Co-Regulation of Cyber Physical Systems

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1 Introduction

Cyber-physical systems (CPS) require the ability to manage both their computational and physical resources. In the context of a feedback control system, this means the CPS must achieve required performance, efficiency, and safety levels through regulation of its physical effectors (e.g. propulsive, steering, switches) and through regulation of its computational resources (e.g. processing and communication). To-date, primarily, research has been specific to one of these effector classes. Control systems engineers focus on regulating physical actuation but have developed techniques to account for the effects of limited computational resources. Conversely, real-time systems experts have focused on regulating computational resources but are still able to include physical control system performance metrics in computational resource scheduling.

Historically, the tradeoff between sampling rate and control authority has been dominated by the need to adequately control the vehicle under the most demanding situations (with the fastest system dynamics). Under normal operating conditions (e.g. idle, open-road cruise), resources may then be wasted. These resources could be used for other safety-critical tasks or toward other trajectory/energy optimization or entertainment activities.

The burgeoning field of CPS, with foundations in Networked Control Systems (NCS), feedback scheduling, and anytime control, has attempted to bridge the gaps between these two effector classes with the goal of analyzing, designing, and synthesizing the CPS as a whole. It has become clear that the full integration, modeling, synthesis, and control of a CPS is a necessary step to satisfy increasingly difficult constraints that balance cyber and physical resources and further the connectedness of physical systems.

We are pursuing a representation and corresponding theory to unify these disparate notions of "effector regulation" into a common framework capable of real-time co-regulation via feedback control. While feedback control of physical systems is a well-established field, co-regulation must also take into account the cyber system as an entity capable of directly affecting the physical system. Most often, from the physical system perspective, this effect appears in the form of response time delay. This position paper summarizes some relevant research, identifies areas of further investigation, and explores some of the benefits of combining the CPS into a single co-regulated model.

2 Relevant Research

NCS, anytime control, and feedback scheduling have proven to be popular and effective improvements to the CPS community by providing important information to the overall system that can be used to synthesize control of the CPS. NCS research addresses the effects of delay, packet dropout, and other ills of an unreliable communication channel. Such effects are taken into account by the controller and important stability, controller design, and estimator design results have been developed [1]. Time-delay systems analysis, hybrid automata, stochastic control, and other fields have contributed to the results obtained. These results allow designers to make informed decisions about the network itself, as well as design appropriate controllers to combat the effects of the poor communication channel.

Anytime control attempts to calculate the right amount of control given limited availability of cyber system resources. As cyber resources remain available an increasingly optimal control solution can be computed.

This is scaled back as cyber resources become scarce to generate a sub-optimal but likely adequate solution. This research leverages important results such as receding horizon control, and modal reduction. Results in this area have been extended recently to utilize a full LQG controller capable of meeting performance criteria even amongst time-varying resource availability [2].

Finally, feedback scheduling is a technique that applies feedback control theory to the cyber system to enable the control of cyber resources, including the control task of the physical system. This enables the cyber system to adjust resources to the tasks that need them. Such algorithms often end up themselves being computationally intense, requiring critical CPU time that could potentially be given to other tasks [3].

3 CPS Co-Regulation

We propose the need for a more tightly coupled system than those explored in NCS research, and one that, unlike anytime control and feedback scheduling, closely co-regulates the cyber and physical states. Our foundational hypothesis is that a coupled model for which traditional control techniques can be applied across the cyber and physical states will result in a closed-loop system that can perform better or equivalently to a feedback controller only modeling physical system states. Such an integrated model has several important advantages that can directly impact the automotive industry in which vehicles are gaining increased levels of computing power and autonomy.

First, by directly controlling, and by extension optimally controlling, the cyber states, the CPS can more appropriately allocate cyber and physical resources to more safety critical tasks depending on conditions. From digital control theory, a designer would typically analyze the bandwidth requirements of the system, choose a sampling rate sufficiently fast, and design the controller assuming that sampling rate. However, during time periods of low demand on the physical system (e.g. cruise on a flat highway perhaps), cyber resources, as well as control effort and sensing resources are being wasted. In a co-regulated, closely-coupled model, the tradeoff of sampling rate vs. control authority can be optimized, ramping up cyber resources and control effort to increase control authority when needed, and directing resources to other tasks during periods requiring little control authority. Such a strategy can potentially reduce wear on mechanical actuators, sensors, and cyber resources, as well free cyber resources for other tasks such as data sharing, optimization, or interacting with the driver.

Second, due to the close coupling and unified framework, design, analysis, and control synthesis can be done using traditional control techniques. Because performance metrics would be available for directly quantifying the effects of cyber states on the physical system, and vice versa, cost can be directly measured and quantified. Such a framework would also potentially offer a more systematic design methodology resulting in a cheaper, more efficient, and more environmentally friendly process from conception to realization.

Finally, such a unified framework would give layers of abstracted intelligence above the CPS a "whole-system" look from which it can reason and make decisions in the same way current AI layers reason about the physical system alone. For example, a navigation system, aware of impending obstacles requiring a high degree of control authority, can appropriately predict the needed resources and adjust the CPS appropriately. During steady cruise conditions on a straight highway perhaps little attention is needed from trajectory optimization tasks, whereas a winding road may require those same tasks receive significantly more processor time.

4 Conclusions

A unified framework for a CPS will be advantageous to the design and analysis of future CPSs in the automotive industry as well as provide for more safety conscious and energy efficient platforms. Such a model would complement previous work in real-time scheduling, feedback scheduling, anytime control, and NCS. Furthermore, a unified CPS model allowing traditional control techniques could pique interests of the controls community and introduce new analysis, and control synthesis for such sytems, while simultaneously broadening research goals for scheduling given increased information of the coupling between cyber and physical systems. We believe that within the coming years more focus on the relationship, coupling, modeling, analysis, and design of CPSs is necessary to bring together the two disparate notions of effector regulation that have, heretofore, largely remained uninformed of the other.

References

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