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Subject: Review of dissertation thesis of Ing. Anna Minaeva titled “*Scalable Scheduling Algorithms for Embedded Systems with Real-Time Requirements*”

Main results and contributions of the thesis

The thesis presents a broad range of results that can be summarized as follows:

- Efficient algorithms for determining time-triggered schedules for mixed real-time and non-real-time applications in a distributed embedded system comprising computational resources exchanging messages over a shared network.
- Methods for addressing the co-design problem between real-time systems and control design, by linking quality metrics from both domains (settle time and end-to-end latencies).
- Quantitative comparison of different exact formalisms (integer linear programming, satisfiability modulo theory, and constraint programming) with different problem formulations.
- Introduction of heuristic algorithms (with main goal to enable design space exploration) including comparison with exact approaches regarding computation time, resource utilization, and control performance.
- Demonstration of applicability based on case studies from automotive and consumer electronics domains.

Relevance of thesis for current/future needs of the scientific community

- The thesis contributes to the classic lines of real-time research assuming well-established mathematical system models, which are still relevant for some application domains using simple hardware platforms. The comparative results and the application to real-world use-cases represent valuable inputs to the scientific community.
- The current and upcoming efforts in the scientific community to extend performance models for capturing more complex HW-SW interactions (e.g. multiple cache hierarchies, DRAM, DMA, middlewares, POSIX operating systems) that are critical for faithfulness for newer HW-SW platforms are not considered in the thesis.
- The contributions of the thesis linking real-time analysis with functional considerations (control quality) are currently under-represented in the scientific

community, and represent valuable input for future research efforts. The state-of-the-art discussion on that topic could have been more thorough.

Appropriateness of methods used in the thesis

- The utilized exact optimization formalisms are state-of-the-art and it is valuable to compare their effectiveness for the presented scheduling problems. They also represent a solid baseline for assessing the effectiveness of the proposed heuristic approaches
- Some of the assumptions of the considered system model are too restrictive in real-world settings (at least for automotive systems), like non-preemptive and purely time-triggered scheduling. Especially for integration use-cases (which are one of the given motivations) and the distributed development style in industry involving many different companies, more flexible and dynamic scheduling mechanisms are needed. Clearly, such mechanisms are hard to encode for the utilized optimization frameworks. A discussion on how the chosen approach is restricted and if it could be extended to cover those more advanced mechanisms is missing.
- The studied exact optimization frameworks (ILP, CP, SMT) have difficulties to scale to larger systems. This is one of the main motivations in the thesis to research into heuristic approaches. From that point-of-view, a discussion on compositional performance analysis approaches such as pyCPA and RTC (real-time calculus) as driver for design space exploration is missing in the thesis. Both approaches are highly scalable to large systems, since they decompose the overall performance analysis into sub-problems. They are potentially also more expressive than ILP/CP/SMT.

Fulfilment of the main objectives of the thesis

The main objectives of the thesis are fulfilled:

- The state-of-the art in TDM scheduling in the context of mixed real-time and non-real-time applications is analysed, and significant extensions advancing the state-of-the-art are presented.
- Exact mathematical problem formulations covering typical design goals in embedded real-time systems are given.
- Efficient heuristic algorithms are proposed that scale to industrial system sizes. The applicability of those algorithms to real-world use-cases is demonstrated.
- The quality of results obtained by the heuristic algorithms are compared to the results obtained by exact optimization formalisms.

Satisfaction of conditions of a creative scientific work

The author of the thesis proved to have an ability to perform research and to achieve scientific results. I do recommend the thesis for presentation with the aim of receiving a Ph.D. degree.

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