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Ad hoc distributed simulation for transportation system monitoring and near-term prediction

Wonho Suh [a,*], Michael P. Hunter [b], Richard Fujimoto [c]

[a] Department of Transportation and Logistics Engineering, Hanyang University, Korea
[b] School of Civil and Environmental Engineering, Georgia Institute of Technology, United States
[c] School of Computational Science and Engineering, Georgia Institute of Technology, United States

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ABSTRACT

The widespread deployment of sensors, computers, and communications in vehicles and roadways is creating new challenges and opportunities to effectively exploit the wealth of real-time data and information that is now becoming increasingly available. In this paper the authors capitalize on these rapid technological advancements using a technique termed on-line ad hoc distributed simulation. This approach utilizes a dynamic collection of autonomous simulations interacting with each other and with real-time data in a continuously running, distributed, real-time simulation environment. Within the ad hoc distributed simulation approach a rollback-based time synchronization method is used to allow the simulations to adapt to unanticipated changes in traffic and to changes in predictions produced by other simulations. The proposed approach is tested on a transportation network with different geographical distributions of client locations and randomized network partitioning under different traffic demand scenarios. The results demonstrate that the proposed approach has the ability to share complex traffic data among participating vehicles and process the data in an effective way to provide drivers/system monitoring with near-term traffic predictions.

1. Introduction

The increasing presence of mobile and ubiquitous computing combined with nearly universal communications is resulting in important new opportunities in transportation system management [1]. Sensors, mobile computing, and wireless communication networks have witnessed dramatic advances over the past few years. Simultaneously, on-line simulations where models are fed by real-time data to predict future system states have been incorporated into diverse areas such as manufacturing [2], supply chain optimization [3] and transportation system operations [4–7], to mention a few. An ongoing challenge in today's transportation management systems is the utilization of these new data and technologies to monitor current operations and provide near-term system performance predications. It is possible to envision a distributed, adaptive, self-optimizing transportation infrastructure that can automatically reconfigure itself to maximize efficiency and minimize the effects of unexpected events ranging from localized incidents to catastrophic natural or human generated disasters.

Ad hoc distributed simulation is an approach to on-line simulation where a collection of autonomous simulators, each independently selecting a portion of the system to model based on local criteria, collectively compute future states of the overall system [8,9]. Unlike traditional simulations where the system being modeled is partitioned and mapped to logical

* Corresponding author. Address: Department of Transportation and Logistics Engineering, Hanyang University, 55 Hanyangdaehak-ro, Ansan, 426-791, Korea. Tel.: +82 31 400 5154; fax: +82 31 436 8147.
E-mail addresses: wonhosuh@hanyang.ac.kr (W. Suh), michael.hunter@ce.gatech.edu (M.P. Hunter), fujimoto@cc.gatech.edu (R. Fujimoto).

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processes in a top-down fashion, ad hoc distributed simulations partition the system bottom-up, leading to unpredictable overlaps and gaps in the areas modeled by different simulators. In [8,9] preliminary experiments showed that the ad hoc approach was effective in a simple test case where it could predict an increase in traffic along a single road corridor that was split into two components. This paper provides detailed Server and Client algorithms and describes a much more extensive and realistic evaluation in predicting traffic under different traffic scenarios including congested traffic conditions in a regular grid. Unlike prior work, the scenario modeled here includes many feedback loops, creating a much more challenging test case for ad hoc distributed simulations. These experiments extend the previous work by examining the impact of the geographical distribution of client locations and randomized network partitioning under different traffic demands in order to evaluate the robustness of the approach. Finally, the work described here focuses on an existing, commercial, off-the-shelf traffic simulation package called VISSIM that was adapted for use with the ad hoc paradigm.

This paper examines embedding on-line distributed simulations operating within transportation network elements (participating vehicles, roadside cabinets, etc.) in an attempt to create a transportation monitoring and near-term prediction system distributed across in-vehicle computer systems, roadside computers, and traffic management centers. In this approach participating vehicles play an active role in the monitoring and prediction of near-term future states of the transportation network. Throughout a vehicle's trip it obtains information from network sensor and other vehicles, performs real-time simulations and predictive functions, and shares its projections with other vehicle's simulators to create an aggregate view of both the individual vehicle's area of interest and the transportation system as a whole. This distributed simulation approach represents a shift in transportation systems monitoring, moving to the vehicle much of the intelligence, computational power, and responsibility for network management. Such an approach will be well aligned with the rapidly evolving in-vehicle driver assist, and ultimately driverless, systems that will dominate the transportation networks of the future. Our current focus is set on investigating whether an embedded real-time distributed system is capable of accurate system monitoring and producing accurate, faster than real time, near-term future state forecasts.

2. Background

On-line simulation refers to a simulation that is driven by real-time sensor data [10]. In on-line simulations in situ sensor data obtained during a simulation run is utilized to enhance simulation projections. Based on on-line simulation concepts significant research has been undertaken recently in dynamic data-driven application systems (DDDAS) [11]. DDDAS is "a paradigm whereby application/simulations and measurements become a symbiotic feedback control system" [12]. DDDAS has (1) "the ability to dynamically incorporate additional data into an executing application" and (2) "in reverse, the ability of an application to dynamically steer the measurement process" [12].

Symbiotic simulation is closely related to on-line simulation [13]. It refers a system where a simulation system and a physical system are closely associated. This close relationship can provide mutual benefit to both systems. The simulation system obtains continuous, real-time measurements from sensors in the physical system. Based on the real-time measurements, the simulation system provides highly accurate simulations of the physical system and decision alternatives for the near future. The physical system acquires near real-time decisions based on simulation analyses allowing for improved system performance [14].

Transportation system may receive benefits from on-line and symbiotic simulations. Related research includes emergency response operation, vehicle-to-vehicle and vehicle-to-infrastructure communication technologies, and system efficiency evaluation and field implementation [4–7]. Also, research on vehicular ad hoc networks has been actively conducted worldwide, such as Car2Car Communication Consortium, CVIS (Cooperative Vehicle-Infrastructure Systems), iTETRIS, and NOW (Network On Wheels) in Europe, ASV (Advanced Safety Vehicle) in Japan, and VII (Vehicle Infrastructure Integration) and Connected Vehicle in USA, to name a few [15–17]. Currently there are ongoing research efforts to incorporate real-time sensor data in traffic monitoring and evaluation. In this effort, centralized and decentralized approaches have been investigated. While the conventional centralized approach can be limited spatially and temporally due to the abundance of available real-time traffic information, the decentralized systems have shown to be able to rapidly respond to changes in traffic conditions [18–21]. In this paper, the authors proposes a new approach where multiple simulations are embedded in the transportation network elements and are used to collectively provide current and near-term traffic predications utilizing real-time sensor data and predictive data from neighboring simulations. This approach is termed ad hoc distributed simulations.

3. Ad hoc distributed simulations

An ad hoc distributed simulation is a set of interacting on-line simulations that collectively predict future states of a physical system. Each simulator, referred to as a client, receives information concerning the current state of the system from one or more sensors as well as predicted future system states from other clients, and generates predicted future states of some portion of the physical system. For example, a client simulator might model some set of road segments and intersections, receive vehicle flow rates on links carrying vehicles into the region modeled by the client, and predict vehicle flow rates on links carrying vehicles out of that region. The clients collectively model the larger transportation system covered by all the participants.