Modeling Distributed Automation Systems in Cyber-Physical View

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***Abstract* — With increasing complexity of automation processes, distributed automation systems are required to meet real-time constraints of control and communication for processes. On the other hand, cyber-physical system is committed for solving complexities of networked embedded systems. In the cyber-physical view, distributed systems are combination of control, computation and communication. One key research topic is to solve design complexities of industrial cyber-physical systems by applying modeling techniques. In this paper, an IEC 61499-based modeling language is propsed for industrial cyber-physical systems. Furthermore, how these modeling techniques could be beneficial for industrial cyber-physical systems are investigated. Finally, an industrial cyber-physical system design tool is implemented by applying the proposed IEC 61499-based modeling language.**

Keywords — Industrial Cyber-Physical Systems; Heterogeneous Modeling; Model-Driven Engineering; Distributed Automation System; IEC 61499 function blocks.

I. INTRODUCTION

With continuously increasing in size and complexity, industrial automation systems are often controlled by multiple programmable logic contollers (PLC) nowadays that are interconnected via industrial fieldbuses [1]. It is impossible to use unique PLC platform with same fieldbus type for all systems as system integrators have their own preferences especially. Design difficulties of distributed automation systems are increasing rapidly as lack of efficient tools and languages during design stage [2]. In order to handle design complexities, software engineers are expected to spend much more efforts.

In embedded system research, cyber-physical system (CPS) attracts many attentions recently. Embedded systems are boosted by advanced semi-conductor and communication technologies in the last decade. A microprocessor available now is often equipped with dual or quad core GHz level CPU, gigabytes RAM and flash memory at very little cost. Also embedded devices could be communicated via many media such as Wi-Fi, Bluetooth and Cellular network. On the other hand, size of embedded device is reducing significantly that these devices could be worn or easily fit into pockets. In the cyber-physical system view, networked intelligent nodes are interacted with environment by adjusting themselves based on feedbacks from physical processes [3].

There are large applications of CPS in industrial automation domain. One challenge of applying CPS in industrial automation is modeling techniques for distributed automation software with integrated physical processes [4]. From design perspective, various hardware platforms, execution semantics and fieldbus communications must be covered by software models. The goal of this paper is to apply cyber-phiscal view in distributed automation system design to provide integrated control, computation and communication software models.

The rest of the paper is organized as following: In section II, related works regarding modeling techniques in cyber-physical systems and existing model-driven approaches in industrial automation will be reviewed. Modeling techniques developed for CPS will be analyzed in section III. In Section IV, CPS modeling techniques is applied to industrial automation by extending the IEC 61499 standard. In section V, the implementation of the IEC 61499 tool with cyber-physical view is illustrated. Finally, paper is concluded with future works in applying CPS in industrial automation research.

II. RELATED WORKS

Cyber-physical systems which are listed as a key research area by US national science foundation (NSF) [5] are integrations of computation and physical processes [6]. Eidson et. al. [4] proposed a programming model PTIDES as a CPS coordination language. PTIDES provides robust distributed real-time software models which are independent of hardware

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platforms and provide deterministic execution semantics which could eliminate variability in clock synchronization and network latencies. Derler et. al. [7] propose modelling techniques for heterogeneous, concurrent and time sensitivity in cyber-physical systems. Hybrid modeling techniques and integrated plant simulation of CPS is demonstrated on a fuel management subsystem in aircraft vehicles. Ptolemy II [3] provides actor-based modeling which supports multiple models of computation in the same design tool. Actors are software components that are triggered by input events, execute control software and generate output events. Actors could be set to different models of computation which represent either physical plants or control software. Hierarchical model is supported in actor that actor could be a modal model in a nested structure. Other modeling languages for CPS such as ExCHARON [8], CPSsHCML [9] and direct using mathematic formulas [10] are based on pure textual without graphical representation.

A real-time data distribution service is proposed for data exchange in cyber-phyiscal systems by Kang et. al. [11]. The publish/subscribe mechanism is proposed on middleware in order to improve reliability of time manner in sensor data collection. Accuracy of sensor model is improved by a monitoring feedback from controllers in real-time. A multi-view of CPS architecture is proposed by Rajhans et. al. [12]. The proposed multi-view framework provides heterogeneity in cyber-physical system. This framework also contains user view during system design. Furthermore, mapping semantics of models are implemented to ensure system consistency by applying formal verification. A group-based programming abstraction for CPS is proposed by Vicaire et. al. [13]. The abstraction model covers sensors and actuators. Heterogeneous devices are supported that sensors and actuators can be modeled and simulated simultaneously.

Some researchers already published their works regarding applying cyber-physical view in industrial automation. Lee et. al. [14] [15] provides state-of-art review of CPS, big data and their impacts in industrial informatics. As a conclusion, applying CPS and big data analysis is a feasible solution for providing predictive manufacturing. The IMC-AESOP project from FP7 framework in Europe proved that applying cloud technologies to CPS is capable for improve flexibility and collaboration level of distributed automation systems [16]. The concept of CPS is tightly linked with multi-agent systems which is applied in power systems [17], material handling systems [18] [19] and manufacturing systems [20]. However, there is not an existing approach for applying cyber-physical in modeling distributed automation systems.

III. MODELING CYBER-PHYSICAL SYSTEMS

The cyber-physical system combines computation, control and communication with physical processes. The cyber-physical systems are closed-loop real-time systems where distributed nodes connected by networks are adaptive and predictive [21]. By continuously monitoring real-time feedback from physical processes, control systems should react with actions within real-time constraints to enable intelligence on device level. Human interactions could be also considered as feedback from environment. CPS covers large application domains from telecommunication systems, power systems, building automation, factory automation, robotics, transportation systems and even military applications.

Modeling is an important task during system design. Models are created to reflect requirements and functional specifications. Models could be used for automatic code generation to save design and development time. Plant models can assist verification process by provide closed-loop testing to control software. So *Heterogeneous Modeling* methodologies for design CPS is essential.

During CPS design process, specifications as well as model analysis are considered by hybrid heterogeneous modeling. The concept of heterogeneous modeling is developed in embedded system domain for decades. CPS provides new definition for heterogeneous modeling that includes syntax, semantics and pragmatics [3]. The syntax part means representation of a design, in another word, software code. The semantics part indicates how syntax should be executed, or models of computation.The pragmatics part refers to how a design is visualized and analyzed by engineers.

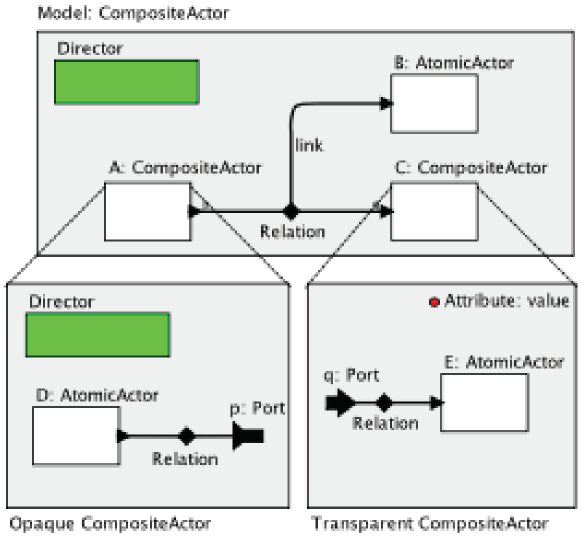


Fig. 1: Heterogeneous Modeling in Ptolemy II [3]

CPS covers all sorts of model of computations: sequential models like finite state machine (FSM) or concurrent models such as Rendezvous, Process Networks, Data Flow, Continuous Time, Discrete Event and etc. For example, physical processes are usually implemented using continuous models as models could be specified by ordinary differentiation equations (ODE). Software for process control is often implemented using discrete event models. Allowing multiple models of computation in single modeling language and visualizing by graphical representation offer huge benefits for CPS design process. As shown in Figure 1, in Ptolemy II, each domain is controlled by an director. Each director consists several actors which is the container for encapsulation. Actors could be either atomic or composite which allows to encapsulate other actors. Actors are connected by ports which refers to events with embedded variable data. Control code could be modelled in one domain and physical plant could be placed in another domain together forms closed-loop simulation.

IV. Modeling Distributed Automation Systems in Cyber-Physical View

As stated in the introduction part, there are lots of common characteristics between cyber-physical systems and industrial automation systems. First of all, both systems are highly distributed and contain various hardware platforms and networks. How to ensure synchronization between networked PLCs is always a mission for engineers. Also execution semantics vary between PLCs that executing an identical code on multiple platforms may result in different behaviors.

The second common characteristic is modularity. In Ptolemy II, actor-oriented design with input and output ports is introduced as basic module for CPS models. In industrial automation, modularity is widely adopted for software development. The IEC 61131-3 standard [22] introduces function and function block as reusable software units. Object-oriented programming is supported in the third revision of the IEC 61131-3 standard [24]. Applying object-oriented programming (OOP) increases efficiency in software design for industrial automation. Modularity is achieved by encapsulate logic in a function block in the IEC 61499 standard [23] known as component-based design [26]. The complexity is hidden from engineers with pre-defined interface between software components, at the same time the flexibility and the reusability is also increased [25].

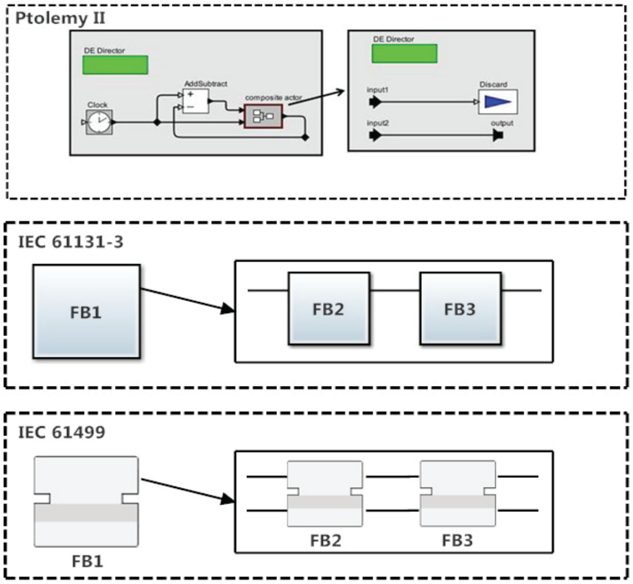


Fig. 2: Composability in Ptolemy II, IEC 61131-3 and IEC 61499

The last characteristic is composability. In Ptolemy II, a model of computation can be a modal model which means other models can be encapsulated. This can be achieved in both IEC 61131-3 and IEC 61499 as shown in Figure 2. In the IEC 61131-3 standard version, functions and function blocks can be composed by another function or function block. In the IEC 61499 standard version, this is achieved by using composite function blocks which contain nested function block structure internally.

To conclude, there are lots of common features between cyber-physical systems and distributed automation systems. Modeling tools and methodologies developed from CPS could be applied for industrial automation as well. One obvious benefit is to enable different execution semantics in one system configuration. Due to limitation of the IEC 61131-3 software model (no system configuration overview), the IEC 61499 standard will be used.

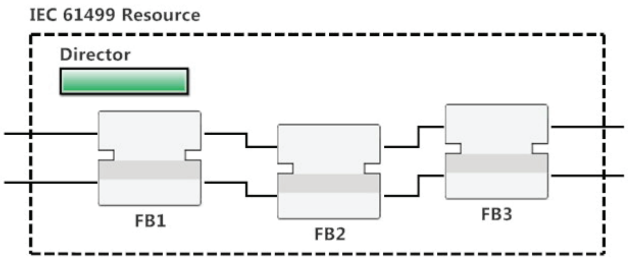


Fig. 3: Introducing Ptolemy Domains in IEC 61499 Design

As execution semantics are not limited by the IEC 61499 standard, there exist numbers of different execution semantics, for instance, cyclic buffered execution [27], buffered sequential execution [27], non-preempted multithreading execution [27] and synchronous execution semantics [28]. When there is more than one execution semantics exist in system configuration, changing deployment plan of function block networks may result in unexpected system behaviors. Execution semantics are hidden from existing IEC 61499 programming tools. As proposed in figure 3, the actor concept from Ptolemy II is introduced in the IEC 61499 resource. The IEC 61499 resource shall indicate execution semantics to allow multiple execution semantics on the same IEC 61499 device.

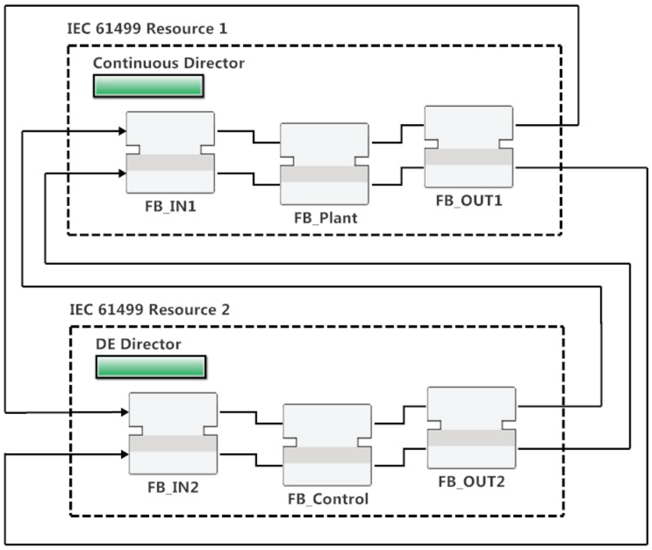


Fig. 4: Closed-Loop Testing with Multiple Models of Computation in IEC 61499

Another benefit is to integrate communication models into design processes for industrial cyber-physical systems. In Ptolemy approach, model of computation also contains communication protocols (synchronuous or asynchronous, sequential or concurrent). In the IEC 61499 standard, communications are normally handled by service interface function blocks which communication protocols are encapsulated [29] [30]. As interface of communication SIFBs is identical to other function blocks, communication part is hard to identify in IEC 61499 system configurations. By introducing domain concepts in IEC 61499 design as stated in figure 4, communication protocols can be highlighted for engineers to provide better user experiences.

Last but not the least, enabling multiple models of computation in industrial CPS design provides better accuracy for plant models. In the CPS approach, physical world can be modeled as concurrent process by using continuous model [7]. The common approach of achieving closed-loop testing in industrial automation is to implement physical plant models using IEC 61131-3 and IEC 61499 co-exist with control code [31]. By applying this approach, no seperated tool is required and engineers are not required to learn high-level programming languages. In existing approahes, the model of execution for plants must be the same as control software which may not be suitable for modeling plants. Models must be implemented using a separated tool. From the cyber-physical view, it is important to include physical process in one software model. As indicated in figure 3, with multiple models of computation support, plant models can be built-in with control code but running different execution semantics.

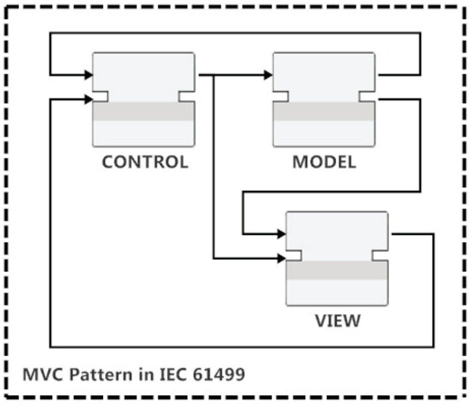


Fig. 5: MVC Design Pattern in IEC 61499

Existing design patterns in automation systems could also combine with cyber-physical view. Model-View-Control (MVC) pattern is a popular design pattern in automation domain. The MVC pattern originally developed from computer science domain has been applied in automation system design. As shown in Figure 5 above, MVC approach splits code into three parts - model, view and control. In industrial automation, the model part is used for describing physical plant, the view part is designed for SCADA/HMI screens and panels, and control part contains PLC code. By applying the MVC pattern, systems can be modified partially without affecting other parts. In addition, both model and control part can connect to two instances of the same view component to verify system consistency. By applying the cyber-physical view, the control part will be in one IEC 61499 resource with discrete event model and the model part will be in another with continuous model. The view part could be in any concurent model of computations as real-time constraint is not necessary.

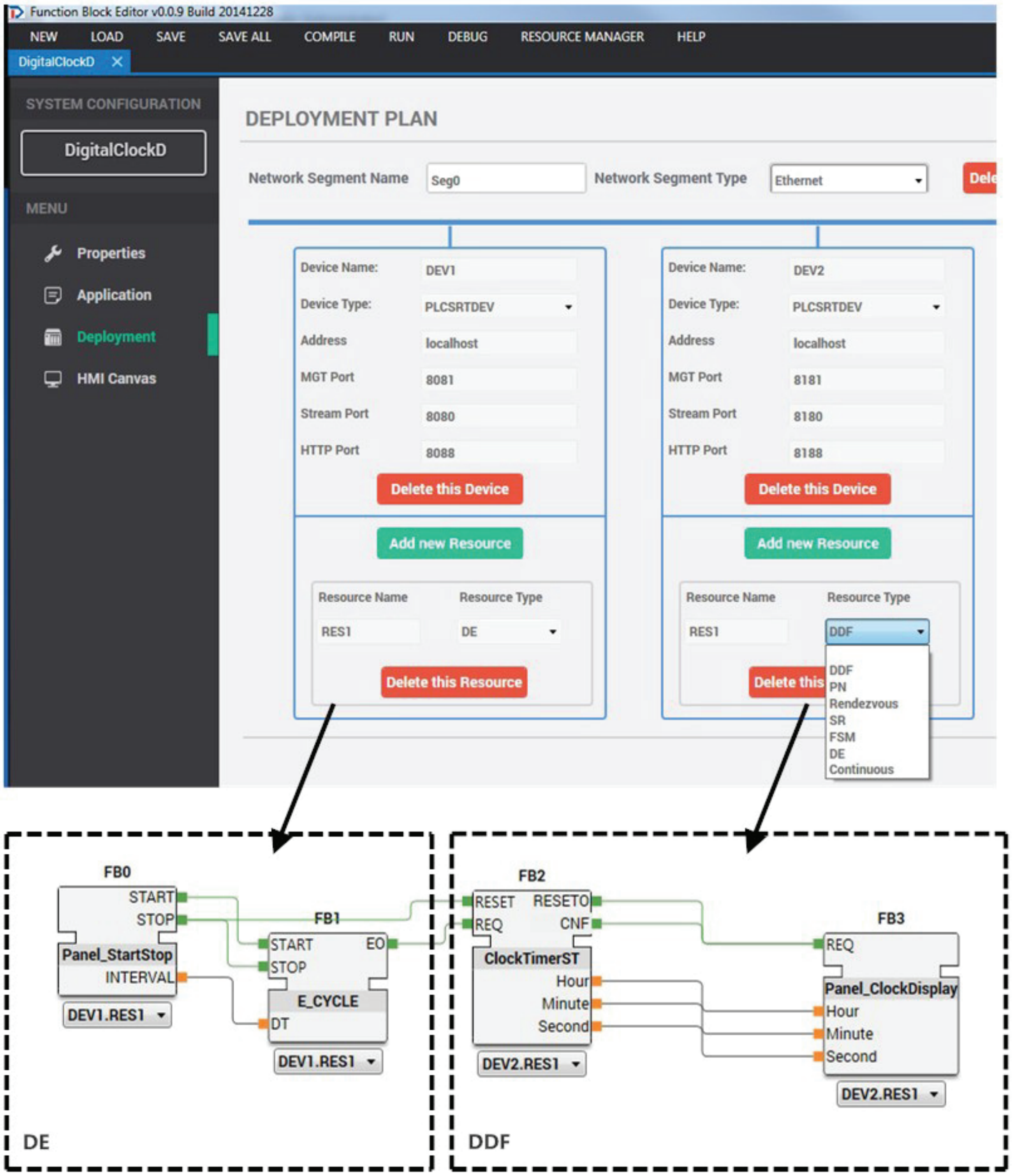
V. IMPLEMENTATION

In order to illustrate cyber-physical view of distributed automation system design, a cyber-physical view-enabled IEC 61499 software tool is needed. In the previous work [32], an IEC 61499 IDE and runtime based on service-oriented architecture is developed to enhance interoperability and flexibility for distributed automaton systems. To extend the existing tool and runtime with cyber-physical view, models of computation including Rendezvous, Process Networks, Synchronous and Dynamic Data Flow, Continuous Time, Finite State Machine, Discrete Event are introduced in the IEC 61499 Function Block Editor as shown in figure 6. One of these computation models shall be selected for each IEC 61499 resource during system design process. In system configuration, function blocks are mapped to IEC 61499 resources which are specified for particular execution models. Providing multiple models of computation could be supported by all IEC 61499 IDEs easily.

As shown in figure 6 below, during deployment configuration, each resource could be set to a particular model of computation. A networked digital clock system where time source generation is separated from display function blocks. For each part, a suitable model of computation is set. In order to support multiple models of computation, various IEC 61499 runtime must be used as all existing IEC 61499 runtime are dedicated for one particular execution semantic. In one IEC 61499 device, multiple resources are allowed however they must use identical model of computation. Function blocks configured for a particular resource will be transferred to the runtime via IEC 61499 management commands. There is not yet a configurable IEC 61499 runtime which suits for all scenarios. The Function Block Service Runtime (FBSRT) developed is using discrete event model. Synchronous and dynamic data flow models are implemented in the FBSRT. Other models will be added in the future.

VI. CONCLUSIONS AND FUTURE WORK

Cyber-physical systems integrate networked embedded systems with physical processes. A comprehensive abstract modeling language to cover existing models of computation, communication networks as well as physical plant models is one of the key feature in cyber-physical system research. Co-simulation of control software, plant model and networking is achieved by concurrent model of computations in cyber-physical systems. Distributed automation systems could be modeled in cyber-physical way by introducing concurrent model of computations in the IEC 61499 standard. By applying the cyber-physical view with the IEC 61499, control, communication and physical plant in distributed automation systems are covered in one graphical modeling langauge.



Network Segment Name: Seg0
Network Segment Type: Ethernet

Device Name: DEV1
Device Type: PLCSRTDEV
Address: localhost
MGT Port: 8081
Stream Port: 8080
HTTP Port: 8088
Resource Name: RES1
Resource Type: DE

Device Name: DEV2
Device Type: PLCSRTDEV
Address: localhost
MGT Port: 8181
Stream Port: 8180
HTTP Port: 8188
Resource Name: RES1
Resource Type: DDF

Fig. 6: Cyber-Physical View Implementation Example in IEC 61499 Function Block Editor

For the future work, this work will continue on integrate real time with the IEC 61499 standard for industrial CPS. By introducing timing-centric programming to distributed automation systems, a deterministic computation model can be established to eliminate differences between hardware platforms. A timing-centric execution semantic will be investigated to ensure software components can be utilized on any hardware platforms without any modification. Also all existing execution semantics in IEC 61499 and IEC 61131-3 as well as fieldbus protocols will be introduced into the IEC 61499 software tool.

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