National Workshop on High-Confidence Automotive Cyber-Physical Systems, Troy, MI, April 3-4, 2008

Automotive Cyber Physical Systems in the Context of Human Mobility

Daniel Work, Alexandre Bayen, and Quinn Jacobson

Abstract— **We discuss the limitations of the current automotive *Cyber Physical System* (CPS). Its vehicle-centric view only provides partial information about the surrounding environment, it is not well suited to address the needs of embedded humans in the system, and it moves too slowly to keep pace with other technologies. In the larger context of human mobility, the automotive CPS must become more open and flexible, new human mobility models need to be developed, and the key issue of privacywill need to be addressed to protect increasingly important and prevalent location based data.**

I. Position

For the past century, the primary function of the automobile has been to move people efficiently. The main challenge has been to build vehicles which are safe and dependable, and meet the intrinsic societal need for mobility. The automobile has enjoyed dominance in meeting this need, which has been characterized at a fundamental level as getting people and goods where they need to be. As the demands for mobility have increased in complexity, from simply enabling people to reach destinations that were previously impractical, to getting people to their destination safely and reliably, technology developed in the automobile sector has also increased in complexity. The vehicle has developed from a purely physical system based on the laws of mechanics and chemistry, to a more sophisticated *Cyber Physical System* (CPS) which embeds electronic components and control systems to improve performance and safety.

The demand for mobility over this time has continued to increase, creating a new set of challenges which cannot be addressed by simply improving the technology of a single vehicle. In California alone, there are 280 billion vehicle miles traveled each year, and the need for human mobility is now a lifeline of the economy. But California commuters spend more than 500,000 hours delayed in traffic each day, with an annual estimated cost of $21 billion per year, and the problem is not isolated to this state. These problems suggest a new *Human Mobility CPS* (HM-CPS) will be required to answer the problems which are faced by all commuters independent of the vehicle. This HM-CPS will emphasize the coupling of the physical movements of people both at an individual and aggregate scale with the cyber communication, computation, and sensing needed to monitor and efficiently enable mobility in the surrounding physical environment.

II. Fundamental Limitations of the Existing Automotive Cyber Physical System

A. Limited Information

Automobiles are well suited to collect information about the local physical world, but they lack the capability to collect global information about the environment in which they evolve. Most automobile sensors are specifically designed to monitor infrastructure within the vehicle itself, such as the engine temperature or the fatigue of some components. Localized sensing is effective at managing issues such as vehicle reliability, but it can only provide limited solutions for larger scale aspects of the CPS such as safety, route planning, and context aware location based services.

As an example of the limitation of the current automotive CPS framework, most safety critical sensing is aimed at minimizing the severity of accidents. While this has undoubtedly saved the lives of several commuters, it does not provide sufficient monitoring to prevent accidents from occurring. Although sensors can be added to the outside of the vehicle to determine where neighboring vehicles are located, better information can be provided if vehicles or surrounding infrastructure share information in cyberspace. While near misses or car crashes on a very short timescale are hard to avoid using automation, new *soft safety* concepts such as warning of upcoming slowdowns are achievable with today's wireless technology (in particular mobile phones). More advanced safety applications will evolve only when the existing sensing and communication limitations are removed.

Another challenge in collecting information is the timeliness in which it must arrive to be useful to the embedded human. Information about the level of use of the immediate surrounding infrastructure can be obtained locally by the vehicle, but this information must be collected before the vehicle arrives for important navigation decisions to be made. Even if a vehicle has a navigation device on-board, it must get traffic information from a global aggregator. Due to the expense of installation of sensing equipment such as *inductive loop detectors* (ILDs) or *radio frequency identification* (RFID) transponders, this information is limited at best.

Interestingly, although no single vehicle has complete information about the current state of the transportation network, it can easily be inferred from the data that each vehicle is collecting locally, such as speed and acceleration. The problem of limited information in this case is manifested as a problem of communication.

B. Inadequacy to Address Human-Centric Needs

Another category of limitations arises from the local/global interaction because the current automotive CPS largely ignores a defining feature of the HM-CPS: embedded humans. Embedded humans in the CPS are important because they are the primary consumer for traditional transportation infrastructure information, such as travel times and route navigation. They will also trigger the development of a new breed of mobility services which have previously been outside the domain of the automotive CPS. Following a trend similar to that found in the mobile phone, context aware location based services will play an increasingly important role in the HM-CPS. The information which ultimately creates the demand for trips will need to be more closely integrated with the vehicle to address the human-centric mobility needs.

Ultimately, embedded humans perform three tasks: (i) they can sense, (ii) decide, and (iii) assess. A poorly designed CPS will require the human to actively participate in information acquisition instead of allowing the system to automatically integrate sensed information into the infrastructure. Instead of requiring the user to integrate driving directions and historic traffic patterns collected from experience, a human-centric system should leverage infrastructure to gather information, leaving the embedded human free to make higher level decisions such as preference for the fastest route or the shortest route.

The most important aspect of the impact of human-centric needs with respect to the automotive CPS is that embedded humans make the overall assessment of how well the system performs. This creates new challenges because humans are exposed to a wide variety of human-centric systems with which the automotive CPS must compete. As new human-centric features appear in other CPSs ranging from mass transit to mobile devices such as cell phones, the utility of the automotive CPS will depend on its ability to adapt and integrate similar features.

C. Pace of Adaptation

As the automobile CPS is forced to interact with other cyber infrastructure systems for data collection and to address human-centric needs, the rate at which it integrates new technology will become critical to its utility.

This poses a significant problem because the automotive CPS inherently moves at three timescales. Changes in the transportation infrastructure may take decades to become fully implemented. Vehicle scale changes may take years. The virtual infrastructure, led by high tech innovation, evolves on Internet timescales of a few months. The automotive CPS simply moves too slow to evolve with cutting edge products and services in an integrated way.

The rapid changes of the virtual infrastructure makes it very difficult for the physical components of vehicles to even integrate themselves at a fundamental level. As communication protocols and ports change, in-vehicle infrastructure runs the risk of almost immediate obsolescence. This problem cannot be ignored: the embedded human which generates the need for mobility is also driving the need for integration with the virtual infrastructure.

III. RESEARCH CHALLENGES

A. Openness

The constraints of the existing automotive CPS suggest that it must be opened to access the surrounding environment, both physical and virtual (cyber). The availability of new data sources will enable the automobile to better navigate the surrounding environment, as well as provide a higher quality commuter experience. When the system is opened, it will force it to directly confront the need to remain dynamic and relevant in the human mobility CPS.

Designing a platform with an open architecture for automobiles will not be easy. The design must be sufficiently flexible to meet the demands both today and decades from now. The key will be to create a platform with which hardware and software are upgradable and replaceable. Interfaces can be built to collect and interact with the vehicle's infrastructure, while leaving core CPS components to be developed through aftermarket devices.

Determining how to verify the safety of applications developed on an open platform presents additional barriers beyond the simple transition to an open platform. In the phone industry, Apple has attempted to walk this delicate line by providing a publicly available software development kit for the i-Phone, but all applications must be approved by Apple before they can be widely distributed. Others, such as the Nokia Maemo platform and the Google Android platform provide less centralized control, because such a structure provides more freedom for the open source communities to create innovative products. The ongoing move to open devices in the mobile phone industry should be viewed as an early indicator of how an open platform increases the functionality of the product, and a similar leap could be expected for the automotive CPS.

B. Data Processing and Analysis

One advantage the automobile has over other technologies such as the phone is that it can be used to enable a powerful and energy demanding sensing platform that physically moves one though the infrastructure. Although automobile location based applications and services have not yet become mainstream, the vast amount of useful data which could be collected from the vehicle is encouraging for their development. This data becomes even more rich when it is put in context with other geo-referenced databases obtained online or from other infrastructure systems. Even vehicle specific data may begin to serve expanded functions when integrated with other services on computers and mobile devices. It would not be difficult to imagine a future mapping service which recognizes your vehicle has insufficient fuel to arrive at your destination to automatically route you to the cheapest gas station. Other potential applications might range from new forms social networking to environmental quality sensing.

The challenge of such cyber-information systems is the transmission, processing, and analysis of the data. The quality and volume of the potential data sources is phenomenal. Because of the mobile aspect of the vehicle, most communications with the vehicle and the virtual environment will need to be made wirelessly. The *Federal Communications Commission* (FCC) has dedicated a portion of the wireless spectrum for this communication, but there has not been sufficient momentum to develop standards which are meaningful outside the immediate context of the vehicle. The *Dedicated Short Range Communication* (DSRC) standard is problematic because the lack of usage of this technology outside the domain of the vehicle limits connectivity with the vast majority of devices in the virtual infrastructure.

One of the biggest research opportunities in this field will be to create large scale distributed CPS models to assimilate the data into useful information. Human mobility modeling is at its infancy, and fundamental questions still exist such as (i) the correct characterization of human mobility at local and global scales; (ii) multi-modal trip modeling; and (iii) transportation in urban networks. The current state of our knowledge still leaves open the debate over the correct model to understand automobile traffic on highways, which is an area which has received a significant amount of attention in the transportation modeling community. Clearly, a new class of models and abstractions will be necessary to interpret the vast amount of data generated by an open automotive CPS correctly and efficiently in the context of human mobility.

C. Privacy

The openness of a networked automotive CPS, and large volumes of data coupled with an embedded human create opportunities for abuse. Specifically, geo-referenced data contains information which is particularly sensitive. Attacks on this data range from direct privacy intrusions such as being able to identify a speeding vehicle, to more sophisticated attacks such as inferences gained from trips taken. A non-direct trip from work to home may reveal personal affairs the driver wishes to remain private. Recent research has shown that simply anonomizing data is insufficient to prevent privacy intrusion.

Worse yet, economic incentives exist for companies (insurance, for example) who can successfully infer information from the data streams collected. The data collected from a HM-CPS could potentially be as sensitive as personal health records, since many health related exposure risks may be determined from location based information.

Determining how to structure data collection and communication in a privacy preserving environment is an area of research that must be developed quickly to enable a functioning human-centric CPS. Ultimately, the success of the HM-CPS system depends on it, since the human-in-the-loop will otherwise make choices to avoid these types of services all together.

IV. Promising Innovations

On February 8, 2008, we successfully demonstrated a new technology for highway monitoring: GPS equipped mobile phones (see Fig. 1). Nicknamed the *Mobile Century* experiment, a pool of 165 UC Berkeley students drove 100 vehicles along loops on I-880 in California for 10 hours with GPS equipped mobile phones on board. The data was collected and processed using a privacy preserving architecture developed for this work, and new inverse models were implemented to enable accurate estimation of the velocity fields on the highway with less than 5% of the traffic stream carrying the devices. Estimates were broadcast live over the Internet to demonstrate the ability to integrate with existing virtual infrastructure. Although still in the early stages of research, this project highlights the value of location based information in a privacy-by-design architecture, while emphasizing the impact of advanced mobility modeling. As the automotive CPS continues to advance and leverage technologies from other industries, the potential for new promising innovations is great.

Fig. 1. *Mobile Century* -Traffic Monitoring using GPS Phones. The Nokia N95 mobile device is used to collect and transmit anonymous speed and position data when on-board vehicles. The height of the columns correspond to the speed of a vehicle equipped with an N95 on I-80 near Berkeley, CA.

V. Biographies

Daniel Work is a Systems Ph.D. Student in the Lagrangian Sensors Systems Laboratory at the University of California, Berkeley (Civil and Environmental Engineering), and a Research Intern at Nokia Research Center - Palo Alto. His research is focused on estimation, control, and optimization of transportation cyber physical systems.

Alexandre Bayen received the Engineering Degree in applied mathematics from the Ecole Polytechnique, France, in July 1998, the M.S. degree in aeronautics and astronautics from Stanford University in June 1999, and the Ph.D. in aeronautics and astronautics from Stanford University in December 2003. He was a Visiting Researcher at NASA Ames Research Center from 2000 to 2003. Between January 2004 and December 2004, he worked as the Research Director of the Autonomous Navigation Laboratory at the Laboratoire de Recherches Balistiques et Aerodynamiques, (Ministere de la Defense, Vernon, France), where he holds the rank of Major. He has been an Assistant Professor in the Department of Civil and Envinronmental Engineering at UC Berkeley since January 2005.

Quinn Jacobson is the Research Leader of the Mobile Internet Services Systems team at Nokia Research Center - Palo Alto, where he is currently investigating issues related to 2nd generation Location Based Services. Before joining Nokia he worked in Intel's Microarchitecture Research Lab, prior to which he was the chief architect for Sun Microsystems' UltraSPARC IV family of processors. He holds a Ph.D. in Electrical and Computer Engineering from the University of Wisconsin - Madison.