A VISION FOR COGNITIVE ENGINEERING IN THE EARLY TWENTY FIRST CENTURY

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Cognitive engineering has grown from the need to better understand human-centered design of information-intensive systems such as new generation aircraft cockpits. Objects have affordances whether they are natural or artificial (artifacts). The analysis of the concept of affordance leads to a functional view of human cognition. Cognitive functions that are useful for the use of artifacts are defined along with three attributes: a role, a context of validity, and a set of resources. Cognitive function allocation among human and machine agents is a key issue that leads to the definition of co-reliability of human and machine agents in terms of cooperation, co-adaptation, co-dependency and situation awareness. Such a cognitive function analysis involves new approaches of human cognition that are more phenomenological than the currently used methods based on cognitivism. This paper initiates a debate on these issues.

Artifacts are concrete models of intelligence, but they often require experienced people to be efficiently used. The user-friendliness concept introduced by human factors specialists needs to be used carefully. We should not believe that user-friendly artifacts will guarantee task efficiency and performance. No matter how sophisticated a tool is, the user often needs to be efficient to obtain satisfactory results. I was amazed to see how a 21 years old carpenter could design and produce a stair case that fit perfectly in my house in just a few hours. The physical tools he used were very basic. I deduced that his conceptual tools (cognitive artifacts) were extremely sophisticated, and he must have learned how to use the appropriate artifacts for the right job at the right time. This carpenter mastered his craft and performed his task in a magnificent way. He was just doing his job!

Very simple artifacts such as door handles have different shapes. An horizontal flat door handle that is located in the middle of a door suggests to push. A vertical cylindrical door handle that is located on one side a door suggests to pull. Human beings establish a relationship between door handles and the appropriate action to open doors, i.e., push or pull. This kind of relationship between a human and an artifact is defined by Gibson as affordances (Gibson, 1977). Objects have affordances whether they are natural or artificial. This kind of relationship is not necessarily visible, known or desirable. It is thus important in some cases to identify affordances, e.g., in safety-critical systems. The important thing to remember is that the best designed operational documentation may not be useful in using artifacts that have counter-intuitive affordances. Affordances of artifacts are properties of their associated cognitive functions. For example, information technology (should) affords:

- making information explicit to others;
- being aware that appropriate information exists somewhere;
- accessing appropriate information at the right time in the right format;
- understanding information chunks.

REINTERPRETING AFFORDANCES

Artifacts are either physical, e.g., hammers, forks, and bicycles, or conceptual, e.g., methods, theories and know-how.
Vicente and Rasmussen's ecological approach to work (Rasmussen & Vicente, 1989) defines the properties of the means-ends relations emerging from human-machine interaction as causal constraints of the physical parts of artifacts and intentional constraints of the people involved. "To be useful for unanticipated problem situations, a representation of the sources of regularity of work environment must identify the world of possibilities that may appear during work. The representation defines the functional inventory of the work system, that is, the functional territory within which the actors will navigate or, in ecological terms, the affordance space." (Rasmussen, 1999).

**A FUNCTIONAL VIEW OF HUMAN COGNITION**

The concept of cognitive function (Boy, 1998), that is presented in this paper, was developed in the framework of human-centered automation in aeronautics systems, and more generally safety-critical systems, in the context of the traditional French school of ergonomics, that emphasizes activity analysis.

The concept of cognitive function helps analyze how people (human agents) and information-intensive systems may interact. A cognitive function can be interpreted in the mathematical sense or in the teleological sense. The former interpretation leads to the definition of an application transforming an input into an output. The input is usually a required task to be performed. The output is the result of the execution of the task. We usually say that a human uses a cognitive function that produces an activity or an effective task. The latter interpretation leads to the definition of three attributes of a cognitive function:

- a role, e.g., the role of a postman is to deliver letters;
- a context of validity, e.g., the context of validity of the above role is defined by a time period that is the business hours and a specific working uniform, for example;
- a set of resources, e.g., the resources necessary to execute the function are a bicycle, a big bag and a delivery procedure, for example. A resource is a cognitive function itself. In a big town for example, the chief postman delegates the letter delivery task to other postmen.

Note that when the postman returns home (different context) the above described cognitive function is no longer active, and he activates different cognitive functions such as father and husband (different roles) using different resources such as affection for his family and helping in home activities.

The cognitive function concept is very similar to Leont'ev's functional organs. "Functional organs are functionally integrated, goal-oriented configurations of internal and external resources. External tools support and complement natural human abilities in building up a more efficient system that can lead to higher accomplishments. For example, scissors elevate the human hand to an effective cutting organ, eyeglasses improve human vision, and notebooks enhance memory. The external tools integrated into functional organs are experienced as a property of the individual, while the same things not integrated into the structure of a functional organ (for example, during the early phases of learning how to use the tool) are conceived of as belonging to the outer world." (Kaptein, 1995).

People develop appropriate cognitive functions to speed up, and increase both comfort and safety of their job, i.e., the tasks that they usually perform. Cognitive functions can be either implicit or explicit. When they are implicit, they belong to what is usually called individual expertise. When they are explicit, they belong to what is usually called sharable knowledge. Sometimes, cognitive functions remain implicit for a long time before becoming explicit and easily sharable. When a cognitive function is persistent, it can be elicited and transferred to a machine that will perform it for its user. This transfer process is commonly called automation. Various levels of automation can be implemented with respect to both human factors involved in the execution of the task and the technological limitations.

**ARTIFACTS EMBED HUMAN COGNITION**

Noone questions the use of the clock today: the function (role) of the clock is to provide the time to its user. Its context of validity is determined by several parameters such as the working autonomy of the internal mechanism or the lifetime of the battery. Its resources include, for instance, a battery, the ability of its user to adjust time when necessary or to change the battery. Note that the user is also a resource for the clock.

Today, external cognitive functions have become more complex than the clock. People delegate to these external cognitive functions some actions that they used to perform by themselves before. They have to plan, monitor, negotiate, supervise, communicate, cooperate and coordinate with composite artifacts, e.g., a travel agent needs to work with a composite world-wide travel system (i.e., a composite artifact that embeds many external cognitive functions). This system is a network of a large number of computer systems. The travel agent learns about information traffic jams in the network, local crashes and tricks for booking a trip using a cheaper carrier, for example. These are cognitive functions that are relevant to his or her job. They are valid in time-specific contexts such as "during a holiday period", or "the Paris Orly airport is always very busy on Monday mornings". Travel systems have taken this into account for a long time with pricing. Cheap flights are usually available during the day, not in the morning or the evening.

Today, such systems "learn" very fast, i.e., both human and external cognitive functions adapt very fast. The travel agent needs to assimilate and accommodate more cognitive functions to handle the increasing number of options.

**CO-RELIABILITY OF HUMANS AND ARTIFICIAL AGENTS**

Co-reliability within a multi-agent system deals with co-dependency among agents. Safety-critical systems are commonly
certified with extremely low probability of failure per hour of use. They are extremely safe from an engineering viewpoint. However, when humans use them, they make errors. More than 70% of aircraft incidents are due to so-called pilot errors. Some of these errors are induced by artifacts themselves, i.e., errors are observable at use time, but are really made at design time because designers did not take into account end-users’ characteristics and the many situations in which artifacts will be used. In other words, artifact usability needs to be better tested and understood.

Co-reliability within a multi-agent system deals with co-operation among agents. According to Tom Sheridan, human errors are mainly due to a lack of feedback (Sheridan, 1999). When people do not know what the results of their actions on a system are they have problems controlling this system. More generally, humans who do not obtain feedback from their acts have problems controlling their lives. In the multi-agent modeling perspective, agents in charge of a job that do not timely obtain appropriate feedback from other appropriate agents have problems accomplishing this job. To the question: “who is in control?”, the answer is anyone who has the appropriate role to be in charge in the right context. In some cases, safety barriers are very efficient; in other cases, as human beings are unique to recover from unanticipated situations. Cognitive function analysis of multi-agent systems is very important to determine who should be in charge, when, why and how.

Co-reliability within a multi-agent system deals with co-adaptation of agents. People tend to construct cognitive skills from training. In the multi-agent modeling perspective, cognitive functions of humans and artificial agents are constructed from interaction among agents. Errors occur and are sources of subsequent modifications of the various cognitive functions distributed among agents. Human adaptation is not the only possible mechanism. Artificial agents can adapt very quickly also. In the past, artifact adaptation to human needs was a very slow process. Since technology evolves very rapidly, human-centered technology-adaptation mechanisms should be put in place in order to better control the evolution. Experience feedback mechanisms and usability engineering are partial answers to machine adaptation.

The key issue, that is emerging from current practice with modern technology, is then awareness of what other agents are doing and have done so far, why they are doing what they do, and what they will do next. The difficulty is that there might be a long chain of agents in space and time in this situation awareness problem. People cannot decide and act without a reasonable awareness of what is going on in their environment. They can work with failing machines when they know what the failures are and why they occur. In some cases, they successfully and safely act without knowing much about a failure if they know that it is not serious. They need to have the right information, in the right format and at the right time. I claim that the search for and satisfaction of the co-reliability of human and artificial agents guide the emergence of distributed-cognition activities, i.e., cognitive function allocation among agents.

**Requirements and Implementation of a Cognitive Function Analysis**

Conventional design methods are based on goal-driven methods, i.e., designers start with an overall goal in mind and attempt to decompose this goal into sub-goals until basic actions can be derived and effectively performed. Goal-driven approaches to design are strongly anchored in industry since they lead to manageable and explainable products. Resulting products are usually technology-centered. In many cases, they are also easy to maintain. The drawback in goal-driven approaches to design is their lack of being able to handle end-users requirements well. At the other end of the spectrum, event-driven approaches to design tend to foster participatory design and use of experience feedback data. Since design is intrinsically iterative, event-driven approaches to design can be very time-consuming and very unstable. The Cognitive Function Analysis (CFA) encourages event-driven cognitive function allocation in human-centered design. Event-driven human-centered design is essentially based on the use of scenarios. CFA proposes to handle these issues in two necessary and complementary ways:

- categorization of experience feedback cases into cognitive functions that may be re-used in design;
- use of an integrated methodology based on the use of active design documents that enable design teams to implement participatory design.

The categorization of cognitive functions in a domain such as aeronautics is carried out using the paradigm of the AUTO pyramid, i.e., experience feedback cases are analyzed and synthesized into four general categories related to the Artifacts (e.g., aeronautics systems), Users (e.g., pilots or other relevant actors of the aeronautical community), Tasks (e.g., flying, maintenance), and Organizational environment (e.g., other actors who are likely to influence or participate in the performance of the task, environmental disturbances). Categorization should be conducted within a group of experts that include operational personnel.

The use of active design documents has two main goals:

- **human-centered design**, i.e., associate a goal-driven approach (analytical description of design rationale and derivation of design solutions) and an event-driven approach (evaluations of incrementally generated solutions) to design; and
- **traceability**, i.e., document the various steps of the design process and its solution.

Active design documents are mediating tools that provide both inputs and outputs of a human-centered design process. This process is human-centered because it systematically encourages the participation of various actors in the design process.
DISCUSSION: THE VALUE OF EXPERIENCE

Current cognitivist paradigms are not appropriate to capture the above emerging concepts. Varela, Thompson & Rosch link the dissatisfaction with a variety of cognitive realism to what they call "the Cartesian anxiety". The Cartesian approach works when the world can be approximated into a "realistic" representation, out of this approximation (or discretisation) everything is so frightening that Cartesian people do not even want to know. The main issue here is that the world that we observe includes our own self. "The link between nihilism and Cartesian anxiety can be seen very clearly in the Society of Mind when Minsky comforts our inability to find a fully independent world. As he notes, the world is not an object, event, or process inside the world. Indeed the world is more like a background–setting of and field for all of our experience, but one that cannot be found apart from our structure, behavior, and cognition." (Varela et al., 1999).

Philosophers such as Merleau-Ponty, Husserl and Heidegger have developed phenomenology as the philosophy of human experience. Phenomenology provides a method for ontology elicitation based on human experience. Introspection is the basic mechanism of elicitation. The phenomenological approach departs from the grounded positivist approach of cognitivism. In the light of phenomenology, I would like to propose that the art of knowledge representation, supported by cognitivism, should be revised. I am not suggesting that the knowledge representation approach does not make sense any longer. It should be reformulated according to human experience. In particular, concepts such as interactivity, cooperation and emergence should be taken into account in knowledge representation. The Art of Memory (Yates, 1966) is coming back to the front line because human experience is growing in our information-intensive world. The need for methods that link abstract concepts to experienced ones, objects to subjects, involves new approaches to human cognition. This is the case in situated actions (Suchman, 1987), or distributed cognition (Hutchins, 1995), and activity theory (Engeström, Miettinen & Punamäki, 1999; Nardi, 1997).

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