Control of Manufacturing Systems by HMS/EPS Paradigms Orchestrating I4.0 Components Based on Capabilities

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Abstract. The fourth industrial revolution has driven initiatives worldwide following the Industry 4.0 (I4.0) context, requiring better integration and relationship between elements. This work was applied the Reference Architecture Model Industry 4.0 (RAMI 4.0) to present new models for standardizing entities in the I4.0 context to migrate legacy systems and standardize assets based on I4.0 Components (I4.0C). The management and orchestration of I4.0C can be achieved by attaching Artificial Intelligence (AI) concepts through intelligent entities describing the behavior and resources relationship, applying Multi-Agent systems (MAS), and adding self-organization, reconfiguration, plug ability, adaptation, and reasoning. Therefore, a manufacturing systems control framework is proposed based on capabilities and HMS/EPS application to orchestrate I4.0C.

Keywords: Industry 4.0 (I4.0) · Holonic Manufacturing Systems (HMS) · Evolvable Production Systems (EPS) · I4.0 Component (I4.0C) · Digital transformation · Artificial Intelligence (AI) · Manufacturing systems control

1 Introduction

In the traditional industry, engineering tasks are systematized, depending on the application domain where tools define the project's functionality, establish necessary resources, formalize the process, and finally determine each real asset's functionalities "skills" throughout its entire life cycle. However, when putting the system into operation, unpredictable behaviors can be identified, such as resource unavailability or new product insertion. In the current concept, service orders link competencies to real resources but, these models no longer respond to the context of I4.0. Therefore new paradigms that better meet the concept of "Intelligent Manufacturing" must be applied [1].

The digital industry transformation requires new approaches related to the virtualization of the physical systems. In [2], the digital transformation can understand the digitization of all processes, operations, supply, production, and logistics, through intensely digital models and ontology. I4.0 platform introduced I4.0C [3] utilizing methods to standardize and systematize the information and communication of assets and be a

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library that comprises different meta-models capable of presenting its semantics and the development of new models that enable applications for Intelligent Manufacturing [4].

This work intends to minimize the gap between emerging manufacturing solutions and intelligent manufacturing concepts. The RAMI 4.0 guidelines are used, and the digital models are described by Asset Administration Shells (AAS), according to the I4.0C context based on "capabilities" [1, 4]. Therefore, concepts of multi-agent systems (MAS) were introduced, based on Holonic Manufacturing Systems (HMS)/Evolvable Production Systems (EPS) paradigms.

It was also foreseen here agents specification, seen as "holons," which internally have knowledge and capacity for self-learning, evolution to seek new capabilities and negotiation. The aspects described deal with artificial intelligence systems (AIs) requirements [1, 7, 8].

This work focuses on designing a framework for controlling and optimizing resources (skills) coalition [1, 3, 8, 14]. Still, in these works, there are no specific control approaches that meet the I4.0 guidelines. Therefore, the scientific gain presented in this work was the conception of agent models based on the EPS/HMS paradigm to orchestrates services through resources "skills" that are reflected in the "Administration Shell" as a point of access and communication between virtual parties, which present their "capabilities" [1, 5–7].

2 Relationship to Applied Artificial Intelligence Systems

Intelligent agents are fundamental components for system control to optimize, improve and organize manufacturing processes. With the objective of modeling iterations between intelligent entities, those are responsible for attributing to the system characteristics such as cooperation, coexistence, or competition, by attaching concepts of Artificial Intelligence (AI) and "Distributed Processing" [6]. Multi-Agent Systems (MAS) are widely studied in the literature [10], i.e.: (i) Tools for intelligent decisions apply MAS to distribute control and automation to components, providing autonomy, flexibility, robustness, or reconfigurability on traditional systems [5, 6, 8–10]; (ii) MAS uses advanced data analysis combined with AI for self-awareness, data mining, processing, calculation of health forecast, or valuable life estimate in manufacturing systems [11, 12]; (iii) In [13] uses a generic data-oriented architecture to interconnect different legacy systems; (iv) An architecture that describes the control of fault-tolerant manufacturing systems based on HMS was proposed [8]; (v) A formalism for EPS was presented, based on the description of models, to create an environment for developing evolutionary systems [9].

However, MAS exposes functionality through services transparently, without clarifying the ontology used from representation, integration, and relationship between assets models.

3 Literature Review

This paper has analyzed the works in Table 1 and combining some prominent features to generate the framework proposal.

In [1, 3], an ontological description represents resource abilities using capacities concepts and standard models in the I4.0 context. This work contributed to an architectural guideline for virtual resources representation by AAS. The works [5, 7] are state-of-art for specific architectural control applications based in HMS and MAS. In [8] has been validated an architectural engineering method using the features described in [5, 7], adding aspects of service based on internal components structure. These works inspire the agents modeled to attend I4.0 (capacities-based and object interactions) described in this paper.

Lastly, in [9, 10, 14], the EPS paradigm has HMS and MAS characteristics for integrated legacy systems based on modules. The disadvantage of these last references was that they presented embedded tools to support applications without clarifying the modeling and mechanisms to add such evolvable aspects. The second point was about society applications that do not deal with I4.0 guidelines architecture.

Therefore, this paper has extracted the means characteristics discussed in this section to generate the framework proposal. That treats a reconfigurable and evolvable application based in HMS/EPS to orchestrate functionalities described in AAS dealing with I4.0 standard.

Asset Administration Shell (AAS) standardizes information and other resources through descriptions in virtual models [4]. The concept of "Capabilities" composing ontological bases for AAS is described; however, different application domains must validate it, such as intelligent systems coordinating resources through "Capabilities" described in AAS [1].

3.1 Architectures to Orchestrate "Capabilities"

It was combined the following architectures to model the intelligent application based on "capacity engineering":

a) Holonic Manufacturing Systems (HMS) - inspired in [8] based on PROSA (Architecture for Holonic Manufacturing Systems [7]) assigns "self-organization" capacity and "coalition" through temporary resource, also provides the system a description for agents specifications in the proposed architecture [5].
b) Evolvable Production Systems (EPS) - apply characteristics of "reconfiguration", "modularity", and "adaptation", inspired in [9] descriptions that present the IADE (IDEAS Agent Development Environment) [14].

3.2 Ontology and Modeling's Approaches for Virtual Representation Using "Component I4.0"

In [1, 3], the I4.0C is detailed, solving the introduction gap and allowing intelligent models to be implemented, such as "capabilities", self-organization of resources, or evolution based on the asset condition.

In addition to described architectures in the previous item, the I4.0 context requires virtual resources guidelines [5]. A three-dimensional model, divided into layers for the treatment of information (including the life cycle and hierarchical levels of traditional systems), was introduced by RAMI4.0 [4]. This reference architecture standardizes and

Table 1. Comparison of characteristics of the reference projects studied in this article

Reference(L)/Features(C)	Project	Paradigm	Mains aspects
1 - Bayha	RAMI4.0/AAS	I4.0/ SOA	Guidelines for virtual entities in I4.0 context, Capability-based engineering, and pluggability
3 - Bedenbender			Granularity abstraction to functionalities and resources representation, I4.0, DIN SPEC 91345
5 - Barbosa	ADACOR2	MAS	Self-organization components, generic architecture with a model for self-organization, and pheromone in entities
7 - Van Brussel	PROSA	HMS	Guidelines for developing a generic control layer, collaboration, changes and disturbances, adaptation, flexibility, a reference architecture for self-configuration, and plug-in plug out
8 - Da Silva	Hybrid	RMCS/ HMAS	A reconfigurable manufacturing control system, flexibility, safety in fault occurrence, architecture for optimizing reengineering
9 - Onori	FP6 EUPASS	HMS/ EPS	Integrate legacy subsystems, evolutive production systems, reconfigurability, distributed control, intelligence, and dynamic control
10 - Dias	PERFoRM	MAS/ SOA	Generic architecture, reconfiguration, legacy systems, distributed-service based layer, modularity
14 - Ribeiro	FP7 IDEAS	MAS/ EPS	Self-organization, plug-ability, tolerance to disturbance, and mechatronic MAS architecture

systematizes virtual resources through technical descriptions in I4.0C. To better describe the techniques and functions of I4.0Cs, [4] presents the "Asset Administration Shell" (AAS), containing a set of sub-models, allowing the "Assets" to perform a specific function through the "Administration Shell".

A sub-model is responsible for defining technical descriptions to support applications, as resources "Tasks" representation, "Events", and "Capabilities". A meta-model

"Capabilities" allows mapping the asset's abilities from systematic descriptions of skills. In this context, the need for intelligent solutions through mechanisms connected to sub-models is evident (for example, "Events" sensing new functionalities, new resource composition, or even monitoring conditions). Besides that, intelligent control for coalition or reconfiguration of resources through the sub-model "Capacities" can be implemented using "Administration Shell".

4 Work Purpose

This work's proposal represented by the "framework" in (Fig. 1) generates a systematic standardization for I4.0 through I4.0C to express an intelligent manufacturing process applying the ontology descriptions in Sect. 3. In Fig. 2 is illustrated a model for "Administration Shell Resources", described in this example as "Distribution Work Station". The resource "capabilities" were represented by two "Task" submodels. In each "Task", the submodel was described specific operations (for example, "removing the base from buffer", "transporting material").

It is noted that "Capacities" are described depends on the "project granularity" in "Product Administration Shell". It implies a certain "Administration Shell Resource" that has knowledge about its assignment but needs an "intelligent entity" to combine "Capabilities" between AAS and to form the production plan described in "Administration Shell Product".

This work purpose determines three "Administration Shell" types to support the representation of components in a manufacturing process: (i) "Administration Shell Production Plan" - represents the standardized knowledge of recipes to design each product; (ii) "Product Administration Shell" - in charge of providing the "Tasks" descriptions needed to manufacture a given product chosen from process steps; and (iii) "Administration Shell Resource" - represents the "functionality" attributes of real "resources", which can choose based on their "ability".

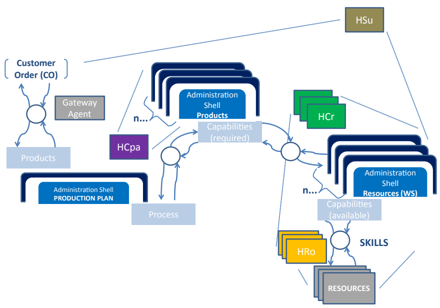

Fig. 1. Proposal framework orchestrating AAS.

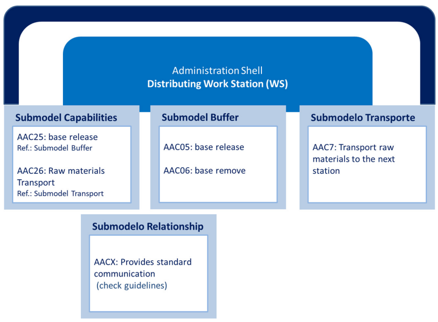

Fig. 2. Administration shells resource example.

When the traditional system introduces a CO, an "Administration Shell Production Plan" is standardizing, and processes are externalized by the MAS control and links "Product Administration Shell - PaS". The PaS describes the process with specific "capabilities" of "resources" contained in the respective "Administration Shell Resource".

The control aspects (Fig. 1) in this proposal deal with the intelligent application, chosen through HMS/EPS, that attributes to the I4.0C capacity of relationship, communication, coalition, reasoning, and decision making. A set of "holons" are assigned in this proposal: Holon Product Capacity (HCpa) is programmed to invoke and externalize the "capabilities" described in "Product Administration Shell". Holon Resource Capabilities (HCr) manages and negotiates with operational holons (HRo) and externalizes resource "capabilities". Holon Operational Resource (HRo) represents the physical resources, perceives the abilities of the resources, has the sequence of operational events, and executes service orders from (HCr), implements conditions, and updates data of "Administration Shell Resources". Holon Supervisor (HSu) coordinates operations and evolution, adds new components, verifies system behavior, and manages coalition and reconfiguration presented in proposal results.

5 Results

In this work, some propositions are made; - Coalition: means the possibility of grouping services described in "Administration Shell" by capacities; - Reconfiguration: means the system's ability to organize itself in case of resources change or if the equipment conditions are different compared with "original plan"; - Skill: defines an agent able to deliver value to an application, considering EPS paradigms [6]. Also, in [1], this term is described in Administration Shell "Tasks" sub-models. Therefore, this section presents two intelligent agents designed to meet these criteria. The integration between these systems PFS (Production Flow Schema) was chosen for modeling, as it is widely known in the engineering area (Figs. 3 and 4).

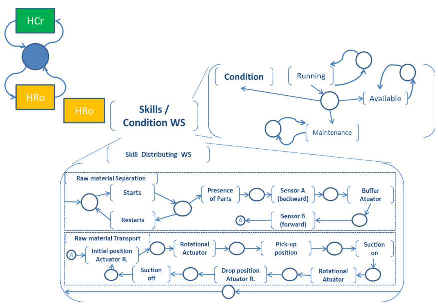

Fig. 3. Modeling intelligent agents "HRo" – Skill and condition monitoring.

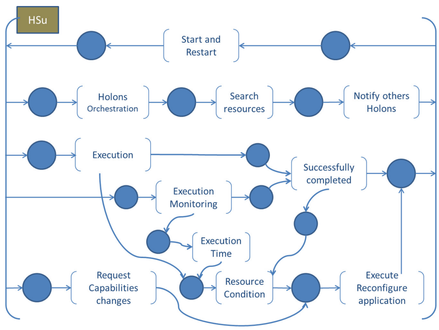

Fig. 4. Modeling "HSu" for supervision of capacities and reconfiguration.

The definition in [1] shows standardized descriptions in sub-models "tasks" of Administration Shell, which meets the requirements in the I4.0 context. However, this information provides a process operations domain, and a superior intelligent entity must access these. For this, this work used the descriptions contained in "HRo" (Holon Operational Resource) inspired in [8], which was revised and modeled to deal with AAS and evolution characteristics observed in [9].

Holon resources (Hro): implements two main routines: (i) Realize the capabilities of the resources (Skills) -Through the agent's knowledge, the Hro externalize "resource skills", as well, negotiate the "service orders" linked by the "HCpa" (Holon Capabilities). HCpa demands "skills" utilizing operation knowledge. An example of this system is dealt with in the PFS in Fig. 3 [8]; (ii) Condition monitoring (Events) - in addition to the knowledge about "skills", to meet the requirements of reconfiguration, plug-and-produce, and evolution of "capacities", the ability to express "events" about resource "condition" was modeled on the "HRo". These events are treated, processed, and then externalized to the respective "AAS-Resource" through the "Hsu".

Holon Supervisor (HSu): This agent is in charge of informing about changes in "capacities", reconfiguring the system by calling other projected holons, as well as adding or removing new agents (Fig. 4). The main characteristics implemented in these agents: (i) Execution Monitoring - this function involves the coordination of "relationships" between holons, monitoring the operations in execution, the tasks related to each interface between holons and AAS in addition to orchestrating the individual strategies of the holons [8]; (ii) Holons orchestration - perform entities coalition by an internal mechanism that determines the sequencing of holons capable of answering a call [8]; (iii) Execution Time - utilizing "events", sending messages within a specified time interval; (iv) Capabilities changes (evolution) - occurs when a CO has finalized the HSu external messages through "Events" to the participants if there was a success or not in the execution, if not a reconfigurable mechanism, must update the information contained in "Administration Shell of Resources".

The advantage achieved by this structure is to enable the coalition of resources by "engineering capacities based". This proposal makes it possible to change the traditional systems. The resources are standardized in the virtual environment (AAS), reducing programming efforts. The manufacturing life cycle is optimized to meet the connected world's demands, characterized by distributed equipment. The EPS/HMS is widely discussed in academia [5, 7–10, 14]. There are few use cases with real data in which they do not apply to the I4.0 (AAS) context. The concept of capacity-based engineering is addressed in this proposal through a framework that seeks to solve the gap for orchestration and coalition of I4.0C.

6 Conclusion and Future Work

This work proposal describes a method for orchestration and reconfiguration of I4.0C based on "Capability-based engineering". These systems are adequate to meet the intelligent control system specification based on HMS/EPS paradigms. A framework containing a multi-agent system (MAS) proposes to add intelligence requirements on AAS.

An application that improves the relationship between virtual entities by adding the characteristics described above establishes its ontology. It requires MAS-based tools to be integrated with the submodels and specifications according to the I4.0 paradigm. It was possible to observe the functional modeling for implementing EPS agents and an elementary domain for holonic systems specification.

The system's behavior presents PFS diagrams, respecting both the MAS project's characteristics and the guidelines for I4.0C through standardized meta-models. That results in preliminary data showing that the proposal is viable and achieves engineering based on capabilities by adding an intelligent framework to control the coalition and reconfigure the resource's abilities (skill). However, more experiments are needed to validate the proposal as a whole.

In the future, can be unified these projects, i.e., can be integrated MAS ontological specifications in different areas of knowledge with the respective AAS through intelligent submodels providing all the necessary characteristics for implementing these paradigms.

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