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Optimisation of battery operating life considering software tasks and their timing behaviour

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Abstract

Users of mobile embedded systems have an interest in long battery operating life. The longer a system can operate without need for recharge or battery replacement, the more will maintenance cost and the number of faults due to insufficient power supply decrease. Operating life is prolonged by saving energy, which may reduce available processing time. Mobile embedded systems communicating with other participants like other mobile systems or radio stations have to satisfy time guarantees ensuring reliable communication. Thus, methods that save energy by reducing processing time are not only subject to available processing time but subject to the embedded system's time guarantees.

By performing parameter optimisations offline, run-time computation can be avoided, decisions can be taken early, design complexity can be reduced, and energy can be saved. Especially, by computing processor shutdown durations offline, no extra circuitry to monitor system behaviour and to wake up the processor needs to be designed, deployed, or power supplied. The resulting optimisation solutions of this research work are designed to depend on minimal extra circuitry: only an energy counter and a programmable timer are required.

For this thesis, software tasks which share one processor are considered. The scheduling algorithm earliest deadline first is assumed, and per task, a relative deadline is assumed. Tasks may be instantiated arbitrarily as long as this occurrence behaviour is given in the notion of event streams. Especially, the theory and the solutions presented in this work do not require tasks to occur periodically.

Scaling the processor's voltage and shutting down the processor are taken into account as methods for saving energy. With given per task worst-case execution times and the tasks' event streams, the real-time feasibility of each energy optimised solution is proven.

The used real-time feasibility test has the advantage that it can be approximated by a combination of step-functions and linear functions. The approximation provides an adjustable small error, and it yields an adjustable number of linear optimisation constraints.

Reducing the processor's voltage reduces processor frequency, therefore, execution time increases. The resulting slowdown becomes the optimisation variable, either global, for all tasks, or local, individually per task. It is shown that a global slowdown factor can be computed from linear constraints together with a linear objective in a linear program, whereas local slowdown factors are shown to require a non-linear objective that is still convex.

Processor shutdown switches off the processor for a specific time; it blocks the processor from processing software. Duration and occurrence become optimisation parameters, and the linearised real-time feasibility test is used to decide whether a parameter setting is feasible or violates deadlines.

With this thesis, two shutdown policies are introduced. Periodic shutdown switches off the processor periodically, thus, besides duration, the period is to be optimised. Task-dependent shutdown switches off the processor with an inherited occurrence behaviour from a certain task, thus, besides duration, the parent task needs to be chosen, as well as

the number of instances of the parent task to fall between two consecutive shutdowns.

In this thesis, a battery model is developed. Influencing factors, design and usage dependent, are discussed. The Peukert-formula for constant discharge, an approximation for battery life known since over 100 years, and its derivation introduced by Rossander and Forsberg for variable currents are evaluated with experiments with non-constant discharge currents, showing significant error of more than 20%. A known theory concerning the influence of periodically discharge is also shown to not hold for chosen commercially available batteries designed for mobile systems. Based on the experimental results, a battery model in closed form is derived which is as simple as the Peukert-formula and provides a significantly less error. An error of less than 7% is achieved.

Each of the presented methods for saving energy, global or local slowdown, or periodic or task-dependent shutdown, yields a different system configuration, out of which the best with respect to operating life is chosen with the help of the developed battery model. Discharge profiles serve as a connection between information in the notion of event streams, task power consumptions, and the battery model.

Zusammenfassung

Benutzer mobiler eingebetteter Systeme haben ein Interesse an einer langen Batterienutzungsdauer. Je länger ein System ohne Nachladen oder Batteriewechsel operieren kann, desto geringer werden Wartungskosten und durch Energiemangel bedingte Ausfälle. Energiesparmethoden helfen die Nutzungsdauer zu verlängern, können jedoch zu einer Reduzierung der verfügbaren Rechenzeit führen. Die Systeme können zeitlichen Anforderungen unterworfen sein, etwa um eine zuverlässige Kommunikation sicherzustellen. Somit ist der Einsatz von Energiesparmethoden neben der verfügbaren Rechenzeit auch an die zeitlichen Anforderungen gebunden.

Indem Optimierungen zur Designzeit durchgeführt werden, lassen sich früh Entscheidungen treffen und weitere Berechnungen zur Laufzeit vermeiden. Insbesondere die Parameterberechnung für die Prozessorabschaltung zur Designzeit ermöglicht ein Auskommen ohne zusätzliche systemüberwachende Schaltkreise, die ihrerseits entworfen und mit Energie versorgt werden müssten. Die sich aus dieser Arbeit ergebenden Optimierungslösungen sind dahin entworfen minimale Hardware-Anforderungen zu haben: es sind nur ein Energiezähler und eine programmierbare Echtzeituhr nötig.

Für diese Arbeit werden Software-Tasks betrachtet, die sich einen Prozessor teilen. Für die Ablaufplanung wird ausschließlich der Algorithmus „nach frühester Frist zuerst“ betrachtet. Es wird den Software-Tasks ein beliebiges Auftreten zugestanden, solange sich dieses mit der Ereignisstrommethodik formulieren lässt. Insbesondere ist es für die präsentierte Theorie und auch für die sich ergebenden Optimierungslösungen nicht erforderlich, dass Tasks periodisch auftreten.

Als Energiesparmethoden werden Prozessorspannungsskalierung und Prozessorabschaltung betrachtet. Mit Hilfe von als gegeben vorausgesetzten Task-Laufzeitoberschranken und auf Basis der Ereignisströme, wird die Echtzeitfähigkeit der energieoptimierten Lösungen geprüft.

Der verwendete Echtzeittest hat den Vorteil durch Treppenfunktionen und lineare Funktionen approximierbar zu sein. Die Approximation bietet einen einstellbar kleinen Fehler und liefert für die Optimierung eine einstellbare Menge linearer Bedingungen.

Prozessorverlangsamung reduziert die Taktfrequenz und erhöht damit die Rechenzeit der Tasks. Der sich aus der Frequenz ergebende Verlangsamungsfaktor wird zur Optimierungsvariablen, entweder global, d.h. für alle Tasks gleichermaßen, oder lokal, d.h. für jede Task individuell. Ein globaler Faktor lässt sich mit Hilfe einer linearen Zielfunktion und den linearen Bedingungen aus dem Echtzeittest in einem linearen Programm optimieren. Wie in dieser Arbeit gezeigt, benötigt dagegen die Optimierung für lokale Verlangsamungsfaktoren eine nicht-lineare Zielfunktion, welche aber noch konvex ist.

Den Prozessor abzuschalten, heißt alle Berechnungen für eine bestimmte Zeit auszusetzen. Dauer und Häufigkeit der Abschaltung werden Optimierungsvariablen, und deren Echtzeitfähigkeit wird mit Hilfe des linearisierten Echtzeittests überprüft.

Mit dieser Arbeit werden zwei Abschaltverfahren vorgestellt. Bei periodischem Abschalten wird, neben der Abschaltdauer, die Periodendauer optimiert. Task-abhängiges

Abschalten koppelt die Abschaltung an das Auftreten einer bestimmten Task. Neben der Abschaltdauer, werden Task und die Anzahl der Task-Instanzen, die zwischen zwei Abschaltungen fallen sollen, bestimmt.

Jedes der präsentierten Energiesparverfahren, ob globale oder lokale Verlangsamung, ob periodische oder task-abhängige Abschaltung, liefert eine andere Systemkonfiguration. Aus welcher sich die längste Batterienutzungsdauer ergibt, wird mit Hilfe eines in dieser Arbeit entwickelten Batteriemodells ermittelt. Entladeprofile dienen der Kopplung der Ereignisströme, der Verlustleistung pro Task und des Batteriemodells.

In dieser Arbeit wird ein Batteriemodell entwickelt. Beeinflussende Faktoren, abhängig von Design und Nutzung, werden diskutiert. Die seit über hundert Jahren bekannte Peukertsche Formel zur Abschätzung der Batterienutzungsdauer für konstante Ströme und die Weiterentwicklung von Rossander und Forsberg für variable Ströme werden anhand variabler elektrischer Ströme evaluiert, wobei die hier gezeigten Messungen signifikante Abweichungen von mehr als 20% aufzeigen. Ein bekannter Ansatz, Batterien periodisch zu entladen, wird auf Signifikanz hin untersucht und dessen Unwirksamkeit für ausgewählte, für den mobilen Einsatz gedachte Batterien gezeigt. Basierend auf den Experimenten wird ein, Batteriemodell in geschlossener Form entworfen, welches wie die Peukertsche Formel einfach ist, und welches einen Fehler von weniger als 7% aufweist.

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1. Introduction

A traffic bridge often serves for many years millions of cars to pass rough terrain. When such a bridge is built, cranes lift and shift large structures. Persons control these cranes to move bridge components into the right positions. Communication between controller and crane is done via radio. If the radio fails or transmits twisted messages communication is interrupted: structures might get broken; people might get severe injuries. Damaged material and hurt humans are the consequences of unreliable communication.

One of the reasons why communication eventually fails is a weak battery, as mobiles and radios usually are powered by batteries. Another reason is the user had no dependable information on the remaining energy within the battery.

On the one hand, methods for saving energy can prolong battery operating life, and the most energy surely is saved by switching the device off, but with the drawback that communication is lost: energy savings must retain the radio's correct functionality.

Modern embedded systems are implemented partly in software and partly in hardware. The software is divided into pieces of execution called tasks. Theses tasks are assigned to a processor which they share. Each task may include communication. For successful operation, communication between tasks, data exchange or communication to the outside of the processor induce timing constraints, i.e. deadlines. Deadlines become part of the system's specification to ensure that the system operates reliably. Methods for saving energy are subject to these constraints, especially those methods which affect a software's processing time. In this thesis, the latter are considered.

On the other hand, a forecast on battery operating life can provide a guarantee on the system's minimal run-time, and an early forecast, at design time of the system, allows for an early maintenance estimation which helps to avoid shortages when the system is in use.

A kind of forecast could be to measure the energy consumption per hour of the embedded device and to divide the specified capacity of the battery to use by this amount, with the result being equal to the amount of time the system could operate. But this simple formula does not yield dependable results: experience and research show that the operating life of a battery heavily depends on the current drawn from it; the operating life depends non-proportionally on the current. For a reliable forecast, a battery model is to be used. This thesis presents a model that is developed from experiments.

Energy savings, timing constraints, and battery modelling are the three topics that are to be brought together to form the optimisation problem. The resulting methodology will provide reliable energy optimised solutions.

1.1. Assumptions and Targeted Problem

For this work, three basic components are considered. These are a processor with several levels of speed and energy consumption, a set of software tasks with deadlines being scheduled earliest deadline first, and a battery. These are shortly discussed next.

To begin with the software tasks, beyond deadlines, parameters that describe embedded software include a description of the software's occurrence behaviour which depict the frequency for each task to become instantiated and be ready for processing. This behaviour can be periodic; the period itself can be affected by deviations (jitters), e.g. caused by time-slot-based communication; the behaviour can be sporadic, yet with a minimal time to pass between two consecutive task instantiations; or, for example, the behaviour can be affected by time shifts, e.g. caused by a clock with skew. Further, parameters include upper bounds on execution times. The bound on a task's execution time and its occurrence behaviour form a task's timing behaviour. Both can be combined to compute upper bounds on the processing demand. The sum of all tasks' demands yields the overall demand, and thus the available idle time, which is to be exploited by methods for saving energy. For the work in this thesis, it is assumed that deadline, worst-case execution time, and occurrence behaviour are given for each task of the task set.

Parameters describing the processor include the processor's ability to perform voltage and frequency scaling, the ability to transit into low-power modes, and the amount of modes available. The processor's power consumption differs for various modes and for different software. Information on power consumption and timing behaviour combines to an energy demand estimation: this is an aim of this thesis, therefore, power consumptions for different modes and software are assumed to be given.

Parameters describing the battery include brand and capacity for various discharge currents. Because the capacity depends on the current to be drawn, the capacity is rated (i.e. determined) for different currents, which results in the rated capacity for a battery. A model based on these parameters is capable of estimating the battery's operating life for a given energy demand. Therefore, these parameters are assumed to be given as well.

Problem statement The problem to be solved is increasing a battery's operating life by applying methods for saving energy on an earliest-deadline-first scheduled set of tasks, with each task not necessarily occurring periodically, and with hard real-time constraints in form of a relative deadline for each task. Different methods may yield different solutions. To rate the possible solutions of the optimisation problem, a battery model is to be developed.

The stated problem is to be tackled by the work presented in this thesis with the help of the theory of event streams. The theory follows the idea of covering all cases by only inspecting worst-cases: if an assertion holds for a worst-case, so does it for all cases included in the worst-case. A successful worst-case test will provide a reliable guarantee for all situations that might happen while the embedded system is running.

Note, event-stream theory can also be applied on preemptive fixed-priority systems.

1.2. Achievements

This work brings together real-time feasibility, energy optimisation, and battery modelling for embedded systems. And it contains the following contributions.

First, a convex optimisation problem for voltage scaling per task and per task set is presented in Chapter 5. The linearity is shown for global slowdown. The convexity is shown for local slowdown. The solutions have reduced complexity compared to the state-of-the-art: the complexity equals the number of tasks times the number of approximations steps. And this is the first work to apply voltage scaling per task to non-periodic task sets with arbitrary but fixed deadlines. A comparison to related work in this field is depicted in Table 4.1 on page 75.

Second, two optimisation problems for processor slowdown, periodically and task-dependent, are presented in Chapter 6, and this is the first presentation of processor shutdown applied to non-periodic task sets with arbitrary but fixed deadlines. Periodic shutdown is shown to be a convex optimisation problem. Task-dependent shutdown is shown to be a non-convex optimisation problem; variation of the variables deadline and worst-case execution time together appears to lead to a non-convex problem. All solutions have reduced hardware requirements for processor shutdown compared to related work: a programmable real-time clock (this is the least possible requirement for external circuitry). A comparison to related work in this field is depicted in Table 4.2 on page 77.

Third, a battery model for predicting operating life is presented in Chapter 7. Measurements are presented with samples of today's batteries for mobile use. These involve constant currents and highly non-constant currents reflecting energy consumptions of today‘s embedded systems. The measurements for the model introduced by Rossander and Forsberg (Peukert-formula for non-constant currents) show an error of 20%. The measurements for the developed model show an error of 6.7%, instead. A state-of-the-art approach to prolong battery life using a discharge with high pulses is falsified by measurements. And finally, the developed battery model is not based on simulation; it is in closed form instead, as opposed to solutions of current research.

This thesis presents an offline optimisation of processor slowdown and shutdown that allows for predicting the energy demand already at design time, and without computational intensive simulation, see Chapter 4 for the concept and Chapter 8 for implementation and experiments.

1.3. Overview of the Work

The work is structured into eight chapters, each composed of sections, subsections, subsubsections, and paragraphs. Each chapter ends with a summary or a conclusion. Chapter 2 includes the foundations helping to understand the rest of the work. Chapter 3 is a discussion of works dealing with similar problems as the one described in this thesis; it gives a survey on battery models.

The concept behind the work presented in this thesis is shown and classified in Chapter

4. This chapter also includes an overview of the assumptions made as well as a comparison to related work. The reader will learn about the interaction of processor slowdown and the real-time feasibility test in Chapter 5; regardless of the occurrence behaviour, optimisation of processor slowdown is done per task and per task set, with the real-time test providing the optimisation constraints. The reader will find in Chapter 6 the idea to model processor shutdown as a hard real-time task, and the optimisation of its occurrence behaviour and execution time in several directions. Chapter 7 discusses properties of batteries affecting their operating life, enriched by experimental results; the chapter presents the chosen battery model and the coupling of task timing and power parameterisation to a battery model in the form of discharge profiles. The reader will find the descriptions of experimental setups and further experimentation results in Chapter 8.

Chapter 9 depicts the conclusion of the results and the achievements presented in this thesis, further, it provides an outlook on future work.

The appendix contains further notable material beyond the thesis. The appendix is followed by a list of bibliographic references. This thesis ends with the index containing frequently used notions and symbols.