# The *iCub* Cognitive Architecture: Interactive Development in a Humanoid Robot

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*Abstract*— **This paper describes the design of a cognitive architecture for the *iCub* : an open-systems 53 degree-of-freedom cognitive humanoid robot. At 94 cm tall, the *iCub* is the same size as a three year-old child and is designed to be able to crawl on all fours and sit up. Its hands will allow dexterous manipulation, its head and eyes are fully articulated, and it has visual, vestibular, auditory, and haptic sensory capabilities. We begin by reviewing briefly the enactive approach to cognition, highlighting the requirements for phylogenetic configuration, the necessity for ontogenetic development, and the importance of humanoid embodiment. After a short look at the the *iCub's* mechanical and electronic specifications, we detail the *iCub* cognitive architecture, addressing the *iCub* phylogeny, *i.e.* the robot's intended innate abilities, the modulation of these skills by circuits inspired by the functionality of the hippocampus, basal ganglia, and amygdala. The architecture also include a prospective ability whereby sensorimotor behaviours can be simulated and then used to influence the action selection in the basal ganglia. We conclude by outlining our scenario for ontogenesis based on human neo-natal development.**

*Index Terms*— **Cognitive systems, cognitive architecture, action selection, enactive systems, neo-natal development.**

## I. ENACTIVE COGNITION

It is becoming increasingly widely accepted that cognitive processes are strongly entwined with the physical structure of the body and its interaction with the environment. This view represents a shift away from the functionalism and dualism of cognitivism and classical AI towards an alternative position that re-asserts the primacy of embodiment, development, and interaction in a cognitive system [1]. By the term interaction, we mean a shared activity in which the actions of each agent influence the actions of the other agents engaged in the same interaction, resulting in a mutually constructed pattern of shared behavior [2], [3]. Accordingly, meaning is negotiated: it emerges through shared consensual experience mediated by interaction.

Enactive approaches [4], [5], [6], [7], [8], [9], [10] assert that the primary model for cognitive learning is anticipative skill construction rather than knowledge acquisition and that processes that both guide action and simultaneously improve the capacity to guide action are taken to be the root capacity for all intelligent systems [11]. Enactive approaches are intrinsically embodied and the physical instantiation plays a pivotal constitutive role in cognition [12], [13], [14]. A strong consequence of this is that one cannot short-circuit the ontogenetic development because it is the agent's own experience that defines its cognitive understanding of the world in which it is embedded. Furthermore, since cognition is dependent on the richness of the system's action interface and since the system's understanding of its world is dependent on its history of interaction, a further consequence of enactive cognition is that, if the system is to develop an understanding of the world that is compatible with humans, the system requires a morphology that is compatible with that of a human. This provides much of the motivation for the creation of a cognitive humanoid robot with a rich portfolio of action.

## II. THE *iCub* ROBOT: MECHANICS AND ELECTRONICS

The *iCub's* design is aimed at maximizing the number of degrees of freedom of the upper part of the body, *i.e.* the head, torso, arms, and hands. The lower body, *i.e.* the legs and feet, has been designed to support crawling and sitting on the ground in a stable position with smooth autonomous transition from crawling to sitting. It has 53 degrees of freedom in total: six in the head (two for azimuth & vergence, one for coupled eye-tilt, and three for the neck) [15], seven degrees of freedom in each of the arms (three in the shoulder, one in the elbow, and three in the wrist), nine degrees of freedom in each of the hands to effect under-actuated control the 17 joints comprising the five fingers), six degrees of freedom in each of the legs (three for the hip joints, one for the knee, and two for the ankle), with the waist also having three degrees of freedom. The sensory system includes a binocular vision system, touch, audition, and inertial sensors to allow it to coordinate the movement of the eyes and hands,

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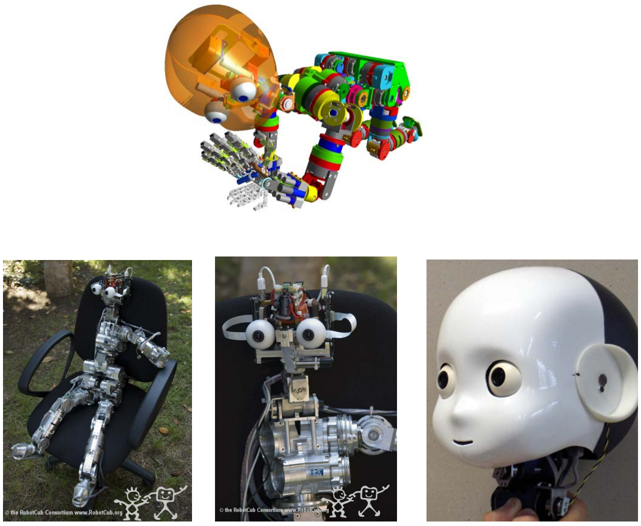

Fig. 1. Details of the *iCub* design and construction.

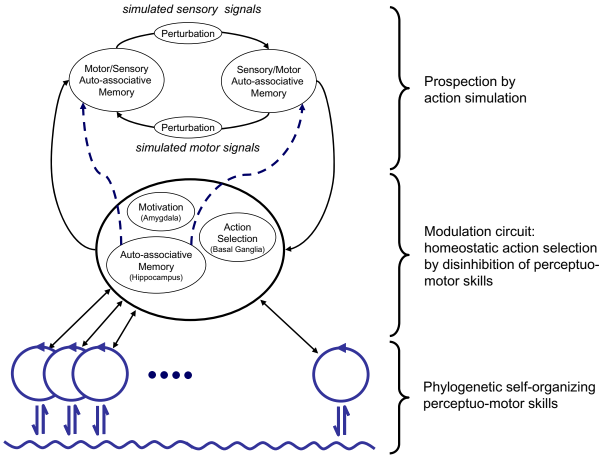

Fig. 2. The *iCub* cognitive architecture.

grasp and manipulate lightweight objects of reasonable size and appearance, crawl, and sit up. Figure 1 shows some details of the current status of design and construction of the *iCub* .

## III. DESIGN PRINCIPLES

The need for a cognitive architecture arises from the intrinsic complexity of a cognitive system and the need to provide some form of structure within which to embed the mechanisms for perception, action, adaptation, anticipation, and motivation that enable the ontogenetic development over the system's life-time. The *iCub* cognitive architecture was designed following an extensive survey of cognitivist, emergent, and hybrid cognitive architectures [16], an analysis of the phylogeny and ontogeny of human neonates [17], [18], and a review of design principles for developmental systems [19], [20], [13]. Two of the architectures surveyed had a particularly strong influence on the design of the *iCub* architecture: Shanahan's Global Workspace Cognitive Architecture [21], [22], [23], [24] and Erlhagen's and Bicho's Dynamic Neural Field Architecture [25]. Before proceeding, we first note three key design principles for developmental cognitive systems.

First, a developmental cognitive system will be constituted by a network of competing and cooperating distributed multi-functional sub-systems (or cortical circuits), each with its own limited encoding or representational framework, together achieving the cognitive goal of effective behaviour, achieved either by some self-synchronizing mechanism or by some modulation circuit. This network forms the system's phylogenetic configuration and its innate abilities.

Second, a developmental cognitive architecture must be capable of adaptation and self-modification, both in the sense of parameter adjustment of phylogenetic skills through learning and through the modification of the very structure and organization of the system itself so that it is capable of altering its system dynamics based on experience, to expand its repertoire of actions, and thereby adapt to new circumstances. This development should be driven by both explorative and social motives, the first concerned with both the discovery of novel regularities in the world and the potential of the system's own actions, the second with inter-agent interaction, shared activities, and mutually-constructed pattern's of shared behaviour. Ultimately, a developmental system should be a model generator [26], rather than a model fitter (*e.g.* see [27]).

Third, and because cognitive systems are not only adaptive but also anticipatory and prospective, it is crucial that they have some mechanism to rehearse hypothetical scenarios and a mechanism to then use this to modulate the actual behaviour of the system.

## IV. THE *iCub* COGNITIVE ARCHITECTURE

### *A. The* iCub *Phylogeny: Innate Abilities*

The focus of the *iCub* cognitive architecture is self-development. However, development implies the existence of a basis for development; in other words, ontogenesis requires some initial phylogenetic configuration on which to build. This section presents a non-exhaustive list of initially-planned

| **Scenario Capabilities: cognitive perception/action behaviours** |
|---|
| Object tracking through occlusion (smooth pursuit & saccades) |
| Learn to coordinate vestibulo-ocular reflex (VOR) & tracking |
| Learn to reach towards a fixation point |
| Attention and action selection by modulation of capabilities |
| Condition modulation based on anticipation |
| Construct sensorimotor maps & cross-modal maps |
| Learn by demonstration (crawling & constrained reaching) |
| Exploratory, curiousity-driven, action |
| Experience-based action selection based on interaction histories |
| Navigate based on local landmarks and ego-centric representations |
| **Quasi-independent Phylogenetic Capabilities** |
| Saccadic re-direction of gaze towards salient multi-modal events |
| Focus attention and direct gaze on human faces |
| Ocular modulation of head pose to centre eye gaze |
| Move the hand(s) towards the centre of the visual field |
| Stabilize & integrate of saccadic percepts |
| Stabilize gaze with respect to self-motion (VOR) |
| Create attention-grabbing stimuli |
| Gait control |
| **Component Capabilities** |
| Compute optical flow |
| Compute visual motion with ego-motion compensation |
| Segmentation of the flow-field based on similarity of flow parameters |
| Segmentation based on the presence of a temporally-persistent boundary |
| Fixation and vergence |
| Gaze control: smooth pursuit with prediction; possibly tuned by learning |
| Classification of groups of entities based on low numbers |
| Classification of groups of entities based on gross quantity |
| Detection of mutual gaze |
| Detection of biological motion |

TABLE I

INITIAL PHYLOGENETIC AND COGNITIVE CAPABILITIES.

innate perceptuo-motor and cognitive skills that need to be effected in the *iCub* in order to facilitate its subsequent development. These skills (or abilities) are based primarily on the results and insights from developmental psychology and from a walk-through of the empirical investigations derived from the scenarios for development set out in Sections V.

The minimal phylogenetic and cognitive capabilities to be developed for the iCub are summarized in Table I. They are assigned to one of three classes:

1) Those that correspond directly to the scenario capabilities; these will usually be based on a combination of (possibly tuned) phylogenetic capabilities, sub-cortical action-selection capabilities, and cortical prospection capabilities.
2) Those that correspond directly to quasi-independent phylogenetic capabilities.
3) Those that correspond to components of these phylogenetic capabilities; these correspond to re-usable general purpose sensor and control utility functions.

Note that this is just a partial list of both perceptuo-motor and enhanced phylogenetic abilities. Neonates have other innate skills that we also intend to implement; see [28] for details.

Before proceeding, is worth making two general remarks about the phylogenetic abilities. First, all the capabilities in Table I will exhibit some form of self-organization by which the sensorimotor contingencies are learned (in the case that no sensorimotor mapping is given *a priori*) or tuned (in the case that some sensorimotor mapping is provided). Second, there will be a need to allow direct interconnection between the distinct phylogenetic perceptuo-motor abilities without having to revert to the modulation circuit or the prospection circuit.

*1) Modulation of Innate Skills:* The perceptuo-motor skills outlined in the previous section operate concurrently, competitively and cooperatively. A cognitive architecture must specify how these skills are modulated or deployed and how the competition and cooperation is effected.

In the brain, the basal ganglia are responsible for action selection and disinhibition has been proposed as the basic mechanism by which these basal ganglia circuits affect behavior [29], [30], [31]. This suggests that any modulation circuit that is proposed for inclusion in the *iCub* architecture should take into consideration the function and operation of the basal ganglia, addressing, *e.g.*, reinforcement learning [32], sub-cortical loops with brainstem sensorimotor structures such as the superior colliculus [33], cortical loops with the neocortex [34], and perhaps some form of short-term memory, possibly effected using an auto-associative structure, for the storage and recall of spatial and episodic events. Rougier, for instance, has proposed and validated an architecture for an auto-associative memory based on the organization of the hippocampus, involving the entorhinal cortex, the dentate gyrus, CA3, and CA1 [35]. A feature of this architecture is that it avoids the catastrophic interference problem normally linked to associative memories through the use of redundancy, orthogonalization, and coarse coding representations. Rougier also notes that the hippocampus plays a role in 'teaching' the neo-cortex, *i.e.* in the formation of neocortical representations. We will return to this point again in Section IV-A.3.

We intend basing the interaction selection on dynamic field theory (or dynamic neural fields) as proposed by Erlhagen and Bicho [25], [36] and the associative memory on Rougier's model of the hippocampus [35].

The question as to what forms the basis for the saliency function which the basal ganglia utilize in making a selection and disinhibiting some sensorimotor circuit remains open. Shanahan suggests the inclusion of the amygdala in the circuit to provide for affective modulation of the action selection process [21].

Figure 2 shows this modulation component of the *iCub* cognitive architecture with three sub-components: auto-associative memory, action selection, and motivation (reflecting saliency). The modulation component is connected to each phylogentic skill. These three components are labelled (in parentheses) hippocampus, basal ganglia, and amygdala to denote their biological inspiration. However, we emphasize that is not intended to produce neurologically faithful models of these regions.

*2) Prospection and Anticipation:* Cognition can be viewed as the complement of perception in that it provides a mechanism for choosing effective actions based not on what has happened and is currently happening in the world but based on what may happen at some point in the future. That is, cognition is the mechanism by which the agent achieves an increasingly greater degree of anticipation and prospection as it learns and develops with experience. One way of achieving this functionality is include a component (or set of circuits) that simulate events and use the outcome of this simulation in guiding actions and action selection.

This action simulation works concurrently with the innate and learned abilities, and the modulation circuitry, that were described above. In fact, as suggested by both Shanahan and Erlhagen & Bicho, the simulation circuitry provides just another 'input' to this modulation process which can work either competitively or cooperatively with existing skills. Another particularly significant feature of this potential capacity for simulation is that it is not structurally coupled with the environment and thereby is not subject to the constraints of real-time interaction that limit the sensori-motor processes [9]: the simulation can be effected faster than real-time.

Naturally, the question arises of how one should accomplish — model and implement — this capacity for simulation. Shanahan's work again provides some insights. As noted above, Shanahan's cognitive architecture [21] is comprised of the following components: a first-order sensori-motor loop, closed externally through the world, and a higher-order sensori-motor loop, closed internally through associative memories. The first-order loop comprises the sensory cortex and the basal ganglia (controlling the motor cortex), together providing a reactive action-selection sub-system. The second-order loop comprises two associative cortex elements which carry out off-line simulations of the system's sensory and motor behaviour, respectively. The first associative cortex simulates a motor output while the second simulates the sensory stimulus expected to follow from a given motor output. The higher-order loop effectively modulates basal ganglia action selection in the first-order loop via an affect-driven amygdala component. Thus, this cognitive architecture is able to anticipate and plan for potential behaviour through its associative internal sensori-motor simulation.

Figure 2 shows the prospective action simulation component of the *iCub* cognitive architecture with two sub-components in the same vein as Shanahan: a sensory hetero-associative memory that receives efferent (motor) input produces afferent (sensory) output. This feeds into a motor hetero-associative memory that in turn produces (simulated) efferent (motor) output. This output is connected recurrently back to the sensory associative memory and also back to the modulation circuit.

Since some form of action selection mechanism is also required in this circuit, just as it is in the primary modulation circuit, two as yet unspecified perturbation components have been added to the interface between the two associative memories. This also allows for some element of innovation in the perception and action signals.

*3) Self-Modification:* We come finally to a crucial aspect of developmental emergent cognition: ability to self-modify. There are two aspects to this: the mechanism of self-modification and the basis (or drive) for the self-modification.

Learning is tightly tied up with mechanisms for self-modification. Three types of learning can be distinguished: supervised learning in which the teaching signals are directional error signals, reinforcement learning in which the teaching signals are scalar rewards or reinforcement signals, and unsupervised learning with no teaching signals.

We need to distinguish carefully between learning in the sense of adjusting or improving innate or existing skills, and learning in the sense of adjusting the system's structure, organization, or operation with a view to accommodating new skills and actions. Both are required in a cognitive system but will recruit different mechanisms and will be driven by different criteria. Learning can be effected as part of the self-organizational process inherent in each innate skill, perhaps effected by supervised learning in the manner of the cerebellum. We speculate that enhanced phylogenentic skills are learned through reinforcement learning in the modulation circuitry outlined in Section IV-A.1, specifically by hippocampus auto-associative memory and basal ganglia action selection mechanism.

This leaves us with the learning associated with development and self-modification. It is plausible that the experience gathered by reinforcement learning and encapsulated in the auto-associative memory of the modulation circuits — a process that involves not only modulation of the phylogentic and enhanced phylogentic skills but also the inputs from the prospective hetero-associative circuits — may periodically update the long-term hetero-associative memories, thereby giving rise to an increased space of potential (simulated prospective) action. In turn, this drives the system's actions and experiences further, increasing its effectiveness and resilience. This memory-memory update would be modulated by on the basis of the entropy-reduction metric. Since such an update process should not interfere with the normal operation of the cognitive system, we *speculate* that this update happens when the system is in a rest state, *i.e.* when it is sleeping. Figure 2 indicates this developmental process by showing return arrows from the modulation circuits to the prospection circuits. McClelland *et al.* have suggested a similar process. They note that the hippocampal formation and the neocortex form a complementary system for learning [37]. The hippocampus facilitates rapid auto- and hetero-associative learning which is used to reinstate and consolidate learned memories in the neo-cortex in a gradual manner. In this way, the hippocampal memory can be viewed not just as a memory store but as a 'teacher of the neo-cortical processing system'. Note also that the reinstatement can occur on-line, thereby enabling the overt control of behavioural responses, as well as off-line in, *e.g.* active rehearsal, reminiscence, and sleep.

## V. THE *iCub* ONTOGENY: SCENARIOS FOR DEVELOPMENT

The primary focus of the early stages of ontogenesis of the *iCub* is to develop manipulative action based on visuomotor mapping, learning to decouple motor synergies (*e.g.* grasping and reaching) [38], [39], anticipation of goal states, learning affordances, interaction with other agents through social motives [40], [41], [42], [43] and imitative learning [44], [45], [46]. Ontogenesis and development are progressive and we emphasize the early phases of development, building on the enhanced phylogenetic skills outlined in the previous section and scaffolding the cognitive abilities of the *iCub* to achieve greater prospection and increased (action-dependent) understanding of its environment and to establish a mutual understanding with other cognitive agents.

It is important to emphasize that the development program that we intend to use to facilitate the ontongenesis of the *iCub* is biologically inspired and tries to be as faithful as possible to the ontogenesis of neonates. Consequently, the development of manipulative action will build primarily on visual-motor mapping. Once the *iCub* has mastered these skills, we will move on to scenarios in which the *iCub* learns to develop object manipulation by playing on its own and or with another animate agent, that is, grasping objects and doing things in order to attain effects, like inserting objects into holes, building towers out of blocks *etc*. At this stage, social learning of object affordances becomes crucial. These scenarios will focus on the use of more than one object, emphasising the dynamic and static spatial relationships between them. In order of complexity, examples include learning to arrange block on a flat-surface, to stack blocks of similar size and shape, to stack blocks on similar shape but different size, and to stack blocks of different shape and size.

## VI. SUMMARY

The *iCub* cognitive architecture comprises a network of competing and cooperating distributed multi-functional perceptuo-motor circuits, a modulation circuit which effects homeostatic action selection by disinhibition of the perceptuo-motor circuits, and a system to effect anticipation through perception-action simulation. The modulation circuit comprises three components: auto-associative memory, dynamic neural field-based action selection, and motivation, based loosely on the hippocampus, basal ganglia, and amygdala, respectively, while the anticipatory circuit comprises paired motor-sensor and sensor-motor hetero-associative memories.

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