

The *RobotCub* Approach to the Development of Cognition

Implications of Emergent Systems for a Common Research Agenda in Epigenetic Robotics

Giorgio Metta, David Vernon, Giulio Sandini
LIRA-Lab, University of Genoa, Italy

Abstract

This paper elaborates on the workplan of an initiative in embodied cognition: *RobotCub*. Our goal here is to provide background and to motivate our long-term plan of empirical research including brain and robotic sciences following the principles of epigenetic robotics.

Introduction

There are quite a few approaches to the understanding and modeling of cognition and each of them makes quite different assumptions about the nature of cognition. Greatly simplifying, we can distinguish between the cognitivist approach forged around the physical symbol hypothesis of Newell and Simon (Newell & Simon, 1975) and the emergent approaches based, to various extents, on principles of self-organization and development (Beer, 2000; van Gelder & Port, 1995). The *RobotCub*¹ approach to the study of cognition coincides with the emergent approach. Our previous work (Sandini, Metta, & Vernon, 2004) developed this argument in greater detail, our attempt here, instead, is to extend this discussion into a rationale for a plan of empirical research on embodied cognition. The significance of the argument to follow is that the very nature of the emergent model of cognition implies and facilitates an incremental and developmental approach to cognition research. This allows us to create a research agenda (a roadmap) which we believe is generally applicable in the domain of cognitive epigenetic robotics.

Definition

According to the emergent approach, we start by defining cognition as the working of a system to preserve its *organization* in face of environmental perturbations. Cognition is an instance of a process of self-organization (Maturana & Varela, 1998) or co-development

between agent and environment. By taking the emergent view, we cannot get past of the study of development and learning.

This definition, inspired by Maturana & Varela's (Maturana & Varela, 1980) work, is related to the definition of autopoiesis. Maturana & Varela's idea of characterizing what is "lively" in biological systems originated from the recognition that living entities are determined by their organization – a network of components – but especially by the preservation of their specific structure through adaptation (or responses) to perturbations:

"A cognitive system is a system whose organization defines a domain of interactions in which it can act with relevance to the maintenance of itself, and the process of cognition is the actual (inductive) acting or behaving in this domain. Living systems are cognitive systems, and living as a process is a process of cognition" (Maturana & Varela, 1980) p.13.

For example, the simplest possible autopoietic level is that of the cell and the structure in this case is the network of chemical processes that characterize its functioning. There is circularity in recognizing that this network is indivisible: its very existence is maintained by the energetically favorable environment (lower entropy) inside the membrane of the cell which is maintained and created by the unleashing of the chemical processes of the cell machinery (nucleus, organelles, etc.) that are possible because of the membrane (here the circularity). The failure of any of them means the failure of the structure. This definition states that the cell "cognizes" as long as it is alive by responding to the environmental perturbations by appropriate chemical reactions. Maturana & Varela see higher levels of autopoiesis at the individual and at the social. Autopoietic systems are homeostatic with respect to their organization (Maturana & Varela, 1998).

This view entails that cognition is *effective action*. Effective is taken here in the sense of the

¹ *RobotCub* is a project funded by the European Commission's Cognition Unit E5.

preservation of the system's organization. A similar consideration, drawn from a large body of empirical research, is reported by Thelen and Smith:

"Knowledge, [...], is not a thing, but a continuous process; not a structure, but an action, embedded in, and derived from, a history of actions" (Thelen & Smith, 1998) p.247

The beauty of this definition is that it is independent from the time scale since effective actions can happen on the short time scale (i.e. be fast in the millisecond to second range) or, rather the response (adaptation) to environmental perturbation can happen in the course of months or years. Generality across time scales is also advocated by various authors such as Kelso (Kelso, 1999) and the already mentioned Thelen&Smith to name a few (Thelen & Smith, 1998).

Among the many approaches classified as emergent, dynamical systems theory seems to be a promising mathematical tool that encompasses the stance on cognition presented here, as well as providing a formal account of various behavioral experiments. On the other hand, as it stands, systems theory has been employed mostly as an analysis tool and it is difficult to envisage a route to designing artificial systems.

Development

Developmental change can also be described by dynamical systems methods and, in fact, this work has been extensively carried out, for example, by Thelen&Smith in (Thelen & Smith, 1998) and Iverson&Thelen (Iverson & Thelen, 1999). No matter what formal approach is taken, our definition of cognition entails that action is the fundamental component of development (von Hofsten, 2004).

Actions are homomorphous to goals, that is, different effectors can be recruited in accomplishing a certain action (Bernstein's equifinality). Extensive evidence is available substantiating this claim (Bekkering & Wohlschlagel, 2000; Gallese, Fadiga, Fogassi, & Rizzolatti, 1996; Woodward, 1998). Thus the fundamental organizing factor of actions is the goal (see for example the literature on mirror neurons). Perception and action in this view are mutually dependent, two parts of the same adaptive system, and a growing body of evidence is now available in various domains: e.g. language (Fadiga, Craighero, Buccino, & Rizzolatti, 2002), manipulation (Gallese et al.,

1996), and attention (Craighero, Nascimben, & Fadiga, 2004).

Development is also about prediction and motivations. Prediction can be a characterization of development on its own, as change can be represented by the ability of foreseeing the consequence of actions and the unfolding of events ahead of time. Detecting ever longer causal chains of events in predicting the course of action is perhaps the measure of developing complex cognitive ability (Metta & Fitzpatrick, 2003). The study of prospective control in infancy has been carried out extensively by von Hofsten (Bertenthal & von Hofsten, 1998) in various domain such as gazing, reaching, and manipulation.

Motivations are perhaps one of the domains where data are most scarce in relation with the control of actions. Beside the difficulty of empirical investigation in infants, only recently it was acknowledged how much they are important for development.

"Perception, cognition and motivation develop at the interface between neural processes and actions. They are a function of both these things and arise from the dynamic interaction between the brain, the body and the outside world." (von Hofsten, 2004)

The next question we would like to consider is then how motivations shape development. The question is on how to bootstrap learning and development, i.e. what "core knowledge" should be available to the system (not necessarily at birth) to start developing new skills (Spelke, 2000), but not less importantly on how explorative behaviors are structured. It is important to note that core abilities are not finished skills but rather means of facilitating the acquisition of skills. Our approach here to determine what type and which amount of core knowledge should be provided is implemented by studying the early behaviors in infants.

On the other hand, exploration and data acquisition has not received much attention in the machine learning literature if not for the reinforcement learning approach where it is generally an integral part of the algorithms reviewed, for example, in Sutton&Barto (Sutton & Barto, 1998).

Conversely, it is not clear how supervised learning methods should apply to a biological system interacting with the environment where data is not provided segmented by a

“collaborative teacher” but rather as a continuous flow of information. Meaning, out of this information, is made through the use of action and the self-exploration of the action space. Only movement can provide order into this vast space of unstructured data (Granlund, 1999). Development is intertwined with exploration and acquisition of skills. Exploration do not need to be a separate mechanism (i.e. we do not need to think as the “exploration” and subsequently the “exploitation” phase) and can be rather embedded in the very structure of the system (for example intrinsic noise due to immature nerves), or directed to reducing the exploration space size (specific core abilities bias exploration). Learning and control can be two parallel processes and not two modes of the functioning of the same system as a traditional control approach would suggest. A thought-provoking summary of exploratory behaviors in human development can be found in (Gibson, 1988).

How much action is then an organizing factor of the flow of information is best illustrated by the literature on the physiology of the premotor cortex both in the monkey and in human experiments (Fadiga, Fogassi, Gallese, & Rizzolatti, 2000). Finally, since after all we are considering the interplay between the cognitive agent and the environment, it is important to mention the aspects of the influence of body morphology into the development of cognition. One example is reported in the already cited paper by von Hofsten (Bertenthal & von Hofsten, 1998). Examples can be found everywhere in the human body, for instance, in the elastic properties of the muscles, in the placement of receptors in the sensory surfaces, and so forth. A more complete argument can be found in (Lungarella, Metta, Pfeifer, & Sandini, 2003)

A roadmap for the study of development (von Hofsten 2005, personal communication) should thus include the study of the “starting point” in terms of core abilities, the motive of the system to explore and gather data, and a few research areas such as looking, reaching & manipulation, posture, locomotion and social interaction. For each of these areas aspects of prospective use of information, motivation, and the mechanisms of exploration have to be experimentally investigated. The *RobotCub* agenda aims at covering, by targeted empirical investigation, most if not all of these aspects.

The tentative roadmap containing the aspects discussed in this paper is summarized in Table 1

below. This contains on one dimension an approximate timeline of human development showing the link between causal understanding/prospective control and acquired skills. This axis indicates how the initiation of the action is delayed from the perception of the effects, and thus how difficult is to learn and find associations between causes and effects of actions. On the other axis, the same skills are investigated in terms of learning, action exploitation, goal, and social interaction. Skills here are not limited to “simple” motor control basics but rather extend toward the very sophisticated use of tools and communication through gestures.

Although it is not shown here, a substantial part of this work has already been done in the field of developmental robotics: this roadmap is intended as a common integrative scenario rather than being specific to *RobotCub*; a recent and complete reference of this research can be found in (Lungarella et al., 2003).

Conclusion

As a natural consequence, eventually this engineering of cognition would perhaps tackle one of the most fascinating aspects of human cognition: that is, the invention of cognitive technology:

“[such tools] permit the [users] to do the tasks that need to be done while doing the kinds of things people are good at: recognizing patterns, modeling simple dynamics of the world, and manipulating objects in the environment” (Hutchins, 1995)

We believe this can be suggestive of the type of test an artificial system should withstand to be deemed cognitive in a meaningful sense.

Acknowledgments

This work is funded by the European Commission’s sCognition Unit, Directorate-General Information Society, as part of project no. IST-2004-004370: *RobotCub* — ROBotic Open-architecture Technology for Cognition, Understanding, and Behaviour. The authors gratefully acknowledge Claes von Hofsten and Luciano Fadiga for the useful discussions about development and motor control in humans and the whole *RobotCub* consortium for the preparation of this research agenda.

Development		Learning what	Perception/Action exploitation	Component of Social Interaction	Goal of system
Immediate	No reaching yet	Head-eye coordination	Gazing, smooth pursuit	Shared attention	Look around
	Pre-reaching	Approach an object	Controlling arm and hand movements in space	Pointing	Touch
Delay between action onset and consequences	Power grasp	Eye-hand coordination based on object position and object motion	Anticipatory closing of the hand	Reaching for object held by other person "I got it!"	Grasp (become "owner")
	Differentiated grasping	Adjustment to object shape and size	Eye-arm-hand coordination based on object's shape	Take and give	Grasp appropriately (geometric)
	Object manipulation	Objects' affordances	Eye-arm-hand coordination based on actions to be executed on objects	Play games	Handle objects appropriately (use)
Long delays	Imitate acts on objects	Associate what is seen with what the system can do	What I do looks like what I see	Play games	Action's interpretation
	Act to communicate	Associate what is seen (perceived) with meaning	What I do generates some reactions	Communication	Action's meaning

Table 1: the roadmap of *RobotCub* experimental research

References

- Beer, R. D. (2000). Dynamical approaches to cognitive science. *Trends in cognitive sciences*, 4(3), 91-99.
- Bekkering, H., & Wohlschlagel, A. (2000). Imitation in children is goal-directed. *The Quarterly Journal of Experimental Psychology*, 53A(1), 153-164.
- Bertenthal, B., & von Hofsten, C. (1998). Eye, Head and Trunk Control: the Foundation for Manual Development. *Neuroscience and Behavioral Reviews*, 22(4), 515-520.
- Craigero, L., Nascimben, M., & Fadiga, L. (2004). Eye Position Affects Orienting of Visuospatial Attention. *Current Biology*, 14, 331-333.
- Fadiga, L., Craighero, L., Buccino, G., & Rizzolatti, G. (2002). Speech listening specifically modulates the excitability of tongue muscles: a TMS study. *European Journal of Neuroscience*, 15(2), 399-402.
- Fadiga, L., Fogassi, L., Gallese, V., & Rizzolatti, G. (2000). Visuomotor neurons: ambiguity of the discharge or 'motor' perception? *International Journal of Psychophysiology*, 35(2-3), 165-177.
- Gallese, V., Fadiga, L., Fogassi, L., & Rizzolatti, G. (1996). Action recognition in the premotor cortex. *Brain*, 119, 593-609.
- Gibson, E. J. (1988). Exploratory behavior in the development of perceiving, acting, and the acquiring of knowledge. *Annual Review of Psychology*, 39, 1-41.
- Granlund, G. H. (1999). The complexity of vision. *Signal Processing*, 74, 101-126.
- Hutchins, E. (1995). *Cognition in the Wild*. Cambridge, MA: MIT Press.
- Iverson, J., & Thelen, E. (1999). Hand, mouth and brain. *Journal of Consciousness Studies*(6), 19-40.
- Kelso, J. A. (1999). *Dynamic Patterns: the self organization of brain and behavior*. Cambridge, MA: MIT Press.
- Lungarella, M., Metta, G., Pfeifer, R., & Sandini, G. (2003). Developmental Robotics: A Survey. *Connection Science*, 15(4), 151-190.
- Maturana, R. H., & Varela, F. J. (1980). *Autopoiesis and Cognition: The Realization of the Living*. Dordrecht: D.Reidel Publishing Co.
- Maturana, R. H., & Varela, F. J. (1998). *The tree of knowledge, the biological roots of human understanding* (R. Paolucci, Trans. Revised Edition ed.). Boston & London: Shambhala Publications, Inc.
- Metta, G., & Fitzpatrick, P. (2003). Early Integration of Vision and Manipulation. *Adaptive Behavior*, 11(2), 109-128.
- Newell, A., & Simon, H. A. (1975). Computer science as empirical inquiry: Symbols and search. *Communications of the*

- Association for Computing Machinery*, 19, 113-126.
- Sandini, G., Metta, G., & Vernon, D. (2004, November 10-12th). *RobotCub: An Open Framework for Research in Embodied Cognition*. Paper presented at the IEEE-RAS/RJS International Conference on Humanoid Robotics, Santa Monica, CA.
- Spelke, E. S. (2000). Core knowledge. *American Psychologist*, 55, 1233-1243.
- Sutton, R. S., & Barto, A. (1998). *Reinforcement Learning: an Introduction*. Cambridge: MIT Press.
- Thelen, E., & Smith, L. B. (1998). *A Dynamic System Approach to the Development of Cognition and Action* (3 ed.). Cambridge, MA: MIT Press.
- van Gelder, T., & Port, R. F. (1995). It's about time: An overview of the dynamical approach to cognition. In R. F. Port & T. van Gelder (Eds.), *Mind as motion - Explorations in the Dynamics of Cognition*. Cambridge, MA: MIT Press.
- von Hofsten, C. (2004). An action perspective on motor development. *Trends in cognitive sciences*, 8(6), 266-272.
- Woodward, A. L. (1998). Infant selectively encode the goal object of an actor's reach. *Cognition*, 69, 1-34.