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Compositional Analysis of Real-Time Embedded Systems

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ABSTRACT

This tutorial is concerned with various aspects of component-based design and compositional analysis of real-time embedded systems. It will first give an overview of component-based frameworks and their underlying principles. It will then go in-depth into abstraction methods for real-time components and techniques for computing their optimal interfaces, for both systems implemented on uniprocessor and multiprocessor platforms, as well as extensions to multi-mode systems. Besides theoretical aspects, the tutorial will also present an implementation of the compositional analysis framework on Xen virtualization and a demonstration of the CARTS toolset with several examples seeing the techniques in action. It will also include two case studies highlighting the utility of the framework, including the ARINC-653 avionics software and a smart-phone application. We will conclude the tutorial with a number of open challenges and research opportunities in this domain.

Categories and Subject Descriptors

C.3 [**Special-Purpose and Application-based Systems**]: Real-time and embedded systems; D.2.2 [**Software Engineering**]: Design Tools and Techniques—*Modules and Interfaces*; D.4.1 [**Operating Systems**]: Process Management—*Scheduling*

General Terms

Algorithms, Design, Performance, Theory

Keywords

Real-time interfaces, Compositional schedulability analysis, Hierarchical scheduling, Multi-mode systems

1. INTRODUCTION

The exponential growth in complexity of real-time embedded systems over the past decades has brought forward an extensive adoption of component-based approach in system design. In this design paradigm, a large complex system is first decomposed into smaller and simpler components, which are developed independently before being recomposed into a complete system via their interfaces. To facilitate component-based design, given a component, one needs to be able to compute the component's interface - an appropriate abstraction of the component that encapsulates internal complexities while exposing only necessary elements required for system integration.

In the context of real-time systems, software components are typically implemented on a shared set of hardware resources under a certain scheduling policy, and each component may employ a different local resource sharing policy for its subcomponents. Consequently, the component's abstraction must encapsulate not only its functional behavior but also its resource requirement, expressed in terms of a resource interface. A component's resource interface can be computed either directly from the component's workload or by composing the resource interfaces of its subcomponents. Accurate and efficient resource interface generation/composition is therefore crucial to guarantee correct timing behavior of real-time systems constructed using the component-based approach. This tutorial will provide a comprehensive overview of recent developments in this domain, as well as highlight several open issues and research opportunities.

2. TOPICS

The topics to be covered will include the following:

- *Motivating example:* A running example that will be used to illustrate the concepts and techniques in the tutorial.
- *Compositional analysis basics:* Introduction to compositional analysis of hierarchical scheduled systems and its role in the component-based development, notions of resource interfaces, key desirable properties of component-based framework.
- *Real-time scheduling background:* Standard real-time task models (e.g., periodic, sporadic), schedulability analysis of common scheduling policies (e.g., Earliest Deadline First, Deadline Monotonic) based on demand/supply bound analysis and worst-case response time analysis, which will serve as basic foundation for compositional analysis.
- *Resource interfaces:* Different interface representations of components' resource requirements (e.g., periodic resource models, explicit deadline periodic resource models).
- *Interface computation techniques:* Notions of optimal interfaces, techniques for generating optimal interfaces, interface composition techniques, special cases (e.g., harmonic task periods, offset-aligned components).
- *Extensions to multiprocessor platforms:* Virtual cluster-based multiprocessor scheduling, resource interfaces for virtualized multiprocessor platforms, optimal interface generation techniques.
- *Extensions to multi-mode systems:* Characteristics and challenges of multi-mode systems, mode-change protocols, multi-mode automata models, interface automata for multi-mode systems, multi-mode compositional analysis.
- *Implementation framework:* An implementation of the compositional analysis framework on Xen virtual machine monitor.

- *Tools:* Demonstration of the CARTS toolset for compositional analysis of real-time systems, its functionality and its usage via several self-contained examples.
- *Case studies:* ARINC-653 avionics software and a smart-phone application.
- *Challenges and opportunities:* Open issues and research opportunities in compositional analysis and its integration to existing component-based development framework, from both theoretical and practical perspectives.

3. INTENDED AUDIENCES

The level of the tutorial will be from introductory to intermediate. It will especially appeal to an audience who is familiar with timing analysis and scheduling of closed real-time embedded systems and is interested in how to extend to compositional analysis and open systems, or an audience who is knowledgeable of component-based development and would like to extend them to incorporate timing aspect. However, the tutorial is self-contained and assumes no background in timing analysis or component-based development. The material to be presented will be useful to researchers, students, software designers and developers working or planning to work in the real-time embedded systems domain.

4. SPEAKERS

Dr. Linh T.X. Phan is a Postdoctoral Researcher in the PRECISE Center at the University of Pennsylvania, where she joined as a Research Associate in 2009. She received the B.S. degree in Computer Science in 2003 and the Ph.D. degree in Computer Science in 2009 from the National University of Singapore (NUS). Her research interests include formal modeling, formal verification, system-level design and compositional analysis methods for real-time embedded systems, cyber physical systems, multi-mode systems, and high-performance computing systems. Some of the application domains she works in include automotive electronics and software, avionics, real-time multimedia, body-area sensor networks and cloud computing. She was a recipient of the Singapore Scholarship (1999-2003) and NUS Graduate Scholarship (2003–2007). For her Ph.D. thesis, she received the NUS Dean's Graduate Research Excellence Award (2009). She also received the Best Paper Award nomination at EMSOFT 2010. She has served as a co-chair of APRES 2011 and CRTS 2011, and a PC member of ETFA 2010-2011, EMC 2010-2011, CRTS 2010-2011, RTAS WiP 2010-2011, CPSNA 2011, WTR 2011, WCTT 2011.

Prof. Insup Lee is the Cecilia Fitler Moore Professor of Computer and Information Science and Director of PRECISE Center at the University of Pennsylvania. He also holds a secondary appointment in the Department of Electrical and Systems Engineering. He received the B.S. degree in mathematics from the University of North Carolina, Chapel Hill, and the Ph.D. degree in computer science from the University of Wisconsin, Madison.

His research interests include cyber physical systems (CPS), real-time systems, embedded and hybrid systems, formal methods and tools, high-confidence medical device systems, and software engineering. The theme of his research activities has been to assure and improve the correctness, safety, and timeliness of life-critical embedded systems. His paper with his student on compositional schedulability analysis received the best paper award in RTSS 2003.

He was Chair of IEEE Computer Society Technical Committee on Real-Time Systems (2003-2004) and an IEEE CS Distinguished Visitor Speaker (2004-2006). He has served on many program committees and chaired several international conferences and workshops, including IEEE RTSS, IEEE RTCSA, IEEE ISORC, CONCUR, ACM EMSOFT, ACM/IEEE ICCPS, and HCMDSS/MD PnP. He has also served on various steering and advisory committees of technical societies, including CPSWeek, ESWeek, ACM SIGBED, IEEE TC-RTS, RV, ATVA. He has served on the editorial boards on the several scientific journals, including IEEE Transactions on Computers, Formal Methods in System Design, and Real-Time Systems Journal. He is a founding co-Editor-in-Chief of KIISE Journal of Computing Science and Engineering (JCSE) since Sept 2007. He was a member of Technical Advisory Group (TAG) of President's Council of Advisors on Science and Technology (PCAST) Networking and Information Technology (NIT). He is IEEE fellow and received IEEE TC-RTS Technical Achievement Award in 2008.

Prof. Oleg Sokolsky received M.Sc in Computer Science from St. Petersburg Technical University (Russia) in 1988 and Ph.D. in Computer Science from SUNY at Stony Brook in 1996. Oleg Sokolsky is a Research Associate Professor at the University of Pennsylvania, where he has occupied research staff positions since 1998. His research interests include formal methods for the modeling and analysis of real-time and hybrid systems, model checking, and formal monitoring and run-time checking. He has published over 40 research articles in these areas. He has been one of the primary developers of the CHARON toolkit, as well as a number of other modeling and analysis tools.

Before joining the University of Pennsylvania, Dr. Sokolsky worked as a Computer Scientist at the Computer Command and Control Company in 1996-1998, where he was the Principal Investigator on an SBIR contract funded by ONR.

Dr. Sokolsky is serving on the Steering Committee of the Conference on Runtime Verification and was the Program Chair of this conference in 2010. He also served as the Program Chair (2005), General Chair (2006), and Finance Chair (2007) of the IEEE Real-Time and Embedded Technology and Applications Symposium and as the Design and Verification track Chair at the Real-Time Systems Symposium in 2009. He also organized several workshops in the domain of real-time and embedded systems, including Runtime Verification (2003, 2007), Innovative Technologies for the Certification of Embedded Systems (2006), Composition of Real-Time Systems (2008,2009), and Composition of Embedded Systems (2006). He has served on the program committees of conferences in the area of real-time and embedded systems, including the IEEE Real-Time Systems Symposium (2002,2005–2010) and IEEE Real-Time Technology and Applications Symposium (2002, 2004, 2007, 2008, 2010), IEEE Conference on Real-Time Computing Systems and Applications (2005–2007), IEEE International Symposium on Object-oriented Real-time distributed Computing (2000, 2002, and 2004, 2008, 2009), European Conference on Real-Time Systems (2006 and 2010).