A Neuro-inspired Approach for a Generic Knowledge Management System of the Intelligent Cyber-Enterprise

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Abstract: The paradigm of Cyber-Physical Systems may be successfully applied to a large number of case-studies, but the most challenging of them are focusing on large scale systems whose dynamics is adapting to various functional scenarios and environmental conditions as energy networks, traffic systems and especially different kinds of cooperative networks of enterprises. However, the large spectrum of possible configurations of such processes raises many issues with respect to the identification of problems to be solved, and furthermore, of the solving method itself, making the efficient use of available knowledge a real challenge. This paper is presenting a neuro-inspired approach for the design of a knowledge management system dedicated to complex networking enterprises organized as Cyber-Physical Systems, and whose functioning is implying dynamical reconfiguration in response to environmental changes, based on the gathering and use of large flows of information, which are referred to as Intelligent Cyber-Enterprises. The proposed ideas are based on a human brain model of reasoning and learning.

1 INTRODUCTION

The tremendous development of the technology in the last 50 years has allowed the solving of many of the socio-economical problems of the world. We may produce many goods faster and transport them at larger distances than whenever in our history, find out rapidly large amounts of information about almost every topic imaginable and we are interconnected by different kinds of networks of information and socio-economical relations.

Manufacturing is one of the fields that have been faced both with an exceptional technological evolution and with a set of extremely complex challenges to face.

Customization of products, scarcity of resources, environment awareness, competitivity, globalization of markets are only some of the factors that are making the management of a manufacturing enterprise an increasingly difficult problem to solve.

Among the tools that are used in this respect, information technologies, implied in control engineering and in knowledge management are the most important. On the other hand, the experience of the last 50 years is showing that there are levels of complexity in certain types of enterprises that require new models and paradigms to be successfully addressed. (Dumitrache, 2013).

Globalization and sustainable development impose a new vision on the economy, considering the social and environmental impact by creation of new sustainable business and production systems. The industry of the future encompasses the concept of an enterprise built on the basis of connectivity – between services, organizational structures, machines, between machines and their human operators, into a network of suppliers, transporters and customers – by means of information as well as material flows.

The high-performance wireless sensors and actuators networks, the Internet of Things and Services, the Cyber-Physical Systems paradigm are only a few of the conceptual and technological drivers for next industrial revolution.

New materials, new technologies, new approaches in control engineering of complex process as networks of embedded systems integrating advanced soft computing technologies and distributed intelligence are a real support for the next generation of enterprises. Advances in the communication technology - M2M and H2M - allow the creation of a real collaborative environment whose components,

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machines and humans, communicate in a smart society of intelligent agents.

The real link between the components of such a heterogeneous system, encompassing processes and products that have to be continuously adapted to the dynamics of the environment, is through information and knowledge.

Not only knowledge was already recognized at the end of the previous century as one of the most important assets of an enterprise (Davenport 1998), but the capability of rapidly and reliably identifying problems and then the adequate knowledge necessary for their solving is crucial for its surviving.

As such, the development of an effective learning knowledge management system is crucial.

Many advances have been made during the last two decades in information acquisition, storage, sharing and retrieving. Knowledge management systems have evolved in terms of goals and tools, (Dalkir, 2005) but, however, there still remain some issues:

- Knowledge codification and sharing is dependent on semantic technologies and on field ontology, so heterogeneous agents networking and information interoperability are still far from reliable
- Problem identification remains difficult as it implies a delicate balance between “ sufficient information” and “ too much information”

The most successful control system that exists at this moment, able to deal with reliably retrieving heterogeneous information and selecting the “right amount” for identifying and solving a problem, while running the smooth dynamic reconfiguration of its process as required by the adaptation to the environmental changes is the human brain. (Bannat, 2011)

Therefore, this paper proposes a behavioral model of the perception-reasoning-learning functional loop on which the human brain is supposed to found its functioning and then to apply it in a knowledge management system architecture intended to support the enterprise of the future, as based on the Cyber-Physical System concept.

The second section will briefly address the concept of the Intelligent Cyber-Enterprise, as a socio-technical complex system. The third section will present the perception-reasoning-learning (PRL) loop, from a functional point of view and with a special emphasis on the awareness concept.

The last section will present some principles of implementation and key issues for a knowledge management system based on the PRL loop.

2 INTELLIGENT CYBER-ENTERPRISE

The concept of Intelligent Cyber-Enterprise (ICE) (Dumitrache, 2013); is based on the largely known paradigm of Cyber-Physical Systems (CPS).

CPS (Baheti, 2011) are representing a research area and a paradigm that considers complex systems formed by the tight interconnection of physical processes (usually of a different nature) and information objects (usually conceptualized as information agents) that are fulfilling a common goal by emergent behavior, responding adaptively, by dynamical reconfiguration, to contextual changes.

The link between the physical nature of processes and their cybernetic counterpart is far more important than simple modeling and reflects exactly the process behavior as hardware-in-the loop and human in the loop modules.

A Cyber-Enterprise is thus composed by physical objects as machines, by knowledge objects as process models (workflows) and control algorithms, by humans (operators, designers, engineers a.s.o) and by information objects (software modules, communication processes, databases, a.s.o). All these objects have to interact and cooperate in order to fulfill enterprise goals, that are specified in terms of production demands, cost, time and resource constraints, working in a dynamic environment represented by customers, suppliers and market evolution.

The proper interaction between these components is ensured by a dimension of intelligence, both in terms of the large amounts of heterogeneous information flows available through the enterprise and by the emergent intelligent behavior of the enterprise (adaptive, reactive, pro-active, optimization), through a global knowledge management system. (Dumitrache, 2014).

The ICE functioning is modeled by problem solving, a problem being defined by a goal to be fulfilled by at least one of the enterprise components, at the lowest level of complexity. At the highest level of complexity, problems to be solved are related to complex goals at the operational level and strategic decisions that imply more or less all the enterprise resources.

From the CPS oriented modeling results that every problem to be solved is implying at least a control loop and at least a single enterprise resource. More complex problems imply interconnected multiple control loops and different resources. At the lowest level of complexity, control loops are working in real time, implement clear algorithms and rules using well defined data; more complex problems use heterogeneous information structures and heuristics.

An intelligence-based model for the ICE is represented in figure 1.

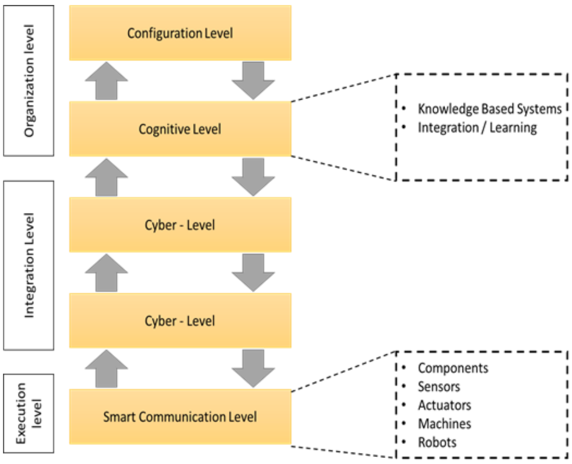

Figure 1: CPS-based enterprise model.

Each component of the ICE architecture should have both the capacity of independent action under pre-defined specifications and the capacity of communication, allowing the transfer of meta-data, information and knowledge in order to provide reliable context oriented behavior.

Also, there is the possibility to connect subsystems in clusters, based on functional requirements. For instance, machines and robots can be grouped in manufacturing cells, by means of communication protocols (software modules) and synchronization rules embedded in their respective control algorithms (process models). Specified functionalities may be added to products by manufacturing cells by means of control algorithms (product models). Manufacturing cells may be connected in a (temporary) manufacturing system for fulfilling a given order by means of emerging product/ process models (workflows) and their software representations (cases and agents). Order dynamics, as well as the current state of resources result in dynamic reconfiguration of the ICE.

2.1 Intelligent Entities

The Intelligent Entity is a concept designed to represent the components of an ICE architecture based mainly on information flows. (Figure 2)

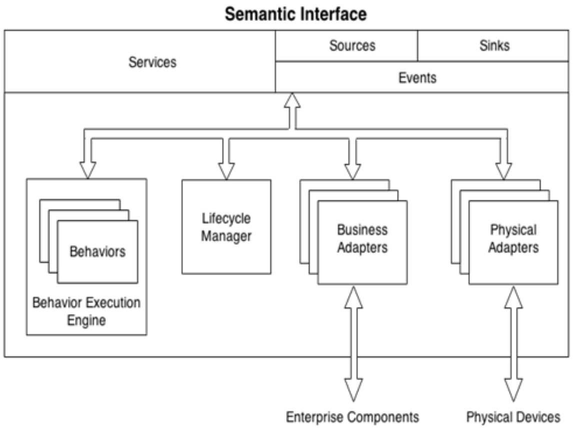

Figure 2: Generic Architecture of ICE.

Intelligent Entities have the following components:

Semantic Interface – provides a unique way of accessing both virtual and physical resources of the system. This interface will allow both service and event-based interactions between the system's components. Components are semantically enhanced and include: services, event sinks and event sources.

Services may be considered as methods to solve well defined problems, which usually arise in the life-cycle of the system.

Events are defining usually perceived inputs that may form a model for a new particular problem.

Business Adapters – Each Intelligent Entity can host a series of specialized components that will connect to existing enterprise components. Components will require connection mechanisms and rules for the semantic enrichment of data.

Business adapters are providing ways for particularizations of generic problems represented by services.

Physical Adapters – Intelligent Entities can also host a set of adapters for the physical devices. Each Physical Adapter will need to handle all aspects of device discovery, configuration, communication and data transformation.

Behavior Execution Engine – instances of intelligent Entities will be able to perform behaviors expressed in various languages or according to different ontology. For each supported language, the Intelligent Entity instance will have a corresponding execution engine. A semantic interface will provide appropriate input and output for the generic behavior models.

Lifecycle Manager – handles all aspects of the Intelligent Entity's lifecycle - initializing, clean-up, monitoring the state of the components hosted on the current instance and deploying new behaviors or adapters. The lifecycle manager can expose a set of operations through the semantic interface, such as a services to deploy / un-deploy components running on the current instance, or an event source through which it will generate events regarding the change in the state of components.

2.2 The Biological Perspective

Interpreting an ICE from biological perspective has to take into account the stepwise functional decomposition of an enterprise from one holistic system, with its own behavior, goal and environment towards a set of (heterogeneous in nature and behavior) atomic components (machines, people, abstract objects) which are intricately networked together by a material and by an information flow.

Those component could be either physical in nature – or subjected to very clear and unbreakable rules (machines, robots, tools), conceptual (control strategies, models, guidelines), informational (implementation of control strategies, product agents, software modules) or biological (humans).

An ICE, by its nature, has already this modular organization, and from the intelligence point of view, every component may be embodied as one of the Intelligent Entities described above, represented as such by an agent in the cybernetic world.

Furthermore, it is inherent for enterprises that no atomic component is working as such: they are linked together by communication and functionalities, in clusters: organizational structures, services, manufacturing cells a.s.o. Every cluster has an emergent behavior resulted by the way in which its components are linked and may reconfigure itself in order to respond to a specific order or environment state. Depending on the cluster nature, they may be similar in functioning with tissues or organs of a body. The material flow sustains the functionality and the information flow directs it and connects components together, in order to obtain emergent behavior and cooperation.

It results then that the information flow among intelligent entities may be considered as a nervous system into an organism.

More than that, this nervous system has different purposes, with respect to the different levels of control it serves: real-time, operational, and strategic.

At ***Real-time Level***, it gathers data and gives (simple) commands for atomic components, whose local functioning is ensured by their own control systems – these are the cells. Commands are usually of the type of “start”/ “stop” events, which trigger embedded and well known functionalities, answering to known problems. It is the goal of operational levels to decompose “their” problems in functionalities and to synchronize them according to patterns. This level may embody the cell functioning into an organism. Data gathered are with respect to the actual state of each component. Control is similar with reflex/ unvolitional actions. There is no real awareness in the reasoning process.

At the ***Operational Level***, problems are solved with respect to external stimuli (orders, for instance), by complex algorithms with a strong adaptive component, reflected in the flexibility of the solution and in the possibility to reconfigure the set of atomic components and their respective functionalities to be involved. Here fuzzy and rule-based reasoning becomes involved, as usually there may exist several solutions to the same problem or very similar problems – and choosing either the best solution or the appropriate algorithm are crucial. The information to be gathered has to be sufficient, relevant, reliable. This is the biological level of volitional actions, as the result of a perceived situation which calls for a (previously learned) solution. Reasoning has a degree of awareness (problem identification; solution search), but stimuli perception does not imply awareness, as the once identified solution is applied as a pattern. Again, the commands are in terms of “start”/ “stop” events, triggering algorithms, but also triggering procedures that check the consistency between the estimated results of an action

This is also the level where, in the framework of the ICE, human operators enter the information flow as agents (human in the loop). As (Davis, 2012) presents, here are the kind of problems where the human capacity of perceiving situations is far exceeding the capability of software control systems and the most recent developments in enterprise control are focusing on H2M interactions in order to obtain the best efficiency.

Finally, ***The Strategic Level*** is that where the existent knowledge is used in new ways, to solve new problems that present similitude with old ones, or where new knowledge is gathered in order to substantiate completely new problems solving. Here is the completely self-aware reasoning as well as self-aware stimuli search and perception; and usually here are mostly people that decide, only assisted by knowledge management and business intelligence systems. Here, the main problems are, firstly to be certain that the available knowledge is appropriately used and secondly, to decide what kind of new knowledge is necessary.

A way of ensuring the smooth interaction of human in the loop systems is to design the information and knowledge flows (and as it is, a knowledge management system) inspired by the human brain functioning. It should be noted that the conceptual knowledge management structure proposed by this paper is dedicated for such systems, as their structure and complexity requires new approaches for their overall management.

As a control system of an ICE, the human brain has a limited capacity (even if extremely large), reflected mostly in the number of volitional tasks it can deal with efficiently. It uses also the capability to work with simple algorithms for managing basic functions of the organism, without implying the operational and strategic levels, and may adapt to a number of (learned) scenarios, reflected by the state of the environment and of the organism.

It may change the resource allocation (focus) either deliberately (when encountering a new situation) or unconsciously (when confronted with an unexpected result from an usual action).

This is the reason that the awareness/ volitional nature of reasoning/ perception and acting/ control is a key concept of the approach proposed in this paper.

3 PERCEPTION, REASONING AND LEARNING

3.1 Some Considerations on Brain Structure and Functioning

The relevant aspects which are associated to the idea of the human brain as a cognitive system may be conceptualized through the paradigm of information processing into a system of maximal complexity from the point of view of the actual knowledge.

At microscopic level, the brain is constituted from more than 10^{12} neural processing units, each one having around 10^3-10^4 input-output axonal connections and practically the same number of dendritic and somatic connections. At the brain level, the connectivity includes hundreds of trillions of connections. Structurally, the brain is hierarchically organized, being formed from recurrent interconnected networks. These networks are fulfilling the different specialized functions of the brain (Baldassano, 2015).

Organizational principles for cognitive functions are based on connectivity patterns distributed among functionally specialized brain regions. In (Friston, 2003) is suggested that every area has a unique input-output connectivity pattern and a pattern corresponding to a task dependent on functional connectivity. The essential characteristics of brain information and knowledge processing are determined by the interconnectivity of cortical networks and by the distributed and parallel functional integration. In order to realize a large area of dynamic behaviors, every network has to have a functional reaction sustained by recurrent anatomical connectivity.

The input-output connectivity specifications and the local architecture of a given brain region are representing the determining factors for the region's behavior and for its cognitive significance. They are indicating its functional specialization and its field of options with respect to the functional integration with other brain regions. The dynamics of interfaces between functionally specialized brain regions is characterizing, at least partially, the specificity of the functional integration in a given processing context.

Additional determining factors of the functional architecture are the mechanisms allowing processing modules to incorporate adaptive changes, to provide the system with the capability to learn, as a functional consequence of processing. It may thus be considered that the overall processing system is parameterized with respect to the adaptability factors of the network which is characterizing the learning process.

In (Starzyk, 2004) is suggested the possibility of developing dynamically reconfigurable models which are incorporating functional neural clusters. One may consider the existence of adaptive agents which connect depending on context and on the complexity of the cognitive goal; the dynamic reconfiguration of such groups of agents being automatically realized. The cognitive functions are emergent due to the global dynamics of agents (as sub-networks in terms of neural Grouping operator) and their interactions. Interactive processing of information and knowledge, as well as fault-tolerance and high robustness are ensuring the emergence at the overall brain level, if considered as a dynamical auto-organizing (large-scale) system.

Each cognitive function implies cooperation from several neural structures and the contribution of different interconnected functional modules. It may be considered that, at brain level, there is an interconnection process of several structural and functional modules in parallel-distributed configurations that are generating emergent behavior.

3.2 The Cognitive Perspective

Perception (https://www.cognifit.com) is the ability of the brain to capture, process, and actively make sense of the environmental information.

From a cognitive point of view, it is the active process that makes possible to interpret environment with the stimuli received throughout sensory organs. It requires both of the two processing approaches:

- "bottom-up" or non-aware (passively receiving stimuli from all sensorial channels)
- "top-down" or aware (anticipating and eventually selecting certain stimuli – perception control)

Reasoning is the (brain) capability of solving problems. A reasoning process is based on problem identification, followed by its categorization and, eventually, by the identification of the appropriate solution.

The ***Problem Solving*** process implies reasoning and acting. Feedback of the acting is triggering a new perception/ reasoning stage.

The categorization phase is the one that determines how the following phases are performed:

- Selection (of the solving patterns – if any)
- Focusing (on relevant input information)
- Planning, estimation, validation: an internal loop whose execution depends on the category of the identified problem, but whose goal is to advance towards the solution by a stepwise decomposition of the problem
- Evaluation of success (achieving the desired goal or estimation of the distance towards it)

Learning is the process by which a piece of knowledge modeling a solved problem is stored in a way that makes its retrieval, (eventually as a volitional action), possible.

There may be also defined a *deep learning*, by which a piece of knowledge, used and validated for a given number of times may be retrieved "reflexively" i.e. without a volitional act.

It is easy to observe that perception is the key element of reasoning, as it offers the necessary information both for problem identification and for the internal loop (by validation).Perception is subject to training ability – which targets the optimization of information capture/ selection, ensuring that the "right amount of data" is received.

Experiments have proved that the brain has the capability to estimate the kind of information is expected in a certain situation and is either focusing on it (neglecting other information) or interpolating data with respect with an existing pattern, when real information is presenting gaps (the phenomenon of "we see what we expect to see"). It is a capability that allows the brain to take decisions with a greater speed, based on previous experience, but has the drawback that sometimes does not allow to correctly identifying a new problem when it presents a high degree of similitude with a known one.

On the contrary, when faced with a recognized new problem, large amounts of (sometimes possible irrelevant) information are gathered, in order to select, during the process of reasoning, the relevant one. This is hindering the capacity of taking informed decisions with speed, but allows for the optimization of the solution.

With respect to these aspects, the cognitive sciences have identified three phases of perception, according to the following gestalt principle: every person has a role in one's perception process, designating a three stage sequence:

Step 1: First hypothesis about what one is about to perceive. This will guide the selection, organization and interpretation of the stimuli.

Step 2: Entrance of the sensory information.

Step 3: Contrast the first hypothesis with the sensory information obtained

So, the efficiency of perception and, subsequently, the reasoning and learning are related to the capability of constructing an adequate "problem model" which includes both a generic knowledge about the structure of the problem and a knowledge about information to be gathered in order to correctly define the problem.

The degree of adequacy of the model depends on the appropriate balance between the awareness/ volitional aspects of perception and reasoning.

The design guidelines and the functionality of the proposed Knowledge Management Architecture will be derived from these considerations.

4 KNOWLEDGE MANAGEMENT SYSTEM OF THE ICE

4.1 General Considerations

The knowledge management system (KMS) of an ICE will be based on "problem models" and oriented towards problem solving. Its functioning will combine the principles of feed-forward and feedback control, as presented in the following fig.3. The feedback may address either a step in the perception/ reasoning loop or the consequences of actions taken as results of a reasoning step.

The infrastructure of the KMS is composed by databases, knowledge bases, communication and interface modules, and data buses as similar with the neural networks and clusters that compose the brain.

A problem model will include:

- a **Structural** part (a pattern) – which will underline the generic model of the problem, as a workflow

composed either by functions of atomic components or by references to other problem models;
- a **Parametric** part: a list of data and information (external stimuli) that have to be gathered in order to allow the proper perception of the problem

The perception process is defined according to the following phases:

- Selection: The number of external stimuli usually exceeds processing capacity. Consequently, the perceived information is selected and eventually filtered with respect to criteria as experience (list of information), necessities (problem pattern) and preferences.
- Organization: Selected stimuli are gathered in groups in order to give them meaning. According to Gestalt principles, stimuli organization is not random but instead it follows specific criteria with respect to the actual goals and functioning of the ICE
- Interpretation: When all the selected stimuli have been organized, they will receive meaning (will enter the pattern as parameters), completing the perception process.

Functions of atomic components (actions performed by a single resources according to a fixed ontology of the ICE) are considered as "reflex actions" that do not necessitate any kind of reasoning awareness, as they are solved according to well defined, non-adaptive algorithms whose applicability as a whole (structure and parameters) follows a binary decision (they may or may not be applied). The perception necessary for this kind of problems is tacit (non-aware). Their solving implies the lower level of the knowledge management architecture. They are not learned following a problem solving successful process, but are pre-defined. However, there may be conceived a reinforcement mechanism reflecting their adequacy.

They are stored in a manner that allows their retrieval with precision.

Knowledge management systems supporting this king of enterprise behavior may be used for any kind of organization; they are not specific for ICE, but represents a necessary condition for building ICE structures.

The architecture of the knowledge management system of ICE may develop in time with Problem Solving (PS) higher levels dealing with:

- New problems to be solved, based on reflex actions
- New problems to be solved based on known (similar) problems – that have to be adapted, either as parameters (stimuli) or even as structural sub-modules
- New problems to be solved, with new contexts

A problem solved (a problem model) may become a reflex action if successfully applied for a number of times (becomes a repetitive occurrence).

Each kind of problem (level of PS) will necessitate a different kind of capturing, storing, sharing and retrieving information procedures (different kind of memory).

Problem models may thus migrate from higher to lower levels of PS, as the perception and reasoning implied in their solving necessitates less awareness and supervision.

The feedback loop in figure 3 is modeling the volitional part of the reasoning mechanism; when a problem is dealt with at a higher PS level, the feedback loop is used at every step of problem solving.

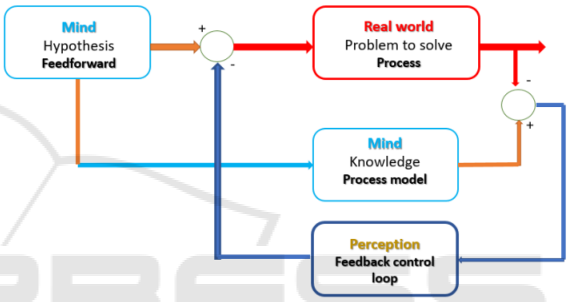

Figure 3: A control model of reasoning.

When it migrates towards the level of reflex actions, the feedback loop becomes less important, and the problem solving process is said to be un-volitional. As it skips some of the phases in its development, the process becomes faster.

4.2 The Design Approach

The design approach of the Knowledge Management System will combine the top-down (behavioral) and bottom-up (formal) modeling.

The design process will have the following phases:

1. Issues identification
2. Framework design
3. Identifying correlations between PS processes at different levels
4. Consistency check of functioning specifications
5. Building algorithms for every phase of perception
6. Find appropriate technology for implementation
7. Validation

Among the issues to be addressed are:

- Conscious (self aware) vs. Unconscious (non-aware or tacit) perception/ reasoning - and the appropriate switching mechanisms
- Retrieving information in reasoning and learning (networks of networks of knowledge)
- Optimization in reasoning: time vs. precision; experience vs. innovation – the use of the Grouping/ Focusing/ Selection operators in information gathering
- How are new problems addressed (building reasoning techniques)

The design framework is consisting in:

- Using two distinct perception mechanisms/ knowledge levels:
- Self-aware/ explicit: taking into account all available external stimuli and checking their relevance vs. Problem models – needs feedback
- Tacit: selecting only the stimuli from the list of information attached to the problem model – does not need feedback
- Reasoning objectives – different for every PS level:
- **Reflex Solving:** known pattern, tacit perception, non-aware reasoning (problem model retrieving and application), un-volitional action (if necessary), eventually reinforcement mechanism
- Solving a **Known Problem:** self-aware reasoning (retrieving a problem model based on a search criterion, comparing with the problem to be solved, selecting the appropriate pattern), tacit perception, un-volitional action, reinforcement mechanism
- Solving a new problem by associative reasoning (**Building** new problem models): self-aware reasoning (decomposition, retrieving, evaluation, estimation – feed-forward), self aware perception (searching for stimuli, eventual volitional actions for gathering information), evaluation of perception results (information feedback), volitional actions, evaluation of results (functional feedback), validation of solution, building problem model (volitional learning)
- Solving a completely new problem (**Capturing/ Acquiring** new knowledge and solving a new problem by trial and error)
- Control approach: feed-forward/ feed-back – with different weights

As mentioned, different types of processes (capturing, comparing, retrieving information, validation, comparing structures and parameters) have to be developed for each PS level, according to Gestalt principles and the ICE functioning.

5 CONCLUSIONS

The paper presents an approach for the design of a generic Knowledge Management System conceived to assist the control of an Intelligent Cyber-Enterprise.

This approach is inspired from the functioning of the human brain, based on a loop of perception-reasoning-learning as a Problem Solving procedure and thus the knowledge management architecture is organized on PS levels.

The proposed architecture is described by some basic concepts and functionalities, issues to be solved an correlations to be made in order to establish a proper information and knowledge flow.

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