Enactive manufacturing through cyber-physical systems: a step beyond cognitive manufacturing

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Abstract: Cognitive manufacturing, as a paradigm for providing intelligence to manufacturing systems and enabling interaction with operators presents limitations. Manufacturing system requires to be adaptive to machine tools, manufacturing environments and operators. In this line, the enactive approach to cognitive science provides a paradigm for the design of new biologically inspired cognitive architectures. Likewise, the advantages of Key Enabling Technologies and the concept of Industry 4.0 reveal new opportunities for increasing industrial innovation and developing sustainable industrial environments. These technologies are appropriated to overcome the limitations of cognitive manufacturing, because they can achieve the integration of physical and digital systems focused on cyber-physical systems. In this work, an architecture for the sustainable development of enactive manufacturing systems based on holonic paradigm is proposed and its main associated informational model is described.

Keywords: Holonic manufacturing systems, Smart manufacturing systems, Cyber-physical systems, Key enabling technologies.

1. Introduction

Manufacturing systems are currently undergoing a deep transformation through the potential of Key Enabling Technologies (KET) [1]. These technologies try to configure intelligent manufacturing systems and reveal innovation and continuous learning as a lever of competitiveness and coevolution with the opportunities of the environment [2,3]. In this line, a key concept of manufacturing systems is Cyber-Physical System (CPS), which together with cognitive manufacturing system, are revealed as elements to support the implementation of Industry 4.0 in terms of innovation and learning in the systems of smart manufacturing [4]. Industry 4.0, mainly under the opportunities of digital twins (which support communication between the virtual and physical twin, between digital twins, and between operators / engineers and digital twins), enables new types of interaction between operators and machines [5].

Cognitive manufacturing, as a paradigm for providing intelligence to manufacturing systems and enabling interaction with operators as a support for tacit and explicit knowledge of manufacturing system, has proven insufficient in psychological areas. Likewise, cognitive manufacturing does not respond to the natural way of knowing manufacturing systems, facilities and operators, in which they operate from what is known and learned based on accumulated knowledge [6].

This work presents the advantages of the enactive cognition paradigm for incorporation into intelligent manufacturing systems, as well as the current opportunities based on KET to develop them.

2. Enactivism

New paradigms of embodied or enactive cognition appear from cognitive science [7], in which is argued that cognition is based and deeply limited by the nature of the body of agent and established from situated knowledge. More specifically, in the field of manufacturing systems studies aimed at conceiving manual work under the embodied mind [8]. Enactivism stresses that the beginning of intelligence is in the body in action. Its reason, according to Varela et al. [9], is based on the arrangement of the interrelation established between the body and the environment, and more specifically between the body and the mind. Thus, the human body is analyzed, not only the brain, as a source of cognition, where its movements and actions, guided by perception in the world, make much of the effort necessary to achieve the objectives [10]. This is contrary to the traditional ideas of how the mind works, characterized by the so-called computational metaphor of the mind, designed to perform an on-demand result / behaviour [11], where the body is reduced to an input and output device.

The enactive theory of cognition provides a paradigm for the design of new biologically inspired cognitive architectures, with an important influence on aspects of self-organization and emerging properties [12], likewise autonomy and adaptability [13], in order to offer improvements in decision making of decisions [14]. The confrontation between reactive agents and cognitive agents has improved the investigation with approaches of enactive agents [12,15].

This allows to gather the parallelism between the new paradigm of cognitive science of enaction or embodied cognition, with the new CPS concept as hybridization of the physical, technological equipment, and the virtual and intelligence in the Cloud [16], to overcome the limitations of cognitive manufacturing. This leads to the field of Enactive Artificial Intelligence [17], based on CPS formed by enactive intelligent agents with embodied, situated, distributed and constructivist intelligence. This embodied intelligence embedded in the physical dimension determines a form of action from the interaction mind (Cloud cognition) body (cell technology) in the context of the manufacturing cell in the manufacturing plant, which gives rise to the term coined in this study as *enactive manufacturing*.

2.1. Limitations of cognitive manufacturing

In regards to intelligent abilities, these are divided into [18]: cognitive abilities, which refer to the capacity of the human brain or artificial intelligence and the ability to carry out mental tasks (that is, awareness, perception, reasoning and judgment) necessary to achieve a certain objective in certain operating environments; and physical capabilities, which refer to human skeletal muscle or mechanical mechanisms, and the ability to perform a physical function (e.g. ability to lift, manipulate, or assemble). These cognitive manufacturing capabilities find an implementation option from the conception of CPS.

Both reactive (instinctive) manufacturing and cognitive manufacturing have limitations to be developed based on reactive, cognitive or deliberative agents and intelligent manufacturing systems in the scope of Industry 4.0, integrating human and technological operators on equal terms. Main limitations include:

- Creating environments for problem solving and improvement under a Lean approach in a collaborative way between CPS and human operators from the detailed knowledge of the context and specific tools of the workers, involving innovations or creation of new methods and work operations [8].
- Analyzing the improvement proposal coming from the different cells or workstations, decontextualizing it from situational and technological aspects (body) for reuse in other workstations through Big data and artificial intelligence techniques.
- Instantiating in technology parameters the improved procedures to reuse them in manufacturing stations with technological parameters (body) and in different contexts, defining knowledge located in operation.
- Explicit knowledge management (existing in the procedures manuals) in the face of new organizational changes in technologies, given that the cycle of the technological body is less than that of the organizational body.

- Building a reconfigurable manufacturing-oriented model, which has always considered the changes to be articulated in the reconfiguration of programs (mind) and technology (body).
- Configuring CPS under the concept of joint cognitive system and its mapping in intelligent agent technology [18], based on CPS as a hybridization of technology (body) and intelligence (mind) embodied, in the Fog or on the Cloud.
- The integration of biological manufacturing as a body of CPS.

These limitations (of the cognitive paradigm as the epistemic framework underlying cognitive manufacturing) have been made clear in the cognitive science literature [11,19]. The cognitive paradigm appears as intelligence formed and sustained by mental representations (symbolic or connectionist paradigm), on which to carry out cognitive processes (information processing). The lack of knowledge of the body and the context, from the connectionist and symbolic paradigm, makes it insufficient to explain human behavior, the result of learning by the interaction of mind and body in a context of manufacturing processes.

3. Enactive intelligent manufacturing agent

The enactivist approach suggests modelling a embodied cognitive agent on the basis of sensorimotor interactions with the environment [20]. Thus, the integrated cognitive computing agent appears [21], which includes an enactive layer that connects the perception layer (sensor and actuator with the environment) with the cognitive layer. Enactive manufacturing is incorporated into the concept of the extended mind, which maintains that certain cognitive processes must be understood as situated, embodied and oriented to certain specific objectives. In these situations, it is proposed that the brain, body, and operational environment become coordinated in a certain way, causing the mind or cognitive manufacturing to spread and build on the outside world. The knowledge and intelligence model of an enactive system such as the one proposed has a structure based on: (i) cognitive knowledge, parameterizable for environment and technology, and (ii) somatic knowledge, supported by technology or body.

Thus, the enactive intelligent manufacturing agent, as shown in figure 1, would be an intelligent agent with a virtual part (mind located in the Cloud-Fog and making itself evolve) and a real part (body located in a context) in the manufacturing plants (edge), tool, machine, manufacturing cell, process or department. This agent would have a parameterizable knowledge based on the context of use in which it is instanced, with learning algorithms under the integration of the flexibility and restrictions of the (technological) body and the specific environmental conditions. Likewise, it will be able the incorporation of projected emotional states in the interaction with humans (affective manufacturing) and the problem-solving strategy from deep learning (constructivism).

3.1. Cyber-physical system design

The concept of CPS is an operational or productive entity that has a material or physical existence on the edge. Next to it there is a digital twin that virtualizes the physical dimension in whole or in part, and enabling an improvement in the process of reengineering of the value chain [22]. It becomes necessary to establish the virtual dimension of the physical equipment and build digital models of them for the needs of the various agents associated with its life cycle, as well as for continuous improvement through artificial intelligence techniques such as machine learning, deep learning, etc.

To lead to the reengineering of a conventional machinery and facilities as a CPS is necessary to act as follows:

- Sensorization data of the physical process are integrated via data communication network, which can be local (for intranet) or in the Cloud, from where it receives data and information.
- Providing a controller. The controller is an on board computer system that monitors the physical process through the reading of sensors in real time or delay.

- Feedback loop by surrogated models. The controller executes the control program from data obtained from the sensors and operates the actuators in real time. The control program can come from the Cloud in the form of surrogated models.
- Providing through Fog and Cloud connectivity with CPS and the integration of computational processes, data communication networks and processes in the field, Cloud or Fog.

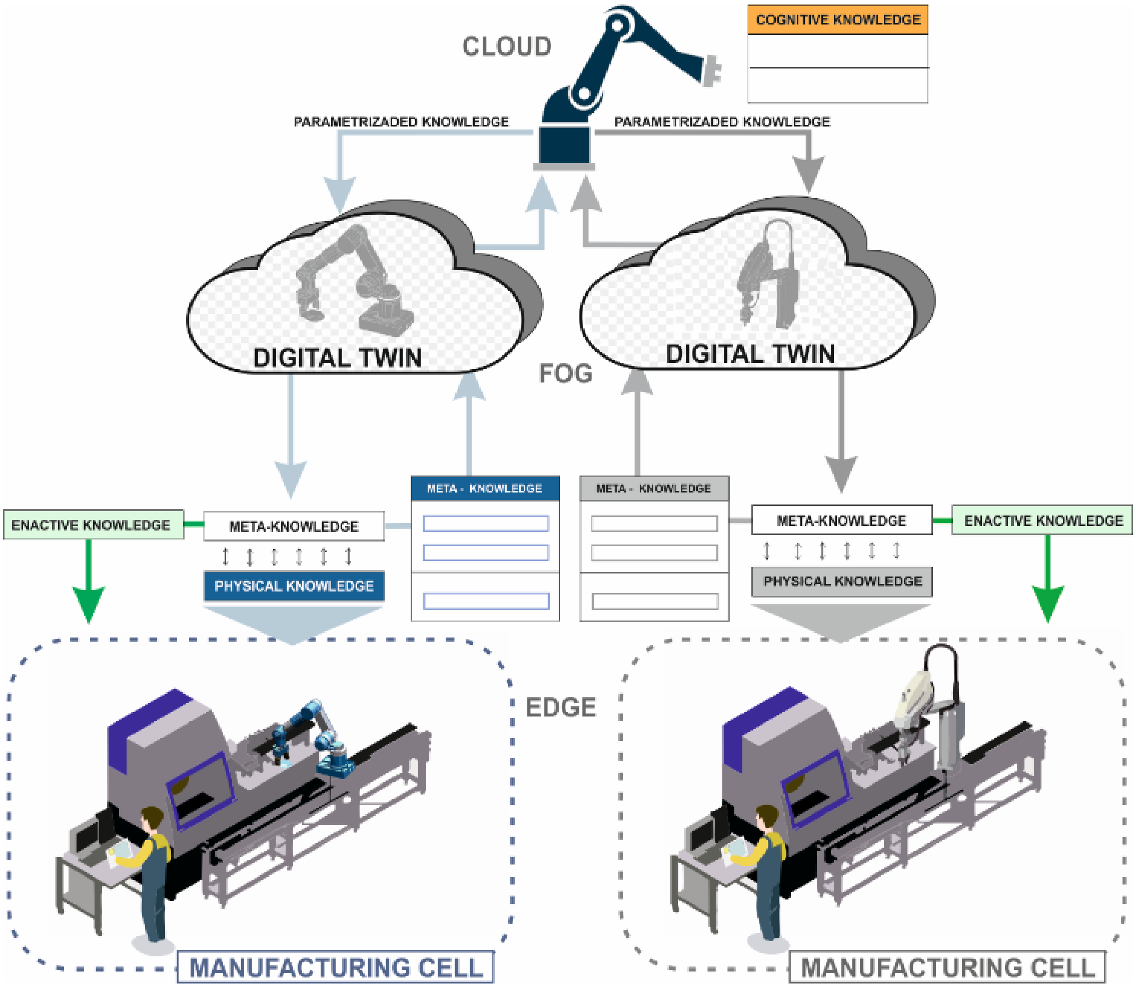

Figure 1. Enactive manufacturing based on key enabling technologies.

4. Architecture for the enactive manufacturing system

In the field of cognitive manufacturing, several frameworks for design and manufacturing, planning, provider of cloud manufacturing solutions, among others are being developed. Same examples are IBM Watson, the architecture of iRobot Factory or Siemens. However, the architecture proposed incorporate embodied and situated learning from the continuous improvement of Lean teams into knowledge engineering processes, taking part of the organization's explicit and tacit know-how, making it possible to co-evolve with the environment.

The learning and innovation paradigm from industry 4.0, which ensures the characteristic features of the construction and use of knowledge in sociotechnical manufacturing systems, is the paradigm of enaction. This determines that the enactive manufacturing system is conceived as a learning and cognition system characterized by:

- Enaction. Knowledge is dynamically constituted through the action of the sociotechnical system

(manufacturing system) interacting as a whole in the operational environment through coupling and operational dynamics, through learning and innovation from the interaction of the service provider and offers products and services.
- Technological Environment. Located in an environment with constitutive and operational coupling, self-regulated and autonomous.
- Embedded. Knowledge (explicit and tacit) is framed in technology, distributed at different levels of technological systems, in organizational modes and the biological body of operators.
- Embodied. An embodiment in a specific technology that promotes efficiency.
- Extended. The operational mind is extended to the surrounding area, not only in the context of the manufacturing system, but it is extended in the markets, suppliers and throughout the value chain.

This model of knowledge, learning and active innovation must be implemented under the focus of: (i) KETs, (ii) the conception of productive agents as CPS with a physical and virtual reality, including the operator as a CPS, and (iii) under a multilevel development (value chain, industrial plant and manufacturing cell).

The exposed enactive manufacturing system has characteristics that must be supported by a reference architecture that supports the CPS in the physical and virtual. Thus, the holonic paradigm is proposed [23,24], whose properties [25,26] include those previously expressed. Figure 2 shows the holonic architecture for the enactive manufacturing system.

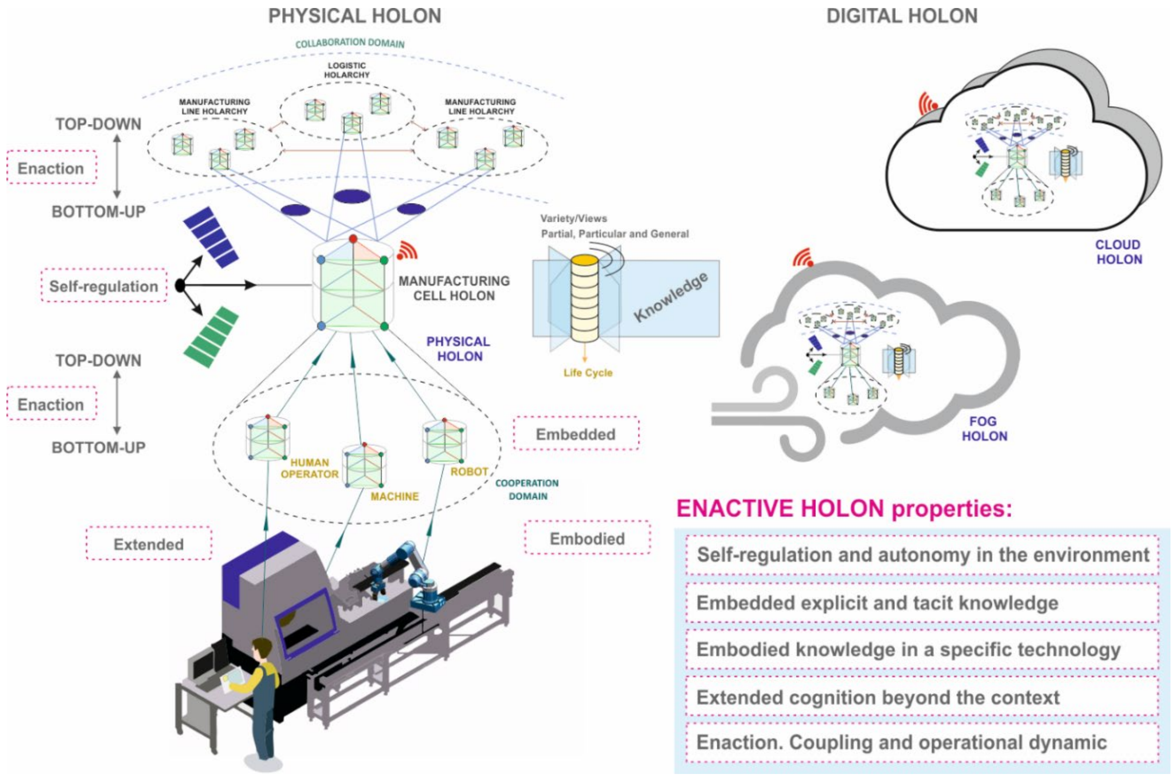

Figure 2. Architecture of enactive manufacturing holon.

Each holon represents an enactive manufacturing system entity. Thus, at micro level, the manufacturing cell holarchy (group of holons) can be constituted by a robot holon, human operator holon and machine holon. This basic architecture, which represents the cooperation domain, possess a collaboration domain at level of holarchy between other manufacturing cell holarchies, manufacturing lines, etc. The architecture proposed has a first level in the physical world (real entities), a second level at Fog (digital twin) with fast operation time, and a third level at Cloud where abstract enactive/cognitive knowledge is processes in a long term. This knowledge parametrizable and improved can be instantiated in a specific manufacturing cell holarchy taking into account its physical considerations (e.g. type of industrial robot) and its particular environment (humidity, temperature, etc.) in order to adapt the requirements of manufacturing process.

The innovation of the proposed architecture lies in the ability to retain, model and instantiate (based on the principles of continuous Lean improvement) the knowledge (explicit and tacit) from one process to another, from one manufacturing cell to another, even if they have different social, environmental, organizational, mechanical characteristics.

The proposed architecture requires an associated informational system, such as that shown in figure 3, which must consider multilevel (micro, meso and macro), multiscale (distributed manufacturing) and time aspects in the operations, tactical and strategic dimension.

In this research, CPS can be conceptually understood as a high-performance fusion of humans, machines, and the environment through information systems that collaborate and unite the physical and digital world.

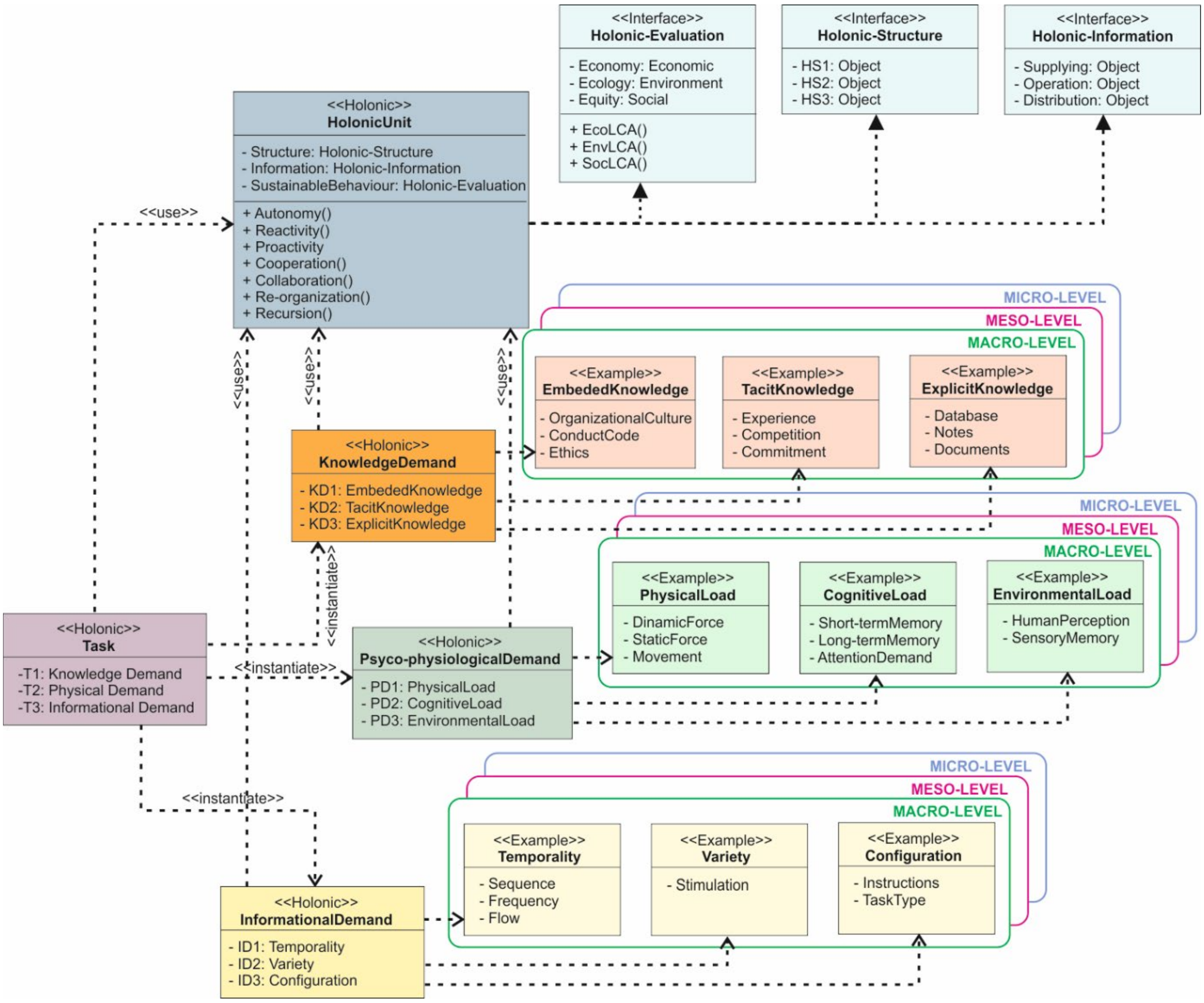

Figure 3. Informational modelling for enactive manufacturing.

The proposed informational model seeks to define the basic classes of holonic architecture for enactive manufacturing and their relationships. The basic properties of the holonic unit are defined as well as the fundamental aspects carried out with the task at any level (micro, meso or macro). The necessary informational level associated with the task presents requirements regarding the type of knowledge (explicit, tacit and embedded), the psycho-physiological demand that the task requires for its performance and the demand for the way in which the information is presented.

5. Conclusions

This work presents a new concept of manufacturing system, called enactive manufacturing. The enactive framework is explored as a form of extension of cognitive manufacturing, which enables embodiment cognitive knowledge in different technologies through its parameterization at the process and workstation level. A bioinspired conceptual architecture based on the holonic paradigm for the development of manufacturing systems is proposed. The proposed architecture will allow future work to be carried out to: (i) extend cognitive manufacturing to different modes of implementation of manufacturing systems technology, (ii) conceive of cognitive manufacturing processes parameterized according to the context of operation, and (iii) develop CPS formed by active agents with embodied, situated, distributed and constructivist intelligence. Likewise, this architecture offers great opportunities for the Smart Factory in terms of: (i) conceiving the manufacturing system as an eco-compatible system with the natursphere from the integration of the economic, environmental and social requirements of sustainability under the triple bottom line, and (ii) intelligently support and leverage the continuous improvement processes that are in place in manufacturing.

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