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Full paper

iCub: the design and realization of an open humanoid platform for cognitive and neuroscience research

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Abstract—The development of robotic cognition and the advancement of understanding of human cognition form two of the current greatest challenges in robotics and neuroscience, respectively. The RobotCub project aims to develop an embodied robotic child (iCub) with the physical (height 90 cm and mass less than 23 kg) and ultimately cognitive abilities of a 2.5-year-old human child. The iCub will be a freely available open system which can be used by scientists in all cognate disciplines from developmental psychology to epigenetic robotics to enhance understanding of cognitive systems through the study of cognitive development. The iCub will be open both in software, but more importantly in all aspects of the hardware and mechanical design. In this paper the design of the mechanisms and structures forming the basic 'body' of the iCub are described. The papers considers kinematic structures dynamic design criteria, actuator specification and selection, and detailed mechanical and electronic design. The paper concludes with tests of the performance of sample joints, and comparison of these results with the design requirements and simulation projects.

Keywords: Humanoid; cognition; mechanical design; force sensing.

1. INTRODUCTION

The development of human-like machines has its basis in ancient mythology where it combines many desirable features, including natural human-like locomotion, and human-friendly design and behavior. However, it is only within the past 30–40 years with the developments in the core enabling technologies (biped walking

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control, mechatronics, computer technology) and advancements in complementary fields such as biomechanics and neuroscience that multi-degree-of-freedom (d.o.f.) humanoid robots have become technically viable. Important advantages of the technology have been shown by pioneering robots such as H6, H7 [1], P2 [2, 3], ASIMO [4], JOHNNIE and LOLA [5, 6], WABIAN-2 [7], LUCY [8], HRP and HRP-2 [9, 10], Cog [11, 12], pneumatic bipeds [13], the flexible spine KENTA and KENJI [14, 15], SAIKA [16] and PINO [17].

With these developments in robotics, computing and neuroscientific understanding has come an increased capacity to build a humanoid robotic platform that will enhance robotic intelligence, programming and learning. Yet, in spite of this growth in humanoid technology there are still significant gaps in the robotic understanding of the cognitive needs for machine intelligence, and equally profound gaps in neuroscientific understanding of the function of the human brain and it how can create a cognitive being.

The RobotCub project is a research initiative dedicated to the realization of embodied cognitive systems [18, 19] and the creation of an advanced robotic platform for neuroscientific study. Its goals are:

(i) Creation of an open hardware/software humanoid robotic platform for research in embodied cognition. This is the iCub.

(ii) Advancing our neural understanding of cognitive systems by exploiting this platform in the study of the development of cognitive capabilities in humanoid robots.

At the heart of the RobotCub philosophy on cognition is the belief that manipulation plays a fundamental role in the development of cognitive capability. As many of these basic skills are developed during the formative years of growth, RobotCub aims at testing and developing these paradigms through the creation of a child-like humanoid. The iCub has as its aim the replication of the physical and cognitive abilities of a 2.5-year-old baby. This ‘baby’ robot will act in cognitive scenarios, performing tasks useful to learning, and interacting with the environment and humans [17]. The small (90 cm tall), compact size (less than 23 kg and fitting within the volume of a child) and high number (53) of d.o.f. combined with the capacity for cognitive development are fundamental differences from the many excellent humanoids already developed.

At the same time the open approach (both for hardware and software), i.e. the open access of the research community to the software and hardware modules of the iCub, will allow a wide range of experimentation in both the software and at the hardware mechanical/sensory level by an enlarged user group, speeding up the development of the cognitive paradigms. In addition to this, the access to the sensory modules of the robot (hand tactile sensor/limb level force sensing and sensing skin) will enable experimentation and evaluation of the sensing facilities, and illuminate their important role in the development of cognitive capabilities.

The paper is organized as follows. Section 2 introduces the specifications from kinematics point of view, and also presents dynamic performance criteria and simulation studies to consolidate the design structure. Section 3 focuses on the actuation selection needed to achieve the performance targets. Details of the physical construction of the robot limbs and body segments is provided in Section 4, while Section 5 reports on the currently developed sensory system of the iCub, the electronic hardware and control architecture. Section 6 shows the constructed iCub prototype and compares the performance against the design requirement, while conclusions and future work are addressed in Section 7.

2. ICUB SPECIFICATIONS

Development of a robotic platform for neural testing that has the embodied capacity of a human child poses many challenges that must be addressed in a methodical and concurrent manner to coordinate and integrate the various components that form the full and complete mechatronic structure. There is clearly a requirement for many iterations of the design process before reaching a final prototype. Nonetheless, there is a need to define a starting point which in this instance was to aim for a robot that has the physical and ultimately cognitive capacity of a 2.5-year-old with the ability to develop to this stage from the equivalent of newborn.

2.1. Kinematics

Among the first and most important questions to be addressed when considering the hardware design is the fundamental kinematic layout, to enable the natural, stable and robust actions found in a young child. The kinematic specifications of the body of the iCub including the definition of the number of d.o.f. required and their actual location, as well as the actual size of the limbs and torso was based on ergonomics studies and X-ray images (Fig. 1) [19].

This ergonomic data was augmented by several iCub simulation models that targeted definition and analysis of the required motions of a baby or young child as it developed its physical capabilities in its first 2.5 years.

From these analyses the total number of d.o.f. for the upper body was set to 38 (seven for each arm, nine for each hand and six for the head) (Fig. 2). For the legs the simulations indicated that for crawling, sitting and squatting a 5-d.o.f. leg is adequate. However, it was decided to incorporate an additional d.o.f. at the ankle to support not only crawling, but also standing (supported and unsupported) and walking. Therefore each leg has 6 d.o.f.: these include three at the hip, one at the knee and two at the ankle (flexion/extension and abduction/adduction). The foot twist rotation was not implemented.

The human spine/waist joint structure has a fundamental role in the flexibility and efficiency of the human torso motions. The spine/waist sections implanted in humanoids robots are typically much simpler mechanisms, mainly providing 2 d.o.f. for the upper torso; however, humanoids that try to replicate the functionally of the human spine have also been developed [14, 15]. Although the latest approach is very

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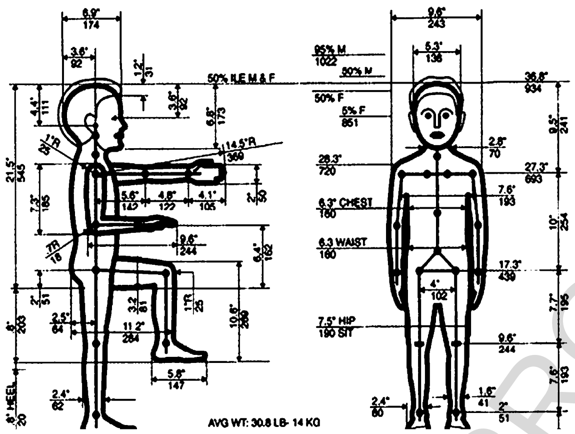

Figure 1. Size specification for the iCub.

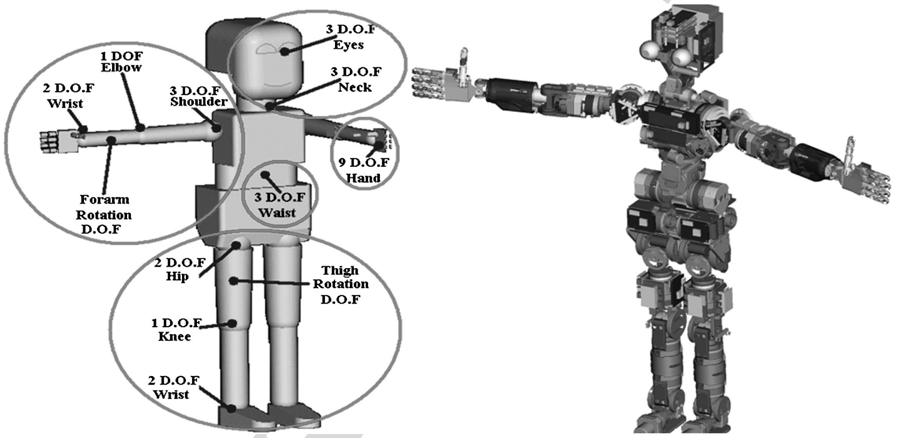

Figure 2. iCub distribution of the d.o.f. and the CAD model of the first prototype.

attractive, its implementation suffers from high complexity and control difficulties as it involves a large number of actuators and sensors. In designing the iCub waist we considered performance criteria such as workspace capacity and motion flexibility. Taking into consideration also the open nature and the compact size of the iCub platform, it was evident that compactness, easy of maintenance and robustness were also critical issues.

Simulation analysis was performed to identify the number of d.o.f. required for the iCub crawling locomotion. This showed that for effective crawling a 2-d.o.f. waist/torso is adequate. However, as there is a strong belief that manipulation plays a fundamental role in the development of cognitive capabilities a 3-d.o.f. waist was incorporated to the iCub body in order to enhance the manipulation space of the robot. A 3-d.o.f. waist provides increased range and flexibility of motion for the upper body when compared to 1- or 2-d.o.f. waist joints commonly found in other

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humanoids, and it results in an amplified workspace for the iCub when performing manipulation tasks using its hands while in a sitting position.

The neck has a total of 3 d.o.f., and provides full and flexible head motions with a final series of 3 d.o.f. offering viewing and tracking motions in the eyes. This gives the iCub a total of 53 d.o.f. in a package that must be both light (approximately 23 kg) and compact (approximately 90 cm tall).

For the realization of the kinematic structure of the iCub a number of unique features not found in other biped robots were considered and implemented. These are:

(i) For the implementation of the hip joint of the iCub and particularly for the hip flexion/extension and abduction/adduction motions, a cable differential mechanism was selected to provide increased stiffness on the hip joint.

(ii) Two of 3 d.o.f. in the iCub's waist (pitch, yaw) are also implemented using a cable differential mechanism. As a result, the increased flexibility of the upper body and the ensuing larger working space of arms are combined with the inherent stiffness of the differential mechanism also adopted for this joint [20].

Since the iCub is a human-like robot and will perform tasks similar to those performed by a human, the range of motion of a 'standard' human baby was used as a starting point for the selection of the movable range of each joint. Table 1 shows

Table 1.
Number of d.o.f. and range of motion (deg) of major joints

Joint	Human		iCub	
	Kinematics	Range of motion	Kinematics	Range of motion
Shoulder	flex/extension	−8, +200	flex/extension	−50, +230
	ab/adduction	−85, +200	ab/adduction	−90, +150
	rotation/twist	−54, +127	rotation/twist	−90, +90
Elbow	flex/extension	0, +160	flex/extension	0, +140
	pron/supination	−36.5, +37	pron/supination	−30, +30
Wrist	flex/extension	−87, +90	flex/extension	−90, +90
	ab/adduction	−90, +90	ab/adduction	−90, +90
Waist	roll	(−35, +35)	roll	−90, −90
	pitch	(−30, +70)	pitch	−10, +90
	yaw	(−40, +40)	yaw	−60, +60
Hip	flex/extension	−45, +147	flex/extension	−120, +45
	ab/adduction	−40, +45	ab/adduction	−31, +45
	rotation	−44, +45	rotation	−91, +31
Knee	flex/extension	0, +128	flex/extension	0, +130
Ankle	flex/extension	−51.5, +34	flex/extension	−60, +70
	ab/adduction	−44.5, +58	ab/adduction	−25, +25
	rotation/twist	−34, +36.5	rotation/twist	–
Neck	pan	−60, +60	pan	−90, +90
	tilt	−60, +90	tilt	−80, +90
	roll	−54, +54	roll	−45, +45

the range of motions specification for the joints of the lower body in comparison with the corresponding ranges found in a human baby.

It can be observed that there is broad agreement between the range of motions of the iCub and the human. In some instances this has resulted in a greater of motion for the iCub than the human and in a few cases the range is less than for the human. Simulation studies have confirmed that the range of motions provided in the specification is sufficient to ensure the iCub can perform the basic exploratory and manipulation procedures required for the 'child'.

2.2. Dynamics

Having determined the desired kinematic structure and range of motion of the joints, it was possible to move to structural and design considerations derived from dynamic performance criteria based on the masses, and projected forces and torques. Clearly the inter-relation of kinematics, mechanical design, range of motion and dynamics is not solved in a single iteration, but requires a continually interactive refining process that ultimately also allows the actuation and drive systems to be selected.

Initial estimates and targets for the masses of all the limbs and mechanical structures were set using the 'real' child model. A design mass for the whole structure was set at 23 kg which is at the top end of normal mass for a young (2.5-year-old) child. A detailed breakdown of body segment masses and their lengths is shown in Table 2.

Using these projections and the kinematic layout as a baseline, dynamic simulations were developed to determine static and dynamic performance requirements for all joints. The simulations were done with Webots [21], a simulator based on ODE (Open Dynamic Engine) which is an open source library for simulating three-dimensional rigid body dynamics. We measured the torques that would be needed by the actuators in order to achieve correct crawling motion. As ODE is not designed as an accurate physics library, all critical values were carefully checked. These simulations particularly focused on performing crawling motions at different gait speeds (0.5 and 1 Hz cycles), and transitions from sitting to crawling pose and

Table 2.
Mass distribution and size of the main body segments

Body section	Mass (kg)	Length (m)
Upper arm	1.15	0.15
Forearm (including the hand)	1.25	0.13
Upper leg (thigh)	1.5	0.17
Lower leg (shin)	1.5	0.17
Ankle and foot	0.5	
Upper torso	3.75	0.12
Lower torso	6.5	0.12
Head	1.5	

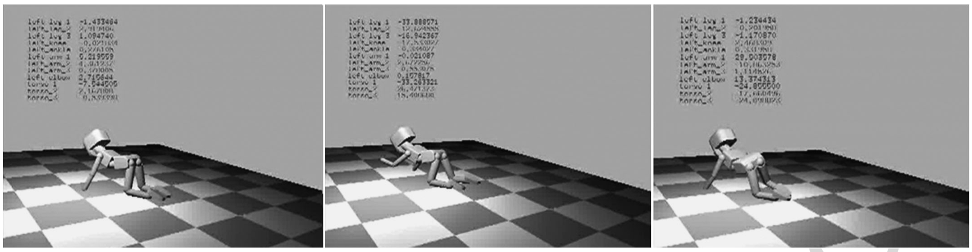

Figure 3. View of the iCub crawling simulation.

Table 3.
Speed and acceleration of leg/arm major joints while iCub is crawling

Joint	0.5-Hz Crawling		1-Hz Crawling	
	Max speed (rad/s)	Max acceleration (rad/s^2)	Max speed (rad/s)	Max acceleration (rad/s^2)
Hip flex/extension	1.25	3.94	2.51	15.79
Knee	0.72	2.27	1.44	9.08
Shoulder flex/extension	1.25	3.94	2.51	15.79
Elbow	1.57	4.93	3.14	19.73

Table 4.
Peak torques of iCub major joints

Joint	Peak torque (N m) at 0.5 Hz	Peak torque (N m) at 1 Hz
Shoulder flex/extension	40.5	48.4
Shoulder ab/adduction	18.1	45.6
Shoulder rotation	7.9	10.9
Elbow flex/extension	18.6	29.4
Hip flex/extension	38.5	46.3
Hip ab/adduction	15.1	37.1
Hip rotation	23.2	36.8
Knee	28.0	27.4
Ankle flex/extension	11.3	12.4
Ankle ab/adduction	–	–
Waist roll	26.5	27.2
Waist pitch	34.3	45.8
Waist yaw	13.7	30.1

vice versa, as can be seen in Fig. 3. From these simulations, the maximum required joints speeds/accelerations were determine, Table 3, together with the peak torque requirements of each joint, Table 4.

Typical torque requirements for the major joints during 1-Hz crawling are shown in Fig. 4. The crawling motion consisted of simple sinusoidal trajectories that the shoulder flexion/extension, elbow, hip flexion/extension and knee joints had to follow using a simple PID controller. Despite the simplicity of these trajectories, they are compatible with real crawling infants. During these tests to establish baseline performance, the maximum angle errors were of the order of 3°, except

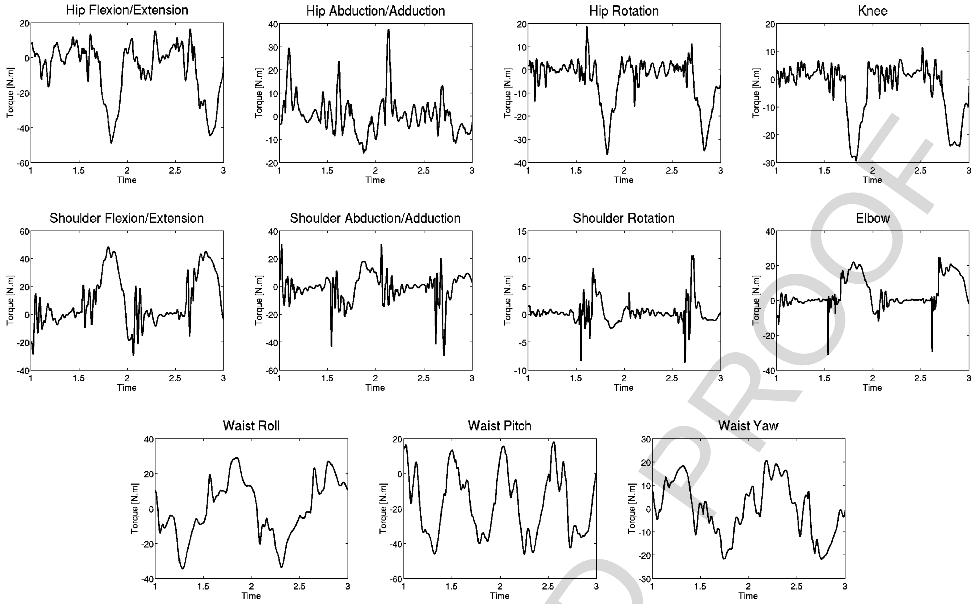

Figure 4. Torque curves of the major joints of the iCub during 1-Hz crawling simulation.

for the waist, where errors could reach 5°. It is to be noted that these numbers are specific to the crawling control/strategy adopted, while it seems possible that the optimization of the controller would reduce the requirements, at least for dynamic tasks.

3. ACTUATOR SELECTION

Using the above simulation data, in conjunction with the constraints imposed when trying to replicate the mechanical and kinematic functionality of a child, it is possible to select the actuation of the individual joints. The actuation solution adopted for the iCub is based on a combination of a harmonic drive reduction system (CSG series, 100:1 ratio for all the major joints) and a brushless frameless motor (BLM) from the Kollmorgen frameless RBE series (Fig. 5). The harmonic drives include no backlash and, high reduction ratios on small space with low weight, while the brushless motors exhibit desired properties such as robustness, higher power density, and higher torque and speed bandwidths when compared with conventional DC brushed motors. The use of frameless motors permits integration of the motor and harmonic system within an endoskeletal structure that minimizes size, weight and dimensions with the immediate benefit of the freedom in shaping the actuator housing. Only three different power actuators groups are needed to power the major joints of the iCub.

(i) The high-power actuator group is capable of delivering over 40 Nm at the output shaft, and has a diameter of 60 mm and a length of 53 mm.

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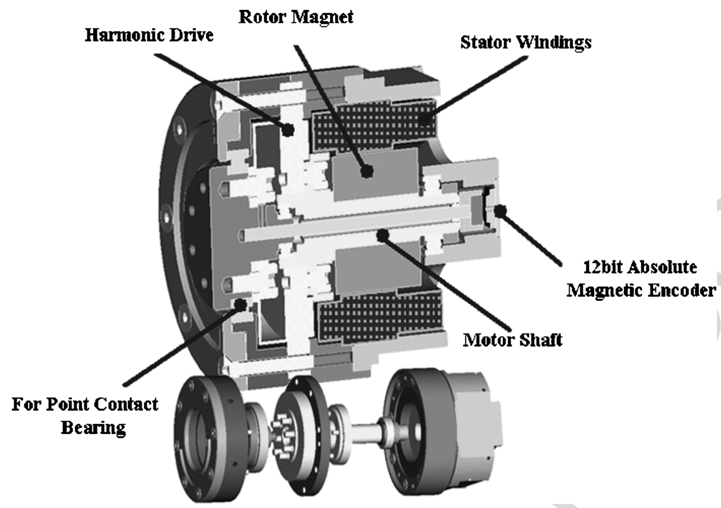

Figure 5. View of the iCub motor/gearbox actuator group.

(ii) The medium-power motor group provides up to 20 Nm with a diameter of 50 mm and a length of 48 mm.

(iii) The low-power motor group delivers up to 11 Nm with a diameter of 40 mm and a length of 82 mm.

The selection of the actuator group for each joint was based on the joint torque/speed requirements. In joints that these conditions could be satisfied by more than one of the actuator groups mentioned above, several iterations of the mechanical design were performed and the actuator group which optimized the design in terms of robustness, simplicity and compactness was finally selected.

4. MECHANICAL CONSTRUCTION

Using the actuator groups presented in the previous section, the various mechanical segments of iCub from the head to the foot were designed. The details on the realization of each individual segment are presented in this section.

The height of the first iCub prototype body from the foot to the head is 945 mm, while the width of the lower torso from left to right is 176 mm. The components of the first prototype that are considered as low stressed parts were fabricated in aluminum alloy Al6082 which is a structural alloy having a medium strength and excellent corrosion resistance. Medium/highly stressed parts components were made of aluminum alloy 7075 (Ergal) that is one of the highest strength aluminum alloys available. Its strength to weight ratio is excellent, and it is ideally used for medium and highly stressed parts such as actuator housing load-bearing parts, etc. Finally, the major joint shafts were fabricated from stainless steel 17-4PH, which delivers an excellent combination of good oxidation and corrosion resistance together with high strength.

4.1. Leg

For the leg design, particular attention was paid to satisfying the dimensional and weight requirements while at the same time maximizing the range of motion and output torque of each joint. The leg modules were designed for easy fitting/removal and maintenance. In general, the leg has an anthropomorphic kinematic form consisting of three major modules, i.e. the hip, knee and ankle (Fig. 6).

The hip module provides 3 d.o.f. to enable the thigh flexion/extension, abduction/adduction and thigh rotation. The realization of the first 2 d.o.f. is based on a cable differential mechanism similar to the one used in the waist. Two medium power actuator groups (20 Nm) located in the lower torso are used to drive the two input pulleys of the differential though a cable transmission system that also provides a secondary (2:1) gear ratio to satisfy the torque requirements of the hip module (Fig. 7).

The third d.o.f. of the hip (thigh rotation) is implemented along the thigh with the actual thigh shell forming the housing of the actuator group that powers this joint. The calf section forms the housing for the two medium-power actuator assemblies (20 Nm) associated with knee and ankle flexion (Fig. 8). Torque to these joints is transferred through cable transmission systems that also provide

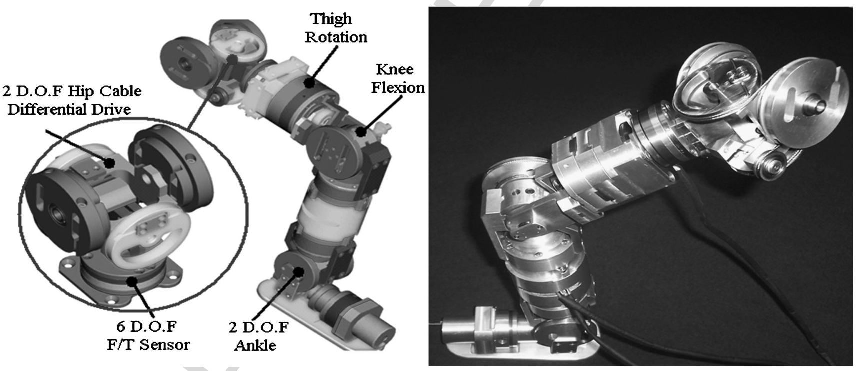

Figure 6. Mechanical realisation of the iCub leg.

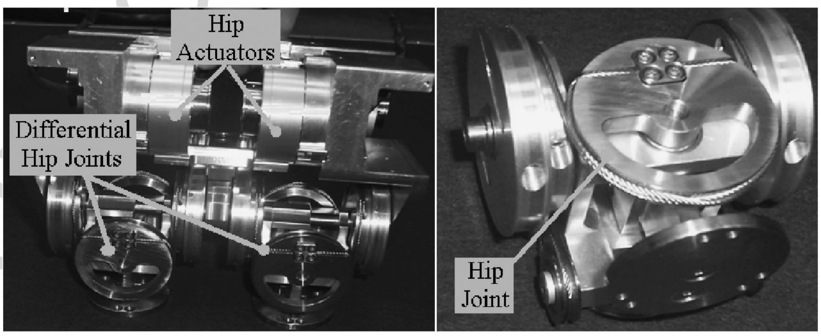

Figure 7. Mechanical realization and torque transmission cable rooting of the differential hip joints.

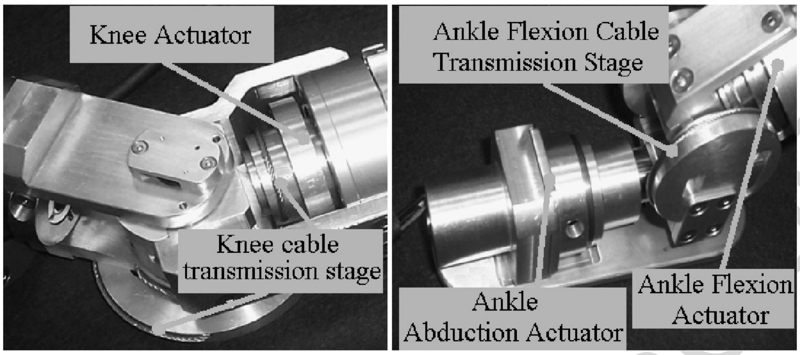

Figure 8. Mechanical realization and torque transmission cable rooting for the knee and ankle joints.

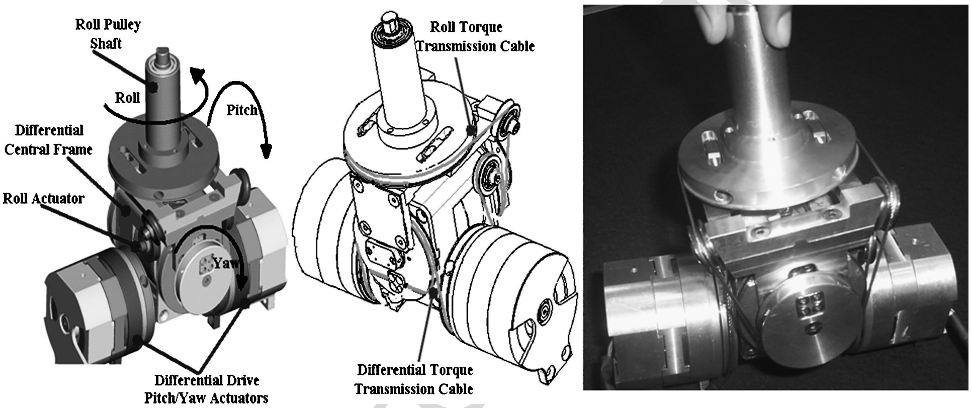

Figure 9. The compact design of the differential 3-d.o.f. iCub waist.

additional secondary gearing of (1.5:1 and 1.25:1) for the knee and the ankle flexion joint, respectively. The last d.o.f. which produces ankle abduction/adduction is implemented using a low-power actuator (11 Nm) located on the foot plate and directly coupled to the ankle abduction/adduction joint.

4.2. Waist mechanism

The role of the waist joint in the flexibility of motion of the upper body has been highlighted in the specifications section. Such flexibility must be accompanied by high positional stiffness for the upper body that is particularly important during manipulation. To satisfy these requirements the iCub's waist was realized using a mechanism where the torque and power of the two actuators used for the upper body pitch and yaw motions is transferred to these two motions using a cable-based differential mechanism as seen in Fig. 9.

For the pitch motion of the waist the two high-power actuators assemblies (40 N m each) that power the pitch and yaw motion apply a synchronous motion to the two directly coupled differential input wheels. For the yaw motion the motors turn in opposite directions and this generates the yaw action on the upper body. This differential mechanism has several advantages when compared with traditional serial mechanisms used in humanoids robots. These are:

(i) Increased stiffness compared to serial waist mechanisms usually seen in most of the humanoid robots.
(ii) The sum of the torque generated by the two actuators that power the differential joint can be distributed in both joints.
(iii) As a result of the previous feature smaller actuators can be used to achieve the maximum output torques required for the pitch and yaw motions.

The roll motion is achieved with the roll pulley shaft that is directly connected to the upper body frame. The actuator assembly of the roll pulley (20 Nm) is located within the square central element of the differential. The torque is conveyed through a cable transmission system that provides additional gearing (1.5:1) to meet the torque requirements of the roll joint (Table 4).

4.3. Torso and arm

In the arm design attention was paid to satisfying the dimensional and weight requirements while at the same time maximizing the range of motion and output torques of the arm joints. Figure 10 shows the arrangement of this module.

The shoulder is a roll–pitch–roll configuration. A single aluminum block houses the three motors, i.e. one high power for abduction and two medium power motors for the flexion and upper arm rotation. This shoulder motors group occupies half of the upper torso space (Fig. 11). The three-motor module of the shoulder and the orientation of the joints have been designed at an angle with respect to the front–back midline to position the range of motion as frontal as possible, which clearly

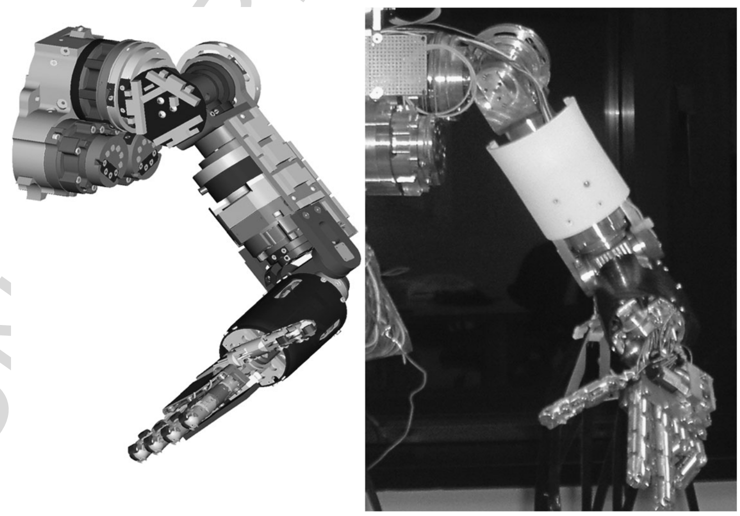

Figure 10. Arm module.

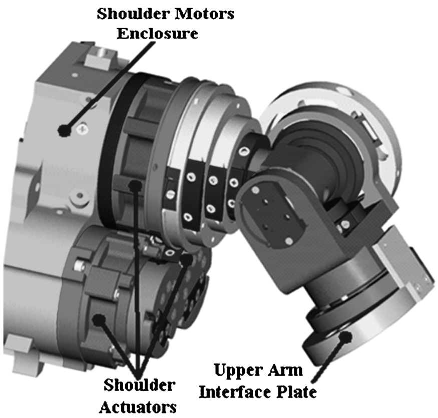

Figure 11. Shoulder mechanism.

enhances the manipulation workspace of the iCub. The joint is tendon driven with all three motors fixed in the shoulder base and not moving with respect to each other resulting in a very light arm structure. The tendon transmission stage for shoulder flexion and upper arm rotation provides additional gearing (1.7:1) to satisfy the torque requirements for these particular motions.

The elbow is driven by another Kollmorgen medium-power motor (20 Nm) occupying almost the entirety of the upper arm link. The forearm attachment is shifted from the rotational axis to allow the maximum possible range of movement (120° in this realization). The space along the axis of the elbow was left empty, which allows a nice routing of the cables coming from the forearm motors.

The forearm consists of 10 Faulhaber motors and their relative support structure. Three of these motors are responsible for the forearm rotation, wrist flexion and abduction, while the rest are donated to the hand actuation. Finally, the wrist joint that allows the hand flexion and abduction is tendon driven by the two motors fixed in the forearm section. The wrist is hollow so that it permits routing of the tendons actuating the fingers.

4.4. Hand module

As part of the physical embodiment of the robot, one of the major challenges is the development of a fully articulated hand with a range of motions comparable with a child's hand while retaining the physical size. This hand has physical requirements for manipulation, and grasping, and at the same time for a child acts as a 'foot' transmitting mobility loads from the limbs during crawling.

Although many anthropomorphic dexterous hands have been developed the small size and high dexterity needed for the iCub make this hand rather unique. The kinematic structure of the baby hand has been designed with a mechanical capacity for 21 d.o.f. although in the iCub with only nine motors available there is coupling actions in the ring and distal fingers and for finger spread (Fig. 12).

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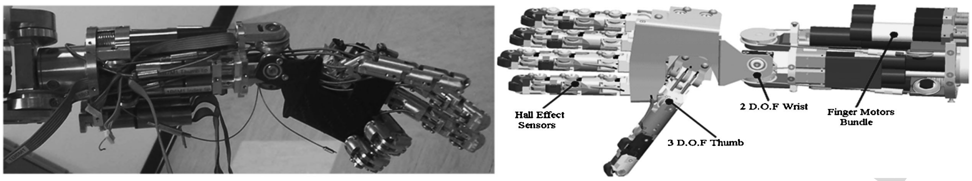

Figure 12. The iCub hand and the forearm section.

From these nine motors, two are located inside the palm while the rest are fixed in the forearm structure. To conform to the dimensions of a hand of a 2.5-year-old child the overall measurements of the palm have been restricted to: length 50.0 mm, palm width at the wrist 34 mm, palm width at the fingers 60.0 mm and depth 25.0 mm. Features of the palmar shell include:

(i) Creation of internal space for the housing of the thumb rotation mechanism, the routing of tendons, and two motors actuating the finger spread and the thumb proximal joint.

(ii) Finger spread (abduction/adduction) using a single tendon.

(iii) Joint position monitoring uses miniature magnetic sensor (Hall effect).

For ease of production the index, middle, ring and little fingers followed a common design and manufacturing process. Motions of the fingers are driven by tendons routed via idler pulleys on the shafts of the connecting joints. The flexing of the fingers is directly controlled by the tendons, while the extension is based on a spring return mechanism. This permits natural flexion of the fingers during manipulation.

All four fingers have coupled distal and middle phalanxes; furthermore, the motions of the little and ring finger has been linked together since these are rarely capable of moving individually. This coupling action eliminates a motor in the small space available in the forearm. The index and middle fingers move independently of each other, and along with the thumb enable very fine movement/grasping and control. All four fingers have Hall effect sensors for motion sensing: one for sensing the coupled motion of the distal and middle phalanx, and one for sensing the motions of the proximal phalanx. The abduction motions of each finger at the proximal joint have been linked together and activated by a single motor.

The thumb is somewhat similar to the other fingers in physical appearance. However, the thumb is fitted with an extra d.o.f., with the independent motion of the distal phalanx. Therefore, an additional sensor is added compared to the other fingers.

4.5. Head

The neck of the iCub head (Fig. 13) consists of a 3-d.o.f. serial chain of rotations, with the 3 d.o.f. placed in a configuration that best represents human movements.

The eye mechanism has also a total of 3 d.o.f. Both eyes can pan (independently) and tilt (simultaneously). The pan movement is driven by a belt system, with the

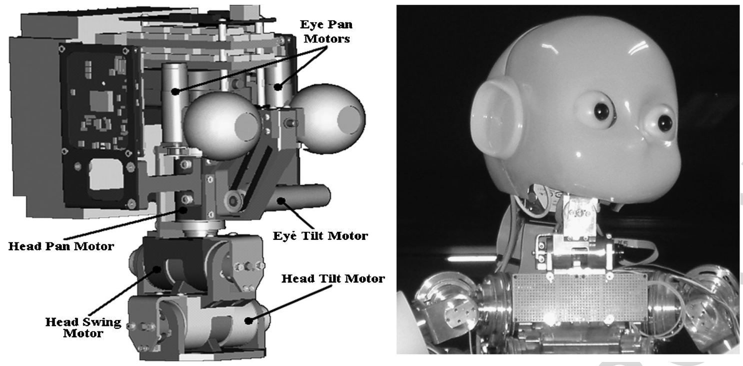

Figure 13. iCub head.

motor behind the eye ball. The eyes (common) tilt movement is actuated by a belt system placed in the middle of the two eyes. Each belt subsystem has a tension adjustment mechanism.

The calculation of the actuators characteristics was based on the desired specifications and the moment of inertia, as well as the various components, weight, given by CAD software. For driving this mechanism, DC micro motors (Faulhaber) equipped with planetary gearheads (Gysin) and optical encoders have been used. An initial prototype has already been built, tested and demonstrated in a tracking experiment. It is important to say that, in spite its simplicity, the mechanism is very robust, easy to control and has high performance, meeting all the desired specifications. Each joint uses an overload clutch system that increases the robustness of the mechanism, by absorbing (by sliding) different kinds of impacts and efforts during its interaction with the external world [22].

5. SENSING AND CONTROL

5.1. Sensing

Motion sensing in all major body and limb joints powered by the three standardized actuator assemblies uses relative position sensing (Hall effect sensors integrated within the motors) and miniature 12-bit absolute magnetic encoders (AS5045; Austria Microsystems) for system initialization and calibration.

In addition to motion sensing, force sensing is currently installed at two levels. To enable global force sensing at the limb (arms/legs) level a 6-d.o.f. force/torque (F/T) sensor has been integrated within each limb. In contrast to most of the humanoids robots where the F/T sensors are usually found at the foot/hand level, the F/T sensors in the iCub are placed at the level of the hip/shoulder between the hip/thigh and the shoulder/upper arm modules. The fixation of the F/T sensor at this level of the limb is justified from the fact that during crawling, which is the primary locomotion requirement of the iCub, the contact of the leg/arm with the ground occurs at

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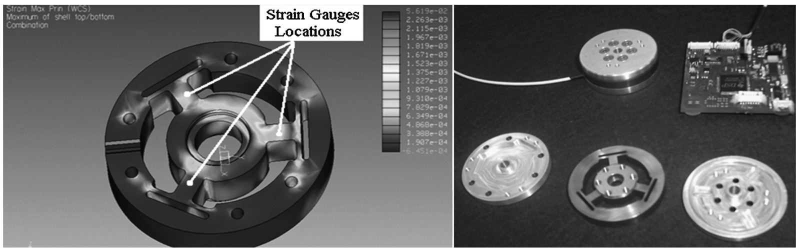
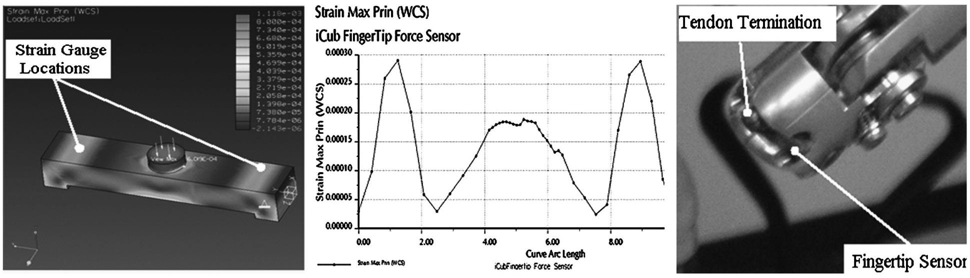


(a)



(b)

Figure 14. (a) The 6-d.o.f. F/T sensor and (b) the tendon force fingertip sensor.

the knee and elbow/forearm level. In addition, F/T sensing at the hip/shoulder level enables the implementation of active compliance control at the lower limbs of iCub. Additional F/T sensors may be required at the level of the foot for the development of the walking capability. Both the load cell and the electronics of the F/T sensor used in iCub were designed in-house for the purpose of dimensional optimization (Fig. 14a). The 6-d.o.f. load cell is based on a three-spoke structure where the strain generated is measured by semiconductor strain gauges that are mounted on the four sides of each of the three spokes in locations determined by the stress/strain simulation results. As a linear response is desired from the sensor, the chosen sensor material must have a linear strain–stress relationship. The body of the sensor is machined from a solid stainless steel block to reduce hysteresis and increase the strength and repeatability. Figure 14(a) also shows the developed signal conditioning and data acquisition electronics of the sensor which is based on a TMS20F2812 150-MHz DSP processor. Each electronic unit with dimensions of $45 \times 45 \times 5$ mm can handle two 6-d.o.f. load cells.

Additional force-sensing capability has been provided at the finger level with the integration of a single axis load cell within the fingertip space of each of the four fingers and the thumb (Fig. 14b). This load cell forms the termination plate where the tendon that drives the middle and proximal joint of each finger is fixed, and it is used for monitoring the tendon tension. This enables the control of the tendon tension when fingers are in free motion while during constraint motions that may occur during grasping/manipulation the signal provided can also be used for the control of the grasping forces.

The iCub sensory system that includes binocular vision and haptic, cutaneous, aural and vestibular sensors will not be considered in this paper since it has been implemented by using off-the-shelf components; however, functionally, the system will able us to coordinate the movement of the eyes and hands, grasp and manipulate lightweight objects of reasonable size and appearance, crawl using the arms and legs, and sit up. This will allow the system to explore and interact with the environment not only by manipulating objects, but also through locomotion.

5.2. Control architecture and electronics

The interface between the iCub and the outside world requires only a Gbit Ethernet cable and a power cable. The robot contains the actuator power drivers, a set of DSP controllers, a PC104 relay station and acquisition card based on a Pentium processor, and the sensors' acquisition and control electronics. Sensory data and motor commands are sent via the Ethernet connection. The PC104 card is responsible for the preparation of the IP packets and in general for the bidirectional communication of iCub with the external control station. The on-board actuator control electronics for iCub (Fig. 15), are embedded at or near the motor/joint assemblies, and are primarily responsible for the monitoring of the actuator sensory signals and the generation of the control signals.

In addition to the drive and control electronics, secondary electronics such as A/D cards used in processing of sensory data, particularly from the hand, e.g. position and tactile sensors, have been included within iCub. Both the control/driver and the A/D cards are connected into iCub's multiple CAN bus structure. Given the open nature of the system and the desire that the robot will be used by researchers from various areas within the cognitive research spectrum, the software architecture is also based on an open and widely available architectural system called YARP (Yet Another Robot Platform). The architecture encapsulates lessons from our experience in building humanoid robots. The goal of a common architecture is to minimize the effort devoted to infrastructure-level software development by facilitating code reuse and modularity, and so maximize research-level development and collaboration. Humanoid robotics is a 'bleeding edge' field of research, with constant flux in sensors, actuators and processors. Code reuse and maintenance

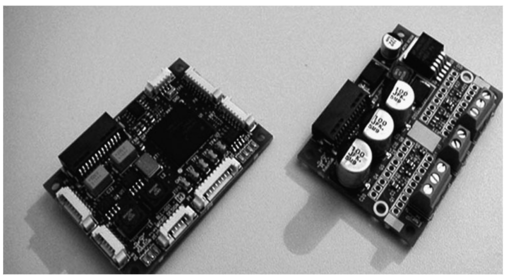


Figure 15. The motor control and driver boards.

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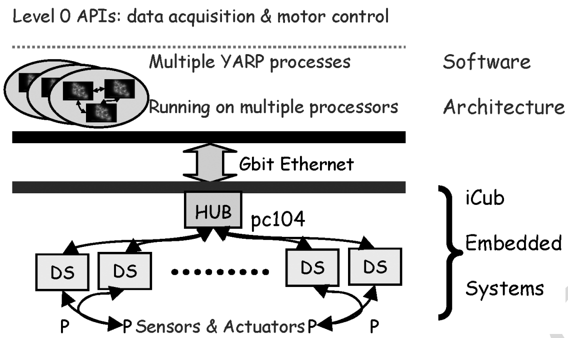


Figure 16. System architecture.

is therefore a significant challenge. In short, the main features of YARP include support for inter-process communication and image processing as well as a class hierarchy to ease code reuse across different hardware platforms. YARP facilitates the implementation of a distributed controller in a cluster (Fig. 16).

YARP is currently used and tested on Windows, Linux, MacOS and Solaris, which are common operating systems used in robotics. We are not supporting any hard real-time operating system at the moment (there exists support for QNX with a previous version of YARP) since the low-level control cycles are all carried out by the localized DSPs. This is consistent with the use of the CAN bus which at the moment constrains the type of controller that runs on the DSPs versus the type of controller one might imagine implementing outside the robot. A complete description of the software architecture is outside the scope of this paper; more information can be found in the YARP website (http://yarp0.sourceforge.net) or in Ref. [23].

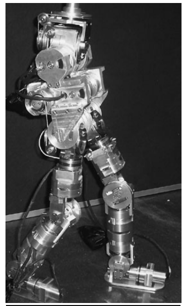
6. ESTIMATED PERFORMANCE MEASURES

The constructed iCub prototype conforms to the mechanical design requirements in terms of dimensions and mass. In fact, at this moment without a 'skin' the robot currently weighs less than 20 kg compared to the design weight specification of 23 kg.

The motion range and torque outputs of the first prototype of the individual joints of iCub are introduced in Table 5. These results show that the torque requirements of the iCub have been fully satisfied by the proposed design and actuator selection. Indeed, for several joints significantly higher torques are achieved than required by the specification, while still achieving the speed of motion and whole compact design. With respect to the range of motion of the individual joints, these in general also meet the specified requirements of iCub with some small limitations in the hip and knee flexion ranges. These are currently being addressed in the first revision of the design and are not considered to be significant issues.

Table 5.
Performance measures and actuation details of iCub's major joints

Joint	Range of motion (deg)	Actuator	Gear	Secondary cable gearing	Torque (N m)
Arm					
shoulder flex/extension	−50, +230	Kollmorgen RBE 1210	HD-CSG14_100:1	1.7	34
shoulder ab/adduction	−90, +150	Kollmorgen RBE 1211	HD-CSG17_100:1	1:1	40
shoulder rotation	−90, +90	Kollmorgen RBE 1210	HD-CSG14_100:1	1.7	34
elbow flex/extension	0, +140	Kollmorgen RBE 1210	HD-CSG14_100:1	1:1	20
elbow pron/supination	−30, +30	Faulhaber 1331	Faulhaber 14/1_159:1	–	0.45
wrist flex/extension	−90, +90	Faulhaber 1331	Faulhaber 14/1_159:1	–	0.65
wrist ab/adduction	−90, +90	Faulhaber 1331	Faulhaber 14/1_159:1	–	0.65
Leg					
hip flex/extension	+50, −100	RBE 1210	HD-CSG14_100:1	2:1	sum of the differential
hip ab/adduction	+47, −35	RBE 1210	HD-CSG14_100:1	2:1	drive torques = 84
hip rotation	+30, −80	RBE 1211	HD-CSG17_100:1	–	40
knee	+115, −10	RBE 1210	HD-CSG14_100:1	1.5:1	30
ankle flex/extension	+70, −50	RBE 1210	HD-CSG14_100:1	1.5:1	24
ankle ab/adduction	+35, −35	RBE 0513	HD-HFUC11_100:1	–	11
Waist					
roll	+90, −15	RBE 1210	HD CSG14_100:1	1.8:1	36
pitch	+45, −45	RBE 1211	HD CSG17_100:1	–	sum of the differential
yaw	+70, −70	RBE 1211	HD CSG17_100:1	–	drive torques = 80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7. CONCLUSIONS

The RobotCub project is a research initiative dedicated to the realization of embodied cognitive systems. This paper discussed the concepts adopted for the design, construction and testing of an embodied robotic child (iCub) with the physical and ultimately cognitive abilities of a 2.5-year-old human infant. It has been shown that this system can achieve all the target physical and mechanical specifications. In so doing it has achieved the first goal of the project, i.e.:

(i) Creating an open humanoid robotic platform for research in embodied cognition and neuroscience—iCub.

This places the research on track for future developments on the second of the goals.

(ii) Advancing our understanding of neuroscientific and cognitive systems by exploiting this platform in the study of the development of cognitive capabilities in humanoid robots.

Cognitive development involves several stages, from coordination of eye gaze, head attitude and hand placement when reaching, through to more complex—and revealing—exploratory use of action. This is typically achieved by dexterous manipulation of the environment to learn the affordances of objects in the context of one's own developing capabilities. Our ultimate goal is to create a humanoid robot—iCub—that can communicate through gestures and simple expressions of its understanding of the environment, an understanding that is achieved through rich manipulation-based exploration, imitation and social interaction.

This papers describes the realization of one of goals of RobotCub, i.e. iCub, while our big bet for the future is that of bringing together several strands of work that contribute to the eventual creation of a model of cognition and an associated architecture which will facilitate the development of a spectrum of cognitive capabilities in the iCub humanoid robot.

Our conceptual framework, which forms the foundation of the RobotCub project, focuses on emergent embodied systems that develop cognitive skills as a result of their action in the world and drawing out explicitly the strong consequences of adopting this stance (and this is one of the reasons why we need a physical robot to work with). In this respect our modus operandi was that of surveying what is known about cognition in natural systems, particularly from the developmental standpoint, with the goal of identifying the most appropriate system phylogeny and ontogeny for the iCub. Neurophysiological and psychological models of some of these capabilities have been explored, noting where appropriate architectural considerations such as subsystem interdependencies that will define and constrain on the overall system organization, i.e. the cognition architecture. Future work will seek to build a community of researchers to use the open nature of iCub to explore neuroscientific understanding.

Acknowledgments

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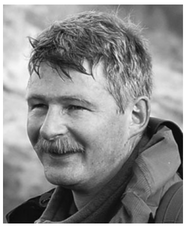

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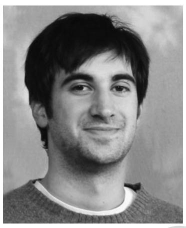

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