Next-Generation Embedded Systems: Functional Reactive Programming, Formal Verification, and Real-Time Virtual Resources

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Professor Cheng was invited to a meeting at the
NASA Johnson Space Center in November 2012.

1. Audience and Duration

This tutorial (half-day lecture, A/V equipment: standard projector) is for anyone interested in emerging technology for developing next-generation embedded, real-time, and cyber-physical systems. The focus is on functional reactive programming, RTL (real-time logic)-based formal verification, response time analysis, and real-time virtual resources. Knowledge of basic operating systems concepts is assumed.

2. Tutorial Description

The use of sophisticated digital systems to control complex physical components in real-time has grown at a rapid pace. These applications range from traditional stand-alone systems to highly-networked cyber-physical systems (CPS), spanning a diverse array of software architectures and control models. Examples include city-wide traffic control, robotics, medical systems, autonomous vehicular travel, green buildings, physical manipulation of nano-structures, and space exploration. Since all these applications interact directly with the physical world and often have humans in the loop, we must ensure their physical safety. Obviously, the correctness of these embedded systems and CPSs depends not only on the effects or results they produce, but also on the time at which these results are produced. For instance, in a CPS consisting of a multitude of vehicles and communication components with the goal to avoid collisions and reduce traffic congestions, formal safety verification and response time analysis are essential to the certification and use of such systems - all described in this tutorial.

The benefits of using the functional (reactive) programming (FRP) over the imperative programming style found in languages such as C/C++ and Java for implementing embedded and real-time software are several. The functional programming paradigm allows the programmer to intuitively describe safety-critical behaviors of the system and connect its components, thus lowering the chance of introducing bugs in the design phase. Its stateless nature of execution does not require the use of synchronization primitives like mutexes and semaphores, thus reducing the complexity in programming. Hence, FRP can potentially transform the way we implement next-generation embedded systems and CPS. However, accurate response time analysis of FRP-based controllers remains a largely unexplored problem. The first part of this tutorial will introduce a framework for accurate response time analysis, scheduling, and verification of embedded controllers implemented as FRP programs.

Real-time resource partitioning (RP) divides hardware resources (processors, cores, and other components) into temporal partitions and allocates these partitions as virtual resources (physical resources at a fraction of their service rates) to application tasks. RP can be a layer in the OS or firmware directly interfacing the hardware, and is a key enabling technology for virtualization and cloud computing. Open embedded systems make it easy to add and remove software applications as well as to increase resource utilization and reduce implementation cost when compared to systems which physically assign distinct computing resources to run different applications. The second part of this tutorial will describe ways to maintain the schedulability of real-time tasks as if they were scheduled on dedicated physical resources and increase the utilization of the physical resources. This tutorial covers the following topics:

(1) Introduction to embedded/RT systems and CPS (20 minutes) [1,5];
(2) Functional reactive programming (FRP) (30 minutes) [3];
(3) Response time analysis (50 minutes) [3];
(4) Formal analysis & verification techniques based on Real-Time Logic (RTL) (30 minutes) [2];
(5) Real-Time Virtual Resources (RTVR) (30 minutes) [6]; and
(6) Case studies of actual systems (20 minutes) [4].

3. Instructor's Biography

Albert M. K. Cheng is Professor and former interim Associate Chair of the Computer Science Department at the University of Houston (UH). His research interests center on the design, specification, modeling, scheduling, and formal verification of real-time, embedded, and cyber-physical systems, green/power/thermal-aware computing, software engineering, knowledge-based systems, and networking. He is the founding Director of the UH Real-Time Systems Laboratory. He received the B.A. with Highest Honors in Computer Science, graduating Phi Beta Kappa at age 19, the M.S. in Computer Science with a minor in Electrical Engineering at age 21, and the Ph.D. in Computer Science at age 25, all from The University of Texas at Austin, where he held a GTE Foundation Doctoral Fellowship. He has served as a consultant for many organizations, including IBM and Shell, and was also a Visiting Professor in the Departments of Computer Science at Rice University and the City University of Hong Kong. He is a co-founder of ZapThru.com, where he is currently the Chief Strategy and Technology Director.

Dr. Cheng is the author/co-author of over 220 refereed publications in leading journals (including IEEE Transactions on Computers, IEEE Transactions on Software Engineering, and IEEE Transactions on Knowledge and Data Engineering) and top-tier conferences (including RTSS, RTAS, ICPADS, ISLPED, LCN, and PADL), and has received numerous awards, including the U.S. National Science Foundation Research Initiation Award (now known as CAREER) and the Texas Advanced Research Program Grant (ranking 12th among 373 funded proposals). He has been invited to present seminars, tutorials, panel positions, and keynotes at over 100 conferences, organizations, and universities (most recently at TU Wien, Caltech, University of California at Berkeley, University of Washington, Sapienza University of Rome, University of Oxford, INRIA, University of British Columbia, UT-Austin, and Columbia University). He is and has been on the technical program committees (including many program chair positions) of over 250 conferences, symposia, workshops, and editorial boards (including the IEEE Transactions on Software Engineering 1998-2003 and the IEEE Transactions on Computers 2011-2015). He is Guest Co-Editor of a 2013 Special Issue on Rigorous Modeling and Analysis of Cyber-Physical Systems of the IEEE Embedded Systems Letters, Guest Editor of the 2014-2015 and 2016 Special Issues on Cyber-Physical Systems of SENSORS, and Guest Co-Editor of a 2016 Special Issue on Real-Time Scheduling on Heterogeneous Multi-core Processors of Microprocessors and Microsystems (MICPRO) - the Elsevier Embedded Hardware Design Journal. He has been the Program Co-Chair of the 2013 IEEE International Conference on Service Oriented Computing and Applications (SOCA) and Program Co-Chair of the System, Models and Algorithms Track of the 2014 IEEE International Conference on Embedded Software and Systems (ICESS), where he delivered an award-winning Keynote. Currently, Dr. Cheng has organized and chaired the First Workshop on Declarative Programming for Real-Time and Cyber-Physical Systems (DPRTCPS) in San Antonio, Texas, USA, December 1, 2015, as well as the International Symposium on Software Engineering and Applications (SEA) in Marina del Rey, California, USA, October 26-28, 2015. He is currently the Program Chair of the First CPSWeek Declarative Cyber-Physical Systems (DCPS) Workshop in Vienna, Austria, April 12, 2016.

Dr. Cheng is the author of the popular textbook titled Real-Time Systems: Scheduling, Analysis, and Verification (Wiley); a Senior Member of the IEEE and an IEEE Fellow nominee (2016); an Honorary Member of the Institute for Systems and Technologies of Information, Control and Communication; and a Fellow of the Institute of Physics. His recent awards include the Outstanding Leadership Award as Track Chair and the Outstanding Leadership Award as Keynote Speaker at IEEE ICESS 2014, and the 2015 University of Houston's Lifetime Faculty Award for Mentoring Undergraduate Research for his "Exceptional efforts in demonstrating a lasting commitment to undergraduate research."

Acknowledgment

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References

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