Bullet Train Operation Simulator including Electric Power Consumption

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Abstract: The larger and more complicated any railway system becomes the more unpredictable incidents and accidents can occur during operation. To understand and minimize unpredictable events simulations have been developed for a range of industrial applications. Space shuttle piloting, nuclear power plant operator training, and flight simulation systems are typical examples in use today. As the cost to performance ratios of computers has decreased over the last ten years, simulators have become practical and economical additions to safety training, product/system design, and product/system testing. There is a rising trend to use simulations in areas where the costs of building a simulation have been prohibitive in the past, such as crowd simulations for emergency egress planning in places of public assembly. High fidelity railroad system simulation is a challenge, even for skilled engineers and railroad operators. This paper discusses an existing high fidelity bullet train operation simulator and extends it use to include electric power consumption of each train and transformer substation. Central Japan Railway Company and West Japan Railway Company have had measured success in applying the Parallel Inference Machine (PIM), an agent-based parallel computing platform, to the Shinkansen (Bullet Train) operation simulator. The simulator tests the central control computers, trains the dispatchers, and can pretest future system additions. We have now developed models of power supply and demand between trains and substations, which can be mapped onto the PIM system. Power consumption and distribution simulation systems will be used in many applications, and the Japanese bullet train is one of the first to benefit from the use of these techniques, i.e., scalable real-time agent-based parallel computing.

Keywords: Traffic simulation; Electric power simulation; Agent-based; Complexity-based; Parallel computer

1. INTRODUCTION

Effective asset management is one of the main reasons for building a simulation. Assets can include, but are not limited to, physical assets, financial assets, social assets, comfort assets and energy assets. In systems where the initial outlay has a very high capital value, such as a railroad track system, the need to transport people in an efficient and timely manner is equally important as asset management. Simulations, based upon behavior, can significantly reduce the assets required for a given dynamic load. In the case of the Japan Railway (JR) the simulation is used to optimize an existing system thereby adapting it to the dynamics of realistic social loads.

Historically, large, complex problems have been solved by developing a system composed of many different types of state variables (states). These states are interconnected but the nature of inter-connectivity is an exponential function with respect to complexity. By that we mean that every time we add a new "state" the connections in the system increase at an exponential rate (Figure 1). Top-down, state-like approaches are suitable for solving very simple problems but were not scalable to the problems of realistic, biological, adaptive, social or monetary systems. An example of this is the extreme brittleness and complexity of the early artificial intelligence systems developed for process control. Whenever a state arose that had not been considered in the control system, the system would halt or fail. This is, in part, due to the number of independent variables in the system and to the relationship between the components. As the JR

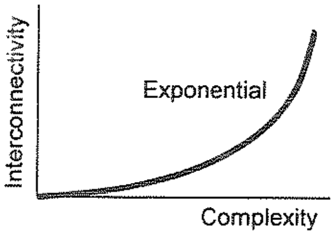

Figure 1. Complexity vs. Interconnectivity

grows to meet the passenger demands, the simulation and its supporting technology will have to be upgraded from time to time. The philosophy of choosing a technology that can match the pace of the JR's growth has obvious advantages for safety and reliability.

We have already developed a high fidelity bullet train (Shinkansen) operation simulator. Using the Parallel Inference Machine (PIM) we have demonstrated the applicability of agent-based parallel computing to a large-scale real-time system, i.e., a bullet train operation simulator. Central Japan Railway Company and West Japan Railway Company have successfully used this system to simulate Bullet Train operations. This simulator tests the central control computers, trains the dispatchers, and can be used to pre-test future possible additions. Yaskawa [1997a], Yaskawa et al. [1997b] and Parunak [1999, 2000a, and 2000b] describe the development and results.

This paper describes a framework to model the electric power supply, demand and consumption of the bullet train system, to be incorporated into the existing and working bullet train operation simulator system. Once these electric power factors are incorporated, the train dispatcher will be able to create and test better recovery schedules to minimize the peak electric power demand. The power companies charge penalties for excess usage of electrical power, and the use of the simulation can provide a valuable service to the Japan Railway.

2. THE PROBLEM AT BULLET TRAIN SYSTEM (SHINKANSEN)

2.1 Bullet Train System

The Tokaido and Sanyo Shinkansen Lines between Tokyo and Hakata, 1,100 km (700 mi.) long, are the busiest among all the Shinkansen lines. On average, the lines carry 350,000 passengers every day, with a peak of 1 million. Approximately 1,000 trains at a speed of 300 km/h (190 mph) travel down these lines every day. This is similar to 4,000 Boeing 747's flying back and forth daily between Sydney and Melbourne. To meet future demands the JR must increase the train frequency while keeping the operation error of 15 to 30 seconds. A further requirement is to maintain their perfect safety record: no passenger accidents in their history of 37 years.

The Shinkansen operation started in 1964. The operation began by running one Hikari super express and one Kodama super express per hour. The Hikari and Kodama lines had the same performance of 210 km/h (130 mph), but Hikari stopped at only major stations and Kodama stopped at every station between Tokyo and Osaka, covering 500 km (300mi.). Today, there are three classes of bullet trains: Nozomi, Hikari and Kodama are running along the Tokaido and Sanyo lines between Tokyo and Hakata, a distance of 1,100 km (700 mi.). Nozomi has the fastest operation, running at a speed of 300 km/h (190 mph).

During peak hours, trains arrive and depart the Tokyo station every three and a half minutes. The train frequency today is two Nozomis, six Hikaris and three Kodamas per hour compared with just one Hikari and one Kodama 37 years ago. Despite this heavy traffic, the system operates right on schedule with a minuscule error of 15 to 30 seconds, most of the time.

2.2 Real-time Problems to be solved

Developing schedules involves months of work for many railway experts. They know what affects the train operations: available trains, maintenance cycle, available drivers, different train performance, stations, distance, signals, track switches, curves, slopes, tunnels, bridges, and so on. Extra trains must be scheduled in advance, and there is no way to run any ad hoc trains within the schedule.

When the JR started operating the Nozomi 270 km/h super express, four of those per day could run early morning and late at night. It took several months before hourly operation of the Nozomi began. There is a bottleneck near the Tokyo terminal station, the busiest station in the system. Since the Tokyo station has no hind tracks, arriving and departing trains must cross over the main tracks.

An additional problem is the location of the train yard, which is located at the front of the terminal station, rather than behind, so that deadhead trains must travel for a while on the busy main tracks. To reduce this problem and increase the train frequency, Central JR will build another terminal station, Shinagawa, a few miles before the Tokyo station. They must check the effects of the new station before construction begins.

The Kobe earthquake convinced Japan Railway to build the second control center in Osaka in addition to the control center in Tokyo. The two centers will work as mutual backup systems. When one center is on-line, the other center is assigned for operational dispatcher training. This requires a simulator system to work in conjunction with the backup system for training purposes.

The JR is running the series 0, 100, 300, 500, and 700 trains at present, although the series 0 and 100 are gradually retiring. New trains with different performance make the already complex system and its scheduling more complicated. When complicated systems reach critical density or optimal performance characteristics tiny perturbation in the system can lead to emergent or chaotic behavior and the safety of the system may be compromised.

The JR requires a simulator system to check a wide range of contingencies. If, for example, snow were to cause a delay, the whole system may become chaotic and virtually impossible to reestablish order. In this scenario there may be no real danger to passengers. The problem is that the system is in an indeterminate state, the schedules are unpredictable, after the cause of the delay is removed.

As the train drivers know only the original schedule, every driver tries to catch up with that schedule. The dynamics of this type of situation leads to a standing compression wave where several trains are stuck, following a lead train as it stops at a station. The resulting disruption to passenger service exasperates the compression wave as uneven loading on the trains cause further delays to dwell times.

Furthermore a power surge occurs immediately after the leading train leaves the station when all the trains that follow start simultaneously. The JR needs to know the full spectrum of asset behavior when the flock of trains converge on the Tokyo station. The JR wants to model revised and feasible contingency schedules on a simulator system faster-than-real-time to evaluate recovery strategies.

An additional complication to the scheduling problem is the phasing out of series 0 and 100 trains. These operate with AC power to drive DC motors. The newer series 300, 500 and 700 have AC motors using AC-to-AC power frequency converters. The AC motors on the new series can act as generators as with the dynamic braking, but the energy could be fed back into the system.

In an ideal case the braking trains could generate a significant proportion of the power demand required by the accelerating trains. In reality, it is very difficult to achieve this type of power distribution even if every train runs according to the schedules. When the schedules have small perturbations, the power losses increase and energy is lost as frictional heat in the braking system.

3. PREVIOUS SIMULATION SOLUTIONS

3.1 A simulator in the Control System

The Shinkansen operation is controlled by the Programmed Route Control (PRC) computer system. The central system sends traffic control signals including speed limit information and route control commands, i.e., track switching commands, based on the train schedules and tracking data.

The PRC computer is usually tested with its own built-in simulator software module, a self-diagnostic program. This type of top-down state-like simulator module verifies that the sequential logic in the PRC works as designed. Further verification of the PRC's ability to cope with various train operations, including perturbations to the schedule, is left to the two levels of tests using actual trains, i.e., monitor-run and control-run.

Monitor-run is a test where all the inputs are fed to the new PRC in parallel with the running PRC and the outputs from the parallel system are monitored. Control-run means that selected trains are controlled by the parallel PRC. It takes many man-hours to complete those two processes.

3.2 Off-line Simulators

Many off-line simulators have been developed for the railroad industry mostly for specific purposes, e.g. scheduling and passenger loading. Monitor and control simulations are performed on-line and in real-time, but variations of the train operation scenarios are limited, and they cannot reproduce the situation where the schedule has been disrupted. Other types of simulators have been developed for the railroad industry for specific purposes for example, specific asset management and off-line testing. Nozue [1995] and [1996] showed some of these simulations.

The more detailed and precise the simulation becomes the slower the processing becomes as previously stated. This was described by Asuka et al. [1996]. However, the cells in the PIM/Paracell system are designed to operate in fixed computing time so that the response stays the same, i.e., real-time (Figure 2).

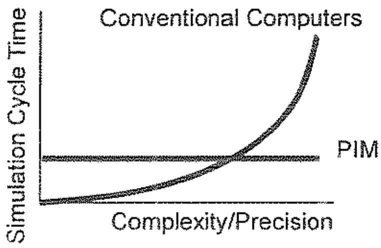

Figure 2. Real-time (fixed cycle time)

4. EXISTING BULLET TRAIN

OPERATION SIMULATOR

A track segment is the basic unit of control for the train traffic. The Shinkansen tracks are segmented into 1.6 km (1 mile) lengths between stations. Lengths in stations and their neighborhood are much shorter. The total number of track segments is about 2,000 since the eastbound and westbound tracks alone are about 1,100 km (700 mi.) each.

Each segment in the simulation consists of several relay logic elements. A track segment generates signals for the following segment. The segment signals are sent to the central control system every three seconds. The central control system sends traffic control signals including speed limit information and route control commands, i.e., track switching command, based on the train schedules and tracking data. At peak hours there may be 160 or more trains on the tracks, and the shortest period between trains is three and a half minutes. The daily total is approximately 1,000 trains.

The present Shinkansen simulator includes 2,000 track agents, 1,000 train agents of which 160 or more may be on the track at any given moment. These simulators have in excess of 3,000 agents working in parallel.

Simulating this system with a conventional programming scheme would require considerable effort in systems design, flowcharting, coding and debugging. The resulting simulation would be brittle, by that we mean that any bug in the system could cause the whole system to fail (Figure 3). Furthermore, the analytical intractability of the problem is compounded by the computational intractability of the solution. In other words you never know if you've programmed all the potential scenarios into the simulation and it will take a long time to run the simulation before you get any answers. In addition to these time-related problems, you really don't know if the answer is correct or a bug in the code has thrown up a "plausible" solution without extensive checking. This is the curse of top-down programming and has been the bane of systems design for decades.

It would be hard to divide the task between many people and, in practice it is impossible to complete a full systems design, build and test promptly. It took only 18 months for JR people without programming experience to successfully complete the PIM/Paracell application system. Most of their computer system development projects had taken longer than two years.

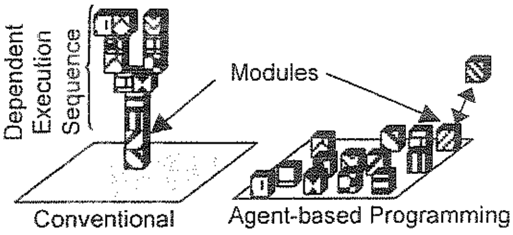

Figure 3. Interchangeability and Independency of Agent-based Programming

Although the number of agents is unprecedented in the train operation area, there are other large-scale systems, such as one being developed by Keith Still [2000] in social management. In his Legion system, there were 3/4 of the number of types of agents as in the bullet train, but on the order of a million instances. In other words, 15 types in a million instances vs. the bullet train, which are 20 types in 30,000 instances.

5. AGENT-BASED REAL-TIME SIMULATOR PLATFORM (PIM/PARACELL)

The programming and execution scheme of the PIM/Paracell system can be thought of as a team of agents with a bulletin board and a clock [Yaskawa et al., 1999]. Each team member gets data from the bulletin board and can post results on the board. The bulletin board frees them from the task of communication instructions with each other and eliminates the subsequent exponential increase in complexity. They don't need to have time-consuming meetings, and they simply get instructions and get on with the job!

Adding team members does not increase the computational overhead as each new member has one link to the bulletin board and one eye on the clock. Therefore each team member can concentrate on his own task and concerted jobs can be achieved through the bulletin board posting and the clock rate. This method of programming is called "Hierarchical Communications" and has obvious advantages for writing, testing, debugging and implementation.

This programming and execution scheme of the Paracell/PIM system maps perfectly to the JR simulation requirements. Programming individual small computing agents that run in parallel, allow train and track agents to be scaled up as required. The concept of communications between agents through a common memory supports the need to have a single coherent image of the system status for running the simulation. This model fits the structure of the Shinkansen system very well. The actual simulator system consists of 40 PIM processor board computers, each housing 1,000 PIM cells. Communication between systems is via Ethernet. One extra PC system works as the central and gateway machine, and the 40 PIM processor board computers simulate the 40 stations and yards that form the entire Shinkansen system.

Typically simulation systems fail because of the need to translate tacit (domain knowledge, in this case the knowledge of the JR system) into code via computer programmers, who rarely have that tacit knowledge. However, as the domain experts, the JR engineers coded the agent-based simulation themselves. This was achieved by using Paracell, a rule-based near-natural declarative language. The engineers did not require detailed programming experience. Their tacit knowledge is converted into code quickly because they ***understand*** the nature of their problem domain; the engineers know the "what's and why's" of the JR system. Therefore they were using their experience to maximum effect and they had the ideas about how to solve their problems. The simulator is their product, not the supplier's, and they have a strong motivation to improve the product further.

6. MODELLING ELECTRIC POWER CONSUMPTION

The power requirement of the JR system has some significant challenges. A finite number of power sources are available to supply the energy required for train startup from the station and continuing train operation. The scope of the power supply problem can vary with the type and number of trains in a station, and the overall status of the line. For example, if an incident has upset the schedule of the line, power demands will be greater as the system is restored to normal operation. Additionally, the AC power drawn from the grid and supplied to the trains must be monitored for source and load power correction factors.

The scalable nature of the PIM/Paracell system allows models of power supply and demand between trains and substations to be added without degrading the system's real-time performance. The electric power characteristics of the supply and demand for each train, and the supply of each electrical substation and peripheral power equipment can be modeled as agents. It is therefore a simple extension of the existing Shinkansen operation simulator to include electric power consumption.

We have identified the agent-types that need to be included in the JR Shinkansen operation simulator for successful power management, from the report by Mochinaga et al. [2000] and the book by Matsumoto [1999]. These are:

- Power substations, every 20 km along the Tokaido line and every 50-70 km along the Sanyo line,
- Frequency conversion substations between the 50 Hz and 60 Hz areas, two locations,
- Automatic voltage phase switching sections, between power substations,
- Trains: impedance and regenerating characteristics.

Each train has a description of its own power demand versus time that will determine the power that it will draw during startup and during steady-state running operation. The instantaneous power will be determined from a model of the time-varying electrical characteristics (mainly the impedance) of the train's electric motors. Additionally, each train has the electric power regenerating characteristics during dynamic braking. Phase shifts and voltage drop along the overhead wiring must also be taken into account. Each train agent will have its power-calculating subagent to decide the demand or regenerated power as the train moves. Each substation agent will total the demand and regenerate power every moment and display it against its capacity or the contracted capacity. This can be achieved using a 15 Hz clock on the existing simulator.

Recently, the PIM/Paracell system has been successfully ported to the Windows-NT/2000 platform. As the processor performance increases, so does the PIM capacity. Furthermore it does so in a linear relationship. This increase means we will be able to expand the scope of simulation to include such areas as power supply and demand between trains and substations.

7. EXPECTED RESULTS

With the real-time power simulation of train operation, JR will be able to improve their schedules ***and*** minimize their normal and peak power requirements. The train dispatchers will be able to create a better recovery schedule minimizing the peak power demand. Power management is sometimes in conflict with the requirements of schedule management.

Train drivers trying to catch up with the original schedules after the cause of delay is removed can be the primary cause of peak power demands. Using the PIM/Paracell system JR will be able to identify the phenomenon of lost braking when too many trains' regenerate electric power and too few trains accelerate.

8. CONCLUSIONS

This paper outlines an agent-based approach to simulate the various components of the JR system including power flow and power demands. We expect this effort will lead to further expansion of the agent-based simulation approach, laying the foundation for including future technologies as they develop. This effort will provide us with an agent-based simulation environment that JR can use in evaluating different power scenarios and approaches. Through monitoring and simulation, we expect that JR will realize a more robust, cost-effective solution for managing the power grid and resources. A key requirement of any simulation is that it can grow with the system it is simulating. The major advantages of agent-based approaches are that they are future proof in that significant changes to computer operating systems and architecture do not require significant changes to the operating code.

In conclusions, it should be noted that the techniques for agent based systems are established (PIM/Paracell) but we are developing a management support application/tool which searches solution space in real-time. The problem we address cannot be reliably solved by human operators who may introduce the "human" factors so often attributed to the disasters we see in other manually operated systems around the world. By integrating a decision support system to the JR our focus is on safety and efficiency without compromise.

9. ACKNOWLEDGMENTS

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