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Adaptability in IEC 61499-Based Distributed Control for Automation Applications

Ernesto Monroy Cruz [1 +], Luis Rodolfo Garcia Carrillo [2], Sandeep Patil [3], and Nicole C. Hellman [4]

[1] Posgrado CIATEQ A.C., Advanced Technology Center, Mexico.
[2] Klipsch School of Electrical and Computer Engineering, New Mexico State University, USA.
[3] Department of Computer Science, Electrical and Space Eng., Lulea University of Technology, Sweden.
[4] Mechatronics Systems Laboratory, CETIS No. 026, Mexico.

Abstract. Today's manufacturing requires a new generation of factories capable of coping with the increasing complexity in process automation generated by the continuous changes in product demand and variety. Thus, automation applications need to be designed to solve this complexity by distributing control execution across different devices. The IEC 61499 standard encourages the design of distributed control applications by defining an application model that can be mapped to numerous hardware components. In that context, this paper presents the way to resolve a system when it extends its functionality, showing an automation solution for a packet sorting system using the distributed approach design through a distributed architecture of the control algorithms, using the IEC 61499 language. Virtual model of the process, a centralized solution, and the distributed control approach are implemented in a commercial IDE platform. These control techniques were compared with metrics, resulting in a better adaptability for distributed control pattern.

Keywords: IEC 61499, distributed control, industrial automation, function block, adaptability

1. Introduction

The evolution of manufacturing systems is mainly based on the development of highly connected resources throughout the process to adapt highly globalized markets, which have brought with them new requirements, such as: product customization, demand uncertainty and allowing the efficient use of available data [1]. This has made it necessary to modify the control architecture to make it flexible, reactive, and sufficiently adaptable to achieve the objectives [2]. In view of this, several control approaches have been proposed: Multi-Agent Systems (MAS) based on entities with intelligence [3]; Intelligent Manufacturing Systems (IMS) that have emerged due to the important role played by programming techniques within distributed control systems [4]; Holonic Manufacturing Systems (HMS) in which highly distributed modules are established, whose intelligence is distributed among individual entities called holons, which are autonomous, cooperative, intelligent, and reusable [5]. Nowadays, as a result of the use of evolved programming techniques, the Cyber-Physical Systems (CPS) promote flexible and distributed control systems inside the paradigm of Industry 4.0 [6]. All the techniques mentioned above, converge by needing to use IT-based controllers with secure infrastructure to manage data in a manufacturing environment. Therefore, a physical resource at the plant level needs to be communicated through standardized protocols. In that sense, the IEC 61499 standard [7] emerges as a modular software that can be used in distributed control processes, developed for algorithms that are compiled in PLCs, implemented through structures called Function Blocks (FBs) [8]. The FB model in IEC 61499 achieves the development of distributed software components, which allows the user to encapsulate and abstract access to hardware, communications, or application programming interface resources. This standard provides features such as: portability, interoperability, configurability, reconfigurability and distribution [9]. Each FB consists of a graphical event data interface and a set of executable functional specifications (algorithms), represented as a state machine called Execution Control Charts (ECC) in Basic FB (BFB), or as a network of other FB instances in

[+] Corresponding author.
E-mail address: ernesto.mz@atitalaquia.tecnm.mx

Composite FB (CFB), or as a set of services in Service Interface FB (SIFB). FBs can be interconnected in a network using events and data connections to specify the complete control application. The execution of an individual FB in the network is triggered by the events it receives. This well- defined event data interface, local data encapsulation and control algorithms make each FB a reusable functional software unit [10]. It is claimed that the FB model provides a framework for intelligence distribution in automation, where intelligence is genuinely decentralized and embedded in software components, which can be freely distributed across networked devices.

The aforementioned features of the IEC 61499 allow it to create large distributed applications in industrial automation domain. One of the main challenges to develop intelligent systems remains as: modeling techniques for distributed automation software that involves physical processes. Therefore, the contribution of this research article is a demonstration in how to optimize automation system designs that needs to be distributed across many devices, based on the IEC 61499 standard. We therefore compare design patterns regarding their adaptability to provide recommendations on their usage. Allowing automation engineers to create distributed applications that promote integrated control, computation and communication, software models. This paper is organized as follows. Section II presents related works regarding modeling techniques in the area of intelligent automation based on the IEC 61499 standard. In Section III, the example system is presented. The system controls are shown in Section IV together with their implementation in nxtSTUDIO IDE. Centralized and distributed architectures are compared in Section V based on adaptability metrics when the classification system is extended. Finally, the paper is concluded in Section VI.

2. Related Works

Since the IEC 61499 standard emerged as a tool for decentralized control of manufacturing processes, it has been the subject of study by the scientific community to obtain more efficient manufacturing systems. Vyatkin presents in [11] the main works related to the design of distributed automation systems with IEC 61499, showing that promising application areas of the standard include flexible material handling systems, reconfigurable automation, and intelligent distribution networks. A multi-agent control approach is presented in [12] to an airport baggage handling system, where each FB component represents a conveyor belt of the entire system. According to holonic principles each component is autonomous and collaborative, so that the structure and behavior can be completely defined by the interconnection of these components in the programming environment. In [13] a solution to the automation of a custom shoe factory is presented using a distributed modular approach for agile factory integration and reconfiguration. This is through a multi-agent architecture that considers a knowledge-based cooperation policy that provides self-adaptation to both internal and external events. Other approaches in the implementation of distributed control models are presented in [14], [15] different degrees of modularity of the components that influence the distribution of control algorithms for the automation of a weighing unit are proposed. Similar, in [16] a controller for a pick and place manipulator composed of four units called intelligent mechatronic components, emphasizing the importance of each unit of the system having its own control device, sensors, actuators, and software, which provides basic services and operations. The units are connected side by side as a network, allowing them to communicate and interoperate with each other. According to [17] there is still three main types of challenges with the transition to IEC 61499. Two of these are system design and system redesign to model IEC 61499 system architectures and to advance its system capabilities. These aspects in system design are of utmost importance in modeling next-generation industrial control for distributed and intelligent automation. Research is still required to apply design and computing paradigms to industrial automation architecture modeling, including evaluation metrics.

3. Case Study

A classification system by packet destination (local, and national) as shown in Fig. 1 has been taken as a case study. The packages arrive at the system through the conveyor belt Conv_In and each of them must be transferred to its corresponding conveyor belt: Conv_Loc for packages with local destination and Conv_Nat for national packages Each box carries an external bar-coded label to identify its destination.

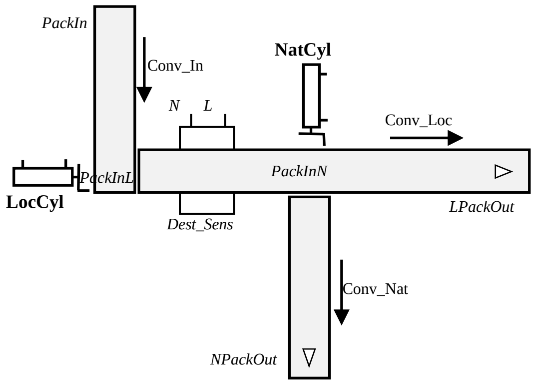

Fig. 1: Package classifier system.

In addition to the belts, the system consists of two double-acting pneumatic actuators: one horizontal (LocCyl) and one vertical (NatCyl) that will serve as pushers to move the packages from one belt to another. 10 Sensors are also available: five of them are position detectors that report the location of the packages (PackIn, PackInL, PackInN, LPackOut, NPackOut) at the different points of the process belts; four sensors are associated with the start and end positions of the two cylinders (XRetracted and XExtended for each actuator); the last sensor is a bar code reader (Dest_Sens) to determine the destination of the packages, the reader has two possible output signals. Therefore, it determines whether it is Local or National.

Each actuator together with its associated sensors are considered as a system unit. Regarding the conveyor belts, it is considered that they are always active, therefore, they are not contemplated in the control, which means that the system to be controlled is made up of two main components. The following is a list of requirements and conditions associated with the operation of the units:

- Each cylinder has two input signals to indicate the type of movement to be performed: XPush and XRetract.
- The LocCyl cylinder is responsible for pushing the package that reaches the end of the Conv_In belt (detected by PackInL) to the Conv_Loc conveyor, where the Dest_Sens barcode reading system detects the boxes with Local or National destination.
- The function of the NatCyl cylinder is to transfer each packet that has been classified as national and in front of it (detected by PackInN), to the Conv_Nat belt.
- Conv_Loc and Conv_Nat conveyor belts have a sensor at their end to detect when a package leaves the sorting system.

4. Implementations

This section presents the implementations carried out on the nxtSTUDIO platform [18] on the model of the system to be controlled, a centralized solution and a distributed approach, under the context of IEC 61499 standard.

4.1. System Model

Since the proposed centralized and decentralized control architectures are considered at the L2 and L1 levels of the ISA 95 standard -which aim at controlling the equipment to achieve the execution of the production process (L0)-, access to the actual hardware inputs and outputs are excluded in the implementation. Therefore, the proposed packet classification system is simulated by running a nxtSTUDIO Runtime on a PC, where such access can be performed by using dedicated FBs to abstract the hardware level. The CAT combines function blocks composed of both the cylinders and their parts as well as the sensors. It is possible to develop the whole packet classification system model by adding in the main application the CATs of the rest of the involved sensors. Resulting Human-Machine Interface (HMI) is shown in Fig. 2, it represents the system described in Section III, showing the two cylinders together with their limit switches, the package position detectors on the conveyor belts and the destination sensor. Once the model of the system that will be controlled is assembled using CAT instances, it is possible to implement the control parts.

These have been developed following the reusable Composite Function Block (CFB) methodology described in [16].

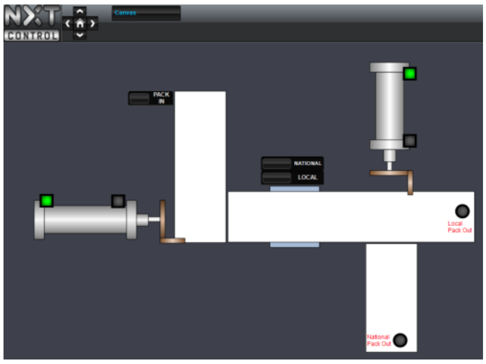

Fig. 2: View of System Model in nxtSTUDIO.

4.2. Centralized Control

The central controller at the L2 level is in charge of supervising and organizing the activities of all the components of the packet sorting system, see Fig. 3a. In this case, it corresponds to a single CFB that sends events/data to the CAT System_Model to push or retract the pneumatic cylinders according to the sensor information and the desired system performance, in Fig. 3b is shown this connection.

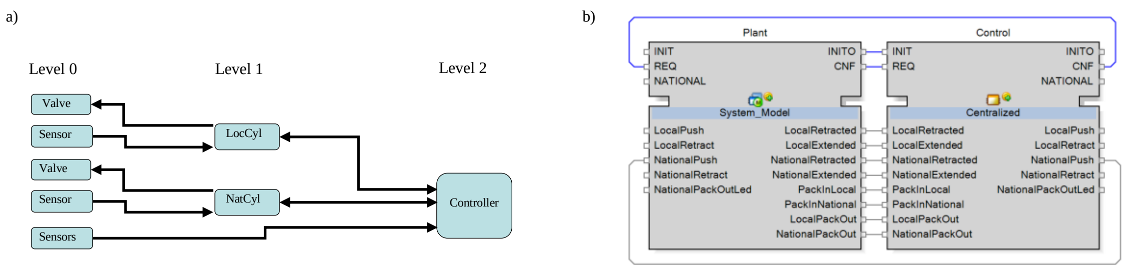

Fig. 3: Architecture: (a) ISA-95 low levels for centralized control in the application; (b) Centralized control (some connections are emitted for simplicity).

The execution control chart (ECC) of the central controller is shown in Fig. 4, it consists of 7 states and 6 algorithms, which allow the centralized control to monitor the location of the packages on the different conveyor belts, as well as to determine the destinations, capturing events from the sensors, and to activate or deactivate the valves of the pneumatic cylinders that position the boxes according to their destination.

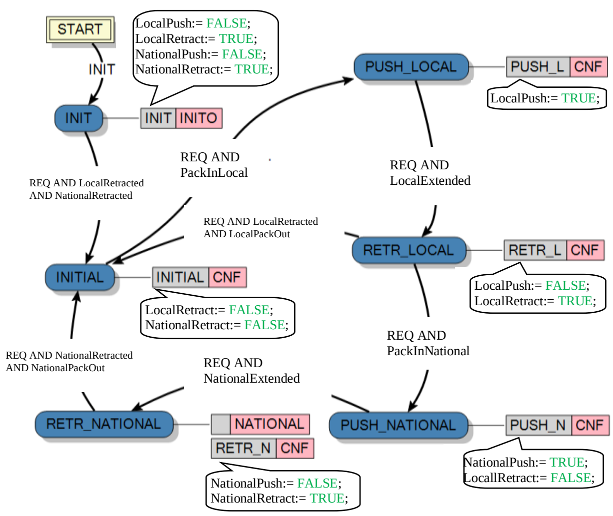

Fig. 4: ECC and its algorithms of the centralized control.

Since the HMI and control nodes communicate between pairs, once executed, the application built using the system's CAT and the controller's FB directly provide full interaction to evaluate the performance of the control implemented in the classifier.

4.3. Distributed Control

Unlike the centralized control shown above, the distributed approach in this application does not contemplate any element in L2, so this level disappears. The functionality of this level is transferred to the individual components in L1. At this level control signals are sent from one component to another. A simple hierarchy is reflected in the lower levels, for example a cylinder module (L1) is connected to its valve and its position detectors (L0). Therefore, the control hardware is distributed throughout each of the pneumatic cylinders. Regarding the corresponding software application in IEC 61499, the distributed control approach considers the use of Peer-to-peer CFBs assigned to each of the hardware devices controlling the cylinders. Each CFB, according to the events/data it receives, and the execution control chart created, is in charge of managing the behaviour of the electromechanic component associated with it, see Fig. 5. In addition, to perform its respective task, each cylinder needs to communicate with the sensors that indicates the position of the package on the belts and continuously request its status.

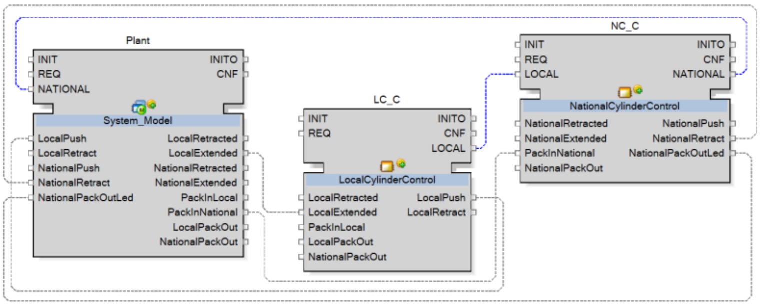

Fig. 5: Distributed control (some connections are emitted for simplicity).

The interaction between CFBs occurs in such a way that the LOCAL and NATIONAL events act as a feedback to the command of another functional block, see Fig.6 - Fig. 7. This relationship conditions the actuation or blocking of the adjacent CFB, for example: the operation of NatCyl is restricted to the transfer a package from Conv_In to Conv_Loc through LocCyl; a situation that triggers the LOCAL output event in the CFB from the local cylinder and connects to the CFB input event of the national cylinder.

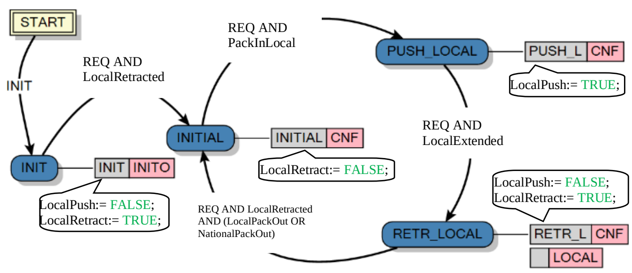

Fig. 6: ECC and its algorithms for local cylinder control.

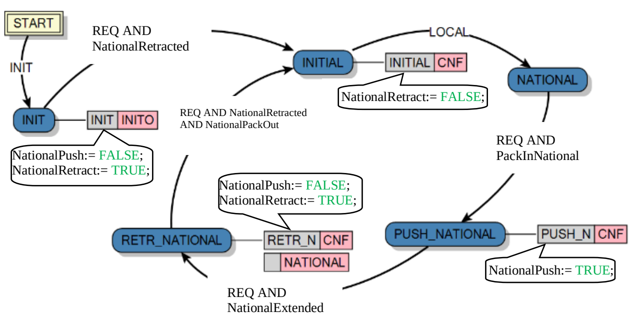

Fig. 7: ECC and its algorithms for national cylinder control.

5. Architectures Comparison for Adaptability

As an experiment for analyzing the way of adapting/extending the functionality in both architectures and compare the implementations with respect to adaptability metrics, now the system must also classify foreign packages. For this the following elements (highlighted in blue in Fig. 8) were added to the original classificatory system: a conveyor belt Conv_For alongside its sensor FPackOut at the end, a ForCyl cylinder which passes foreign boxes to the Conv_For belt when they are in front of it (detected by PackInF), and a bar code reader NatOrFor_Sens that determines whether the destination is National or Foreign.

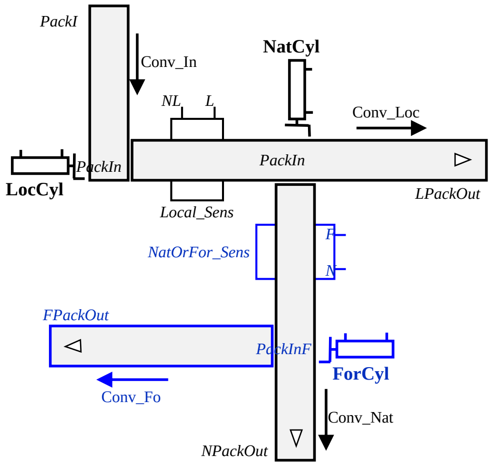

Fig. 8: Additional elements in the Package classifier system.

1) Centralized Control: the added instances of the elements in the strictly hierarchical design requires updating the top-level controller ECC, whose complexity increases significantly with 2 new states, 3 new transitions, and 6 new interface elements, see Fig. 9. This reflects that implementing all the functionality in a single ECC implies a greater effort in the correct definition of the states and their transitions, in addition to the fact that the extension of the diagram can cause confusion during the design and during the testing of the whole application. Besides, the control FB has a low reusability and is valid only for a certain scenario. Not to mention that the failure of the single control hardware represents the complete shutdown of the entire system since the elements of the L1 and L0 levels would not receive signals.

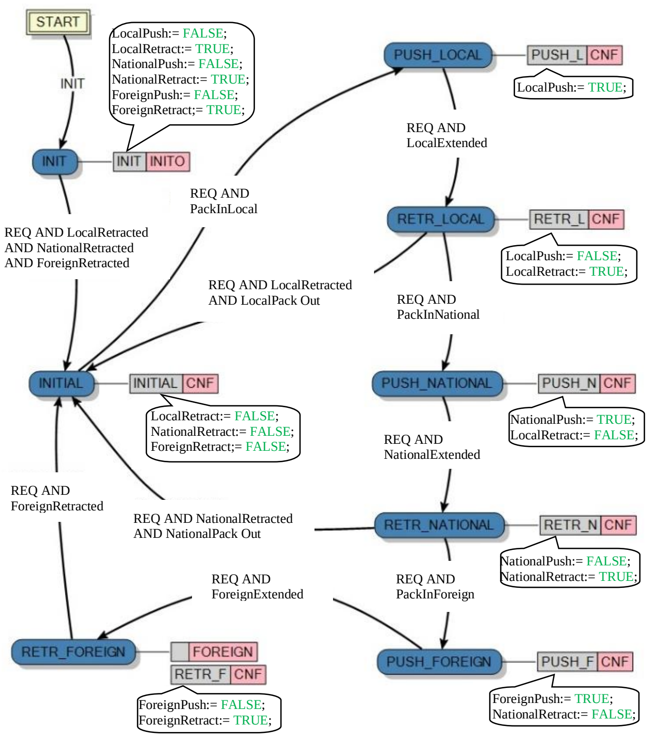

Fig. 9: ECC of the centralized control for the extended system.

In terms of adaptability and flexibility, as soon as another component needs to be added to the process, the ECC must be restructured according to the operating conditions of the new element. Then, as the size of the system to be controlled grows, the complexity also increases, therefore, this approach is not feasible for software development and implementation at industrial level.

2) Distributed Control: in this architecture, there is the possibility of reusing their software functionalities by simply modifying it with minimal effort. Then the NationalCylinderControl FB is copied to be instantiated as ForeignCylinderControl, which keeps the same number of states, transitions, algorithms, actions and interface elements. The control flow is adapted only by changing event connections and rename some interface elements as the ECC shows in Fig. 10. The output event NATIONAL now triggers the functionality of ForCyl. The ForeignCylinderControl is also connected to the corresponding sensors. For this implementation, neither the extension of the application requires creating new or different types of FB nor extend existing ones as in the centralized control previously mentioned. Other advantages of this control structure in IEC 61499, it is noted that, due to the distribution of the application, software components can be easily assigned to devices. Furthermore, in case any control hardware fails, the software logic control could be easily redeployed to some of the other hardware that are functional [19]. The system configuration model in IEC 61499 for the case study extended is shown in Fig. 11.

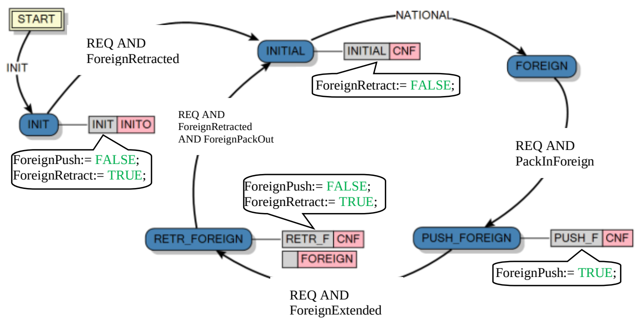

Fig. 10: ECC and its algorithms renamed from an existing control.

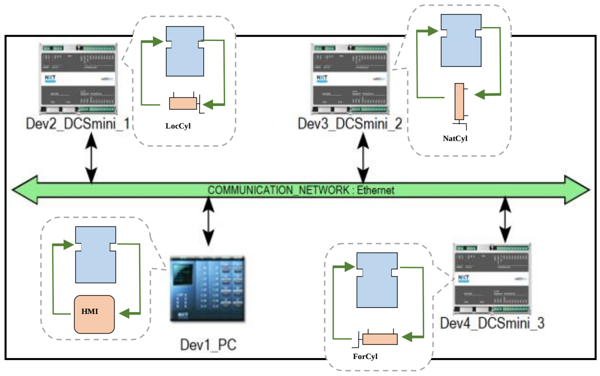

Fig. 11: IEC 61499 System configuration for the extended distributed application.

A four-device distributed control system is simulated by running four nxtSTUDIO Runtimes on a PC; one from the extended System_Model -which represents the actual process and is displayed on the HMI- and three of the DCSmini controllers from NXTControl. Thus, each part of the system is designed to be controlled by an individual PLC identifiable by its unique ID port. The Ethernet segment models the communication channel for all device instances in nxtSTUDIO. The data and event tracking of the complete application created in nxtSTUDIO IDE adequately reflects the description of the behaviour case study with the extended functionality.

In order to evaluate and compare the adaptability of the architectures, the software metrics for the IEC 61499 were calculated based on the *Spider Chart BFB Measures* described in [20]. These metrics were applied to both the initial and adapted centralized control FBs. On the other hand, in the distributed approach the NationalCylinderControl and ForeignCylinderControl were considered as initial and adapted FBs respectively, because one of them was created from the other. The results for the centralized and distributed systems are shown in Fig. 12. In most parameters, the complexity of the adaptability is higher in centralized implementation. It is also observed in the spider chart that the control FB for ForCyl did not increase the parameters values when it's obtained from the control FB for NatCyl. That means a minor effort in adapting system control for applications require extending or changing their operation through a distributed architecture.

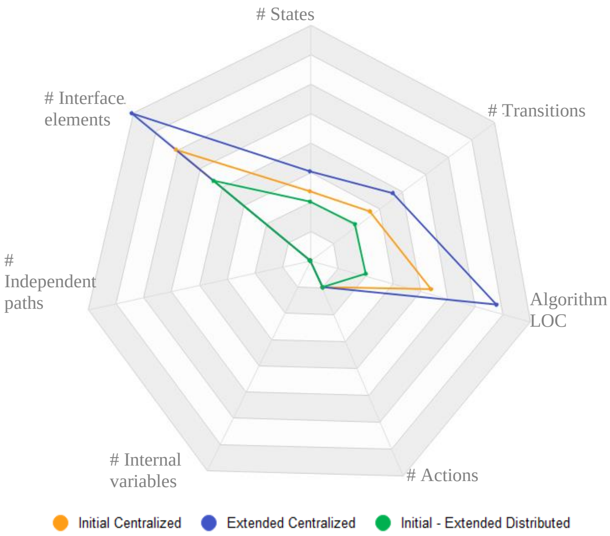

Fig. 12: *Spider Chart* BFB Measures of the Controller FBs mentioned above.

6. Conclusion

Centralized and distributed controls were successfully implemented in the nxtSTUDIO environment. In the first of these approaches, the rigidity and centralization of the control structure implies a weak response to change, so these types of architectures are not designed to exhibit the adaptability and evolution that is required today. Regarding the second approach, the close relationship of intelligent systems with the IEC 61499 standard offers a distributed way to design control applications in industrial automation because they are better suited to modularity solutions. Similar, distributed automation systems can be modeled by applying IEC 61499 FBs in which control, communication and physical process are covered in a graphical modeling language.

To achieve the control distribution objectives, the IEC 61499 standard has been adopted as the design paradigm, due to its orientation to the deployment of modular and distributed control solutions. A function block (FB), representing a software functional unit, associated to a hardware resource of the control system, properly connected with more FBs can define an application, and the distribution of this can be configured among various devices of the control system. Hence why we recommend to use distributed control design for automation applications that could be later split on several controllers. Finally, adapting functionality in the distributed design does not seem to require so many modifications in the FB types, thus reusability is increased and development effort and time decreases as confirmed by applied metrics.

7. Acknowledgement

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