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# A rule-based parametric modeling method of generating virtual environments for coupled systems in high-speed trains

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ABSTRACT

A rule-based parametric modeling (RPM) method is proposed to dynamically generate virtual environments for simulation and analysis of the dynamics of coupled systems in high-speed trains. First, a precise and complete basic-element model base is built according to the modeling requirements of virtual simulation environments. Meanwhile, the classes of and relationships between the basic-element models are defined with respect to the geometrical, topological, semantical and appearance properties of these models. Then, multi-level semantic constraint rules and a parametric modeling method are designed to accurately analyze the simulation parameters and to rapidly integrate various basic-element models for automatic generation of virtual high-speed railway environments. Finally, after a prototype system is developed, various experiments are carried out for analysis of the advantages of the RPM method. The experimental results show that the RPM method can be used to normalize the error-prone modeling procedure and rapidly generate precise and realistic virtual environments.


## 1. Introduction

In the theoretical framework for the dynamics of coupled systems in high-speed trains, the track, catenary and airflow are coupled with the high-speed train. Therefore, the dynamicity of and correlation between a high-speed train and all of its related systems can be determined for global simulation, optimization and control of high-speed trains (Zhang, Zhang, & Jin, 2007; Zhang & Zhang, 2008; Zhang, 2013, 2014). This theory has become a scientific foundation, scientific concept and analytical tool for high-speed railway construction (Zhang et al., 2007; Zhang & Zhang, 2008). It has also developed into a scientific basis for creating technical standards under a certain speed target for the six systems of surveys and designs, foundation engineering, equipment manufacturing, communication signals, system integration and operation management (Zhang, 2014). However, the simulation of the dynamics of coupled systems is a highly complex dynamic process due to the complexity of influencing factors such as dynamicity of the simulation process and uncertainty existing in interactions (Xia, Cao, & Roeck, 2010; Biondi, Muscolino, & Sofi, 2005; Pombo, Ambrósio, Pereira, et al., 2009; Seo, Kim, Jung, et al., 2006).

Virtual environments have a large potential for scientific research and have become a standard tool for scientists to explore domains that are inaccessible by theories and experiments (Bainbridge, 2007; Lin et al., 2013; Lin, Chen, & Lu, 2013; Bell, Hey, & Szalay, 2009). It has become a major development trend to conduct scientific experiments on large complex systems and to perform management analysis in virtual environments (Zhu, Zhang, Yang, et al., 2015a; Lin, Huang, & Lv, 2009, Lin, Zhu, Gong, et al., 2010). During the dynamic process of high-speed train coupling simulation, there are very complex relationships inside and between each subsystem (Zhang, Xia, & Guo, 2008). Therefore, it is of great significance to construct virtual environments for reorganization, representation and analysis of simulation data.

At present, constructing a virtual railway environment mainly involves three modeling methods, that is, manual modeling methods, parametric modeling methods, and semi-automatic modeling methods that use manually created 3D models.

In a manual modeling method, 3D models are manually placed for generation of a virtual railway environment. This modeling method yields good modeling effects and texture mapping effects, but consumes a large amount of time and labor. Meanwhile, it does not permit dynamic generation of a virtual environment according to constantly changing simulation requirements. In addition, due to the lack of a unified description of the relationships between subsystems, this method may

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lead to an unclear definition of and a poor guidance for the modeling process.

A parametric modeling method solves the preceding problems by controlling the sizes and dimensions of 3D models according to variable parameters. The feature points of 3D models (for example, subgrades, bridges (Wang, Han, & Wang, 2013; Tang, Zhang, Xu, et al., 2014) and tunnels (Gröger & Plümer, 2011)) and the geometric features of a profile (Wang, Lawson, & Shen, 2014; Liu, Xia, & Han, 2010; Zhu, Wang, Hu, et al., 2014) can be obtained automatically by this method. However, this method uses surface descriptions and texture mapping for visual representation, which cannot meet the simulation requirements for precision and realism. Therefore, it cannot provide services for a precise coupling simulation. It is for this reason that CAD models are still needed in this method for construction of virtual high-speed railway environments that contain a large number of complex artificial objects (Zhu, Zhang, Chen, et al., 2015b).

Based on CAD models, a semi-automatic modeling method builds a combined model by combining basic-element models, for example, building a bridge model by combining a bridge pier model and a bridge abutment model (Xikui, Wang, & He, 2014). Meanwhile, during the modeling process, various constraint rules are used for construction of complex models (Xie, Zhu, Du, et al., 2013; Zhao, Zhu, Du, Feng, & Zhang, 2012; Gonzalez-Badillo, Medellin-Castillo, Lim, Ritchie, & Garbaya, 2014). In addition, the spatial position of a 3D model can also be calculated for generation of a virtual environment (Zhu, Min, & Dai, 2012; Wang, 2011; Wei & Xu, 2013), where the running state of a train is simulated after the train motion equation is established (Guan, Chang, & Xu, 2013; Tanabe, Komiya, Wakui, et al., 2000). However, for lack of a clear description of spatial relationships and constraint mechanisms, this method cannot guide or control the modeling process in an intelligent way.

Although many studies have been conducted, there is still much work to be done regarding generation of virtual environments for the dynamics of coupled systems in high-speed trains, including: (1) Multi-field collaborative modeling. High-speed railways involve such fields as railway track maintenance engineering, traction power supply engineering and communication engineering, and the subsystems in these fields differ in specialized knowledge. Thus, modelers need to possess not only 3D modeling capabilities but also professional knowledge in related fields. To make matters worse, the modeling process becomes more complicated and error-prone because modeling operations and professional knowledge are tightly coupled. (2) Accurate semantic description of a complex virtual environment. An increase in the running speed of high-speed trains has created a higher demand on an accurate semantic description of the spatial relationships and semantic constraint mechanisms for a precise coupling simulation (Zhao & Li, 2014; Richard, 1987; Zeng & Wu, 2004). If semantic information about objects in the virtual environment is imperfectly defined and unclearly described, non-standard modeling operations and inefficient management analysis may also occur. In addition, existing methods mostly emphasize geometric modeling and texture rendering methods, but barely involve semantic information. The spatial relationships and semantic constraint mechanisms are not well presented either. Therefore, existing modeling methods are not accurate enough to meet the demands of delicacy management and simulation services. (3) Efficiency of dynamic modeling. During the modeling process for the dynamics of coupled systems, simulation parameters of operating conditions are constantly modified for a better simulation result. Therefore, the ability to rapidly analyze these changing parameters and to automatically generate a virtual environment is important for simulation of the general coupled systems.

In this paper, a rule-based parametric modeling (RPM) method is proposed to automatically generate virtual simulation environments for the dynamics of coupled systems in high-speed trains. The proposed method aims to reduce the complexity and difficulty of multi-field collaborative modeling, normalize modeling operations for a complex virtual environment and increase modeling efficiency and accuracy. The remainder of this paper is organized as follows: Section 2 presents the modeling framework and principles of the RPM method. Section 3 describes the development of a prototype system and analyzes the advantages of the RPM method. Section 4 presents concluding remarks and future work.

## 2. Rule-based parametric modeling method

### 2.1. Overall modeling framework

Fig. 1 shows the overall modeling framework of virtual environments for simulation and analysis of the dynamics of coupled systems in high-speed trains. The framework consists of the construction process and semantic description of basic-element models, multi-level semantic constraint rules and a parametric modeling method. Basic-element models are basic elements that cannot be further divided. They are basic units used to build a virtual environment.

First, a basic-element model base was built by following the four steps: object classification, geometric modeling, texture processing and model optimization. Meanwhile, the geometrical, topological, semantical and appearance properties of the basic-element model base were described by use of geo-ontology. Therefore, the ontology base corresponds with the basic-element model base (the upper sub-diagram of Fig. 1). Second, multi-level semantic constraint rules were defined to accurately and rapidly integrate various basic-element models for automatic generation of virtual environments. These rules included spatial layout semantic constraint rules, combinational modeling semantic constraint rules and spatial attitude semantic constraint rules (the sub-diagram in the middle of Fig. 1). Finally, a parametric modeling method was designed to obtain model spatial coordinates and attitudes based on analysis of the operating condition parameters. The three types of rules guide the three steps in the modeling method. The spatial layout semantic constraint rules were used to obtain the centerline of each type of basic-element models. The combinational modeling semantic constraint rules were used to obtain the discrete point of each basic-element model. The spatial attitude semantic constraint rules were used to obtain the spatial attitude of each basic-element model (the lower sub-diagram of Fig. 1). After semantic information about these points was analyzed and the points were matched with the corresponding basic-element models, a virtual high-speed railway environment was instantiated by means of various 3D graphic tools or platforms.

### 2.2. Basic-element model base and its semantic description

High-speed railways involve such fields as railway track maintenance engineering, traction power supply engineering and communication engineering, and each field contains numerous entities. For example, the railway track maintenance engineering field contains such entities as bridges, subgrades and tunnels. The traction power field contains such entities as substations and general catenaries. The communication engineering field contains such entities as transponders and signal controllers. These numerous entities were first divided into different categories according to field classification and then further divided into different basic-element models based on generic 3D modeling methods. All of the basic-element models obtained in this manner constituted the basic-element model base. The complete process of building a basic-element model base is as follows: (1) collecting related data and removing redundant or false data; (2) analyzing the modeling content and scale; (3) extracting the characteristic parameters from various components to build geometric models; (4) mapping textures onto the models; (5) optimizing the models and generating different LOD models; and (6) constructing the basic-element model base with all these models.