Towards Network-Wide Energy Estimation for Adaptive Embedded Systems

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Abstract—**This paper discusses the next steps towards how system developers can easily and accurately evaluate the impact of their system design choices on energy consumption during the early stages of the design process. To do this, energy estimations in every phase of system development are necessary. Our research focuses on adaptive systems, where applications are activated according to the actual need.**

In this paper we present an approach which derives the energy consumption per application using a combination of energy-relevant software and hardware parameters. The aim is to create energy building blocks for applications to estimate the energy consumption of a system with multiple applications running on it. This approach utilizes the high environmental interaction of embedded systems where sensors and actors consume more energy than CPUs. The granularity of the energy estimation is the application level, due to focusing on adaptive systems.

Keywords - embedded systems, energy-efficiency, network-wide optimization, adaptive systems, automotive

I. Introduction

This paper focuses on estimating energy consumption in adaptive networked embedded systems during the early stages of design. As embedded systems become more prevalent and powerful, they are consuming more energy. Our research concentrates on the area of networked embedded systems commonly found in automobiles, aircraft and industrial systems. To save resources, these systems will be designed more adaptive in future. These systems activate their applications only when they are required. In today's luxury-class vehicles for instance, the electrical and electronic components draw up to 2.5 kW ([1], [2]). An increase of 100 W thus means that fuel consumption rises by 0.1 liter per 100 km, leading to an increase in CO2 emissions of 2.5 g per km [2]. This illustrates the considerable potential for energy savings, an aspect that must be factored in during the development process.

Embedded systems designers, such as those active in the automotive industry, are frequently given energy consumption requirements for the finished product. Because the automotive industry has especially long development cycles, hardware and software design choices must be made very early during the development process [3]. This makes it necessary to estimate the energy consumption early in the design process. Networked systems feature a wide range of technologies and topologies that significantly impact energy consumption down the road. For instance, the placement of functionality within an ECU impacts partial networking modes, which involves deactivating certain system components that are not being used. It was shown that partial networking can reduce energy consumption by as much as 30 percent [2].

Figure 1, which depicts the various phases of a typical system development process, reveals exemplarily that the energy savings potential gradually decreases over the course of development. Energy savings estimates are also imprecise, as shown by the dotted line.

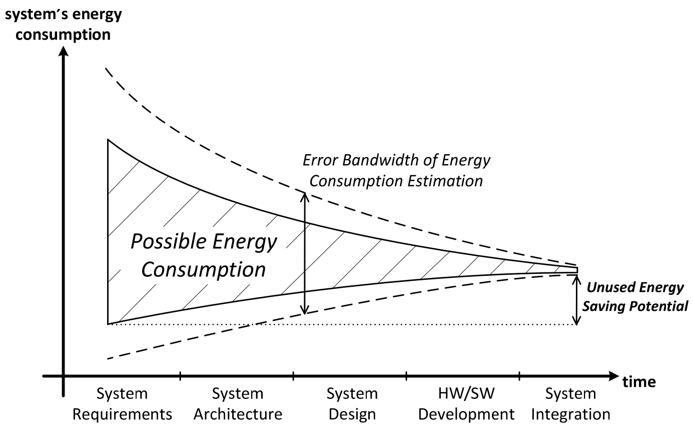

Fig. 1: Energy Design Space during System Development [4]

A structure to estimate the energy consumption of a system throughout the entire system design process is already presented in [4]. Here models for estimating the energy consumption at the different phases of development are presented which use the available system information at the particular phase.

The aim of this paper is to show the next steps towards how system developers can easily and accurately evaluate the impact of their design choices on energy consumption during the early stages of the design process. To do this, accurate energy estimations at every phase of system development are necessary. In this paper we present an approach which derives the energy consumption per application using a combination of energy-relevant software and hardware parameters. The aim is to create an energy building block per application to estimate the energy consumption of a system with multiple applications running on it.

II. Adaptive Networked Embedded Systems

In this section, the system characteristics of adaptive networked embedded systems and the resulting challenges for estimating energy consumption are discussed.

Adaptive: Within systems such as automobiles and the context of energy saving, adaptiveness means the activation and deactivation of applications according to the current need of functionality. At the moment most automobiles support only two systems states, i.e. all on and all off, which does not utilize the existing energy saving potentials. Future systems will have a lot more system states, because not all functionalities are necessary at every point during operation. These systems will switch their system states caused by external conditions and will be able to save energy by deactivating unused components. However, planning a lot of system states is challenging and it is unresolved how many system states optimize the energy consumption of a system [5], because also changes between system states consumes energy.

Networked: A networked embedded system consists of a number of components which communicate with each other. These components are independent processing units commonly known as Electronic Control Units (ECUs) within the automobile industry. Tasks executed on ECU depend on each other and form together applications which are visible for the user. Estimating energy consumption of networked embedded systems, for example, includes the energy demand of network communication. In addition to that, energy saving is commonly largest by deactivating whole ECUs. This is attributable to the fact that energy consumption of peripherals, memory and other parts are often not scalable – contrary to CPUs [6].

Embedded: Embedded systems are characterized by a larger amount of non-functional requirements compared to other systems such as personal computers. These limitations are for example limited resources (energy, memory, etc.) or strict time limits for the execution of tasks (deadlines). The need to design energy efficient systems makes it necessary to estimate the energy consumption as early as possible in the design process. Embedded systems are also characterized by a high degree of interaction with the environment using sensors and actors. Normally almost every application within automobiles is interacting with the environment. This results in our approach to estimate energy consumption, which is presented in the following section.

III. An Approach to Estimate Energy Consumption During System Design

In this section, an approach to derive the energy consumption per application using a combination of energy-relevant software and hardware parameters is presented. The aim is to create an energy building block per application to estimate the energy consumption of a system with multiple applications running on it. This granularity is necessary because adaptive systems activate individual applications, i.e. tasks on ECUs, according to the actual need as mentioned in section II.

To realize this, the energy consumers of embedded systems were analyzed and it was ascertained that the energy consumption of peripherals, such as sensors and actors, is much larger than the consumption of CPUs. Although CPUs are not the major consumers of energy, they are nevertheless of great importance for the energy consumption – and the software which runs on the CPU respectively. The impact of software and CPU is the resulting active time of peripherals or the whole component, because energy is defined by the used electrical power over a specific time. That means for energy estimation per application power and time estimations are necessary. We suggest deriving these information from software and hardware as outlined below.

Power Consumption: Power consumers within embedded systems are CPUs, sensors and actors and other hardware modules. Within embedded systems the major amount of power consumption is performed by sensors, actors and other application-specific hardware – not by the CPU. This results in the fact that the main part of the energy is consumed by using peripherals, i.e. when applications are active and use their specific peripherals. Applications consist of several individual tasks and the power consumption per task is assumed to be constant. This mapping of power consumption simplifies the estimation for adaptive systems, because the power consumption is assignable to a specific task, i.e. application. Through that the main part of the energy consumption of applications depends on the active time of the application, i.e. how long an application uses its peripherals.

Active Time: As discussed above the major power consumption depends on the application-specific hardware which is used by software running on the CPU. There are two causes which result the active time of an application. On the one hand there are functional requirements, for example on and off duration of indicator lights, and on the other hand the execution time of a task on a CPU. To estimate task execution times existing methods such as [7] can be used.

This approach aims energy estimation per application which can be used to estimate the energy demand of the different system states of adaptive embedded systems. Future research evaluates usability and accuracy of this approach and identifies the relevant software and hardware parameters.

IV. Conclusion and Further Steps

This paper has discussed an approach which estimates the energy consumption per application using a combination of energy-relevant software and hardware parameters. These parameters are the power consumption of application-specific hardware and the active times of this hardware resulted by software running on a CPU. This approach assigns energy demands to applications and simplifies the energy estimation for adaptive systems, because such systems activate individual applications according to the actual need. This assignment is founded on the reason that peripherals such as sensors and actors are the main consumer of energy within networked embedded systems.

Our approach allows one to evaluate the impact of the design choices on energy consumption during early stages of the design process. This enables the design of adaptive networked embedded systems which are more energy efficient. Validating our approach and evaluate the accuracy is necessary and planned for future work.

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