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Design and Validation of Distributed Control with Decentralized Intelligence in Process Industries: A Survey

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Abstract -**This paper presents an overview of the works on design and validation of distributed control in process industry. Due to the significant market demand for distributed reconfigurable systems, not just in manufacturing industry but also in process industry, several researches are undertaken to look at the design techniques in implementation of such a decentralized control approach. It has shown that a distributed control can bring benefits such as flexibility, reconfigurability and software reusability. International standards such as IEC61499 and IEC61804 are established for such distributed application with newly introduced Function Block (FB) concepts. Intelligent control and multi-agents approach are emerging techniques for distributed control application. In particular, a process control system is generally considered as a hybrid system because it usually contains both discrete and continuous dynamics. Therefore when handling validation of distributed systems, hybrid verification and simulation will have an important role.**

I. INTRODUCTION

In the recent years, the production plants in process industry became much more complicated due to the ever changing market demands, which required production of small quantities of many customised products rather than mass production of a single product [1, 2, 3, 4]. This, in turn, has changed requirements to the control and automation architectures of such production plants.

The automation in process industry has seen introduction of the so called *distributed control systems (DCS)* approach since a few decades. This was mainly influenced by the physical distribution of the plants. Such distribution requires the use of field area networks (aka Fieldbus) to connect sensors and actuators with the data processing units. However, while increasing the flexibility of maintenance, the DCS approach, as such, has little to do with the flexibility of production.

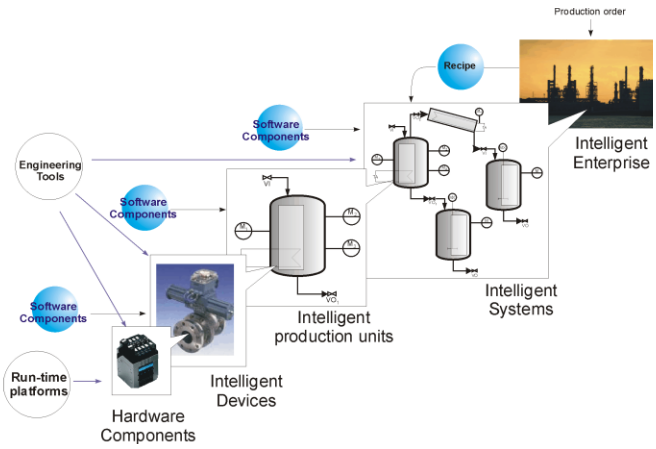


Fig. 1. Range of intelligent components in process industries

In the meantime, in discrete manufacturing industries, which are facing similar market challenges, there was a substantial body of research on the use of *intelligent mechatronic components* in order to increase flexibility of production systems. Such intelligent components, equipped with embedded controllers, can be aggregated to machines and systems, arguably easier, than traditional, dumb mechanical components. As a result, they can also be easier re-configured. This approach was mapped by OOONEIDA to the value-creation chain of automation industries in [5]. The use of intelligent components and object-oriented design promise to bring essential benefits for design and re-configuration of automated production systems. These benefits account to encapsulation and reuse of a good deal of the intellectual property relevant to a particular mechanical component, machine or system.

The progress in embedded systems technology allows an extension of the intelligent mechatronics approach also to the components, used in process industries. Thus, a valve with embedded sensors and embedded controller can perform some operations locally without recourse to the central controller unit.

The automation value-creation chain based on the idea of intelligent components can be presented as in **Fig. 1** and is explained as follows.

Intelligent devices, such as valves, motors and pumps, can be equipped by their own hardware which runs specific control algorithms, as well as communication and diagnostic functions. Machines, such as reactors, boilers, etc., which may include other intelligent devices, implement functions by means of corresponding software components. Intelligent systems can be built from intelligent machines encapsulating hereby their respective properties. The added functionality of the machine is defined by software components, which interact with the corresponding software components embedded into the constituent machines. Advanced intelligent batch systems are capable of understanding product recipes and translating them into sequential controller which operates with basic functions of the constituent machines, specifying interconnections and parameters of the encapsulated software components.

Implementation of this vision leads to the process control with essentially decentralized logic.

It is possible to implement such concept with traditional Programmable Logic Controller (PLC) and Local Area Network (LAN). However researchers face various difficulties in software development for distributed systems in the traditional way. One of these is that controllers in a distributed system may come from different venders. This complicates the process of creating interaction between different controllers.

Besides, scenarios of intelligent component creation and application would certainly differ between manufacturing and process technology domains. While in the process technologies certain machines can be built in a very similar way of including other intelligent components (say a reactor may be delivered with some internal pipelines and intelligent valves), the reconfiguration rarely would be done by re-shuffling of the machines or re-piping them.

In multi-purpose plants based on the batch-processing principle, reconfiguration is also done purely on the level of "intelligence" – physical reconfiguration of the equipment is not necessary.

The international Electrotechnical Commission (IEC) established new international standards, IEC61499 [6] and IEC61804 [7], to set common criterion in implementation of distributed control. They enhance the interoperability and re-usability in a complex distributed system, aiming to increase flexibility and reconfigurability of the control systems in terms of both software and hardware.

Here, this newly introduced distributed control system is different to the classic Distributed Control System (DCS), as it still has a centralised control unit that controls all the devices, connected on a network, in the system.

Another research stream in manufacturing has been dealing with intelligent control approaches based on biological principles, for example, the holonic manufacturing concept or multi-agent control in manufacturing [8, 9]. Intelligent control and Model Predictive Control (MPC) are also popular in the present process related research. The incorporation of these control approaches with distributed control may become a future research area of interest.

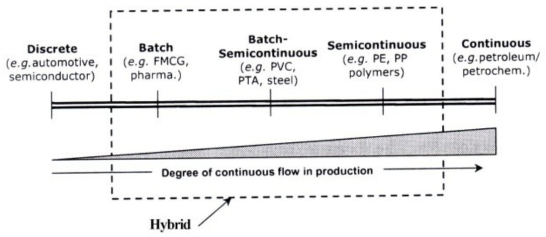
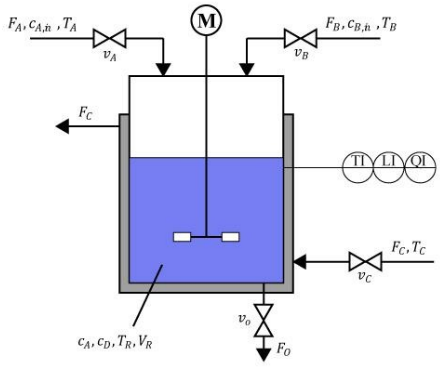


Fig. 2. Hybrid Systems with different degree of continuous flow [4]

In general, a system in process industry is not purely discrete or purely continuous. A system may contain discrete operations (such as sequences of valves openings along a pipeline) as well as continuous control of flows or of some chemical reactions. Such systems are also known as "hybrid" [11]. They are substituting continuous production in response to the growing demand for flexibility. A batch processing is one example of such a system (See **Fig. 2**). The process in the batch process reactor (**Fig. 3**), for example, can be described by both continuous variables (temperature etc) and discrete variables (switches s1 and s2) Batch processing was introduced first in the production of high value, low volume products, such as pharmaceutical, cosmetics and perfume products. It spreads gradually to the food processing and other industries. Modelling, verification and validation of systems with hybrid, i.e. continuous and discrete dynamics, executing intelligent control algorithms in decentralised nodes, are highly sophisticated. A big challenge will be incurred when introducing truly distributed control approach into a process control system of such.



Equations
$\frac{dc_A}{dt} = \frac{s_1 \cdot F_A}{V_R} \cdot (c_A^{in} - c_A) - 2 \cdot r$ $\frac{dT_R}{dt} = \frac{s_1 \cdot F_A}{V_R} \cdot (T_A - T_R) - \frac{s_2 \cdot k_C \cdot A_C}{\rho \cdot c_P \cdot V_R} \cdot (T_R - T_C) - \frac{H_R \cdot r}{\rho \cdot c_P}$ $\frac{dc_A}{dt} = s_1 \cdot F_A, \quad A_C = \frac{\pi}{4} \cdot D_R^2 + \frac{4}{D_R} \cdot V_R$
Variables
c_A - concentration of substance A (kmole/m³) T_R - temperature of the reactor content (K) V_R - liquid volume within the reactor (m³) t_R - reaction time (sec)
$s_1 \in \{0,1\}$ - switch the valve v_A to close or open $s_2 \in \{0,1\}$ - switch the valve v_C to close or open

Fig. 3. Batch Process Reactor and its hybrid model [10]

The aim of this paper is to obtain an overview of the implementation of the new distributed control approaches in the process industry and identify the challenges (for verification and validation in particular) by surveying implementation of new distributed approaches. The rest of the paper is organised as follows: Section II discusses in detail what is a truly distributed reconfigurable control and its benefit over centralised control. Section III focuses on specification of the international standards that relates to distributed control implementation in industry. Section IV summarises some existing work done with Multi-agent and Intelligent Control in process industry. Section V lists out the verification and validation techniques that have already been implemented.

II. DISTRIBUTED RECONFIGURABLE SYSTEMS

The idea of distributed system originates from the control implementation in process industry. This is where each physical element such as switches, pumps and valves is directly connected to its own control unit. The concept of distributed systems is to replace a central controller with multiple controllers that control a particular part of a system. This means every single object or subsystem inside a system can potentially have its own control unit. Distributed control has various implementations in variety of industries such as Manufacturing, Electrical Power Generation, Oil Refining, and Pharmaceutical Manufacturing etc. In [4], the reconfigurability was considered as the target of distributed control. **Fig. 4** shows one example vision in distributed reconfigurable process control.

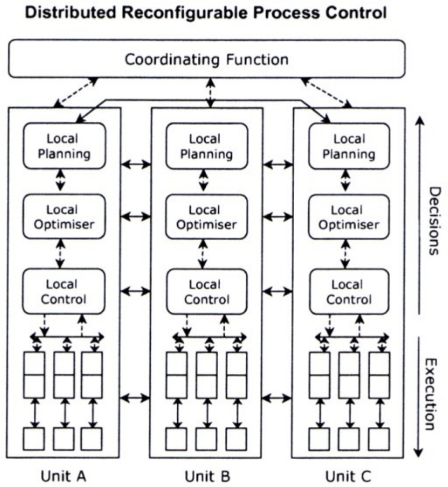


Fig. 4. Distributed Process Control [4]

However, one problem with distributed process control lies upon the realization of implementation in industrial practice, where no proper design methodology and software tools have yet been developed. Further investigation in tools for human interaction is essential to define human involvement (i.e. degree of semi-automation) in distributed process control.

III. International Standards

A. The IEC61499 Standard

The IEC61499 standard introduces the concept of event-driven modules, known as *Function Blocks* (FB), to address the increasing demand of flexibility, reusability, reconfigurability and distributed control applications [12]. An example FB system is presented in **Fig. 10**.

Researchers start exploring the benefits that the Function Block approach can introduce not only in discrete manufacturing systems but also in the process industry. For example in [1], specific distributed process control programming tools for Function Block description were developed, and the problems occurring when introducing this new standard into the process control domain were investigated. As a starting point, researchers integrated models to a lab-scale model of batch process such as the FESTO MMP (Mini Pulp Process), shown in **Fig. 5**.

Fig. 6 also presents a simple example of distributed implementation to the FESTO process station, where each circle area can be considered as a subsystem (Tank1, Tank2 and Pump) with its own controller.

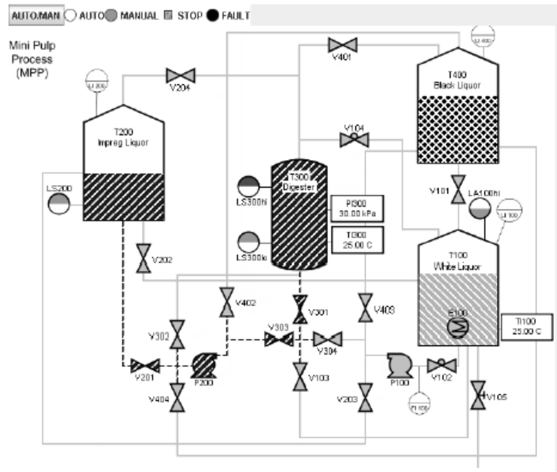


Fig. 5. FESTO MMP

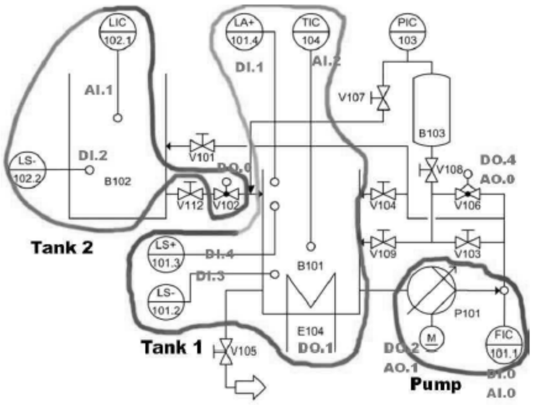


Fig. 6. An example of Distributed Process Station [13]

From the results, the authors of [1] are seeking a migration path to this recently developed standard for the distributed batch process industry. In [14], an attempt to exploit the IEC61499 model in the batch process is described. Here, a hybrid approach of integration IEC61499 with UML is explored to address the current trends in software engineering such as component based and model driven development [15]. This approach aims to transform and reduce switching cost from the ISA SP88 [16], an industrially accepted family of standards in batch control, to IEC61499.

Also, the work [17] has specifically exploited the possible migration path to IEC61499 standard for the distributed process industry by considering switching cost. It stated that the adoption of this new standard is only possible if the perceived switching cost is less than the perceived benefits. From their previous experiments with professionals, the switching cost is very high due to the bewildering range of design decisions. Therefore direct adoption in the context of IEC61499 cannot be applied successfully. Their proposed solution is to use SP88 standard as a specification and set up formal rules or general guidelines to construct corresponding IEC61499 blocks [17, 13]. This paper also suggests the component based approach for the batch process industry presented in [18] may ease the adoption. Even though switching cost is highly reduced as a result, this approach introduces retraining cost. Therefore improving the industrial acceptance of IEC61499 in process industry still remains as a challenge.

B. The IEC61804 Standard

The IEC61804, in particular, describes the specification and requirements of distributed process control systems based on Function Blocks [7]. Electronic Device Description Language (EDDL) is the language that is stated in the part 2 of IEC61804 standard and describes the properties of automation system component [19], such as vendor information, version of firmware/hardware and data format etc. Through this language, all the information will be carried between the devices (controllers, sensors, actuators and engineering stations etc) by fieldbus. This language fills in the gap between the Function Block specification and product implementation by allowing manufacturers to use the same description method for devices of different technologies and platforms (**Fig. 7**).

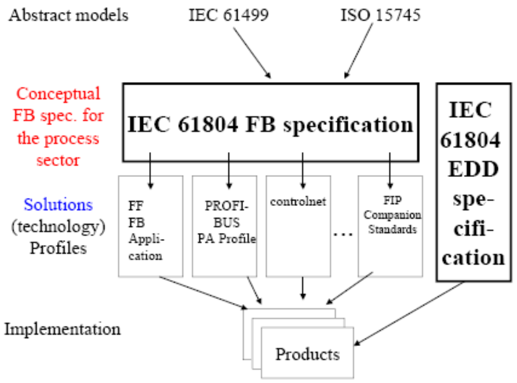


Fig. 7. IEC61804 Relations to other standards and products

The Function Block design, of a process control system for example, is only an abstract representation which may be implemented differently with different device types [7], such as Field Devices (FD), Programmable Logic Controller (PLC), visualisation stations and Device Description (DD).

C. CAEX

Computer Aided Engineering Exchange (CAEX) is a data transfer language or a data exchange format that enables storing information with hierarchical module-based plant [20]. This standard is also known as IEC/PAS 62424, an emerging standard in the process control and manufacturing automation engineering. However it is only about data exchange, based on XML and provides a common exchange format between process control tools. A tools called CAEX Analyser, based on CAEX description, is capable of capturing process topology and linking plant information and results with data-driven analysis [21].

IV. MULTI-AGENT AND INTELLIGENT PROCESS CONTROL

The term "Intelligent control" is now common when dealing with distributed systems because of its ability to comprehend and learn about processes and operating conditions [22]. Also an intelligent system is able to automatically improve upon performance as experience is gained. One advantage of intelligent control is where the information and knowledge about the system can be maintained even when upgrading to a newer system. Intelligent (or knowledge-based) system is particularly useful as a supervisory application in a distributed system. It works as an operator assistant. A real-time intelligent system can tune and monitor control loops, based on the real-time knowledge it gathered. It is also useful in alarm analysis and process diagnosis. An experiment work [23] presents the intelligent knowledge-based supervisory control (IKBSC) system implementation for a hot rolling mill. This experiment demonstrates the advantage of a knowledge-based system as IKBSC helps in scheduling for a timely, accurate and safe rolling.

Due to the complex nature of distributed systems, agent-based control becomes a popular approach and a powerful tool [24]. An agent-based architecture provides robustness and flexibility and is proven to be specifically appropriate for dynamic distributed systems [8]. Because of its modular nature, it is also appropriate to develop modular system with no single central controlling unit. An agent-based system includes both local and global controller agents which organises all the information obtained from the entire system. As an example in process industry, this approach is particularly useful when dealing with a system of networks of interconnected continuous stirred tank reactors (CSTRs) [24].

In a multi-agent system (MAS), each single agent exchanges information with one another in order to achieve its own objectives. The work [8] presents some case studies of MAS applications in process industry, including an intelligent search system to provide a knowledge management platform and a system to provide concurrent process design to ease communication between system engineers.

V. VERIFICATION AND VALIDATION TECHNIQUES

The term "verification and validation" corresponds to the process of checking whether a system complies with specifications. Model-checking [25] and simulation are both verification techniques. Simulation specifically looks at a system's correctness for one specific case (i.e. with a fixed set of input variables). Formal verification via model-checking provides evidences to prove a system's correctness for all cases. Both verification and simulation can take an important role in design flow of a distributed system, especially with high degree of system complexity [26]. Particularly with the tool chain and the design flow suggested in [25], because of the benefit (the software re-usability with encapsulated models and programming codes for validation and deployment purpose) from modular design (i.e. IEC61499 Function Block), simulation and validation can be implemented in parallel within the system design flow to check the system's correctness. If there is any issue of violating specifications, a change made immediately to the system validation model also corresponds to a change in the codes for deployment. Once the validation is the completed, the software program is also ready to deploy into the real system.

Our focus is on validation tools for distributed systems here. Therefore other common simulation tools, such as Control Build Validation developed by TNI-SOFTWARE [26], are not discussed because they are not intended to deal with systems with decentralised intelligence.

A. Hybrid verification & Simulation

From previous sections, it can be concluded that distributed control systems in process industry are usually modelled as hybrid systems. In other words, when considering validation techniques of distributed systems, hybrid verification and hybrid simulation are most appropriate.

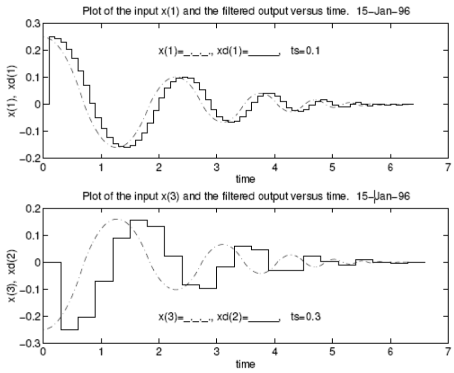


Fig. 8. Sample simulation results from MATLAB and SIMULINK [28]

A language called Hybrid System Modelling Language (HSML) is created specifically for modelling hybrid systems. It is able to construct state events and discrete time modules in MATLAB and SIMULINK [27, 28]. In [28], it is indicated that HSML is particularly useful for time- and state-event handling (see **Fig. 8** for sample simulation results).

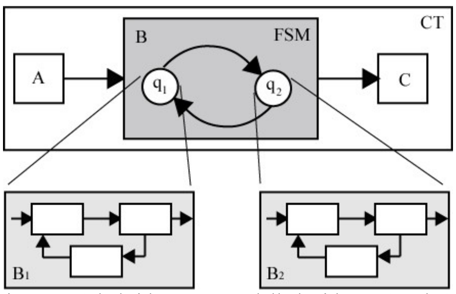


Figure 9. A hybrid system modelled with FMS and CT

There are also some other software tools being developed to handle simulation and verification of different type of hybrid systems:

1) *HyTech* uses symbolic model checking techniques in continuous state space to verify systems modelled with linear hybrid automata (LHA) [29].
2) *CHECKMATE* is a MATLAB-base tool for simulation and verification of hybrid systems with non-linear continuous dynamics [30].
3) *VERDICT* [31] provides an environment for modular modelling and simulation for timed and hybrid systems.
4) *Ptolemy II* is a JAVA-based software framework developed (with graphical user interface called Vergil) which can model and simulate hybrid systems [32]. Here, a hybrid system can be modelled by finite state machine (FSM) with continuous time (CT) models, shown in **Fig. 9**.

B. Simulation Works with Modular Approach

The work [33] presents an industrial case study of a distributed continuous process simulation of a beet sugar factory. This simulation work is done by using distributed component object model (DCOM) components written with a modelling language called "EcosimPro." DCOM is the Microsoft solution for a component software bus.

Software tools such as Function Block Development Kit (FBDK) and FBench are able to provide simulation with IEC61499 Function Block design of a system. As an example, **Fig. 10 and Fig. 11** show the FB system structure and simulation results of a 2-tank system. The simulation is able to demonstrate a dynamic visualised simulation of the water flow inside the system, while the pump (at the bottom), valve (at the top) and the tap (right) is diverting the water flow in the system with the actual distributed control code connected to a model and view of the plant. Thus the code can be directly deployed afterwards.

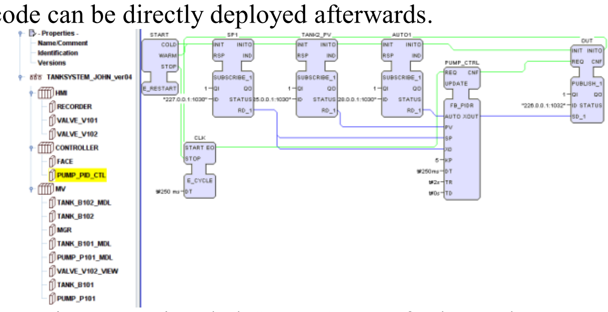


Fig. 10. Function Block System Structure for the 2-tank system

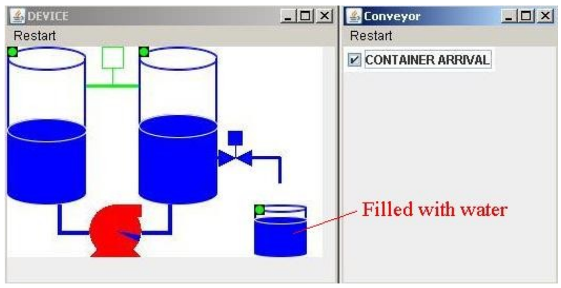


Fig. 11. FBDK Simulation of a 2-tank system

Lastly, [34] presents an object-oriented framework for process simulation. This matches with the idea of modular approach of software design in Function Blocks.

C. Challenges

According to what has been described above, there is still no single validation tool that is able to handle and provide both simulation and verification of distributed control system. It would be a benefit if a software package can contain pre-set models specifically for process control (i.e. models for pipe-line, valve etc). The tools handling hybrid systems only works with their own modelling language and are not yet combined for implementation purpose to the real system. Therefore, a challenge here is to find a path of integrating models for hybrid validation with programming codes for deployment purpose, for distributed systems. This idea is also suggested in [25]. Also evaluation of including validation in design flow of a complicated distributed system is required to prove that such approach can benefit the industry from the perspectives of saving time and cost, while meeting the demand for flexibility and reconfigurability.

VI. Conclusion

This paper provides a short survey of recent research on distributed control in process industry and to provide some structural categories for the approaches found in the reviewed papers. The survey is done from the perspective of system validation challenged by the reconfigurability demand achieved via decentralised control approach. In general, most of the approaches to distributed control suggest modular modelling approach and object-oriented concept in software. International standards IEC61499 and IEC61804 use Function Blocks as the modelling concept. Intelligent and Multi-agents approach has agents to represent distributed subsystems or units. Because of the hybrid nature of a process control system (such as a batch process), hybrid verification and simulation techniques is useful when handling validation of distributed system in process industry.

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