DESIGN APPROACH OF DISTRIBUTED SYSTEMS FOR THE CONTROL OF INDUSTRIAL PROCESS

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Abstract: This article describes a methodological approach to the design of distributed systems for the control of industrial process. The designer tackles the problem by specifying the behaviour of the process rather than by specifying a solution. In this way he defines the "what to control". This specification can then be converted not only into a Petri net to allow the checking of certain properties of the described behaviour, but also into a logical network of communicating modules which defines the logical structure of the process control system. In both cases, the rules of conversion are direct and simple.

1 INTRODUCTION

In various fields of application, the constraints that computer systems have to take into account increasingly force their design as distributed systems. Also, at various stages of design, the need to take into account the expression of the distribution (Chen and Yeh, 1983), (Krause and all, 2009), (Lamport, 1983), as well as the expression of parallelism, soon makes itself felt. However, in the face of the complexity of the problems to be resolved, the effective utility of such linguistic tools remains largely dependent on methodological analysis and design guides, which allow us to move from the wording of the problem to a choice of solutions.

In this article we present a methodological approach to the design of distributed systems for the control of production systems, which can guide the designer from the initial specification of a problem right up to the implementation of his solution on an execution structure. In this approach we identify three stages:

- the logical construction of the control system in terms of communicating modules;
- the detailed design of the modules and their programming;
- the definition of a system execution structure.

These three stages allow the gradual construction, by levels of abstraction, of a solution which is, as far as possible, independent of the physical network of the sites. In this article we tackle the first stage by presenting an approach which uses a coherent combination of guides and tools, to facilitate the construction, specification and correction of the logical structure of industrial process design systems in terms of communicating modules (Kramer and all, 1989), (Kramer and all, 1983). This approach is based essentially on a problem-oriented approach. In comparison with other methods, the designer does not approach the logical structuring of his control system by asking himself at the outset "how to control" his industrial process. Instead he approaches the problem by first asking himself "what to control". Rather than specify the control system, he specifies the behaviour of the industrial process by identifying the existing physical processes and their temporal dependences. It is this specification which constitutes the terms of the problem to be resolved and which is then used to deduce the logical structuring of his control system. He considers for this that the modular entities of his control system are merely abstract views of the physical processes of his industrial process and that the temporal relationships which interlink these physical processes specify the inter-modular behaviour of the control system. It is during this phase dedicated to the analysis of "what to control" rather than "how to control" that the designer is best placed to make good choices which guarantee the quality of the functional breakdown (clarity, efficacy, robustness, maintainability and reusability) and which take into account the constraints of the

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problem posed (flexibility in the distribution of the control system in different sites, parallelism and safety). It is also the optimum moment to discuss his choices with the user.

In this article we deal with the modelling of the behaviour of the processes. We present the formalisms (textual and graphic) which enable the specification of this behaviour by following a top-down or a bottom-up approach. This specification can then be directly converted into a Petri net (Brams, 1983) (Cao and all, 2003) (Drzymalski and Odrey, 2008) so that the behavioural properties of the modelled process can be checked. We will then demonstrate that it is equally possible, through direct and simple conversion, to pass from this specification of the system behaviour to the logical construction of the control system in terms of communicating modules. Finally we will illustrate our argument with an example.

2 THE INDUSTRIAL PROCESS DESCRIPTION MODEL

An industrial system is defined by a set of entities (trucks, robots, atmospheric environment, …) whose attributes are likely to evolve with time, and also by a set of physical processes. At any given moment the physical state of the process is determined by the attributes of its entities. This physical state could correspond to a state of normal functioning or to a state of breakdown. The role of the individual physical processes is to enable the industrial system to evolve from one state to another, by carrying out a particular physical activity in a determined time.

The process model is represented by $<P, Q, C>$ where:

- P represents the set of physical processes p_i,
- Q the set of its physical states q_i,
- and C its behaviour.

If a_{ij} is the jth activity carried out by the physical process p_i, then $t(a_{ij})$ denotes the start date of this activity and $t'(a_{ij})$ its finish date.

The history of a physical process p_i at any given moment is defined by the chronological order of the activities carried out since the start of the system.

This order is expressed as $h_i = (a_{i0}, a_{i1}, ..., a_{in})$ where $t'(a_{ij}) \leq t(a_{ij+1})$. The behaviour of a process defines a partial order among the elements of the orders h_i of the set of the physical processes p_i. This ordering is determined by four types of temporal dependence which interlink the physical processes. These are: **causal precedence, coupling, temporal precedence and independence** which are defined in Sections 2.1, 2.2, 2.3 and 2.4.

To specify the behaviour of a process we present two formalisms. The first allows us to specify independently for each physical process p_i of the process, all its direct temporal dependences, with the help of temporal relationship operators (″→″ for causal precedence, ″⇒″ for coupling, and ″-->″ for temporal precedence) and physical process composition operators *″*″(and), ″+″(or) and ″⊕″ (xor).*

The second formalism permits the specification of the temporal dependences of the physical processes in a graphical form close to that of Petri nets (Dong and all, 2001) (Kara and all, 2009). In this formalism the places are labelled and retain their habitual representation and meaning. We call E the set of labels e_i associated with these places. We can associate each of these labels with a specific physical state defined in Q. We call R: E*Q the relationship which joins a physical state q_j to each place e_i. The transitions represented by rectangles correspond to the physical processes p_i of the system. These transitions are not necessarily atomic: new rules, according to the temporal dependences of the process concerned, define the conditions of activation and the effect of an activation on the input and output places of a transition. The type of dependence is determined by the type of arcs which link the places and the transitions between them (″→″ for causal precedence, ″•⇒″ and ″⇒•″ for coupling, and ″-->″ for temporal precedence).

A marking M: is a function from $P*E \rightarrow N$ (where N is the set of positive integers).

$M(p_i,e_j)$ denotes the number of tokens in the place e_j before activation of the physical process p_i, and $M'(p_i,e_j)$ denotes the number of tokens in the place e_j after activation of the physical process p_i

$M(-,e_j)$ denotes the initial state of the place e_j.

The two formalisms used are equivalent. In comparison with Petri nets, this type of formalism permits a more concise expression which is thus easier to read and to write. It can be converted into a Petri net to enable the formal checking of the properties of the described behaviour. In the following paragraphs we will deal more precisely with the definition of the different temporal dependences and their specification in the two formalisms, before addressing, in Sections 3 and 4, the approach to modelling and to checking the behavioural properties of a process.

2.1 Causal Precedence

Given two physical processes p_1 and p_2 of an industrial system, if $h_1 = (a_{10}, a_{11}, ..., a_{1n}, ...)$ and $h_2 = (a_{20}, a_{21}, ..., a_{2n}, ...)$ respectively represent their histories, we will say that p_1 precedes p_2 and we write $p_1 \Leftrightarrow p_2$ if at any given moment for each couple (a_{1k}, a_{2k}) we have $t'(a_{1k}) \leq t'(a_{2k})$, if this condition is not met we write $\neg(p_1 \Leftrightarrow p_2)$.

$p_1 \rightarrow p_2$ if and only if

(1) $p_1 \Leftrightarrow p_2$

(2) there exists no p_i such that $p_1 \Leftrightarrow p_i$ et $p_i \Leftrightarrow p_2$

(3) there exists no $p_i \neq p_1$ such that $p_i \Leftrightarrow p_2$ et $\neg(p_i \Leftrightarrow p_1)$

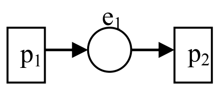
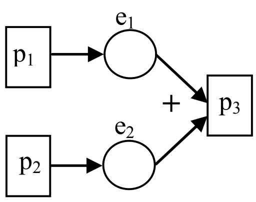
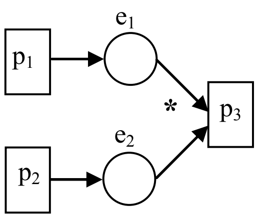
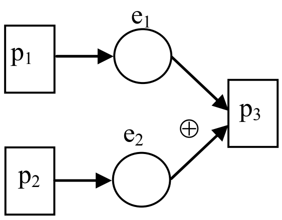
(4) there exists no $p_j \neq p_2$ such that $p_1 \Leftrightarrow p_j$ et $\neg(p_2 \Leftrightarrow p_j)$

We will say that p_1 is the immediate predecessor of p_2 and that p_2 is the immediate successor of p_1. We can deduce from this on the one hand that p_2 can only start an activity if and only if p_1 finishes an activity and on the other hand that each completion of activity p_1 can lead only to the start of an activity by p_2. These definitions relate to the definitions of precedence and causal precedence presented for the events in (Baker and Hewitt, 1997). In a relationship of causal precedence we can describe a physical process as having several immediate successors or several immediate predecessors. For this we use the physical process composition operators ″*″ , ″+″ and ″⊕″. The basic notation of such temporal relationships is defined in Table 1. These basic relationships can be combined to express more complex temporal relationships, in which the usual rules of parenthesis allow the definition of priorities among the composition operators.

2.2 Coupling

Given two physical processes p_1 and p_2 of an industrial system, if $h_1 = (a_{10}, a_{11}, ..., a_{1n}, ...)$ and

Table 1: Basic notation of causal precedence relationships.

Textual Form	Graphical Form	
	Representation	Rules of progress of the token
Designation of immediate predecessors		
$p_1 \rightarrow p_2$		Before activation of p_2 : $M(p_2,e_1)>0$ After activation of p_2 : $M'(p_2,e_1)=M(p_2,e_1)-1$
$p_1 + p_2 \rightarrow p_3$		Before activation of p_3: $M(p_3,e_1)>0$ or $M(p_3,e_2)>0$ After activation of p_3 : $M'(p_3,e_1)$=if $M(p_3,e_1)>0$ then $M(p_3,e_1)-1$ or $M(p_3,e_1)$ else $M(p_3,e_1)$ and $M'(p_3,e_2)$= if $M(p_3,e_2) > 0$ then $M(p_3,e_2)-1$ or $M(p_3,e_2)$ else $M(p_3,e_2)$ and $M'(p_3,e_1) + M'(p_3,e_2)= M(p_3,e_1)+ M(p_3,e_2) - 1$
$p_1 * p_2 \rightarrow p_3$		Before activation of p_3 : $M(p_3,e_1)>0$ and $M(p_3,e_2)>0$ After activation of p_3 : $M'(p_3,e_1) = M(p_3,e_1) - 1$ and $M'(p_3,e_2) = M(p_3,e_2) - 1$
$p_1 \oplus p_2 \rightarrow p_3$		Before activation of p_3 : $M(p_3,e_1)>0$ and $M(p_3,e_2)=0$ or $M(p_3,e_1)=0$ and $M(p_3,e_2)>0$ After activation of p_3 : $M'(p_3,e_1)$ = if $M(p_3,e_1)>0$ then $M(p_3,e_1)-1$ else $M(p_3,e_1)$ and $M'(p_3,e_2)$ = if $M(p_3,e_2)>0$ then $M(p_3,e_2) -1$ else $M(p_3,e_2)$

$h_2 = (a_{20}, a_{21}, \ldots, a_{2n}, \ldots)$ represent their respective histories, we will say that p_2 is coupled to p_1 for its start if at any given moment, whatever a_{21} denotes, there exists an a_{1k} such that $t(a_{1k}) \leq t(a_{21}) \leq t'(a_{1k})$.We will write $p_1 \Rightarrow p_2$. From this relationship we can deduce on the one hand that p_2 can only start an activity if and only if p_1 has an activity in progress, and on the other hand that if p_1 has an activity in progress, this activity can only start an activity in p_2. Moreover, we will say that p_2 is coupled with p_1 for stopping if at any moment, whatever a_{21} denotes, there exists an a_{1k} such $t(a_{1k}) \leq t'(a_{21}) \leq t'(a_{1k})$. To designate the predecessors of p_2 we will note $\underline{p_1} \Rightarrow p_2$, and we can deduce from this that p_2 can only finish an activity if and only if p_1 has an activity in progress. In the same way, to designate the successors of p_1 we note $p_1 \Rightarrow \underline{p_2}$ and it can be deduced that if p_1 has an activity in progress this activity can only provoke the end of a p_2 activity.

As well as the operators ″*″, ″+″ and ″⊕″ we use the composition operator ″;″ to link several physical processes into a coupling relationship. This operator allows us to define an order for the starting or stopping of coupled physical processes. The coupling relationships can also be represented graphically. The implied transitions are not considered to be atomic.

2.3 Temporal Precedence

Physical processes p_1, p_2, ..., p_n which are not interlinked by a relationship of causal precedence or coupling, are linked by the relationship of temporal precedence, if at any given moment just one of these n processes could be active. In other words, it must be possible at any given moment to describe the history of these n processes in a chronological order of activity $h_x = (a_{x0}, a_{x1}, \ldots a_{xi}, \ldots)$ where each activity a_{xi} designates an activity carried out by any one of n physical processes, such that whatever the value of i, $t(a_{xi}) \leq t(a_{xi+1})$ and $t'(a_{xi}) \leq t'(a_{xi+1})$.

This type of temporal dependence which was also introduced in for events, supposes the existence of a sequencer whose job is to put into an arbitrary order the physical processes ready to start an activity. Let us suppose this order is created by a priority circulating on a unidirectional virtual ring, on which are placed the n physical processes. A process can only start an activity if it receives the priority, which it retains until the end of this activity. A process which receives the priority must transmit it to its successor if it cannot start an activity immediately. The specification of a temporal precedence relationship under these conditions comes down to specifying the order of the physical processes on the virtual ring. Given two physical processes p_1 and p_2,

we note p_1 --> p_2 to state that p_2 is the immediate successor of p_1 or that p_1 is the immediate predecessor of p_2 on the virtual ring. In a temporal precedence relationship we can use the process composition operator, ″⊕″, to stipulate that a physical process at any given instant is part of a virtual ring chosen among several.

2.4 Independence

When two physical processes p_1 and p_2 are not linked by any one of the three temporal dependences we have just described, we will say they are independent. Under these conditions, activities p_1 and p_2 can take place at the same time or in any order. In the two formalisms that we are using, the relationship of independence is not explicitly expressed.

3 THE APPROACH TO MODELLING THE INDUSTRIAL PROCESS

This relies on finding a good level of abstraction in the description of the behaviour of the industrial process allowing reflection on its organisation and also allowing good functional breakdown.

It could be top-down: in this case one would proceed by successive refining of physical processes to more elementary physical processes. It could also be bottom-up: in order to understand the behaviour of the industrial process one would proceed first with the identification of elementary physical processes. In this phase one could proceed either by successive refinements or directly by intuition. In a second phase these physical processes are regrouped. This is the approach adopted in (Yau and Caglayan, 1983). It allows the integration of a bottom-up approach within a globally top-down approach. In the case of a top-down approach, there exists a well-defined criterion of latest stopping point: the designer must stop when he obtains physical processes which cannot be further broken down into more elementary processes assuring activities of a different nature. The other criteria are based on the designer's competence and his knowledge of the problem he is tackling. In a top-down approach it is about the criteria of the latest stopping point, and in a bottom-up approach the criteria of the earliest stopping point. Whatever the case, in order to manage more easily the complexity of the analysis of the behaviour of his process, the designer can first identify only the independent physical processes or those interlinked by causal precedence and temporal precedence relationships, and only then can he proceed in a more local way to a breakdown into coupled physical processes. In the first instance the relationships of causal and temporal precedence are defined, and only after that the coupling relationships. The textual formalism that we are using allows us to key in and carry out automatically the usual syntactic checks on the specification of the behaviour of a process. It is then possible to convert this specification automatically into a Petri net using the conversion rules defined in Table 1 and in (Yan and Caglayan, 1983). The existing tools surrounding Petri nets thus allow us to assure that the described behaviour respects certain properties of good functioning: mutual exclusion, deadlock, liveness and termination (Kara and all, 2009). Moreover, as the places in our graphical model are associated with physical states of the process, we can deduce automatically all the accessible global states of the process by constructing a graph of markings. These global states must describe coherent situations.

4 LOGICAL STRUCTURE CONSTRUCTION RULES

To describe the logical structure of a control system we use the concept of communicating modules. These are modular, multi-task entities which do not communicate by variables, but communicate with one another (for coordination purposes) via internal ports and with the process (which they control) via external ports. The inter-modular links defined between the ports can be of different types:
1 towards 1, 1 towards n, n towards 1 or n towards m. They allow us to describe the logical structure of the system as a logical network of autonomous communicating modules, in which checking is decentralised, and where the following circulate:
- events reporting on the evolution of the process,
- controls, requests and reports,
- or again the data or the results of the data-processing.

In this description, the modules are represented graphically by rectangles, the input ports by the symbol ▷ and the output ports by the symbol ◁

The logical structure of a control system in terms of communicating modules is largely directly deduced by the graphical representation of the process behaviour described in Section 2:
(1) Each transition is replaced by a communicating module which abstracts the corresponding physical process p_i.
(2) The arcs which interlink the transitions thus become inter-modular links via which control transfer messages will circulate.
(3) Analysis of the control algorithms of each physical process allows us to determine, for the corresponding modules, the other ports where will circulate external messages exchanged with the process, as well as potential data shared between these modules.

5 ILLUSTRATION OF THE APPROACH

To illustrate our approach, we use as our example a mixer, a test example, which has the feature of bringing into play various physical processes.
This is a process which manufactures a product *x* by mixing a given quantity of two liquid products *a* and *b*, and a given quantity of soluble product *y* that we call rolls. The liquid products are contained in two vats A and B which feed vat C via controllable valves Va and Vb. Vat C is equipped with a level sensor, which allows it to measure the required quantity of the two products, and a controllable valve Vc which allows it to empty its contents into the mixer. Moreover, the rolls are transported into the mixer via a controllable, motorised conveyor belt. There is also a device which detects the passage of each roll. Finally, the mixer has a controllable motor which operates both the mixing process of its contents and also the emptying process. For this last operation there is a sensor which can detect the high and low positions of the mixer.

Table 2 identifies the entities which constitute the process and whose attributes are likely to evolve with time. We have also defined in Table 2 the level of observation of this evolution, by specifying for each entity the attributes which describe it, and for each attribute its domain of definition.

Four physical processes lead from one physical state to another. These are: the emptying of vat C, the filling of vat C, the transport of the rolls, and the mixing-emptying of the mixer. The temporal dependences which interlink these physical processes define the behaviour of the process.

Table 2: List of constituent entities of the industrial process.

Entities	Attributes	Domain of definition of the attributes
Vat A and Vat B	State of valves Va and Vb	(closed, open)
Vat C	State of content State of valve Vc	(full, empty) (closed, open)
Conveyor belt	State of operation	(stopped, moving)
Mixer	Position State of content State of operation	(high, low) ([empty], [liquids a and b], [rolls], [liquids a and b, rolls]) (off, mixing, emptying)

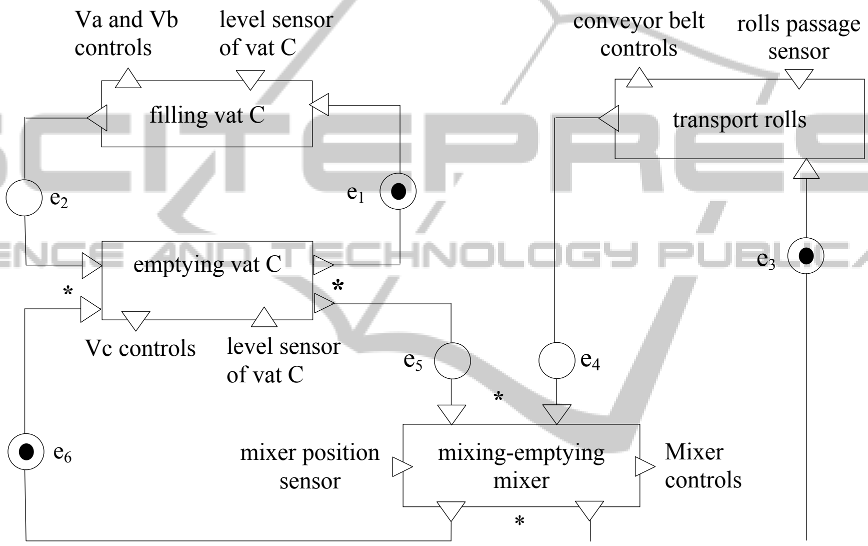


Figure 1: Graphical representation of the behaviour of the process superimposed on the graphical representation of the logical structure of its control system.

We specify these dependences in the following way, by indicating in each case for each physical process, first of all its immediate predecessors and then its immediate successors:

For the filling of vat C:
Emptying-vat-C → *Filling-vat-C*
Filling-vat-C → *Emptying-vat-C*
For the emptying of vat C:
*Filling-vat-C*mixing-emptying-mixer* → *Emptying-vat-C*
Emptying-vat-C → *Filling-vat-C*Mixing-emptying-mixer*

For the transport of the rolls:
Mixing-emptying-mixer → *Transport-rolls*
Transport-rolls → *Mixing-emptying-mixer*

For the mixing-emptying of the mixer:
*Emptying-vat-C * Transport-rolls* →
Mixing-emptying-mixer
Mixing-emptying-mixer → *Emptying-vat-C**
Transport-rolls

Figure 1 shows the graphical representation of the behaviour of the process superimposed on the graphical representation of the logical structure of its control system in terms of communicating modules. In Table 3 we show for each place in the diagram the corresponding physical state of the process.

6 CONCLUSIONS

This article has essentially been concerned with the functions of control and supervision of the process, which we approached from a perspective of synchronisation, in view of the nature of the problems which arise in industrial processes and more particularly in flexible manufacturing systems. In the first stage of our approach, the designer starts

Table 3: Correspondence of the places and physical states of the process.

Places	Physical states	Places	Physical states
e1	State of valves Va and Vb=closed State of valve Vc=closed State of content of vat C=empty	e4	State of operation of conveyor belt= stopped Position of mixer=high [rolls] in state of content of mixer State of operation of mixer=off
e2	State of valves Va and Vb=closed State of valve Vc = closed State of content of vat C=full	e5	State of valve Vc=closed Position of mixer=high [Liquids a and b] in state of content of mixer State of operation of mixer=off
e3	State of operation of conveyor belt = stopped Position of mixer=high No [rolls] in state of content of mixer State of operation of mixer=off	e6	State of valve Vc=closed Position of mixer=high No [liquid a and b] in state of content of mixer State of operation of mixer=off

with the analysis of "what to control" in order to break the control system down into communicating modules, and to specify the inter-modular behaviour of this system. At this stage of the design, his aim must be to reveal the possibilities of distributing the control system in different sites, by carrying out a functional breakdown where he introduces no artificial constraints on the distribution: so he should ignore the distribution of the modules in different geographical sites. Moreover, by describing the temporal dependences of the physical processes, the designer merely uses time as a means of sequencing: thus he also avoids the constraints of "real time". It is during the course of the second stage, dedicated to the analysis of "how to control" that the designer will need to move on to a more precise definition of the constraints of "real time" at the same time as the behaviour of the modules (communication policies on the ports and relationships between the input and output of a module).

The third stage is devoted to finding the execution structure which responds best to the constraints of 'real time", distribution and operating reliability. We are currently working on the second stage of the approach, but also on the production of a prototype JAVA programming environment based on these ideas in order to facilitate the methodological construction of industrial process control systems.

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