Feedback Scheduling of Real-Time Control Systems with Resource Constraints

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Despite rapid advances in information technologies, real-time control systems (RTCSs) are becoming ever-increasingly resource limited in recent years. At the same time, RTCSs often have to operate in dynamic environments that feature workload fluctuation. As a consequence, the available computing and communication resources are typically non-deterministic. In this new implementation environment, traditional control systems design and implementation methodology, which separates control from scheduling, cannot always provide quality of control (QoC) guarantees. From a resource scheduling perspective, existing open-loop real-time scheduling algorithms obviously lack flexibility when applied to RTCSs, and consequently cannot achieve optimal usage of available resources. Therefore, it is of paramount importance to develop novel paradigms for enabling real-time control under dynamic environments and optimizing the overall QoC under dynamic resource constraints associated with implementation platforms.

This thesis observes the emerging trend of convergence of control with computing and communication. By exploiting control and scheduling codesign, we study some practical and open problems in RTCSs from a unique viewpoint of dynamic resource management. Considering constraints on three representative kinds of resources, i.e. CPU time, energy, and network bandwidth, we present a set of feedback scheduling methods that exploit a unified technological framework. They provide enabling technologies for closed-loop dynamic resource scheduling, and tackle some essential problems in the emerging field of feedback scheduling. Meanwhile, this thesis holistically addresses the problem of dynamic allocation of bottleneck resources within RTCSs, thus providing flexible QoC management mechanisms and achieving overall performance optimization under dynamic environments.

As regarding CPU scheduling, we are concerned with multitasking embedded control systems where the processing capacity of the processor is limited. With the goal of optimizing overall control performance, we analytically formulate the problem of optimal feedback scheduling, and then discuss relevant mathematical solutions. Because algorithmic optimizer is too computationally expensive to be used online, we suggest a new method called neural feedback scheduling using neural networks. It could considerably reduce the feedback scheduling overhead, while delivering almost-optimal overall control performance. Besides, it is also characterized by good adaptability, robustness, fault-tolerance, etc. Taking into account the unavailability of task execution times and the presence of measurement noises, we propose a fuzzy feedback scheduling scheme, which introduces fuzzy control technique into the area of feedback scheduling. Thanks to the powerful capacity of fuzzy logic in handling non-linear, imprecise and uncertain situations, fuzzy feedback scheduling doesn't rely on task execution times, and makes the feedback scheduling system robust against measurement noises inside temporal parameters by copying with the uncertainty of workload and available resources in an intelligent fashion. Additional merits of this method include e.g. ease of implementation and low runtime overhead.

In the part of energy management, we aim to reduce the energy consumption of the processor as much as possible while preserving the QoC of embedded control systems. A feedback control real-time scheduling approach, i.e. energy-aware feedback scheduling, which combines energy management with QoC management, is presented to solve such practical problems as CPU workload variations and task execution time unpredictability. This approach exploits the dynamic voltage scaling (DVS) technique and indirectly changes task execution times through dynamically adjusting the CPU speed. The objective is to control the CPU utilization at a desired level. After analytically modeling the DVS system, we present a control theoretic design and analysis method for the feedback scheduler. In this way, predictable performance of feedback scheduling is achieved and closed-loop energy management is realized. With the goal of further reducing energy consumption based on energy-aware feedback scheduling, we analyze the dynamic behavior of control systems with variable sampling periods and suggest an enhanced energy-aware feedback scheduling scheme, which adopts the methodology of graceful performance degradation. It dynamically adapts the CPU speed using the DVS technique, and at the same time, adjusts the sampling period of each control loop according to its current control performance. In this way, it takes advantage of flexible timing constraints associated with control tasks. Since sampling periods are enlarged as much as possible given that the QoC is not jeopardized, energy consumption is further reduced, which in turn yields higher energy efficiency.

With regard to bandwidth allocation, we focus on networked control systems that use priority-based fieldbuses and wireless control systems employing random medium access protocols. From a viewpoint of feedback control and network scheduling codesign, we present an integrated feedback scheduling scheme for multi-loop networked control systems. Exploiting a cascaded feedback scheduler, it adapts sampling periods with respect to the dynamic changes in available bandwidth. The objective is to maintain the deadline miss ratio at a desired low level and also optimize the bandwidth allocation. In order to further improve the overall control performance, we suggest a direct feedback scheduling mechanism, which re-assigns priorities to control loops at runtime based on their actual control performance. It is argued that integrated feedback scheduling could maximize resource utilization in underloaded scenarios, and could achieve graceful degradation of control performance under overload conditions. Consequently, the overall control performance could be significantly improved. Recognizing the inherent uncertainty of available link resources in wireless control systems, we present an adaptive feedback scheduling scheme that integrates the methodology of cross-layer design. This scheme deals with noise interference and variations in link transmission rate by exchanging information between the physical layer and the application layer. The deadline miss ratio is controlled in a way that the overall control performance is optimized. Furthermore, we propose an event-based invocation mechanism for feedback schedulers, which is quite effective in that quick response is enhanced while the feedback scheduling overhead decreases. The result is that practical efficiency of feedback schedulers could be considerably improved.

In this thesis we go beyond the traditional control systems design methodology that features separation of concerns of control and scheduling, and discard the classical control task model with fixed timing constraints. A systematic framework of feedback scheduling has been preliminarily established with a set of promising results, which enrich this emerging area in various aspects. It is believed that the achieved results will promote the holistic integration of control with computing and communication.

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