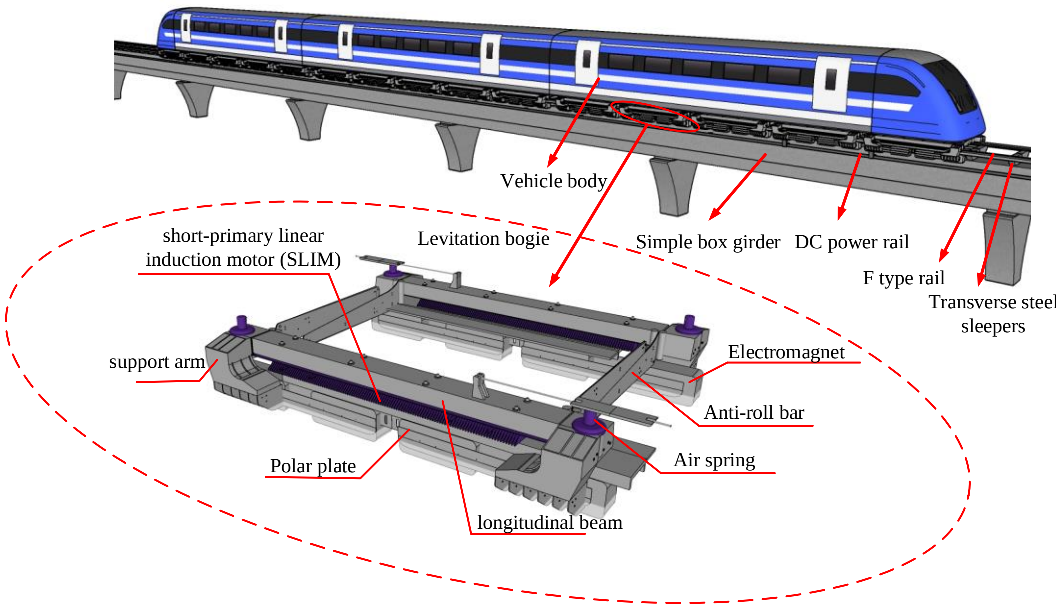

Figure 1. The configuration of maglev system.

AN OVERVIEW OF MAGLEV VEHICLE-SUSPENSION-GUIDEWAY COUPING SYSTEMS

The HM cloud platform presented in this paper was installed on a low- and medium-speed maglev test line. The total length of the maglev line is 1.7 km which includes the straight segment, curve segment, climbing segment, and a rail switch. The low-speed maglev system consists of a multi-span elevated guideway, a power rail, and an EMS-type train with three carriages. Figure 1 shows the configuration of the maglev vehicle-suspension-guideway system. The elevated guideway consists of a simple box girder, transverse steel sleepers, and an F-type rail. The Maglev train is powered through the contacts between the power rail and the current collector on board. A maglev carriage is composed of a vehicle body and five levitation bogies. Each levitation bogie consists of two levitation modules with functions of levitation, guidance, and traction of the vehicle, and the two modules are connected by an anti-rolling beam. The levitation module is mainly composed of two support arms, one longitudinal beam, one short-primary linear induction motor (SLIM), four levitation electromagnets, and one polar plate. Its suspension and guidance functions are realized with the levitation electromagnet and the F-type rail, and its traction adopts the SLIM. Each levitation module has four suspension modules which is the basic suspension function unit of a Maglev train with two independent degrees of freedom (vertical and pitching). The adopted control strategy involves the division of system into two independent subsystems, with two parallel connected electromagnets and one corresponding controller, each controlled separately. This control method is feasible without considering the mechanical coupling between the two subsystems. However, if the left subsystem is affected by outside disturbance, the right suspension gap fluctuates along with it. In addition, if either controller is disabled, the whole system will fall apart.

SYSTEM ARCHITECTURE OF HM CLOUD PLATFORM

The HM cloud platform based on Big Data analytics, designed for maglev systems, consists of six tiers: sensory network (SN), data acquisition and transmission (DAT), cloud storage and management (CSM), data processing and control (DPC), health evaluation (HE), and display interface (DI). Figure 2 shows the architecture of these six tiers. As an on-site measurement tier, the SN is installed on the maglev vehicle body, levitation bogie, F-type rail, and bridge to collect the data of maglev system. Vast amounts of diverse and complex data collected by the SN tier are transmitted to a cloud platform for data storage and analysis by DAT. The data are stored in the CSM tier using distributed file storage system. The data in the CSM will be reused by the DPC tire for data processing, analysis and visualization, using distributed computing clusters. After that, the system condition is evaluated in the HE tier based on Big Data algorithms, and the results are shown through the DI tier.

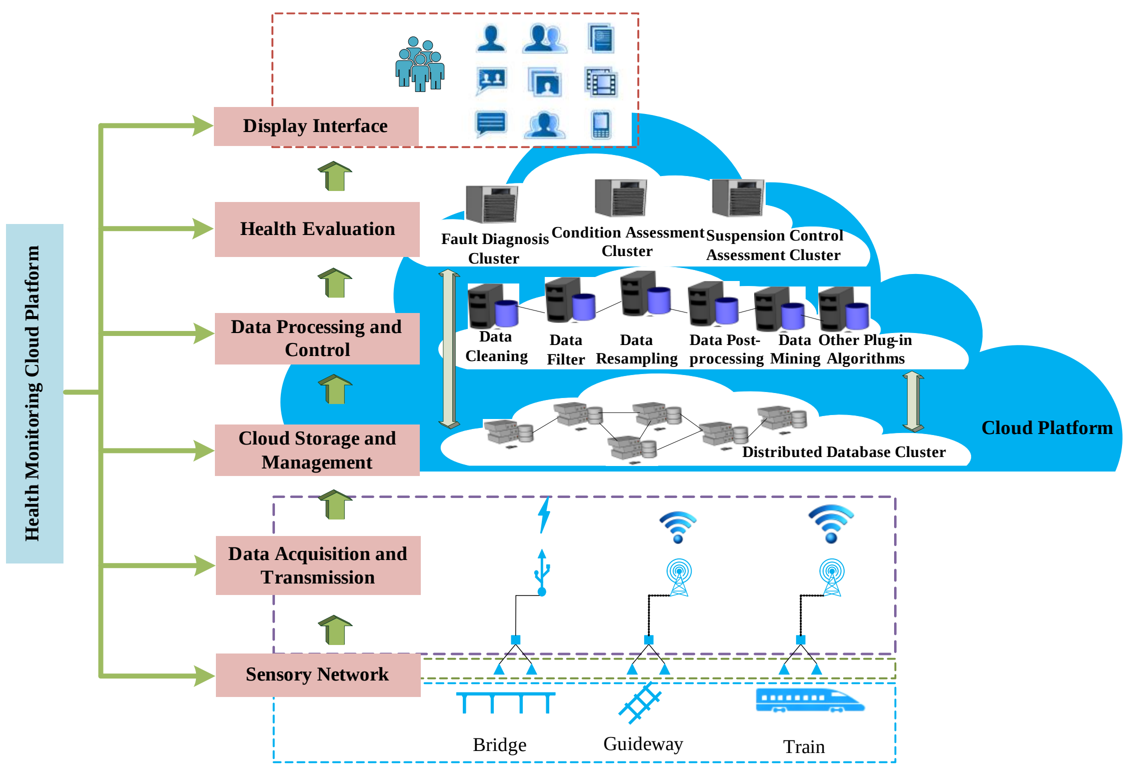

Figure 2. The architecture of HM cloud platform.

INTEGRATION OF ON-BOARD AND WAY-SIDE MONITORING

For a maglev train with three carriages, there are 15 levitation bogies and 60 suspension controllers. It is unrealistic and costly to equip an on-board sensor network for each levitation bogie or suspension controller to evaluate their operating condition. Additionally, it is also impossible and uneconomic to install a sensor network along the guideway for track condition inspection. Hence, most on-board sensor networks are used for track inspection and way-side sensor networks for train condition evaluation. Even though different sensor configurations are currently being implemented for monitoring railway and vehicle parameters, they mainly fall as either on-board or way-based systems. The proposed HM cloud platform which is designed for maglev system exercises a pioneering HM practice that integrates on-board and way-side monitoring. To monitor the condition of the maglev train and track, the sensor network is deployed only on one maglev vehicle body, two levitation bogies, and several critical segments of the guideway. In the integrated monitoring platform, it is important to collect the data from on-board sensor network in synchronism with track-side sensor network. Owing to the distributed storage and computing of the cloud platform, the data from sensor networks of on-board and track-side monitoring systems are synchronously recorded using an established virtual sensor system, and the data exchange of each component also can be realized.

The integrated monitoring platform enables the measurement of the dynamic response of the whole maglev coupling system. This is necessary for evaluating the real safety state of system components and the impact of extreme events (resonance of train and track, power cut, vehicle rail crashing, etc.) on the system condition. Besides monitoring the condition of the maglev system, the motivation to design and implement such an integrated monitoring system also lies in 1) being able to track complete data history including the vehicle body, levitation bogie, track, and bridge for investigating the interaction mechanism of the maglev coupling system, 2) fault diagnosis and localization of each suspension controller, and 3) collecting long term maglev bogie and track data to enable suspension controller optimization. When the history data of different components of the maglev system are obtained by the integrated monitoring platform, it is possible to establish an accurate model for the maglev coupling system by real-time model updating. Meanwhile, the parameters of the suspension control system are so sensitive to the deformation of F-type rail and need to be updated artificially according to the track deformation under different environment. Hence, the history data of the maglev train and guideway together with an accurate simulation model, will make for the investigation of the influence of track deformation under different environments related to the stability of the suspension control system.

BIG DATA ANALYTICS IN HM PLATFORM

Continuous monitoring of maglev systems can guarantee the availability of data that will be used to assess the running condition of the maglev trains and also present the least possible disruptions [13, 14]. However, the database constructed from continuous data monitoring will become increasingly large as a result of the frequent measurements from the HM systems of the maglev system. In addition, the data collected from the sensor network have different characteristics: 1) discrete or continuous, 2) spatial or temporal, 3) signal and image among others [13, 15]. Considering such data amount and specific characteristics, traditional data processing systems are inefficient, and cannot meet the data analytics requirement [16]. As a result, applying a Big Data analytics approach is necessary to monitor the system condition adequately and efficiently [17].

Big Data analytics are applied in the whole process from raw monitoring data to actionable maintenance knowledge [18]. Big Data analytics have resolved three problems: data storage, data analysis, and data application [16]. The original data including structured data, semi-structured and mixed data is transmitted to the cloud platform via wired or wireless communication. A virtual sensor system based on Spark is established on the cloud platform for distributed storage. The duplicate data are then selected and removed using the data cleaning techniques. The useful and accurate data is used to extract the hidden information by descriptive analysis and predictive analysis using machine learning theory (to be discussed in the next section). The analysis results are then applied in different circumstances, such as condition evaluation and prediction, fault diagnosis and location, and degradation detection.

Data fusion, as an important Big Data technique, realizes the merging of different databases to extract more consistent, accurate, and useful information than that provided by any individual data source. Studies in HM platform utilize data from various sources (such as data from on-board and way-side sensors) and evaluate the system performance based on multiple aspects. Hence, data fusion techniques, combining multiple data sources for data association, state estimation, and prediction, are adopted for HM cloud platform integration. In general, more than one sensor is installed on the critical location of the maglev system for calibration. Using data fusion technology such as Probabilistic Data Association [19], data from different sensors at the same location can be associated according to their similarity [20]. When data are collected from both on-board and way-side sensors to give a conclusive explanation of track conditions, common techniques such as Particle Filter and the Covariance Consistency Model can be used to track condition estimation by using collected multiple data. Meanwhile, such multiple data will be used for track damage prediction by applying data fusion technologies together with a prediction method such as regression or forecast modeling.

VERIFICATION OF SUSPENSION CONTROL EFFECTIVENESS BY HM

The HM cloud platform for the maglev system has been designed to enable the verification and evaluation of the effectiveness of the suspension control system, the latter being a unique and interesting practice of the HM cloud platform. Four suspension controllers are installed on one levitation bogie and each controller controls two electromagnets by a series of hybrid systems. A set of gap sensors and accelerometers is deployed on a series of two electromagnets for real-time monitoring the gap between the electromagnet and F-type rail and the dynamic levitation bogie response. The linear proportional-integral-derivative (PID) method is adopted for the simplified design process of the suspension controller. First, a local linear approximation process is implemented at the equilibrium point of the nonlinear mathematic equation of the suspension system. The monitoring data from the gap sensor and accelerometer are then selected as control feedback variables. Despite the simplified linear control algorithm having satisfied the requirement of control in most situations, environmental interference is difficult to control. When the vehicle vibration is out of balance under environmental interference, the control system may become unstable. To enable the monitoring of the stability of the suspension control system, the accelerometers are installed on a longitudinal beam of the levitation bogie. The FBG-based strain sensors are also deployed at the polar plate. To verify the effectiveness of the suspension control system under different rail conditions, a set of FBG-based sensors are installed at a 1.0 distance on the F-type rail to monitor the deformation of that rail. A real-time structure condition assessment technique based on the Bayesian dynamic linear model (BDLM) and Bayesian forecasting is proposed. Once the BDLM is available, a one-step (or multi-step) forecasting probability density function (PDF) can be obtained before proceeding to the next observation. This prediction model and its alternative model (which is usually formulated by shifting the mean value by a prescribed offset) can be statistically compared to determine which better fits the actual observation. If the comparison results are in favor of the alternative model, it is claimed that a potential change has occurred. The Bayes factor and cumulative Bayes factor in line with Bayesian hypothesis testing can then be elicited to accomplish outlier identification and condition assessment. The suspension condition can be evaluated automatedly by the BDLM. Meanwhile, through the long-term monitoring of the suspension control system, the relationship between the stability of the suspension controller and climate change will be investigated. The results will be used for updating the control algorithm to accommodate environmental changes.

CONCLUSIONS

The HM platform based on the cloud platform installed on a maglev system which is a kind of advanced transit has great practical significance for the application and development of HM technologies in the railway industry. The integrated on-board monitoring system, way-side monitoring system, and suspension control system greatly facilitate the deployment of sensor networks, hence providing all-aspect monitoring regarding the static and dynamic responses of the whole maglev system. This includes bridge, track, and vehicle components. The utilization of the cloud platform with powerful computing and storage, and the application of Big Data technologies in the HM platform make the operation of each module concurrent in practice. This feature also makes it possible to implement reliability-based methods for structural health and condition evaluation. The comprehensive HM platform and abundant field measurements for the maglev system thus make it a desirable full-scale test bed to enable a thorough investigation of any current burgeoning wide range of benchmark problems of the maglev system. It has been found that the implementation of the proposed HM platform is a meaningful exploration of the HM technology in maglev transit, and its successful application to the maglev system is expected to provide useful information for further construction and design of maglev systems.

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