ROBotic Open-architecture Technology for
Cognition, Understanding and Behavior

RobotCub.org

Cogsys
Cognitive Systems

Project no. 004370

RobotCub

Development of a cognitive humanoid cub

Instrument: Integrated Project
Thematic Priority: IST – Cognitive Systems

D8.1
Initial Specification of the CUB Open System

Due Date: Month 12
Submission date: Month 12

Start date of project: **01/09/2004** Duration: **60 months**

Organisation name of lead contractor for this deliverable: UGDIST

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Revision: **1.1**

Project co-funded by the European Commission within the Sixth Framework Programme (2002-2006)		
Dissemination Level		
PU	Public	
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CO	Confidential, only for members of the consortium (including the Commission Service)	**CO**

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1 Introduction

The iCub is the humanoid baby-robot being designed by the RobotCub consortium. The iCub will be a full humanoid robot sized as a two year-old child. The total height is estimated to be around 90cm. It will have 53 degrees of freedom (dof), including articulated hands to be used for manipulation and gesturing. A study is being conducted for determining if and how many degrees of freedom are minimally required to produce/generate plausible facial expressions. The robot should be able to crawl and sit (to free the hands from supporting the body) and autonomously transition from crawling to sitting and vice-versa.

This document presents the specifications of the hardware, electronics, and software platform of the iCub. These three components of the robotic architecture are being developed by the consortium in parallel and synergistically. Our goal is to produce an integrated design, of an open platform, apt to support various behaviours, and of the most general use possible. Complementary to this requirement, it has to be noted that the RobotCub project is very much about manipulation, and for this reason the robot platform should incorporate this additional requirement by providing sophisticated hands, a flexible oculomotor system, and a reasonable bi-manual workspace. Finally, on top of this, we need to support, global body movements such as crawling, sitting, etc. These many constraints have to be considered in preparing the specifications of the robot and later on during the whole design stage, which will last for approximately two and a half years.

1.1 Rationale of the specifications

The behaviours we set forward for representing the robot's skills at the end of the project can be summarized into two types of constraints:

- Kinematics: about the geometrical construction of the robot
- Dynamics: about the forces and torques we require from the robot

The possibility of achieving certain tasks is favoured by a suitable kinematics, and in particular this translates into the range of movement and the number of controllable joints (where clearly replicating the human body in detail is fairly impossible with current technology). Kinematics is also influenced by the overall size of the robot. We decided *a priori* to target the size of a two and a half year old child (approximately 90cm high). This size can be achieved with current technology. QRIO (Sony Corp.) is an example of a robot with similar size although with less degrees of freedom. In particular, our specifications have to consider at least the same degrees of freedom found in QRIO plus hands and moving eyes. Also, we wanted to consider the workspace and dexterity of the arms and thus a three degree of freedom shoulder is required. Later, we will elaborate these considerations into a proper list of joints, ranges, and sensory requirements at the joint level.

Considering dynamics, the most demanding requirements clearly appear in interacting with the environment. Impact forces, for instance, have to be considered for the crawling behaviour, but also and more importantly, developing cognitive behaviours such as manipulation might require exploring the environment very erratically. As a consequence, it is likely that impact forces are generated in various elements of the robot structure. These turns out to require strong joints, gearboxes, and more in general powerful actuators. In order to evaluate at least the scale (order of magnitude) of the required forces we decided to run simulations of various behaviours in a reasonable

model of the robot. These dynamic simulations provided data for starting the design of the robot.
At a more general level we had then to evaluate the available technology, compared to the experience of the consortium and the targeted size of the robot: it was decided that electric motors represent the most suitable technology for our platform, given also that the iCub has to be ready by month 30 of the project. Other technologies (e.g. hydraulic) are left for the “technology watch” activity and they are not considered further at the moment.
In addition, given the size of the robot, and given the power density available, considerations of speed for certain joints lack of significance: i.e. given the power and the torques required, speed is a consequence rather than a design parameter. In certain cases, in comparing to human data, clearly also the power density is much lower than desired (e.g. the wrists cannot possibly stand the weight of the robot).
Finally, the iCub is not only about motors, sensors are equally important. Also in this case, we have to deal and exploit at best the available technology. The robot will have vision, audition, joint sensors, force sensors, tactile sensors – where possible – and temperature sensors in many of the motors. The robot will also be able to provide feedback to humans through a speaker. iCub will thus include:

- Cameras
- Microphones
- Gyroscopes
- Linear accelerometers
- Encoders (or other positional sensors)
- Temperature sensors, current consumption sensors
- Various tension, force/torque sensors
- Tactile sensors

The choice of these components is clearly related to these specifications.
To recapitulate, the constraint of size and available technology determines a good part of the design choices – i.e. our freedom is deciding which components to use. In parallel, we simulated some of the robot’s behaviours to determine the required joint torques. These two pieces of information were then used in selecting the best available motors compatible in size, torque, and strength. As we mentioned, speed is a consequence rather than a design parameters here, although, in simulation we examined the dependency of speed to torque for crawling.
Other design choices described regard the embedded electronics and the structure of the software. The iCub will have many sensors and actuators working in parallel. We would like to exploit this parallelism also at the computational level and, consequently, the iCub API will be multi-process and will be amenable to be run on multiple machines with full-blown parallelism.
The remainder of this document is organized as follows: section 2 describes the kinematic constraints and design choices; section 3 deals with dynamics and section 4 wraps this up into the current design choices and result of the CAD design activity. Section 5 describes the elements of the controlling electronics required to drive the robot and acquire its sensors; the list of sensors currently included into the design is reported in section 6 and, finally, section 7 deals with the software architecture that is being planned for the iCub. We then include a longer document in appendix with more details on some of the design path that led to the current design.

2 Kinematics

The gross kinematic features of the iCub are the number of degrees of freedom (dof) and the overall size. The latter was determined by approximate technological evaluation and already reported in the Technical Annex: the iCub will have the approximate size of a two and a half year old child. The number and allocation of degrees of freedom reflects the use of the robot for manipulative tasks and the general resemblance with human form. The main decision is how many degrees of freedom to allocate for the hands. Clearly, the most part of the hand's actuators can only be located in the forearm for evident reasons of space. By analyzing the requirements for grasping and manipulation and drawing on our past experience we estimated that 9 degrees of freedom in the hand will be optimal – always given the size and technological constraints. The hand of the iCub will be underactuated: i.e. the 9 motors will in fact move 17 joints coupled in different ways. The thumb, index, and middle finger will be independent; the last two fingers will act as a simple 1 dof device. The thumb will have three degrees of freedom, one of which will be actuated from a small motor inside the palm (the opposition movement). The remaining two degrees of freedom will move the remaining three joints, the last two being coupled together perhaps through a small rotational spring. It remains to be decided whether the actuator will provide both agonistic and antagonistic forces (a loop wire). The index finger will have the same number of joints of the thumb with a similar arrangement and actuation. The abduction/adduction movement will be driven together with the ring and little finger, by keeping the middle finger fixed with respect to the palm. The middle finger will thus have only three joints and two controlled dof. Finally, the ring and little finger will be connected together, coupled by means of springs and actuated by a single motor. The abduction/adduction movement will be driven by a little motor inside the palm. It has been shown [1] that 9 dof distributed on three fingers allow full manipulability (e.g. rotation and translation) by allowing the positioning of three points of contact onto the object (the fingertips). The iCub hand will have one dof less since the middle finger is fixed with respect to the palm. Given the targeted size we believe nothing more can be done at the moment.

Next we analyzed the requirements for the oculomotor system. The simplest and yet flexible configuration sees three degrees of freedom for moving the eyes, allowing for independent panning (and thus vergence control) and a common tilt. The neck complements this module with three additional degrees of freedom. We did not considered additional degrees of freedom in the neck as in some existing robot head to save in complexity. The remaining 47 dof are quite a feat anyway.

The minimum number of dof for the arm is seven. While theoretically six would already allow reaching any point in the workspace with every attainable orientation, in practice, the seventh dof provides a means to reach without interfering much with vision. This additional flexibility is very much desired if we have to deal with grasping and the interaction with objects in front of the robot while maintaining sight of the action. It is worth mentioning that the full range of motion for the shoulder can only be obtained by a double joint mechanism similar to the human clavicle and collar bones. Since it is difficult to include also this additional dof, we might expect a constraint on the final range of movement. This will be verified and the range of bi-manual manipulation considered as a parameter to optimize.

Legs are supposed to support crawling but we discovered that, in practice, the requirements for crawling are not very different from walking. It is thus possible, although not fully verified because outside the domain of RobotCub, that the iCub could be made to stand and walk. This aspect, as mentioned, will not be covered by RobotCub, but clearly it is an advantage for the iCub openness, since it can stimulate other groups outside the present consortium to invest in the iCub platform and develop walking, balance, etc. Each leg will consist of 6 degrees of freedom: the hip will contain three joints, the knee one, and the remaining two will be allocated in the ankle. The foot yaw rotation will not be implemented.

For each joint we have to simultaneously consider the available sensors. Encoders or potentiometers will provide position feedback. Absolute sensors will be preferred and they are, in fact, a requirement for all the major joints (shoulders, hips, elbows, etc.). Tension sensors will be integrated in each joint controlling the fingers, especially if a single tendon solution is chosen (in which case they are mandatory). Temperature sensors are useful as a safety measure for the most mechanically stressed actuators. We will consider the incorporation of these sensors within the motor housing.

The robot external shell size was provided at this stage and it is shown in Figure 1. This is to be regarded as imposing the overall length without the pretence to be defining the final shape or appearance of the iCub. Actual dimensions were taken from books of ergonomics and x-ray images [2].

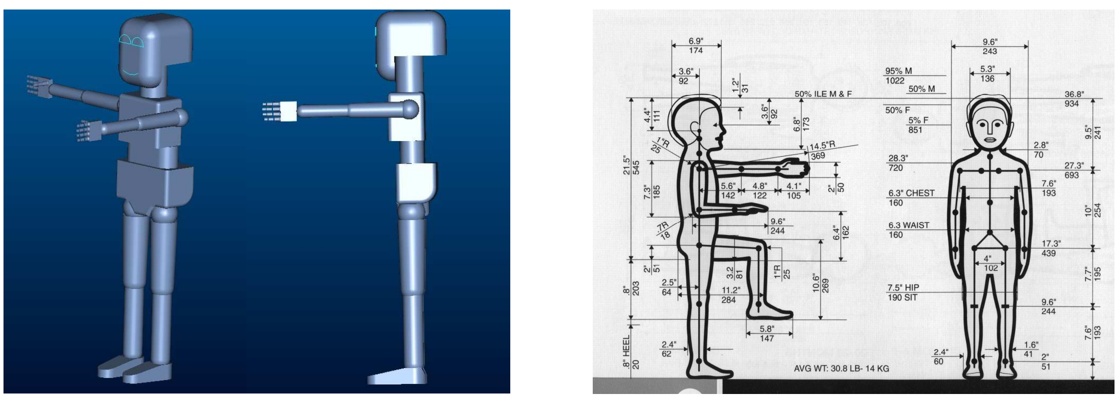


Figure 1: Overall size of the iCub.

The following set of tables summarizes the kinematics of the iCub although the exact placement of joints is still amenable to change.

Table 1: List of joints and range of movement.

(1) please specify joint names as much as possible when filling the table
(2) see the picture below the table for the meaning of joint names
(3) given as reference (real range must be the one on column C)

Head

Name (1)	Range of motion (°)	Range for the HOAP2 humanoid (3)	Latest DSIT/TLR realization (3)	Human (3)	Zero (of the range)
Left eye	-45,+45 degrees				eye looking frontal
Left eye vergence	-45,+45	-	+/-45°	-35, +35	frontal
Right eye vergence	-45,+45	-	+/-45°	-35, +35	frontal
Eye tilt (common?)	-45,+45	-	+/-45°- +/-45°	-25(up),+35(down)	horizontal
Neck pan	-90,+90	-60,+60	+/-180°	-60,+60	midsagittal plane
Neck tilt	-80,+90	-15,+60	+60°/-30	-60,+90 (including partial rotation of the spine of 60deg)	vertical
Nect roll	-45,+45	-	+/-45°	-54,+54	midsagittal plane

Arm X2

Name	Range of motion (°)	Range for the HOAP2 humanoid (3)	Latest DSIT/TLR realization (3)	Human (3)	Zero (of the range)
Shoulder 1 / Twist	-90,+90	-91,+91	+/-90° main roll	-54, 127 (reference is the forearm pointing upwards)	Along the body
Shoulder 2 / Left-Right	-50,+230	-1,+96	-50/+230	-8, +200	Along the body
Shoulder 3 / Front-Back	-90,+150	-91,+151	+/-90°2nd roll	-85, +199.5	Along the body
Elbow	0, +140	-115,+1	+135°/0°	0, +160.5	Along the body
Wrist 1 / Front-Back	-90,+90	-	+/-45° roll	-90, +90	Aligned with the arm
Wrist 2	-90,+90	-	+/-90° pitch	-87.5, +89.5	Aligned with the arm
Wrist 3	-30,+30	-	+30°/-15° yaw	-36.5, +37	Aligned with the arm

Hand X2 (*)

(*) We are considering 9 degrees of freedom for the hands, including 3 for the thumb, 2 for the index finger, 2 middle finger, 1 for the last two fingers, and 1 for the adbuction of all the fingers (coupled)

Name	Range of motion (°)	Range for the HOAP2 humanoid (3)	Latest DSIT/TLR realization (3)	Human (3)	Zero (of the range)
Thumb 1	0, +90		0/90° opposition		flat hand/thumb ortho to palm
Thumb 2	0, +90		0/90°		proximal
Thumb 3	0, +90		0/90°		distal and intermediate
Index 1	0, +90		0/90°		proximal
Index 2	0, +90		0/90°		distal and intermediate
Middle 1	0, +90		0/90°		proximal
Middle 2	0, +90		0/90°		distal and intermediate
Ring+little 1	0, +90		?		
Adbuction	0, +30		30°		middle straight/ oth, symmetric with respect to middle

Spine

Name	Range of motion (°)	Range for the HOAP2 humanoid (3)	Latest DSIT/TLR realization (3)	Human (3)	Zero (of the range)
Spine pan	-90,+90	-		-35, +35	Standing
Spine tilt	-10,+90	-3,+90		-30, +70	Standing
Spine roll	-60,+60	-		-40, +40	Standing

Leg X2

Name	Range of motion (°)				Zero (of the range)
Hip 1 / Twist	-91,+31	-91,+31		-43.5, +45.5 (external)	Standing
Hip 2 / Left-Right	-31,+45	-31,+21		-40, +45 (external)	Standing
Hip 3 / Front-Back	-120,+45	-82,+71		-45, +147	Standing
Knee	0,+130	-1,+130		0, +127.5	Standing
Ankle 1 / Front – Back	-60,+90	-61,+61		-51.5, +34 (upward)	Standing
Ankle 2 / Left-Right	-25,+25	-25,+25		-44.5, +58 (external)	Standing
Joint not included in current plan				-34, +36.5 (ankle rotation)	Standing

Table 2: List of joints and type of feedback.

Head

Name (1)	Feedback signal/type	Other sensors
Left eye	incremental encoder 5V open collector	None
Left eye vergence	Encoder	
Right eye vergence	Encoder	
Eye tilt (common?)	Encoder	
Neck pan	Encoder + potentiometer	Torque and temperature
Neck tilt	Encoder + potentiometer	Torque and temperature
Nect roll	Encoder + potentiometer	Torque and temperature

Arm X2

Name	Feedback signal/type	Other sensors
Shoulder 1	Encoder + potentiometer	Torque and temperature
Shoulder 2	Encoder + potentiometer	Torque and temperature
Shoulder 3	Encoder + potentiometer	Torque and temperature
Elbow	Encoder + potentiometer	Torque and temperature
Wrist 1	Encoder	Torque
Wrist 2	Encoder	Torque
Wrist 3	Encoder	Torque

Hand X2

Name	Feedback signal/type	Other sensors
Thumb 1	Encoder or hall effect sens.	Torque
Thumb 2	Encoder or hall effect sens.	Torque
Thumb 3	Encoder or hall effect sens.	Torque
Index 1	Encoder or hall effect sens.	Torque
Index 2	Encoder or hall effect sens.	Torque
Middle 1	Encoder or hall effect sens.	Torque
Middle 2	Encoder or hall effect sens.	Torque
Index+little 1	Encoder or hall effect sens.	Torque
Adbuction	Encoder or hall effect sens.	Torque

Spine

Name	Feedback signal/type	Other sensors
Spine pan	Encoder + potentiometer	Torque, temperature
Spine tilt	Encoder + potentiometer	Torque, temperature
Spine roll	Encoder + potentiometer	Torque, temperature

Leg X2

Name	Feedback signal/type	Other sensors
Hip 1	Encoder + potentiometer	Torque, temperature
Hip 2	Encoder + potentiometer	Torque, temperature
Hip 3	Encoder + potentiometer	Torque, temperature
Knee	Encoder + potentiometer	Torque, temperature
Ankle 1		
Ankle 2		

Finally, for each joint we have to consider the type of actuation (DC or brushless DC) taking into consideration the complexity of the driving electronics, speed, torque, etc. The range of movement is specified for each joint according to the two previous tables. The column to be considered as *requirements* is the first from the left. Next to it, comparison values are reported (including human values where available).

3 Dynamics

The next step of the design of the iCub requires taking into account masses, forces & torques, and starting to consider the dynamics of the robot in action. The dimensioning of the motors will follow from this activity. The first number we need is the distribution of the mass of the robot. It has been defined starting from our experience with previous designs. A reasonable estimate of what can be achieved with current actuation technology and materials falls in the range of the 20Kg. The maximum weight allowed is 23Kg divided as per the next table (which includes the length of the body segments as used in the simulation).

Table 3: Mass distribution and main body segments size.

Body part	Mass (Kg)	Length (m)
Arm	1.15	0.15
Forearm (includes thehand)	1.25	0.13
Tight	1.5	0.17
Leg (lower part)	1.5	0.17
Ankle – foot	0.5	
Upper torso	3.75	0.12
Lower torso	6.5	0.12
Head	1.5	

We then performed a simulation of crawling using the Webots platform, which in turn uses ODE – a dynamical simulator. The aim of the simulation is to obtain values of the torques at the various joints both in static and dynamic situations. The static values were also cross checked through more traditional calculations and they were in very good agreement with the results of the simulation. Clearly, many factors impact on the torque values including the crawling strategy, and the simulation might not be guaranteed to be perfect. Nonetheless, these numbers, and their verification in the static case, are a good basis to start the design of the robot.

For the simulation, as ODE does not implement a PID controller but uses some approximation to control motors, we had to implement our own PID to control the simulated motors of the iCub. We made some basic experiments with simple movements to make sure the torque values were consistent with theoretical values. Subsequently, we measured the torque generated by the PID during crawling and also while doing some simple push-up like movements on the arms.

3.1 Simple simulation

In a first experiment, we generated a simple sinusoidal motion of the shoulder in a world without gravity (*g=0*) and compared the torques generated by our PID with the theoretical torques needed to generate such a movement. We control the angle of the front-back DOF of the shoulder with the input *0.4 sin(π t)*. Results are shown in Figure 2 below.

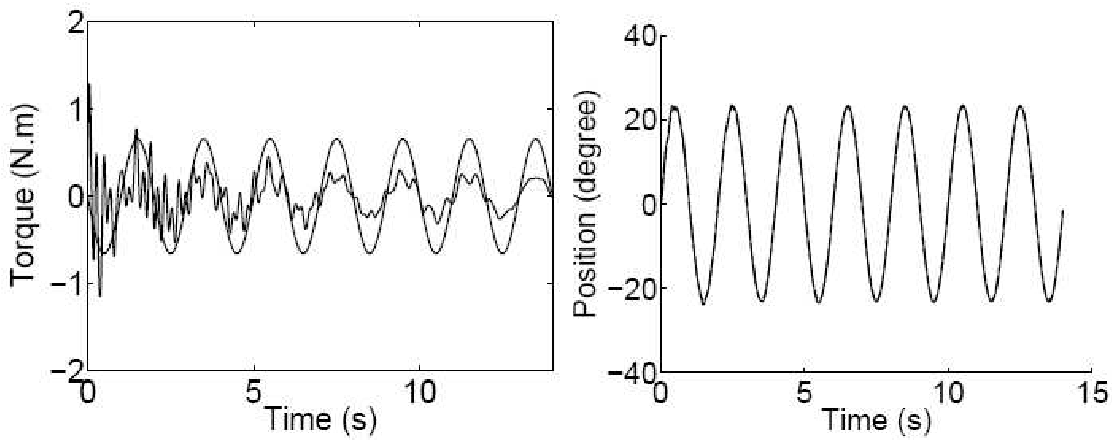


Figure 2: Torque applied to control the arm (left) and position of the arm (right). The right display contains both real position of the arm and of the desired position (input of the PID), we clearly see that they match very well (since we cannot distinguish them).

3.2 Push-ups

The goal of this experiment was to better characterise the range of torque needed by the arms to support the whole body. In this case, only the elbow and left-right arm are moving, following a sinusoidal trajectory (for the angle), *0.3 sin(2 π t)* for the 4 dofs. All the other dofs just have to maintain their initial position. The error of positioning is less than 1 degree for each dof. The followed trajectory is similar to the one in Figure 2. The maximum torque is given in the following table and characteristic plots are shown in Figure 3.

Table 4: Simulated torques during push-ups.

Joint	Torque (Nm)
Left arm 1	8.9
Left arm 2	19.5
Left arm 3	7.3
Left elbow	12.5
Torso 1	6.3
Torso 2	2.3
Torso 3	3.9
Left leg 1	10.8
Left leg 2	3.1
Left leg 3	2.5
Left knee	3.7
Left ankle	0.2

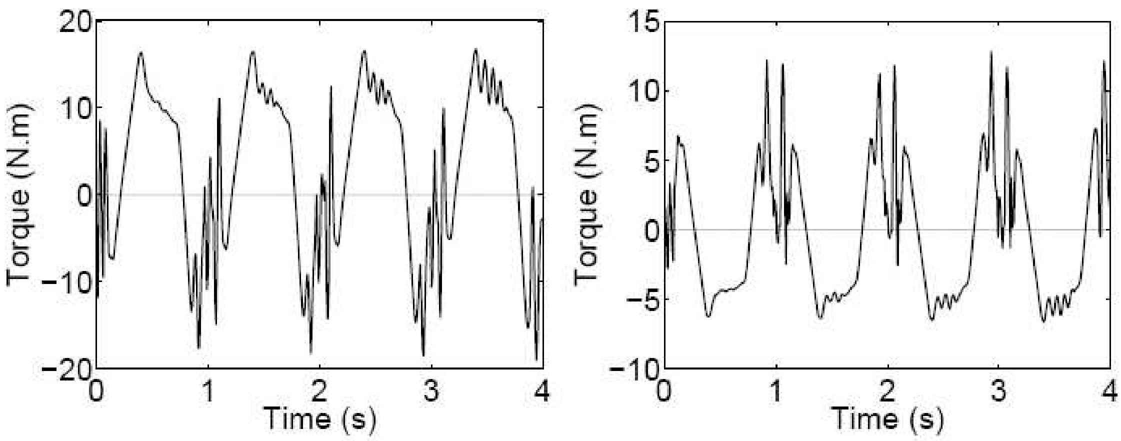


Figure 3: The left plot shows the torque applied to control the "left arm 2" joint.The right figure is a plot of the torque applied to control the left elbow.

3.3 Crawling results

The final experiment is about crawling; we measured the torques at each joint, for a 1Hz and 0.5Hz crawling. In this crawling motion, only the front-back dofs of the arms and legs, the knees and the elbows have sinusoidal reference trajectories. The other dofs just have to maintain the initial angle. The period and phase of the reference trajectories was manually tuned to actually generate a suitable crawling behaviour. Results are collected in the three tables below.

Table 5: Speed and acceleration while crawling.

	0.5Hz crawling		1Hz crawling	
Joint name	Max speed (*rad.s*$^{-1}$)	Max acceler (*rad.s*$^{-2}$)	Max speed (*rad.s*$^{-1}$)	Max acceler (*rad.s*$^{-2}$)
Right leg 1	1.25	3.94	2.51	15.79
Right knee	0.72	2.27	1.44	9.08
Right arm 1	1.25	3.94	2.51	15.79
Right elbow	1.57	4.93	3.14	19.73

Table 6: Torques for 1Hz crawling.

1Hz crawling	
Joint	Maximum torque (Nm)
Left arm 1	48.4
Left arm 2	45.6
Left arm 3	10.9
Left elbow	45.8
Torso 1	45.8
Torso 2	27.2
Torso 3	30.1
Left leg 1	46.3
Left leg 2	37.1
Left leg 3	36.8

Left knee	27.4
Left ankle	12.4

Table 7: Torques for the simulated crawling at 0.5Hz.

0.5Hz crawling	
Joint	Maximum torque (Nm)
Left arm 1	40.4
Left arm 2	18.1
Left arm 3	7.9
Left elbow	18.6
Torso 1	34.3
Torso 2	26.5
Torso 3	13.7
Left leg 1	38.5
Left leg 2	15.1
Left leg 3	23.2
Left knee	28.0
Left ankle	11.3

The maximum errors of angle are of the order of 3 degrees, except for the torso, where errors can reach 5 degrees. It is to be noted that these numbers are specific to the crawling control/strategy adopted, while it seems plausible that the optimization of the controller would reduce the requirements at least for dynamic tasks. On the other hand, the static case still requires torques at the shoulder in the order of 40Nm, which we are taking as a reference in the following.

Armed with these numbers, we can look at the best possible motors able to guarantee the required torques, given the speed for crawling at, let's say, 0.5Hz and that possibly fit within the dimensions provided by the CAD model of the robot (i.e. the two and a half year old child). We proceeded again by drawing from the consortium experience with designing robots. In particular, we analyzed various brands and gearboxes in combination. The most critical joints are those of the shoulder; the requirement of about 40Nm is very demanding especially for the gearbox. In fact, at the shoulder, the power requirement is in the order of 450W per motor. The issue of the total weight of the robot is also important, since typically, power comes at the cost of bulkier actuators. The following table shows a comparison chart for different gearboxes.

Table 8: Comparison table of gearboxes.

D	BRAND	Nom torque (Nm)	Peak torque (Nm)	ratio range	lenght range (mm)	backlash	weight (g)	notes	
20	FAULHABER	.5	.7	3.71:1-1526:1	18:38	<1°	28:68		
20	HARMONIC DRIVE	.3	.55	50:1-100:1	20	<4'	30		
22	MAXON	2	3	3.8:1-3189:1	25.4-52.6	<1°	42.94		
22	GYSIN	1.5	3	4:1-343:1	23:37	<30'	50:100		
32	FAULHABER	7	10	3.71:1-1526:1	34:65	<1°	160:300		
32	HARMONIC DRIVE	2	2.7	50:1-100:1	40	<2'	120		
32	MAXON	6	7.5	3.71:1-4380:1	26.4:56.4	<1°	118:258		
32	**GYSIN**	**6**	**12**	**2:1-512:1**	**32:50**	**<15'**	**135:250**		
35	MIJNO	5.4	8.4	3:1-49:1	30:41	<20'	200:300	MRC110	
Actual index motor benchmark									
D	BRAND	model	ratio	out. torque nom (mNm)	out. torque max (mNm)	radial load (N)	out speed (rpm)	efficency	lenght (mm)
16	FAULHABER	15/5+1516	141:1	46.53	59.5584	25	35.46	.66	37.3
14	**FAULHABER**	**14/1+1319**	**66:1**	**60.06**	**133.98**	**20**	**75.75**	**0.7**	**44.9**
13	MAXON	GP13A+RE13	67:1	63.8175	80.9025	16	119.5	0.75	50.2
13	MAXON	GP13A+REmax13	*67:1*	*69.479*	*96.815*	*12*	*470.6*	*0.85*	*49.3*

Eventually, especially because of the total weight, the choice fell onto the Harmonic Drive gearbox. They are very compact, lightweight, and can be purchased without the enclosure (housing), which can save some additional weight and space. On the actuator proper side, we compared the most common solutions of DC motors, but eventually we had to resort to the Kollmorgen (http://www.danahermotion.com) motors, also, without housing. Then, by designing the package, it is possible to mount the motor and Harmonic Drive gearbox in an approximate cylinder of about 60mm in diameter and 50mm in length (not counting the motor shaft and pulley). This is the basic module, now under testing, on which we are basing the design of the major joints of the iCub.

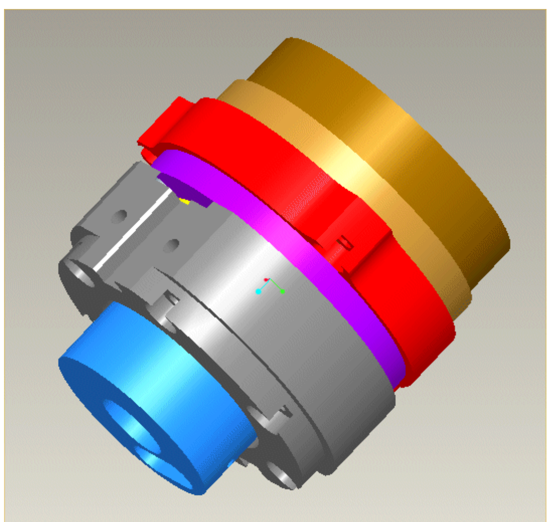


Figure 4: The Kollmorgen motor and Harmonic Drive gearbox.

4 Choices: how the design is coming along

We have already discussed the choice of the motors. The following excerpt from the Kollmorgen catalogue gives an idea of one of the motors we considering in our design.

Winding Constants	Symbols	Units	A	B	C	A	B	C	A	B	C	A	B	C
Current at Cont. Torque	Ic	Amps	5.41	3.89	6.95	5.81	3.63	9.06	5.42	3.38	8.45	5.77	4.00	8.88
Current at Peak Torque	Ip	Amps	15.0	10.6	18.9	20.0	10.6	26.8	20.0	10.6	26.8	22.5	13.4	30.1
Torque Sensitivity	Kt	oz-in/Amp	3.34	4.64	2.60	5.80	9.30	3.72	8.49	13.6	5.45	10.0	14.5	6.50
		N-m/Amp	0.0236	0.0328	0.0183	0.0410	0.0657	0.0263	0.0600	0.0962	0.0385	0.0707	0.102	0.0459
Back EMF constant	Kb	V/KRPM	2.47	3.43	1.92	4.29	6.88	2.75	6.28	10.1	4.03	7.41	10.7	4.81
Motor Resistance	Rm	Ohms	0.698	1.38	0.431	0.664	1.75	0.276	0.803	2.11	0.334	0.733	1.55	0.307
Motor Inductance	Lm	mH	0.280	0.54	0.17	0.32	0.83	0.13	0.44	1.1	0.18	0.47	0.97	0.20

*Rth assumes a housed motor mounted to a 4.0" x 3.75" x 0.25" aluminum heatsink or equivalent

In particular, note the current consumption of the second motor type RBE01211 which for the winding type B gives currents in the order of 10.6A, in our case with 48V supply and a maximum torque of about 0.4Nm at a maximum speed of 4000rpm. Coupled with the Harmonic Drive, which provides a reduction ratio of 1:100, we obtain the 40Nm required by the dynamic/static analysis on the crawling behaviour. It is worth noting again that crawling seems to be the worst case scenario for the iCub, involving in fact a strong interaction with the environment and possibly high impact forces. The Kollmorgen motors are brushless DC thus requiring tri-phase control signals which are going to be generated by a suitable DSP based microcontroller. The packaging we have chosen does not leave much room for an encoder. Luckily, the brushless motor is already equipped with digital Hall-effect sensors that are used by the controller for driving the commutation of the phases. The same signals can be used as an incremental encoder. The resolution for the motor we consider is of 24 impulses per turn which gives a resolution of 0.15 degrees on the position feedback only slightly higher than the required precision (0.1 according to the specifications). It is still to be determined whether electronic 2X or 4X circuits could be applied in this case.
For the brushless motors we are planning to include the temperature sensors as discussed earlier. The sensor will be directly mounted inside the enclosure.

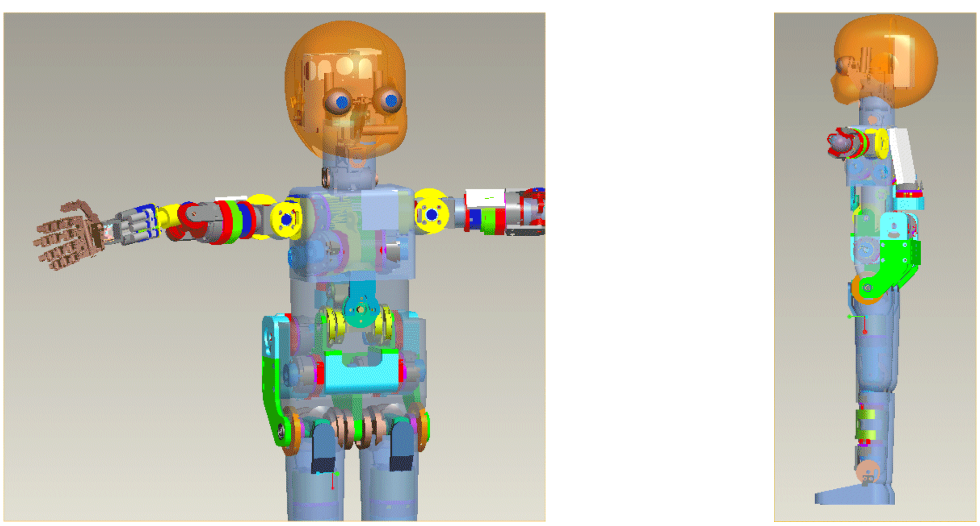
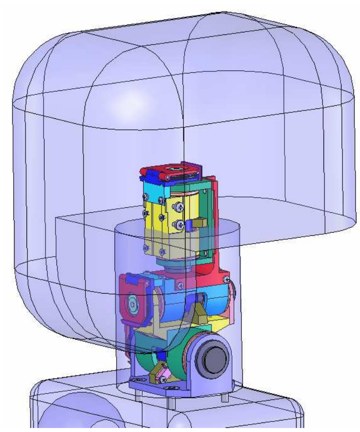


Figure 5: CAD drawing of the latest iCub.

For smaller joints, such as the wrist and the fingers, the brushless motors are out of question because of their size and the complexity of the control electronics. We chose instead to employ the Faulhaber/Minimotor with their standard gearbox and encoders. The Faulhaber motors are very standard DC micro-motors and the consortium has a very long experience in developing solutions using them. Motors here range from the 8mm for the thumb opposition and abduction/adduction, to the 17mm in the neck. The controller in this case is also much simpler (single phase), which helps in fitting several of them inside the robot.

The current design uses 23 brushless motors in the arms, legs, and the waist joints. The remaining 30 degrees of freedom are controlled by the Faulhaber DC motors. Most of the joints are tendon driven, some are direct, according to the placement of the actuators which is sort of constrained by the shape of the body. A comprehensive picture of the latest design is shown in Figure 5.

The head is based completely on the Faulhaber type motors. The neck (3 dof) consists of a serial kinematic chain, with the three degrees of freedom, placed in a configuration that best represents human movements. For driving this mechanism, DC micromotors (Faulhaber) with planetary gearheads have been used. An initial prototype is already built, tested, and demonstrated in a light tracking experiment. It is important to say that, in spite its simplicity, the mechanism is very robust, easy to control and has high performances, meeting all the desired specifications. Each joint uses an overload clutch system (Figure 6) that increases the robustness of the mechanism, by absorbing (by sliding) different kind of impacts and efforts during its interaction with the external world.



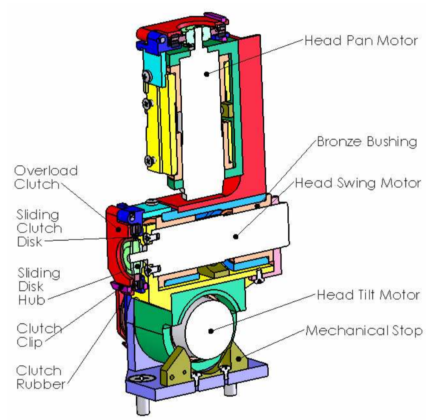


Figure 6: The neck mechanism.

The eyes mechanism has also a total of three degrees of freedom. Both eyes can pan (independently) and tilt (simultaneously). The pan movement is driven by a belt system, with the 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 different components weight, given by the CAD software.

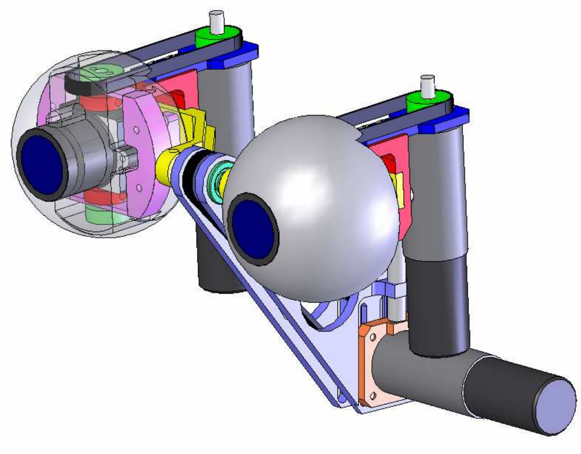


Figure 7: The eye assembly.

The shoulders were designed from the Kollmorgen motor assembly described earlier. A single aluminium block contains the three motors required for each shoulder. The joint is tendon driven; the motors do not move with respect to each other. The following pictures (Figure 8) show the arrangement of this module. The shoulder is a roll-pitch-roll configuration. The motor group and the orientation of the joint has been designed at an angle with respect to the front-back midline to position the range of motion as frontal as possible which clearly enhances the manipulation workspace of the arms.

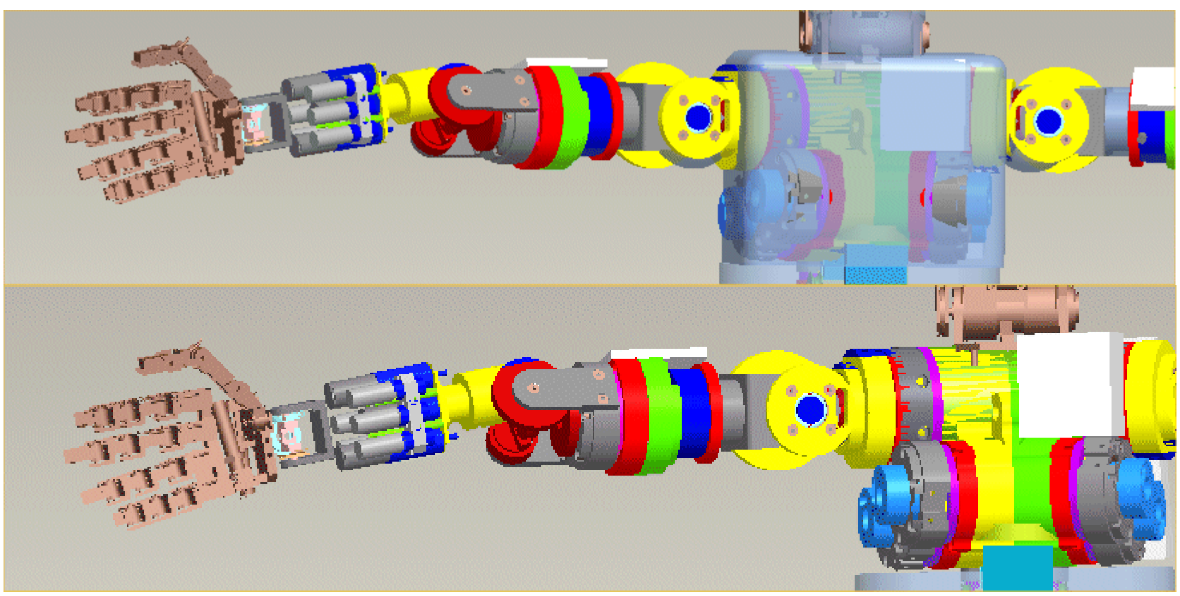


Figure 8: One of the latest design of the arm subsystem with and without the external shell.

The elbow is driven by another Kollmorgen motor 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 (estimated in 120 degrees in this realization). The space along the axis of the elbow is 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. The wrist is hollow so that it can house the tendons actuating the fingers. Finally two motors are mounted inside the palm.
The waist joint (3 degrees of freedom) and the legs are designed with the Kollmorgen actuators which make the whole design very uniform. Only two brands of motors are employed: the Kollmorgen in the brushless version and the Faulhaber in the DC version. The following Figure 9 shows the waist and legs design.

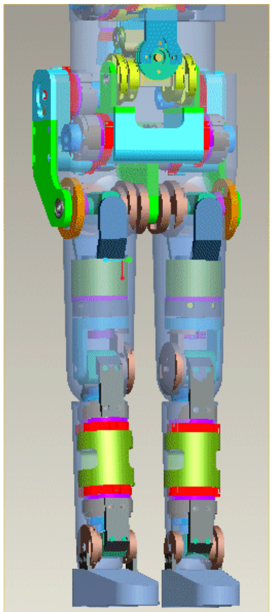


Figure 9: Latest design of the legs.

The design strategy seems to be converging at this stage of the project. The legs are conceptually similar to the shoulders and arms (apart from the evident simplification). The legs are 6 dof each. The first 3 dof are allocated at the hip joint, 2 motors per leg are placed in the lower body; the third motor is located inside the tight. The knee and ankle motors are, at the moment, located both in the lower leg. The foot design is still to be completed (1 dof).

This section in practice contains all the information required for drawing the kinematics of the robot. We are planning to improve the simulation including kinematic constraints and singularity to make sure the planned skills are not hampered by an incorrect placement of the axes. Also, the range of movement and especially the manipulation workspace will be checked carefully. It is to be reminded that the overall size of the robot, in many respects, does not leave options available to the designer.

Although not yet included in the design, we are evaluating the inclusion of weak points and clutches where possible to protect the robot from over-shocks that might damage either the gearboxes or the sensors. Given the available space, the solution to be preferred seems to be that of the weak points. The neck includes a first prototype of a clutch system. The possibility of reducing the gear ratio of the Harmonic Drive gearboxes is being considered. In particular, since the performance of the brushless motors can be increased by improving the cooling system, in a next release of the robot we could increase the driving voltage and pull more torque out of the Kollmorgen, bringing simultaneously the gear ratio down to 50 or 33 (now it is foreseen to be 100). This will increase backdriveability of the main joints of the iCub. The drawback is the requirement of voltages higher than 48V, which require a different set of specifications and standards. Also, safety of operation would need to be considered.

5 Electronics

The electronics of the iCub will be mostly embedded for what concerns the control and the sensory data acquisition. The interface between the iCub and the outside controller will happen through a Gbit Ethernet cable and a power cable. The robot will contain the amplifiers, the DSP controllers, a PC104 acquisition card based on a Pentium processor, and the sensors' acquisition and control electronics. Sensory data and motor commands will eventually travel on the Ethernet connection. A rough sketch of the iCub hardware is shown below in Figure 10.

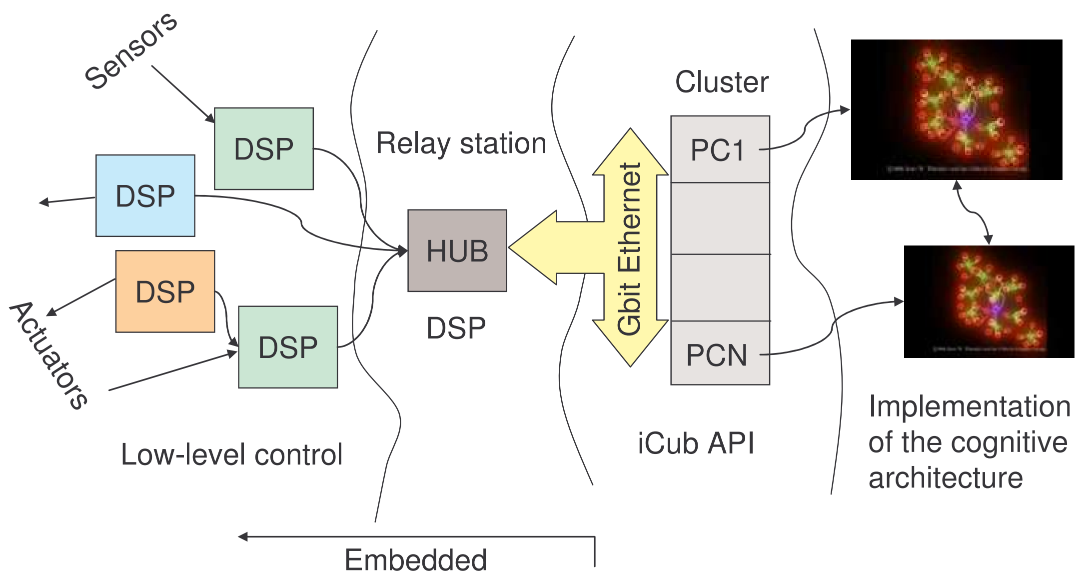


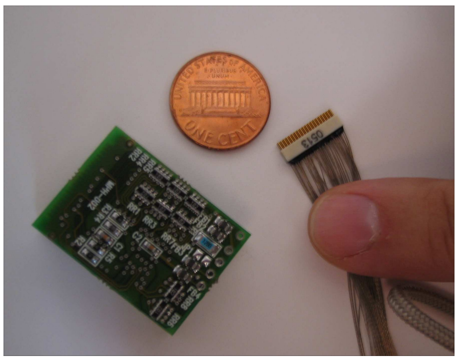
Figure 10: Levels of the hardware of the iCub.

The low level control contains two types of card for the brushless and the DC motors respectively. Both are likely to be based on the same CPU (a DSP). Other cards might be employed to digitize sensory data locally to be subsequently sent to the relay station. In the latest evaluation, the HUB is going to be a PC104 processor card with some additional custom hardware for the data acquisition. The PC104 processor will take care of preparing the IP packets for communicating with the external world. We believe that a cluster of PC will be employed for the implementation of the RobotCub cognitive architecture.

The controller for the Kollmorgen motors will take most of the empty space of the robot because of the high currents required (10A, 48V). A heat sink is likely to be required and will probably be incorporated on the iCub chassis. The Faulhaber motors employed so far are all with maximum current below 0.5A, 12/24V which is very convenient to contain the size of the amplifier. Capacitors will be included where needed to allow the rapid transients that might be required by the robot. In addition, AD cards are foreseen in various places, for example in the hand, to read the position and tactile sensors. These cards will be connected to the iCub multiple CAN bus structure.

The design of the electronics will start now with the requirements derived from the motor specifications (e.g. maximum current, voltage, etc.). Particular care will be made to minimize the size of the electronics. Special small connectors might be used.

The following Figure 11 shows examples of the cards we have realized for other similar robotic platforms.



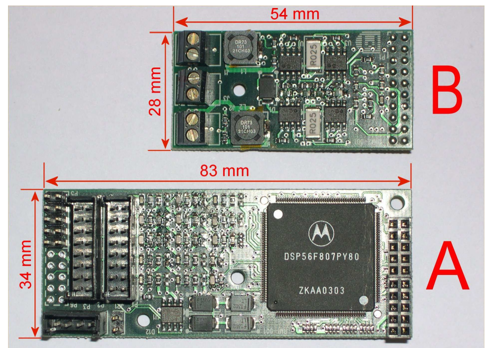


Figure 11: Left, ADC card. Right, motor controller card (A processor card, B amplifier card).

The size available for controllers, DSP and amplifiers is:

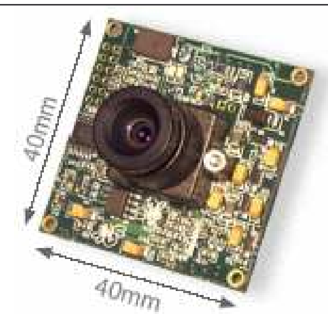
- 55x69x15mm: brushless amplifier
- 48x52x25mm: DSP cards (2X)
- 50x30x5mm: DC controllers (including DSP)

6 Sensors

Given the size mostly of the iCub, sensors are being evaluated for performance but also weight, easiness of interface, etc. The following subsections contain a list of possible components that, at the moment of writing, are under evaluation for inclusion in the iCub final design. We are considering several alternatives when available.

6.1 Camera System

Cameras Specifications	
Dragonfly	**Firefly 2**
Imaging Device	
1/3'' Sony CCD 640x480 Option: ICX084, B&W or Color 1024x768 Option: ICX204, B&W or Color HAD image sensor with square pixels Progressive scan	1/4'' Sony CCD (ICX098AK) Color VGA 640x480 format HAD image sensor with square pixels Progressive scan

Supported frame rates:	
640x480 Option: 30, 15, 7.5, 3.75 FPS 1024x768 Option: 15, 7.5, 3.75, 1.875 FPS	3.75, 7.5, 15 & 30 FPS
Signal to noise ratio:	
> 60dB	>40dB
Supported formats	
B&W models: 8-bit or 16-bit Mono Color models: 8-bit or 16-bit Bayer tiled image (color space conversion done on the host computer)	YUV 4:1:1, YUV 4:2:2, YUV 4:4:4, and RGB 24-bit
Synchronization: < 120µs	
Dimensions	
64 X 51mm	40 x 40mm
	

A Dragonfly2 camera has recently been released by PointGrey.

6.2 Microphones

Model	**Shure – Model MX183**	**RS – Model 242-8911**
Type	Condenser (electret bias)	Condenser (electret bias)
Frequency Response	50 to 17,000 Hz	de 50Hz a 16kHz
Polar Pattern	Omnidirectional	Omnidirectional
Open Circuit Sensitivity (at 1 kHz, ref. 1V/Pascal*)	–27.5 dB (42.2 mV)	-65dB +-3dB
Max SPL (1kHz at 1%THD, 1 kΩ load	116.7 dB	not specified
Equivalent Output Noise (A-weighted)	20.5 dB	not specified
Signal to Noise Ratio (referenced at 94 dB SPL)	73.5 dB	not specified
Power Requirements:	11 to 52 Vdc phantom, 2.0 mA	1,5 Vdc
Output Impedance	180Ω	1.000Ω
Dimension	12 x 22 mm	8×18mm

Observation: The microphone Shure MX183 will probably be the final choice due to its superior specifications and in spite of its higher cost.

6.3 Inertial sensor

	Xsens MTi				InterSense InertiaCube 2			
	Output				**Output**			
	3D orientation (Quaternions/Matrix/Euler angles)				3D orientation			
	3D acceleration				------			
	3D rate-of-turn				3D rate-of-turn			
	3D earth-magnetic field (normalized)				------			
	Temperature				------			
	Orientation performance				**Orientation performance**			
Dynamic Range:	all angles in 3D				all angles in 3D			
Angular Resolution[1]:	0.05 deg				0.01deg(Enhancement filter off=0) 0.05(Enhancement filter full=2)			
Static Accuracy (Roll/Pitch):	<0.5 deg				1 deg RMS			
Static Accuracy[2] (Heading):	<1 deg				1 deg RMS			
Dynamic Accuracy[3]:	2 deg RMS				3 deg RMS			
	Sensor performance				**Sensor performance**			
	rate of turn	**acceleration**	**magnetic field**	**temperature**	**rate of turn**	**acceleration**	**magnetic field**	**temperature**
Dimensions	3 axes	3 axes	3 axes	-	3 axes			
Full Scale (standard)	± 300 deg/s	± 17 m/s^2	± 750 mGauss	-55...+125 °C	1200 deg/s			
Linearity	0.1% of FS	0.2% of FS	0.2% of FS	<1% of FS				
Bias stability4 (1σ)	5 deg/s	0.02 m/s^2	0.5 mGauss	0.5 °C accuracy				
Scale Factor stability4 (1σ)	-	0.0005	0.005	-				
Noise density	0.1deg/s/√Hz	0.001 $m/s^2/\sqrt{Hz}$	0.5 mGauss (1σ)	-				
Alignment error	0.1 deg	0.1 deg	0.1 deg	-				
Bandwidth (standard)	40 Hz	30 Hz	10 Hz	-				
	Options				**Options**			
Full Scale	± 150 deg/s	± 100 m/s^2	-	-				
	± 900 deg/s		-	-				
	± 1200 deg/s		-	-				
	Interfacing				**Interfacing**			
Max update rate:	512 Hz (calibrated sensor data) 100 Hz (orientation data)				180 Hz			
Digital interface:	RS-232, RS-422 and USB (external converter)				RS-232 and USB (external converter)			
Analog interface (optional):	0 - 3.3V (Roll, Pitch, Heading)				-----			
Operating voltage:	4.5 - 15Vdc				6 Vdc			
Power consumption:	360 mW (orientation output)				600mW			
	Housing				**Housing**			
Dimensions:	58x58x22 mm (WxLxH)				29x25x34 mm (WxLxH)			
Weight:	50 g				25g			
Ambient temperature operating range:	0 - 55 deg Celsius				0 – 50 deg Celsius			
Obs.	1- 1σ standard deviation of zero-mean angular random walk 2- in homogenous magnetic environment 3- may depend on type of motion 4- deviation over operating temperature range (1σ) specifications subject to change without notice							
								

O sensor Xsens MTI tem grandes vantagens em relação ao Inertia Cube 2. Entre elas podemos destacar:
1 - Maior número de dados de saída;
2 - Software aberto
3 - Saída analógica
Os fatores negativos do Xsens, são o tamanho e peso, mas esses fatores podem ser contornados em nosso projecto.

6.4 Force-torque sensors

We are evaluating the ATI-Mini45 for inclusion in the arms and legs (http://www.ati-ia.com).

Product Advantages

One of the Smallest 6-axis Sensors in the World: The Mini45 has a compact, low-profile design with a through-hole to allow passage of linkages or cables.

Extremely High Strength:

- EDM wire-cut from high yield-strength stainless steel.
- Maximum allowable overload values are 5.4 to 23 times rated capacities.

High Signal-to-Noise Ratio: Silicon strain gauges provide a signal 75 times stronger than conventional foil gauges. This signal is amplified, resulting in near-zero noise distortion.

The Mini45 F/T transducer
The transducer is made of hardened stainless steel with integral interface plates made from high-strength aircraft aluminum.

Typical Applications

- Telerobotics
- Robotic hand research
- Robotic surgery
- Finger-force research

English Calibrations

SENSING RANGES Axes	Calibrations US-30-40	US-60-80	US-120-60
Fx, Fy (±lbf)	30	60	120
Fz (±lbf)	60	120	240
Tx, Ty (±lbf-in)	40	80	160
Tz (±lbf-in)	40	80	160

RESOLUTION	System Type*					
Axes	CON	DAQ	CON	DAQ	CON	DAQ
Fx, Fy (lbf)	1/40	1/320	1/20	1/160	1/20	1/160
Fz (lbf)	1/40	1/320	1/20	1/160	1/10	1/80
Tx, Ty (lbf-in)	1/44	1/352	1/44	1/352	1/22	1/176
Tz (lbf-in)	1/88	1/704	1/44	1/352	1/22	1/176

Metric Calibrations

SENSING RANGES Axes	Calibrations SI-145-5	SI-290-10	SI-580-20
Fx, Fy (±N)	145	290	580
Fz (±N)	290	580	1160
Tx, Ty (±Nm)	5	10	20
Tz (±Nm)	5	10	20

RESOLUTION	System Type*					
Axes	CON	DAQ	CON	DAQ	CON	DAQ
Fx, Fy (N)	1/8	1/64	1/4	1/32	1/2	1/16
Fz (N)	1/8	1/64	1/4	1/32	1/2	1/16
Tx, Ty (Nm)	1/376	1/3008	1/188	1/1504	1/94	1/752
Tz (Nm)	1/752	1/6016	1/376	1/3008	1/188	1/1504

Contact ATI for complex loading information. Resolutions are typical. All Sensors calibrated by ATI. *CON: Controller F/T System, DAQ: 16-bit DAQ F/T System

16 VISIT WWW.ATI-IA.COM FOR CURRENT PRODUCT SPECIFICATIONS, 2-D DRAWINGS, AND 3-D CAD MODELS

Particularly interesting is the maximum overload of 110Nm angular and about 5000N linear.

6.5 Tactile sensors

Various technologies are currently being examined according to the survey presented in Deliverable 7.2.

6.6 Potentiometers

Standard potentiometers will be included (they are not yet in the latest design) to simplify the calibration of the main joints.

6.7 Cable tension measurement

Cable tension measurement will be included according to the prototypes described in Deliverable 7.2.

6.8 Temperature sensors

We are evaluating the inclusion of temperature sensor in the brushless housing. This would be most beneficial if periods of sustained torque are required or if the motors are for any reason under extreme stress in certain body configurations. Standard off-the-shelf components will be employed.

6.9 Other sensors

Other details of the sensors specifications can be found in Deliverable 7.2.

7 Software

As we mentioned in Deliverable 8.2, the iCub software is potentially parallel and distributed. Apart from the interface API that speaks directly to the hardware, the upper layers might require further support libraries. These libraries are known as middleware. We analyzed various alternatives [3] and eventually decided to try following our own version of the middleware called YARP [4]. YARP is open-source and thus suitable for inclusion with the newly developed iCub code. The rationale of this choice lays in the fact that having the source code available and especially well understood could potentially simplify the software integration activity.

To facilitate the integration of code clearly the simplest way would be to lay out a set of standards and ask developers to strictly follow them. In a large research project we should also allow for a certain freedom to developers so that ideas can be tested quickly. These two requirements are somehow conflicting. Especially, they are conflicting when different behaviours are to be integrated into a single system and the integrator is not the first developer.

To allow developers to build upon the already developed behaviours, we plan to layer the software and release packaged behaviours in the form of APIs. The idea is to produce behaviours that can be used without necessarily getting into the details of the middleware code employed. While for lower levels there is no much alternative than following a common middleware approach, higher levels and user level code can be developed by considering a less demanding scenario. In the latter case, we will distribute modules with interfaces specified in an API (possibly a C++ class hierarchy). Internally, each module will unleash a set of YARP processes and threads whose complexity will be hidden within the module. We foresee various levels of configuration. In one case, the given module would be capable of running on a single processor machine. This is a tricky and difficult choice since in many cases the behaviour of the robot relies explicitly on timing, synchronization, and performances of its submodules. Considering that eventually each module is a very specialized controller, issues of real-time and performances have to be carefully evaluated. The modules' APIs will include tests and indications on the computational timing and additional requirements in this respect to facilitate the proper configuration and use.

The following Figure 12 exemplifies the iCub software architecture.

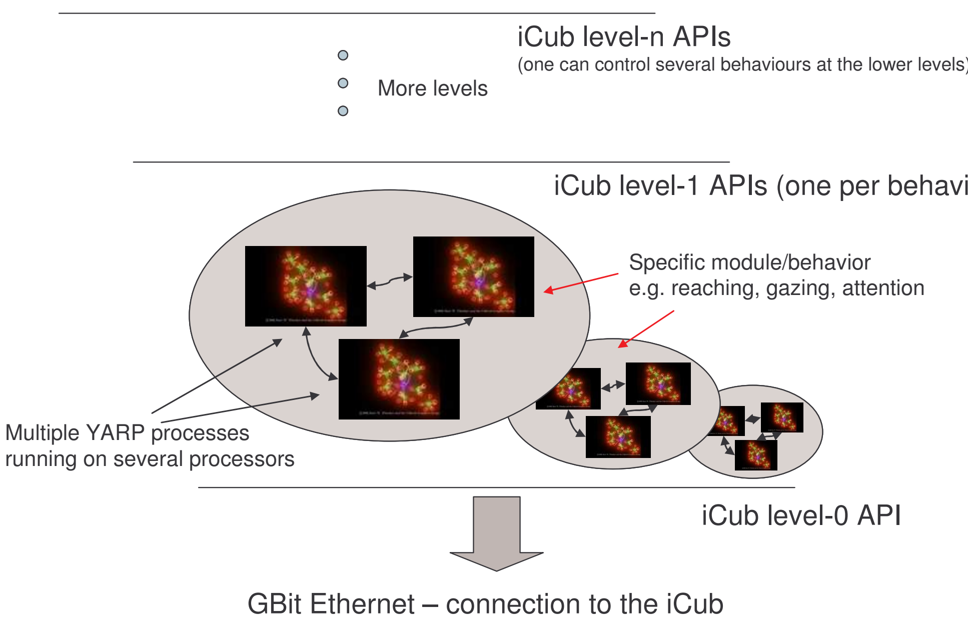


Figure 12: The software architecture of the iCub.

The lowest level of the software architecture consists of the level-0 API which provides the basic control of the iCub hardware by formatting and unformatting IP packets into appropriate classes and data structures. IP packets are sent to the robot via the Gbit Ethernet connection. For software to be compliant to the iCub the only requirement is to use this and only this API. The API will be provided for both Linux and Windows. The iCub behaviours/modules/skills will be developed using YARP to support parallel computation and efficient interprocess communication. YARP is both open source and portable (OS independent) so it fits our requirements in this sense. Each module can be composed of several processes running on several processors.
To shield potential users from this complexity, the access to the modules will be provided through a set of neutral APIs, which do not need to speak YARP. These are noted in Figure 12 by level-1 APIs. A potential user who is content with these modules can run the iCub without fiddling with YARP altogether. Those who need to change or

re-implement one of the modules will either need to learn YARP (whose documentation will be improved to the RobotCub level) or rely on other methods of doing IPC.

To be part of the RobotCub software a module will be checked to comply with both the interface standards (not yet defined) and with the internal standards (in practice YARP). Integration and testing will be then carried out to assure a certain level of functionality on the actual robot in a certain number of situations.
It is then possible to consider multiple levels of software development and level-n APIs that re-use the underlying levels to create even more sophisticated modules. The same rationale of level-1 APIs clearly applies to higher levels.

8 Companion document – Annex I

The Annex I to this deliverable can be retrieved from: http://www.robotcub.org under the path: RobotCub/Administration/Deliverables/D8.1 of the private section of the site.

9 References

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