Design of an Automatic Train Operation (ATO) system based on CBTC for the management of driverless suburban railways

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***Abstract*- The interest of train signaling vendors in systems for driverless operation is gradually increasing in order to reduce the operational costs and improving the frequency of service. Many examples of installations all over the world follow the different available standards: VAL (Torino, Lille, Rennes), SelTrac (London, Vancouver, Shangai), etc. In this paper the focus is placed on the Communications-Based Train Control (CBTC) system, which is based on moving-block signaling. In particular, a design solution for the Automatic Train Operation (ATO) subsystem is presented. Numerical simulations in Matlab-Simulink^{TM} obtained through the modeling of the train and of the track make it possible to compare the provided control logics, under realistic conditions including the presence of constraints imposed by the safety subsystems.**
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***Keywords*- CBTC system, safety subsystem, moving-block signaling.**

I. Introduction

Communications-Based Train Control (CBTC) systems, through the moving block signaling, overcome the limitations of systems based on track circuits, mainly relying on the so called "Conventional Fixed Block System", and allow a more effective use of the transit infrastructure as well as an increase in the density of rail traffic. As defined in the IEEE 1474 standard [1], CBTC is an automatic train control system capable of implementing Automatic Train Protection (ATP) functions, as well as optional Automatic Train Operation (ATO) and Automatic Train Supervision (ATS) functions. The present paper is focused on some design solutions for the ATO module of a metro train. First, it has been decided that the ATO subsystem should allow the maximum degree of automation of the journey management, so as to make the driver's presence unnecessary. The system has been designed to perform, in a completely autonomous way, speed tracking, scheduled stopping and control of train access through doors. Specifically, two different controllers have been implemented: a speed controller, active up to a certain distance from the stations and a position controller, which aims to stop the train at the desired point of the station, so as to ensure the matching between the train doors and the platform doors. The approach used to the design of the speed controller is based on trajectory planning: a reference speed profile meetings the imposed requirements is first designed; this profile is then used as speed reference input to a PID controller. In the similar way, the position controller for train stopping design a suitable position profile to be used as position reference input to another PID controller. This planning makes use of the information provided by some magnetic tags appropriately placed along the ground infrastructure for train localization purposes.

A. Preliminary specifications of system

In the context of signaling, three operating margins are defined:

- Nominal operation: $V_{TRAIN} < V_{SEG} + 3\frac{km}{h}$
- Warning margin: $V_{SEG} + 3\frac{km}{h} < V_{TRAIN} < V_{SEG} + 8\frac{km}{h}$
- Emergency margin: $V_{TRAIN} > V_{SEG} + 8\frac{km}{h}$

The proposed algorithm will be able to guarantee the fulfillment of nominal operation conditions. Other requirements are regarding the maximum error of stopping and maximum value of acceleration and jerk (see Table 1).

Table 1: Operative requirements

Stopping Error	Maximum acceleration	Maximum Jerk
±10 *cm*	$\pm 0.8 \ \frac{m}{s^2}$	$\pm 0.6 \ \frac{m}{s^2}$

B. Modeling of the suburban train

The starting point is the definition of the equations that describe the mechanical interactions between the train cars, through a multiple-mass-spring-damper model [2].

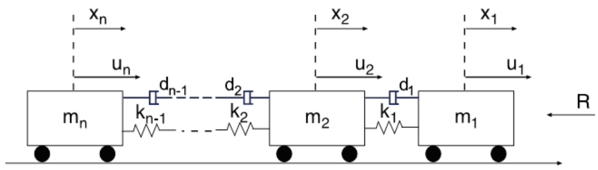

Fig.1. Multiple mass-spring- damper

For the present work a short railway composition of four coaches is considered: the first and last coaches are motorized ones ($B_0 - B_0$ wheelset). For the two intermediate trailer coaches a 2-2 wheelset is assumed. The values of mass, length, damping and spring coefficients are inspired to existing EMU and DMU units, retrieved by the experience of the MDMLAB (see Table 2). Table 2 shows the parameters of convoy object of study.

Table 2: Definition of convoy parameters

Parameter	Value	Units of Measurement	Description
m_1	35000+m_p	*kg*	Mass of the first carriage
m_2	30000+m_p	*kg*	Mass of the second carriage
m_3	30000+m_p	*kg*	Mass of the third carriage
m_4	35000+ m_p	*kg*	Mass of the fourth carriage
m_p	0,1360	*kg*	Length of the first carriage
l_1	17,455	*M*	Length of the first carriage
l_2	16,84	*M*	Length of the first carriage
l_3	16,84	*M*	Length of the first carriage
l_4	17,455	*M*	Length of the first carriage
K	300000	*N/m*	Spring coefficient
D	30000	*N/m*^{2}	Damping coefficient

To complete train modeling, suitable models for traction, braking and resistant forces have been adopted.

C. Modeling of the track

A scenario consisting of four stations has been simulated, with inter-station distances in the range 500-1.500 m. The track should be characterized by curved and sloped parts (30 ‰ of maximum slope). In Tables 3 and 4 main design parameters of the simulated line are shown.

Table 3: Position of stations along the line

	Starting point (*m*)	Final point (*m*)	Slope-Radius
Uphill	650	750	3%
Downhill	1800	1900	-3%
Curve	1600	1700	100*m*

Table 4: Line design (slope and curves)

	Starting point (*m*)	Distance from the previous station (*m*)
Station 1	1500	1500
Station 2	3000	1500
Station 3	3500	500
Station 4	4500	1000

II. Description of control strategies

The goal of the speed controller is to take the train up to 50 m from the arrival station with a speed of 15*km/h*. At that point, control is switched to the position controller up to the stopping of the train.

A. Closed loop speed control

This approach consists of planning a speed profile to be used as reference input to a PID speed controller that minimize the error between the reference speed and the measured speed of train through a proportional, integral derivative action. The schedule is designed as a function of the position along the track. In order to satisfy the requirements on acceleration, deceleration and jerk, a trapezoidal acceleration profile has been chosen. Given the desired jerk profile, the resulting acceleration, velocity and position functions are obtained by integration (Fig.2).

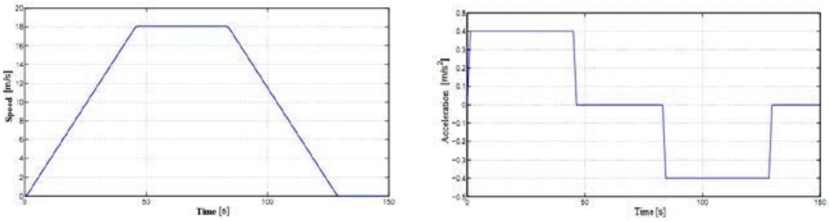

Fig.2. Planned trajectory- Trapezoidal acceleration

Tracking of the speed reference is realized by means of two PID controllers, chosen according the rate of the reference signal.

- PID1 Parameters: **Kp, Ki, Kd**. The controller realizes the tracking when the reference signal is increasing
- PID2 Parameters: **KpF, KiF, KdF**. The controller realizes the tracking when the reference signal is decreasing

The reference signal is chosen as the minimum value between service and signaling profile. The PID parameters were calibrated using flexible simplex method [4] .

Table5: Controller PID parameters for closed loop speed control

Parameters	Value
K_p	5.4781
K_i	0.0097
K_d	0.0079
K_pF	0.3859
K_iF	0.0277
K_dF	0.0097

In the results will be shown as the controller is able to ensure the chase against load variations.

B. Closed loop position control

The previously presented controller is designed to bring the convoy to 50 *m* from the station at a desired speed of 15 *km/h*. In order to ensure a precision of ± 10 *cm* for the stopping at the station (requirement due the presence of the platform doors), a position control is implemented. The controller exploits the information provided by three magnetic tags (T1, T2, T3), which identify three sections: the position control is implemented in the final section (between T3 and the arrival point), a speed control being used in the first and second sections. For each section a speed or position scheduled profile, obtained by integration of a constant deceleration reference, is used as reference for a PID controller.

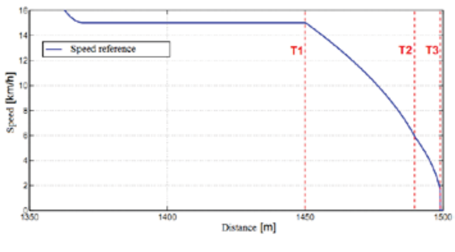

Fig.3. Speed reference in position for stopping at the station

Fig 5 shows the speed reference for the stop controller: after T3 the speed reference is null because in the last track the position control is put on. The control action is composed by three PID regulators, two for speed control and one for position control. One speed controller ensures the tracking when the reference signal is decreasing, and another one ensures the tracking when the reference signal is constant. Also in this case, the tuning of PID controllers has been performed by means of the flexible simplex method, for speed controller, while, for the position controller, an optimization approach based on genetic algorithms, minimizing the error on the stopping point has been adopted [3].

Table 6: Controller PID parameters for stopping at the station

Parameters	Value
$K_p S$	0.6832
$K_i S$	0.2242
$K_d S$	0.2401
$K_p F$	0.3859
$K_i F$	0.0277
$K_d F$	0.0097
$K_p P$	0.7926
$K_i P$	0.2764
$K_d P$	0.7683

II. Results

In this section are presented the results showing that the system carries out the functions assigned to them. The section will be divided in the following sections:

A. **Architecture of the system**: is presented a Simulink^{TM} model implementation of the system that complies with the ATO division into functional blocks.
B. **Implementation of scheduled service:** it checks the fulfillment of requirements in the ideal and real case, where measurement errors on position and velocity signals, provided by the ATC system, are considered.
C. **Verification of compliance with the constraint signaling:** is checked the satisfaction of constraint of stopping and speed decreasing imposed by signaling**.**

A. Architecture of the system

The model is composed by

- **Hardware of Railway Line**: in which signals from balises and tags are generated.
- **A Control Center:** that provides the positions of station and authorizing the opening and closing of the doors.
- **ATC:** provides the measure of position and speed make by board odometry affected by errors.
- **Passenger:** this block simulates a emergency request from a passenger

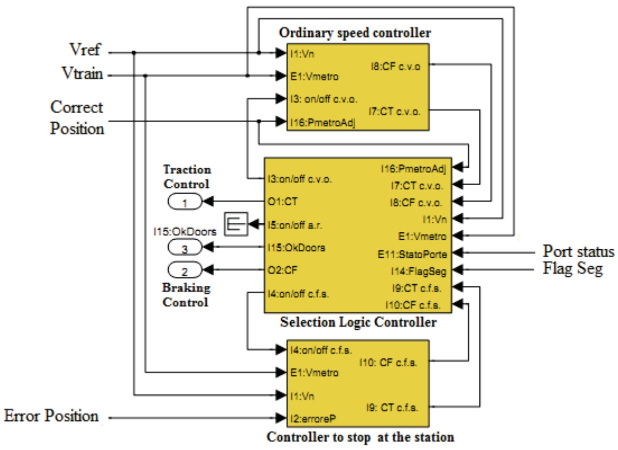

Fig.4. Simulink model of Control Center

B. Implementation of scheduled service

At first the algorithm is validated for the respect of requirements in ideal case, in which there is no error in measurement of position and speed signals.

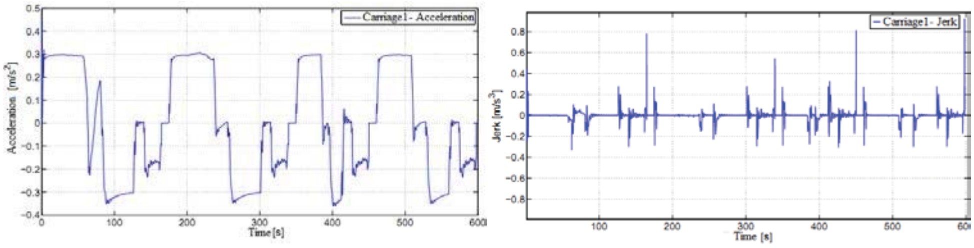

Fig.5. PdT Acceleration and Jerk in ideal conditions (carriage 1)

Fig.5 show as PdT algorithm is able to satisfy acceleration and jerk limit requirements and the relative stopping error at various stations is within the tolerances provided (see Table 7).

Table 7: Stopping error at the station: ideal case-full load

Station I	Station II	Station III	Station IV	Mean
1,01 *cm*	-0,006 *cm*	-1,7 *cm*	-0,564 *cm*	0,824 *cm*

Numerical simulations have been performed assuming error measurement of position signals and speed, braking system with random delay. In the following simulations three different conditions of load are considered, obtained varying the weight of passengers. Table 8-9 show the mean of stopping error at each station, each systematic error (from -1 to 5%) and load conditions for braking system with fixed and random delay respectively.

Table 8: Stopping error with fixed delay of braking system (1s)

A	**STOPPING ERROR (*cm*) Passengers: 0%**				**STOPPING ERROR (*cm*) Passengers:50%**				**STOPPING ERROR (*cm*) Passengers: 100%**			
	Station I	**Station I**	**Station I**	**Station II**	**Station III**	**Station IV**	**Station II**	**Station III**	**Station IV**	**Station II**	**Station III**	**Station IV**
Mean Station	3,21	2,24	5,47	3,36	4,46	2,72	2,66	2,83	4,25	1,94	3,61	3,59
Mean Load	3,57				3,17				3,35			

Table 9: Stopping error with random delay

A	**STOPPING ERROR (cm) Passengers: 0%**				**STOPPING ERROR (cm) Passengers:50%**				**STOPPING ERROR (cm) Passengers: 100%**			
	Station I	**Station I**	**Station I**	**Station II**	**Station III**	**Station IV**	**Station II**	**Station III**	**Station IV**	**Station II**	**Station III**	**Station IV**
Mean Station	3,90	3,93	3,62	3,54	3,11	2,86	2,67	2,86	2,98	2,49	2,70	2,83
Mean Load	3,75				2,87				2,75			

Results show that, on average, there is no situation in which the control does not meet the requirements of stopping error.

C. Verification of compliance with the constraint signaling

This section presents the behavior of the system in case where the signaling constraint is more restrictive than that of service. Is hypothesized that the signaling imposes this scenario:

- Stopping for signaling at 450 *m*
- Decreasing of maximum speed to 40 *km/h* at 1500*m*
- Increasing of maximum speed to 70 *km/h* at 1900 *m*

The input signal to the speed controller will be the most restrictive between the signaling generated and the service profile. Fig.6 shows the action of controller that follow the most restrictive constraint between signaling and service profile.

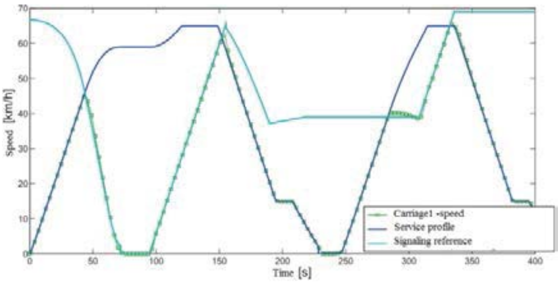

Fig.6. Tracking of the reference speed, taking into account signaling impact

Fig.7 shows the acceleration and jerk in a signaling scenario.

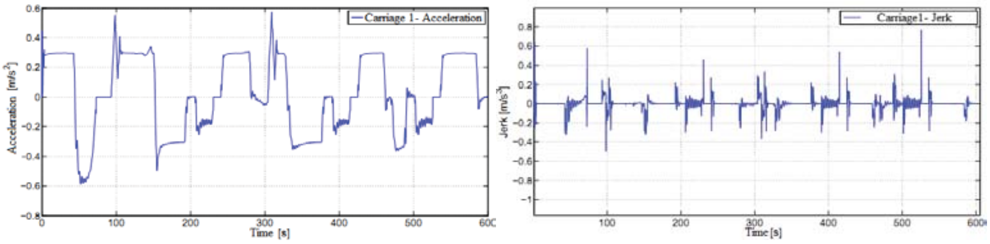

Fig.7. Acceleration and jerk- signaling scenario

The results show the good functioning of the ATO system which is able to guarantee the specific requirements of acceleration and jerk, too.

III. Conclusion

The work that has been developed in ECM had as its objective the development of an ATO system for a metropolitan convoy managed with CBTC signaling system. The first step was the preparation of a preliminary specific of system, containing all the information needed to develop the ATO system. We proceeded to the modeling of the metropolitan train and verification of controllers. The problem of control of gear has been divided into two sub-problems: the ordinary speed control and the control of stopping in station. A closed loop speed and position controller is used, both based on schedules of the trajectory. These controllers were compatible with service and signaling specifications.

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IV. References

[1] 1999. IEEE-Standard for Communications Based Train Control CBTC Performance and Functional Requirements. IEEE Std 1474.1-1999.4
[2] C.Bettini & T.Lorenzetti,2011. *Tecniche di controllo multi-obiettivo per metropolitane automatiche.* Tesi di laurea magistrale. Università degli Studi di Firenze.21
[3] Seong-Ho Han, Tae-Ki An, Yun-Sub Byen, Jong-Hyen Baek, Su-Gil Lee & Hyun-Jun Park,1999. An optimal automatic train operation (ATO) control using genetic algorithms (GA). *Proceedings of IEEE, IEEE Region 10 Conference TENCON 99 Multimedia Technology for AsiaPacific Information Infrastructure, Cat No99CH37030, vol. 1,pp 360-362.34*
[4] J.A.Nelder & R.Mead, 1965. A Simplex Method for Function Minimization, *Computer Journal*, vol. 7, pp.308-313.69,122