Universiteit
Leiden
The Netherlands

Towards design space exploration of industrial distributed cyber-physical systems

Saadatmand, F.S.

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English Summary

The increasing complexity and performance demands of industrial Distributed Cyber-Physical Systems (dCPS), such as lithography machines in semiconductor manufacturing, necessitate early-stage design validation techniques that are both efficient and accurate. Design Space Exploration (DSE) is essential in this context, as it enables the evaluation of alternative hardware and software configurations before deployment. However, existing DSE tools and methodologies fall short for industrial dCPS: they lack a global system model, rely heavily on manual and impractical model construction, and often lack scalable simulation and optimization support that can efficiently explore large system-level design spaces.

To overcome these limitations, this thesis introduces CompDSE, a structured methodology for conducting system-level DSE tailored to the cyber components of industrial dCPS. The methodology integrates efficient system-level modeling with automated tools for model derivation, model transformation, and simulation-ready code generation, resulting in a coherent workflow for system performance evaluation. CompDSE is particularly suited to existing complex industrial dCPS that are being explored for next-generation upgrades.

CompDSE is structured around three abstract models following the Y-chart approach: the application workload model, the hardware platform model, and the mapping model. The application workload model captures the behavior and interactions of distributed software processes; the hardware platform model describes the available computing infrastructure, including processing components and interconnection networks; and the mapping model specifies how software processes are assigned to hardware resources. In addition, CompDSE introduces the environmental influence model that captures the timing impact of untraced embedded hosts interacting with the physical environment (e.g., through sensors and actuators) that cannot be explicitly modeled. All these models are defined at a high level of abstraction to enable efficient DSE while preserving sufficient accuracy for meaningful performance evaluation.

The CompDSE toolbox includes a set of algorithms that automatically derive the abstract models from execution traces collected from real-world industrial systems. This trace-based approach allows the modeling framework to generate a dedicated model for each operation mode of the system, accurately reflecting the distinct behaviors

and interactions of processes in that mode. The toolbox further includes model-transformation algorithms that convert these abstract models into simulation-ready entities for execution in a discrete-event simulation environment, as well as code-generation algorithms that produce the required simulation code. Together, these tools enable efficient and systematic performance analysis of each design point.

The effectiveness of CompDSE is demonstrated through an evaluation on ASML TWINSCAN lithography machine as a representative industrial dCPS case study. The results show that the models automatically derived by CompDSE closely reproduce the observed behavior of the real system. In particular, the simulated average wafer processing time differs by 2.7% from the actual system measurements. Despite the complexity and scale of the resulting models, each design point can be simulated in under one minute. These findings demonstrate that CompDSE achieves sufficient accuracy for meaningful DSE while maintaining the level of simulation efficiency required for exploring the large design spaces typical for industrial dCPS.

To further enhance concurrency analysis, the thesis introduces a refined application workload model capable of capturing both inter-process and intra-process execution dependencies. This refined model is automatically derived from execution traces and supports a method for identifying tasks within software processes that can be safely reordered or executed in parallel without modifying the existing software structure. The refinement enables deeper performance analysis and reveals parallelism opportunities that are crucial for improving the performance of software workloads on modern multi-core CPUs within the computing subsystems. Experimental validation confirms that simulations based on the refined model expose measurable performance improvements.