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Period selection for integrated controller tasks in cyber-physical systems

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Abstract Performance optimization of cyber-physical systems (CPS) calls for co-design strategies that handle the issues in both computing domain and physical domain. Periods of controller tasks integrated into a uniprocessor system are related to both control performance and real-time schedulability analysis simultaneously. System performance improvement can be achieved by optimizing the periods of controller tasks. This paper extends an existing model to select task periods in real-time for CPS with fixed priority controller tasks scheduled by rate-monotonic algorithm. When all the tasks can be integrated, the analytic solution of the problem is derived by using the method of Lagrange multipliers and gradient descent method is evaluated to be suitable online. To further deal with the condition that the system is overloaded, an integrated method is proposed to select periods of tasks online by selecting a subset of tasks first and then optimizing the periods for them. Experimental results demonstrate that our method yields near-optimal result with a short running time.

1. Introduction

Cyber-physical systems (CPS) are integrations of computation and physical process.[1] A CPS is often implemented using distributed architectures with many computing nodes which connect with each other through networks. Improving processor computing power and network performance enables some applications to be integrated into a uniprocessor node, which conserves hardware resources and improves the overall system performance. For example, integrated modular avionics (IMA)[2] integrates some subsystems, which are traditionally implemented as independent nodes, in some portable modules. IMA reduces the weight of computing equipment and saves the space of cabinet, improving the overall performance of the aircraft.[3]

When multiple tasks are integrated into a uniprocessor system and run concurrently, CPU resources should be allocated to these tasks to guarantee that they can finish their executions before deadlines, which is referred to as system schedulability.[4] One of the elements that affect system schedulability is the task period, which also has an impact on control performance. Therefore, it is reasonable to assign periods for controller tasks with considerations of schedulability as well as control. Approach to design the system integrating control domain and real-time computing domain is referred to as

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real-time/control co-design[5–7] and a lot of work has been focused on it.

Seto et al.[8] modeled the co-design problem as an optimization problem, where period is selected as the optimization variable, system performance index is expressed as a function of period and the period variable is restricted within its feasible region to guarantee system schedulability. As different performance functions guide different targets and the real-time scheduling policies fall into different scheduling types with different schedulability criteria, the model is adopted and further extended by many researchers, tackling the period assignment issues based on earliest deadline first (EDF) and rate-monotonic (RM) scheduling policies.[9–13] Different from classical RM and EDF, the feedback control scheduling (FCS)[14] is a closed-loop scheduling policy which adjusts resources allocation online. Some of the efforts in co-design problem based on FCS can be found in Refs.[15–18] More work about real-time control co-design can be found in survey.[7]

The motivation of this paper is to assign periods to fixed priority controller tasks in real-time considering the condition that a uniprocessor system is overloaded. To be specific, RM scheduling policy and linear-quadratic-Gaussian (LGQ) controller tasks are studied as the RM is an optimal scheduling policy for system with fixed priority (FP) tasks[4] and the LGQ control problem is one of fundamental optimal control problems. Overload condition may occur when a part of the computing nodes in a CPS crashes and a subset of tasks should be selected and assigned with proper periods to maximize the overall performance. As the high dependable safety critical requirements, the periods re-assign procedure should be finished quickly and in real-time (e.g. 100 ms). A near-optimal result is considered acceptable.

Efforts in Refs.[10–11] contribute to the period selection problem with FP tasks scheduled by RM scheduling algorithm, but the control stability was not explicitly investigated, besides, the overload condition was not considered either. As a result, we extend the model and emphasize fast and real-time requirement of solving the optimization problem in this paper. Two sub-problems are solved, the first problem is to assign period to controller tasks in real-time with system schedulability and control stability constraints, and the second one is to select a subset of tasks and assign periods to them.

The rest of this paper is organized as follows.

In Section 2, the optimization model and related work are reviewed. We state the period selection problem for FP tasks in CPS and formulate the model as an optimal problem in Section 3. The procedure of solving the optimal problem is given in Section 4 in the case that all the candidate tasks can be integrated in a uniprocessor system. We introduce an integrated approach to handle overload situation in Section 5. Section 6 demonstrates experimental results and compares the proposed algorithm with other approaches. Section 7 summarizes the main results and concludes the paper.

2. Computation scheme and related work

Optimization model for period selection problem with FP tasks scheduled by RM scheduling algorithm has been further extended from optimal function and constraints these two aspects. Both optimization model and existing work relating to period selection algorithms are reviewed in this section. We adopt the triple $<C, D, P>$ to model a task in this paper, where C denotes the worst-case execution time (WCET), D the delay constraint and P the period respectively.[4]

2.1. Optimization model

2.1.1. Constraints on period

The period of a controller task should be longer than its WCET and shorter than an upper bound to guarantee control stability, which can be formulated as

$$C_i \leqslant P_i \leqslant P_{i\text{-max}} \tag{1}$$

where C_i is the WCET of the task τ_i, and $P_{i\text{-max}}$ is its maximum period.

Besides, period of an integrated task should keep the whole system schedulable. Schedulability of a system with FP tasks scheduled by the RM algorithm can be tested by performing CPU utilization analysis[4,19] or response-time analysis (RTA).[20,21] Liu and Layland[4] proved that a system with parameters satisfying Eq. (2) is schedulable, where n is the number of tasks integrated in the system and U_b is the utilization bound. Inequality Eq. (2) can be transformed to a linear form by replacing $1/P_i$ with frequency f_i.

$$\sum_{i=1}^{n} C_i/P_i \leqslant U_b = n(2^{1/n} - 1) \tag{2}$$

Different from research on relationship between CPU utilization and schedulability, Joseph and Pandya[20] tested the system schedulability by RTA. The response time of a task is the time elapsed from the request of resource to the completion of execution and the system is schedulable if the response-time of any task is shorter than its deadline, which can be formulated as

$$R_i = t = C_i + \sum_{j<i} \lceil t/P_j \rceil C_j \leqslant D_i \tag{3}$$

where R_i is the response time of task τ_i, and t is the time variable.

2.1.2. Performance function

System performance can be formulated as a function of parameters. It is a function of task period in this work. The performance function represents the design goals, e.g. power consumption. Seto et al.[8] used the cost-function Eq. (4) to describe their design goal, where α_i and β_i are coefficients.

$$J_i(P_i) = \alpha_i e^{\beta_i/P_i} \tag{4}$$

The performance of LQG control is formulated as Eq. (5) in Ref.[22], where $\boldsymbol{x}$ is the state vector, $\boldsymbol{u}$ the control vector, and T the maximum time to be considered in the performance evaluation; $\boldsymbol{Q}$ and $\boldsymbol{R}$ are weighting matrices.

$$J = \lim_{T\to\infty} \frac{1}{T} E\left\{ \int_0^T (\boldsymbol{x}^{\mathrm{T}}(t)\mathrm{Q}\mathrm{x}(t) + \boldsymbol{u}^{\mathrm{T}}(t)\mathrm{R}\mathrm{u}(t))\mathrm{d}t \right\} \tag{5}$$

Melzer and Kuo[23] proved that in the case of LQR control, the derivative of cost-function Eq. (5) at zero is zero and the second derivative is positive, which means the cost-function Eq. (5) can be approximated by a simple quadratic form, i.e.

$$J_i(P_i) = \alpha_i + \beta_i P_i^2 \tag{6}$$