Research application submitted to *ARTES (A network for Real-Time research and graduate Education in Sweden)*

Identification of Complexity-Reduction Techniques for Optimal Scheduling in Embedded Distributed Real-Time Systems

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Summary

The application of optimal search strategies to scheduling for distributed real-time systems is, in general, plagued by an inherent computational complexity. This has effectively prevented the integration of search strategies such as branch-and-bound [1] in scheduling frameworks and tools used in practice today. The integration of an optimal scheduling strategy could lead to, for example, higher application schedulability, better utilization of scarce resources, or higher system reliability, than can be attained for a sub-optimal scheduling technique. Inspired by recent research results, this ARTES project aims at demonstrating that optimal scheduling is, in fact, a viable alternative for many real-time scheduling scenarios. Our approach is based on the hypothesis that, with detailed knowledge about the real-time application and its characteristics, it is possible to make intelligent choices in the configuration of the search algorithm in such a way that the time it takes to generate an optimal assignment of tasks to system resources is reduced to a tractable value.

The project is a cooperation between two ARTES nodes: Department of Computer Engineering, Chalmers, Göteborg and Mecel AB, Göteborg, and one external node: Real-Time Computing Laboratory, University of Michigan, Ann Arbor. One senior researcher and one Licentiate/Ph.D. student from Chalmers will be actively working on the project. In addition, a scientist at Mecel AB will contribute to the project with expertise in design techniques for distributed vehicular real-time applications and by providing examples and case studies.

1 Problem Statement

In recent decades, distributed real-time systems have emerged in many application domains including drive-by-wire automotive systems, intelligent traffic control systems, banking systems, and autonomous robots. Depending on application domain, one may strive for an optimal or a sub-optimal solution to the task assignment and scheduling problem. For embedded, safety-critical real-time systems, where schedules must be generated *a priori*, optimal scheduling is an attractive choice because it leads to (depending on scheduling objective) higher application schedulability, better utilization of scarce resources, or higher reliability, than does a sub-optimal scheduling technique. For example, a high utilization of the system hardware is extremely important in high-volume real-time systems (*e.g.*, vehicles) where the hardware cost is a dominating factor in the total product cost. In fact, one can foresee increasingly higher demands on the computing services that will be offered by future high-volume embedded systems. However, the requirements on such systems often result in conflicting design goals. In order to deliver high performance, it is essential to use as powerful hardware as possible; on the other hand, hardware cost and power dissipation must be kept at a minimum to allow for a large sales market and high mobility. This kind of multifaceted optimization criteria calls for effective scheduling techniques that can keep resource utilization at a maximum while still meeting other optimization criteria.

Among the optimal task assignment and scheduling techniques, the branch-and-bound (B&B) strategy [1] has been successfully used within different application fields, such as real-time control systems [2], digital signal processing systems [3], and fault-tolerant systems [4, 5]. Unfortunately, scheduling of real-time applications with the objective of finding an optimal solution is, in the general case, hampered by an inherent computational complexity[1]. This has effectively prevented an adaption of optimal strategies in scheduling frameworks and tools used in practice today. To investigate whether a practical use of optimal search strategies, such as the B&B algorithm, indeed exists, it is important to assess the complexity of these strategies for real-world applications. Recent research [6, 7] has indicated the viability of finding techniques that can offer significant complexity reduction under the assumption of certain optimization criteria. While these techniques duly account for general application characteristics such as task execution times, task deadlines or the number of processors used in the system, they are not cognizant of constraints that represent other important characteristics of the application and its environment. Examples of such constraints are those that stem from demands on high system reliability (task replication constraints) or a low total system cost (minimize the number of communication links).

The proposed project addresses the problem of scheduling embedded distributed real-time systems using algorithms that are cognizant of the application and its operating environment.

2 Main Ideas

Our approach is based on the hypothesis that, with detailed knowledge about the real-time application and its environment, it is possible to make intelligent choices in the configuration of the B&B algorithm in such a way that the time it takes to find an optimal schedule is reduced to a tractable value. Examples of such configuration choices are those that determine the order in which search-tree vertices are traversed [6], or those that identify and avoid redundant branches in the search tree [7]. Other configurations deliver tractable performance by making explicit assumptions about the underlying task-scheduling policy [2, 5].

Unfortunately, the techniques proposed to date in the open research literature all suffer from the same major drawback, namely that they assume a general application model with very limited semantics for describing specialized application constraints typically found in embedded computer systems. In such systems, the application and its behavior is well-known which allows for a large degree of fine-tuning as regards the scheduling algorithm used. Furthermore, the design optimization criteria used for

[1]In the case of the B&B algorithm, the search for an optimal solution is organized by means of a *search tree*, where the vertices in the tree represents partial and complete solutions to the problem. To measure the computational complexity of the algorithm, we use the *time complexity* of the B&B algorithm, that is, the number of vertices explored during the search for an optimal solution.

such systems differ relatively much from that of general computer systems. Some examples of specific assumptions that can be made for an embedded system are listed below:

Locality constraints: Many functions in an embedded system encompass handling external sensors and actuators. To avoid unnecessary communication network traffic, the tasks implementing these functions need to be located close to the corresponding sensors or actuators.

Vendor-specific constraints: In many embedded systems, certain tasks are handled by computer nodes delivered by an external vendor. In these cases, the designer may not have many options in the assignment of task periods and deadlines or in the choice of task dispatching policy.

The salient feature of the B&B strategy is its ability to avoid inferior and redundant branches in the search tree by means of intelligent heuristics. One of the more powerful heuristics in this context is the *lower-bound function* which calculates optimistic predictions on the quality of all complete solutions emanating from a branch in the search tree. If the predicted quality of a specific branch is inferior to that of the best solution found so far, no solution in that branch will be optimal and, hence, the branch does not have to be explored at all. Much research has been done in finding powerful lower-bound functions and a plethora of such functions exist for various optimization criteria. A somewhat overlooked technique for reducing the B&B search complexity is to use *dominance relations* [8, 9], that is, rules for determining whether one partial solution is inferior to another. With the aid of dominance relations, it is possible to avoid the exploration of even more branches in the search tree without any loss of optimality. The usefulness of the dominance concept in general real-time computing has been demonstrated in, for example [2]. Surprisingly enough, however, no studies have been made to evaluate and compare the actual impact of different dominance relations on the complexity of the B&B algorithm for realistic applications. This is what we intend to pursue in the proposed project.

The proposed project aims at discovering techniques (lower-bound functions and dominance relations) that will significantly reduce the search complexity when detailed information is given about the application and its operating environment.

3 Expected results and impact

The expected research contributions of this project are as follows:

C1. Support for multiple concurrent optimization criteria in the B&B framework. Current work only considers a single optimization criteria.

C2. Heuristic lower-bound functions and dominance relations tailored for embedded distributed real-time systems. Current work has focused on finding techniques that are generally applicable but that are not cognizant of application-specific constraints.

By applying our techniques to applications provided to us from Mecel, the research will demonstrate practical techniques to achieve high resource utilization and meet other design criteria for interesting test cases. Since embedded distributed real-time systems is a rapidly-emerging application domain, the research is expected to generate new design-support tools for these applications. Furthermore, the task assignment problem is solved predominantly “by hand” in industry today. With the aid of a well-functioning automated framework — such as the B&B algorithm — the task-assignment process will be less error prone and will lead to more cost-effective design solutions.

4 Project plan

Experimental plan. The first phase of the project will be concerned with the analysis of distributed real-time applications and the identification of their optimization criteria. This investigation is carried out by the project members at Chalmers in cooperation with application designers at Mecel.

The second phase is concerned with developing techniques within the B&B framework that will aid in reducing the complexity associated with finding optimal schedules. The impact of the new techniques will be evaluated using real applications as well as randomly-generated applications. An evaluation platform, called **GAST** [10, 11], and developed at Chalmers will be an important experimental resource for this part of the project. One of the salient features of **GAST** is an implementation of a parametrized B&B framework [12, 6] that can be used as a test-bed for implementing new techniques for complexity reduction and evaluating their impact on scheduling performance.

To demonstrate the applicability of the techniques expected as a result from this projects, we will assume realistic real-time architectures. One of the target systems used in the project will be **EMERALDS** [13, 14], a real-time kernel for embedded applications. **EMERALDS** has been developed at University of Michigan and is available as a software product that can be run on many existing hardware platforms, for example, the Digital Alpha or the Motorola 68340 microprocessor. Furthermore, our approach for modeling the real-time applications will follow the guidelines of **BASEMENT** [15], a distributed architecture for real-time control applications.

Milestones and deliverables. The milestones and deliverables apply for the period 990301–040301. This encompasses 2×2 years of research and one year of teaching.

Activity 9901–9903: ARTES Ph.D. student recruitment.

Activity 9903–0003: The first phase of the project. Identification of optimization criteria used in the design of distributed vehicular real-time applications.

Deliverable 0003: State-of-the-art report on B&B algorithms and their application to real-time system design. Refined specifications of the Licentiate project topics and project plans.

Activity 0003–0109: The second phase of the project. Development of concepts for complexity-reduction techniques in the B&B framework.

Deliverable 0109: Licentiate thesis. Specification of the activities in the remaining time period.

Activity 0109–0309: Development of complexity-reduction techniques in the B&B framework.

Deliverable 0309: Integration of developed techniques in academic evaluation tools and industrial design tools. Detailed evaluation of the performance of the developed techniques.

Activity 0309–0403: Writing of Ph.D. thesis.

Deliverable 0403: Ph.D. thesis.

5 Preliminary budget

We ask for funding of one Ph.D. student[2]. The activity level of the student is 80%. Thus, the student is expected to get a Licentiate/Ph.D. degree in 2.5/5 years. Cost for the Ph.D. student including salary costs and additional costs (supervision, travels, equipment, administration, premises): **400.000 SEK per year**

Mobility funding to allow experts from RTCL, the University of Michigan, to participate in the project and to allow the ARTES Ph.D. candidate to spend longer time periods at the University of Michigan: **50.000 SEK per year**

The annual funding we ask ARTES to support is **450.000 SEK**.

Total project cost for 2×2 years of research is **1.800.000 SEK**

6 Related research

The application of the B&B technique to real-time system scheduling in the general sense has been studied recently, most notably at the University of Michigan [2, 5]. To the best of our knowledge, however, there is no published research that describes a successful (with respect to tractable complexity) integration of the B&B technique into industrial development and evaluation tools. In particular, we are not aware of any work in Sweden that addresses this problem.

7 Industrial relevance

Optimal scheduling in distributed real-time systems has mainly been reserved for academic purposes. With the introduction of multiple processors in high-volume embedded systems, the scheduling of scarce computing resources can no longer be allowed to be in the hands of an *ad hoc* designer. The techniques developed in the project are expected to be useful for a quite broad range of embedded applications. The general results of the project are expected to be useful, not only for Mecel AB, but also for other industries concerned with the design of embedded real-time systems, such as Ericsson Microwave Systems or Volvo Technical Development.

8 Relation to ARTES and other SSF programmes

This project matches the key goals of ARTES in that it focuses on the problem of designing real-time systems under the relatively strict constraints associated with embedded systems. Similar to some other ARTES projects this project addresses the issues of effective real-time system design. However, the other ARTES projects focus mainly on developing interactive design environments for reducing the scheduling turn-around time when changes are made in the design, this project focuses on one particular step of the design process, namely effective task assignment and scheduling techniques for maximizing resource utilization and other optimization criteria. We expect the output from this project to be useful

[2] A current candidate for this position is Monika Andersson Wiklund who has recently been employed at the Department of Computer Engineering at Chalmers as a teaching assistant.

in the other related ARTES projects. In particular, we anticipate synergy effects with the ARTES project "Incremental Static Scheduling" which is led by Dr. Gerhard Fohler at Mälardalen University.

We see the following connections to other SSF programs. The Personal Computing and Communication (PCC) program targets mobile communication to enable multimedia applications and focuses on the communications infrastructure. The proposed project related to PCC in the sense that the design techniques developed in the project are also applicable to the design of mobile communication systems.

9 Context

This research will be carried out in the High-Performance Computer Architecture Group at Chalmers which is led by Professor Per Stenström and consists of three senior researchers (Per Stenström, Fredrik Dahlgren, and Jan Jonsson) with a very strong scientific background. Per Stenström has conducted research in multiprocessor technology since 1984 and his work within memory technology and performance issues in multiprocessor architecture has been internationally recognized. Fredrik Dahlgren is also widely recognized for his contributions in multiprocessor architecture. Jan Jonsson has made significant contributions in the field of design and scheduling of parallel and distributed real-time systems.

Mecel AB has a group consisting of around 10 persons working with the design of distributed real-time systems in vehicular applications. The group is led by Mikael Strömberg.

The Real-Time Computing Laboratory at the University of Michigan is led by Professor Kang G. Shin and consists of seven senior researchers with an outstanding scientific background. Two of the researchers at RTCL (Kang G. Shin and Farnam Jahanian) have conducted internationally recognized research in distributed real-time and fault-tolerant computing systems since 1985. In addition, Kang G. Shin has made significant research contributions in the fields of process control, computer architecture, and computer networking.

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A Short CV for Jan Jonsson

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Permanent positions and degrees

- Assistant professor of real-time systems, Chalmers (Sweden), since May 1998.
- Assistant professor of data communications, Halmstad University (Sweden), 1997.
- Ph.D. degree in computer engineering, Chalmers (Sweden), in 1997.
- M.Sc. degree in computer science and engineering, Chalmers (Sweden), in 1992.

Visiting positions

- Visiting scientist, Real-Time Computing Laboratory, University of Michigan, Ann Arbor (USA), August–December 1996.

Main research interests

- Real-time scheduling strategies for multiprocessor architectures
- Real-time data communications

Selected professional activities

- Member of the program committe for the *7th IEEE Workshop on Parallel and Distributed Real-Time Systems*, San Juan, Puerto Rico, April 1999.

Selected publications (refereed) that are relevant for the project

1. J. Jonsson, "GAST: A Flexible and Extensible Tool for Evaluating Multiprocessor Assignment and Scheduling Techniques," In *Proceedings of the 27th International Conference on Parallel Processing*, August 1998.
2. J. Jonsson, "Exploring the Importance of Preprocessing Operations in Real-Time Multiprocessor Scheduling," In *Proceedings of the 18th IEEE Real-Time Systems Symposium – Work-in-Progress session*, December 1997.
3. J. Jonsson, "The Impact of Application and Architecture Properties on Real-Time Multiprocessor Scheduling," PhD Thesis, School of Electrical and Computer Engineering, Chalmers University of Technology, September 1997.
4. J. Jonsson and K. G. Shin, "A Parametrized Branch-and-Bound Strategy for Scheduling Precedence-Constrained Tasks on a Multiprocessor System," In *Proceedings of the 26th International Conference on Parallel Processing*, August 1997.
5. J. Jonsson and K. G. Shin, "Deadline Assignment in Distributed Hard Real-Time Systems with Relaxed Locality Constraints," In *Proceedings of the 17th IEEE International Conference on Distributed Computing Systems*, May 1997.