Guest Editors’ Introduction: Special Issue on Time-Critical Systems Design

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Time-critical computing systems are required to meet real-time deadlines. Currently, there is widespread popularity and adoption of Internet-of-Things (IoT) and cyber-physical systems, where the computing systems need to continuously interact with the physical environment. Often, this interaction demands precise timing guarantees. Examples of such time-critical systems range from control systems to smart drones, medical devices, autonomous vehicles, robots, industrial IoT, and smart grid. The software execution time in response to external stimuli in such systems is no longer a performance metric, but instead an issue of functional correctness. However, modern computing platforms with their complex system stack, including the processor architecture, the operating system, and the sophisticated programming language features, are all geared toward improving performance at the cost of timing predictability. Thus, designing systems that can provide predictable timing remains a conundrum.

In this context, the special issue on Time-Critical Systems Design introduces, explores, and investigates the challenges and opportunities in supporting the time-criticality of computing systems. The aim is to offer the readers a clear perspective of the rich landscape of academic as well as industrial endeavors in time-critical systems design and testing. The special issue highlights the state of the art, but also articulates innovations and advances required for universal adoption of such technologies in existing and emerging application domains.

In response to the call for papers for this special issue, we received 28 submissions, which is an overwhelmingly positive response illustrating the importance and the timely nature of the topic. We have selected 12 articles from these submissions for publication, following a rigorous peer review process. The curated papers in the special issue cover both architectural and software-level mechanisms to analyze and enhance timing predictability. They include inventive designs of processor architectures with the explicit goal of achieving time predictability. On the software side, the articles delve into deterministic and probabilistic timing analysis, real-time scheduling theory, operating systems, and middleware to support timing, control systems, and mixed-criticality system design. The special issue also incorporates modeling, verification, and testing approaches for time-critical systems. Six of these articles appear in this Part I of the special issue and the remaining six will appear in Part II.

In “For Safety’s Sake: We Need a New Hardware–Software Contract!,” Gernot Heiser (University of New South Wales and Data61, CSIRO) focuses on the inadequacy of the hardware–software contract in the form of ISA in supporting timing guarantees, which may lead to both safety and security issues. Heiser points out the lack of information on the temporal aspects of the execution of programs on a processor as the root cause...
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of the problem and calls for an augmented ISA that exposes the microarchitectural features (e.g., caches, pipeline, etc.) introduced for performance optimizations and hence affects timing.

In “Mixed-Criticality Scheduling Theory: Scope, Promise, and Limitations,” Sanjoy Baruah (University of North Carolina) delves into scheduling theory for mixed-criticality systems with real-time constraints, where several applications of different criticality levels, such as safety-critical and non-safety critical, can execute concurrently. Aircraft and automotive are prime examples of mixed-criticality systems, where the passenger infotainment system coexists with the safety-critical flight/automotive control system. While mixed-criticality scheduling theory has enjoyed sustained academic excitement, there are apprehensions regarding its practical relevance. Baruah presents a nuanced viewpoint that provides clarity to the exact promises and the limitations of the theory.

In “A Multicore Processor for Time-Critical Applications,” a research team led by Martin Schoeberl (Technical University of Denmark) presents the design of T-CREST—a time-predictable multicore processor. T-CREST has been specially designed to focus on the worst-case timing behavior (which is more important for real-time systems) rather than the average-case performance. The architecture includes time-predictable processor core, software-controlled, time-predictable scratchpad memory per core, and time-predictable communication among the cores. This makes it easy to estimate the bounds on execution time of software running on T-CREST architecture.

The next two articles champion probabilistic (stochastic) timing analysis as opposed to deterministic timing analysis. In “Reconciling Time Predictability and Performance in Future Computing Systems,” a research team from the Barcelona Supercomputing Center, Universita Degli Studi di Padova, and Rapita Systems Ltd., take a different perspective in reconciling the conflict between timing predictability and high performance. The authors offer two complementary approaches to achieve low-cost, high-confidence, and tight performance predictions on high-performance computing systems using measurement-based timing analysis. It requires the processor to expose key indicators of the internal timing behavior of selected hardware resources for increased observability and to expose the full extent of execution-time variability. These solutions are complemented with probabilistic timing analysis to predict the extreme variability in program execution time.

In “Predictability Analysis of Interruptible Systems by Statistical Model Checking,” Josef Strnadl (Brno University of Technology) models and analyzes the timing predictability of real-time systems from the interrupt perspective. The goal is to analyze the parameters such as interrupt latency and interrupt servicing time accurately under various dynamic scenarios. The system components (CPU, interrupt controller, interrupt service routine, and interrupt sources) are modeled using a network of stochastic timed automata and statistical model checking is applied to analyze the timing properties.

In “What Is Real-Time Computing? A Personal View,” Edward Lee (University of California at Berkeley) presents a personal perspective on controlling timing behavior of software in cyber-physical systems, where physical interaction of the computing system with the external environment demands precise timing. Current computing systems, from the instruction-set architecture (ISA) to the programming languages treat timing as a performance metric and not as a correctness criterion. These design decisions are at odds with predictable and repeatable timing of software required in real-time systems. Lee argues that temporal semantics should be applied throughout the abstraction stack starting with deterministic models of timing and building predictable systems (processor, network, and software) that match the behavior of the models with high confidence.

Apart from the contributed articles, the special issue also includes a survey on time-critical systems design by the guest editors. The survey provides a bird’s-eye view of the advances in the design and analysis of hardware–software systems for timing properties.

Acknowledgments

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bringing this special issue to fruition. We would like to thank the Editor-in-Chief Jörg Henkel, who encouraged us to propose a special issue on time-critical systems and accompanied us through all of the steps of the process. We would also like to express our sincere gratitude to Sara Dailey for her continuous support in assembling the special issue. It is with great pleasure that we offer this selection of excellent articles to you. We trust you will like reading this special issue as much as we enjoyed putting it together. We hope these articles will inspire your future works and thoughts. Enjoy!

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