An Integrated Control and Scheduling Optimization Method of Networked Control Systems

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Abstract Feedback control systems wherein the control loops are closed through a real-time network are called networked control systems (NCSs). The limitation of communication bandwidth results in transport delay, affects the property of real-time system, and degrades the performance of NCSs. An integrated control and scheduling optimization method using genetic algorithm is proposed in this paper. This method can synchronously optimize network scheduling and improve the performance of NCSs. To illustrate its effectiveness, an example is provided.

Key words networked control systems; genetic algorithm; network scheduling; transmission error

Modern computer and communication network technology has made it convenient to construct networked control systems. Feedback control systems wherein the control loops are closed through a real-time network are called networked control systems (NCSs)\textsuperscript{[1]}. NCSs exhibit the characteristics of high reliability, simple installation, low maintenance, good diagnostic capability, and low cost. Recently, the research of NCSs has been the focus of a large number of applied researches.

In NCSs, information such as sensor signals, controller signals and actuator signals are transferred through the interconnected network among control system components. The typical configuration of NCSs is shown in Fig.1.

When control and feedback signals transmit through the network, the network delay emerges unavoidably because of the limitation of network bandwidth and information collision. The network-induced delay affects the property of real-time system, and degrades the performance of NCSs. The performance of NCSs depends on control algorithms and real-time network scheduling. Therefore, the integrated method of control and scheduling should be considered when we design networked control systems. Control theory and real-time scheduling theory are relatively two independent subjects in the past. However, the integrated research of control and scheduling has recently received great attention\textsuperscript{[2~5]}. 

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In order to minimize the performance degradation of NCSs due to network delay, we use a new schedule to increase the system resource utilization. In this paper, genetic algorithm (GA) combined with rate monotonic scheduling (RMS) is used to optimize transmission periods and to improve the performance of NCSs.

1 Real-Time Scheduling Method of NCSs

1.1 Task Model of an NCS

The purpose of scheduling of NCSs is to assign the limited network resources to the control tasks, and to ensure that every control task in NCSs is completed by deadlines. In this study, we only consider linear plant and control with no actuator-plant communication and assume that the information of every NCS is sent in one pocket and network scheduling of NCSs is non-preemptive.

An NCS task can be characterized by a number of parameters, as shown in Fig. 2. The task model is described by a transmission period \(T_i\) between consecutive tasks releases, a deadline \(D_i\), an execution time \(C_i\), and worst time during which the task may be blocked \(B_i\).

![Fig.2 Some parameters for an NCS task](image)

Each NCS transmits its data during transmission period \(T_i\). If all transmissions are completed within their deadlines based on a scheduling algorithm, NCS transmissions are said to be schedulable and the transmission schedule is considered feasible.

1.2 Real-Time Scheduling

The scheduling in NCSs is to assign a transmission schedule to each node on the network. Because there are a lot of analogies between network scheduling and processor scheduling, the rate monotonic scheduling algorithm from processor scheduling is applied to schedule real-time network here[6]. When a set of distributed plants are connected over the real-time network, an NCS requiring higher transmission rate is given higher priority over a slower one based on the RM scheduling algorithm.

All of the non-preemptive periodic tasks in NCSs will meet their deadlines if the total utilization factor \(U\) of the network is below a certain bound. Control tasks can be feasibly scheduled by the RM algorithm.

\[
U = \frac{\sum_{i=1}^{n} C_i}{T_i} + \frac{B_i}{T_i} \leq n(2^\frac{1}{n} - 1) \quad i = 1, \cdots, n \quad (1)
\]

where \(B_i\) is the worst-case blocking time of the task.

2 Stability and Performance Index of NCSs

In NCSs, the transmission period \(T_i\), which relates to the control performance of NCSs, is identical to the sampling period. As transmission periods get smaller, network traffic becomes heavier, which may cause data dropout and longer delay. Lower bounds of transmission periods satisfy Eq. (1). As transmission periods get longer, the performance of NCSs gets worse. Zhang W developed the upper bounds condition of transmission periods in networked control systems to preserve system stability[3]. The upper bounds of transmission periods \(T_{up}\) can be easily calculated as follows

\[
T_{up} = \frac{1}{a} \ln \left( \frac{k}{a} + 1 \right)/\left(\frac{k}{a} - 1\right) \quad (2)
\]

The performance of a control system is measured by performance index, we select the relative error among transmissions as performance index of NCSs in this paper[2]. The transmission error \(e(t)\) of an NCS is given as follows

\[
e(t) = x(t) - x(t_i) \quad t \in [t_k, t_{k+1}] \quad (3)
\]

where \(x(t)\) is the vector of networked control systems, \(t_i\) \((k=0, 1, \cdots)\) is the sampling instant.

3 Scheduling Optimization Based on Genetic Algorithm

3.1 Model of Scheduling Optimization

The scheduling optimization of NCSs is to select an optimal feasible schedule, which minimizes system performance index. In this paper, the relative transmissions error \([e(t)]/[x(t_i)]\) of every NCS is chosen as performance index \(f_i(T_i)\). Real-time
scheduling and system stability constraints are selected as restriction conditions of NCSs optimization.

An integrated model of scheduling optimization of NCSs can be stated as

\[
\min f(T) = \sum_{i=1}^{n} f_i(T_i) \quad (4)
\]

subject to

\[
\begin{align*}
\frac{\sum C_i}{T_i} + \frac{B_i}{T} & \leq n(2^{T/2^l} - 1) \\
1 \leq i \leq n & \quad T_i \leq T_1 \leq \cdots \leq T_n \\
T_i & \leq T_{wp} - B_i \quad i = 1, \ldots, n
\end{align*}
\]

We need to solve \( T_i \) and reach the minimum performance index \( f(T_i) \) based on Eq.(5). This is a constrained optimization and nonlinear programming problem, which is difficult to solve by using general optimal methods because of their lower probability of getting extremes. Because GA is powerful and flexible in searching large spaces and different criteria, we use it to realize the integrated optimization of scheduling and control of NCSs.

### 3.2 Genetic Algorithm for Scheduling Optimization

#### 3.2.1 Gene Coding

GA works with a population of strings (chromosomes). The transmission periods of NCSs are coded as a string in this paper. The gene code is designed as shown in Fig.3.

**Fig.3 Gene coding**

\( T_i (i=1,2,\ldots,n) \) denotes the transmission period of every control subsystem with lower and upper bounds. Float-coding method is chosen to represent the real values of \( T_i \) with a chromosome. The length \( m \) of variable \( T_i \) is determined by the required precision.

#### 3.2.2 Fitness Function

The fitness function is a measure of the suitability of a string. A string with higher fitness value has a higher probability of contributing offspring in the next generation. The purpose of scheduling optimization in NCSs is to minimize the performance index \( f(T_i) \). In other words, the lower the \( f(T_i) \) is, the better the performance of NCSs. In this research, we define the fitness function as \( F = f(T_i) \).

#### 3.2.3 Genetic Operators

A simple GA consists mainly of selection, crossover and mutation. The selection operator determines which of the individuals will survive and continue on to the next generation. The proportional fitness assignment is performed here, the probability \( P_i \) is equal to \( f(T_i)/\sum f(T_i) \), where \( \sum f(T_i) \) is sum of fitness.

The crossover operator takes two chromosomes (parents) and exchanges part of their genetic information to produce new chromosomes (children). The offspring keeps some characteristics of their parents. The crossover operator involves the chromosomes cutting of the parents at a randomly chosen common point, and a constant probability is applied to the individuals. We use the one point crossover method. Mutation is a simpler operation where a new gene is derived from the original by inserting a random change in the value of one of the genes, one point method is used here.

### 4 A Case Study

An example of GA-based scheduling optimization is shown as follows. Consider three scalar plants represented by \( \dot{x} = ax + u \), \( u = -k_x \) (\( a_i = 20, 15 \) and 10, \( k_j = 45, 35 \) and 30). Assuming that every subsystem has the same performance, the execution time \( C_i \) of each subsystem is the same (4 ms)\(^3\), the fitness function of NCSs can be written as

\[
F = f(T_i) = \sum_{i=1}^{3} \beta_i e^{\lambda_i T_i} 
\]

where \( \beta_i = (-\bar{a}_i/a_i, \bar{a}_i = a_i - k_j) \). The parameters of three NCSs are summarized in Tab.1.

**Tab.1 NCSs parameters and optimization result**

<table>
<thead>
<tr>
<th>Loopi</th>
<th>( \bar{a}_i )</th>
<th>( \beta_i )</th>
<th>( B ) / ms</th>
<th>( T_{wp} ) / ms</th>
<th>( T_i ) / ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-25</td>
<td>1.25</td>
<td>4</td>
<td>55.757</td>
<td>14.249</td>
</tr>
<tr>
<td>2</td>
<td>-20</td>
<td>1.33</td>
<td>8</td>
<td>61.086</td>
<td>15.564</td>
</tr>
<tr>
<td>3</td>
<td>-20</td>
<td>2.00</td>
<td>8</td>
<td>69.341</td>
<td>16.815</td>
</tr>
</tbody>
</table>
This example is completed via simulation based on Matlab with the genetic algorithm toolbox\cite{7}. The function initialize ( ) is used to initialize the population, the chromosome is formed by a 15-bit string, the float-coding method is used to represent real values of the variable \( T_i \), and each chromosome is initialized randomly. The function arithXover ( ) and nonUnifMutate ( ) are used to perform crossover and mutation. The parameters for GA are listed in Table 2.

<table>
<thead>
<tr>
<th>String length / bit</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population size</td>
<td>50</td>
</tr>
<tr>
<td>Selection</td>
<td>( f(T_i) / \sum f(T_i) )</td>
</tr>
<tr>
<td>Crossover probability</td>
<td>0.85</td>
</tr>
<tr>
<td>Mutation probability</td>
<td>0.02</td>
</tr>
</tbody>
</table>

The minimum fitness after 100 generations evolved is \( F = f(T_1, T_2, T_3) = 7.984 \times 10^8 \), and the optimal transmission periods of three NCSs are 14.249 ms, 15.564 ms and 16.815 ms respectively. It is obvious from the simulation results in Table 1 that optimal transmission periods satisfy the network utilization factor equation. The optimal result with RMS constraint is strict and the transmission error of the NCSs is minimized. The optimal schedule based on GA improves the network resource utilization and performance of NCSs at the same time.

5 Conclusions

Based on the research result from Ref\cite{3}, this paper presents a GA-based scheduling optimization method to improve the performance of networked control systems. The transmission error of NCSs is used as performance function. Both scheduling and stability of NCSs are selected as restriction condition of optimization. An example demonstrates the effectiveness of the method. Future work will be conducted to study the effect of control performance using scheduling optimization method and to find the global scheduling solution for NCSs with multiple-pocket transmission.

References


Brief Introduction to Authors

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