Digital twin based comfort scenario modeling of ATO controlled train

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Abstract. Whether in Europe or China, ATO based train control system has become a trend. However, the application time of ATO is short and the user experience is insufficient. In order to better carry out system research and development, system test, system optimization and other work, the construction scheme of the simulation platform based on digital twin is proposed. In this paper, by comparing five-dimension model with three-dimension model, digital twin is built based on the five-dimension model of digital twin, and the virtual model in the five-dimension model is introduced in detail. Physical, behavioural, rule and geometric models are constructed from the four perspectives of the effect of each element in the scene on the train, the dynamic characteristics of the train, the correlation between the elements and the scene, and the visualization of the scene. Based on digital twin, the paper designs the framework of simulation platform to support ATO performance optimization and other work. The parameters in the model can be adjusted repeatedly through field data to achieve higher consistency between the model and the simulation object.

1. Introduction

With the development of virtual simulation technology, the digital representation of object model is becoming more and more perfect. The gradual improvement of automation, digitalization and intelligentization in the production process leads to a surge in data sources and volumes. It has become an urgent problem to realize the effective fusion and management of multi-source heterogeneous dynamic data in the operation process.

Under this background, the digital twin technology arises at the historic moment [1]. Based on digital twin, Ayani et al. [2] realized the maintenance and virtual debugging of the equipment in the absence of technical documents. Seshadri and Krishnamurthy [3] completed the development of multidisciplinary integrated structural health management tools using digital twin to detect and predict aircraft faults in flight. Violeta [4] proposes a privacy management system of smart cars based on digital twin, which is used to provide the privacy protection strategy of smart cars’ drivers. Boschert and Rosen [5] believed that digital twins were faithful mappings of physical objects, and can optimize physical objects based on increasingly rich models. Schluse and Rossmann [6] believed that the ability of digital twins to interact between real and virtual objects made them play an intelligent core role in the Internet of things. Gichane et al. [7] used digital twin to improve the simulation performance of the simulation model.
Train operation is a complex dynamic process of multiple systems. It is influenced by the control system, the train system and the railway line environment. The traditional train operation simulation method is to simplify and abstract the train operation and realize the simulation of the system at the expense of some information. In handling performance simulation of ATO system, especially the quantitative simulation, precise models which contains more information need to be built to ensure the accuracy of simulation results. It poses a challenge to the traditional simulation modeling. Considering the performance of digital twin in other fields, it has great potential in the performance simulation of train operation.

The paper proposes a construction scheme of ATO comfort scene model based on digital twins. The parameters in the model can be adjusted repeatedly through field data to achieve higher consistency between the model and the simulation object.

2. Early structure of digital twin
In 2003, Grieves [8] introduced the early concept of digital twins in his advanced course in product life cycle management (PLM) and the digital twin is refined into three-dimensional structures that contain physical entities, virtual models, and data connections (figure 1).

The study of digital twins was first conducted for the maintenance and management of products, especially aerospace products. With the development of related theories and the change of application demand, the application of digital twins is gradually expanding to the civil field.

With the expansion of the application field, digital twin needs to focus on the different business needs of users at all levels, such as equipment assembly, equipment maintenance, dynamic process simulation of complex systems, visualization of key data. Therefore, the development of digital twin service should become an important part of digital twin construction. However, this structure lacks guidance for application services based on digital twin.

3. Five-dimensional structure of digital twin
Aiming at the problems mentioned above, new progress had been made in the study of digital twins. Tao et al. [9] proposed an extended five-dimensional digital twin architecture (figure 2), including Physical entity model (PE), Virtual equipment model (VE), Services model (Ss), Digital twin data (DD), Connection (CN).

3.1. Physical entities
Physical entities consist of functional subsystems. In train operation scenario, the equipment in the scene is the unit level, the train dynamics system can be divided into the system level, and the scene can be regarded as the physical entity of the complex system level [10]. According to the actual needs
of the physical entity structure hierarchy division is the foundation of building digital twin. By clarifying the system grades, the corresponding virtual models can be constructed accordingly.

3.2. Virtual equipment model

Virtual model is a digital model with high fidelity of physical entity. In the five-dimensional structure of digital twin, virtual model contains four dimensions: geometric model, physical model, behavior model and rule model.

\[ VE = (G_r, P_r, B_r, R_r) \]  

Based on multi angle and multi-scale simulation, virtual model and physical entity will have higher consistency. This article will focus on building virtual models.

3.3. Service system

The service system is the encapsulation of various algorithms and models in the application layer. It can be divided into two levels: functional service and business service. Functional services are designed to assist in building the digital twin model, such as modeling and simulation services, model checking and parameter adjustment services. Business services are designed for digital twin application development, such as comfort calculation service.

3.4. Digital twin data

Digital twin data is the driver of digital twin [11]. It consists of five parts, data of physical entities (\( D_p \)), data of virtual equipment model (\( D_v \)), data of service system (\( D_s \)), data of domain knowledge (\( D_k \)), data from fusion results (\( D_f \)).

\[ DD = (D_p, D_v, D_s, D_k, D_f) \]  

3.5. Connection channel

The connection channel realizes the information interaction of all parts of the digital twin, including the connection between service system, twin database, physical entity and virtual model.

\[ CN = (CN_{SD}, CN_{PD}, CN_{VD}, CN_{PS}, CN_{VS}, CN_{PV}) \]  

4. Case study

4.1. Analysis of factors influencing train comfort

The comfort level of high-speed trains is used to evaluate people's satisfaction with the overall environment of trains. The comfort level of ATO controlled trains is an important indicator to reflect the performance of ATO controlled trains. Table1 shows some situations that may affect the simulation of train operation. In this paper, two factors affecting comfort are considered. One is the braking force change caused by the electric-gas conversion when the train is running at low speed, and the other is the acceleration change caused by the idling and skidding of the train.

|                        | Traction shock | Idling / slipping | Electro pneumatic conversion |
|------------------------|----------------|-------------------|----------------------------|
| Train start up         | existence      | existence         | Non-existent               |
| Steep slope            | Non-existent   | existence         | Non-existent               |
| Passing phase separation| Non-existent   | existence         | existence                  |
| Train stop             | Non-existent   | existence         | existence                  |

Table 1. Analysis of factors influencing train comfort.
4.2. Frame design of digital twins
Based on the analysis of the factors affecting the comfort of the train and the five-dimensional model of digital twin, this paper designs the following simulation platform framework (figure 3).

![Figure 3. Framework of digital twin simulation platform.](image)

4.3. Physical model of train operation

4.3.1. Wheel rail adhesion.
The adhesion between wheels and rails is the basis of the train's traction and braking force. By introducing the analysis of the adhesion between wheels and rails, model of train operation on actual railway line can be built.

![Figure 4. Force analysis of train wheel.](image)

The creep rate between wheels and rails is determined by the train body velocity $v$ and the train rotation angular velocity $\omega$. Based on the model proposed by Kiencke [12], the train wheel and rail adhesion model can be written as equation (4).

$$F = \frac{\mu_0 v(v - \omega r)Mg}{v^2 + P_1(v - \omega r) + P_2(v - \omega r)^2}$$

(4)

Where $\mu_0$ is the initial slope of the adhesion characteristic curve, $P_1$ and $P_2$ are rail surface parameters.
4.3.2. Electro pneumatic conversion model.

When the train is running at high speed, the braking force is generally provided by electric braking, while when braking at low speed, the braking force is provided by air braking, and there is a process of conversion between electric braking and air braking. The force analysis of a single wheel is as equation (5).

\[
F_k(p_z) = \frac{\pi}{4} d_z^2 p_z \eta_z \gamma_z
\]

(5)

Where \( F_k \) means the pressure of brake pads, \( d_z \) is the working diameter of the brake cylinder, \( p_z \) is brake cylinder air pressure, \( \gamma_z \) is brake ratio of brake clamp and \( \eta_z \) is the base drive efficiency. The formula of air braking force \( B_z \) can be deduced by ignoring the moment of inertia.

\[
B_z = n \frac{\pi}{4} d_z^2 p_z \eta_z \frac{r_z}{R} \phi_z \gamma_z
\]

(6)

In this paper, the values of each parameter are shown in Table 3.

| Orbital condition       | P1  | P2  |
|-------------------------|-----|-----|
| High adhesion           | 120 | 280 |
| Low adhesion            | 200 | 500 |
| Extremely low adhesion  | 350 | 1000|

4.4. Scene rule model

The rule model is based on the historical correlation data, the standards and criteria in the field of column control, which can be obtained through the integration of domain knowledge. Considering various constraints of train operation, ontology modeling is adopted to describe these mutual constraints based on domain knowledge. Scenario model is constructed as figure 5. The description of influencing factors of train traction and braking are shown in figure 6, 7.
4.5. Train dynamics model

The basic operating resistance is mainly caused by mechanical friction and air resistance. Generally, mathematical fitting formulas for different models are determined through a large number of field experiments, and the general form is as equation (7).

$$w_b(v) = \alpha + \beta v + \delta v^2$$  \hspace{1cm} (7)

In this article, the values of $\alpha$, $\beta$ and $\delta$ are 0.00557966, 0.00003974 and 0.0000013. In accordance with the above content, dynamic model of the train can be built based on Simulink (figure 8).

The initial velocity is set to 80 km/h. The type of braking is emergency braking. The adhesion degree of rail surface is set as high adhesion and start slope is 1% up hill. The simulation results are shown in figure 9. In the simulation, the maximum impact rate is 0.98633 m/s$^3$. 

When the train and the scene instance are constructed, the constraint relation of the ontology will be referred to.
4.6. Scene visualization
As an important part of digital twins, the geometric model of the virtual model plays an important role in the interaction between the system and the user. The geometric model describes the geometric parameters of the train and its route. It provides a visual interface.

The interface is built according to the dynamic model and scene, and the train speed and position calculated by the dynamic model will be displayed in real time in combination with the railway line conditions in the interface (figure 10). Users can intuitively obtain the information of acceleration, impact rate, idling and skidding in the figure 11.

5. Conclusions
In this paper, a digital twin-based simulation system for train operation is proposed and the simulation platform is constructed by using the five-dimensional model of digital twin. Besides ATO comfort simulation, it can also provide optimization simulation work such as energy saving and other performance.

In the future, the system will add the influence of weather, human factors and train dispatching to the scenario model for further improving the accuracy of simulation.

This scheme can provide a reference for the digital twin construction of other railways including heavy-haul railways.

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