Developing Basic Research Agendas for CPS based Transportation Systems

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Executive Summary

The cyber physical systems (CPS) based systems calls for high risk, high return research to develop high performance machinery, by taking full advantage of the unprecedented computing capabilities offered by the information technology. For the transportation industry, CPS based transportation systems would offer energy efficient, environment friendly transport of passengers and goods, with little or no sacrifice of service quality. As the hallmark of the CPS technology development process, researchers are called to develop scientific principles and their technology realization that can be broadly applied to different application domains. As the community begins to take on the challenge, systematic development of research methodologies and effective evaluation of research results would have broad impact on the long term success of the program. In this whitepaper, we advocate a few major system issues that call for long term investigation to bring the CPS-based transportation technologies from concepts to reality.

Reach the Long term goals through short term steps

The CPS initiative calls for radical thinking to explore the potential opportunities offered by deep integration of the computing devices, algorithms, physics/chemistry, and the physical carriers. However, with the long separation of research fields in the past decades, many researchers and practitioners find it time consuming to establish research problems that can effectively cross the discipline line to advance the CPS based advanced technology. How to help the researchers in different disciplines identify their common interests, and furthermore, leverage on intellectual capitals of the whole community to develop joint research goals is a pressing issue.

Behavior modeling, computing and control are among some of most critical technologies to advance the performance of vehicles on land, in sea, and on the air and space. The performance measure can range from speed, acceleration rate, safety, to reliability, just to name a few. It is not surprising that the auto industry declared in an earlier CPS automotive workshop that electrification is one of the major challenges. Replacing the piston engines with electrical motors implies complete rethink of the next generation vehicles together with their logistics systems: storage and (safe) consumption of energy, transmission, motion devices (wheels, propellers or turbine), the breaking system, flow management systems (traffic light, right of ways, and infrastructures (roadways, rails, airports, etc), just to name a few. Practically, every system subfield can benefit from clever embedding of computing and sensing technologies to achieve better performance. Yet, the key issue is how to establish long term and short term research roadmaps for the broad spectrum of opportunities so that the research investment can have a better chance to be transformed into real products.

Common Apparatuses

We claim that one of the most effective approaches to seed a critical mass of the CPS researchers is to develop a series of reference apparatuses to “carry” the research problems. A conventional view about basic research is to impose little, or no constraint on the investigation process. While this strategy may be responsible for the extraordinary success of the information technology in the past two decades, it needs to be carefully scrutinized for the CPS research process. The coexistence of real-time computing and physical activities in a CPS system changes the natures of both worlds (i.e., the cyber and physical) drastically. In addition to producing correct results, the computing subsystem must also deliver them to the actuators timely. Both Instruction Set based architectures (microprocessors) and Field Programmable Gate Array (FPGA) offer unprecedented flexibilities in optimizing the balance between power consumption rate, computing speed, and even I/O assignments. As a result, *ad hoc* selection of computing platforms may lead to suboptimal solutions. On the other hand, the mechanical structures can be made more compact, lighter and operate at less table yet higher performance (more energy efficient, faster, etc) states. With the powerful design capabilities offered by modern CAD tools, it will be very interesting and useful to investigate techniques to customize computing machinery starting from the very beginning of the design phase, rather than retrofit the computers after the mechanical designs are completed.

Theoretical foundations: Common grounds and disjoints

System modeling and analytical methods are essential for creation of general solutions in system designs. It is not surprising that a large body of analytical models have been developed for modeling of the dynamics of both the cyber world and the physical world. Before researchers focusing on the two different worlds can develop convergent new theories for the emerging CPS system theories, it will be critical for them to gain some understanding of the fundamental premises of their counterparts. This effort could be implemented in many different forms. For instance, joint workshops focusing on the founding system models, and their design principles on the two worlds, would be an interesting and useful starting point. The goal of such exercises is to develop fundamental CPS system models when the two worlds are treated as one, and when researchers from two different research environments can follow a common vision to develop one common body of knowledge that would treat issues on the two sides as whole. In addition to workshops, another broad participation-dissemination approach is adopting an Internet Protocol development process, in which specific topics can be initiated and developed by the community through a self selection process. These models, when applied to the select apparatuses, can serve as a basis for researchers to develop their common languages, common goals and common methodologies.

A simple example is the difference between digital clocks, and the continuous time. Physical system designers often assume the time is continuous, because the time resolution of most digital clocks is fine enough not to make any significant difference. However, for the cyber system designers, any unused clock cycles are considered a wasted, and they would try to use them for system management functions such as system health monitoring, scheduling, etc. It is therefore necessary for the CPS system researchers understand the subtle implication of time management in their integrated design process. A similar argument can be made for numerous system issues such as memory space, electrical power, weight, size and physical stress, and temperature, etc.

Determinism vs. Uncertainty

The cyber and physical systems designs represent sharp contrasts on their views of their design spaces. The cyber design space needs to be deterministic, so that a software program will always produce the same outputs for a given set of inputs. Any factors causing non-deterministic outputs would require lengthy, thorough investigations to ensure the predictability of the software system.

Physical systems always need to function under uncertainty in the real world. Thus, such systems need to be robust to large scale uncertainty in the world as well as inherent uncertainties in the system itself. However, the problem of decision making under uncertainty is an extremely high dimensional computational problem, and optimal methods for dealing with such systems are computationally infeasible given even today's computational resources. For instance, consider the case of an autonomous robotic system operating in an uncertain, dynamic and hazardous environment such as a disaster area. The system has to be able to make a model of its world, along with its attendant uncertainties, and its location within that world using only its onboard sensors while at the same time having to plan its actions in an intelligent fashion such that it achieves its assigned goals. The estimation and planning problems inherent in this application are very computationally demanding and are made even more so by the requirement that these intelligent actions have to be taken in near "real time". Thus, the use of optimal methods from traditional decision making literature is infeasible in any realsitic application. Thus, there is a need for methods that are robust both to uncertainties as well as to computational requirements, i.e., the requirement that a decision has to be made with the limited computational resources available in a given time frame. Thus, one of the primary requirements for the design of robust CPS systems are the design of estimation and planning methodologies that are robust to uncertainties in the world while at the same time they are computationally tractable enough so that they can be implemented in near "real-time" systems.

Harmonize the cyber and physical designs

A promising approach to such a problem would exploit the separation of time and length scales of the innately multi-scale planning problem through a hierarchical, multi-resolution decomposition of the environmental uncertainties inherent in the problem and a hybrid problem formulation. This multi-scale framework reduces the complexity of the problem at each layer of the hierarchy and enables development of algorithms that are real-time feasible at each of these levels. Such an approach leads to a *separation of concern* between uncertainties at different time and length scales, a *hybrid system framework* to bridge the gap between the discrete and continuous methods of planning, and the *propagation of uncertainty* between the layers of the hierarchy in order to study the stability and robustness of the coupled hybrid system. The real-time aspect of the problem can be addressed by implementing the planning algorithms using *anytime computational models* that incrementally improves the algorithm performance with available computational time.

Summary

The scope, ambition and complexity of the CPS research paradigm represents a quantum leap on how one view the two design spaces from the perspectives of cyber and physical worlds. When investigated as two independent domains, clearly the interface between the two worlds becomes a major system bottleneck because of their conflicting underlying assumptions. These issues will need to addressed, and competing requirements will need to be consolidated to eliminate the design bottlenecks. The examples raised in this whitepaper represent only a very small portion of the myriad of technical issues. They will need to attacked and solved by teams of researchers across knowledge domains. Working in isolation will only keep one in the old comfort zone with no possibility of making tangible contributions to the CPS community.