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Title: ***Intelligent, integrated, and Intermodal Transportation Services***

In the 70's, Greyhound was a major bus company and United Parcel Service (UPS) a major (trucking) packet delivery company. After the Airline Deregulation Act (1978), air transportation became more efficient, affordable, and comfortable. Greyhound's decision to dedicate itself to a single mode of transportation (bus) contributed to its decline. In contrast, UPS transformed itself successfully into an integrated logistics company, by thinking of trucks as one of several means of transportation, rather than an end.

It is our contention that future transportation systems will provide a multi-dimensional *service*. More than merely taking humans and goods from point A to point B, this service will optimize the transportation process along a number of dimensions such as cost, timeliness, duration, reliability, safety, security, and personal comfort, as well as global concerns such as environmental sustainability. Customers will choose a combination of these parameters, and the transportation service will carry out the delivery through an optimized combination of transportation modes most appropriate for that concrete task at that specific time, including airplanes, ships, railroads, subways, cars, trucks, busses, bicycles, and other means.

We call this vision *Intelligent, Integrated, and Intermodal Transportation Services* (I^{3}TS). As a good example of cyber-physical systems (CPS), I^{3}TS has both physical and cyber components. The first component of I^{3}TS is physical interoperability among the varied transportation modes and the goods to be transported. The second component of I^{3}TS consists of intelligent integration of heterogeneous information on I^{3}TS components ranging from simple sensors on cars and planes to complex ERP (enterprise resource planning) systems running in large data centers. Although societal challenges exist in the evolution of I^{3}TS systems (**Figure 1**), we are mainly concerned with the technical challenges of the second (cyber) component here.

Advances in the CPS sub-fields of remote sensing, communications, and computing offer tremendous opportunities for measuring travel time and reliability on a more frequent basis and more accurately than possible today. Wireless technologies, ubiquitous communication networks, communications devices, and geographic location technologies all contribute to a future where (a) travelers have better knowledge of the I^{3}TS system around them, and can make decisions to maximize their personal mobility, and (b) the I^{3}TS system has better knowledge of the locations of travelers, and can make control and pricing decisions to optimize the entire system.

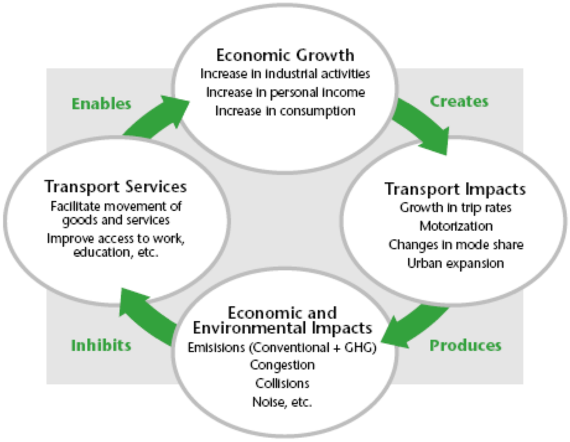

Figure 1 - Challenges in making continued mobility improvements ([4], p. 214)

Challenge 1 (Mobility Indicators): Integration of real-time information from many sensors (thousands today, millions tomorrow, and billions worldwide), plus historical data, to be synthesized, combined, aggregated, and transformed into indicators useful for long-term I^{3}TS infrastructure management, short-term I^{3}TS operations and system optimization, and real-time user travel choice decision making.

Challenge 2 (Mobility Prediction): Integration of real-time information flow from sensors to simulation models and on to users, extending the mobility indicators from measures of past and current system performance to predictions of future performance, e.g., in "what if" scenarios. This is a critical CPS capability that enables smooth real-time traveler adaptation and recovery from failures and accidents, facilitates short-term I^3TS operations adaptation to large-scale disasters, and optimizes long-term infrastructure decision making.

Software Architecture for CPS. To support the many dimensions of I^3TS, the software infrastructure must provide multi-dimensional quality of service (QoS) guarantees for the critical information flow in I^3TS. Needed QoS dimensions include performance, timeliness, availability, reliability, safety, security, privacy, cost, and power consumption. Although many of these QoS dimensions have been successfully demonstrated in research and in practice, it is a challenge to provide all or a subset of them in a flexible way, as required by I^3TS systems. The software architecture will include a flexible communications substrate, formed by adaptive push/pull streaming and event delivery facilities augmented by the QoS dimensions mentioned above.

Architecture Component: Push/Pull with QoS. A flexible communications substrate supporting these QoS dimensions is non-trivial due to the variety of underlying networks and platforms. For example, typical sensors communicate through wireless (mobile) ad hoc networks (MANET). Communications with cars includes vehicle-to-vehicle (V2V) message forwarding, a wired backbone with wireless last-hop as is used in cellular telephone networks, or a hybrid architecture combining V2V, MANET, cellular, wi-fi, or other alternative networks. Adding the required QoS dimensions present another set of challenges that need new breakthroughs in resource management and system composition.

Architecture Component: Sensors. On one end of the architecture, sensors capture real-time information from the real world for the I^3TS, e.g., the congestion points on the highways, location of airplanes in the air, and position of trains on the rail tracks. Other examples of useful information include current (and forecasted) weather along the planned path, and the availability of alternative delivery methods and transportation modes. Sensor information is filtered and delivered through the communications fabric when interesting events happen (as defined by the I^3TS system).

Architecture Component: Simulation Model for Prediction. On the other end of the architecture, complex models provide the predictive power with real-time input from the sensors. As a concrete example, several groups at Georgia Tech (Prof. Michael Hunter at Civil and Environmental Engineering and Prof. Richard Fujimoto at College of Computing) have been working on large simulation-based models for an increasingly detailed study of traffic in the Atlanta area. They have demonstrated a model of a section of I-75 including downtown Atlanta with approximately 45 signalized intersections, 100 miles of arterial, and 16 miles of freeway (approximately 190 nodes and 350 links). A model of the Atlanta metropolitan area will include over 800 signalized intersections, 900 miles of arterial, and 200 miles of freeway (approximately 800 nodes and 4500 links). For the I^3TS, such models along the delivery path need to be composed for the required QoS.

QoS-Preserving Composition. To address the challenges of Mobility Indicators and Mobility Prediction, the architecture components (examples above) need to be combined, with the appropriate end-to-end QoS properties. For example, by integrating thousands and millions of sensors and delivering real-time information for trip planning and guidance, end-to-end QoS requirements on real time, accurate and reliable current and predicted system- and individual- travel time measures are needed for recovery from unpredictable events such as accidents and natural disasters. Current software engineering composition method can achieve the needed functionality, but have deficiencies with respect to the preservation of end-to-end QoS properties in I^3TS.

Need for Correctness Properties. Modern auto vehicles are excellent examples of Cyber Physical Systems (CPS) that present significant practical and research challenges [1,2]. In the CPS context, concrete challenges include the need for *guaranteeing the functional correctness of complex interactions* [2] and to *specify, integrate, validate and verify complex distributed systems* [1]. These challenges are non-trivial due to the severe real-time requirements coupled with highest safety requirements on the one hand, balanced with the cost constraints and evolution of models and system functionality on the other hand. Some practical and theoretical advances have been made in automotive systems, e.g., in the development of ECUs (electronic control units) and in the area of component-based software engineering applied to automotive applications [3]. However, revolutionary advances are needed in order to meet the system and software complexity and correctness challenges in future CPS scenarios where I^3TS is formed by composing components such as intelligent automobiles, trains, and airplanes.

PTIs. In contrast to (and complementing) traditional verification and validation techniques that focus on the internal states and properties of programs, we propose to do research on *para-transactional invariants* (PTIs) that protect program and information sharing properties typically outside of program source code. The term PTI was suggested by run-time properties that generalize the atomicity property of atomic database transactions. Unlike traditional program verification invariants, which are verified only at a specific point of execution and are expected to be violated at other parts of the program, PTIs must be valid throughout the execution of the entire program module (the block of statements enclosed by PTI). Successful PTIs in both research and practice include serializability in atomic transactions, mutual exclusion in monitors and critical regions, specialization predicates in program specialization, and consistent memory access in transactional memory. Our experience shows that generic PTI specifications are more difficult to guard, but specialized PTIs are applicable to narrow domains. Finding new PTIs with the right balance in this trade-off between PTI generality and efficiency is one of the research challenges in applying the PTI concept and techniques.

Putting Everything Together. We believe the successes of the known PTIs show the promise of PTI as a unifying and general concept for the compositional construction of highly dependable software systems needed in I^3TS. New specialized PTIs may provide the correctness properties needed during composition. By composing the information flow from sensors to simulation models with appropriate PTIs, the I^3TS will be able to provide the required end-to-end QoS dimensions.

References

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Bio: Calton Pu received his PhD from University of Washington in 1986 and he is holding the position of Professor and John P. Imlay, Jr. Chair in Software in the School of Computer Science, Georgia Institute of Technology. He is building software tools to support information flow-driven applications such as digital libraries and electronic commerce. He is interested in and has published in operating systems, transaction processing, systems reliability and security, and Internet data management. He is working on automated system management (with HP Labs), service computing (with IBM Research), spam and denial of information (with several academic and industry partners), and information integration through code generation (with Emory Univ.). He has published more than 60 journal papers and book chapters, 170 refereed workshop and conference papers, and served on more than 100 program committees for more than 50 international conferences and workshops. He served as PC co-chair for SRDS, ICDE, CoopIs, DOA, and general chair for CIKM, ICDE, CEAS, and SCC. His research has been supported by NSF, DARPA, ONR, AFOSR, and industry grants from AT&T, IBM, HP, Intel. He is a member of ACM, a senior member of IEEE, and a fellow of AAAS.