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WORKING PAPER

Towards Human-Centered Cyber-Physical Systems: A Modeling Approach

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Internal working paper no 16-01

June 2016

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ABSTRACT

In this paper we present a new CPS model that considers humans as holistic beings, where mind and body operate as a whole and characteristics like creativity and empathy emerge. These characteristics influence the way humans interact and collaborate with technical systems. Our vision is to integrate humans as holistic beings within CPS in order to move towards a human-machine symbiosis. This paper outlines a model for human-centered cyber-physical systems (HCPSs) that is based on our holistic system model URANOS. The model integrates human skills and values to make them accessible to the technical system, similarly to the way they are accessible to humans in human-to-human interaction. The goal is to reinforce the human being in his feeling of being in control of his life experience in a world of smart technologies. It could also help to reduce human bio-costs like stress, job fears, etc. The proposed model is illustrated by the case study of smart industrial machines, dedicated machines for smart factories, where we test the human integration through conversation.

Keywords

Human-centered system · cyber-physical system · holistic system modeling · cybernetics · conversation · human-machine symbiosis · smart industrial machine · smart factory · industry 4.0

1. INTRODUCTION

Humans are often partially integrated in classical system architecture. For instance, in business software architecture they are often seen as "app-user" and put above the presentation layer indicating that they are interacting with apps. In embedded system architecture on the other hand, they are treated as "hardware devices" interacting with sensors and actuators. Neither approach is wrong, but not sufficient when modeling human-centered technical systems. Our research focuses on the holistic integration of humans in cyber-physical systems, so that their capabilities are accessible to the system, just as they are accessible to people in human-to-human interaction. This is a major cornerstone for any human-machine symbiosis.

This paper presents a model for pervasive computing and human-centered cyber-physical systems (HCPSs). It is an instantiation of our holistic system model ([8] and [9]) URANOS that allows to consider the system as a whole, integrating all relevant entities including humans. The design of such HCPSs addresses, besides other things, the following questions: How flexibly and adaptively can humans interact with technical systems? How can goal-oriented systems collaborate with humans? Systems based on classical interaction paradigms often have difficulties meeting these challenges since their responsiveness is limited. Their behavior is in many cases precompiled and the possibilities to exchange information are limited.

We state that the way out of this situation entails a paradigm shift towards the model of conversation proposed by G. Pask [19]. This enables an HCPS to become an adaptive learning organization, where humans can feed their knowledge into the system, and where conversely the system can train and educate human beings. The conversation between humans and machines leads to a shared agreement of understanding. Humans are not patronized, they can collaborate with the technical systems in a mutually beneficial manner. This will reduce the bio-costs of humans working with a system, and at the same time it will increase the efficiency of the human-machine collaboration. For instance, working with smart industrial machines means less waste, stress and misunderstanding which is good for both business and employees.

The paper first gives some background on human-centered systems and their distinction from user-centered systems in section 2. In section 3 it presents the holistic and generic system model URANOS, from which the model for pervasive computing and CPS in section 4 is derived. Here we illustrate the concrete model on the example of smart industrial machines that are an integral part of a smart factory project. Section 5 presents conclusions and a research outlook.

2. HUMAN-CENTERED CYBER-PHYSICAL SYSTEMS

Our aim is to clarify the concept of HCPS through some of the latest advances in human-centered research, in particular through the holistic integration of people with technical systems.

2.1 Human-Centered Systems

Human-centered systems (HCSs) are often mistaken for user-centered systems, but there are significant differences between them. As S. Gasson [4] argues, the main difference lies *"in the way in which technology is designed"*. A user-centered system treats humans as technology users, persons who work with this system which was designed to be convenient for them. In HCS people are not treated as stand-alone organisms. As stated by R. Kling et al. in [13] *"the term human includes and goes beyond individuals and their cognitions to include the activity and interactions of people with various groups, organizations, and segments of larger communities"*. HCSs put human beings into the focus and are marked by their respect of humanistic values, in particular by preserving human integrity in a human-machine-symbiosis (i.e. not harmed, slaved, reduced, etc). But HCS also encompasses environmental sustainability, since human being and their environment are interdependent.

Existential and social values are important to human beings. S.H. Schwartz [23] 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 [13] and are devoted to human welfare. R.E. Jacobson states in [11] 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, social togetherness and potentiality and puts them into the center of systems processes (K.S. Gill et al. [6]).

An important goal of HCSs is the reduction of human's bio-costs. M.C. Geoghegan et al. defines bio-cost in [5] as a *"measurable, biological cost to any system performing an activity in pursuit of 'getting what it wants'"*. It covers the key components of time, attention and energy that a living system must pay for its activities. The design for HCSs must take into account the reduction of bio-costs.

From our generic and systemic point of view, HCSs must consider the following basic points: (1) it must holistically integrate humans as enactive entities - this includes the different levels of interaction, conversation and social cohesion [8]. (2) It must be devoted to humanistic values and help to reduce the bio-costs of humans; and (3) it must adapt to the evolution of humans and their social communities enabling new human activities. Building such systems implies having a model that handles all relevant entities (e.g. humans and CPS) consistently.

2.2 Cyber-Physical Systems

CPSs are smart entities encompassing physical components that are seamlessly integrated into the cyber (virtual) world of computing. There are many challenges in the modeling of CPSs. Two of them need special attention for human-centered approaches. The first concerns the interaction between components (physical and virtual), and the second focuses on the integration of humans.

The design of how physical and virtual entities interact with each other is fundamental. In particular how the discrete and exact domain of computing and logic can be brought together with the continuous and uncertain world of physical and engineered systems. E.A. Lee [14] 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. 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 [24]. 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 [21]. However, attention is needed to ensure that such systems neither patronize or limit people in their daily activities, nor violate humanistic values. As stated by E.M. Frazzon et al. *"even though CPS strongly rely on technological advancements, the creativity, flexibility and problem solving competence of human stakeholders is strongly needed for their operation"* [3].

A first step towards HCPS is the approach of *human-in-the-loop*. The focus is on how to integrate humans in CPSs, especially as part of control loops. One of the key questions is, how can a CPS identify or detect human behavior, which is a complex intent due to psychological and physiological aspects of being human (S. Munir et al. [17])? We think that some of the issues that are addressed by human-in-the-loop could be solved more easily by asking a different question: how humans can collaborate with CPSs in a mutually beneficial manner, so that human skills can become naturally accessible for CPSs? Research in this direction could help to compensate for missing skills through the holistic integration of an appropriate entity (such as humans). The latest research on CPS tends to also integrate the social aspects of humans with the cyber and physical dimensions. Examples are the anthropocentric CPS (C.B Zamfirescu et al. in [26]), the NSF's cyber-human systems progam [1] or the socio-cyber-physical system (E.M. Frazzon et al. in [3]).

3. URANOS: A HOLISTIC SYSTEM MODEL

Holistic and systemic approaches that try to integrate human beings as a whole are a cornerstone for HCS design. When we speak of holistic approaches, our world view is based in holism, which 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 [1]).

A comprehensive and generic model is required to design human-centered systems. In [8] and [9] we proposed a model that can be used for holistic system modeling, named URANOS. It deals with all relevant entities, including living systems, using the same model.

3.1 Systemic Orders

URANOS is based on an abstraction continuum char-

[1]NFS's website http://www.nsf.gov/cise/iis/chs_pgm13.jsp

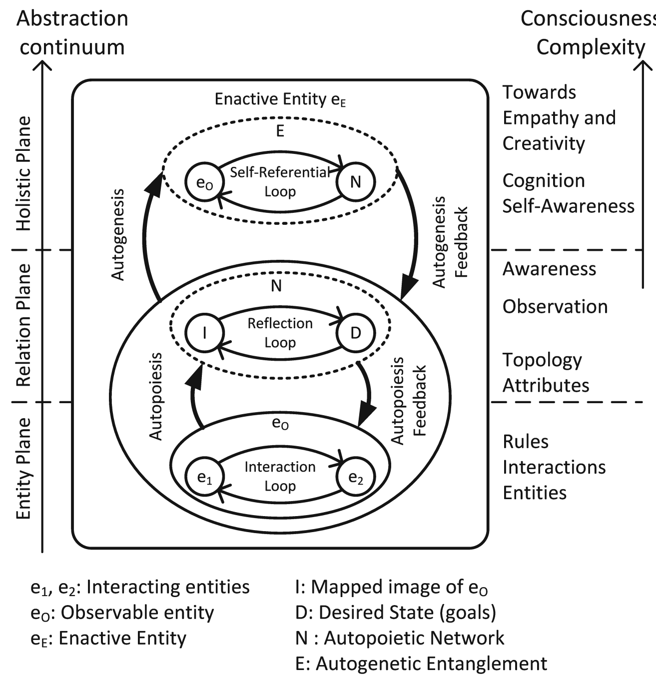

Figure 1: URANOS describes a system using three cybernetic orders, each describing the sytstem from a certain point of view.

acterizing the system organization. The continuum is split in to three planes: (1) the *entity plane* describes the concrete existence of components and dynamics; (2) the *relation plane* includes relationships and models of concrete entities; and (3) the *holistic plane* describes the holistic characteristics of a system.

The model also addresses the system dynamics in three cybernetic orders, describing the system from a particular point of view (paradigm) (Fig. 1). The first-order is called *observable entity* and is placed completely on the entity plane. It describes a well bounded system that can be observed from the outside. Interaction and rules express the system dynamics, which are denoted as an *interaction loop* maintaining and evolving the system.

Second-order systems encompass observable and observing systems and are called *smart entities*. Smart entities are described from a constructivist and relativist point of view, where their internal structures and boundaries (e.g. mental or physical) are generated through interactions. This process of self-producing and self-maintaining is called *autopoiesis* (H.R. Maturana [16]). The product is an *autopoietic network*, a relational structure that reflects the subjective cognition of the observed. Each smart entity is unique in the way it constructs its internal autopoietic network. This leads to a universe of individuals where there are no doppelgangers possible (G. Pask in [20]).

The third-order expresses the holistic nature of living systems. Such systems are called *enactive entities*, which are described by three characteristics [8]:

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, autogenesis).
3. Enactive entities are also able to differentiate themselves from the environment (individuation).

3.2 Integration of Entities

URANOS proposes a holistic integration of all relevant entities into the system, including enactive entities like humans, animals, plants, etc. This integration enables entities to participate in the system, without being totally controlled by the system. In its perfection it could lead to a symbiosis between systems (e.g. human-machine symbiosis).

The integration of systems is realized through three loops connecting the integrated entities: *interaction*, *conversation* and *social cohesion* (Fig. 2).

The interaction-loop expresses the concrete interaction between the entities, for instance the physical interaction between a human and a CPS. The conversation loop connects the entities on the relation plane. It represents the exchange of information, novel concepts and goals. It is responsible for continuous construction and creation of knowledge between two or more entities (G. Pask in [19]). Through conversation, the participating entities could reach an agreement of understanding, which is essential for any collaboration between them. On the holistic plane a social cohesion loop allows enactive entities to be part of a social group. It's a prerequisite for a symbiosis between enactive entities, where symbiosis is to be understood as a kind of collaborative entanglement between the entities.

3.3 System Governance

A human-centered system can be seen as a governance system, as it cooperates with people to manage and support human activities. Governance in this sense is understood as a *"decision-making and decision implementing process"* so that stable organizations can arise and persist [25].

3.3.1 Control

An important construct in system governance is *control*, which is a continuous process for conducting and exerting power over another process.

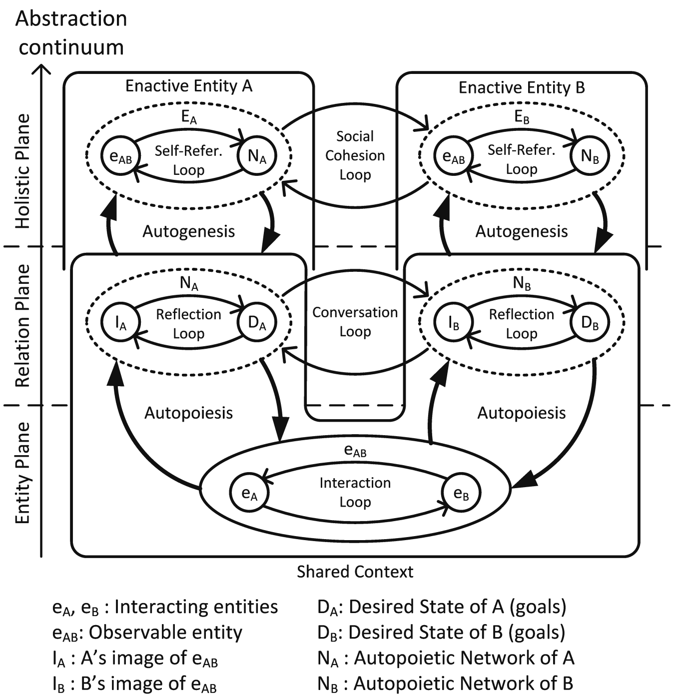

Figure 2: URANOS showing an integration of two entities through three horizontal connecting loops.

From a generic point of view a system can be split into two subsystems: the *controlled system* A and the *controlling system* B (Fig. 3). While A transforms inputs X_A into outputs Y_A, B measures some of A's outputs and directs A toward a desired goal. This kind of interaction between A and B is called "it-referenced" because A has no choice and must obey the instructions given by B, B treats A like an "it" (G. Pask in [19], P. Pangaro in [18]).

A special case of a control system is the *perceiving-acting process* (B. Hadorn et al. in [9], F. Heylighen et al. in [10]), also called the *perceptual control loop* (Fig.

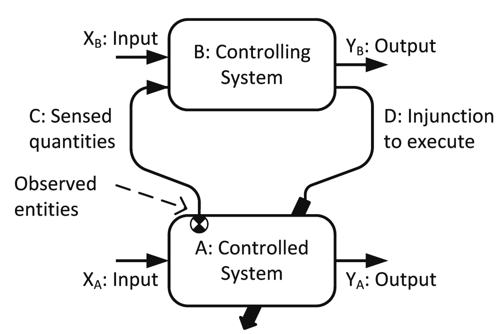

Figure 3: Notation for a controlling system B directing a system A.

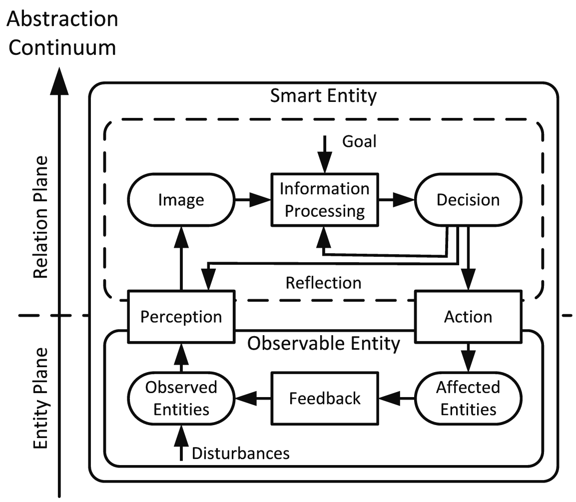

Figure 4: Perceiving-acting process as a perceptual control loop.

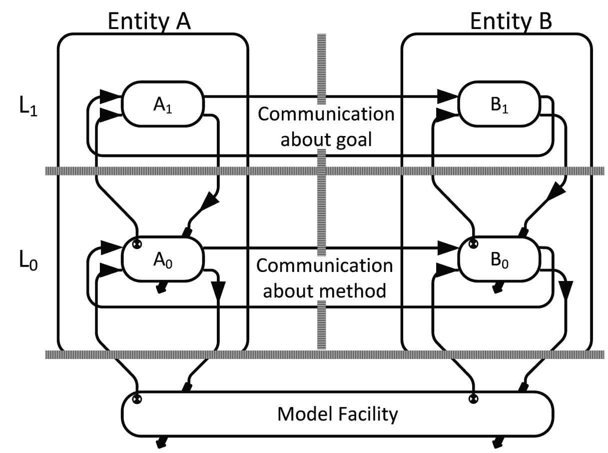

Figure 5: Conversation model from G. Pask.

4). Concrete entities are recognized by a perception function, which maps them as internal, abstract representation. This is also called *image* of the observed entities. It can be processed by an information-processing function, which leads to a decision on how to respond to the perceived situation. The decision can be transformed into actions that affect some concrete entities in the environment. A *feedback* function closes the process loop, whenever the set of affected and observed entities overlap each other. Besides this main loop our model proposes *reflection loops* on the relation plane (B. Hadorn et al. [8]). They enable the system to influence the perception and decision-making functions in an adaptive manner.

3.3.2 Conversation

System governance is not only about control, it also encompasses communication, exchange and creation of knowledge between participating entities. We propose to follow the principle of *conversation* presented by G. Pask in [19] and P. Pangaro in [18] as a comprehensive cybernetic and dialectic framework. For illustration of their framework they take the example of a student (entity A) and a teacher (entity B). Note that these roles of student and teacher are not fixed, but could change depending on the subject for discussion. Also A and B could stand for machine or human likewise.

Conversation is a complex interaction between entities that namely depends on one entity's interpretation of the other's behavior. For instance B (teacher) explains some novel concepts to A (student) and checks if it appears that A has understood. If B still finds marginal differences he might use another example to illustrate what he meant. To do so the entities must share a common conversation language, which allows them to express and describe topic content. A language can be any means for expressing concepts, emotions, intentions etc. The embodiment of language might be body language, speech, pheromones or even actions. The basic units of a conversation language are topic relations R_i (index i indicates that there could be more than just one topic in a conversation). Each relation R_i is described in that language by grammar-like permission-giving structure, which states how R_i may be satisfied (G. Pask in [19]).

Conversation happens on at least two levels (Fig. 5): L_0, called the *method level*, dealing with A's reinterpretation of modeling instructions delivered by B, and L_1, called the *goal level*, providing the explanation of the model itself. The processes A_0 and B_0 handle the modeling instructions, where A_1 and B_1 handle the explanations. Each participant entertains a hypothesis about how to model a topic relation R_i. The model is generated out of a repertoire of procedures able to process R_i (e.g. A_0 or B_0) forming the entity's own subjective intension of R_i. Within the bounds of a *modeling facility*, on a universe of the participant's own choice, he can instantiate and verify or deny the model. Once the model of B matches the one of A the conversation stops on R_i. One can say that A and B reached a mutual understanding of R_i. The conversation may continue on another topic relation.

The conversation process allows entities of a higher order (e.g. smart and enactive entities) to share their subjective perception. It also 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 (H. Dubberly et al. in [2]). Conversation is a central piece for any human-centered system and for good system governance. Concerning technical systems, it enables them to learn new concepts from humans and to teach humans, a prerequisite for any cooperation, collaboration or subjective coordination. This rather comprehensive interaction between two or more entities is enclosed in URANOS as a conversation loop (Fig. 2).

4. MODEL FOR HUMAN-CENTERED CPS

This section presents an instantiation of URANOS for pervasive computing and CPSs. We aim to illustrate the model with our case study on smart industrial machines (condensed smart machines), which are dedicated machines to implement smart factories (H. Kagermann et al. in [12]). Our goal is to explore new system characteristics that go beyond the current approaches to sustainable and smart manufacturing towards human-centered and cognitive manufacturing systems that incorporate humans, ecological and economic environments. Special attention is paid to the learning behavior of such smart machines; particularly how they can learn about novel and changing manufacturing processes through conversation with humans (e.g. from operators, production managers, engineers).

4.1 System Learning

Often, manufacturing processes are based on complex physical parameters that can be estimated only heuristically (e.g. processes based on multiple-point tools like grinding wheels). In contrast to a classical industrial machine whose behaviors are predefined and limited, smart machines are adaptive and able to learn novel manufacturing concepts from humans or from other smart machines. This allows the smart factory (as a human-centered CPS) to respond to new production jobs and situations.

The learning process of a smart machine is a combination of self-learning (learning by doing) and conversation with humans and other smart machines. Self-learning can be applied to optimize manufacturing processes. It is based on observation and reasoning which leads to the adaptation of the process workflows and parameters. But self-learning is not the primary approach to learn novel manufacturing concepts. This is achieved through conversation, especially with humans. For instance, if a process requires tooling that is novel for a smart machine, then the machine can ask a human how and why this should be used. The "how" gives some answers to the concrete transaction, whereas the "why" gives a more general explanation that could also apply to similar situations. The conversation can happen anytime (before, within or after the process). A human operator can intervene at any time and teach the machine to refine the manufacturing concepts. The conversation ends when the participants (machine, human) agree on

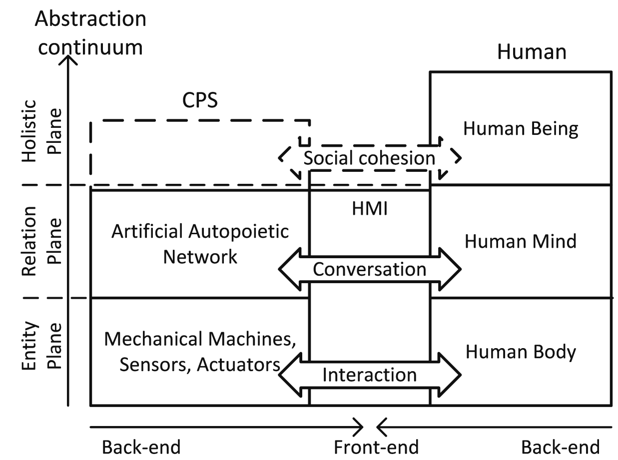

Figure 6: Integration of humans within CPSs.

the manufacturing concept.

4.2 Integration of Humans

System learning based on self-learning and conversation requires a holistic integration of humans into the CPS. CPSs, like smart factories, are spread across physical and cyber environments. The two domains (physical and cyber) are represented by corresponding planes on the abstraction continuum. The physical domain correlates to the entity plane and encompasses all physical devices, communication media and physical signal passing. The cyber domain is realized on the relation plane as a kind of autopoietic network, which includes images, goals, decisions and their relationships to each other (Fig. 6).

The interface between a CPS and other enactive entities plays a central role in their integration. In the future this interface will also enable social cohesion between humans and machines. In our case study the interface between humans and smart machines is called the *human-machine-interface* (HMI). It separates the human from the machine interior and facilitates physical interaction and conversation between them. In the case of interaction within smart machines we would rather speak of machine-to-machine interfaces (M2MI). For simplicity, we use the term HMI, knowing that the counterpart of a smart machine may be a human or another smart machine.

In classical systems an HMI encompasses some peripheral devices (screen, mouse and keyboard) and software implementing a graphical user interface (GUI). The HMI is much more extensive in smart machines. Any sensors and actuators which are in direct contact with human beings, belong to an HMI. Through the HMI each part of the CPS can interact with the one corresponding to the human (Fig. 6). On the entity plane, there's an interaction loop between physical devices and the human body. It expresses the concrete physical interaction between them. On the relation plane the conversation loop allows the CPS to share its subjectivity like images, goals and decisions, with the human.

Conversation with humans can be realized through classical HMI components, like a touch screen. In such setups the screen can be seen as a "white board", where human and machine meet each other, visualize, manipulate and exchange their goals, models and ideas. A comprehensive conversation can be realized with the inclusion of each available sensor or actuator. This allows an entity (human or machine) to observe its opponent, to interpret their behavior and to react accordingly. For instance, if some of the results of a human-machine cooperation don't meet the requirements as anticipated, a conversation can be launched. The smart machine observes the instructions of a human operator, trying to understand and finally reproduce/reflect these instructions (or vice versa when humans learn from smart machines). In contrast to classical machine learning, where learning is limited to some selected topics and parameters, conversation allows humans and machines to build an adaptive learning organization, which is not limited to one topic. The conversation participants become designers of their collaboration.

4.3 Layers of Control

HCPSs are complex control systems. The layering in such systems is an architectural task that helps to divide some high level goals, like visions or strategies into more concrete goals. In this architecture an upper layer controls the lower ones. It is important to note that no new system properties are created by layering. The opposite is the case. A rigid system organization leads to a reduction of its adaptability and responsiveness, as P.P. Lemberger mentioned. *"Organizing a system requires decreasing the number of possible configurations available to that system"* [15].

The question arises how many layers are needed for smart machines (or HCPSs in general). Generally, the number of layers could be arbitrary. But the design for human-machine-conversation should be easy to understand and should follow a natural control layering. Whereas a single layer inhibits conversation, too many layers could irritate human users, (e.g. where should I feed in my ideas?). We propose to use five layers for smart machines (Fig. 7), a layering that is inspired by complex industrial process control systems [22]. The first layer, A_0, deals with basic control issues like motion control. The advanced control layer, A_1, handles for instance NC-programs and self-learning functions for complex motion controls. Often A_0 and A_1 are implemented in real-time embedded systems (e.g. Computer Numeric Controls). The operational layer, A_2, manages the process workflow and composes NC-programs. The tactical A_3 and strategic A_4 layers manage production strategies that help to optimize the manufacturing process holistically.

Each layer of entity A is connected horizontally to some equivalent layer of entity B. Whereas horizontal connections indicate a physical interaction loop on the entity plane, they designate conversation loops on the relation plan. Conversation between A and B can be done at all layers. This means that, for example, the exchange of new methods over A_1 (the "how") can trigger the exchange of new goals on A_2 (the "why"). In the sense of Paskian Environments[2] each layer could serve as a model facility for the upper layers. This even holds for the physical level A_0 that could keep the concrete physical model of A_1.

4.4 Two-Dimensional System Architecture

A dedicated system organization helps to manage the increase in structural complexity, which is caused by the high responsiveness and adaptivity of HCPS. In classical software architecture the 3-layered architecture is very common to distinguish between back-end and front-end components (e.g. P.P. Lemberger in [15] p. 150f). The focus in embedded system architecture is more on the hardware abstraction and implementation of hardware-independent applications. For HCPS we propose a two dimensional layering, which combines both approaches and which also helps to integrate humans as an enactive entity (Fig. 8).

The first dimension is based on the abstraction continuum [7] and describes the level of abstraction. It is divided into 3 areas: *hardware*, *middleware* and *application*. The hardware encompasses all physical components and forces of a system. The middleware is used to abstract hardware and to provide a hardware-independent interface for applications. Middleware and applications comprise dedicated software components for information processing and decision-making.

The second dimension reflects the need to distinguish between back-end and front-end components (e.g. towards the human). It can be split into three areas: *infrastructure*, *target-oriented implementation* and the *human-machine interface* (HMI). The infrastructure of a system comprises any environments and components that operate in the background (e.g. physical environment, data base, coordination media). Target-oriented implementation includes all the components that have been designed for a particular purpose. In software engineering this is often called the "business logic layer" or "service layer". The HMI encompasses all components that are in direct contact with humans. It denotes the

[2] http://www.haque.co.uk/paskianenvironments.php

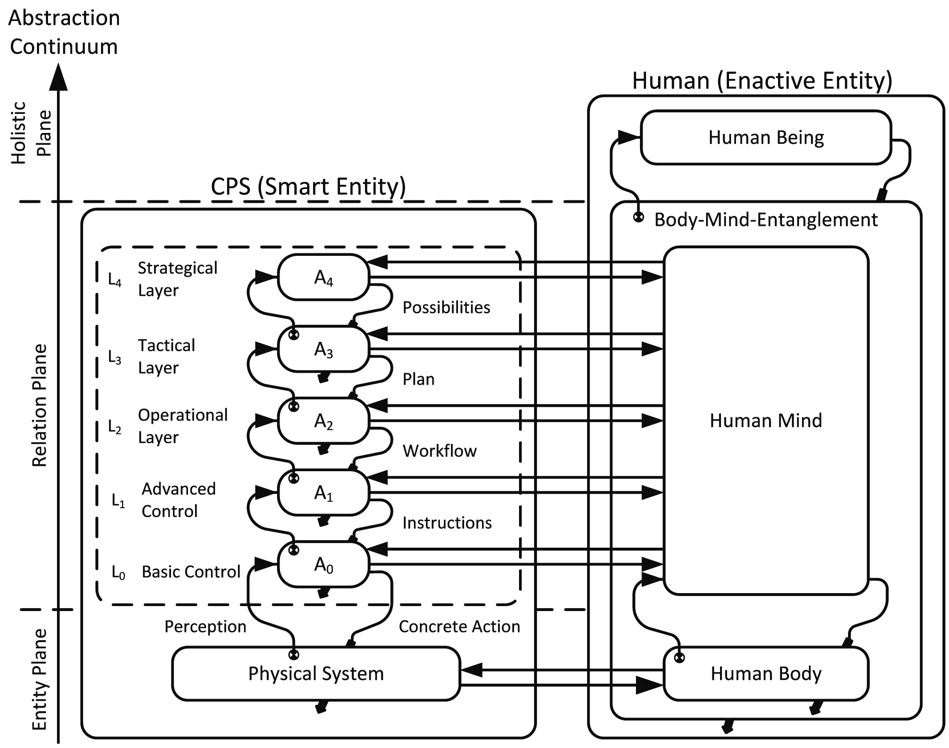

Figure 7: System dynamics point of view: CPS as a layered control system, which is horizontally connected with a human being through conversation and interaction loops.

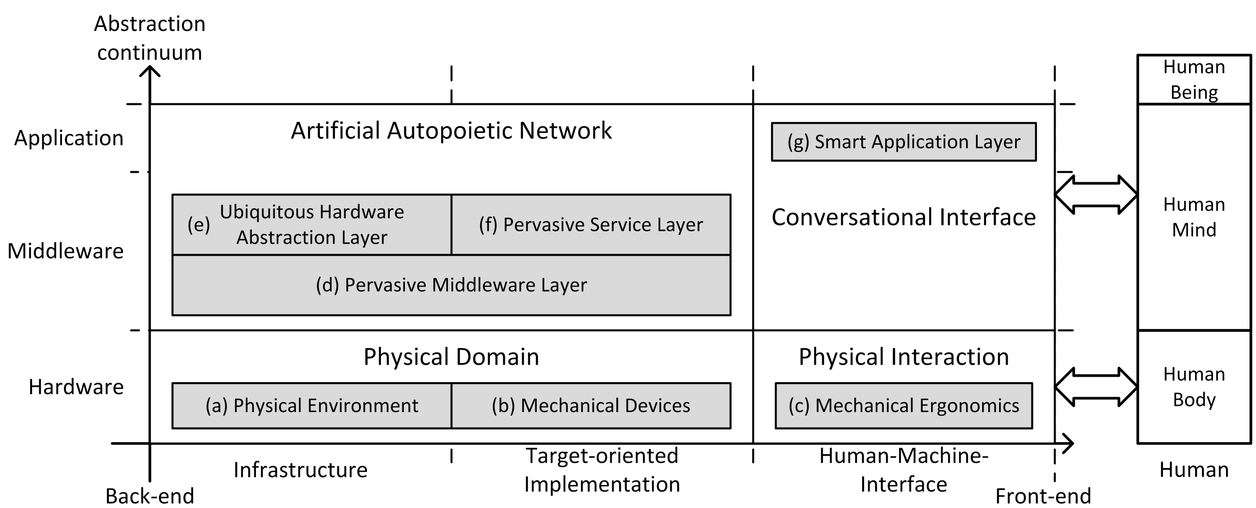

Figure 8: System organizational point of view, where components of a CPS are organized in two dimensions, the abstraction continuum and the back to front end axes.

front end of a CPS and includes physical and cyber entities likewise.

Smart machines are made of three components from the physical domain. The *physical environment* (Fig. 8a) works as an infrastructure for any kind of hardware assembling. It encompasses among other things electrical current and wiring, fluid and piping systems. *Mechanical devices* (Fig. 8b) are targeted implementations, artifacts, made in order to pursue specific purposes (e.g. tooling, industrial computer). *Mechanical ergonomics* (Fig. 8c) is an implementation towards the human-body and it can be seen as the physical HMI, like a screen, buttons, door handles or windows.

The cyber domain is structured into four components. The *pervasive middleware layer* (Fig. 8d) interfaces with the entity plane and encompasses drivers, operation systems, databases and frameworks. The *ubiquitous hardware abstraction layer* (Fig. 8e) implements services to handle the infrastructure and devices. The *pervasive service layer* (Fig. 8f) implements target oriented services towards an HMI (e.g. business logic). The *smart application layer* (Fig. 8g) implements the front end. Its primary concern is direct conversation with other systems (humans, other CPSs).

4.5 Benefits and Challenges

We see great potential when integrating humans holistically into CPS. These days CPSs are classified as "smart entities". In the future CPSs could become enactive due to new technology and to holistic integration of humans [8].

We do not intend to build human-like systems, but we focus on the holistic integration of people in technical systems, especially to make their skills and creativity usable for those systems. High responsiveness of HCPSs will bring the following major benefits: (1) through conversation with humans an HCPS can actively learn new concepts, 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. This could support education and intuitive working with technical systems. (3) The success of their collaborative activities is more likely once humans and HCPSs have a shared agreement of understanding. And finally (4) the human-centered design reduces the bio-cost of humans and reinforces the human being in his feeling of being in control of his life experience.

In our case study, we have seen that the design of HCPS leads to interdisciplinary collaboration, which is challenging from a communication point of view and from maintaining an overview over the whole. It requires different engineering approaches and methodologies to handle the complexity and interdisciplinarity of HCPSs. In particular implementing generic conversation is a complex undertaking that requires a collaboration of psychologists, sociologists and engineers.

5. CONCLUSION

We presented a model for human-centered cyber-physical systems (HCPS). It's an instantiation of our holistic and generic system model URANOS that allows to treat all kinds of entities with the same model. Our approach to CPS is based on human-centered design, with a focus on respecting and protecting humanistic values and the integrity of human beings. We state that the proposed integration of human beings will lead to a human-machine symbiosis, where human characteristics like creativity and empathy become accessible to technical systems.

Conversation, as presented, allows humans and CPSs to learn from each other and to enter into an adaptive learning organization. It is a prerequisite for human-centered design, so that humans and CPSs can become designers (and co-designers) of their collaboration. We illustrated the conversation between human and machine on the example of smart industrial machines.

A multi-layered control architecture has been presented that allows to design system dynamics and conversation between CPSs and humans. High level goals like strategies and visions are broken down on each layer, ending with concrete actions executed in the physical environment. To express the system organization a two dimensional system architecture has been presented, where the first dimension ranges from physical to cyber and the second from back-end to front-end (towards the human).

The main benefit of HCPS is that the bio-cost of humans can be reduced because the system respects human values and has a high responsiveness. Through active learning with the human, the system can adapt to new circumstances.

Our next steps are to investigate how humans can be technically integrated into CPSs, especially through conversation, and to design an HCPS prototype on the basis of smart industrial machines.

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