Cyber-Physical Control for Future Transportation Systems

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We believe future transportation systems are characterized by three significantly improved properties--reliability, efficiency, and transparency---over the current state of the art. All three properties call for a new theoretical framework of cyber-physical control of cyber-physical systems (CPS). Within this framework, we propose a new direction to develop algorithms for **timing control** of CPS. In addition to innovative research, new educational effort is needed at both undergraduate and graduate level to convey an integrated view of CPS.

1. Research

We view the future transportation system as a very large scale CPS. Each agent (a car, an aircraft or a train) is equipped with computing capability that is able to achieve intelligent control over its physical motion. Meanwhile, agents are able to perform computation tasks based on communication with their neighbors and with an infrastructure level information network. CPS research has the potential to achieve greater reliability, efficiency, and transparency for future transportation systems.

Reliability requires guaranteed performance under worst case scenarios, as well as predictable performance change under shifted conditions. For example, an automatic lane tracking system should be successful to follow the tightest possible turn on a highway when speed limit is obeyed. Meanwhile, it should give the driver the correct perception that the car becomes more difficult to handle when speed increases. Reliability has long been a central topic of control theory with its focus on guaranteeing performance of physical systems. Due to the increased complexity in the electronic control units (ECUs), control theory alone is often unable to produce accurate performance predictions for networked CPS. We formulate timing control as a joint optimization problem: we must simultaneously guarantee stability of the plant and schedulability/power bounds of the computational controller. Timing control algorithms will allow us to operate cyber-physical systems more safely (plant stability) and efficiently (power consumption). Timing control realizes the central idea of cyber-physical systems research---co-design control, computing, and power scheduling algorithms to achieve superior performance for both the physical and cyber dynamics. Existing cooperative control and sensing algorithms are typically designed to guarantee physical performance with oversimplified assumptions on computing and power scheduling. On the other hand, the communication protocols and task scheduling algorithms over a wireless network typically aim to optimize the network throughput and processor utilization. A co-design approach allows reasonable trade-off between physical performance, network throughput, processor utilization, and power consumption.

Higher efficiency is required for future transportation systems. Communication media, processor time, and energy are all limited resources that are shared by multiple agents in networked CPS. In general, resource limitations can be managed with scheduling and allocation. Therefore, many communication protocols, task scheduling algorithms, and power scheduling algorithms exist to regulate the access of these resources. Typically, a scheduling algorithm is developed as a result of an optimization process that maximizes a performance metric, and a series of time instants are allocated for a certain agent to access the resource. We may call a collection of these time instants an "operation point". Multiple operation points can be computed under different conditions or for different performance metrics so that switching between the operation points are allowed based on measurements of system performance. Such switching algorithms are often called *feedback scheduling algorithms*.

Our research on timing control aims to develop feedback scheduling algorithms that guarantee the transient performance---both transients in the plant behavior and in the load on the computational controller. Whenever switching happens, physical systems often suffer transients, i.e. temporary behaviors that need certain time to vanish. Different switching algorithms may achieve the same starting and ending operation points but have significantly different transients. In general, sudden switch between distant operation points may cause large transients that may even destabilize the system. For example, a large impulsive steering of a car may result in an overturn. Timing control addresses the relationship between movement of the operation point and the resulting change in the performance metric. This relationship is modeled by a dynamical system with the position of the operation point serving as the control input and the performance metric as output. To ensure transient performance, smooth movements of the operation point between different locations on a typically nonlinear surface are necessary. We view the operation points as virtual particles subject to drift, and hence use motion planning methods similar to those developed in robotics community to produce smooth point to point motion.

In current transportation systems, it happens frequently that local events and singularities are escalated into larger scale faults due to lack of transparency in information. Steps have been taken to increase transparency by constructing an adaptive sensing network that enables automatic collection of information about road conditions and traffic load. As such systems developing into the future, it will be very difficult for human beings to keep track of the large amount of information. Therefore, online models of portions of the networked CPS should be running on each agent to generate predictions that guide human decisions. Automation middleware systems needs to be constructed so that the models can perform online data assimilation through the information network and simulate the possible results of various decisions the driver might take. For example, when driving on an unfamiliar road, if an accident happened 10 miles ahead, the driver should be able to get suggestions on what are the two most efficient alternative paths that lead to his destination.

On the other hand, since a fully automated and accurate information network will not be available in the near future, one major challenge for timing control in CPS is the estimation of the system performance based on partial information that may be outdated and inaccurate. There is a trade-off between more complex and accurate algorithms that require higher power consumption and simple, less accurate algorithms that consumes less power. This trade-off can be viewed as selecting between two strategies: “more accurate control less often” or “less accurate control more often”.

2. Education

The study of cyber-physical systems unites two disciplines---engineering and computer science---that have remained remarkably separate until recently. Departmental and disciplinary barriers discourage students from learning what they need to know to help build this new field. We propose to develop new educational program to break down those barriers and to provide students with explicit training in component disciplines and in the interactions between those disciplines. We plan to both develop new courses and update existing courses to better reflect the state-of-the-art in cyber-physical systems. In Georgia Tech, two new courses will serve as the foundation for our CPS curriculum:

- *Fundamentals of Cyber-Physical Systems*. This course will concentrate on control/computing co-design for relatively small, lumped systems. The course will review some basic concepts in both control and computing. It will then move onto key CPS problems, such as scheduling constraints imposed by control systems, joint power management of physical plant and computing platform, and the implications of execution time variations for both control and computing.
- *Large-Scale Cyber-Physical Systems*. This course builds upon the *Fundamentals* course to consider the problems of networked cyber-physical systems. Such systems are distributed in both the control sense (large, physically distributed plant) and computing (distributed computing platform) sense. This course will cover topics including ad hoc networks, distributed algorithms and middleware, and distributed control.

3. Biography

Dr. Fumin Zhang is an Assistant Professor in the School of ECE at Georgia Institute of Technology. Dr. Zhang has started the research and teaching program in the fields of robotics and control in the coastal Savannah campus of Georgia Tech. His major research efforts are in cyber physical systems, underwater robotics, and mobile sensor networks. He is the founder of the Lab for Autonomous Mobile Observational Networks (LAMON) and the co-founder of the Robotics Teaching and Out-Reach Lab (RoToR).

Dr. Wayne Wolf joined Georgia Tech as the Rhesa "Ray" S. Farmer, Jr. Distinguished Chair in Embedded Computing Systems and Georgia Research Alliance Eminent Scholar. He has developed a number of techniques for embedded computing, ranging from hardware/software co-design algorithms and real-time scheduling algorithms to code compression and distributed smart cameras. He is a co-founder of Verificon Corporation, which designs smart camera systems. He helped to start several technical conferences, including CODES and MPSoC. He served as founding editor-in-chief of ACM transactions on Embedded Computing Systems and as one of the organizers of the recent NSF Cyber-Physical Systems Summit. He has written four textbooks.