SIMUL9: APPLYING UML TO A METRO SIMULATOR

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ABSTRACT
Custom-designing a simulator in a graphic environment requires use of two methodologies: one for software engineering and one for modeling of real systems. UML is a methodology geared to the design and specification of software that enables visualization, specification, construction and documentation of a system; therefore, it is ideally suited to modeling of real systems. Herein are described UML components that proved invaluable for modeling a real system, namely, for developing a simulator of Line 9 of the Barcelona metro.

Keywords: metro simulation, manless train operation (MTO), fixed block

1. INTRODUCTION

Conventional metro control systems, known as automatic train protection (ATP) systems, are based on the use of a fixed block that ensures a safe distance between two consecutive trains on the same track. Advances in contemporary control systems, combined with automation of certain processes, have reduced the role of a human operator: thus, at increasing levels of train automation (i.e. automatic, driverless or manless train operation [ATO, DTO or MTO]), the responsibilities—and indeed, the mere presence—of an operator become less and less significant.

Simulations of ATP systems can be run quite synthetically, as a chain of events in the route between stations combined with the simulator's coordination of train departures from a given station (in function of accessibility to the fixed block). However, these models cannot be extrapolated to MTO, in which trains are allowed to circulate with a variable block (i.e. a variable distance between two trains traveling in the same direction, which varies in function of the trains' respective accelerations and decelerations).

Herein are described the design, scheduling events, and experimental validation of a simulator that was specifically developed for the study entitled "Optimization and Simulation of Barcelona Line 9".

2. L9: BARCELONA'S NEW AUTOMATED METRO LINE

Line 9 (L9) is slated to be Europe's longest subway line. Spanning 47.8 km, it will link the cities of Santa Coloma de Gramenet, Badalona, Barcelona, L'Hospitalet de Llobregat and El Prat de Llobregat.

Line 9 will serve neighborhoods that currently lack metro service, such as Bon Pastor, Llefià, La Salut, Singuerlín, Pedralbes and Zona Franca, connecting residents of the five cities that it will pass through. Moreover, it will link strategic hubs, logistics centers, and major infrastructure or services areas, such as El Prat airport; Zona Franca; La Fira convention center; the Barcelona Port extension; the City of Justice judicial complex; the Diagonal university campus; Sagrera high-speed train (TAV) station; Sant Pau Hospital; Park Güell; Camp Nou; and Ciutat del Bàsquet basketball complex. It will encompass 52 stations, including 20 transfer stations that will further improve transport within the metropolitan area of Barcelona, namely, through connections with other branches of the local railway network: Rodalíes RENFE suburban rail; high-speed rail (TAV); other metro lines (Lines 1, 2, 3, 4 and 5); FGC suburban rail (Lines 6, 7 and 8), and the Trambaix and Trambèsos tram lines.

Line 9 will be completed by 2014. Transit studies have predicted an average daily ridership of 350,000 passengers, equivalent to 130 million passengers per year.

3. SIMUL9

SimuL9 is a custom-made simulator that runs on Windows XP (SP3) and Framework.Net 2.1. It is a specific, object-oriented simulator based on an event-scheduling methodology that combines discrete simulation (temporal management of periodic events) with continuous simulation (train traction).

Owing to its various advantages, including scalability, reusability and parallel task operation, the Model-View-Controller programming paradigm was chosen for development of SimuL9. This paradigm enables separation of a business model's logic from its view, via a controller which communicates the events that occur.

3.1. Control Elements in MTO

Line 9 of the Barcelona metro, like most automated lines, will be equipped with an array of logic and physical elements to guarantee control and tracking of the automated trains. These include:

- Controller zone (CZ)
- Automatic train supervisor (ATS)
- Automatic train control (ATC)
- Supervisory control and data acquisition (SCADA) systems

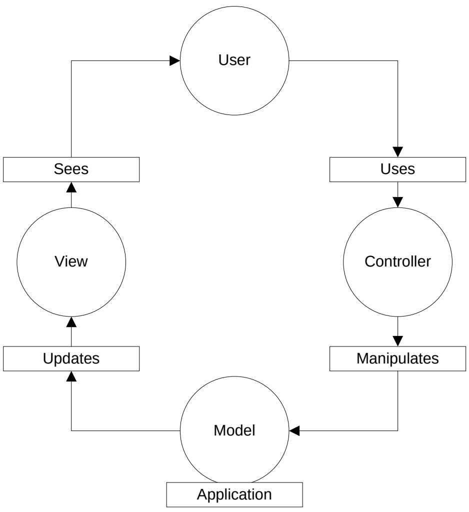

Figure 1: Schematic of the Model-View-Controller programming paradigm

Furthermore, L9 will feature sensors and odometric elements to enable teledetection of the position of different trains circulating on the same track. Obviously, L9 will also require a backup system to ensure correct operation in the event that the primary system fails.

Simul9 was designed expressly to behave exactly as an MTO control system would behave.

4. UML

Developing a specific simulation model requires a firm grasp of the domain to be modeled; the deeper the programmer's knowledge on the domain, the easier the programming of the simulator.

Unified Modeling Language (UML) is geared towards the design and specification of software that enable visualization, specification, construction and documentation of a system.

Design by UML is built around a series of diagrams and documentation practices, including conceptual and relational models, class diagrams, use-cases sequences, and collaboration diagrams.

4.1. Conceptual model

The UML conceptual model (Figure 2) is used to identify the major concepts in the subject domain.

Based on the objectives defined for the simulator, the significant elements for the simulator's conceptual model are established.

The final objectives for SimuL9 enabled the railway infrastructure to be treated as a single simulation object (Railway) which would contain all of the railway segments (Tracks), have the correct parameters, and dictate the logic of the queries from the remaining simulation elements.

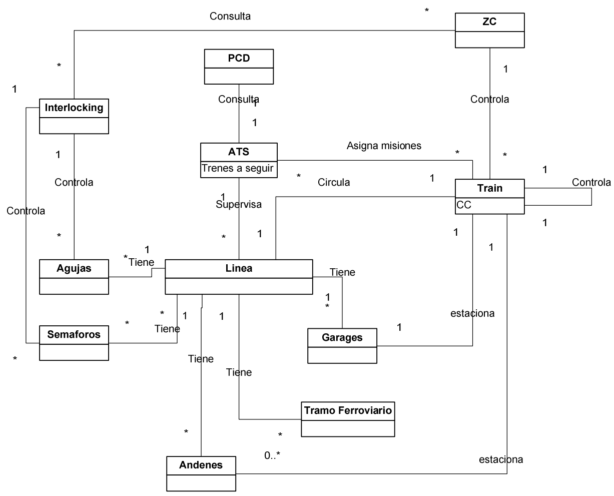

Figure 2: Conceptual model

Connecting all of the railway segments yielded a plot which enables dynamic breakdown of the trains according to operation time.

4.2. Relational model

The UML relational model is used to establish the logic that rules the system's constituent elements.

The relational model for SimuL9 proved invaluable in communication the simulator to the client, from whom accreditation of the model is pending.

This model was devised by combining the simulator's conceptual model with the use cases for each element, which generated a list of responsibilities and obligations for each simulator element.

4.3. Class diagram

Generalizing the aforementioned models provided a class diagram, and consequently, the objects that had to be encoded such that, once queried, they could enable specific simulations to be run (in this case, of L9 or any other automatic train under the same Siemens control system).

Interestingly, objected oriented design facilitates the scalability and specialization of the current model, meaning that other train control systems could be integrated into an expanded version of SimuL9 through specific coding of new simulation elements.

4.4. Application architecture

After the definition of the programming paradigm and the specification of the data model, the application architecture has been developed.

The application has a central database where all data is stored, from physical model of the network to simulation results. As the system uses a MVC schema, there are different modules for each activity. They are: the simulation kernel, the physical model of the rail network, the statistics module and the representation module. All of them are linked with the database and, of course, with the Graphical User Interface (GUI). All these elements are described in Figure 3.

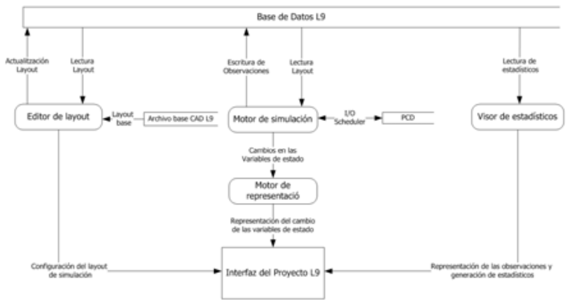

Figure 3: Application architecture

The physical model module is also in charge of the conversion of CAD models to logic ones and the simulation kernel also uses operation plan to control the rail system.

5. SIMULATION MODEL

The UML specification enables definition of all the components required to develop the simulator, as well as of the logic that dictates the interactions among them.

To complete the simulation model, a series of discrete and continuous simulation events had to be managed and linked together. These events were needed to allow temporal evolution and state-variable value changes in the model.

5.1. Traction, system continuity, control, and supervision model

The system is controlled and supervised at two levels:

1. Simulation of train dynamics with the advantages offered by use of a mobile block;
2. Use of interlocking, which guarantees transit safety on a given train route.

5.1.1 Metro dynamics

The basic continuous equations used to model the metro dynamics are:

$$\begin{aligned} T - R &= m \cdot a \\ R &= A + B \cdot v + C \cdot v^2 \end{aligned} \qquad (1)$$

Whereby T is the traction effort; R is the resistance to the train’s movement; m is the train’s mass; and a is the train’s acceleration. The coefficients A, B and C depend on the mechanical resistance, aerodynamic drag and grade resistance, respectively. Using these equations, the acceleration in traction mode is given by:

$$a = \frac{1}{m}\left[T - (A + B \cdot v + C \cdot v^2)\right] \qquad (2)$$

The Barcelona metro L9 network uses a moving block control system. Under these systems, computers calculate a safe zone around each moving train, which no other train is allowed to enter. The system requires knowledge of the exact location, speed and direction of each train, which is determined by a combination of several sensors, namely, active and passive markers along the track, plus onboard tachometers and speedometers. With a moving block, lineside signals are not required, and instructions are passed directly to the trains. This has the advantage of increasing track capacity by allowing trains to run closer together while maintaining the required safety margins.

5.1.1. Interlocking

When trains circulate over a system of tracks, they generate circuit routes that must be carefully protected. In SimuL9, this protection was achieved by dynamically creating petitions from circulating trains. These petitions are managed by the controller zone (CZ), which is responsible for receiving circulation notifications (i.e. variations in the circuit route) sent to it by the trains over the course of the simulation. Thus, when the CZ detects a set of available segments, it proceeds to exclusively assign the transit segments requested by a given train. Likewise, this same train notifies the CZ once it has abandoned a given segment, such that the CZ can then determine when the interlock will be available. Efficient management of these interlocks enables safe control of the circulating trains in the simulation.

5.2. Discretization of the system

Discrete simulation of L9 is achieved through temporal events associated to a daily operations schedule known as *PCD*, namely, mission start (see below), and passenger boarding and exiting services, and to events in Emergency Mode, which enables simulation of line failures.

5.2.3 PCD

A single PCD encompasses all required daily operations. The PCDs are defined based on the service missions and lines. A mission is a sequence of stations and transit segments in which a train must complete a series of operations (e.g. stopping for passengers or traveling without stopping).

Initiating a mission at a given point in time generates a services line in which the service time for each passing point is provided; each mission start can be considered a valid PCD operation.

5.2.4 Safety operations

Safety operations in SimuL9 are simulated in Emergency Mode, through a special interface that enables the user to define *PCDs* and line operating incidents.

Operating incidents are described according to the time that they occur, the track segments that they affect, and their duration.

Each event associated to an operating incident that affects a given train is linked to a service recovery event for that train.

6. EXPERIMENTATION

SimuL9 can run simulations of L9 under daily operations schedule (PCD), as well as in emergency scenarios, such that the line's operations can be evaluated in terms of train service time and frequency in each experiment.

6.1. Emergency Mode

Emergency Mode was developed to allow the user to select the type of safety operations strategy to adopt (*i.e. bypass* or *split*) in the event of an operating incident (Figure 4).

1. In bypass, or VUT, operation, trains switch tracks in order to avoid the affected train while preserving the service line.
2. In split operation, the system divides all of the service lines in order to provide full service along the entire L9 route.

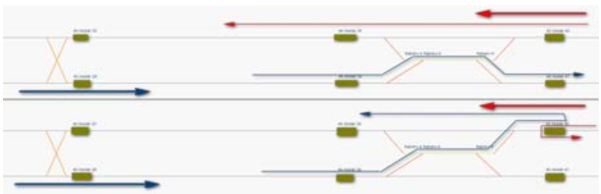

Figure 4: Bypass/VUT (top) and split (bottom) safety operations

6.2. Case studies

Examples of cases being evaluated in the final phase of SimuL9 include:

- Extra service for sporting or other large events (e.g. for FC Barcelona games at Camp Nou or for the Mobile World Congress at the Fira de Barcelona convention center).
- Sequencing missions with passenger service at alternating stations.
- Simulation of the full L9 and L10.

7. SIMULATION RESULTS

This section reports on some of the results obtained from simulations run under Standard Mode; however, results from simulations run with optimized PCPs are not described.

Analysis of the simulations of missions with passenger service at alternating stations reveals time savings of roughly 10% for covering the entire route, equivalent to approximately 7 minutes per trajectory. This reduction in time opens the possibility of introducing more trains over the course of the day, and consequently, the chance to increase the total number of kilometers covered daily.

Running simulations in Emergency Mode with various periodic operating incidents provided a table of service frequencies that ensure proper transit along the line without any losses in train circulation and enable determination of which emergency option (bypass/VUT or split) is the best suited according to the location of the operating incident.

Interestingly, bypass/VUT operation generally provided better performance than split operation, given that the latter penalizes transit at the point of return, as revealed in Figure 5, below. The illustration shows that when Train B begins its return maneuver, Train A must slow down, and ultimately, stop.

Figure 5: Transit is penalized at the point of return

8. GUI

The graphic user interface (GUI) in SimuL9 was designed to meet three objectives, all of which are necessary for developing a specific simulator:

- Verify that the simulator is working correctly, through experimentation and execution of different encoded processes, including:
  1. Generation of missions, assignment of a train to a service line from the PCD, etc.;
  2. Transit control, safety system, etc.;
  3. Management of operating incidences.
- Validate train circulation operations under optimized PCPs and in Emergency Mode;
- Establish credibility for the simulation model.

The interface in SimuL9 comprises the essential elements of any Windows application: a menus system, toolbar, properties windows, and graphics views.

8.1. Menus system and toolbar

The menus system and the toolbar in SimuL9 are the first element of interaction between the user and the application. They enable the user to:

1. Create simulation scenarios;
2. Configure transit tracks;
3. Configure Emergency Mode;
4. Define experimental *PCDs*;
5. Control the simulation.

8.2. Properties window

The properties window allows configuration of the simulation's general parameters, including:

- The integration step;
- Parameters such as friction, masses, kinematics, etc.
- Generic parameters, such as a simulation's interval of representation.

8.3. Graphics views

Lastly, SimuL9 features two graphics views, Pane and Zoom, which enable tracking of train movement and operating incidences at two different levels of magnification: total and partial.

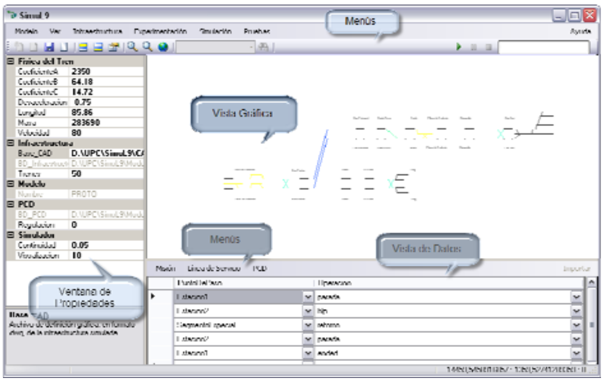

Figure 5: SimuL9 GUI

9. CONCLUSIONS

Unified Modeling Language (UML) is a specification language that facilitates developer's work for a specific simulator, namely, by enabling clear identification of a conceptual data model and direct relation of this model to a conceptual simulation model.

In the case reported here, development of the train simulator SimuL9, UML elements such as case-use diagrams and relational models allowed specification of the logic that dictates the simulation objects integrated into the model.

Unified Modeling Language has proven essential for attaining credibility for SimuL9 from the client, by enabling the client to actively participate in the initial phases of the simulator's development.

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Born in 1968, Jordi Montero earned his BS in Computer Science in 1998, and has worked as a PAS at UPC since 2000. His research interests include discrete simulation systems. He has worked on several projects for various companies (*e.g.* Aena, Agbar, Almirall Prodesfarma, Damm, Indra and Siemens) from diverse sectors (*e.g.* airport, transport, manufacturing and pharmaceuticals).

Born in 1958, Dr. Antoni Guasch is a research engineer focusing on modeling, simulation and optimization of dynamic systems, especially continuous and discrete-event simulation of industrial processes. He received his PhD from UPC in 1987. After a postdoctoral stay at the California State University, Chico (USA), he became a professor at UPC. He is now Professor in the department called *Ingeniería de Sistemas, Automática e Informática Industrial*. Since 1990, Prof Guasch has led 35 industrial projects related to modeling, simulation and optimization of processes for the nuclear, textile, transportation, auto manufacturing and steel industries. Prof. Guasch has also served as scientific coordinator and researcher on seven scientific projects. He has also helped organize local and international simulation conferences. For example, he was the Conference Chairman of the European Simulation Multi-conference held in Barcelona in 1994. He recently published a modeling and simulation book that is now being used in many Spanish university classrooms. Prof. Guasch's current research project, sponsored by Siemens, is related to the development of power management optimization algorithms for Barcelona's new subway Line 9. Line 9 will be the first driverless metro in Spain and one of the largest (45 km) and most advanced driverless lines in the world. Prof. Guasch is also contributing to the development of tooPath (www.toopath.com), a web server system for free tracking of mobile devices.

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Born in 1974, Jaume Figueras earned his Degree in Computer Science in 1998. His research is in automatic control and computer simulation & optimization. He designed and developed CORAL, an optimal control system for sewer networks, used in Barcelona, Spain; and PLIO, an optimal control system and planner for drinking water production and distribution, used in Santiago de Chile, Chile, and Murcia, Spain. He is currently collaborating on different industrial projects, including the power-consumption optimization of tramway lines in Barcelona, in conjunction with TRAM and Siemens, and the development of tooPath (http://www.toopath.com), a free web tracking system of mobile devices. Jaume Figueras is also the local representative of OSM (http://www.openstreetmap.org) in Catalonia and participates in different FOSS projects.