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Timed synthesis control approach for tolerant-fault control of Discrete Event Systems (DES)

I. Tahiri^{1&2}, A. Philippot¹, V. Carré-Ménétrier¹

¹Research Centre in Information and Communication
Science and Technology (CReSTIC)
University of Reims Champagne Ardenne (URCA),
FRANCE

imane.tahiri@univ-reims.fr, alexandre.philippot@univ-reims.fr,
Veronique.carre@univ-reims.fr

A. Tajer²

² LGECoS Laboratory
University Cadi Ayyad - ENSA Marrakech, MOROCCO
a.tajer@uca.ma

Abstract— This paper presents an approach of a safe control synthesis of Timed Discrete Event Systems, based on timed properties. This synthesis aims to realize a fault-tolerant control during the detection of sensor faults. To establish this synthesis, the proposed approach relies on the modularity of the manufacturing systems to avoid the combinatorial explosion recurrent to several approaches. An example of a manufacturing system illustrates our remarks.

Keywords— *Timed discrete event systems, supervision theory, fault tolerant control, distributed control, manufacturing systems, modeling.*

I. Introduction

A Discrete Event System (DES) is defined as a dynamic system that can be described in a discrete state space and whose evolution is described by state transitions triggered by events [1]. One of the recurring problems with these systems is the establishment of an adequate control law that guarantees the safety of equipment and personnel while performing the tasks required. In [2], Ramadge and Wonham (R&W) initiated the Supervisory Control Theory (SCT) of DES (fig.1).

Fig. 1. Supervisory Control Theory principle

This approach consists of determining a controller (called supervisor) which has the effect of restricting all possible states of the system to a subset of permissible states. R&W use finite state machines (FSM) and languages to model these systems. Although this approach is very formal, it shows a major disadvantage of its use on complex systems: the combinatorial explosion. In [3], [4], [5], [6] and [7], some approaches for control synthesis of DES have been proposed to overcome this problem. Although these approaches may have reduced the combinatorial explosion problem, they nevertheless remain dependent on Boolean information. But it is not the only information present when we consider time. This is called Timed Discrete Event Systems (TDES).

Several approaches of literature [8], [9], [10] and [11] use timed automata, Petri nets, or finite state machines as a TDES modeling tools. In these works, time is modeled in two ways:

- The discrete time, for which the progression of time is discrete and measured by a digital clock which is incremented by one unit at a time.
- The dense time, for which the progression of time is continuous and measured by clocks taking positive real values.

However, taking into account the passage of time makes the modeling step as well as the synthesis of the control by supervision more complex. To overcome these difficulties, we propose an extension of control synthesis approach proposed in [5] by exploiting its distributed design and introducing the time factor in the first stages of modeling.

The purpose of this proposal is to construct a control structure that can be used as a fault-tolerant control. Indeed, many industrial applications require fault tolerance and continuity of service. Therefore, some strategies are defined from the earliest stages of the control design to facilitate the detection of faults, their location and the control reconfiguration. Several approaches have been proposed to overcome this problem. In [12], the authors have defined a switch control formalism that revises the controller parameters when a change of an embedded sensor network occur or when it's repaired. The DES and its specification controller are modeled by a finite state machine. A mega-controller changes in the observation chains and selects the appropriate logic controller when changes occur. In [13] a reconfiguration approach based on supervisory control theory (SCT) was developed, the authors proposed a procedure based on SCT to reconfigure the controller without reconstructing its complete design. The reconfiguration keeps the behavior that does not change, eliminates the one that becomes useless after a faulty evolution, and adds the new updated behavior. Subsequently, the SCT ensures that the specifications are respected if a control synthesis is applied. Therefore, a partial reconfiguration using the SCT continues to adhere to the specifications that have not changed and ensures that the updated ones are also complied with in the new control law. In [14] a generic plant model of a

DES that generates two behaviors is formulated: a nominal one and a failing one under a set of functional specifications and security constraints. The approach proposed an active fault-tolerant control architecture such that the supervisor actively responds to faults as follows: (i) Design a nominal supervisor imposing faultless specifications, (ii) Design a diagnoser that unambiguously detects faults, and finally (iii) plant automatic switching to the second supervisor after a fault detection such that the system continues to operate safely.

However, the use of these different methods is not easy. Indeed, the construction of fault-tolerant supervisors is a difficult task when the models to be treated are presented under a large size. This disadvantage is generally due to the fact that most of the approaches proposed in the literature for fault-tolerant control have been developed for systems where the information used is decentralized, centralized or hierarchical. However, the majority of manufacturing systems, are informally distributed.

Therefore, our contribution will be a fault-tolerant control method (fig.2). based on this axis of distributivity. When a sensor fault appears thanks to the diagnostic module, the information lost on a sensor will be replaced by a timed information through a coordinator that allows the switch between the distributed controller (G_{DCi}) interpreted by a grafset modelling (IEC 60848) of the normal behavior mode and the reconfigured one (G_{TDCi}) in order to guarantee the continuation of the plant tasks in spite of the faults which may hinder its normal functioning. The diagnoser and coordinator determination is not the aim of this work, so we opt for the approach evoked in [15] to diagnose our system, and a method for determining the coordinator will be proposed in future works.

Fig. 2. A fault-tolerant control loop

The proposed approach consists of the following steps (Fig. 3):

1. Modular and timed plant modeling: the resulting automaton is a timed plant element $G_{(TPE)}$.
2. Definition of local functional and safety constraints in order to synthesis a local controller: the resulting automaton is a timed local controller $G_{(TLC)}$.
3. Taking into account overall behavior constraints to determine timed distributed controllers: the resulting automaton is a $G_{(TDC)}$.

4. Interpretation of timed distributed controllers into grafcet specification and their implementation in a programmable logic controller (PLC) through a standard language (IEC 61131-3).

The paper is organized as following: Each step of the proposed approach is described in Section 2. Section 3 illustrates our results around a transfer system benchmark. Conclusions and discussion close the paper in section 4.

II. Basic Concept of Distributed Approach of TDESSs

A. Synthesis of timed local supervisory control

Based on works evoked in [5] and [16], we propose an extended approach to synthesis timed local controllers TLC, with a method allowing their obtaining using Supremica software by the following steps:

- Define the timed plant element (TPE) automaton $G_{(TPE)}$.
- Define an extended model of $G_{(TPE)}$.
- Define the set of local specifications.
- Synthesize the timed local controllers $G_{(TLC)}$.

Fig. 3. The proposed distributed supervisory control architecture

The timed plant modeling is an extension of the practical model [17] that describe the most respectful behavior of a component by introducing time.

A Plant Element (PE) is obtained by a synchronous composition of detector, pre-actuators and actuators models. Each PE does not always have a set of detectors sufficient to be described. Therefore, a timed detectors models are introduced. It is then necessary to determine a timed actuators models.

Formally, if the timed detectors model is modeled by an automaton $G_{(TD)}$ and the timed actuators model is defined by an

automaton $G_{(TA)}$, The TPE automaton' model is obtained by a synchronous composition of these two models:

$$G_{(TPE)} = (S, \Sigma, T, D, \delta, s_0, S_m) = G_{(TD)} \parallel G_{(TA)}$$

With:

- S : Finite set of states
- Σ : Finite set of events such as: $\Sigma = \Sigma_c \cup \Sigma_{uc}$. With:
 $\Sigma_c = \uparrow\downarrow Z \cup \uparrow\downarrow T \cup D$ and $\Sigma_{uc} = \uparrow\downarrow E$
 $\uparrow\downarrow Z$: Set of activations and deactivations of control orders z_i (actuators outputs).
 $\uparrow\downarrow E$: Set of rising and falling edges of inputs variables e_i (sensors inputs).
 $\uparrow\downarrow T$: Set of activations and deactivations of clocks T_i .
With: $\Sigma_{nT} = \uparrow\downarrow Z \cup \uparrow\downarrow E$ set of not-timed events, and $\Sigma_T = \uparrow\downarrow T \cup D$ set of timed events.
- T : Set of clocks, such as $T = \uparrow t_i \cup \downarrow t_i$.
- D : Finite set of durations d_i associated to each clock t_i , such as $D = \{d_1, d_2, \dots, d_i\}$.
- δ : Transition function. A transition is defined by: $\delta(s_1, \sigma) = s_2$ such that s_1 is the initial state and s_2 is the final state. σ is the occurrence of a timed event or not of Σ .
- s_0 : Initial state
- S_m : Set of marked states

Once $G_{(TPE)}$ is obtained, its extended automata is determined through an Extended Finite State Machines EFSM generated by supremica [16]. Differently to finite state machines (FSM), EFSM uses variables, guards and actions that can help the operator to compactly represent a large and complicated DES. Guard expressions are used to restrict the behavior of the system and action functions are used to update variables. The resulting extended automata of $G_{(TPE)}$ generated by supremica is noted $G_{(TPE_curr)}$.

A TLC is obtained using models of the TPE and its associated set of specifications, such that it is minimally restrictive with respect to the plant behavior, while still guaranteeing that the specifications are upheld.

These specifications are defined by a logical implication in the form of:

$$x \Rightarrow \bar{y} \quad (1)$$

With $x \in S_i$ and $y \in \Sigma_c$.

The implication (1) means that if x is true then y is forbidden, which is proved that can be also interpreted in the following form [18]:

$$x \cdot y = 0 \quad (2)$$

In this paper we choose equation (2) to interpret the set of specifications related to each TPE, and for an implementation purpose, the set of specifications is defined as an (EFSM) as shown in fig.4.

Fig. 4. EFSM specification example

The EFSM specification is composed of a single state and a self-loop transition. A guard " $G_{(TPE_curr)} \neq x$ " (the current state is different to x) is associated to the transition labeled with event y , the transition is enabled if and only if the guard formula is true. And by applying the synthesis of supervisory control on supremica of the two automata presenting $G_{(TPE)}$ and specifications, we obtain a $G_{(TLC)}$.

B. Synthesis of timed global supervisory control

To pass from a TLC to a timed distributed controller (TDC), it is necessary to go through two steps: the first one is the aggregation of the controllable events in macro-states and the second one is the integration of the functional and security constraints of the overall behavior. An extract of a TLC automaton is shown in fig.5.

Fig. 5. Extract from a timed local controller automaton $G_{(TLC)}$

The aggregation of a TLC is carried out in two steps:

Step 1: Associate the states reached by the controllable events ($\uparrow\downarrow z_i \in \{\Sigma_c \cap \Sigma_{nT}\}$) in macro-states linked by uncontrollable events ($e_i \in \Sigma_{uc}$), and timed events: ($\uparrow\downarrow t_i \in \Sigma_T$) $\cup$ ($d_i \in \Sigma_T$). If the TLC' state is associated to a rising edge of a controllable event, then the order is authorized and belongs to the set Ord . If it's associated to a falling edge of this event then the order is inhibited and belongs to the set Inh .

Step 2: Aggregate timed events $\uparrow\downarrow t_i$ in macro-states linked by uncontrollable events ($e_i \in \Sigma_{uc}$) and timed events d_i . If the state of the timed local aggregated controller by the first aggregation is reached by an event corresponding to the clock' activation, then this event belongs to a set noted A_{clock} . If it is reached by an event corresponding to the clock' deactivation, then this event belongs to a set noted D_{clock} . The self-loop transition will be the transition that links the two macro-states that contain the two sets (A_{clock} and D_{clock}). The resulting automaton is the timed local aggregated controller called TLAC. An extract of TLAC automaton is shown in fig.6.

Fig. 6 Extract from a timed local aggregated controller automaton $G_{(TLAC)}$

The TLCs behave locally while respecting local security constraints. In order for these controllers to communicate and synchronize with each other, a set of global functional and security constraints must be determined in order to obtain timed distributed controllers TDC able of behaving in both local and global contexts, while ensuring the security of each plant element. A global constraint is modelled as follows:

$$\text{If } a \text{ then } \begin{cases} b = 1 \\ b = 0 \end{cases}$$

If “b” is allowed and belongs to the set Ord, then (b=1) if and only if the condition “a” is true.

If “b” is inhibited and belongs to the set Inh, then (b=0) if and only if the condition “a” is true.

A TDC automaton is formally defined by: $G_{(TDC)} = (S_{(TDC)}, \Sigma_{(TDC)}, D_{(TDC)}, \delta_{(TDC)}, E_{(TDC)}, C_{(TDC)}, S_0(TDC), S_m(TDC))$, with:

- $S_{(TDC)}$: Finite set of states.
- $\Sigma_{(TDC)}$: Finite set of events such as $\Sigma_{(TDC)} = \{\Sigma_{uc(TDC)} \cup \Sigma_{c(TDC)}\} = \{\Sigma_{T(TDC)} \cup \Sigma_{nT(TDC)}\} \neq \emptyset$.
- $D_{(TDC)}$: Finite set of durations d_i associated to each clock t_i .
- $\delta_{(TDC)}$: Transition function. A transition is defined by: $\delta(s_1, \sigma) = s_2$ such that s_1 is the initial state and s_2 is the target state. σ is the occurrence of a timed event d_i or uncontrollable event e_i .
- $E_{(TDC)}$: Set associated to each state of $S_{(TDC)}$, $E_{TDC}^{s_i} = \{Ord^{s_i}, Inh^{s_i}, A_{clock}^{s_i}, D_{clock}^{s_i}\}$.
- $C_{(TDC)}$: Finite set of constraints allowing authorization or inhibition of an order z_i .

The example of Fig.7 illustrates a TDC automaton. Each rectangle represents a state with its associated actions (authorised and inhibited orders), clocks (activated and deactivated clocks), and conditions, if any.

Fig. 7. Example of a timed distributed controller automaton $G_{(TDC)}$

The set of $S_{(TDC)}$ states is defined by $\{s_0, s_1, s_2\}$, the initial state $s_0(TDC)$ is identified by an incoming arrow. $\Sigma_{(TDC)} = \{\Sigma_{T(TDC)} \cup \Sigma_{nT(TDC)}\}$ with $\Sigma_{nT(TDC)} = \{\uparrow \downarrow e_0, \uparrow \downarrow z_0\}$ is the set of non-timed events and $\Sigma_{T(TDC)} = \{\uparrow \downarrow t_0, d_0\}$ is the set of timed events. $E_{TDC}^{s_0} = \{z_0, \emptyset, \emptyset, \emptyset\}$, $E_{TDC}^{s_1} = \{\emptyset, \emptyset, t_0, \emptyset\}$, $E_{TDC}^{s_2} = \{\emptyset, z_0, \emptyset, t_0\}$. Empty actions, clocks and conditions are not represented.

C. Grafset interpretation of the TDC

For an implementing purpose of timed distributed controllers in a PLC, an approach is followed to translate them into grafset language.

The clock activation ($A_{clock: t_i}$) is translated by a timed action t_i , associated to the grafset step X_i , and the duration d_i is transformed into transition receptivity after X_i . The clock deactivation is not introduced in the grafset because once the

duration elapses, it causes the passage to the next step X_{i+1} . An example of this interpretation is shown in Fig. 8

Fig. 8. example of timed distributed controller interpretation

III. Application to a manufacturing system

To illustrate our contribution, we use 3D FACTORY I/O simulator (<https://factoryio.com/>). It's a digital twin for learning automation technologies, designed to be easy to use, it allows to quickly build a virtual factory using a selection of common industrial parts. FACTORY I/O also includes many scenes inspired by typical industrial applications, ranging from beginner to advanced difficulty levels. Using this tool, we built a boxes transfer system (fig.9), which is composed of:

Fig. 9. The manufacturing systems

- Two pushers (monostable single effect cylinders): The first one (P_1) pushes boxes in front of the second one (P_2) which transfers them to the evacuation conveyor.
- Two conveyor belts, to transport boxes in front the pusher P_1 , and to evacuate them to the stock.
- Six sensors: $\{e_0, e_1\}$ sensors for the presence of a box in front of the pushers, $\{e_2, e_4\}$ sensors associated to the pushers input, and $\{e_3, e_5\}$ sensors associated to the pushers output.
- A start' push button Pb_{Start} .

In this example we assume that the sensor e_3 don't work anymore and must be replaced by a timed information. the element that allows us to ensure this information is the clock t_1 . In the following figure (fig.10) we present the two models of the system with and without sensor e_3 . We then show that the information lost on e_3 due to a fault is replaced by a clock. the flow of the predetermined duration means that the pusher has reached its final output position.

In order to obtain a timed local controller that describes the desired local behavior, some functional specifications must be determined:

- **First specification:** The deactivation of P is due to the clock deactivation, so $\downarrow P$ must be forbidden to appear in state s_1 and s_3 . This specification is defined by the following equation (3).

Fig. 10. Timed plant element automaton corresponding to the pusher 1 $G_{(TPE)P1}$

$$(s_1 + s_3) \cdot \downarrow P_1 = 0 \Leftrightarrow \begin{cases} s_1 \cdot \downarrow P_1 = 0 \\ s_3 \cdot \downarrow P_1 = 0 \end{cases} \quad (3)$$

The automaton that translates this specification is shown in fig.11.

Fig. 11. Specification 1 automaton

The figure above shows that if the current state of $G_{(TPE)P1}$ is different from s_1 and s_3 , then $\downarrow P_1$ is allowed to appear.

- **Second specification:** The deactivation of t_1 is due to the sensor e_1 deactivation, so $\downarrow t_1$ must be forbidden to appear in state s_5 . This specification is defined by the following equation.

$$s_5 \cdot \downarrow t_1 = 0 \quad (4)$$

The automaton that translates this specification is shown in fig.12.

Fig. 12. Specification 2 automaton

Applying these two specifications, the two transitions associated to $\downarrow P_1$ and outgoing from s_1 and s_3 , and the transition associated to $\downarrow t_1$ and outgoing from s_5 are deleted. Consequently, the state s_4 becomes inaccessible and will be also deleted. The timed local controller describing the desired behavior obtained is shown in figure 13.

Fig. 13. The timed local controller automaton of pusher 1, $G_{(TLC)P1}$

Applying the untimed and timed aggregation explained in previous sections, we obtain the following automaton:

Fig. 14. Timed local aggregated controller of pusher 1 $G_{(TLAC)P1}$

In the initial state s_0 , P_1 is authorized and belongs to the set Ord of the authorized events, the deactivation of e_1 causes the activation of the clock t_1 , this activation is aggregated in a macro-state s_1 and belongs to the set A_{clock} of clocks activation. After the flow of the duration d_1 associated to the clock t_1 , t_1 will be deactivated and will cause the deactivation of P_1 . Therefore, in the state s_2 , t_1 will belong to the set D_{clock} (set of clocks deactivation) and P_1 will belong to the set Inh (Set of inhibited orders).

To be able to obtain the distributed controller corresponding to the pusher P_1 , the overall functional and security constraints must be taken into account. The pusher must push out if a piece is present ($e_0 = 1$), but to guarantee the safety, it must be verified that the pusher 2 is in the retracted position which is ensured by ($e_4 = 1$). Therefore, these constraints will be translated by the following equation:

$$\text{If } (e_0 \cdot e_4) \text{ then } P_1=1 \quad (5)$$

Taking into account this specification, we obtain the following timed distributed controller automaton $G_{(TDC)P1}$.

Fig. 15. Timed distributed controller of pusher 1

If the overall behavior specifications are verified, the output of pusher P_1 is allowed, which causes the deactivation of sensor e_1 associated to P_1 input. Once e_1 is deactivated, the clock is activated until the passage of the duration d_1 which leads to t_1 and P_1 deactivation. Therefore, P_1 returns to its initial state and e_1 will be reactivate.

The grafcet equivalent of this TDC automaton is shown in fig 16.

Fig. 16. Grafcet interpretation of $G_{(TDC)P1}$

IV. Conclusion and prospects

In this work we have proposed a new approach of integrating time in order to synthesis a timed distributed control for discrete event systems DES. This control synthesis aims at achieving a fault-tolerant control during the detection of a sensor fault through the diagnoser. A decision block decides whether the fault is tolerable or not. If it is tolerable, a reconfiguration where the information lost on the sensor is replaced by a timed information is necessary. Our timed distributed control is based first on a timed modelling of each plant element, the second step is determining the different timed local controllers by taking account the local functional and security constraints. In order to define timed distributed controllers, the overall functional and security constraints should be verified. The resulting controllers are interpreted into grafcet language for an implementation purpose. In our short-term works, a formal method to determine the coordinator that allows the switching between the normal behavior controller to

its equivalent reconfigured behavior controller will be proposed.

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