FUZZY FEEDBACK SCHEDULING OF RESOURCE-CONSTRAINED EMBEDDED CONTROL SYSTEMS

FENG XIA¹,², YOUXIAN SUN³, YU-CHU TIAN²*, MOSES O. TADE⁴, AND JINXIANG DONG¹

¹College of Computer Science and Technology
Zhejiang University
Hangzhou 310027, P. R. China
f.xia@ieee.org

²Faculty of Information Technology
Queensland University of Technology
GPO Box 2434, Brisbane QLD 4001, Australia
y.tian@qut.edu.au
*Corresponding author

³State Key Laboratory of Industrial Control Technology
Zhejiang University
Hangzhou 310027, P. R. China

⁴Department of Chemical Engineering
Curtin University of Technology
GPO Box U1987, Perth WA 6845, Australia

Received August 2007; revised January 2008

Abstract. The quality of control (QoC) of a resource-constrained embedded control system may be jeopardized in dynamic environments with variable workload. This gives rise to the increasing demand of co-design of control and scheduling. To deal with uncertainties in resource availability, a fuzzy feedback scheduling (FFS) scheme is proposed in this paper. Within the framework of feedback scheduling, the sampling periods of control loops are dynamically adjusted using the fuzzy control technique. The feedback scheduler provides QoC guarantees in dynamic environments through maintaining the CPU utilization at a desired level. The framework and design methodology of the proposed FFS scheme are described in detail. A simplified mobile robot target tracking system is investigated as a case study to demonstrate the effectiveness of the proposed FFS scheme. The scheme is independent of task execution times, robust to measurement noises, and easy to implement, while incurring only a small overhead.

Keywords: Feedback scheduling, Fuzzy logic control, Embedded control systems, Resource management, Mobile robot

1. Introduction. Despite their popularity, embedded systems are typically resource limited [1, 2, 3]. For instance, there are usually constraints on the processing speed, memory size, and communication bandwidth. As the complexity of various applications grows continuously, multiple tasks have to compete for the limited processor resource in many cases. In this context, the overall quality-of-control (QoC) of an embedded control system depends not only on the design of control algorithms, but also on the scheduling of
shared computing resources. With traditional open-loop scheduling schemes, however, the temporal attributes of these systems will be significantly affected by workload variations. This may potentially cause the overall QoC to deteriorate [4, 5].

Feedback scheduling offers a promising approach to flexible QoC management in dynamic environments with variable workload [1, 3]. The basic idea of feedback scheduling is to allocate available resources online among tasks by adapting their timing parameters, e.g., periods, based on feedback information about the actual resource utilization. By exploring the integration of feedback control and real-time scheduling, feedback scheduling can deal with uncertainties in resource availability, and thus provide QoC guarantees for the system. In the last decade, much effort has been made in this area, for example, [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15]. Conventional feedback scheduling schemes, particularly the most widely studied optimal feedback scheduling [6, 7, 8], require that the following information be available at runtime: 1) the control cost function as a function of sampling period for each control loop; 2) the execution times of control tasks; and 3) the CPU utilization. In practical systems, however, some of this information may not always be available. In many complex control systems, it is difficult, if not impossible, to describe the performance index of QoC as a function of sampling period. In a variety of commercial off-the-shelf (COTS) operating systems, direct measurement of task execution times is not always supported [12]. Measurement noises inevitably exist in real-world applications, even when online measurement of task execution times is supported by the underlying operating system kernel. Available measurements or estimations of the system workload are consequently imprecise. When the availability and accuracy of critical information cannot be guaranteed, conventional feedback scheduling schemes may not perform as expected or even become ineffective in some circumstances.

This paper considers resource-constrained embedded control systems in which 1) the runtime availability of some important information such as task execution times cannot be guaranteed; and 2) the system parameter measurements are imprecise. To provide QoC guarantees in dynamic environments, this paper will propose a fuzzy feedback scheduling (FFS) scheme that takes advantage of both fuzzy logic control [16, 17, 18, 19] and feedback scheduling. A mapping from feedback scheduling to fuzzy logic control will be built. Through dynamically adjusting the periods of control tasks, the fuzzy feedback scheduler attempts to maintain the CPU utilization at a desired level, thus enabling flexible QoC management.

The use of the fuzzy control technique in feedback scheduling is mainly inspired by its powerful capability in dealing with nonlinearity, imprecision, and uncertainty. Since direct mathematical modelling of the controlled process is not required for fuzzy control system design, the proposed scheme does not depend on explicit formulation of the relationship between control cost functions and sampling periods. As a formal methodology to emulate the intelligent decision-making process of a human expert, fuzzy control provides a simple and flexible way to reach a definite conclusion based on imprecise, noisy, or incomplete input information. Consequently, the FFS scheme is independent of task execution times, and capable of handling uncertainties, imprecision, and incompletion of system parameters. Since fuzzy controllers have a simple structure, the proposed scheme is easy to implement with only a small computational overhead.

Applying fuzzy control techniques to resource management in general-purpose computing and communication systems has attracted increasing attention, e.g., [10, 20]. However,
none of these papers have dealt with control applications where the QoC is the main concern. Jin and colleagues [11] employed fuzzy logic in scheduling control tasks. However, feedback scheduling based on fuzzy logic control remains unexplored for real-time control tasks. In our previous work [15], a fuzzy feedback scheduler has been developed to manipulate the execution times of anytime control algorithms; however, it does not deal with anytime control algorithms. The present work substantially extends our preliminary work reported in [13, 14]. Instead of task execution times, the sampling periods will be chosen as the manipulated variables in this work. A generalized framework of fuzzy feedback scheduling and detailed design procedures for the fuzzy feedback scheduler will be described along with a case study. To reduce the computational overhead, this paper employs the look-up table method, which has not been explored in [13, 14].

The paper is organised as follows. The problem to be addressed is described in Section 2. Section 3 presents the basic framework of fuzzy feedback scheduling. In Section 4 the design procedures for fuzzy feedback scheduler are discussed in detail. Section 5 evaluates the performance of fuzzy feedback scheduling and compares the results with those of the traditional open-loop scheduling scheme and an ideal feedback scheduling scheme. The paper is concluded in Section 6.

2. **Problem Statement.** Consider a system in which $N$ independent control tasks are running concurrently on a processor with limited processing power. Each control task executes a well-designed control algorithm, which is responsible for the control of a physical process. In addition to these control tasks, some non-control tasks for, e.g. data backup, human machine interaction, and remote communication, may also exist. For simplicity, all tasks in the system are assumed to be periodic. The timing parameters of control task $i$ are defined below:

- $h_i$: task period, which is equal to the sampling period of the corresponding control loop, and is available precisely online.
- $c_i$: task execution time, which is time-varying and unavailable at runtime.

Without loss of generality, assume that the measurement of CPU utilization is calculated by:

$$
\hat{U} = \sum_{i=1}^{N} \frac{c_i}{h_i} + U_{\text{others}} + \delta_U
$$

where $U_{\text{others}}$ represents the total CPU utilization of all non-control tasks, and $\delta_U$ is measurement noise. It is worth mentioning that the design of a fuzzy feedback scheduler does not rely on how to compute the CPU utilization measurement. In the system considered here, $c_i$ and $U_{\text{others}}$ are unavailable to the feedback scheduler. The information available to the feedback scheduler includes the utilization measurement $\hat{U}$ and the sampling periods $h_i$.

Since the task execution times vary over time, it is possible that the system becomes overloaded. In this situation, the overall QoC deteriorates and the system may even become unstable [5]. On the other hand, when the system is underloaded, some computing resources will be wasted, thus yielding worse performance than possible. Therefore, flexible QoC management should be provided in this dynamic environment so as to guarantee the QoC in overloaded conditions and to improve the overall QoC in the presence of light workload through making better use of available resources. Accordingly, the problem to
be addressed can be stated as follows: Given a set of control tasks with time-varying and unknown execution times and a processor with limited computing resources, design a feedback scheduler to dynamically allocate available resources among these control tasks such that flexible QoC management is achieved in the presence of measurement noises. Due to the unavailability of task execution times, conventional feedback scheduling strategies that depend on complete formulation of task models become inapplicable.

3. Fuzzy Feedback Scheduling Framework. To address the above problem, this section proposes an intelligent feedback scheduling scheme based on the fuzzy control technique. Figure 1 depicts the architecture of the proposed FFS scheme. In addition to the control loops, an outer feedback loop is introduced to implement feedback scheduling. The basic role of the feedback scheduler is to adjust the periods of the control tasks dynamically to achieve a desired level of CPU utilization. The timing attributes of all non-control tasks cannot be changed by the feedback scheduler.

From the control perspective, the fuzzy feedback scheduler is a fuzzy controller with CPU utilization being the controlled variable and sampling periods being the manipulated variables. It is intuitive that the desired CPU utilization $U_R$ should not violate the schedulability constraint associated with the system. In practice, some schedulability margin must be preserved when choosing $U_R$ because of the presence of measurement noises.

To simplify the design of the feedback scheduler, a simple rescaling method is employed to adjust the sampling periods:

$$h_i(j) = \eta(j)h_i(j-1), \quad i = 1, \ldots, N$$

(2)

where $\eta(j)$ is the period rescaling factor, and $j$ denotes the invocation instant of feedback scheduler. In [6] Cervin et al have used a similar method, which delivers good scheduling performance.

Taking into account the maximum allowable sampling period $h_{i,max}$, the calculation of the sampling periods is expressed as:

$$h_i(j) = \min\{h_{i,max}, \eta(j)h_i(j-1)\}, \quad i = 1, \ldots, N$$

(3)

Ideally, if the timing attributes of all tasks are precisely known, the period rescaling factor can be set to:

$$\eta(j) = \frac{\sum_{i=1}^{N} c_i(j)}{U_R - U_{\text{others}}(j)}$$

(4)
After the sampling periods are altered using (3) and (4), the total CPU utilization of the control tasks in the next invocation interval becomes:

\[ U(j) = \sum_{i=1}^{N} \frac{c_i(j)}{h_i(j)} + U_{others}(j) = \frac{1}{\eta(j)} \sum_{i=1}^{N} \frac{c_i(j)}{h_i(j-1)} + U_{others}(j) \]

\[ = \frac{U_R - U_{others}(j)}{\sum_{i=1}^{N} \frac{c_i(j)}{h_i(j-1)}} \sum_{i=1}^{N} \frac{c_i(j)}{h_i(j-1)} + U_{others}(j) = U_R \]  

(5)

Using this ideal method, one can easily achieve the desired level of CPU utilization in the next invocation interval. However, this is only true for the ideal case where all necessary system parameters are precisely known. In the systems described in Section 2, it is impossible to use (4) to compute the period rescaling factor. In this paper the fuzzy control technique is employed to determine the period rescaling factor \( \eta \).

The work flow of the fuzzy feedback scheduling system can be outlined as follows. At every invocation instant, the feedback scheduler samples the CPU utilization that the system has been monitoring from the previous invocation instant, and compares it with its desired value. Based on the control error of the CPU utilization and the change in the control error, the fuzzy controller acting as the feedback scheduler produces a corresponding period rescaling factor. The sampling period of each control loop is then re-assigned using (3).

4. Fuzzy Feedback Scheduler Design. This section will describe in detail the design procedures of the fuzzy feedback scheduler. Throughout the description, a simplified mobile robot target tracking system is used as the target application.

4.1. A case study. Consider a simplified mobile robot system [21] as shown in Figure 2. The robot is treated as a point \((x, y)\) on the plane. It can move on \(x\)-axis and \(y\)-axis freely and independently. The coordinate of the robot on each axis, i.e., \(x\) or \(y\), is respectively controlled by a separate control loop. The overall goal of the system control is to track as closely as possible a mobile target, which is also modelled as a mobile point on the plane.

The transfer functions of both control loops are \(G(s) = \frac{1000}{0.5s^2 + s}\). Controllers are designed by discretizing continuous-time controllers that use the PID (proportional-integral-derivative) algorithm. The controller settings are taken from [4]. Two control tasks, denoted by \(\tau_1\) and \(\tau_2\), respectively, together with a third periodic and non-control task \(\tau_3\), are running on one processor concurrently.

![Figure 2. A simplified mobile robot system.](image-url)
4.2. **Design methodology.** Figure 3 shows the internal structure of the fuzzy feedback scheduler, where the component of the sampling period adjustment is omitted for simplicity. Like almost all fuzzy controllers, the fuzzy feedback scheduler consists of four main components, i.e., a fuzzification interface, a rule-base, an inference mechanism, and a defuzzification interface. Inputs to the fuzzy feedback scheduler are the control error of the CPU utilization, \( e(j) = U_R - \hat{U}(j) \), and the change in the control error, \( ec(j) = e(j) - e(j-1) \); while the output is naturally the sampling period rescaling factor \( \eta \). The inner work flow of the fuzzy feedback scheduler is as follows. Firstly, the fuzzification interface translates numeric inputs \( e(j) \) and \( ec(j) \) into fuzzy sets characterizing linguistic variables \( E \) and \( EC \), respectively. The inference mechanism then activates a predetermined set of linguistic rules in the rule-base with respect to these linguistic variables, and produces the fuzzy sets of the output linguistic variable \( RF \). Finally, the defuzzification interface converts the fuzzy conclusions, which are reached by the inference mechanism, to a numeric value \( \eta(j) \).

![Diagram of Fuzzy Feedback Scheduler](image)

**Figure 3.** Internal structure of fuzzy feedback scheduler.

To simplify online computations, the look-up table method is employed to implement the fuzzy feedback scheduler. As shown in Figure 3(b), the procedures of using this method are as follows. Firstly, construct a fuzzy control table, which is also called look-up table, via offline computations using the original fuzzy feedback scheduler depicted in Figure 3(a), and store the table in the memory. During runtime, the resulting feedback scheduler quantizes the inputs \( e(j) \) and \( ec(j) \) using the input scaling factors \( GE \) and \( GEC \), and then searches in the fuzzy control table to find out the quantized output value corresponding to the quantized inputs. The final output \( \eta(j) \) is generated by multiplying the quantized output value with the output scaling factor \( GRF \). A key step in this method is to build a good fuzzy control table. The design procedures of the fuzzy feedback scheduler for the simplified mobile robot system are detailed below.

1. **Specify the structure of the fuzzy feedback scheduler**

   From the above descriptions, a two-dimension fuzzy controller is used, which has two input variables (\( e \) and \( ec \)) and one output \( \eta \). The universes of discourse for \( e, ec, \) and \( \eta \) are chosen to be \([-0.3, 0.3]\), \([-0.3, 0.3]\), and \([0.5, 1.5]\), respectively.

2. **Describe inputs and outputs linguistically**
The sets of linguistic values for the linguistic variables $E$ and $EC$ are NB, NS, ZE, PS, PB, and the set of linguistic values for $RF$ is NB, NM, NS, ZE, PS, PM, PB, where NB represents negative big, NM represents negative medium, NS represents negative small, ZE represents zero, PS represents positive small, PM represents positive medium, and PB represents positive big. To facilitate the construction of the look-up table, both inputs and output should be quantized. The sets of quantized values for the two inputs are $\{-6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6\}$. The set of quantized values for the output is $\{-7, -6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6, 7\}$. Accordingly, $GE = 6/0.3 = 20$, $GEC = 6/0.3 = 20$, and $GRF = 1/14 = 0.0714$.

3. **Specify membership functions for linguistic values**

Figure 4 depicts the membership functions used in this paper for all linguistic values of both input and output linguistic variables.

![Input and output membership functions](image)

**Figure 4.** Input and output membership functions.

4. **Determine fuzzy control rules and inference mechanism**

The linguistic rules are established through analyzing the system behaviour under various conditions. The fuzzy control rules are constructed as follows. If the measured CPU utilization exceeds the desired level significantly, a big sampling period rescaling factor should be used so that the sampling periods are enlarged quickly enough to avoid too many deadline misses. If the measured CPU utilization is lower than the desired level, sampling periods should be decreased slowly to reduce the possibility of overloading. As shown in Table 1, a total of 25 linguistic rules are built in this paper for the mobile robot system.

For the inference mechanism, the max-min method is adopted. In the defuzzification interface, the most popular centre of gravity method is used to produce a real number in the universe of discourse of the output.

5. **Create look-up table**

The final step for offline design of fuzzy feedback scheduler is to generate the fuzzy control table that can be used online, as given in Table 2. For this purpose, the quantized value of the output corresponding to each pair of quantized values of the input variables
is calculated. Once the look-up table is constructed, it can be used at runtime within the framework given in Figure 3(b).

The computation of the fuzzy feedback scheduling algorithm is relatively simple with a time complexity of $O(1)$, implying that only a small feedback scheduling overhead has been introduced.

5. **Performance Evaluation.** To evaluate the performance of the proposed FFS scheme, this section conducts simulations for the case study system described in Section 4. The FFS method will be compared with the following two methods:

- Open-loop scheduling: No feedback scheduling strategy is used; control loops always run with fixed sampling periods;
- Ideal feedback scheduling: Actual CPU utilization and all timing parameters of the tasks are precisely known; and the feedback scheduler adapts sampling periods using (3) and (4).

The open-loop scheduling method is chosen for comparison because traditionally it is the default solution for embedded control systems and almost all existing embedded control systems are based on open-loop scheduling. By comparing FFS with the ideal
feedback scheduling scheme, it is possible to examine how the FFS scheme will maximize the system performance. The simulation environment is based on Matlab/TrueTime [21]. As a performance metric for mobile robot control, the tracking error is defined as the distance between the robot and the target:

$$ERR_{\text{track}} = \sqrt{(x_{\text{act}} - x_{\text{ref}})^2 + (y_{\text{act}} - y_{\text{ref}})^2}$$  \hspace{1cm} (6)

where the tuple $\left( x_{\text{act}}, y_{\text{act}} \right)$ denotes the actual coordinates of the robot, and the tuple $\left( x_{\text{ref}}, y_{\text{ref}} \right)$ denotes the reference coordinates of the mobile target.

5.1. Setup overview. Suppose that the mobile target moves along a half circle with a constant angular speed. It starts from point $(0, 0)$ at time $t = 0$, and reaches point $(2, 0)$ at time $t = 4$s. The default unit on the plane is meter (m). At runtime, the actual execution times of three tasks are generated by $c_i = (1 + \varepsilon) \bar{c}_i$, where $\varepsilon$ is a sequence of white Gaussian noise with zero mean and a variance of 0.01, and $\bar{c}_i$ is the average execution time of each task, as given in Table 3. The nominal period for each control task is 3, 4 and 5 ms, respectively, where the period of non-control task 3 (i.e., $h_3$) is fixed. The maximum allowable sampling periods of two control loops are $h_{\text{max}} = 7$ ms.

| Time (s) | 0-1 | 1-2 | 2-3 | 3-4 |
|---------|-----|-----|-----|-----|
| Control Task 1 (ms) | 0.6 | 1.2 | 1.2 | 1.2 |
| Control Task 2 (ms) | 0.4 | 0.4 | 1.2 | 1.2 |
| Non-control Task 3 (ms) | 1.0 | 2.0 | 2.0 | 1.5 |

Fixed priorities are utilized in the system. The feedback scheduler is implemented as a periodic task with the highest priority. The second highest priority is assigned to the non-control task $\tau_3$, while $\tau_2$ has the lowest priority. In the feedback scheduling loop, the desired CPU utilization is set to $U_R = 85\%$. The invocation interval of the feedback scheduler task is $T_{FS} = 20$ ms, and its execution time is assumed to be 0.1 ms. The measured CPU utilization is generated by $\hat{U} = \frac{c_1}{h_1} + \frac{c_2}{h_2} + \frac{c_3}{h_3} + \delta_U$, where $0 \leq \hat{U} \leq 1$, and $\delta_U$ is a consequence of zero-mean white Gaussian noise with a variance of $r^2$.

5.2. Results and analysis. Under open-loop scheduling, the tracking trajectory of the mobile robot and the tracking error are given in Figure 5. In the upper part of Figure 5, the solid line gives the trajectory of the target and the centre of circles corresponds to actual position of the robot. Because the robot is too far from the target, there is no robot trajectory within the scope of the very right part of the upper sub-figure.

After time $t = 2$s, the robot becomes unable to track the mobile target effectively, implying that the system finally becomes unstable. This happens because the system is overloaded from $t = 2$s to 3s with the average workload of $(1.2/3+1.2/4+2/5)\times100\% = 110\%$. Since task 2 has the lowest priority, the control loop for the $y$ coordinate of the robot suffers from severe deadline misses, preventing the robot from well tracking the target.

The performance of the ideal feedback scheduler is shown in Figure 6. It can be seen from Figure 6 that the robot can track the target very well. The average tracking error
throughout the whole experiment is as small as 0.51mm. A comparison between Figures 6 and 5 reveals that feedback scheduling is effective in dealing with dynamic variations in system workload and thus enables flexible QoC management. With feedback scheduling, control performance guarantees can be achieved for systems operating under changing conditions.

To assess the performance of the FFS scheme, extensive simulations have been conducted for systems with measurement noises of different magnitudes. Some representative results are depicted in Figure 7. The moving tracks of the robot are the same as that in the case of ideal feedback scheduling and hence are omitted here. Figure 8 depicts the task periods for the case $r=0.1$. Clearly, the fuzzy feedback scheduler dynamically adjusts sampling periods at runtime, which is in contrast to the open-loop scheduling scheme that uses fixed sampling periods.

It can be seen from the above results and analysis that: 1) The proposed FFS scheme is capable of coping with uncertainties in resource availability; 2) It is robust to measurement
noises of different magnitudes; and 3) It can deliver system performance comparable to that of the ideal feedback scheduling scheme.

6. **Conclusion.** A fuzzy feedback scheduling scheme has been proposed to deal with the uncertainty in resource availability in embedded control systems. Featuring co-design of control and scheduling, the scheme integrates fuzzy control technology and feedback scheduling. The framework and the design methodology of the scheme have been described. Using the look-up table method, an intelligent feedback scheduling algorithm has been developed which incurs only a small computational overhead, is easy to implement, and can deal with measurement noises effectively. Unlike conventional feedback scheduling methods, the FFS scheme does not rely on the availability of task execution times and thus is a useful tool in practical embedded control systems.

**Acknowledgments.** This work is partially supported by the China Postdoctoral Science Foundation under grant number 20070420232, the Australian Research Council (ARC) under Discovery Projects grant number DP0559111, the Australian Government’s Department of Education, Science and Training (DEST) under International Science Linkages grant number CH070083, and the Natural Science Foundation of China under grant number 60774060.

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