Conférence Internationale en Automatique & Traitement de Signal (ATS-2017)
Proceedings of Engineering and Technology – PET
Vol.23pp.57-61

Robust Control facing disturbances: Application to a coil winding machine

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***Abstract*— Manufacturing and modern production systems offer high flexibility and various benefits in order to deliver the required production rates, a higher products quality, while minimizing the use of resources. In such systems, time control is a very important area. In this study a robust control strategy towards time disturbances is presented. It consists of generating by the control a temporal shift similar to the disturbance in order to avoid the death of marks on the levels of synchronization transitions of the P-time Petri net model. A computing algorithm allowing the application of the proposed approach at various graph nodes is established. Finally, to illustrate the effectiveness and accuracy of proposed robustness approach, an application to a coil winding unit is outlined.**

***Keywords*— Robustness, time disturbance, P-time PNs, coil winding machine**

I. Introduction

Manufacturing workshops, rail or road transport networks and computer networks can be considered as Discrete Events Systems (DES). However, the discrete nature of flows run does not exclude the existence of schedules to respect, delivery and expiry dates. All these temporal constraints are generally characterised by a minimum and a maximum time constraints assigned to an operation or a state.

The processes control must guarantee, for each operation, the specifications of operational durations in order to ensure the conformity of the product and the production rate. Such systems have a robustness property in order to maintain product quality when there are time disturbances. The robustness is defined as the ability of the system to preserve the specifications facing some expected or unexpected variations. So, the robustness characterizes the capacity to deal with disturbances. In this context, the work presented attempt to build a robust control approach facing time disturbances.

The paper is organised as follows. The first section is dedicated to the presentation of the coil winding unit. The latter is used as a case study modelled by P-time Petri nets. The following section is divided into two parts. The first performs some reminders on the definitions of robustness of the DES with time constrains. The second presents the approach for robust control. This strategy consists of generating by the control a temporal shift similar to the disturbance in order to avoid the death of marks on the levels of synchronization transitions of the P-time Petri net model. Finally, an application of the control strategy to coil winding machine is outlined.

II. Relevant Literature

There has been much research considering the robustness control of manufacturing systems in order to save time and to ameliorate service quality.

Riera [1] presents an original approach for safe control synthesis of manufacturing systems. This approach is based on the use of a logic filter (placed at the end of PLC (Programmable Logic Controller)) robust to control errors, and formally validated using a model checker. The proposed approach, which separates the functional control part from the safety control part, is simple to implement and ensures that the designed controller is safe.

To model the robustness of manufacturing system in design, Gao [2] proposes a new approach. Firstly, a metric model for the index of manufacturing system robustness is built based on the information axiom and independence axiom of Axiomatic Design. Next, the quantitative computation approach of manufacturing system robustness by means of fuzzy theory is achieved. Benderbal [3] considers the design problem in Reconfigurable Manufacturing System (RMS) and introduce a new index of system robustness. They present a new approach of RMS design to ensure the best process plans by selecting the best set of machines from a set of available ones. The approach is based on an adapted non-dominated sorting genetic algorithm (NSGA-II) guided by the minimization of two objectives which are the total completion time and the perturbation caused by the unpredicted unavailability of selected machines (caused by failure, maintenance, human or technological errors...).

Other control approaches and applications can be found in Mhalla et al. [4], Li al. [5], Yue et al. [6] and Wu et al. [7].

III. Modelling of Coil Winding Machine

A. P- time Petri net

Definition 1 [8]: The formal definition of a P-time Petri net (Rp) is given by a pair: < R; IS>, where:

– R is a marked Petri net,

– IS : P $\rightarrow \mathcal{Q}^{+} \times (\mathcal{Q}^{+} \cup \{+\infty\})$

$p_i \rightarrow IS_i = [a_i, b_i]$ with $0 \le a_i \le b_i$.

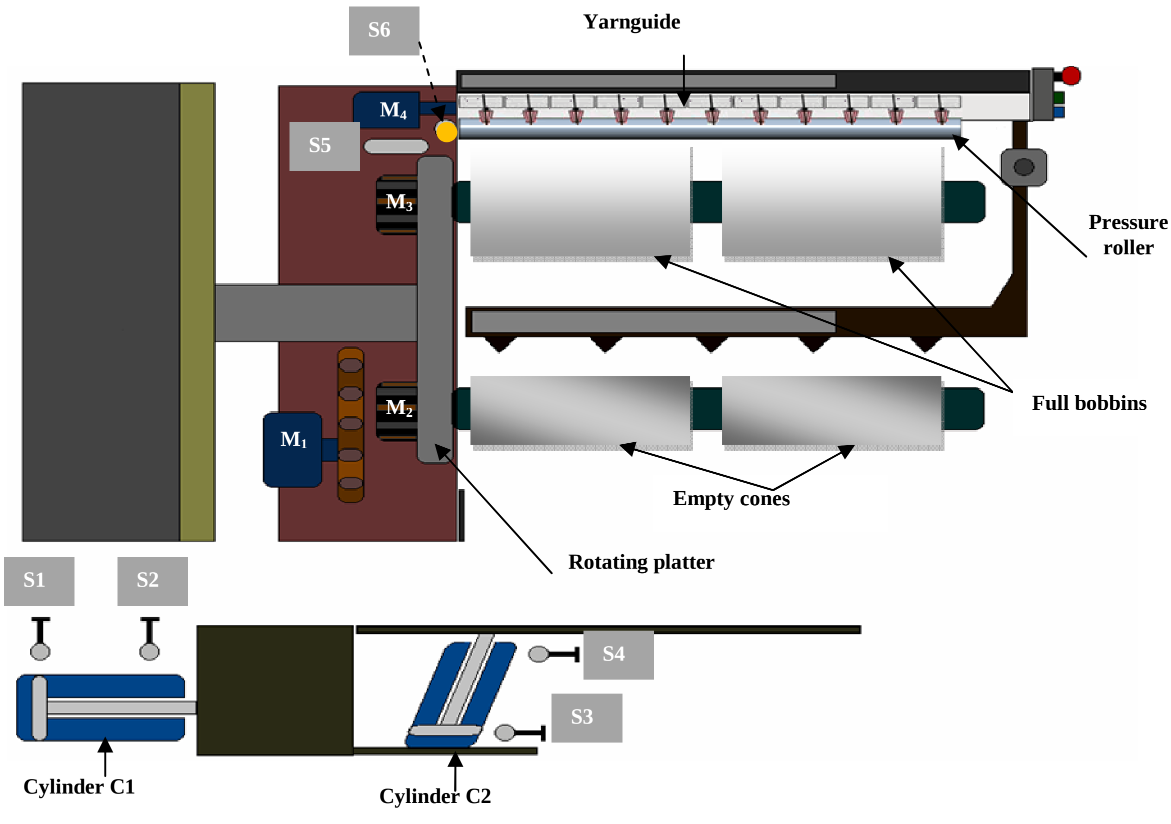
IS_i defines the static interval of staying time of a mark in the place p_i ($\mathcal{Q}^+$ is the set of positive rational numbers). A mark in the place p_i is taken into account in transition validation when it has stayed in p_i at least a duration a_i and no longer than b_i. After the duration b_i the token will be dead.

B. *Presentation of coil winding machine*

Winding machines are used heavily in textile manufacturing, especially in preparation to weaving where the yarn is wound on to a bobbin. In our study, the obtained bobbins are used for the production of fishing nets, fig. 1.The winder is responsible for winding the nylon filament, and evacuates the full bobbins. Once the winding operation is completed, the coils deviate from the pressure roller and the servo motor "M1" provides the inversely of the two brooches, fig. 1. The lever arm is responsible for cutting the yarn. The full bobbins are then discharged by an evacuation trolly and a new winding operation is started.

C. *Modeling of winding machine*

In the studied workshops, a time interval is associated to each operation ($[L_i, H_i]$ with *u.t*: unit time). Its lower bound (L_i) indicates the minimum time needed to execute the operation and the upper bound (H_i) fixes the maximum time to not exceed otherwise the quality of product is deteriorated. Fig. 2, shows a P-time Petri net (G) modeling the production unit. The obtained G is used to study the robustness of the winding unit. The full set of time intervals of operations "IS_i" and effective sojourn time "q_{ie}", are summarized in table 1 (u.t: unit time second). The full set time intervals of clamping, winding, cutting and unloading are computed using the CPLEX 12.5 on a computer with Intel (R) at 2.16 GHz and 2 Go RAM.



M_1 : servo-motor ; **M_2**, **M_3** :Brooch motors; **M_4** : Yarnguide motor; **$S_{i=1,2...,6}$**: Sensors

Fig.1 Components of the winding machine

TABLE 1: FULL SETS OF TIME INTERVALS

Place	Operation	Task	IS_i	q_{ie}
P1	Op1	**Clamping empty cones**	$IS_1=[1, 11]$	$q_{1e}= 5$
P2	Op2	**Winding**	$IS_2=[6600,7200]$	$q_{2e}=6780$
P3	Op3	**Yarn cutting**	$IS_3=[2, 5]$	$q_{3e}= 4$
P4	Op4	**Brooch inversion**	$IS_4=[2, 20]$	$q_{4e}= 5$
P5	Op5	**Motor braking**	$IS_5= [1, +\infty]$	$q_{5e}= 19$
P8	Op6	**Extending of pneumatic cylinder C1 (Sensor S2)**	$IS_8=[2, 4]$	$q_{8e}= 3$
P9	Op7	**Retracting of the pneumatic cylinder C1 (Sensor S1)**	$IS_9=[2, 5]$	$q_{9e}= 3$
P10	Op8	**Extending of pneumatic cylinder C2 (Sensor S4)**	$IS_{10}=[5, 9]$	$q_{10e}=8$
P11	Op9	**Retracting of the pneumatic cylinder C2 (Sensor S3)**	$IS_{11}=[3, 10]$	$q_{11e}= 7$

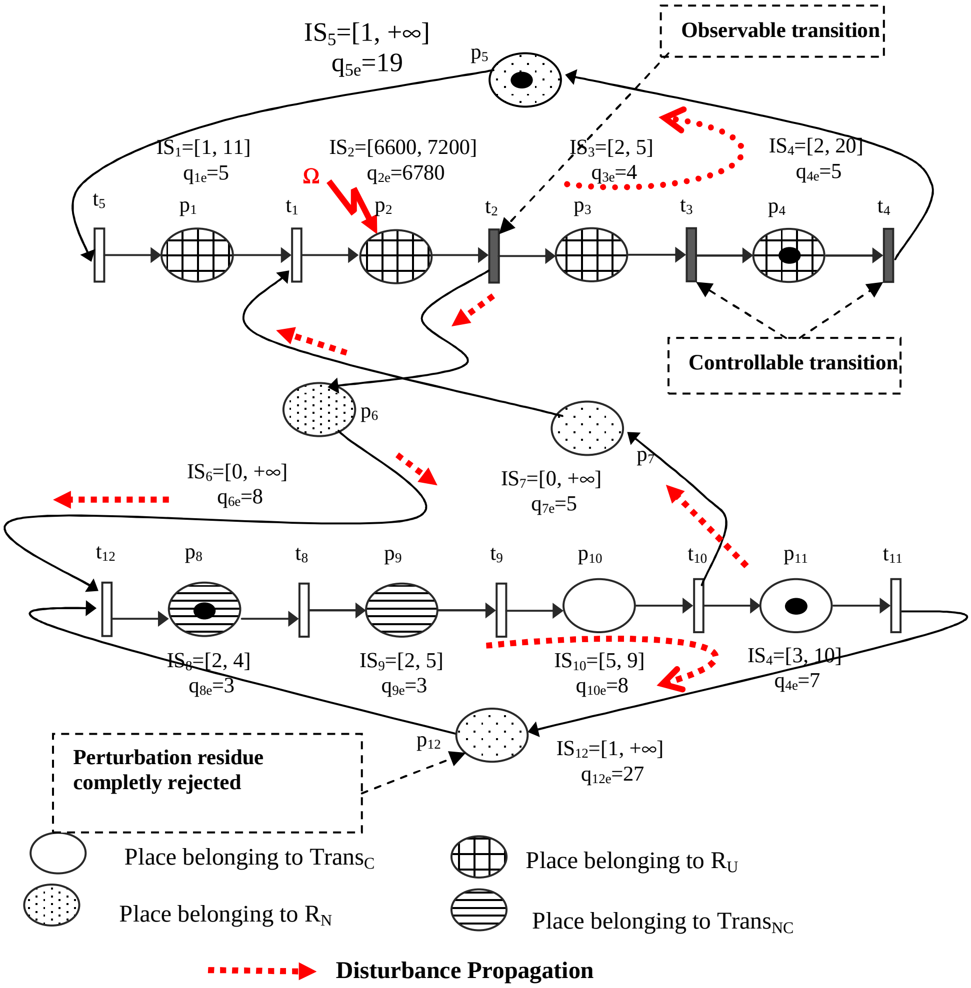


Fig. 2 Winding unit modeled by a P-time Petri net

D. *Functional decomposition*

As the sojourn times in places have not the same functional signification when they are included in the sequential process of a product or when they are associated to a free resource, a decomposition of the P-time Petri net model into four sets is made using [9]. The assumption of multi-product job-shops without assembling tasks as it was established:

While using [9], a functional decomposition of the Petri net model in four sets is established, fig. 2, where:

- ✓ R_U is the set of places representing the used machines,
- ✓ R_N corresponds to the set of places representing the free machines which are shared between manufacturing circuits,
- ✓ $Trans_C$ is the set of places representing the loaded transport resources,
- ✓ $Trans_{NC}$ is the set of places representing the unloaded transport resources (or the interconnected buffers).

IV. Approach for the Active Robustness

A. *Basic definitions*

Let us remember some definitions.

Definition 2 [10]: A mono-synchronized subpath SP_{TH} is a path containing one and only one synchronization transition which is its last node.

Definition 3 [10]: A perturbation Ω is locally rejected by a path "P_{TH}" if its last transition is fired as it is planned.

Definition 4: It is said that a path P_{TH} has a local passive robustness on $[\Omega_{min}, \Omega_{max}]$ if the occurrence of a disturbance $\Omega \in [\Omega_{min}, \Omega_{max}]$ at any place $p \in P_{TH}$ does not involve a token death at the synchronization transitions of SP_{TH}.

Definition 5: A temporal control is the modification of transitions firing instants using controlled P-time Petri net.

Definition 6: The transferable margin "δtr_k" on the mono-synchronized subpath "SP_{TH}" is defined as:

$$\delta tr_k = \min_{\substack{p_i{}^\circ = OUT(SP_{TH}) \\ p_i \notin SP_{TH}}} (H_i - q_{ie}) \tag{1}$$

Definition 7: The passive rejection ability interval of a path "P_{TH}" is $PR(P_{TH})=[PRa(P_{TH}), PRd(P_{TH})]$ where:

$$PRa(P_{TH}) = \sum_{p_i \in P_{TH} \cap (R_N \cup Trans_{NC})} (q_{ie} - H_i), \tag{2}$$

$$PRd(P_{TH}) = \sum_{p_i \in P_{TH} \cap (R_N \cup Trans_{NC})} (q_{ie} - L_i). \tag{3}$$

$PRa(P_{TH})$ (resp. $PRd(P_{TH})$) is called the time passive rejection ability for an advance (resp. a delay) time disturbance occurrence.

Definition 8: The available control margin for an advance, CMa (p_i), and the available control margin for a delay, CMd (p_i), associated to the place p_i are defined as:

$$CMa : P \to Q^-$$

$$p_i \to CMa(p_i) = \begin{cases} L_i - q_{ie} \text{ if } q_i \le L_i \\ q_i - q_{ie} \text{ if } L_i < q_i < q_{ie} \\ 0 \text{ if } q_{ie} \le q_i \le H_i \end{cases} \quad (4)$$

$$CMd : P \to Q^+ \cup \{+\infty\}$$

$$p_i \to CMd(p_i) = \begin{cases} H_i - q_{ie} \text{ if } q_i \le q_{ie} \\ H_i - q_i \text{ if } q_{ie} < q_i < H_i \end{cases} \quad (5)$$

Definition 9: If a transition t is controllable ($t \in T_C$)**,** it constitutes an elementary subpath locally controllable on [max ($CMa(p_i)$), min ($CMd(p_i)$)]

$p^o_i = t$ $\quad$ $p^o_i = t$

Notations

Let us denote by:

–T_C: the set of controllable transitions,

–T_O: the set of observable transitions,

– T_S: the set of synchronization transitions,

–T_P: the set of parallelism transitions,

– $t_i°$ (resp. $°t_i$): the output (resp. the input) places of the transition t_i,

– $p_i°$ (resp $°p_i$): the output transitions of the place p_i (resp. the input transitions of the place p_i),

– q_{ie}: the expected sojourn time of the token in the place p_i,

– q_i: the effective sojourn time of the token in the place p_i,

– $St_e(n)$: the n^{nd} expected firing instant of the transition t,

– $St(n)$: the n^{nd} effective firing instant of the transition t,

– $IN(P_{TH})$: the first node of the path P_{TH},

– $OUT(P_{TH})$: the last node of the path P_{TH},

– C_{ms}: the set of mono-synchronized subpaths,

– C_{se}: the set of elementary mono-synchronized subpaths.

B. Robustness approach: Generation by the control a temporal shift similar to the disturbance

To avoid the death of marks at the level of synchronization transitions, the developed strategy consists of generating by the control, on the parallel paths, a temporal shift similar to the disturbance. The aim is to search on a given parallel path, a set of controllable transitions. In these transitions, trying to generate by controlling a temporal shift of the same nature as the disturbance (delay or advance) paths. If the disturbance type is a delay (respectively advance) time, then the temporal shift will be a delay (respectively an advance) time obtained by changing the firing instants of controlled transitions belonging to the parallel paths.

C. Algorithm

Consider G the P-time Petri net model of the workshop and Ω a delay time disturbance in p_i (node n), observed in a transition t ($t \in T_O$).

Let M_{pk} (respectively $M_{OUT(P_{TH})°}$) the set of mono-synchronized subpaths containing the place p_k (respectively $OUT(P_{TH})°$).

{

F={Ω, $OUT(P_{TH})$} (F is a doublet composed by the residue of the disturbance and the output node of the path P_{TH})

$\forall P_{TH} \in M_{pk} \Rightarrow \Omega' = \Omega - PRd(P_{TH})$

If

$\Omega' > (H_i - q_{ie}) / \{p^o_i \in T_S \wedge p_i \notin P_{TH} \wedge p^o_i \in P_{TH}\}$, there is a control problem on p^o_i : Application of the control strategy allowing to generate a temporal shift, to the set of controlled transitions, similar to the disturbance

Else

$\Omega' < (H_i - q_{ie}) / \{p^o_i \in T_S \wedge p_i \notin P_{TH} \wedge p^o_i \in P_{TH}\}$, we apply the same procedure for each element of $M_{OUT(PTH)°}$

}

V. Application of the robustness approach to a coil winding machine

In the studied workshop, the operations have temporal constraints which must be imperatively respected. The violation of these constraints can induce some catastrophic consequences. This example is a direct application of the proposed algorithm. Let Ω=23 a time disturbance in p_2, observed in t_2 (Fig. 2).

- The sojourn time of the token in p_2 is equal to 6803 ($q_2=q_{2e}+23$).
- The disturbance Ω is propagated towards the two paths $P_{TH1}=(t_2, p_3, t_3, p_4, t_4, p_5, t_5, p_1, t_1)$ and $P_{TH2}=(t_2, p_6, t_{12})$ (Mp_2=[P_{TH1}, P_{TH2}]).
- On the path P_{TH1}, the disturbance is partially rejected in p_5 ($PRd(P_{TH1})=18$). The perturbation change passively the firing instant of the transition t_1 and also the sojourn time in the place p_1: $St_1(n)= St_{1e}(n)+5$ and $q_1=q_{1e}+5$. There is not death of mark on p_1 since we can accept a delay equal to 6 ($IS_1=[1, 11]$; $q_{1e}=5$)
- On the path Lp_2, the disturbance is partially rejected in p_6, and the mark is available in p_6 with a delay equal to 15 ($PRd(P_{TH2})=8$). Given the available control margin for a delay in p_{12} ($CMd(p_{12})=+\infty$), a death of mark on the level of synchronization transition t_{12} is evitable.
- After the crossing of the transition t_{12}, the residue $\Omega'=15[\Omega'=\Omega-PRd(P_{TH2})]$ is transmitted to the two paths $P_{TH3}=(p_8, t_8, p_9, t_9, p_{10}, t_{10}, p_7, t_1)$ and $P_{TH4}=(p_8, t_8, p_9, t_9, p_{10}, t_{10}, p_{11}, t_{11}, p_{12}, t_{12})$ through the starting place p_8 (Mp_8=[P_{TH3}, P_{TH4}]).
- On the path P_{TH4} , it is easly to check that the perturbation is completely rejected since the time passive rejection ability for a delay time disturbance is equal to 26 ($PRd(P_{TH4})= 26$).
- On the path P_{TH3}, the disturbance is partially rejected in p_7 ($PRd(P_{TH3})=5$) and the mark is available in p_7 with a delay time equals to 10 (Ω"=10); there is a death mark in p_1 since the available control margin for a delay accepted is equal to 6 ($CMd(p_1)= 6$).

– On the parallel path P_{TH1}, if the two transitions t_3 and t_4 are controllable ($t_3 \in T_C$, $t_4 \in T_C$) then they constitute two sub paths locally controllable respectively, on [-2, 1] and [-3, 15] (according to definition 11). So, by applying the proposed approach, we can generate a delay on the firing instants of the controlled transitions belonging to the parallel path of the propagation of the disturbance[$(St_3(n)=St_{3e}(n)+1)$ and $(St_4(n)=St_{4e}(n)+15)$]. As a result, the transition t_1 ($t_1 \in TS$) is fired normally and the death of marks on the levels of synchronization transitions is avoided.

■ **Physical interpretation**

The industrial sector is subject to numerous disturbing events which induce variations of the residence time initially computed by the scheduling layer. A temporal disturbance, exceeding the bounds of passive robustness, can cause a violation of constraints specifications. In P-time, this violation constraints is materialized by a death marks. In the winding machine, the detection of a constraint violation implies that there is a deterioration of product quality and a degraded production cycle (delay on unloading bobbins and production cycle).

In the studied example, we assumed that the winding operation is delayed (occurrence of a delay disturbance Ω on p_2). This delay is estimated to 23 u.t. The observed perturbation causes a delay on the level of evacuation operation (propagation of the disturbance to the paths P_{TH3} and P_{TH4}). The implementation of the proposed approach, which is consists to generate by the control, on the parallel paths, a temporal shift similar to the disturbance, allows compensating this delay. Indeed, the proposed approach consists to generate a delay on the execution of the two operations (cutting and yarn brooch). This lateness is manifested by a delay on the firing of the two transitions t_3 and t_4 on P-time Petri Net model (fig. 2).

In conclusion, if the disturbance is a delay type, we generate, on the parallel paths, a temporal shift of the same nature as the disturbance (deceleration on cutting, inversion, retracting or extending of pneumatic cylinder,…). Consequently, both the death of marks on the levels of synchronization transitions and undesirable impact are avoided.

VI. Conclusion

The study of the robust control strategy facing disturbances in manufacturing workshops with time constraints, constitute the contribution of this paper. Controlled P-time Petri nets are used for modelling. Some definitions are quoted in order to build a theory dealing with such problem. They are illustrated step by step on a coil winding machine. The proposed robust control strategy tries to generate, on the level of controllable transitions a temporal shift of the same nature as the disturbance.

It is shown that the established strategy allows continuing the production in a degraded mode. This degraded functioning mode allows keep on producing while providing correct products.

It will be interesting to extend the application of the presented robust control strategy to transport networks. The study of the robustness of transport networks as DES would have a concrete assessment of the robust approach contributions. An important criterion for the evaluation of transport networks is stability. The latter is defined as the ability of a network to resume normal operation after the appearance of traffic perturbation (delay).

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ISSN 2356-5608