A framework for modeling train control systems based on agent and cellular automata

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Abstract

A train control system is a system that is geographically and functionally distributed. Its subsystems have a high degree of autonomy. Because of these characteristics, this paper describes a two-layer framework for modeling train control systems. The upper-layer is defined by agents. The lower-layer is the cellular automata (CA) traffic model to simulate the train following dynamic. The CA model delivers the knowledge needed by the agents to make decisions. The interaction between agents can describe the decision-making processes of train control systems to achieve its functions. Its functions are classified into three levels: Service Control Functionality, Signaling Functionalities and Train Operation Functionality. A case study is used to illustrate the applicability of the proposed framework. The study results show that the proposed framework can be successfully used to analyze the influence on traffic flow, which is caused by the train control system.
Keywords: modeling, train control system, agent, Cellular Automata (CA).

1 Introduction

A train control system model is an important tool to research train control systems. The previous models are based on the equipments that are used in the practical train control system. For different train control systems, they may have different equipments. In other word, the equipments that constitute the train control system can be tailored towards requirements. This leads to different systems having different system configurations. It is possible to accept the non-uniformity of the configurations in practical projects; however, it is not conducive to understanding the train control system.

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This problem can be solved by modeling the train control system based on its functions. Its functions are achieved through the equipments in the system. Although the equipments are various and their configurations are distinct, the functions are the same for the different train control systems. It is fundamental to railway control systems that they should be concerned with the positional control of trains [1]. Therefore, the essential purposes of the functions for any train control system are [2, 3]:

- To maintain a safe distance between following trains on the same track;
- To safeguard the movement of trains at junctions and where crossing a path that could be taken by another train;
- To control train movement between and at stations;
- To regulate the passage of trains according to the service density and speed required, accounting for the planned schedule.

This places the train control system at the heart of the railway [4].

2 The function-oriented model of train control systems

According to these essential purposes, the functionality of the train control system can be summarized in three levels:

- Service Control Functionality: The functionality in this level is to maintain the quality of transportation service, both in normal and abnormal situations. It will compare the real-time traffic status with the schedule and reschedule in order to reduce the delay.
- Signaling Functionality: The functionality in this level is to ensure the safety of the train movement. It will collect the information related to the movement of trains first. Then, based on the information, it will allocate the movement authority (MA) for each train. Moreover, it will send the corresponding signal information to the Train Operation Functionality and the Service Control Functionality respectively.
- Train Operation Functionality: The functionality in this level is to operate trains in an effective way. The operation will consider energy saving and comfort as the object of train operation.

Next we will introduce the above three kinds of functionality in details.

2.1 Service Control Functionality (SCF)

The Service Control Functionality is enforced through the train control system. Where more serious service abnormalities occur, it is necessary to manage the service in real time to ensure that train destinations are appropriately balanced, that bunching/conflicts are minimized, and that staff and stock resources are available when and where required. This function is referred to as Service Control [4].

Service Control Functionality includes the Centralized Manual Control function, Local Manual Control function, Platform Management function and Automatic Train Supervision function.

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The Centralized Manual Control function manages the service on the whole railway line. Normally it will not control the service directly. The control order will be transmitted to the Local Manual Control function first and then it will be transferred to other functions. In particular, the temporary speed restriction order will be sent to other safety critical functions in order to ensure its consistency, completeness and validity.

The Local Manual Control function manages the service around one or several stations on the railway line generally. It is not only a transfer station for exchanging information between the Centralized Manual Control function and other functions, but also a commander to control the local service. The local service includes the management of the platform.

The Platform Management function is to reduce the dwell time at stations. Dwell times result from a number of delays associated with train and platform design, service regularity, operating practice and passenger behavior. Their effects can be limited by implementing systems and techniques for platform management. The systems and techniques can be found in [4].

The Automatic Train Supervision function takes on the automation of the signalers' and controllers' roles. It is therefore responsible for the monitoring and co-ordination of individual train movements in line with the schedule and route assignments [2]. Its function is accomplished through the cooperation among the functions of Automatic Train Regulation, Automatic Route Setting and Automatic Traffic Monitoring. Currently these functions are usually used to operate an alarm to draw a human operator's attention to the need for action and, subsequently to provide information to support decisions by that operator.

2.2 Signaling Functionality (SF)

The movement of trains is in accordance with the signaling information in railway system. The signaling information includes the aspect of signal, slope, curve, the status of points (lock or unlock, normal position and reverse position), train position, train integrity, train route information, and so on. The information should be collected by the SF. In some ways, SF is a set of functions that gather the information related to the movement of trains, select and send to the destination functions who will act upon the information. Among the information, the aspect of signal, slope, curve and the status of points will be collected by the Line Information Collection function; train position will be collected by the Train Location function; train integrity will be collected by the Train Integrity Check function; train route information will be collected by the Interlocking function.

First, all of the collected information is the input of other sub-functions in SF, such as the In Cab Signaling, the MA Allocation, the Interlocking and the Automatic Train Protection.

The In Cab Signaling function will receive the track-side signal and display it in the cab. That will benefit driver to drive, especially when trains run at high-speed. The MA Allocation function needs the trains' position and route information. The trains' position and route information is necessary for the MA allocation function. The Interlocking function needs the aspect of signal, status of points and MA information so that it can evaluate this information and permits movements via the signals. The Automatic Train Protection (ATP) function is a safety critical function. It will intervene in real time to slow, even stop a train when the train runs over the permitted speed restriction. In order to decide the permitted speed restriction, the ATP requires the following information [5–7]:

- Dynamic data: the current train location and speed (detected by the Speed Measurement function), and master controller position;
- Train data: the class, length, acceleration performance, braking performance (for service and emergency braking) and maximum permitted speed of the train;
- Route data: gradients, current maximum line speed, the line speed profile ahead (relevant to the particular class of train) including the start and finish points of temporary speed restrictions, the distance to the next signal/marker/data transmission point, the distance to go before the train must slow down or stop (the movement authority).

Besides supplying information to the sub-functions in SF, it will provide information for other two functionalities. The Automatic Train Operation function or driver (Manual Driving function) needs the signaling information to guide the operation of train. Automatic Train Supervision, Centralized and Local Manual Control needs to know the actual traffic condition.

All information is transmitted in a dedicated data communication network, which can be classified into wired and wireless communication. The wireless communication is used between train and trackside, hand signaling equipment and control center respectively. In other conditions it is wired communication. No matter it is wired or wireless communication, it is safety critical if it transmit safety related information.

2.3 Train Operation Functionality (TOF)

In addition to the above two kinds of functionality, the Train Operation Functionality is also a key functionality in train control system.

Most of trains on railway lines are operated manually. As technology continues to advance, the Automatic Train Operation function became feasible. It has to operate trains in a comfortable and energy-saving way, depending on the information collected from other functions. The information includes the current train location and speed, train length, acceleration performance, braking performance (for service and emergency braking) and maximum permitted speed of the train, gradients, current maximum line speed, the delay of the front train and so on.

It is not safety critical because it only represents the movement control aspects of the driving function. It cannot therefore exist without the Automatic Train Protection (ATP) function, since it relies upon ATP to provide the movement safety functions [8, 9].

At last, the movement control is implemented through the Train Traction/Brake Control function.

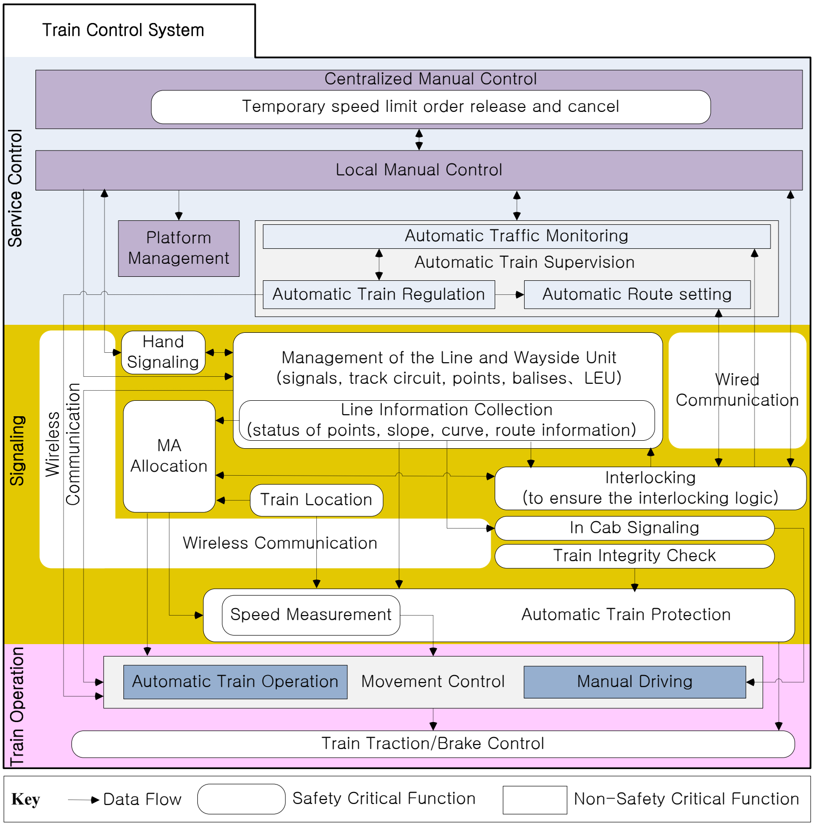


Figure 1: Function-oriented model of a train control system.

As mentioned above, the three functionalities have the principal task of ensuring the safe separation of trains. Meanwhile, they affect the performance of train control system in aspect of capacity. The train control system should provide a means of improving the performance. So, the train control system has competing requirements placed upon it: those of safety (safety critical functions) and those of operational capacity (capacity related functions). Based on the aforementioned functions, a function-oriented model of train control system is shown in fig. 1. It is a generic model because no special equipment is involved.

3 Two-layer framework for modeling train control systems

3.1 Two-layer framework

According to the study in [10], the NaSch model(one of cellular automaton models) has been proposed to simulate the railway traffic. Some complicated traffic conditions, such as mixed traffic, overtaking, can be generated. These studies demonstrate NaSch model is applicable to simulate the dynamic of the railway traffic.

However, there is a problem in the NaSch model. Since it is too complex to achieve full functions of train control system by using rules, it uses some basic rules to describe the functions of train control system in a relative simple way. This leads the decrease of the accuracy of the model, and that will have bad influence on the study of the train control system when using the NaSch model.

Actually, these functions are generally achieved through the interactions between the units, which are distributed in the railway system. So it is doable to model the functions of the train control system through the interaction between agents in multi-agents system (MAS).

So, we proposed a two-layer framework for modeling train control system:

- The upper-layer is designed by the agent technology based on the function-oriented model of train control system. The interaction between agents can achieve the functions of train control system.
- The lower-layer is the cellular automata (CA) railway model to simulate train following dynamic. The CA model provides the knowledge needed by the agents to make decisions and react upon the decisions.

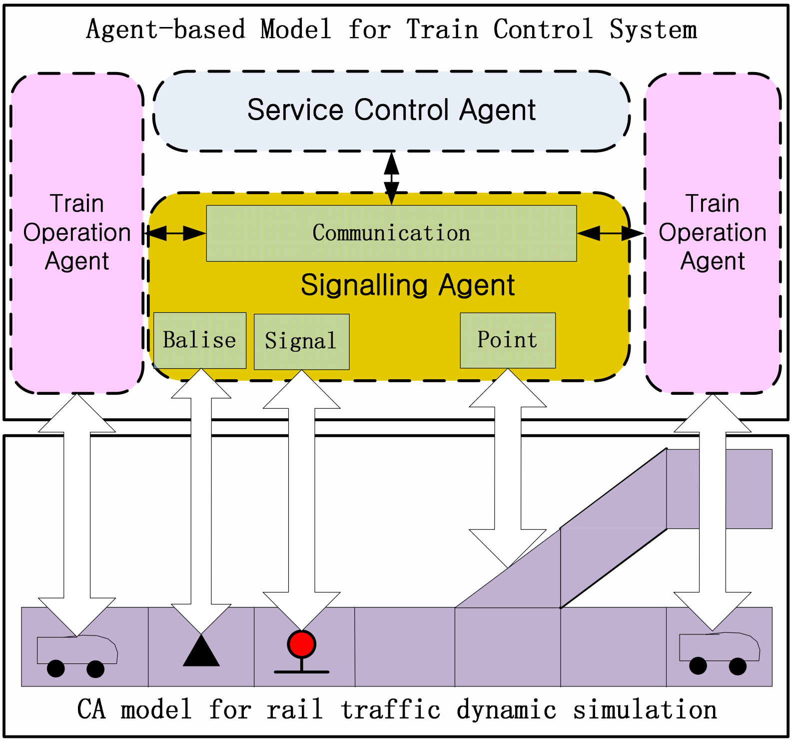


Figure 2: Sketch of the two-layer framework.

3.2 Design of train control systems by agents

In general, the railway traffic system consists of many autonomous, intelligent units, which are distributed over a large area and interact with each other to achieve certain goals. These units may be completely different: drivers, trains, signals, but all of them have a high degree of autonomy, actively perceive the environment and act upon that environment. Owing to these characteristics, many systems in this domain are developed based on an agent approach [11, 12].

Vernazza and Zunino [13] proposed a methodology which is to use Distributed Artificial Intelligence techniques to overcome the limitation of the centralized methodologies. It exhibits an upper bound on the size of the controlled area because of the requirement of real-time processing.

Intelligent agents have successfully solved the train pathing problem on a small portion of railway network [14]. Next, based on this research, Blum and Eskandarian [15] introduced a method to enhance the collaboration of the agents. A protocol is proposed that makes the agents operate as efficiently as possible.

One of the most recent references about multi-agent railway system [16], presents a multi-agent system for communication based train traffic control. The system infrastructure has an architecture composed of two independent layers: “Control” and “Learning”. “Control” layer includes three agent types: “Supervisor”, “Train” and “Station”.

In order to design a system by agents, several components have to be defined precisely: the agents, the interactions and the environment.

3.2.1 Agents

In our generic model, we propose three categories of agents:

- SCF agents that achieve service control functionality. They detect conflicts and find a solution to minimize delay time. To find a solution, many intelligent technologies, such as expert system, compute intelligence, machine learning and searching, can be used.
- SF agents that achieve signaling functionality. These agents includes the signaling-related information which is the aspect of signal, slope, curve, the status of points (lock or unlock, normal position and reverse position), train position, train integrity, train route information.
- TOF agents that achieve train operation functionality. Each TOF agent is the abstract model of an actual train running on the railway network and its dynamic status can be collected by SF agents.

3.2.2 Choice of interaction method: the environment modeling approach

Interactions between agents through message exchange are an important part of a multi-agent system. Our interaction model is based on EASI model (Environment as Active Support of Interaction) [17]. In this model, agents share a common communication media, the environment, which is used to support interactions. The environment contains description of messages and agents, which is represented by a set of entities, $\Omega = \{\omega_1, \ldots, \omega_m\}$. An entity ω_i is related to a component of the MAS and has a description given by observable properties. In order to find these properties that it is interested in, the agents have the ability to put filter in the environment. A filter f_j is the description of the constrains on the observable properties of the entities that are related to the connection j .In other words, a filter is a reification of a connection, by which a message transmitted. Let $P = \{p_1, ..., p_n\}$ be the set of the n observable properties of the MAS. An observable property p_l is a function that gives for an entity ω_i a value that can be used for the connect, $\forall p_l \in P, p_l : \Omega \rightarrow d_l \cup \{unknown, null\}$, with d_l the description domain of p_l . d_l can be quantitative, qualitative or a finite data set.

Figure 3 shows an illustration of our environment modeling for a scenario in railway. Here are four entities, $\Omega = \{\omega_1, \omega_2, \omega_3, \omega_4\}$ that are respectively the description of the train operation agent TOA_1 and TOA_2 , of the service control agent SCA_1 and of the message m_1 . The train operation agents have three properties called pos , $speed$ and $connectionObject$, which is for position, speed and its connection object respectively. The value $pos(\omega_1)$ is the position of a train who is represented by TOA_1; the value $pos(\omega_3)$ is $unknown$ because the value has not been given; the value $pos(\omega_4)$ is $null$ because ω_4 does not have this property in its description. The value of a property can be modified by the agent in real-time.

According to the Definition of Filter in [17], three types of filter can be defined and put into the environment: reception, emission and interception filter.

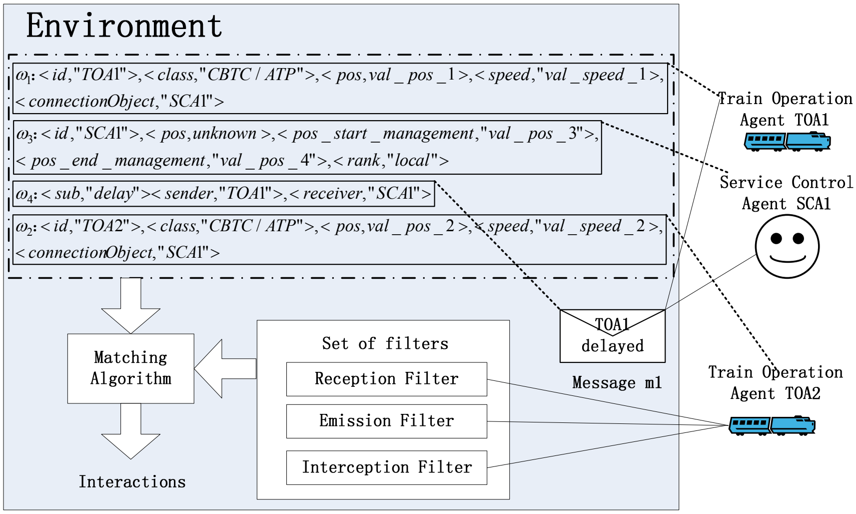


Figure 3: Example of EASI interaction model.

- Reception filters: to search the value of a specified property for the agent to decide the receiver. For instance, if the agent has an id property, the filter that enables interaction based on the value of this property is a reception filter.

$$f^{\text{env}}_{\text{reception}} =< [id(a) = "SCA1"], [sub(\omega_4) = "delay"]$$
$$, "reception", 0, environment >$$

This type of filter is put by the environment generally.

- Emission filters: to match the potential receivers of a message. For instance, the delay message should inform to not only the local service control agent SCA_1 but also the central service control agent SCA_2.

$$f^{\text{TOA1}}_{\text{emission}} =< [rank(a) = "central"] \wedge [sons(a) = "SCA1"],$$
$$[sub(\omega_4) = "delay"], "emission", 0, TOA1 >$$

This type of filter is put by TOA_1 generally.

- Interception filters: to allow the agent to receive a message that has not been sent to it directly, but it is interested in. For instance, the delay message from TOA_1 may be useful to the control of TOA_2. TOA_2 is the following train of TOA_1. Hence, TOA_2 can put an interception filter to overhear the delay message from TOA_1.

$$f^{\text{TOA2}}_{\text{interception}} =< [id(a) = "TOA2"], [sub(\omega_4) = "delay"]$$
$$\wedge [sender(\omega_4) = "TOA1"], "interception", 0, TOA2 >$$

The example of the three types of filter is illustrated in Figure 4.

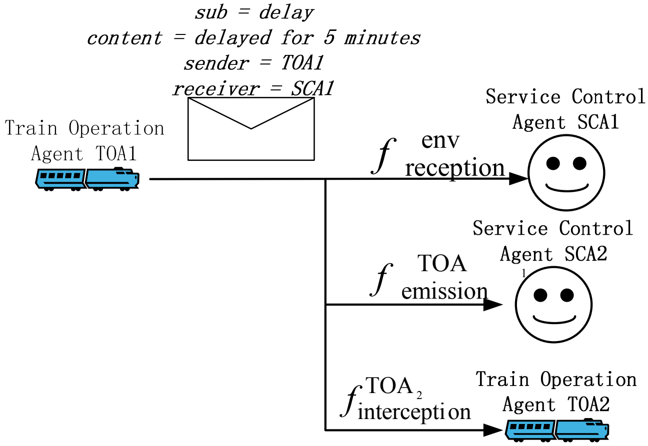


Figure 4: Transmission scenario of a train delay message.

3.3 CA model for rail traffic dynamic simulation

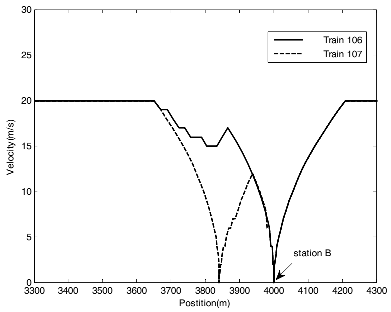
The lower-layer extends the model in [18]. The state of a cell is not only a symbol of if there is a train but also used to represent other information of infrastructure on the track-side. The information possibly includes the status of signal and point, slope, curve, and so on. More details can be found in [18].

4 Simulation

In this section, we apply the proposed framework in our simulation. The simulation is based on a $8000\ m$ long line, which has three stations A, B and C. The stations A, B and C are located at $1\ m$, $4000\ m$ and $8000\ m$ respectively. Trains depart from station A successively with interval I under a moving block system and stop at station B for a dwell time T_{dw}, then leave and run to station C. Finally, they move out of this system after staying at station C for T_{dw}. The length of the computational time is taken as $T = 1000\ s$. The other parameters used in the simulation are as follows:

(1) Train acceleration and deceleration is $a = 1\ m/s^2$ and $b = 1\ m/s^2$;
(2) Train length $L_T = 100\ m$;
(3) Safe distance $L_s = 60\ m$;
(4) Maximum speed of train $V_{\max} = 20\ m/s$;
(5) Speed limit of line $SL_i = 20\ m/s, i \in (1, L)$;
(6) Interval of the train's departure time at station A $I = 60\ s$ (I is a variable when we calculate the minimum time headway);
(7) Dwelling time at the station B and C $T_{dw} = 30\ s$, and for the delayed train 106 the dwelling time is $T_{dw} = 60\ s$.

Based on the proposed framework, a train delay scenario is simulated and the simulation results are shown in Figure 5. The Train 106 is delayed at station B in Figure 5(a). If the following train 107 does not percept the delayed information, it results that the following train 107 has to stop outside of station B (The dotted line in Figure 5(a)). After rescheduling, the Train 106 will have a new departure time. In our model, the message of the new departure time (or the delay of the train 106) can be overheard by the following train 107 by an interception filter, which it put in the environment. With this information, it could brake earlier and run with a slow speed as shown by the dotted line in Figure 5(b). The optimization of their speed profile will avoid stop and benefit their energy-saving and comfortable object.



(a) (b)

Figure 5: Results of simulation.

5 Conclusions and future research

In this paper we present a two-layer framework for modeling train control system. The upper layer describes a function-oriented model of train control system by using an agent-based approach. The agents in the proposed framework are classified into three types: SCF, SF and TOF agents. The interaction between agents is based on a model called EASI. The model defines an interaction in a generic way to achieve some functions of train control system. The lower layer is a CA model that describes the perception and reaction of agents in upper layer. It represents the actual dynamic of railway traffic.

The preliminary simulation result demonstrates the availability of the model. Until now this has been a framework. Through the proposed framework, the agents in the system can get more information. The use of the available information is not discussed in this paper. The future research should focus on how to optimize the performance of the train control system by using the available information.

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