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The *iCub* humanoid robot: An open-systems platform for research in cognitive development

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ABSTRACT

We describe a humanoid robot platform — the *iCub* — which was designed to support collaborative research in cognitive development through autonomous exploration and social interaction. The motivation for this effort is the conviction that significantly greater impact can be leveraged by adopting an open systems policy for software and hardware development. This creates the need for a robust humanoid robot that offers rich perceptuo-motor capabilities with many degrees of freedom, a cognitive capacity for learning and development, a software architecture that encourages reuse & easy integration, and a support infrastructure that fosters collaboration and sharing of resources. The *iCub* satisfies all of these needs in the guise of an open-system platform which is freely available and which has attracted a growing community of users and developers. To date, twenty *iCubs* each comprising approximately 5000 mechanical and electrical parts have been delivered to several research labs in Europe and to one in the USA.

1. Introduction

Robotics, by definition, takes inspiration from nature and the humanoid concept is perhaps the best example. When we consider the possibility of creating an artefact that acts in the world, we face a preliminary and fundamental choice: efficiency (achieved by being task-specific) or versatility (achieved by biological-compatibility development). The first option leads to the realization of automatic systems that are very fast and precise in their operations. The limitations of automatic systems are purely technological ones (e.g. miniaturization). The second option is what we consider to be a humanoid: a biological-like system which takes decisions and acts in the environment, which adapts and learns how to behave in new situations, and which invents new solutions on the basis of the past experience. The fascinating aspect of the humanoid is the possibility to interact with it: to teach, to demonstrate, even to communicate. It should be stressed that the attempt to adopt the strategy of 'biological compatibility' does not represent an intellectual exercise but is prompted by the idea that a humanoid interacting with human beings must share with them representations, motor behaviours and perhaps, even kinematics and degrees of freedom.

To interact, a humanoid must first act (and not simply move), perceive, categorize and therefore, understand. These capabilities cannot arise from pre-compiled software routines. On the contrary, they realize themselves through an ontogenetic pathway, simulating what happens in developing infants. In other words, humanoids must act in the environment to know it. It should be stressed that 'to know the environment' does not mean to categorize an assembly of static structures and objects but requires, as an essential requisite, to understand the consequences of generated actions (e.g. a glass breaks when it falls on the ground). During this knowledge acquisition, attempts and errors are fundamental because they increase the field of exploration. This is the main difference between a humanoid and an automatic system: for the latter, errors are not allowed by definition.

The developmental process leading to a mature humanoid requires a continuous study of its human counterpart. This study only partially overlaps with traditional neuroscience, because of its peculiar interdisciplinarity. In other words, the synergy between neuroscience (particularly neurophysiology) and robotics, gives rise to

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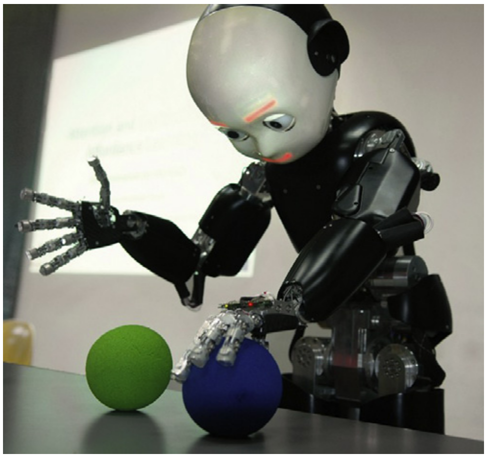

Fig. 1. The *iCub* humanoid robot: an open-systems platform for research in cognitive development.

a new discipline in which bi-directional benefits are expected. In fact, this knowledge sharing rewards not only robotics but also neuroscience since the developing (learning) humanoid forms a behaving model to test neuro-scientific hypotheses by simplifying some extremely complex problems. Particularly, it allows what is not conceivable in human neuroscience: to investigate the effects of experimental manipulations on developmental processes. This opens up vast new opportunities for advancing our understanding of humans and humanoids.

This paper describes the development of the *iCub* humanoid robot (see Fig. 1) and our efforts to navigate this unchartered territory, aided by a constantly growing community of *iCub* users and developers.

The *iCub* is a 53 degree-of-freedom humanoid robot of the same size as a three or four year-old child. It can crawl on all fours and sit up. Its hands allow dexterous manipulation and its head and eyes are fully articulated. It has visual, vestibular, auditory, and haptic sensory capabilities. The *iCub* is an open systems platform: researchers can use it and customize it freely since both hardware and software are licensed under the GNU General Public Licence (GPL).[1]

The *iCub* design is based on a road map of human development (von Hofsten, Fadiga, & Vernon, in press) (see Section 3). This description of human development stresses the role of prediction into the skillful control of movement: development is in a sense the gradual maturation of predictive capabilities. It adopts a model of "sensorimotor" control and development which considers "action" (that is, movements with a goal, generated by a motivated agent which are predictive in nature) as the basic element of cognitive behaviours. Experiments with infants and adults have shown that the brain is not made of a set of isolated areas dealing with perception or motor control but rather that multisensory neurons are the norm. Experiments have proven the involvement of the motor system, including the articulation of speech, in the fine perception of the movements of others. The *iCub* employs a computational model of affordances which includes the possibility of learning both the structure of dependences between sets of random variables (e.g. perceptual qualities *vs.* action and results), their effective links and their use in deciding how to control the robot. Affordances form the quintessential primitives of cognition by mixing perception and action in a single concept or representation. It builds on a computational model of imitation and interaction between humans and robots by evaluating the automatic construction of models from experience (e.g. trajectories), their correction via feedback, timing and synchronization. This explores the domain between mere sensorimotor associations and the possibility of true communication between robot and people. The *iCub* involved the design from scratch of a complete humanoid robot including mechanics, electronics (controllers, I/O cards, buses, etc.) and the related firmware and it adopted and enhanced open-systems middleware (YARP) (Metta, Fitzpatrick, & Natale, 2006). Finally, it has resulted in the creation of a community of active users and researchers working on testing, debugging, and improving the *iCub* of the future.

[1] The *iCub* software and hardware are licensed under the GNU General Public Licence (GPL) and GNU Free Documentation Licence (FDL), respectively.

2. Design goals

The design of the *iCub* started from the consideration that the construction of cognitive systems could not progress without a certain number of ingredients: the development of a sound formal understanding of cognition (Vernon, Metta, & Sandini, 2007), the study of natural cognition and, particularly important, the study of the development of cognition (Sandini, Metta, & Konczak, 1997; von Hofsten, 2003), the study of action in humans by using neuroscience methods (Fadiga, Fogassi, Gallese, & Rizzolatti, 2000; von Hofsten, 2004), and the physical instantiation of these models in a behaving humanoid robot (Metta, Sandini, & Konczak, 1999; Metta, Sandini, Natale, & Panerai, 2001).

Our research agenda starts from cognitive neuroscience research and proceeds by addressing, for example, the role of manipulation as a source of knowledge and new experience, as a way to communicate socially, as a tool to teach and learn, or as a means to explore and control the environment. We would like to stress here that collaboration between neuroscience, computer science, and robotics is truly intended as bi-directional. On one side, the *iCub* cognitive architecture is a system as much as possible "biologically oriented".[2] On the other side, real biological systems were examined according to problems that we deemed important for elucidating the role of certain behaviours or brain regions in a larger picture of the brain. Examples of this research are: the ability to grasp unknown objects on the basis of their shape and position with one and two hands, to assemble simple objects with plugs, and to coordinate the use of two hands (e.g. parts mating, handling of soft materials). These abilities require visuo-haptic object recognition and multimodal property transfer, visual recognition of the body gestures of others, imitation of one and two-hand gestures, and communication and interaction through body and hand gestures.

A no-less-important scientific objective is the study of of the initial period of human cognitive development and its implementation on the *iCub* . Our working method is, in fact, not to preprogram the cognitive skills outlined earlier but, similarly to what happens in humans, to implement them into a system that can learn much like a human baby does. We understand aspects of human development and can make specific informed choices in building an artificial adaptable system. For example, developmental science now points out at how much action, perception and cognition are tightly coupled in development. This means that cognition cannot be studied without considering action and embodiment and how perception and cognition are intertwined into

[2] It is important to note that biological plausibility or similarity in the *iCub* is not intended as a faithful implementation of neural simulations to a very detailed level. We don't think that this approach is feasible given the available hardware. The digital computer is not the brain and it would be wasteful to try to use computers in this sense. On the other hand, the gross features of the architecture are biologically plausible by including attention, memory (procedural and declarative), reaching, grasping, action selection, and affective states.