Future Mobile Cyber-Physical Systems: spatio-temporal computational environments

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September 8, 2006

1 Position

A Cyber-physical system is a system of computer systems that interact with the physical world in real-time. These systems must sense constraints imposed by a dynamically changing environment and predictably react to those changes in real-time.

Cyber-physical systems exist today, but at a much smaller scale in size and complexity than the cyber-physical systems of the future. Consider, for example, vehicle-to-vehicle (V2V) systems. Today’s V2V systems are single vehicle centric. The vehicle senses objects in front of or behind the vehicle and either slows the vehicle to avoid a collision or alerts the driver so that the driver can do the same. However, no data is regularly shared with other vehicles or objects in the environment. Future V2V systems will be much more complex and necessarily integrated with the environment. It is easy to imagine fleets of vehicles traveling together, sharing information about road and weather conditions ahead, and even working together to conserve energy. Similarly the vehicles could share data with smart bridges or highways, or at the very least, “sensor depots” along the highway.

Our position is that future mobile cyber-physical systems, unlike the real-time systems as we currently think of them, will be spatio-temporal systems of systems that create computational environments. These systems are spatio-temporal in the sense that correct behavior will be defined in terms of both space and time. As real-time systems, computations must be completed within established response times, for which we will need new notions of timeliness (see Section 2), but they may also have varying temporal requirements based on the current frame of time. As spatial systems, the computations performed and their timeliness will be dependent on (i) the location of the platform in its environment, (ii) the velocity with which the platform is moving, (iii) the number of objects in the environment, and (iv) the velocity vectors of the objects in the environment. A computational environment consists of multiple levels of heterogeneous systems interacting with each other. These systems are heterogeneous in terms of processing capability (simple sensors to 2048-core chips), communication interfaces (wireless, bus, wired-network), and even time scales in which events are measured (microseconds to minutes, or even longer).

2 Fundamental Limitations

The complexity of future mobile cyber-physical systems is beyond the state of current theory and practice in reasoning about space and time; real-time scheduling; cyber-physical graphs; resource management; dynamic group communication; security; fault tolerance; and even systems analysis and development. Due to space limitations, we limit our discussion to only the first three of these limitations.

Reasoning about Time and Space. The database community has recently begun researching spatio-temporal objects. However, that research has focused on relatively static objects with respect to both time and space. The existing theory for describing objects in both space and time is not applicable to mobile cyber-physical systems for at least three reasons: (1) the theory ignores physical attributes and constraints on the objects; (2) the interaction of objects in space in time is not addressed; and (3) the range and precision of time resolution is not adequate for real-time
Real-time Scheduling Theory. The workload will be very dynamic. Existing theory is not adaptive enough to support quickly changing work loads of mobile cyber-physical systems. Due to physical constraints of the platform or the environment, some events may have hard response deadlines. However, simple changes, such as slowing down or speeding up the platform, can extend allowable response times. In other cases, the deadline is not hard, but cannot be described as firm or soft either.

Cyber-Physical Structures. Cyber-physical objects will have complex hierarchical structures and will interact in an intricate manner in spatio, temporal and physical dimensions. The management of resources cannot stop at the CPU boundary. Existing graph theoretical models like process graphs, structured graphs or petri-nets can not adequately capture the structural and operational complexity of mobile cyber physical systems.

3 Research Challenges

There are many open research challenges in the context of mobile cyber-physical systems. Once again, however, we limit our discussion to three significant research challenges.

Challenge 1—New Reasoning Paradigm: New abstractions and a new theory for reasoning about real-time spatio-temporal objects is needed. Mobile cyber-physical platforms move through space at rates that often depend on the number of objects in the environment. They communicate with both moving and stationary objects. New abstractions, models, and theory are needed for reasoning about the current and future location of both the platform and the objects in its environment. An important question is whether the velocity vectors of objects should be relative to the moving platform, or normalized to some common reference point. The difference is significant. In the former case, every computational platform has a different set of velocity vectors. In the latter case, a consistent global state can be maintained and shared.

Challenge 2—New Real-time Scheduling Theory: Real-time models and scheduling theory must be extended in many ways. Perhaps the first and simplest step is to support new notions of real-time, beyond hard, soft, and firm. Second, the new theory must also support more dynamic and adaptive task sets and event processing. While progress has been made in recent years on both of these problems (e.g., stochastic task models, utility functions, and variable rate-based execution), these models and supporting real-time scheduling theory are still too primitive to adequately support today’s real-time spatio-temporal systems, let alone future mobile cyber-physical systems. Third, we need much better models to abstract the wide variety of events that must be processed in future mobile cyber-physical systems. The concept that all events are captured by one or two models (e.g., rate-based or aperiodic) or a simple combination of existing models is inadequate. In many systems there will be combinations of multiple types of events, as well as priority-based events whose priorities change based on environmental factors. Finally, we need better methods for reasoning about end-to-end response times when the processing resources span multiple CPUs, SoCs, and networks of systems.

Challenge 3—Cyber-Physical Graphs: The challenge is to create graph theoretic models that capture the structure of mobile cyber physical systems to facilitate their development, operation and analysis. For example the model should be able to handle the hierarchical nature of resource management that provides local physical management, but global virtual management. Achieving this goal requires new powerful graph concepts abstractions as well as theories to model complex spatio-temporal physical structures.

4 Promising Innovations and Abstractions

The challenges identified are formidable. If we are to meet these challenges, a bold new research agenda must be set that creates new innovations and abstractions. The following ideas provide a starting point.

Real-time Spatio-Temporal Object Models. One promising approach to reasoning about real-time spatio-temporal objects is to apply the concept of mobility models. These models can be used to predict the motion of an object by integrating kinematic models with application domain knowledge. The ability to predict where an environmental object will be in the future is of paramount importance in mobile cyber-physical systems. This knowledge can be used to compute the rate at which the environment must be
sampled, the computational complexity of environmental processing algorithms, and even by the application itself in accomplishing mission-specific goals.

**Real-time Spatio-Temporal Scheduling Theory.** The real-time task models and supporting scheduling theory make time a “first class” property. New models that integrate space and time will be much better suited for mobile platforms. However, spatio-temporal models that also capture physical constraints of the environment hold the most promise for future mobile cyber-physical systems. We conjecture that the integration of real-time spatio-temporal object models will provide better abstractions and predictors of event processing needs. Clearly new models and supporting theory will need to be much more flexible and dynamic than today’s technology. However, existing theory should provide a strong foundation, and offer guidance in the development of new real-time spatio-temporal scheduling theory.

**Smart Devices and Resource Management.** Even with simple real-time task models on a single processor, the existence of non-preemptable resources move the resource management and scheduling problems from P to NP space. Smart resources, and especially smart devices, that appear fully preemptable to higher-level resource management algorithms will greatly simplify the resource management problem. Of course, physically the resource may not be preemptable. However, if the resources itself can save state, and perhaps provide limited request buffering and scheduling, the resource can be treated as though it were preemptable by the rest of the system(s). Thus, while the object is physically non-preemptive at a very local level, it is virtually preemptive at a global level.

**5 Roadmap**

Here we provide a focused research roadmap based on the position and vision espoused in this paper:

**Early stages.** A taxonomy of mobile cyber-physical systems must be one of the first things our community creates. Mobile cyber-physical systems are but one classification of cyber-physical systems. Even mobile cyber-physical systems can be further sub-classified based on a number of different factors.

**Years 1-2.** In the short term, new real-time spatio-temporal object models are needed that consider the constraints imposed by the physical world.

**Years 2-6.** New real-time spatio-temporal scheduling theory and the concept and theory of cyber-physical graphs must be developed that adequately supports design, development, operation and analysis of mobile cyber-physical systems.

**Years 6-10** The new models and theory must be implemented and evaluated in actual systems. From this experience, new tools will be developed to assist engineers, which will be required to facilitate a technology transfer.

**6 Conclusion**

New research will be needed to meet the challenges posed by mobile cyber-physical systems. It is our position that future mobile cyber-physical systems will be spatio-temporal systems of systems that create computational environments and not real-time systems as we currently think of them. Limitations in today’s technologies create a number of challenges in building future mobile cyber-physical systems that only a new, bold, research initiative will overcome.

**Biographies**

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