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Traffic regulation and simulation - a predictive adaptive control system

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Abstract

The project referred to in this paper consists of three phases. First, the development of a very accurate simulator in order to analyse the train and track performance of a balanced line, to be used as a CAD tool. Second, the development of a very accurate simulator in order to analyse the behaviour of a line under train-to-train disturbances and different passenger-flow scenarios. Third, the development of a control system to guarantee a constant time interval between trains, using the accurate simulator of the second phase as a workbench for case studies.

This paper describes in detail the second and third phases of the project. As a result of this work, a software tool (PACO) is currently running at DIMETRONIC S.A. It simulates accurately, controls and displays the behaviour of a circle line of about 20 trains and 30 stations up to 30 times faster than real-time requirements. It is implemented on a UNIX workstation, using the ANSI-C language.

1 Introduction

This paper is focused on the simulation and control of railway systems that can be modelled as circle lines (see [1]). The basic problem is the natural instability of such lines, especially in rush-hour scenarios. The goal of a control system is either to keep a regular interval between trains or to respect a given timetable. The control system described in this paper is applicable to both situations, but it has been implemented to face the first problem. This is due to the fact that keeping a regular interval is the most common problem in a circle line during rush-hours.

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An optimal control system should keep a regular interval with minimum global delays with respect to the nominal speed (or some customer-oriented satisfaction factor), and minimum energy consumption.

There are two basic approaches to this problem. A first group of controllers start to operate when a significant disturbance is detected; the type of disturbance is then identified and corrected by means of heuristic rules based on a previous classification of the control strategies, as [2], [3]. These controllers do not face properly multiple and steadily disturbed situations. A second group of control systems are based on mathematical models (mainly linear feedback state-variables models) as [1]. This models are adequate for small-disturbance scenarios, but may have problems with highly disturbed ones due to the relevant non-linearities found in real systems.

Some of these non-linearities are the control operations, the protection systems, the maximum load of the trains, and the minimum and maximum station dwell times.

The approach described in this paper is based on an on-line simulation module that includes the main non-linearities of the system. This simulator allows the evaluation of alternative control strategies based on the current state of the system and its estimated evolution. The parameters of the simulator are updated according to measures of the actual behaviour of the system, in order to predict the evolution of the disturbances.

2 General approach

The goal of the control system is the regulation at a constant interval of circle lines keeping a constant number of trains. The controller must meet the following requirements:

- It must be able to maintain a constant interval under disturbed scenarios.
- It must lead the system to a balanced situation from any initial conditions.
- It should operate keeping a maximum satisfaction level of the customers (minimum delays).
- It should take into account the energy consumption cost of the control actions.

There are two types of control actions on the system. The first one operates on the movement of each train between two consecutive stations (stage), by means of alternative sets of ATO speed commands (control options). The second one imposes extra dwell times on the trains at each station, and it is only used in highly disturbed situations.

For each stage, there is a fixed number of alternative control options. Each one has been previously designed so as to meet a target runtime with a minimum energy consumption [4].

The measures taken on the actual behaviour of the system are the arrival/departure timetable of each train at each station. This information is used to estimate the current intervals, the passengers affluence at each station and other system parameters.

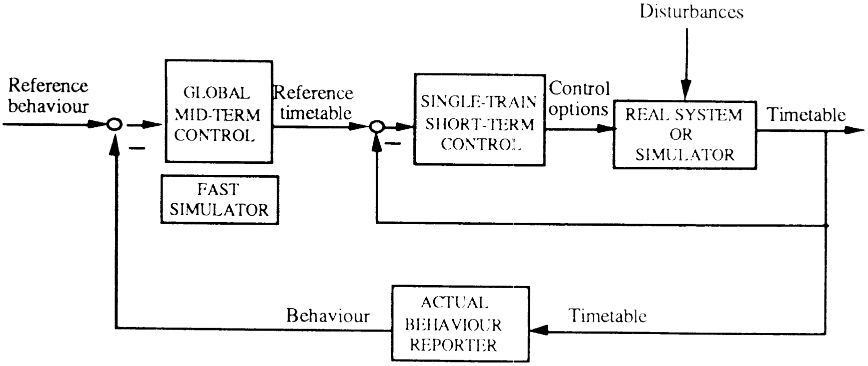

Figure 1. Structure of the control system.

Figure 1 shows the global structure of the control system. The "real-system" box represents either the circle line or an accurate simulator used as a workbench. The control system is hierarchical, consisting of two control loops. The "short-term control" is a fast-response module that provides control options to the trains, trying to follow individual reference timetables. These timetables are generated by the "mid-term control", taking into account the global behaviour of the system. It uses a fast non-linear simulator in order to evaluate and select alternative control plans.

The reference for the "mid-term control" is a desired behaviour of the system, which may include interval and timetable regulation, as well as energy saving criteria. The current behaviour of the system is estimated by the "actual behaviour reporter", being this module in charge of the adaptation of the "fast simulator" parameters. The role and the response time of each control loop are explained in section 5 in more detail.

The disturbances may be classified into two groups. First, random delays produced both in the movement of the trains and in the station stops. Second, systematic delays due for instance to steady variations in the passengers flow and global voltage drops. The controller is able to adapt its behaviour to the second ones by updating the parameters of the fast simulator.

Energy saving is applied both in the off-line design of the control actions and in the on-line elaboration of mid-term plans. The short-term controller includes energy-saving criteria in that it tries to minimise (when possible) the extra dwell times in the stations.

3 Accurate simulation of the system

The development and implementation of the control system requires a module that can resemble as closely as possible the behaviour of the target system. In the second phase of this project a very accurate simulator of circle lines has been developed, based on the movement and energy consumption models used in [4].

The additional features of the simulation models come from the need to represent unbalanced situations:

- Accurate simulation of the protection systems.
- Variable ATO commands.
- Variable passengers load in the trains (variable mass).
- Accurate simulation of the dwell time at each station, according to deterministic passenger-flow scenarios. These scenarios include both a variable affluence and a variable destination of the passengers.
- The simulation speed is user-defined, in order to test the controller against systems that are faster than real ones.
- An animated real-time display of the behaviour of the line at the user-defined simulation speed.

4 Special features of the simulation technique

The simulation technique is based on the combination of continuous parametrised curves and discrete-event simulation described in [4]. The global simulation of the system is decomposed into single-train asynchronous simulations, based on the efficient storage and retrieval of the history of the movement of a train as a list of parametrised equations.

The global simulation of the system consists of a four-step basic algorithm: select the train to move next, move the train by time, move the train by space and update simulation time. It is based on the concept of movement-history, i.e., the storage and retrieval of the evolution of a train along time:

(i) Select the train to move next. The one with the shortest history (train A).

(ii) Move the train by time. The movement of a train A can be simulated as long as the history of the preceding train B in the line is known, since the evolution of the protection systems affecting train A is determined up to that time.

(iii) Move the train by space. The movement of a train A can be simulated beyond the history of the preceding train B as far as it does not depend on that history. Assuming the worst case -train B remains still- train A is simulated as far as the protection systems do not affect its movement.

(iv) Update simulation time. Simulation time is the most recent time for which the history of every train has been already simulated. Updating simulation time also means that the past history can be forgotten.

The global simulation algorithm is thus decomposed into a succession of single-train simulations, limited either by a time constraint or by a space constraint. The single-train simulation problem consists of two different processes: the train stop and the train movement. The simulation of a train movement, basically explained in [4], includes here the influence of the protection systems.

The simulation of a train stop requires a passenger-flow model. The passengers scenario includes both the affluence to each platform and their destinations (as according to their destination, so that the unloading process can be accurately simulated. Both the loading and the unloading processes are simulated as linear functions with saturations. A minimum stop time (no passengers) is considered, as well as the effect of the control and protection systems on the departure time. The idea of defining deterministic scenarios is to test the control strategies against typical and worst-case disturbances: rush-hour beginning and end, connection to other transportation systems, massive affluence of passengers due to -for instance- football matches, etc. (see section 7).

5 Hierarchical control

Figure 1 shows the two-loop hierarchical structure of the control system. The inner loop (short-term control) is a fast-response module that must select a control option for each train departing from a station according to a reference timetable stated for the next station. Its response time must be below one second, which means below three seconds (including the communication delays) from the departure time.

A control option is a set of ATO commands that is assumed to yield a target running time. There is a reduced number of alternative control options. In the study case that is further described in this paper, there are four control options for each stage, with approximately a five-second step between two consecutive options.

The role of the short-term control is to follow a reference timetable stated by the mid-term control, compensating small disturbances with a short response time. It only uses local and individual information about each train.

The outer loop (mid-term control) is responsible for the global behaviour of the system. It elaborates a global timetable for all the trains (plan) every certain period of time, using a fast simulator to predict the future evolution of the whole system under alternative plans. This module behaves as follows:

(i) It detects when the current plan (current reference timetable) is close to be overtaken by the evolution of the system.
(ii) It simulates the evolution of the system up to the end of the current plan.
(iii) It elaborates a new plan for the next period of time, taking into account the desired behaviour of the whole system (which may include intervals, timetable and energy saving criteria). Alternative plans are evaluated until the new plan is needed.
(iv) It applies the new plan to the system; the outer control loop remains open until step (i)

The behaviour of the control system is user-adjustable, by means of the choice of the following parameters:

- Duration of each planning cycle. Although the choice of this parameter is not critical (there is a wide range of acceptable values for each line), there are some practical boundaries that must be respected. The plans

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should be long enough so as to let the system react, and also to let enough time for the elaboration of the next plan (evaluate some alternatives). Plans should be short enough so as to keep the system under control in the presence of important disturbances (the capability of the short-term control is limited), as well as to keep the results of the fast simulator close enough to reality. A sensible range of values for this parameter is from two to five times the average running time between consecutive stations of the line under study.

- Maximum forced dwell time at a station. This is a passenger-oriented factor. Even in highly disturbed situations it is intolerable to keep a train at a given platform for a long time.
- Forced dwell time threshold. This parameter determines the level of disturbance (with respect to the natural interval of the line) beyond which forced dwell times are allowed.

6 The fast simulator

The behaviour of the control system relies on the accuracy of a fast simulation of the future. The model used in this simulator is similar to the linear one proposed by [5] and used in [1]. In order to represent the main non-linearities of the real system, the model has been modified as follows.

The running times at each station are associated to the available control options, and therefore there is a limited number of possible times (see figure 2). Furthermore, a minimum interval is considered between each pair of consecutive platforms in order to represent the effect of the protection systems on the running time.

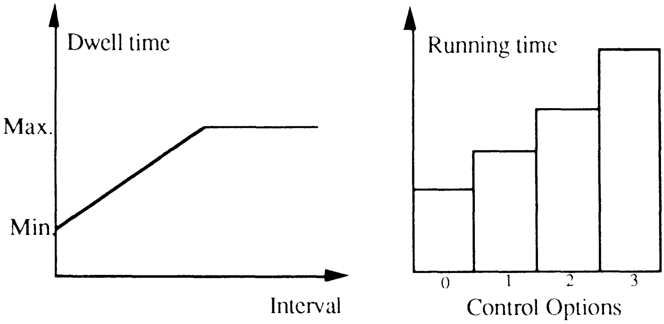

Figure 2. Models used in the fast simulator.

The dwell time of a train at each platform is proportional to the interval of the train with respect to the preceding train in the line. This dwell time is modified by saturations: minimum dwell time (no passengers) and maximum dwell time (full train), see figure 2. The forced dwell times due to the control system are also taken into account.

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There are some parameters of the fast simulator that are updated depending on the estimation of the behaviour of the actual system:

- Ratio between the dwell time of a train at a platform and its interval with respect to the preceding train. This parameter measures the passenger affluence ratio.
- Minimum interval between consecutive trains at each stage.
- Maximum dwell time at each platform.
- Running time of each control option at each stage

There is another parameter that is updated on-line, and affects the control strategies of the mid-term control. This is the "natural interval" of the line, defined as in [6]. It measures the interval of a balanced line when all the trains are running at their nominal speed, using the current passengers flow at each station.

7 Results obtained by the tool PACO

The tool is made of an accurate system simulator (see sections 3 and 4), a short-term control module, and a mid-term control module (section 5). Another module is in charge of the synchronous animated display of the behaviour of the system, including the passenger loads in both the trains and the platforms, the current status of the intervals, the predicted intervals and energy consumption information. The tool also generates detailed reports on the evolution of the system.

The user can adjust both the control parameters (section 5) and the simulation speed. The initial conditions of the system and the global passenger flow scenario are also imposed by the user.

A study case is here described to show the behaviour and capabilities of the tool, based on a real metro line with 22 platforms and 17 trains running. The protection system simulated is ATP. The nominal passenger affluence to every platform is 40 kg/s. The destinations are fixed according to the relative importance of the stations.

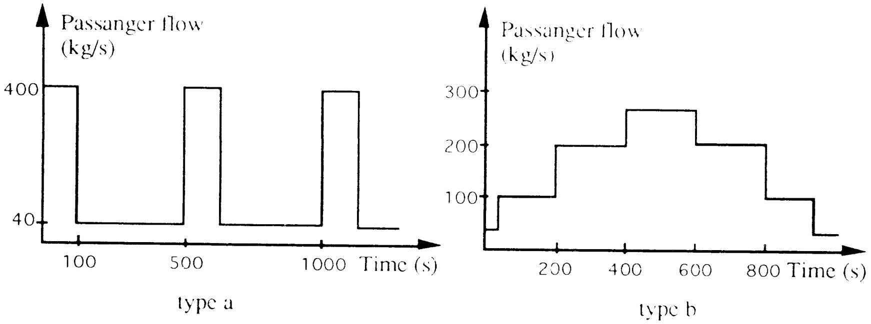

Figure 3. Types of disturbances

Three types of passenger-flow disturbances are used. The first one is just an increase of the passenger affluence from 40 to 100 kg/s. The second disturbance tries to resemble a connection to local trains that arrive every 500 seconds (type "a" in figure 3). The third one represents an affluence peak that may happen -for instance- due to a rock concert (type "b" in figure 3).
Two simulations about this case study are shown in figure 4. In the first one (figure 4.a), the initial status of the system is highly unbalanced. After 2000 seconds, when a regular interval has been already reached, the disturbances are simultaneously applied to the line, each one on four platforms, during 2000 seconds. In the second simulation (figure 4.b) the disturbances are applied on the initial situation

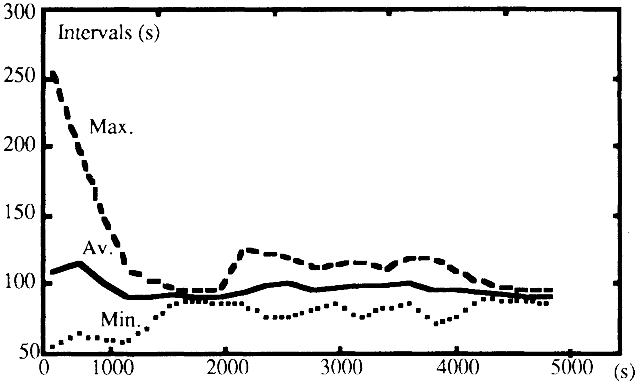

Figure 4.a. Disturbances after recovering a regular interval.

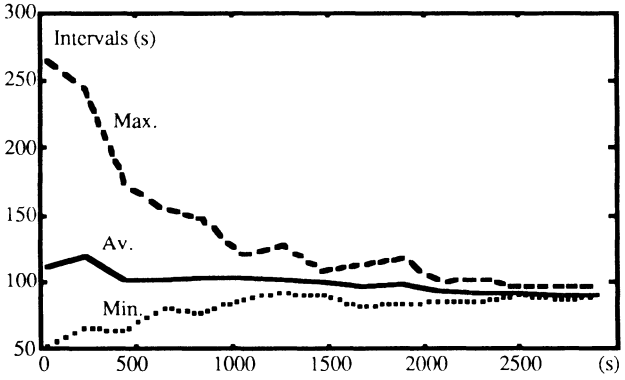

Figure 4.b. Disturbances during recovering a regular interval

The figures show the evolution of the average, minimum and maximum intervals between consecutive trains. It can be seen the high capability of the system to recover a regular interval from a very unbalanced situation, and how

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the system is degraded but kept under control in the presence of big disturbances.

8 Conclusions

The behaviour of the tool PACO have been successfully tested against realistic test cases. The general approach to the simulation and control problem has proven to be adequate and efficient. The control system shall be implemented on real lines in a few months. Currently, work is in progress in order to extend these concepts to railway systems with more complex topologies.

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