Holistic System Modelling for Cyber Physical Systems

Benjamin HADORN
PAI-Research Group, University of Fribourg
Fribourg, Switzerland

and

Michèle COURANT
PAI-Research Group, University of Fribourg
Fribourg, Switzerland

and

Béat HIRSBRUNNER
PAI-Research Group, University of Fribourg
Fribourg, Switzerland

ABSTRACT

Cyber physical systems (CPSs) are built of physical components that are integrated into the cyber (virtual) world of computing. Such systems offer many open questions and challenges, such as time modelling, big data mining, system awareness, coordinating activities, and managing collaboration with and within external systems. Much of the published work focusses on how virtual and physical systems can be designed, coordinated and managed. We argue that drawing a border between virtual and physical is misleading the design of CPS, especially for the integration of humans. In this paper, we present a holistic modelling approach to move classical CPSs towards human-centered CPSs. The approach is based on our generic coordination model. The goal is not the creation of human-like systems, but rather a holistic integration of enactive entities (e.g. humans, animals, plants, cells) into CPSs. Closely connected to this integration is the understanding and modelling of cognitive coordination. We argue that this approach could enable CPSs to integrate human intelligence and to become a smart partner for daily human activities.

Keywords: Coordination model, cognitive coordination, human-centered systems, cyber-physical systems, conversation.

1. INTRODUCTION

Our research tends to model systems in a holistic way, meaning we want to consider a system as a whole, in which all relevant entities (such as humans and animals) are fully integrated. In particular, we want to model human-centered systems that integrate human intelligence and encompass humanistic values. In [3] we presented a generic coordination model that is applicable to different problem domains. The model allows understanding and designing systems in a holistic manner, notably human-centered systems. In this paper, we focus on the concept study of cyber physical systems (CPSs) and we intend to show how a CPS can become human-centered using the holistic approach of our model.

A CPS is built of physical components that are integrated into the cyber (virtual) world of computing. Whereas a CPS is built of physical and virtual components, our model introduces a third level addressing the holistic character 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 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. Integration must be done on all three levels (physical, virtual and holistic) to be fully understandable and to not mislead the design of a CPS.

Our generic coordination model encompasses humans or other bio-systems with the denotion of *enactive entities*. 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*, that deals with holistic coordination strategies and processes based on shared knowledge, creativity and empathy among enactive entities. Our holistic approach could enable the CPS to become a smart partner for daily human activities.

The paper starts with the definition of human-centered and cyber physical systems. In section 4, we give an overview of cybernetics and conversation theory. In section 5, we present our generic coordination model and its components. Finally, section 6 concludes our current state of research on holistic modeling.

2. HUMAN-CENTERED SYSTEMS

In classical systems, humans are often regarded as outside entities who interact through dedicated interfaces using predefined protocols. The consequence is that human-to-human Interaction is not handled by the system and blocked out. Human-centered systems (HCSs) put human beings into the focus and are marked by their respect of humanistic values such as linguistic, cultural and geographical diversity. Rather than diminishing or simplifying them, HCSs are devoted to human welfare. As mentioned by R. E. Jacobson in [5] *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.

From our generic and systemic point of view, HCSs encompass the evolution of human and of human interaction. We consider humans as *enactive entities*, which are defined by three characteristics:

1. they are aware of their surroundings or themselves (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 the behavior of enactive entities changes while the system evolves.
3. enactive entities are also able to differentiate themselves from the environment (individuation).

The term "enaction" was developed by F. Varela et al. [18] 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"*.

3. CYBER PHYSICAL SYSTEMS

R. Rajkumar et al. [12] define cyber physical systems (CPSs) as *physical and engineered systems, whose operations are monitored, coordinated, controlled and integrated by a computing and communication core*. CPSs bridge the physical world with the world of computing and communication. They bring the discrete and exact domain of computing and logic together with the continuous and uncertain world of physical and engineered systems. CPSs *will transform how humans interact and control the physical world* [12].

There are different approaches modelling and designing such systems. E. A. Lee mentioned two strategies in [7]: *"cyberize 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 CPSs, how physical and virtual components interact with each other is fundamental. Components are coordinated and collaborate with each other through interaction in order to serve a greater common purpose. Often, interaction is designed as simple receiving, processing, sending back messages, and connecting ports from physical to virtual entities, as illustrated by G. Simko et al. in [17]. H. Kagermann et al. [6] propose that the concept of *"Internet of Things"* could be used to interconnect physical entities in CPSs. It allows connecting physical entities (e.g. everyday objects, smart devices) like a nervous system, which is naturally a profound technology for any CPS. However, autonomy, enaction, collaboration and coordination are not automatically solved by using it.

We define a CPS as *the non-separation and entanglement of physical and virtual entities and processes*. Through the holistic integration of enactive entities (especially humans), a CPS becomes an autopoietic organization fulfilling the properties of autopoietic machines described by H.R. Maturana et al. in [9]; namely autonomy, individuality, unity through self-creation, and self-maintaining. We state that human-centered CPSs are *living systems*, like Maturana et al. stated *"a physical system if autopoietic, is living"*. Eventually a living system can be seen as an enactive entity itself. Because enactive entities tend to become autonomous due to the autogenetic process, we characterize them as *autogenetic systems.*

4. CYBERNETIC APPROACHES

A more sophisticated and holistic model is required to integrate enactive entities like humans. 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 [20] 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. Ever since, cybernetics has been relevant for the study of biological, cognitive, and social systems. Heylighen et al. give a detailed evolution of cybernetics in [4]. The focus of cybernetics aims more at goal-directedness and functional behavior of systems rather than their components.

Cybernetic Orders

Different cybernetic orders have been defined to understand, describe and model complex systems. As M. Yolles et al. [21] 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*.

First order cybernetics defines systems that are observed from the outside. K. Krippendorff [22] stated that *first order cybernetics is concerned with circular causal processes e.g. control, negative feedback, computing, adaption*. First order cybernetics can be used to describe systems that are defined by an external designer (e.g. a thermostatic control system).

Second order cybernetics goes a step further away from mechanistic approaches. It addresses the concepts of observation, cognition, self-reference and autonomy. 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 [19]). F. Heylighen et al. presented in [4] a formalism for *goal-directedness* and *control systems* towards such concepts, especially for autopoietic systems. They describe the characteristics of an autopoietic system as *the fact that it pursues its own goals, resisting obstructions from the environment that would make it deviate from its preferred state of affairs*. Its highest goal is its survival. F. Heylighen et al. further presented a functional model for control systems (Fig. 1a). A control system perceives some variables of an environment, mapping them to an internal representation. Through appropriate processing and a preset goal, the system arrives at certain decisions that finally end up as actions executed in the environment. If the affected variables (some also affected by disturbances) interfere with the observed variables, then the system can start to control these variables. This model allows to create double looped control systems (Fig. 1b). The upper loop controls the lower loop by changing its goals.

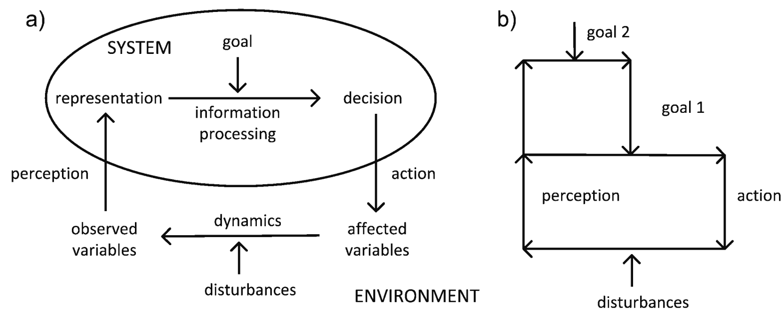

Figure 1: (a) Model of a control system. (b) Double loop control system (Source [4]).

In *third order cybernetics* a system is seen as a whole. The system comprises an autogenetic circuit between observer and observed towards their inseparable representation and co-evolution. The whole cannot be decomposed into subcomponents without losing relevant information about the whole. E. Schwarz defined a holistic meta model for general systems, and especially complex ones, in [14] and [15]. He identified seven stages of increasing abstraction in which a system becomes more and more complex and autonomous during its long-term evolution.

Conversation Theory

The way enactive entities interact within human-centered CPSs is far more complex than classical human-machine interaction. As G. Pask explains in his conversation theory [10] interaction 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. This kind of interaction is called *conversation*.

There is a significant difference between communication and conversation. The goal of conversation is "concept sharing" and its value is agreement between participants [11]. H. Dubberly et al. describe in [2] 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. Systems using the communication model based on C.E. Shannon et al. [16] 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. state that using Shannon's model it is impossible to say something novel to someone else. The model of conversation on the other hand enables the exchange of novel concepts, to construct meaning and finally be able to have an *"agreement over understanding"*. As a result, entities could agree to perform actions beyond the conversation.

This model could enhance the CPS model by integrating enactive entities in a more holistic manner. H. Dubberly et al. argue in [2] that it could allow 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*.

The conversation model influences the CPS in many ways. We see three main characteristics: (1) the system is able to gain knowledge from enactive entities. Due to their cognitive capabilities, enactive entities can feed their knowledge into the system. (2) The system can give accommodated knowledge back to enactive entities. It supports the education of enactive entities. (3) The system can support the conversation between two or more enactive entities by its infrastructure, providing them a conversation of context.

Integrating conversation into CPS could lead to a self-learning organization, a system fully adaptive to new behaviors and requirements and able to exchange abstract concepts with enactive entities.

5. GENERIC COORDINATION MODEL

Our generic coordination model follows a holistic approach to integrate all relevant entities into the system, especially humans, animals etc., as enactive entities [3]. The model is based on two main spectra: the *abstraction continuum* and the *coordination spectrum*.

Abstraction Continuum

The abstraction continuum describes system components from their concrete existence (reality) and their representation as models and concepts towards their holistic characteristics. We split the continuum into three planes: *entity*, *relation* and *holistic*.

The entity plane comprises everything that exists or could potentially exist, called *entities*. Two types of entities can be distinguished: *interactions* and *rules* (Fig. 2). Entities can interact with each other; we define interaction as an exchange of anything between two or more entities. Rules restrict interaction and limit the way a system could evolve. Some of the evolution paths become impossible due to rules.

The next abstraction plane is the *relation plane*. The basic elements of this plane are attributes and relations. Whereas attributes describe entities, relations emerge when two or more entities share the same attributes. Both elements underlie the subjectivity of biased perception within a system. The way a system describes entities through attributes depends on its capabilities of perceiving those entities. Therefore, relations and the corresponding arrangement of entities on a topology are both of subjective nature. This leads to the concepts of observation and awareness. The dynamic process of *perceiving-acting* connects the entity and relation plane as a second order cybernetic loop. A system can perceive and observe concrete entities by mapping them to an *image*. The image is an abstract representation of an entity (model of entity). Through

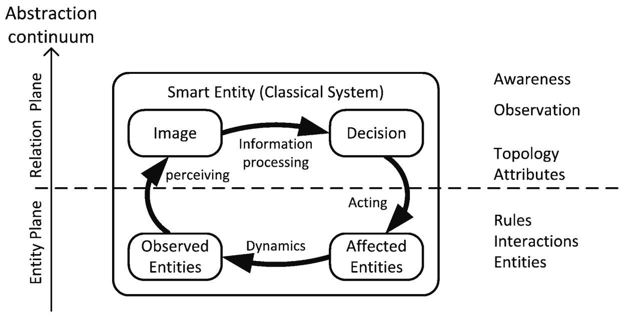

Figure 2: A smart entity is typically spread over the entity and relation planes.

information processing the system could come up with a *decision* about how to react upon the perceived images. The perceiving-acting process enables a system to become aware of its surroundings and its activities in the environment, a characteristic called *awareness*. Classical systems like CPS are spread over these two planes. We call such systems *smart entities*.

As E. Schwarz [14] proposes, 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. They are the main cause of increasing complexity and autonomy of systems during their long-term evolution. With increasing complexity due to the entanglement of entities with their images (cf. holistic plane Fig. 3), such systems cannot be decomposed into its subcomponents without losing relevant information about the whole. Therefore, they cannot be seen as smart entities anymore. They must be considered as holistic beings. We introduce a third plane, called the *holistic plane*, describing such holistic beings as autogenetic systems (Fig. 3). We refer to them as *enactive entities*.

There is a holistic process connecting the lower planes with the holistic one. We call this third order cybernetic process the *individuation process*. It expresses circular influences of the whole to the lower loop of perceiving-acting.

There is also a consciousness spectrum ranging from awareness to the cognitive capabilities of enactive entities. It expresses the increasing consciousness complexity of a system leading to characteristics like creativity and empathy.

Coordination Spectrum

The second main spectrum of our modes constitutes the characteristics of coordination processes, called *coordination spectrum*. Coordination processes control and direct the interactions within a CPS and therefore influence evolution of the whole. There are three areas of characteristics: *objective*, *subjective* and *cognitive* (Fig. 4).

Schumacher [13] split coordination into objective and subjective coordination. He states that design and finally the implementation become complicated without differentiating coordination due to describing subjective meaning with objective coordination. *Objective coordination* describes how rules are applied to interactions between entities. Self-organization can be mentioned as an example of objective coordination. There is no "coordinator" needed, self-organization happens spontaneously by applying rules to interaction entities. This could be caused by small triggering fluctuations that are then amplified by positive feedback to the whole system.

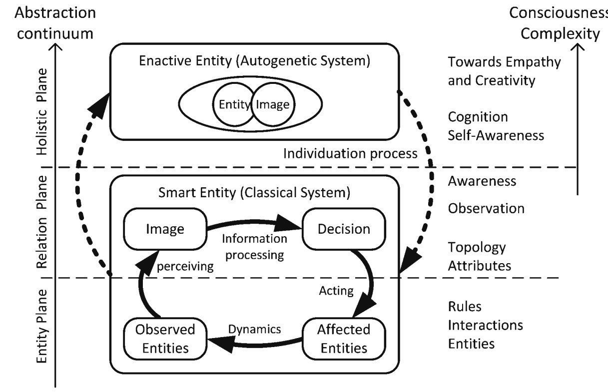

Figure 3: Enactive entity emerging on the holistic plane.

Subjective coordination characterizes the coordinative behavior of smart entities, each one observing and acting from their point of view. Through observation, smart entities can perceive system states (mainly partially). As they become aware of their surroundings through internal information processing, they start to act in a subjective manner. Such behavior is often accompanied by adapting and reinforcing rules in order to follow certain goals. Objective and subjective coordination are common for smart entities.

Cognitive coordination deals with holistic coordination strategies based on shared knowledge, creativity and empathy among enactive entities [3]. In CPSs, the uncertainty and incompleteness of knowledge about the interacting entities are the basic features that have to be addressed. A more comprehensive and holistic approach could lead to a new range of coordination processes on cognitive aspects. Especially for human-centered CPSs, this could reinforce the human being in his feeling of being in control of his life experience in the world of technology. Finally, cognitive coordination helps to reduce the bio-cost and to increase the acceptance and success of CPSs [1].

Integration of Enactive Entities through Conversation

If an entity can participate in all abstraction planes of a system, we call this a *holistic integration* of that entity into the system. In this sense, participation is a loop connecting entities on the corresponding planes. The loop on the entity plane is called the *interaction loop*. It expresses the concrete interaction between the entities. Entities of higher order (e.g. smart and enactive entities) often intend to share their subjectivity, like images and goals. This exchange happens through the *conversation loop*. It enables the entities to share their knowledge with others. This loop also allows entities to agree upon an understanding that influences the performance of their collaborative activities [10].

For instance, the holistic integration of a human (enactive entity) into a CPS (smart entity) comprises participation on the entity plane through an interaction loop and on the relation plane through a conversation loop. This enables the CPS to learn novel concepts and goals from humans, and vice versa. We see the following major benefits: (1) a CPS can actively learn from humans, rather than having a predefined behavior designed by engineers. Users can become a teacher of the system. (2) The CPS can give back the gained knowledge to the user. For

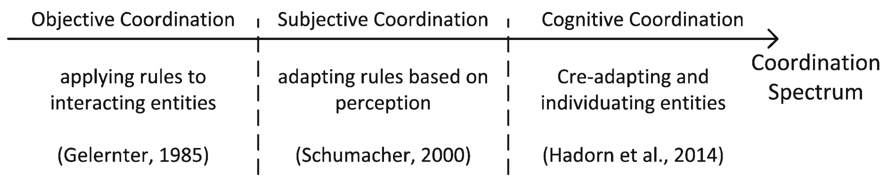

Figure 4: Coordination spectrum.

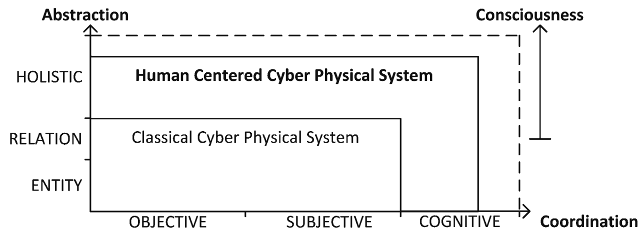

Figure 5: Classical vs. human-centered CPS.

instance, the CPS could teach new users. Finally (3), the success of their collaborative activities is more likely once user and CPS have a shared agreement of understanding.

A holistic integration of humans leads to human-centered CPS, a system encompassing humans and classical CPS. It likewise inherits the characteristics of humans and CPSs. In this sense, it can be seen as an overall enactive entity, comprising holistic and cognitive aspects (Fig. 5).

6. CONCLUSION

Our approach allows handling all entities with the same model, including smart and enactive entities. Further, it allows integrating them as a whole instead of reducing them to their sub-components. Moreover, it handles complex and dynamic processes in a holistic manner, as we state that living systems affect coordination through their cognitive capabilities. Finally, we state *coordination is more than just managing dependencies between activities* as defined by Malone et al. in [8]. It is about managing the evolution; especially for human-centered systems, it handles 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 have shown that the generic coordination model can be used for holistic system modeling, especially for human-centered CPSs. In contrast to classical CPSs, human-centered CPSs respect the holistic and cognitive characteristics of enactive entities (Fig. 5). Their integration leads to autogenetic systems.

Our next step is to continue deriving the generic coordination model towards a dedicated model for pervasive computing systems and human-centered CPSs. We think that focusing on conversation could show new ways for human-machine-interaction and for holistic integration of enactive entities.

7. REFERENCES

[1]. H.Dubberly, C. J. Maupin, and P. Pangaro. Bio-cost An Economics of Human Behavior. **Cybernetics and Human Knowing**, 16(3-4):187-194, 2009

[2]. H. Dubberly and P. Pangaro. On Modeling - What is conversation, and how can we design for it? **Interactions**, 16(4):22-28, 2009.

[3]. B. Hadorn, B. Hirsbrunner, and M. Courant. A Holistic Approach to Cognitive Coordination. Technical report, University of Fribourg, Switzerland, April 2014.

[4]. F. Heylighen and C. Joslyn. Cybernetics and Second-Order Cybernetics. In R. Meyers, editor, **Encyclopedia of Physical Science & Technology**. Academic Press, New York, 2001.

[5]. R. Jacobson and R. Jacobson. **Information Design**. MIT Press, 2000.

[6]. H. Kagermann, W. Wahlster, and J. Helbig, editors**. Securing the Future of German Manufacturing Industry: Recom-mendations for Implementing the Strategic Initiative INDUSTRIE 4.0, Final Report of the Industrie 4.0 Working Group**. Forschungsunion im Stifterverband für die Deutsche Wirtschaft e.V., Berlin, Apr. 2013.

[7]. E. A. Lee. CPS Foundations. In **Proceedings of the 47th Design Automation Conference**, DAC '10, pages 737-742, New York, NY, USA, 2010. ACM.

[8]. T. W. Malone and K. Crowston. The Interdisciplinary Study of Coordination. **ACM Comput. Surv**., 26(1):87-119, 1994.

[9]. H. R. Maturana, F. J. Varela, and S. Beer. **Autopoiesis and Cognition: The Realization of the Living**. D. Reidel Pub. Co Dordrecht, Holland; Boston, Dordrecht, 1980.

[10]. G. Pask. **Conversation, Cognition and Learning: A Cybernetic Theory and Methodology**. Elsevier Publishing Company, New York, 1975.

[11]. G. Pask. The Limits of Togetherness. In **IFIP Congress**, pages 999-1012, 1980.

[12]. R. Rajkumar, I. Lee, L. Sha, and J. Stankovic. Cyber-Physical Systems: The Next Computing Revolution. In **Design Automation Conference (DAC), 2010 47th ACM/IEEE**, pages 731-736, June 2010.

[13]. M. Schumacher. **Objective Coordination in Multi-Agent System Engineering: Design and Implementation**, volume LNAI No. 2039. Springer-Verlag, Berlin, Heidelberg, 2001.

[14]. E. Schwarz. Can Real Life Complex Systems be Interpreted with the Usual Dualist Physicalist Epistemology - Or is a Holistic Approach Necessary? **Special Issue: Proceedings of the fifth European Systems Science Congress**, 2:9 p., October 2002.

[15]. E. Schwarz. On the Nature of Consciousness - On Consciousness in Nature. **AIP Conference Proceedings**, 1303(1):334-342, 2010.

[16]. C. Shannon and W. Weaver. **The Mathematical Theory of Communication**. Number Bd. 1 in Illini books. University of Illinois Press, 1949.

[17]. G. Simko, T. Levendovszky, M. Maroti, and J. Sztipanovits. Towards a Theory for Cyber-Physical Systems Modeling. In **Proceedings of the 4th ACM SIGBED International Workshop on Design, Modeling, and Evaluation of Cyber-Physical Systems**, CyPhy '14, pages 56-61, New York, NY, USA, 2014. ACM.

[18]. F. J. Varela, E. Thompson, and E. Rosch. The Embodied Mind: Cognitive Science and Human Experience. The MIT Press, Cambridge/MA, 1993.

[19]. H. von Foerster. Ethics and Second Order Cybernetics. **Cybernetics and Human Knowing**, 1(1):9-19, 1992.

[20]. N. Wiener. **Cybernetics: or Control and Communication in the Animal and the Machine**. MIT Press, Cambridge, MA, 2 edition, 1948.

[21]. M. Yolles and G. Fink. Generic Agency Theory, Cybernetic Orders and New Paradigms. Organisational Coherence and Trajectory (OCT) Project, July 2014.

[22]. K. Krippendorff. A Dictionary of Cybernetics. The American Society of Cybernetics, Norfolk, VA, USA, 1986.