Abstract

This paper studies on a fuzzy predictive model based high speed train fault tolerant control method, which is very important for high speed train’s high-precision control. After analyzing related research works about fault tolerant control and the development of modern high speed train, design of the high speed train fault tolerant control system is given. Afterwards, the high speed train fault tolerant controller is made up of two main modules, which are fault detection and isolation and model predictive control. Meanwhile, twelve parameters used in the proposed high speed train model are listed, and some related constraints are also given. Next, nine membership functions are aggregated by a conjunction operator. To verify the performance of the proposed method, computer simulations are conducted on position tracking and velocity tracking in 1500s, and simulation results demonstrate that the proposed high speed train fault tolerant controller can maintain high level control precision.

Keywords: High Speed Train, Fuzzy Predictive Model, Fault Tolerant Control, Model Predictive Control

1. Introduction

High speed trains are recognized as one of the most promising next generation ground transportation systems, which cannot only save travel time and delivery costs in tourism and logistics, respectively, but also keep a clean environment with reduced air pollution\(^1\).

As is well known, high speed train is a kind of passenger rail transport which can operate significantly faster than the traditional train. In the year of 2012, the maximum speed of it has reached nearly 300 km/h in many countries, such as China, Germany, Italy, Japan, South Korea, UK and so on. Particularly, 310 km/h in Spain and 320 km/h in France, and the speed of Shanghai Maglev Train reaches 431 km/h. Furthermore, high speed trains run at the maximum speed on specific tracks, and nearly all using conventional tracks, generally using standard gauge.

The speed of the high speed trains determines not only the high speed railway transport capacity and efficiency but also the technology system of high speed railway system. Until now, high speed train has carried out a series of technical innovation and practice around the speed promotion. After more than 40 years of development, high speed train speed has been promoted from 210km/h to 350km/h. In 2007, China implemented the sixth time speed promotion on existing lines. By the implementation of technological transformation, the maximum driving speed of harmonious number CRH series of high speed train has achieved 250km/h under the mixed running operation condition\(^2\)[3][4].

Fault tolerance refers to tolerate the failure, and the concept originated in the field of computer system design. Fault tolerance means that when there are faults occurring, the system is still able to maintain the normal operation. Later, when designing controller, people also try to be reflected in the control system of this characteristic, thus, the concept of fault tolerant will be extended to the control system. Moreover, considering the fault tolerant performances of the system controller, in the case of certain components have faults the closed-loop system can still remain stable. Furthermore, a slight decrease in the original performance or performance indicators can be acceptable, if control tasks can be completed successfully.

Fault tolerant control has been an active research topic during the past two decades with a view to increasing the safety and reliability of high speed train design. Fault tolerant control is an area of research which aims to increase applicability by specifically designing control algorithms capable of maintaining stability and performance despite the occurrence of faults.
The rest of the paper is organized as the following sections. Section 2 introduces the research background of this paper. Section 3 gives the design of the high speed train fault tolerant control system. In section 4, a high speed train fault tolerant control method based on fuzzy predictive model is illustrated. In section 5, a series of simulations are conducted to test the effectiveness of the proposed method. Finally, we conclude the whole paper in section 6.

2. Research background

In this section, the research background of the proposed problem is illustrated in two aspects. Firstly, related research works about of fault tolerant control are given in section 2.1, and the development of modern high speed train is listed in section 2.2.

2.1 Related research works about of fault tolerant control

Fault tolerant control has been studied by many researchers in many research fields as follows. Li et al. divided wireless sensor networks into a series of logical domains, and each domain is composed of the council nodes, the key node, the gateway nodes and ordinary nodes. The proposed method transforms traditional node-based networks into domain-based networks, and the new networks are more stable than the former ones. This new communication model can maintain a steady network despite instability of the network nodes, so it can raise the communication success rate[5].

Yu et al. propose a fault tolerant thread-level redundancy, in which redundant threads maintain independent memory accesses and different coherence states of L2-cache line. Additionally, we compare three strategies in the use of simultaneous multithreading, which is another important design objective[6].

In paper [7], the authors address the problem of how to schedule DAGs in Cloud with high reliability so that service failures can be avoided in the presence of multi-processors faults. They first propose a system model, including task model, communication model and reliability model for evaluating fault-tolerant performance of the system. Based on the active replication technology, they develop the Dynamic and Reliability-driven Real-time Fault tolerant Scheduling Algorithm in the case of arising massive resource failures, which targets maximizing reliability to dynamically schedule dependent, non-preemptive, non-periodic real-time tasks, trying to improve the quality of service through scheduling.

Xia et al. proposed a SMS network data fault-tolerant transmission optimization algorithm based on improved Kautz diagram by using file and data distribution idea in Ad Hoc network, so data can be transmitted via Ad Hoc mesh network. If the next hop node or network connection is invalid, a method can be used to “bypass” invalid nodes or connections for higher performance[8].

Jing studied on the Fault-tolerant scheduling, which is an important issue for optimal heterogeneous distributed systems. The authors proposed a improve list scheduling algorithm, called heterogeneous communication-aware fault-tolerant scheduling. The new approach for computing task priority is proposed which considers the performance difference in heterogeneous systems[9].

Ravi et al. discussed a tool designed for developing fault-tolerant Multi-stage interconnection networks. The designed tool is one of its own kind and will help the user in developing 2 and 3-disjoint path networks. The 1-Fault tolerant MIN provides two disjoint paths to solve collision situation. The java technology has been used to design the tool and have been tested on different software platform[10].

Particularly, the high speed train based fault related works are listed as follows. Zhang et al. studied on an absolute positioning sensor for a high-speed maglev train and its fault diagnosis method. Based on the analysis for the principle of the absolute positioning sensor, the authors described the design of the sending and receiving coils and realized the hardware and the software for the sensor. To enhance the reliability of the sensor, a support vector machine is used to recognize the fault characters, and the signal flow method is used to locate the faulty parts[11].

Qi et al. investigated the position and velocity tracking control problem of high speed trains with multiple vehicles connected through couplers. A dynamic model reflecting nonlinear and elastic impacts between adjacent vehicles as well as traction/braking nonlinearities and actuation faults is derived. Neuro adaptive fault tolerant control algorithms are developed to account for various factors such as input nonlinearities, actuator failures, and uncertain impacts of in-train forces in the system.

Tao Tao, Xu Hongze
simultaneously. The proposed algorithms can automatically generate the intermediate control parameters, neuro-weights, and the compensation signal\(^{[12]}\).

### 2.2 Development of modern high speed train

In this subsection, as is shown in Fig.1, we will survey on the development of modern high speed train in several different countries or regions such as French, Germany, Italy, Spain, China, Finland, Japan and so on.

<table>
<thead>
<tr>
<th>Multiple world-speed-record holder, the French TGV family</th>
<th>The German ICE 3 high-speed electric multiple unit</th>
<th>The Italian ETR 500 Frecciarossa</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Spanish AVE Talgo-350, derived from the Talgo family</td>
<td>The Chinese CRH380A,</td>
<td>Allegro train at Helsinki Central railway station</td>
</tr>
<tr>
<td>Taiwan's Japanese-built 300km/h</td>
<td>The Japan Shinkansen N700 Series Shinkansen</td>
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**Figure 1. Typical high speed trains of the world**

In recent years, there are several countries which have concentrated on high speed trains’ development, and the following are the typical high speed trains which are proposed in Wikipedia.

(1) **Japan**

By the mid-1950s, the Main Line in Japan was operating at full capacity, and construction of the first segment of the line between Tokyo and Osaka started in 1959. This line is the most heavily-traveled high speed line in the world, carrying 138 million people in 2009.

(2) **France**

In France, the main line between Paris and Lyon was projected to run out of capacity by 1970. In both cases the choice to build a completely separate passenger-only line allowed for much straighter lines and higher speeds. The commercial success of both lines inspired those countries and their economies to expand or start high speed rail networks.

(3) **United States**

The US does not have any form of high speed rail system to compare to European and Asian standards. In post-World War II United States, travel by cars and planes became easier for a greater percentage of Americans due to improvements in these technologies. Thus, U.S. passenger trains were unable to compete with the postwar growth in airline and highway travel.

(2) **China**

In China, plans for the largest high-speed railway network in the world were driven by a combination of capacity constraints on existing lines and a desire to shorten journey times, while promoting development along the route. The construction schedule was significantly accelerated due to...
additional funding in the 4 trillion CNY stimulus package of 2008 and a number of lines would be completed by 2013.

3. Design of the high speed train fault tolerant control system

For the high speed train, fault-tolerance control refers to the property which can enable a system to continue operating properly when failure of some of its components occurs. If its operating quality decreases at all, the decrease is proportional to the severity of the failure, as compared to a naively-designed system in which even a small failure can cause total breakdown. Fault-tolerance is particularly sought-after in high-availability or life-critical systems.

![Diagram of high speed train fault tolerant control system](image)

**Figure 2. High speed train fault tolerant control system**

Fig.2 illustrates the framework of the high speed train fault tolerant control system, which is a kind of active fault tolerant control method. When the failure occurring, the first step is to detect faults and their identification, and then make a corresponding adjustment of the control strategy based on the type of fault. If necessary, the structure of the controller may also need to change. The proposed framework can reflect the deal with the failure of the initiative, which is embodied by fault detection and diagnosis subsystem. Therefore, fault detection and diagnosis subsystem is needed by the majority of active fault tolerant control system. Furthermore, it do not need to fault detection and diagnosis subsystem, of which these unwanted fault detection and diagnosis subsystem active fault tolerant control systems rely on the a priori knowledge of the failure to deal with failure.

On the other hand, the framework of Fig.2 is an active fault tolerant control system, including sensor fault detection and isolation subsystem, actuators, and fault-tolerant controller. The proposed system is a complete active fault tolerant control system, and its role is on the respective components of the control system in real-time fault monitoring, with the ability of fault estimation and fault isolation. Hence, the detected information is transmitted to the controller, and then the controller to make the appropriate adjustments to the control strategy according to the type of fault. If necessary, the structure of the controller may need to change in order to ensure the system's control effect provide strong protection.

Next, we will explain the advantages of introducing fuzzy policy into high speed train fault tolerant control system. Fault tolerant control usually utilizes a multiple model selection approach, where a fuzzy model for the process running in normal operation and one model for each one of the faults are used. In the predictive control process, the user can specify some requirements by modifying the cost function. Moreover, this feature is very useful in fault tolerant control, because it allows different control specification for faulty models, in order to have minimal losses when the system is running in a faulty mode.

4. High speed train fault tolerant control method based on fuzzy predictive model

As is shown in Fig.3, The proposed method is implemented by two parts, which are fault detection and isolation and model predictive control. The model predictive control is fairly useful in fault tolerant
control, the reason lies in that it can allow a different control specification for the faulty models, then the high speed train system could have minimal losses when the system is running in a faulty mode. Particularly, the control action can consider the element of the prediction horizon. Moreover, the receding horizon principle can be obtained at each time instant to assess the situation when any change happening in the fault status to adopt the best control action.

**Table 1. Parameters used in our high speed train model**

<table>
<thead>
<tr>
<th>Parameter ID</th>
<th>Parameter Name</th>
<th>Parameter ID</th>
<th>Parameter Name</th>
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<tbody>
<tr>
<td>p1</td>
<td>Wheel inertia</td>
<td>p7</td>
<td>Vehicle MASS</td>
</tr>
<tr>
<td>p2</td>
<td>Wheel velocity</td>
<td>p8</td>
<td>Vehicle weight</td>
</tr>
<tr>
<td>p3</td>
<td>Wheel rotation</td>
<td>p9</td>
<td>Chassis velocity</td>
</tr>
<tr>
<td>p4</td>
<td>Driving torque</td>
<td>p10</td>
<td>Driving resistance</td>
</tr>
<tr>
<td>p5</td>
<td>Wheel radius</td>
<td>p11</td>
<td>Slip ratio</td>
</tr>
<tr>
<td>p6</td>
<td>Friction force</td>
<td>p12</td>
<td>Friction coefficient</td>
</tr>
</tbody>
</table>

For the parameters in Table.1, some constraints should be satisfied:

\[
p_1 \cdot p_2 = p_4 - p_5 \cdot p_6 \\
\]

\[
p_7 \cdot p_8 = p_6 - p_{10} \\
\]

\[
p_9 = p_3 \cdot p_5 \\
\]

\[
p_9(p_{13}) = p_{12} \cdot p_8 \\
\]

Next, the vector of residuals \( \delta \) is defined as follows:
\[ \delta = y - \overline{y} \]  \hspace{1cm} (5)

Where \( y \) is the output of the high speed train system and \( \overline{y} \) is the output of the proposed model in its normal operation. When there are \( n \) models, of which a model represents each kind of fault, \( n \) vectors of residuals are obtained. Particularly, for residual \( j, j \in \{1, 2, \cdots, n\} \), it can be calculated as follows.

\[ \delta_{y_j} = y - y_{\overline{y}_j} \]  \hspace{1cm} (6)

where \( \overline{y}_{\overline{y}_j} \) is the output of the model of its \( i \)th kind of fault. Using Eq.6, the residual set \( \{\delta_{y_{j1}}, \delta_{y_{j2}}, \cdots, \delta_{y_{jn}}\} \) is obtained. Afterwards, the fault or faults detected are the outputs of the fault detection and isolation system, and fuzzy decision-making method is used in the fuzzy fault isolation process. To implement the above fuzzy predictive model of high speed train system, 9 membership functions defined for each variable as follows:

\[ \mu_i(x) = \frac{1}{1 + \exp(5(x + 0.8 \times \alpha))} \]  \hspace{1cm} (7)

\[ \mu_1(x) = \exp\left(-\frac{x + 0.6 \times \alpha}{\beta}\right) \]  \hspace{1cm} (8)

\[ \mu_2(x) = \exp\left(-\frac{x + 0.4 \times \alpha}{\beta}\right) \]  \hspace{1cm} (9)

\[ \mu_3(x) = \exp\left(-\frac{x + 0.2 \times \alpha}{\beta}\right) \]  \hspace{1cm} (10)

\[ \mu_4(x) = \exp\left(-\frac{x}{\beta}\right) \]  \hspace{1cm} (11)

\[ \mu_5(x) = \exp\left(-\frac{x - 0.2 \times \alpha}{\beta}\right) \]  \hspace{1cm} (12)

\[ \mu_6(x) = \exp\left(-\frac{x - 0.4 \times \alpha}{\beta}\right) \]  \hspace{1cm} (13)

\[ \mu_7(x) = \exp\left(-\frac{x - 0.6 \times \alpha}{\beta}\right) \]  \hspace{1cm} (14)

\[ \mu_8(x) = \frac{1}{1 + \exp(5(x - 0.8 \times \alpha))} \]  \hspace{1cm} (15)

Next, the above 9 membership functions \( \mu_1(x) - \mu_8(x) \) functions should be aggregated by a conjunction operator as follows.

\[ \tau_i = t(\mu_1, \mu_2, \cdots, \mu_8) \]  \hspace{1cm} (15)
where \( t \) is a triangular norm, and \( \tau_i(j) \in [0,1], i \in \{1,2,\cdots,n\} \) is a fuzzy decision factor. Then the vector of fuzzy decision factors is represented as \( \eta(j)=[\tau_1(j),\tau_2(j),\cdots,\tau_n(j)] \). Particularly, the proposed method regards the fault \( i \) in isolated state when the condition \( \eta_i>T \) and \( \eta_i<T, \forall q \neq p \) are satisfied.

5. Simulation results and analysis

To test the effectiveness of the proposed high speed train fault tolerant control method, simulation is conducted in this section, and a train with 8 vehicles is simulated. The total mass of the eight vehicles is 385000kg. The actuator failure variable is used as a random function, and the value is arranged between (0,1). The distribution matrix is equal to \( B = \text{diag}([1.8,1.8,1.8,1.8,1.8,1.8,1.8,1.8]) \), and 9 membership functions are used which has been present in Section 4.

The goal of the proposed method is to make the actual velocity track, the desired velocity, the actual position track, and the desired position with high precision. Then, the simulation results are illustrated in the following figures.

**Figure 4.** Simulation results for position tracking in 1500s

**Figure 5.** Simulation results for velocity tracking in 1500s

As is shown in Fig.4 and Fig.5, we can see that compared with the real state, the simulation results are approaching to the real values. Furthermore, several conclusions can be drawn that all signals involved are bounded and the system velocity and speed asymptotically track the corresponding desired trajectory. The above simulation results also show that the proposed high speed train fault tolerant controller is able to maintain high level control precision.
6. Conclusions

In this paper, we propose a novel fuzzy predictive model based high speed train fault tolerant controller, and the design of high speed train fault tolerant control system is illustrated. Next, the high speed train fault tolerant controller is made up of “fault detection and isolation” and “model predictive control”. Afterwards, twelve parameters and related restricts are given. Moreover, membership functions are aggregated by a conjunction operator to make fuzzy control.

References

[12] Song Qi, Song Yong-Duan, "Data-Based Fault-Tolerant Control of High-Speed Trains with Traction/Braking Notch Nonlinearities and Actuator Failures", IEEE TRANSACTIONS ON NEURAL NETWORKS, Vol. 22, No. 12, pp. 2250 ~ 2261, 2011