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**Topic 1 Idea: Co-regulation of Cyber and Physical States**

In CPS, the notion of control requires the management of both computational and physical activities. Much of feedback control theory was born out of practical need, and initially, was highly experimental. In more recent years a strong mathematical framework and accompanying theory has governed many advancements in the field. The need to utilize periodically-executing feedback controllers was identified early, and the community responded by developing a theory of digital control systems. The primary representational challenge was to remap the differential equations representing continuous-time evolution of a system into discrete difference equations better representing a periodically-executing control system. Tools such as the Z-transform were matured, enabling representations for digital systems with analogues to continuous-time tools such as frequency domain and state space analyses. Digital computing devices provided much of the motivation for digital control theory and have consistently been a means by which feedback controllers have been implemented; typically such control laws are modeled either as digital systems executing at a constant frequency or are approximated as continuous-time given a sufficiently high execution rate.

Digital control systems analysis presumes ideal periodic sampling by the computer. Furthermore, conservative controller designs make worst-case assumptions on disturbances and model imprecision then requiring scheduled execution rates to exceed minimum values for stability by a nontrivial multiplicative factor. Perhaps most importantly is the recent advances providing the ability to vary the control loop execution rate. This may come in the form of variable voltage processors which allow their overall operating frequency to be adjusted. More likely, it stems from the ability to dynamically adjust Quality of Service (QoS), or in some other way re-adjust the real-time task schedule.

An important side-effect of a strict digital control design is the requirement to select a particular operating/sampling frequency that is then maintained throughout the controller’s life cycle. An increasing burden is being placed on the cyber system in the form of additional tasks such as communication, complex sensor data processing, and embedded decision-making. Control system designers have traditionally specified one execution frequency that real-time system engineers are required to accommodate regardless of utilization requirements for other tasks, although in reality this fixed rate is quite conservative as discussed above. In many applications this results in a nontrivial waste of resources that can adversely impact the system should competing tasks viewed as flexible require degradation to accommodate the fixed controller rate. For example, in Miniature Unmanned Air Systems (MUASs) the worst case requirements for determining the sampling frequency may be governed by take-off and landing modes of the system, while longitudinal flight may have more modest control requirements. While mode switches analyzed through means such as hybrid systems can support a limited set of execution frequencies for different controllers such as those required for takeoff versus landing versus cruise flight, changes within a traditional flight mode such as different wind gust conditions experienced or predicted during cruise can themselves also be more efficiently managed by a dynamically-changing control loop execution rate.

One vision for achieving integrated CPS is to incorporate information from computational and physical models into a more unified modeling framework both for offline or dynamic optimization and for real-time control. Over the past two decades, attention to digital control has waned as control engineers have viewed the speed of computational devices and hard real-time schedulers as robust mechanisms allowing them to schedule their controllers at rates sufficiently fast that they can ignore digital control in favor of continuous techniques. In a similar vein, real-time system designers often assume the physical system designers will specify task execution properties such as execution frequency allowing them to narrowly define an acceptable operating envelope. Optimal holistic CPS operation requires, however, that information from each system be
integrated in a manner that allows the computational and physical resource use to be minimized rather than simplistically abstracted.

As an example, we have pursued techniques for incorporating cyber “state” information into existing state variable representations of physical systems. This has allowed us to dynamically adjust the sampling rate of the cyber system in response to changes in the physical system. In addition to addressing some of the problems mentioned above such as providing the ability for reallocation of cyber resources, and conservation of energy, this approach could allow for CPSs to reduce the sampling rate for controlling a particular physical system to a rate below the threshold for instability provided by digital control analysis.

This motivates another important vision for CPS research - developing mathematical tools capable of analyzing key system properties such as stability for the holistic CPS. To our knowledge, there are no tools available for guaranteeing stability results of a system in which the controller itself dynamically adjusts a continuously variable sampling rate (or perhaps more appropriately - the continuous delay associated with that continuously variable sampling rate). Time-delay systems, and results from stability robustness have made progress toward that end, but the delays under investigation in those cases are usually not the delays that arise as a result of the controller itself and are, rather, a sideeffect of the physical system in question. Additionally, results from research into QoS have analyzed systems with varying fixed execution rates but with appropriate assumptions allowing them to use existing digital control tools for analysis. We believe that advancements in time-delay systems, in conjunction with traditional Lyapunov analysis could provide an appropriate framework for CPS system stability analysis.

Advancements in CPS research require strong mathematical frameworks leveraging both differential and discrete difference equations, automata theory, as well as functional differential equations. It will also require an increase in creative methods for incorporating features and characteristics of all main parts of the system into appropriate models that leverage their strengths, or conversely, dissipate their weaknesses for the holistic CPS. We believe the community is making good progress toward these goals and look forward to conferences, conventions, and consortia that invite cross-discipline collaboration to examine and design for a wide variety of systems and applications.

Graduate Student Research Assistant
Aerospace Engineering Dept. University of Michigan
CPS Interest Area: Dynamics and Control


**Topic 1 Idea: Future Challenges for CPS Systems**

A cyber physical system (CPS) integrates software and hardware components with human agents within a shared complex physical environment. Future engineers will have to design components that trade the increased complexity for increased benefits. Consequently, sound methods for validating and verifying the performance benefits of engineered CPS are necessary. Let us consider the example of an intelligent traffic light on a road that is used by autonomous, semi-autonomous, and human-driven automobiles. Existing traffic systems are vulnerable to:

- Accidents; more than 1 million people die in automotive accidents globally
- Undesired traffic delays; the average U.S. driver spends a week stuck in traffic every year

The next generation of traffic light control systems will be CPS that must simultaneously protect against these disruptions while maintaining enhanced control of the system. The potential benefits of these systems include:

- Increased safety in the presence of higher density traffic
- Increased fuel and time efficiency as less time is wasted by queuing
- Decreased demands on human drivers to coordinate driving decisions

Consequently, verification and validation techniques are needed to certify that such novel technologies are at least as safe as the technologies they are replacing while also delivering the promised performance increases. This example motivates three computing areas that will be critical to the development of future CPS:

1. **Verification of CPS**
   
   Increased autonomy means that designs have a greater responsibility for maintaining driver safety. Consequently, tools are needed to verify both the efficacy and the safety of CPS designs. At the moment, theorem-based provers are available that verify safety properties of software. These provers step through lines of code and use known information about the inputs, outputs, and side effects of each program call to prove larger properties of the whole program. Similarly, model-checking tools are available that use mathematical models of physical phenomena to make similar statements about their evolution in continuous time. However, few tools exist that attempt to meld aspects of both kinds of tools, and those that do exist are either unsound in general or not complete. Thus, software verification tools are needed that use provided specifications of physical behavior to prove statements about the entire CPS.

2. **Reduction of Complexity**
   
   To accelerate the production of verification tools, designers should take care to reduce unnecessary complexity in their own designs. For the traffic light example with a heterogeneous mixture of fully and partially autonomous automobiles, some solutions may involve packet-radio networks that broadcast a variety of information to and from cars and the traffic light. Consequently, the communications infrastructure itself adds significant complexity and reduces the tractability of verifying properties of the CPS. Instead, if vehicles and the traffic light can infer bounds on the braking characteristics of surrounding vehicles using passive identification tags, then dynamic traffic timing may be possible that reduces waste with very little communications infrastructure for coordination.

3. **Integration of Human Behaviors**
   
   Another important concern for the CPS is the integration of human behaviors with the autonomous computational system. In the far future, all drivers on highways may be automaton with no human intervention, but this situation is unrealistic for the short-term transitory period. Thus, especially in present
human-dominated contexts like transportation, new solutions must integrate with human agents. This may mean for a better understanding of effective human–computer interfaces, but it also may mean building models of human behaviors that are sufficiently simple for analysis and sufficiently rich to capture real human behaviors. Some of these models will simply be identical to those used with autonomous agents but with wider bounds on parameters. However, other models will require working with psychologists to understand human decision making. As humans adapt to increasing automation, engineers may need to work with psychologists to improve such models.

Graduate Research Associate
The Ohio State University

CPS Interest Area: Autonomous Automotive CPS Systems
Topic 1 Idea: Fault Diagnosis and Prognosis for Health Management of Automotive Cyber-Physical Systems

Rapid advances in electronics, control, communication, and computing technologies have led to the development of complex network-embedded automotive systems. Today’s vehicles contain more than 70 distributed electronic control units (ECUs), 100’s of MegaBytes of software, 5 or more distinct communication networks, a wide variety of sensors and actuators, and 1000’s of data and control signals exchanged in real-time every second. ECUs in modern vehicles perform a variety of cyber-physical functions, for example, stability control, remote monitoring (e.g., via OnStar), energy-efficient propulsion, adaptive cruise control, by-wire steering and braking, keyless entry with push button start, blind zone detection, lane departure warning, and autonomous driving. Approximately 80-90% of these vehicle innovations are based on software-embedded systems, and this has resulted in an increase in the number of interactions among heterogeneous subsystems. Thus, in order to enhance vehicle performance and reliability, it is essential to model the complex interactions and failures in physical devices (e.g., sensors, batteries, motors), software algorithms running on ECUs, and the communication networks (e.g., controller area network, FlexRay). Failures range from issues that affect a single subsystem (either hardware or software), to issues that occur as a result of coupling among multiple subsystems (coupled subsystems). Furthermore, the accuracy of sensors, the linearity of actuators and the reliability of system memory in the ECUs change over a vehicle’s lifetime. Hence, advanced diagnosis and prognosis (D&P) technologies are needed to quickly isolate faults (hardware, software, interfaces, and network faults), in complex automotive systems, and to predict the degradation path so that appropriate corrective reconfiguration and maintenance actions can be taken.

The key system health management elements that are critical for enhancing the safety, testability, dependability and reliability of future vehicular systems, and that have the ability to advance the science, technology, and engineering aspects of next generation cyber-physical systems are as follows:

(1) Fault Modeling: The first and foremost element for early D&P involves understanding the fault-error-failure-symptom characteristics of automotive systems via fault injection experiments and hardware-in-the-loop simulations. Given the complexity of automotive systems, it is difficult to model multifaceted interactions among subsystems and to anticipate every possible driving scenario and usage conditions. Hence, characterizing the faults and their effects by understanding the interactions among multiple subsystems, ECUs and the network are critical to developing fault detection, diagnosis and prognosis methods.

(2) Sensor Suite Optimization: Sensor-data plays a crucial role in providing feedback control signals and for generating system state awareness via appropriate signal processing and pattern recognition for anomaly detection. While adding redundant sensors improves availability and fault detection capability, it has deleterious effect on weight, volume, and the associated acquisition costs. The key element here is to optimize sensor allocation and system configuration in the design phase, while maximizing the fault detection and diagnostic ability subject to specified weight, volume, power, and cost constraints.

(3) Online and Offline Inference Algorithms: Automotive systems experience multiple and intermittent faults, and it takes time for the failure effects to manifest and propagate through a network of interconnected-subsystems due to subsystem dynamics, transmission, and propagation delays. Hence, online and offline inference algorithms are essential for timely diagnosis of coupled faults in the presence of error propagation and network delays.
Prediction: A typical automotive system consists of a network of subsystems that are (mechanically/electrically) interconnected via different feed-forward/feedback links. Therefore, a fault in one or more component(s) may influence the outputs of several other healthy subsystems thereby causing false alarms or may even lead to cascading failures. Prognostic algorithms to predict degradations in coupled systems and to accurately estimate the remaining useful life of components/systems are needed.


Proposed Solution: The proposed integrated diagnostic, prognostic, and reconfiguration control process for health management of automotive CPS comprises of six major steps: modeling, test design and sensor allocation optimization, adaptive learning, inference, prognosis, and reconfiguration control. In the modeling step, failure progression information generated via on-board data-driven diagnosis/dealership maintenance, mathematical/physical-based fault models (for components with well-understood dynamics), and knowledge-based rules developed over the years by design engineers and service personnel are used to understand fault-error-failure-symptom characteristics of complex cyber-physical systems. In test design and sensor optimization step, test procedures that detect failures, or onsets thereof, are developed to minimize false alarms, while improving their detection capability. Some of the techniques include statistical change detection methods, signal analysis, graphical methods, multivariate statistical methods and neural networks. The fault-test dependency model extracted via fault simulations enables us to generate model-based failure modes, effects and criticality analysis and conduct testability analysis (viz., fault detection, isolation, ambiguity groups, and detection and isolation delays). If the analysis results are not satisfactory, additional and/or improved test procedures are designed to improve the diagnostic metrics (% detection, % isolation). In adaptive learning step, the model is evolved to correspond to actual failure progression data observed in test vehicles, onboard data and dealership data. In inference step, the fault-test dependencies are used to evaluate the health of the embedded system. The inference algorithms can be embedded in the ECU and/or a diagnostic maintenance computer for real-time maintenance, or downloaded to a service facility to assist repair personnel in rapidly identifying replaceable component(s). In prediction step, the remaining useful life of components/systems is computed. Model-based prognostic techniques based on singular perturbation methods of control theory, coupled with an interacting multiple model estimator, provide a systematic method to estimate the RUL of vehicle components. In reconfiguration control step, adaptive control strategies are employed for system recovery from unanticipated adverse emergency conditions. The proposed framework provides a systematic and repeatable process for effective monitoring of cyber-physical systems via online/remote diagnosis and reconfiguration control actions for “fail-safe” operation. This enhances safety, and reliability of vehicular systems, and improves customer satisfaction through enhanced vehicle availability; and in turn contributes to the CPS vision of building safer, reliable, and more efficient next-gen transportation systems.

Graduate Student
University of Connecticut

CPS Interest Area: Fault Diagnosis and Prognosis, Reconfiguration Control, Dependability and Reliability of CPS
Topic 2 Idea: Attack-Resilient Algorithms for In-Network Computing in CPS

One of the most pressing measurement and technological challenges facing Cyber-Physical Systems (CPS) is the development of scalable and adaptive attack-resilient algorithms and architectures for CPS. Security is significantly complicated in CPS due to the interactions between the cyber and physical aspects of the system. This is exacerbated by the tight integration and heterogeneous nature of CPS. Attackers may exploit knowledge of the interactions between the physical processes under control to inflict greater damage. For example, suppose that a water distribution system is equipped with myriad sensors that monitor the condition of the various water lines, and that these sensors are networked with a set of controllers. It is feasible that a physical attack on several major water lines may induce high levels of network traffic caused by alarms and remedial actions taken within the SCADA system. If the attackers are then able to launch a flood attack on the network, the controllers may be rendered ineffective and result in serious damage.

Although inevitably CPS must be tightly integrated, one manner to introduce more robustness and resilience against these kinds of attacks is to exploit in-network computing and distributed methods of controlling CPS. These algorithms must be adaptable to changing network topologies caused by physical disturbances and the natural expansions and contractions of the CPS. In order for the algorithms to be amenable to dynamically changing networks in a reliable and robust fashion, these algorithms should make use of only local information. In turn, certain constraints must be placed on the network topology in order to ensure sufficient redundancy of information flow in a single hop, so that local computation may be feasible. Such robust network topologies are important for the design of distributed algorithms that are resilient against malicious attacks.

This concept of resilient in-network computing is not a one size fits all solution. CPS are much too complex for this and have several layers of network flows, such as data, logical, mass, and energy flows. Each of these abstraction layers requires a different network model, giving rise to multiple graph models to represent CPS. But, for a given network abstraction model many coordination objectives in CPS, such as broadcast, consensus, synchronization, and leader election may be addressed using a robust network framework for the design of distributed algorithms that produce in-network computations and decisions. In order for this to be effective, more research needs to be done on appropriate robust network topologies, including: (i) How to construct robust networks for CPS? (ii) How to test a network for robustness? (iii) How to adapt the distributed algorithms to account for the robustness of the network? (iv) Can certain nodes be assigned to be trustworthy and thereby reduce the number of required links in the network to make it robust?

PhD Candidate
Vanderbilt University

CPS Interest Area: Reliable, Safe, and Secure Systems You Can Trust Your Life With
Topic 2 Idea: Ensemble Control of Cyber Physical Systems

Overview

A common paradigm in Cyber Physical Systems involves a centralized agent controlling many other agents using a shared signal. Examples of this phenomenon span many fields: steering swarms of micro/nano robots with an external electromagnetic signal, balancing active and reactive power on a smart grid from a central source, and parts manipulation of multiple objects with one manipulator.

These systems are difficult to control because they

- are extremely underactuated
- experience unmodelled dynamics and external disturbances
- often lack sensors to fully measure the system state

Our framework for approaching these problems is to model them as systems of ordinary differential equations, each with an unknown parameter and apply ensemble control techniques to steer the state to a desired target state. In this white paper, we will provide an overview of our methodology using 2 CPS examples; steering a swarm of micro/nano robots with a single control channel, and steering the orientation of a collection of spheres by rolling them in the plane.

Example System 1—Steering a Swarm of Robots with a Single Control Channel

As a child my grandmother once gave my brother and I each a new RC car. We were delighted—until we discovered they were both set to the same communication channel. Both cars moved forward or turned whenever either of us pushed a switch. This problem is a common problem in micro/nano robotic systems. An example is the ‘nanocar’, a molecule synthesized by James Tour and his research lab with molecular wheels and a tiny unidirectional motor actuated by a specific wavelength of light. These nanocars are synthesized in large numbers, but are each actuated by the same wavelength of light. Relevant questions abound: Is such a system controllable? What useful tasks can be accomplished? What tasks are impossible?

We model such robots as kinematic unicycles. A kinematic unicycle has two inputs corresponding to linear and angular velocity. We are interested in controlling groups of unicycles that share a single global control signal. It is easy to show that a group of identical kinematic unicycles is uncontrollable. In earlier work we proved that if each unicycle has a unique parameter that scales its linear and angular velocity, the entire collection is controllable with regards to position. These results took the form of open-loop motion paths.

In recent work, through Lyapunov analysis, we derive a globally asymptotic stabilizing (GAS) controller. In simulation, we show that the system handles disturbances from a standard noise model. We describe and demonstrate online calibration to learn the unknown parameter for each robot in hardware experiments. As a surprising corollary we show in hardware experiments and simulation that 1.) the GAS controller converges when all wheel sizes are wrong 2.) the GAS controller converges when all wheel sizes are the same.

We use the differential-drive robot as a hardware platform because the application of ensemble control theory to this system is easy to understand and leads to results that readers may find surprising. For example, our approximate steering algorithm—derived for an infinite-dimensional family of control systems and not just for a single unicycle—ultimately requires solving only one set of linear equations, which can be precomputed in closed form. Similarly, the formulation of these linear equations relies on series expansions that make explicit the trade-off between the cost and complexity of the resulting input trajectory and the extent to which this input trajectory is robust to model perturbation. Finally, the fact that inputs executed in open-loop will bring a
real mobile robot to a neighborhood of the same Cartesian position regardless of wheel radius is something that we did not initially think possible.

**Example System 2--Revisiting the Classic Ball Plate System**

Consider the classic plate-ball problem introduced by Brockett and Dai, a case study of rolling bodies in contact. In this problem a ball is reoriented by rolling without slip on a flat plate. If the ball has unknown but bounded radius, the resulting system is ensemble controllable. This result hints at a new approach to robust manipulation of so-called “toleranced parts”, an ongoing problem in automated assembly and industrial parts handling.

We model the sphere as an ensemble control system, show that this system is ensemble controllable, and derive an approximate steering algorithm that brings the sphere to within an arbitrarily small neighborhood of any given orientation.

We are motivated by progress in sensorless part manipulation, particularly the work of Canny and Goldberg as well as Erdman and Mason showing that simple actuators are often sufficient to robustly orient a wide array of planar objects without using sensors. Canny and Goldberg employed a tray that could be tilted in two axis and while Erdman and Mason used parallel-jaw grippers. These methods exploit differences in part geometry. Robustly orienting the rounded surface of a sphere offers special challenges due to its inherent symmetry.

Our research has led to a new implementation of the classical ball-plate manipulator that, using the original two input degrees of freedom, can now manipulate multiple balls simultaneously.

**Future Research and Development**

We hope that these results stimulate interest and provoke a new line of inquiry that may lead to practical application in Cyber Physical Systems. Our own interest in ensemble control, for example, is largely motivated by potential application to grasping and sensorless manipulation. These result hints at a new approach to robust manipulation of so-called “toleranced parts”, an ongoing problem in automated assembly and industrial parts handling. A considerable amount of work remains to be done, however, before ideas like this one find their way into practice.

**Ph.D. Candidate**

University of Illinois at Urbana-Champaign

**CPS Interest Area: Robotics, Control of a Smart Grid, Self-Driving Cars**
Topic 2 Idea: Cyber-Physical Systems for Civil Infrastructures

Cyber-physical systems (CPS) are smart systems that have cyber technologies, both hardware and software, deeply embedded in and interacting with physical components, and sensing and changing the state of the real world. Growing attentions are given to the CPS as they are important for the economic future of the country and to national and homeland security. Several reports from the White House have recommended developments and progresses in the CPS areas. While CPS systems have a broad scope which include: energy and utilities, manufacturing, medical care and health, etc., application of CPS in buildings and infrastructures for structural health monitoring (SHM) and structural control purpose is one of the attractive fields.

The deterioration of civil infrastructure is a growing problem both in the US and around the world. For example, during their lifetimes, bridges suffer from environmental corrosion, persistent traffic and wind loading, material aging, extreme earthquake or other catastrophic events, etc., which inevitably result in structural deficiencies. The American Society for Civil Engineers 2009 Report Card for America’s Infrastructure awarded an America’s Infrastructure G.P.A. of D, noting that “more than 26%, or one in four, of the nation’s bridges are either structurally deficient or functionally obsolete” and “the number of deficient dams has risen to more than 4,000, including 1,819 high hazard potential dams”. Visual inspection remains the current practice in monitoring the safety of civil infrastructure. High cost, limited frequency, and high false negative rates call into question the efficacy of visual inspection as the sole method of structural health monitoring.

The recent development of CPS based on wireless sensor networks (WSNs) enables monitoring and control of civil structures at unprecedented temporal and spatial granularity. Sensing and actuation devices that compute and communicate are crucial to the evaluation and optimized operation of structural systems. The use of such cyber elements in conjunction with mechanical and structural systems to manage, monitor and control the behavior of such systems represents a fundamental change in the way in which we interact with these structures.

Challenges associated with WSNs applications in civil infrastructures include synchronization issue across the sensor network and energy management to extend the lifetime of monitoring system. Precise time synchronization is critical in many SHM and structural control systems, where data from an array of sensors is fused to obtain a global view of the state of the monitored structure. In contrast to applications such as environment monitoring and rare event detection, which feature sampling periods on the order of minutes or even hours, SHM and structural control applications collect data at hundreds of Hz. The sensitivity of damage localization algorithm to phase offsets requires network-wide time synchronization error to be as low as 50 microseconds in some cases. This level of precision is quite challenging to achieve in a multi-hop sensor network.

To reduce the time synchronization error, customizable WSN based on the precision and allowable overhead required by different applications should be developed. For energy management, a holistic energy management scheme which minimizes total energy cost of the sensor network and energy cost of any single sensor should be developed. To develop WSNs with distributed SHM and structural control systems which deal with the abovementioned challenges, collaborative research work are going on among Dr. Dyke’s group (Civil and Mechanical Engineering) from Purdue University, Dr. Lu’s group (Computer Science and Engineering) from Washington University in St. Louis and Dr. Spencer’s group (Civil Engineering) and Dr. Gul’s group (Computer Science and Engineering) from UIUC.

Purdue University

CPS Interest Area: Architecture and Platforms for Cyber-Physical Systems
Topic 2 Idea: Cyber-Physical Theory, Interfaces, and Programming Abstractions for Conjoined Semantics

A fundamental need in advancing CPS as a field is to develop comprehensive theoretical underpinnings, and practical system design and development techniques based on that theory, for how conjoined semantics of different cyber and physical domains can be represented, managed, and guaranteed when combined in different ways in different cyber-physical systems. For example, while real-time scheduling theory is able to offer guarantees of completion of specific jobs of a control computation prior to specific deadlines, exactly when deadlines and other temporal features may occur, and the consequences of missing one or more of them, is sensitive to the nuances of the physics, scheduling algorithm, and control algorithm involved.

New advances are thus needed towards co-design of scheduling, control, physics, and platform semantics (especially with the increasing prevalence of multi-core computing) so that how each sub-domain of a cyber-physical system can be coordinated with the others in a manner that meets timing, physical, and other constraints rigorously, can be readily understood.

In addition, to allow such systems to be developed affordably and evolved feasibly, each sub-domain must be configurable or reconfigurable independently without costing system developers or users the ability to assess and manage the impact of any such (re)reconfiguration on the cyber-physical system as a whole. This in turn demands that existing modeling and development approaches (such as encapsulation via components, indirect composition using interfaces, etc.) be extended to handle timing, physical trajectories, and other cyber-physical nuances in combination with traditional functional ones. Furthermore, new techniques, e.g., to identify correspondences among similar but varying trajectories, constraints, etc., also are likely to be required, and their theoretical basis, and practical application will require careful study in different categories of cyber-physical systems: for example at different time scales, etc. when considering otherwise common semantics of pneumatic vs. electrical phenomena.

Ph.D.

Washington University in St. Louis

CPS Interest Areas: Real-time Parallel Scheduling, Cyber-Mechanical Systems
The national electric power grid (EPG) is a heterogeneous Cyber Physical System (CPS) being composed of different physical and computational components connected through communication networks. The EPG is going through a transformation to be an efficient, reliable and secure smart grid in line with national energy security priorities. The EPG can be defined as a network that connects generation sources to end use customers. A smart electric grid utilizes enhanced communication, digital information and control technology to improve efficiency and reliability of the system. Modeling and simulation of the EPG is required for operation and planning, which is a challenge given the cyber physical nature of an EPG. Presently, there exists no universal modeling software which can model the entire EPG.

1. There is no single tool to model the power system, communication, and control system.
2. There is no single tool to model the system at transmission and distribution level with attention to all details.
3. There is a need for tools to combine data that is multi-rate, multi-scale, multi-data, multi-user, multi-model from different domains.

These above facts quickly demonstrate a gap for modeling the EPG in an efficient manner. The characteristics of the EPG are varied and diverse. There are several events/phenomena at disparate time and geographical scales which need to be modeled. Multiple mechanical and electrical components are connected in an EPG, which can be non-linear, non-continuous and have to be simulated for both steady state and transient conditions. Energy Management Systems (EMS) and Supervisory Control and Data Acquisition systems (SCADA) represent the computational part of the system, which receives data through communication channels from different locations in the network. The data needs to be sent at different rates using multiple protocols depending on the system application and capabilities. For analysis algorithms, such as state estimation, it is required to have data sent in with time stamps or arranged in proper time frames. Current modeling and simulation efforts are typically focused on a narrow set of issues, such as modeling and simulation of the physical components and cyber systems separately. It can be clearly seen that the way forward is the integration of the modeling efforts of the physical and cyber system. One possible solution to this problem is to model the physical power grid as a virtual grid using software tools while modeling cyber part of EPG with real world components and provide interface in between. This type of modeling efforts will be hardware in the loop (HIL).

The Real Time Digital Simulator (RTDS) is an example of virtual power system simulator designed for continuous real time operation. The simulator uses discrete time semantics with adjustable time steps. The RTDS architecture enables users to interact with a running real time simulation via digital and analog I/O channels. Due to its real time operation, RTDS can be connected to external devices that allow closed loop testing of real-world physical equipment. Consequently, multi-modeling simulation environments that include RTDS require time management that synchronizes logical time of discrete event simulators with real time. The RTDS along with physical equipment forms a local area communication network. Hence, RTDS can be one of the components for HIL simulation of EPG Cyber Physical System analysis.

Cyber physical system analysis is required for efficient operation and control. One of the examples is cyber security analysis during a malicious cyber-attack scenario, which can be modeled using HIL setup. In the case of the cyber threats to a power system, we are concerned with the potential effects of a criminal, terrorist, nation state, or inside attacker intrusion into the communications network of a power system. In a cyber-attack scenario, the intelligent electronic devices (IEDs) integrated throughout the power system for purposes of monitoring, controlling, and protecting the physical power system could, if compromised, be utilized in maliciously causing an adverse reliability impact. However, attack scenarios of consideration need not be limited to sophisticated
attacks on a control center or SCADA system that enable malicious interactions with multiple generators and substations. Cyber-attacks can be as simple as utilizing remote engineering or metering access to substations and generators to pose as a trusted agent, and corrupt relay settings or CT/PT data that control decisions are based upon. In RTDS, a power system can be simulated in real time, with hardware components like IEDs in the loop. Accordingly, we can model an attack on a cyber-component within the electronic perimeter of a specific generator or substation in the power system, and assess the effects the attack has on the entire network. With such a model, mitigation strategies can be tested and issues associated with coordination with other IEDs in the system uncovered.

In summary, modeling and simulation of cyber physical system like smart electric power grids is challenging given heterogeneous nature with diverse time and geographical scale. Hardware in the loop modeling provides an alternative approach for modeling of such a cyber-physical system.

Graduate Research Assistant
Washington State University, Pullman
CPS Interest Area: Modeling of CPS
**Topic 2 Idea: A CPS Approach to Chemical Process Control**

Optimal process operation and management of abnormal situations during plant operation are major challenges in the process industries since, for example, abnormal situations account for at least $10 billion in annual lost revenue in the US alone. This realization has motivated extensive research in the area of chemical process control to ensure safe and efficient process operation. From a control architecture standpoint, control systems traditionally utilize dedicated, point-to-point wired links to measurement sensors and control actuators to regulate process variables at desired values. While this paradigm to process control has been successful, we are currently witnessing an augmentation of the existing, dedicated local control networks, with additional networked (wired and/or wireless) actuator/sensor devices which have become cheap and easy-to-install the last few years. Such an augmentation in sensor information and networked-based availability of data has the potential to be transformative in the sense of dramatically improving the ability of the control systems to optimize process performance (i.e., achieving control objectives that go well beyond those that can be achieved with dedicated, local control systems) and prevent or deal with abnormal situations more effectively (fault-tolerance). The addition of networked sensors and actuators allows for easy modification of the control strategy by rerouting signals, having redundant systems that can be activated automatically when failures occur, and in general, it allows having improved control over the entire plant. However, augmenting local control networks with real-time sensor and actuator networks challenges many of the assumptions in traditional process control and monitoring methods dealing with continuous measurement/actuation and dynamical systems linked through channels with flawless communication. In the context of designing networked and fault-tolerant control systems which utilize sensor and actuator networks, key fundamental issues that need to be addressed include the use of asynchronous and delayed measurements in the control system as well as the occurrence of network malfunctions due to field interference and device power losses (see [1] for a recognition of these issues by industrial and academic members). These issues need to be carefully handled because networked and fault-tolerant control systems introduce more components in order to substantially improve closed-loop performance and fault-tolerance, and this increases the probability of faults at any given point in time. In addition to improved process control and monitoring, networked control may enable the incorporation of economic considerations directly in feedback control. Traditionally, economic considerations are addressed via a two layer approach in which the upper layer carries steady-state process optimization to obtain economically optimal process operating points (steady-states) while the lower layer utilizes appropriate feedback control systems to steer the process state to an economically optimal steady-state.

Model predictive control (MPC) is widely used in the lower layer to obtain optimal manipulated input values by minimizing a (typically) quadratic cost function which usually penalizes the deviation of the system state and manipulated inputs from their economically-optimal steady-state values subject to input and state constraints; however, this two-layer approach usually limits process operation around a steady-state. We have been working on the emerging area of economic model predictive control (EMPC). EMPC focuses on a reformulation of the conventional MPC quadratic cost function in which an economic (not necessarily quadratic) cost function is used directly as the cost in MPC, and thus, it may, in general, lead to time-varying process operation policies (instead of steady-state operation), which directly optimize process economics.


Ph.D. Candidate

UCLA

CPS Interest Area: Networked, cooperating, human-interactive systems
Topic 3 Idea: Computational Dynamic Analysis for a Citizen

The current exponential growth of technologies is providing novel, frequently as of yet unimagined ways of leveraging its applications for human needs. Ubiquitous communication capabilities allow for a redefinition of computer-based solutions to provide a new and better world for an average person. Computing plays a critical role in advancing research across almost every scientific discipline. The fact that everyday computing is becoming exponentially cheaper holds the promise to vastly increase manifold data flows and revolutionize the practice of science and engineering.

Integrating simulation, that represents the third pillar of scientific inquiry first introduced by Nobel Prize winner, Ken Wilson in 1989 with the fourth pillar of scientific inquiry (i.e., data-intensive analysis) invented by Turing Award winner, Jim Gray in 2007 is a fascinating research and development prospect for challenges that humanity is facing.

Democratizing modeling and simulation by enabling an ongoing access to the right technologies and data as well as making them easily usable and widely available for everybody makes this integration a fascinating day-to-day solution prospect. It enables a mile step from science and engineering towards creating daily-life enhancements for a human.

Herewith, an online platform for Modeling and Simulation on Demand for a Citizen is proposed. It serves as a means for society in developing advanced human and technical skills, raising the awareness, applying computation results, and using them for the improvement of the quality of daily life.

Reference: [https://sites.google.com/site/computationofthings/call](https://sites.google.com/site/computationofthings/call)

PhD
Harvard University; SimulatedWay; GUT
CPS Interest Areas: Modeling, Simulation, Computation; Application
Topic 3 Idea: Real Time Hybrid Simulation

Recent earthquakes (Wenchuan, Haiti, Chile, and Tohoku) have demonstrated that societies still face a broad range of challenges related to the effects of earthquakes. To overcome these challenges, understanding of damage and its progression in the civil engineering structures are indispensable. A promising method for the evaluation of structures is found in real time hybrid simulation (RTHS). In this approach, a cyber-physical system, numerical and physical substructures from a single structure shown in fig.1, must be integrated with high fidelity at runtime.

This cyber-physical system allows for studying highly complicated structures by dividing them into numerical and experimental substructures, leading to considerable reduction in the costs and time associated with a single test. Hence, RTHS has progressively been recognized as a powerful cyber-physical methodology to evaluate structural elements under operating conditions. Even though RTHS is a very attractive methodology in terms of cost-effectiveness and rate-dependency preservation of structural elements, there are a lot of challenges (as some listed below) that necessitate further studies and research before considering highly complex cyber-physical experiments.

- Ability to achieve synchronization of boundary conditions between the computational/physical elements governing the stability and accuracy of a RTHS
- Complex interaction between the numerical and physical substructures
- Computation and communication delays and actuator dynamics
- Limitations in the physical components of the test that will overshadow certain restrictions on the computational side

In spite of a tremendous amount of progress made recently, further research and studies are required to address these many challenges. Moreover, due to the power of this cyber-physical approach in terms of costs and rate-dependency preservation of elements, it is highly expected to impact aerospace/vehicle dynamics and performance in near future.

PhD Student
Purdue University
Topic 3 Idea: Multi-Scale Systems Collaboration Challenges

A radical transformation is occurring in the field of information technology and cyber-physical systems. Next-generation applications reach far beyond traditional computing and communication functions in multiple fields influencing the way we address problems facing society. Smart and micro-grids are revolutionizing ways of delivering power to households and reconfiguring the relationship between customer and service provider. Emergency response systems are dependent on wireless transmissions and multiple mobile agents – the coordination of which is a difficult task. Aircraft and automotive vehicle systems technology are becoming increasingly complex in terms of autonomy, reliability, and real-time situational fault-tolerance. These new applications emerging will undoubtedly be driven to run in distributed form on platforms that incorporate high-performance computer clusters, high-fidelity sensor networks, and mobile technology.

The ultimate goal is to create a systematic and comprehensive solution to the distributed, multi-scaled systems design problem. The far-reaching scope of these cyber-physical systems requires the collaboration of multiple teams in various domains of expertise. Herein lies the double challenge: attempting to systematically design multi-scaled, heterogeneous systems leads to the problem of how to coordinate different groups and teams in different research fields and geographical locations and direct them toward the same end-goal. This applies to different teams within one industry (i.e., groups working on different subsystems), as well as to teams across different schools who wish to address a problem on various levels of abstraction.

Because future cyber-physical systems will undoubtedly grow more complex and distributed in design, collaboration amongst scientists and engineers is a pressing challenge that needs to be first addressed before any real progress can be made. There are three main difficulties.

1. Defining the problem and application: The first challenge is agreeing to the scope and setup for the specific design problem. The application and problem statement must be general enough to encompass the types of multi-scale and heterogeneous characteristics that will arise in cyber-physical systems and complex enough so groups can choose a task which will not conflict or overlap with each other. Conversely, the problem statement should be specific enough so that groups are clear on an achievable and consistent goal. Yet bounds on the problem should still allow for creative thinking and be open to new paths to pursue should the need arise.

2. Terminology, language, and modeling tools: The second challenge is an agreement, or at least a clear understanding, of the terminology, modeling language, and modeling tools that will be used in order to solve the design problem. For instance, particular research groups or teams may wish to use a particular set of tools or their own developed software programs in order to model the system. This in itself is an asset, because multiple models and methods would be capable of uncovering different obstacles or types of problems that could occur. Each particular modeling tool has its own focus or domain. A simple example could be the difference between Mathematica, which is useful for symbolic and numerical mathematical calculations, and MATLAB, which is useful for computation algorithms and simulations. Both are capable of the same functionality, but their specialties set the scope of the types of problems that can be explored. Communication is key in explaining terminology and scope of the problems solved. The academic community oftentimes has difficulty in conveying their ideas with industry and government officials. The academic community, amongst themselves, has an equally difficult task in explaining their ideas to members in other fields, who use different terminology, and who may not share the same viewpoints.

3. Integration: The third, and perhaps most difficult, challenge is the integration of group models or solutions. If individual subtasks are solved at varying levels of abstraction, linking subsystems or models carries no meaning. A common simulation tool or hardware testbed could be an answer to this problem. Then the next task
is to ensure compatibility of the individual models with the common testbed or simulation software. Conversion of tools or languages is not difficult, but agreement of what common platform to use (similar to the agreement upon a common problem formulation) is difficult. These tasks are not considered avenues of research exploration, however, and are thus low on the priority list.

Thus the three main barriers to development of cyber-physical systems with regards to collaboration are: problem definition, common terminology or understanding of tools, and integration of models and tasks. Current approaches to collaborative efforts involve regularly scheduled conference calls, annual or bi-annual review sessions in which teams report on progress, and quarterly reports on research results. These methods, while opening the channels of communication, do not address the specific problems mentioned in (1)-(3). In actuality, groups cite their own progress, but for large-scale efforts, there is little incentive fully link efforts. Furthermore, the competitive nature of research and publishing results leads to reluctance to share too many details of work or possible new ideas to pursue.

A new approach to this problem could be the following:

1. Incentivize the end-goal: Similar to cash prizes for DARPA Grand Challenge, create an incentive for teams to develop a solution to a common challenge problem. The goal (or sub-goal) should be clear, and teams should have the freedom to pursue their own interests as long as the result is the same.

2. Designate integration teams: There should be dedicated teams or individuals whose task is to write software or fully integrate group models and languages into a common platform. This is a crucial iterative step in order to make any progress between teams.

3. Open-source repositories: Models, papers, and source code should be made available to all group members. This allows for transparency as to the current work status of each team, and hopefully provides easier access and understanding to each group’s efforts.

Graduate Student

California Institute of Technology

CPS Interest Area: Multi-Scale Systems and Distributed Architecture Design