15th Triennial World Congress, Barcelona, Spain

ANALYSIS AND HEURISTIC SCHEDULING FOR PERIODIC MESSAGES IN FF SYSTEM

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Abstract: The remote periodic message not only has timing constraints but also often has precedence constrains in Foundation Fieldbus system. In this paper, analysis and heuristic scheduling for remote periodic messages are proposed. Firstly, precedence constrains are considered and described by modifying release times and deadlines of remote periodic messages. Secondly, a heuristic algorithm for building FF schedule time list is proposed to find acceptable scheduling solutions by some simple strategies in order to meet these messages' timing constraints. Finally, an example of application shows the process of building FF schedule time list. *Copyright©2002 IFAC*

Keywords: FF schedule time list, precedence constraints, real-time communication, non-preemptive, heuristic algorithm.

1. INTRODUCTION[1]

The key to success in using a distributed real-time system for applications, such as industrial process control, automation manufacturing, and spaces vehicle system etc, is the timely execution of computation tasks that usually reside on different nodes and communicate with one another to accomplish a common goal. End to end deadline guarantees of these hard real-time tasks are possible only if a communication network support the timely delivery of inter-task messages (Kopetz, 1997; Buttazzo, 1997).

Foundation Fieldbus (FF), as one of the most popular infrastructure of communication to support real-time traffic among field devices such as sensors, acuators and controllers, is the standard developed by the Fieldbus Foundation. FF system sets the Function Blocks (FBs) down in field devices to perform control application, thereby, which realizes distributed process control really (Fieldbus foundation, 1996). At the same time, it brings forward the real-time communication requirements for some remote periodic message transfers which are used to refresh data of FBs input/output buffers, i.e., these messages are sternly demanded to successfully transferred to their destinations within a precise and bounded interval in order to guarantee FF control system run normally.

To support the timely transfer of the remote messages with timing constraints, FF protocol is based on a centralized communication media access control mechanism, where a link active scheduler (LAS), according to a schedule time list pre-defined, controls all remote message transfers between different field devices on a bus. These messages in the FF schedule time list are called as messages scheduled and have

[1] This work is supported by NSFC (60084001).

timing constraints (Yang, 1999). In order to meet timing constraints, it is crucial how to schedule these remote periodic messages, i.e., to build an effective schedule time list. To facilitate the description in following sections, remote periodic message scheduled is simply called periodic message.

So far, the majority of the methods to build schedule time list of Fieldbuses, such as WorldFIP and FF, have assumed that all periodic messages are independent, and are based on critical instant (Tovar, 1999; Wang, 2000). Critical instant is the time that all periodic messages simultaneously sent request to access the bus. It can occur for independent periodic messages and is the worst-case. However, the periodic message transfers have to consider precedence constraints caused by the execution sequence of FBs in FF systems. This means that all periodic messages cannot send simultaneously requirement to access the bus. Hence the methods based on critical instant to build FF schedule time list become pessimistic and unreasonable.

In this paper, analysis and heuristic scheduling for real-time communication messages in a single segment FF system are proposed. Firstly, periodic messages are modeled in section 2, in which precedence constrains are considered and described by modifying release times and deadlines. Secondly, a heuristic algorithm for scheduling all periodic messages is presented to find acceptable scheduling solutions by some simple strategies in order to meet these messages' timing constraints in section 3. Finally, an example of application shows the process of building FF schedule time list in section 4.

2. PERIOIDIC MESSAGES SET MODEL

2.1 Periodic message model considering precedence constraints

It is known that FF system is composed of interrelated and independent FBs to perform control functions desired. Moreover all field devices have a common sense of time, they can be cyclically scheduled to execute the FBs in a determined sequence and to publish their messages, which may be used by FBs located in other field devices, at a determined time. And these FBs will be executed only after the required inputs are scheduled to be available (Fayad, 2000).

The engineer only chooses FBs type, location and links by configuration pre-run-time to perform some control application. Fig.1.shows a cascade loop field devices configuration. There are 5 FBs (AI1, AI2, PID1, PID2, AO), 3 external links (Mp1, Mp2, Mp3) and 3 internal links in 3 field devices in this configuration. Each external link corresponds to a periodic message. Local periodic message corresponding to internal link is dealt with in local and is not transmitted in bus, so it is not considered in this paper.

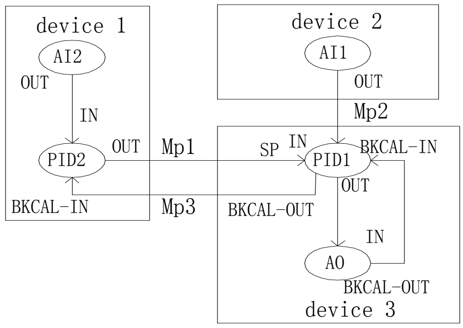

Fig.1. A cascade loop field devices configuration

From Fig.1, PID2 is executed after AI2 finishes, then, message Mp1 sends request to access the bus, i.e., message Mp1 is released; after PID2 and AI1 finish, and message Mp1and Mp2 arrive device3, PID1 will be executed. This means that all messages cannot be simultaneously released. Hence the precedence constraints of periodic messages have to be considered in the process of building the schedule time list.

To solve precedence constraints, an algorithm was presented (Chetto, et al., 1990). The base idea of their approach is to transform a set J of dependent tasks into a set J* of independent tasks by an adequate modification of timing parameters. The transformation algorithm ensures that J is schedulable and the precedence constraints are obeyed if and only if J* is schedulable.

Therefore, according to the requirement of control system, the control scan time, i.e., period of each control loop, is set. Then, considering their execution sequence, execution time and external links, FBs' start times are set and referred to system management, which will not be introduced in this paper. After FBs' start times were set, release time at which message send requirement to access the bus, and deadline for each periodic message should be modified to meet precedence constraints.

Without loss of generality, a single segment of FF has n devices, mp FBs, and np periodic messages. Moreover, the start time and execution time of each FB are known. In this case, Rp_i and Dp_i of periodic message Mp_i are modified as,

$$Rp_i = S_{FBj} + C_{FBj}, \forall i : FB_j \rightarrow Mp_i \quad i = 1,\ldots,np, and \quad j = 1,\ldots,mp \tag{1}$$

$$Dp_i = \min(S_{FBj}), \forall j : Mp_i \rightarrow FB_j \quad i = 1,\ldots,np, and \quad j = 1,\ldots,mp \tag{2}$$

Where $FB_j \rightarrow Mp_i$ denotes that Mp_i is released by FB_j, S_{FBj} and C_{FBj} denote the start time and execution time of FB_j respectively, $Mp_i \rightarrow FB_j$ denotes Mp_i is received by FB_j, of course, a periodic message can be received by several FBs simultaneously. Equation (1) and (2) mean, for all periodic messages, the release time Rp_i of periodic message Mp_i is equal to the end time of the FB producing Mp_i, at the same time, the deadline Dp_i of Mp_i is equal to the earliest start time of the FBs receiving Mp_i.

Therefore, considering timing constraints and precedence constraints, each periodic message can be described as,

$$Mp_i = (Rp_i, Cp_i, Tp_i, Dp_i), \quad i = 1,\dots,np \qquad (3)$$

Where Rp_i, Cp_i、Tp_i and Dp_i denote the first release time, maximum transfer time, period (which is equal to control scan time of the control loop in which Mp_i lies) and the first deadline of periodic message Mp_i.

From above, the periodic message in same control loop may be look as independent by modifying their release time and deadline. And the periodic messages between different control loops are also independent. Thus, all periodic messages will be look as independent in following sections. The FF schedule time list will be built based on independent messages, but not on critical instant.

2.2 Periodic Messages set model

Definition 1: Macrocycle. It is the lease common multiple of period of all periodic messages.

As before, LAS will cyclically schedule all periodic messages according to a pre-defined schedule time list. The cyclic interval is the macrocycle, which regulates the size of the list and adequately reflects the periodic messages scheduling.

Thus, each periodic messages Mp_i will be scheduled $n_i = Macrocycle / Tp_i$ times in a macrocycle, and the model of its j[th] time scheduling is described as,

$$Mp_{ij} = (Rp_{ij}, Cp_{ij}, Dp_{ij}) \qquad (4)$$

Where the j[th] release time Rp_{ij}, transfer time C_{ij} and the corresponding deadline Dp_{ij} of periodic messages Mp_i are described as,

$$\begin{cases} Rp_{ij} = Rp_i + (j-1)Tp_i, \\ Cp_{ij} = Cp_i, \\ Dp_{ij} = Dp_i + (j-1)Tp_i, \end{cases} \quad j = 1,\dots,n_i \qquad (5)$$

The total number of messages scheduled in a macrocycle is,

$$n_m = \sum_{i=1}^{np} n_i = Macrocycle \times (\sum_{i=1}^{np} \frac{1}{Tp_i}) \qquad (6)$$

It is the periodic messages set M that consists of these messages,

$$M = \{m \mid m = Mp_{ij}, i = 1,\dots,np, j = 1,\dots,n_i\},$$
$$m = (R_m, C_m, D_m) \qquad (7)$$

Where R_m, C_m、and D_m denote the release time, maximum transfer time, and deadline of message m.

3. HEURISTIC SCHEDULING ALGORITHM

Definition 2: Schedulable message. When following properties simultaneously come into existence,

(1) The bus is idle at current time t;
(2) Message m has already be released at time t;
(3) Message m will meet the requirement of its deadline if it is started to execute at time t;
(4) Message m will not affect the requirement of other messages' deadline if it is started to transmit at time t.

The message m is schedulable at current time t.

From definition 2, the state $s_m(t)$ of message m is described as,

$$s_m = \begin{cases} 0: m\ cannot\ be\ schedulable\ at\ time\ t \\ 1: m\ \ is\ schedulable\ \ at\ time\ t \\ 2: m\ \ is\ being\ transmitted\ at\ time\ t \end{cases} \qquad (8)$$

Definition 3: Schedulable set $S_1(t)$ at time t, $S_1(t) = \{m \mid (s_m(t) = 1) \cap (m \in M)\}$, consists of the messages which are schedulable at time t;

Non-schedulable set $S_0(t)$ at time t, $S_0(t) = \{m | (s_m(t) = 0) \cap (m \in M)\}$, consists of the messages which cannot be schedulable at time t.

It is known that scheduling messages (packets) for transmission is different from scheduling tasks. A message (packet) transmission cannot be preempted (Krishna and Shin, 1997). In FF system scheduling the periodic messages for transmission is non-preemptive. That is, a message, once started, is transmitted on bus until completion. If it, started to transmit at time t, message m will affect the requirement of other messages' deadline. This means that message k is released before and while m is transmitting, but k will not meet its timing constraint if it is started to transmit after m. In correspondence to this, we introduce blocked set $\mathrm{I}m(t)$.

Definition 4: Blocked set $\mathrm{I}m(t)$. It consists of all messages that will not meet their timing constraints if m is transmitted at time t, and which is described as,

$$\begin{aligned} \mathrm{I}m(t) = \{k \,|\, &[(R_m < R_k < B_m + C_m) \cup (R_k \ge R_m)] \\ &\cap (B_m + C_m + C_k > D_k)_{|s_m(t)=2}\} \end{aligned} \quad (9)$$

Where B_m is the instant m starts to transmit. Of course, the state of m at time t is not schedulable currently, that is, $s_m(t) = 0$.

Definition 5: Allowed waiting time $W_m(t)$. It is the time message m can be delayed on its buffer from current time t to complete within its deadline, which is described as,

$$W_m(t) = D_m - C_m - t \quad (10)$$

In this paper, the method to schedule all periodic messages is based on heuristic algorithm. The purpose is to find acceptable scheduling solutions by some simple strategies in order to meet these messages' timing constraints. The process can be performed by following steps:

S1: Let $t = 0$, the bus is idle. And set up two sets: $S_0(t)$ and $S_1(t)$. If $t > Marcocycle - \sum C_m$, where $m \in (S_0(t) \cup S_1(t))$, end the process and return that the messages set is not schedulable; Or else, it continues.

S2: If $S_1(t) \ne \phi$, turn to S7; Or else, turn to S3.

S3: Let $r = \min(R_m)$, where $m \in S_0(t)$, and let $m^* = m$, where $R_{m^*} = r$. Set current time $t = \max\{t, r\}$, and update $S_0(t)$ and $S_1(t)$. If $t > Marcocycle - \sum C_m$, where $m \in (S_0(t) \cup S_1(t))$, end the process and return that the messages set is not schedulable; Or else, it continues.

S4: If $S_1(t) \ne \phi$, turn to S7. Or else, that is, $S_1(t) = \phi$ and $\mathrm{I}m^*(t) \ne \phi$, turn to S5.

S5: Let $r = \min(R_k)$, $k \in \mathrm{I}m^*(t)$, and $m^* = k$, where $R_{m^*} = r$. Set current time $t = \max\{t, r\}$, update S_0 and S_1. If $t > Marcocycle - \sum C_m$, where $m \in (S_0(t) \cup S_1(t))$, end the process and return that the messages set is not schedulable; Or else, it continues.

S6: If $S_1(t) \ne \phi$, turn to S7; Or else, delete m^* from the set $\mathrm{I}m^*(t)$, i.e. $\mathrm{I}m^*(t) = \mathrm{I}m^*(t) - \{m^*\}$, and turn to S5. Until $\mathrm{I}m^*(t) = \phi$, end the process and return the messages set is not schedulable.

S7: In set $S_1(t)$, according to following priority rules,

Rule 1. Select the messages whose allowed waiting time $W_m(t)$ is minimum.

Rule 2. Select the messages whose transfer time C_m is the shortest.

Rule 3. Select at will.

Select message m, arrange to schedule it at current time t, and set m is $s_m(t) = 2$. And delete m from set $S_1(t)$.

S8: Compute the finish time of m, $f_i = t + C_m$, and set current time $t = f_i$, update $S_0(t)$ and $S_1(t)$. If $t > Marcocycle - \sum C_m$, where $m \in (S_0(t) \cup S_1(t))$, end the process and return that the messages set is not schedulable; Or else, it continues.

S9: If $S_0(t) \cup S_1(t) = \phi$, end the process and build FF schedule list with success；Or else, turn S10.

S10: If $S_1(t) \neq \phi$, turn to S7；Or else S3.

Thus, according to the heuristic algorithm proposed, all scheduling times, i.e. the start instants when these messages are transmitted, compose a schedule time list, which is referred to the LAS.

In S7, Rule1 assigns priorities to messages according to allowed waiting time at time t. Messages with shorter allowed waiting time at time t will have higher priorities. Rule2 lets the message with shorter C_m, that is, with earlier deadline, be transmitted as earlier as possible.

Note that, if one or more messages in the message scheduled set are not scheduled by using the algorithm, it is necessary to reset the start time of FBs, to change the place of FBs, or to turn the single segment into multi-segment FF system.

4. AN EXAMPLE OF APPLICATION

Considering a single segment FF system shown in Fig.2, 3 independent control loops consist of 11 FBs in 7 field devices. 6 periodic messages, corresponding with 6 external links, need real-time communication.

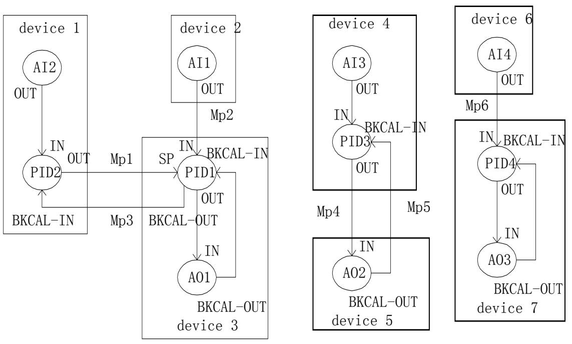

Fig.2. A single segment FF system configuration

As before, considering execution sequence, execution time and external links, FBs start times are set. Then, release time and deadline for each periodic message should be modified, and the periodic message model considering precedence constraints will be obtain. Table 1 shows the time parameters of 6 periodic messages.

Table 1 Time parameters of periodic messages

Message	Rp_i /ms	Cp_i /ms	Dp_i /ms	Tp_i /ms	T_{Si} /ms
Mp1	100	20	152	300	32
Mp2	35	20	152	300	97
Mp3	240	20	300	300	40
Mp4	100	15	150	200	30
Mp5	170	15	200	200	15
Mp6	20	15	35	100	0

Then, there are 18 messages which will be scheduled in a macrocycle. Applying the heuristic algorithm proposed in this paper, the schedule time list is built and the scheduling process within a macrocycle is shown in Fig.3

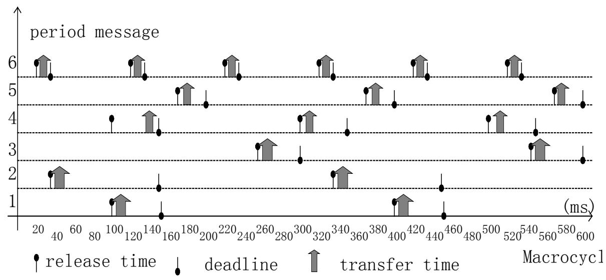

Fig.3. Scheduling process of messages

5. CONCLUSIONS

In this paper, analysis and heuristic scheduling for all remote periodic messages in a single FF system are proposed. Precedence constrains are considered and described by modifying release time and deadline. The heuristic algorithm for building FF schedule time list is presented to meet timing constraints Finally, the building process of the list is showed by an example of application, which will be useful to engineers and researchers.

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