Holistic Integration of Enactive Entities into Cyber Physical Systems

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***Abstract*—Cyber physical systems (CPSs) are built of physical components that are integrated into the cyber (virtual) world of computing. Whereas there are many open questions and challenges, such as time modeling, interaction between cyber and physical components, our research focuses on how humans can be holistically integrated. Our vision is to link human intelligence with CPS in order to get a smart partner for daily human activities. This will bring new system characteristics enabling to cope with self-awareness, cognition and creativity as well as the co-evolution of human-machine-symbiosis. In this sense, we state that drawing borders between virtual and physical or between users and technical artifacts is misleading. In contrast to that, we aim to treat the system as a whole. To achieve this, the paper presents a generic coordination model based on third-order cybernetics. In particular, the holistic integration of humans and other living systems into CPSs is presented, which leads toward human-centered CPSs.**

Keywords*—*Coordination model; cybernetics, human-centered cyber physical system; enactive entities; holistic integration

I. INTRODUCTION

Our research focuses on holistic system modeling, meaning we want to consider a system as a whole, where all relevant entities, such as humans and animals, are fully integrated. We have presented in [7] a generic coordination model that is applicable to different problem domains, like technical and social. In our case study we apply this model to pervasive and cyber physical systems (CPSs). In particular, we want to model human-centered CPS that integrate human intelligence as well as encompassing humanistic values. In [8] we have shown how a CPS can become human-centered using the holistic approach of our model. This paper presents an extended model allowing the holistic integration of humans and other living systems, whose system dynamics can be described by first-, second- and third-order cybernetics.

Whereas a CPS is built of physical and virtual components, our model introduces a third level addressing the holistic aspects of the system itself. This level expresses many of the system's trends and behaviors that cannot be explained otherwise. For instance, even a CPS that performs well can fail if no human wants to use it, which can be caused by unsatisfying design, patronizing humans or sudden changes in customer requirements. Such problems often come from fading out complex and holistic aspects, as well as the incomplete integration of humans into the system. It is not enough to integrate them only on the physical or virtual level. Humans are much more than physical entities composed of eyes and hands, and more than virtual entities specified through identifiers and preferences.

In our generic coordination model, humans and other bio-systems are denoted as *enactive entities*. They cannot be reduced or decomposed into subcomponents without losing relevant information about the whole. Their integration is, in contrast to physical and virtual entities, far more complex due to their cognitive capabilities. Behaviors like self-awareness, cognition, creativity and empathy must be considered. This leads to a new level of coordination, called *cognitive coordination*. This level takes coordination strategies and processes based these cognitive behaviors into account. Based on our generic coordination model we propose a *holistic integration* that can be achieved through coupling entities on all abstraction planes. For instance, the integration of humans into social-technical systems must be done on three planes (physical, virtual and holistic) to be fully understandable and to not mislead the system design.

The paper aims to present the model we designed for addressing holistic integration of humans into technical systems. It starts with the definition of human-centered and cyber physical systems. In section III, we introduce the generic coordination model and in section IV, we present how entities can be holistically integrated. Finally, section V concludes our current state of research on holistic modeling.

II. HUMAN-CENTERED CYBER PHYSICAL SYSTEMS

Most approaches handle humans as outside entities integrated only through a dedicated interface. This section gives an overview of some research advances in the direction of how human-centered systems can be modeled and where humans are completely and holistically considered. It also gives some explanation and clarification of the term *human-centered cyber physical system*.

A. Cyber Physical Systems

A cyber physical system (CPS) is a physical and engineered system that is integrated into the cyber (virtual) world of computing. One of the major challenges is how the discrete and exact domain of computing and logic can be brought together

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with the continuous and uncertain world of physical and engineered systems. E. A. Lee [11] mentioned two strategies for how these two domains can be linked: *cyberizing the physical* and *physicalizing the cyber*. Cyberizing the physical means creating software wrappers around physical entities. Physicalizing the cyber, on the other hand, is about endowing software and networking entities with abstractions suitable for physical entities.

The design of how physical and virtual entities interact with each other is fundamental. In order to serve a greater common purpose, entities must collaborate with each other through interaction. Often, interaction is designed as simple receiving, processing and replying messages, and connecting ports from physical to virtual entities, as illustrated by G. Simko et al. in [22]. In such models, humans are reduced and put on the level of either physical or virtual entities. Surely CPS will change how humans will interact with and control the physical world as pointed out by R. Rajkumar et al. in [17]. However, attention also has to be paid that such systems do not patronize or restrain human beings and to spurn humanistic values.

A first step towards human-centered CPS is the approach of *human-in-the-loop*. The focus is put on how to integrate humans with CPSs, especially as a part of control loops. It addresses several interesting challenges in this matter. For instance, how can a CPS identify or detect human behavior (S. Munir et al. [14]), which is a complex intent due to psychological and physiological aspects of being human. Nevertheless, we think that some of the problems addressed by human-in-the-loop could be more easily solved by posing the problem differently.

B. Human-Centered Systems

There are significant differences between user- and human-centered approaches. As S. Gasson [5] argues, the main difference lies *"in the way in which technology is designed"*. Whereas user-centered systems treat humans as technology users, human-centered systems (HCSs) put human beings into the focus and are marked by their respect to humanistic values, in particular by preserving human integrity in a human-machine-symbiosis. Values are important in human lives. S. H. Schwartz [18] presents a value theory based on ten basic human values, which are motivationally distinguished from each other. They are derived from the *"needs of individuals as biological organisms, requisites of coordinated social interaction, and survival and welfare needs of groups"*. Rather than diminishing or simplifying the nature of humans, HCSs consider them as holistic beings and are devoted to human welfare. R. E. Jacobson states in [9] that *"HCS envisages quite different forms of human-machine interactions resulting in a human-machine symbiosis. It regards the social and cultural shaping of technology central to design and development of future technology systems and society as a whole"*. It can be seen as a design principle that focuses on human needs, skills, creativity and potentiality and puts them into the center of systems processes (K. S. Gill et al. [6]).

From our generic and systemic point of view, HCSs must consider four basic points: (1) integration of humans as wholes (beings), (2) consideration of different levels of interaction with humans, (3) devotion to humanistic values, and (4) encompassing the evolution of humans and their social communities. This implies having a model handling all relevant entities (e.g. humans and CPS) consistently.

C. Conversation

One of the cruxes in human-centered design is how flexible and adaptive humans can interact with technical systems, and how goal-oriented systems can collaborate with humans. In classical systems, humans are often regarded as outside entities, which interact through dedicated interfaces using predefined protocols. Systems based on the communication model of C.E. Shannon et al. [21] are limited, because an information source is able to select messages only from a known and precompiled set of possible messages. H. Dubberly et al. [4] state that using Shannon's model it is impossible to say something novel to someone else. They describe that it is fundamental for system design to use the concept of *conversation*, which is a closed loop through all participating entities, rather than simple input-processing-output interaction.

G. Pask explains in his conversation theory [15] that conversation leads to the construction of knowledge where participating entities belong to a symbolic, language-oriented system (social system). Their interaction is mainly dependent on one entity's interpretation of another entity's behavior. It allows entities to agree upon a common understanding of shared goals. H. Dubberly et al. argue in [4] that conversation allows coordinating *"actions in ways that are mutually beneficial for all participating entities. In practice, society is a complex market of coordination based on conversation and conversation is the primary mechanism for complex social coordination. It is a highly effective form of bio-cost reduction and therefore an engine of society"*.

D. Holistic Approaches

Holistic and systemic approaches could lead to the design of human-centered systems ([6] and [8]). When we speak of holistic approaches, our world view is based in holism. Holism states that a system cannot be understood completely by the study of its components. Its functioning must therefore be viewed as a whole, as Aristotle said *"the whole is greater than the sum of its parts"*. There is evidence, like the body-mind-problem, that some system properties (i.e. behaviors) cannot be deduced from the properties of their components alone. They are called *emergent properties* and defined as *"supervenient properties, which are distinct from the properties on which they supervene"* (T. Crane in [2]).

A more sophisticated and generic model is required to design human-centered systems. The research field of cybernetics encompasses general concepts (e.g. goal-action-feedback) as well as complex decision-making and learning. N. Wiener has defined cybernetics in [25] *"as the scientific study of control and communication in the animal and the machine"*. He intended to develop a general theory describing organizational and control relations within systems. The focus of cybernetics aims more at goal directedness and functional behavior of systems rather than their components. Different cybernetic orders have been defined to understand, describe and model complex systems. As Yolles et al. [26] stated *"higher cybernetic order facilitates simpler modelling under increasing complexity. Thus, while the models become more complex with increasing order, they are simpler relative to increasing complexity. Each higher order has a potential to create a family of paradigms through new ways of seeing"*. *Third-order cybernetics* in particular has come into focus for model living systems. In third-order cybernetics, the observed system and the observer form a new system through self-referenciality (P. Boxer et al. in [1] and E. Schwarz in [19], [20]).

A holistic meta model for general systems and especially complex ones, is presented by E. Schwarz in [19], [20]. Objects follow not only pure physical laws but are also influenced by networks connecting them on abstract and existential planes. His focus is on phenomena and stages leading to complexity. There exist at least two forces driving the dynamics of self-organization: one leading to disorder and complexification/ heterogenization, and one leading to order/homogenization corresponding to entropic drift [19]. They are the main cause for increasing complexity and autonomy of systems during their long-term evolution. E. Schwarz proposes a spiral of self-organization describing how any complex system can step from one level of organization and complexity to another one. This model can be seen as a third-order system model.

III. Generic Coordination Model

Our generic coordination model [7], [8] is a third-order cybernetic system model following the holistic approach to integrate all relevant entities forming a new system. Humans and other living systems are considered as *enactive entities*, holistic beings that cannot be reduced. The term "enaction" was developed by F. Varela et al. [23] and emphasizes *"the growing conviction that cognition is not the representation of a pregiven world by a pregiven mind but is rather the enactment of a world and a mind on the basis of a history of the variety of actions that a being in the world performs"*.

A. Modeling Spectra

The generic coordination model is based on two main spectra: the *coordination spectrum* and the *abstraction continuum*. The *coordination spectrum* constitutes the characteristics of coordination processes, which control and direct the interactions within a system and therefore influence the evolution of the whole. It is split into three areas: (1) *objective coordination*, describing how rules are applied to interactions between entities; (2) *subjective coordination*, respecting coordinative behavior depending on observers and their point of view; and (3) *cognitive coordination*, dealing with strategies based on shared knowledge, creativity and empathy among enactive entities.

The second spectrum, called the *abstraction continuum*, describes system components and dynamics from their concrete existence (entity plane), their representation as models and concepts (relation plane) towards their holistic characteristics (holistic plane) like inseparability due to the entanglement of structures on the entity and relation planes. The model is built of three nested systems, each one of increasing cybernetic order: (1) The first-order system called the *observable entity*, (2) the second-order system dealing with observation and subjectivity, called the *smart entity* and (3) the third-order system, called the *enactive entity*.

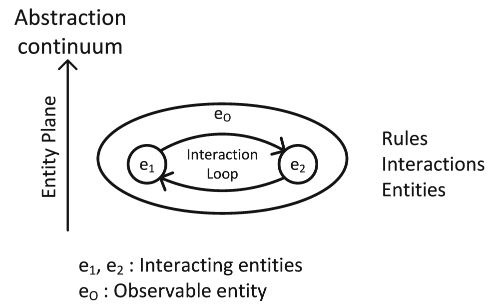

Fig. 1. A trivial system made of two interacting entities e_1 and e_2 forming an observable entity e_O.

B. Observable Entities

First-order cybernetics defines systems that are well bounded and observed from the outside. K. Krippendorff [10] states that *"first order cybernetics is concerned with circular causal processes e.g. control, negative feedback, computing, adaption"*. We call such systems *observable entities*. They are completely described on the entity plane from a objectivist positivist point of view.

The entity plane comprises everything that exists or could potentially exist, called *entities*. Two kinds of entities can be distinguished. The first kind is called *interaction*, which is defined as an exchange of anything between two or more entities [7]. Examples are energy-matter fluxes in the physical domain or human-computer interaction. The second kind denotes *rules* that restrict interactions and limit the way a system can evolve. Due to rules, some of the evolution paths become impossible.

Interactions and rules express the dynamics on the entity plane and can be seen as a loop maintaining and evolving the system, called the *interaction loop* (Fig. 1).

C. Smart Entities

Second-order systems are spread over the entity and relation planes. The observer is no longer an external entity but is included in a larger circularity where he enters into his own observation. The study of this circularity is also referred as *cybernetics of cybernetics* (H. von Foerster in [24]). We call second-order systems *smart entities*. Smart entities are described from a constructivist and relativist point of view, where their internal structures and boundaries (e.g. mentally or physically) are generated through interactions.

In addition to the observable entity e_O, a smart entity e_S also encompasses autopoietic network N, which is described on the relation plane. Attributes and relations are the primitives on that plane. Whereas attributes describe entities, relations emerge when two or more entities share the same attributes. The way a system describes entities through attributes depends on its capabilities of perceiving those entities. Therefore, relations and the corresponding arrangement of entities (topology) are both of subjective nature. This leads to the consequence that each smart entity is unique in terms of their autopoietic

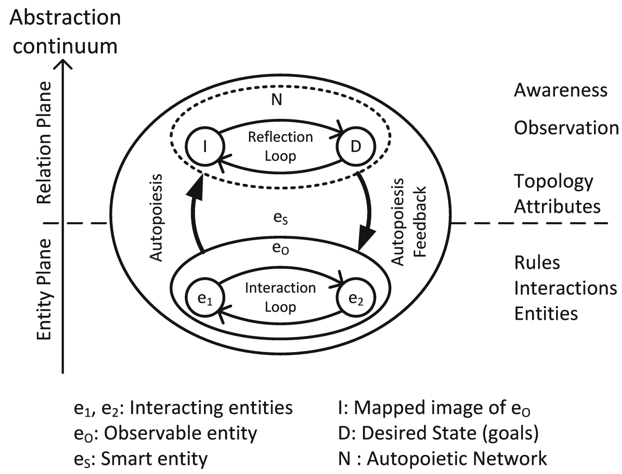

Fig. 2. Smart entity defined by first- and second-order cybernetics.

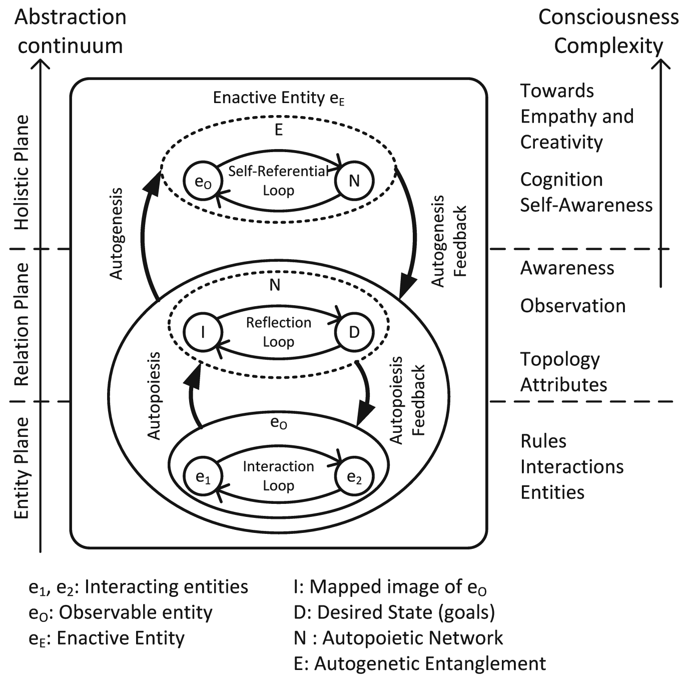

Fig. 3. Enactive entity comprising third-order cybernetic loops.

network. Each one has its own observation and awareness, *"there are no doppelgangers"* possible (G. Pask in [16]).

The primitives on the relation plane emerge through *autopoiesis*, the process of self-creation and self-maintaining [13] (Fig. 2). It describes how a network of higher abstraction is created through interaction and how that influences that interaction (feedback). For instance, the perceiving-acting process [8] that enables a system to become aware of its surroundings and its activities in the environment is a special kind of autopoiesis.

The autopoietic network N, is a composition of images I (e.g. perceived states) and desired states and decisions D (e.g. goals, motivation). This network is maintained by a *reflection loop*, which describes all kinds of information processing leading from images I to desired states and decisions D and conversely (feedback). For instance, a CPS can perceive some of the physical entities through sensors. The perception process maps these entities to an internal image leading to a subjective image of the outside world that is biased to the perceiving capabilities. The reflection loop is often implemented as computing processes transforming the perceived data towards goal-oriented decisions. While some decisions lead to activities in the environment, others lead to perception adaptations, like changing the sensor configuration or data recording.

D. Enactive entities

With increasing complexity due to the entanglement of observable entities e_O with their autopoietic network N, the system cannot be decomposed into its subcomponents without losing relevant information about the whole. We propose to consider such systems as holistic beings and introduce a third plane, called the *holistic plane* describing such holistic beings as autogenetic systems (Fig. 3). We refer to them as *enactive entities*, and its dynamics as *third-order cybernetics*. Living systems like humans, plants, cells, etc. are considered as enactive entities [8]. They are described by three main characteristics:

1) They are aware of themselves and their surroundings (consciousness).
2) They are able to adapt their behavior or create new behaviors, denoted as *cre-adaption*. Cre-adaption is a capability that is enforced by consciousness and intentional acting. It respects the fact that an enactive entity is able to change its own rules (self-creation).
3) Enactive entities are also able to differentiate themselves from the environment (individuation).

The interactive influence of the lower-ordered system and the holistic being is represented by *autogenesis*, a process of self-creation and differentiation that leads towards complete autonomy [19]. The result is an autogenetic entanglement, which is maintained by a loop between the observed system e_O and its autopoietic network N, called a *self-referential loop*. This loop is the main cause for higher consciousness that is an epiphenomenon of the abstraction continuum. It can be described in a separate consciousness spectrum ranging from awareness up to the cognitive capabilities of enactive entities like creativity and empathy.

IV. Holistic Integration

In our model, integration is understood as combining entities in order to work together or to form a whole[1]. The integration of an entity A with an entity B leads to a new entity (composition) that inherits the characteristics of both A and B. How the new system can benefit from its components A and B depends on the completeness of their integration. If an entity A participates in all abstraction planes of B, we call this a *holistic integration*. In this sense, participation is a loop connecting them on the corresponding planes (Fig. 4).

[1]We borrowed this definition from linguistics (M. Rouse in http://searchcrm.techtarget.com/definition/integration). Other communities like computer science or immigration use integration in an asymmetric sense, where an entity A is integrated into B, e.g. foreigner into a country community.

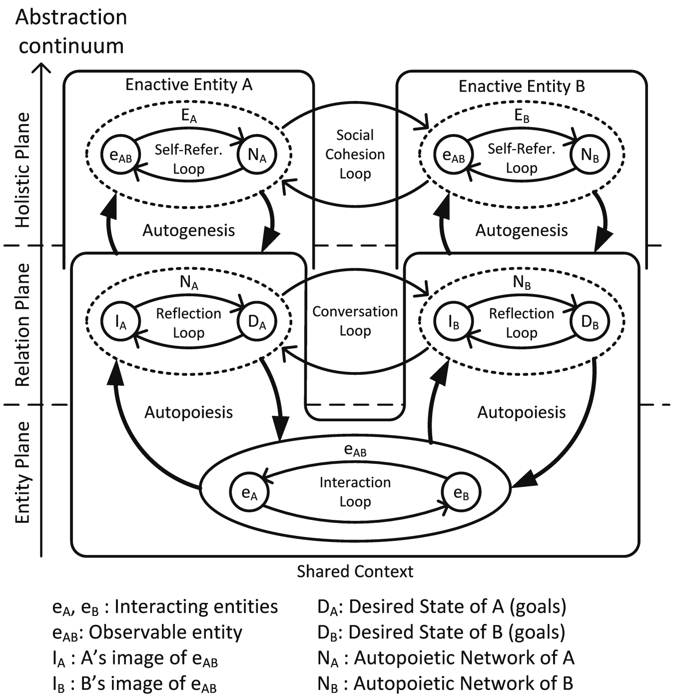

Fig. 4. Holistic integration of two enactive entities A and B.

Nr.	entity A	entity B	integration loops	composed entity
a	observable	observable	interaction	observable
b	observable	smart	interaction	smart
c	observable	enactive	interaction	enactive
d	smart	smart	interaction conversation	smart
e	smart	enactive	interaction conversation	enactive
f	enactive	enactive	interaction conversation social cohesion	enactive

TABLE I. POSSIBLE INTEGRATIONS OF ENTITY A WITH ENTITY B LEADING TO A NEW COMPOSED ENTITY.

There exists an integration loop on each plane, which denotes the integration of entities on that plane. The loop on the entity plane is called the *interaction loop*. It expresses the concrete interaction between entities A and B. The interactive system e_{AB} can be seen as a shared context between A and B.

Conversation is a loop connecting the participating entities on the relation plane. This loop allows entities of higher order (e.g. smart and enactive entities) to share their subjectivity like images, goals, and decisions. This leads to the construction of shared knowledge between the participating entities allowing them to negotiate about goals and to agree (or disagree) upon a common understanding of concepts [4]. Conversation is a prerequisite for any cooperation, collaboration or subjective coordination.

On the holistic plane, the loop connecting enactive entities is called the *social cohesion loop*. It allows enactive entities to enter into a social group (society) and to be a part of it. For instance, it allows humans to be integrated with each other forming racial, religious, or ethnic groups and to feel as a part of a whole.

A. First-, Second- and Third-Order Integration

Higher ordered integration loops always depend on lower ordered loops and cannot exist without them. Hence, there are six possible combinations to integrate observable, smart and enactive entities (Tab. I). Each combination leads to a new system (composed entity), which inherits the highest order of its components A resp. B if the integration is done holistically.

The integration can be classified in three orders: *first-order*, describing the integration through interaction loops, *second-order*, encompassing interaction and conversation loops, and *third-order*, which includes all three integration loops.

First-order integration is typically applicable to integrate observable entities (Tab. Ia, b, c). For instance, two physical components can be assembled through physical interactions (physical forces) creating a larger physical component.

Second-order integration is the integration of two smart entities or an enactive entity with a smart entity (Tab. Id, e). The integration includes in addition to the interaction loop the conversation loop connecting two entities on the relation plane. Collaborative activities require that loop in order to be able to exchange and finally to agree on shared goals.

Third-order integration can be achieved when integrating enactive entities (Tab. If). It encompasses all three integration loops. For instance, humans can be integrated, forming a social group. This group is maintained by all three loops, the interacting loop expressing physical interaction between its members (talking, collaborative activity), the conversation loop used to exchange goals and concepts to find an agreement, and the social cohesion loop leading the group to a unity.

B. Consequences for CPS Design

As described above, the holistic integration of a human (enactive entity) with a CPS (smart entity) creates a new system (composition) that inherits the characteristics of both, the humans and the CPS. This could lead to a self-learning organization, a system fully adaptive to new behaviors and requirements and able to exchange abstract concepts with humans. We call this emerging system a *human-centered cyber physical system*. It is marked by holistic and cognitive characteristics (Fig. 5). We see the following major benefits: (1) a CPS can actively learn from humans, rather than having a predefined behavior designed by engineers. Due to their cognitive capabilities, humans can feed their knowledge into the system. (2) The system can give accommodated knowledge back to humans. It could support their education. Finally (3), the success of their collaborative activities is more likely once humans and CPSs have a shared agreement of understanding.

Holistic integration could reinforce the human being in his feeling of being in control of his life experience in the world of technology. It could also help to reduce the bio-cost of humans [3] that leads to an increase of acceptance and finally to the success of CPSs.

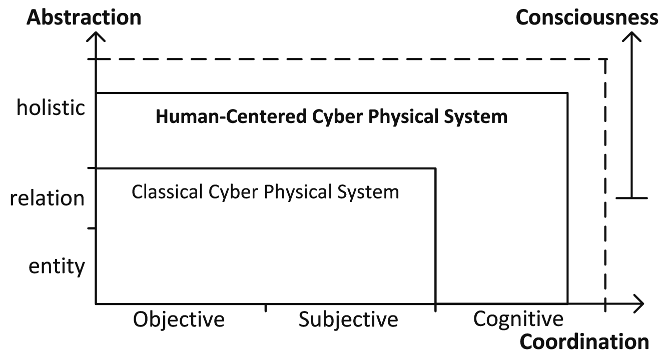

Fig. 5. Classical vs. human-centered CPS.

V. Conclusion

We have presented a generic coordination model that can be used for holistic system modeling, handling all entities including smart and enactive entities with the same model. It allows to integrate enactive entities as a whole, rather than reducing them to their sub-components. The holistic integration is achieved through a three plane modeling, each plane involving integration loops. In particular, conversation and social cohesion loops enable the targeted humanistic human integration. This may lead to a self-learning organization, which is fully adaptive to new behaviors and requirements and able to exchange abstract concepts with humans, called human-centered cyber physical system. The major benefits of such systems are the exchange of knowledge as well as high performing collaboration with humans.

Moreover, our model handles complex and dynamic processes in a holistic manner. It shows that coordination is more than just managing dependencies between activities as defined by Malone et al. in [12]. It is about managing the evolution; especially for human-centered systems, it handles the evolution of the human-machine symbiosis. In former system models, evolution is often seen as an outside changing process. In autogenetic systems, evolution comes from the inside. We state that living systems affect coordination through their cognitive capabilities. This leads to cognitive coordination dealing with strategies based on shared knowledge, creativity and empathy among enactive entities.

Our next step is to evaluate this model through prototyping. An instantiation is built for pervasive computing systems and human-centered CPSs. This will serve as a testbed for evaluating the model and refining it. We think that focusing on holistic integration is leading to a renewal of the paradigm for human-machine-collaboration.

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