

Lower Body Design of the Baby Humanoid - ‘iCub’

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Abstract—Nowadays, the understanding of the human cognition and its application to robotic systems forms a great challenge of research. The iCub is a robotic platform that was developed within the RobotCub European project to provide the cognition research community with an open baby-humanoid platform for understanding and development of cognitive systems.

In this paper we present the design requirements and mechanical realization of the lower body developed for the “iCub”. In particular the leg and the waist mechanism adopted for lower body in order to match the size and physical abilities of a 2½ year old human baby are introduced.

I. INTRODUCTION

DURING the last decade the rapidly growing emergence of humanoid robots was mainly due to their potential observed within a number of intrinsic features of these robotic systems. Specific inherent features of this kind of platforms include but not limited to anthropomorphism, friendly design, natural and adaptive locomotion and human friendly behavior. These features make humanoid robots very suitable for prospective applications in all kinds of human environments and daily activities. As a result, multi degree of freedom human like robots have become very common. Following the development of the first humanoid back in 1973 [1] a number of other humanoid platforms in different sizes were developed. The large scale anthropomorphic prototypes include the H6, H7 [2], P2 [3, 4], ASIMO [5], JOHNNIE and LOLA [6-7], WABIAN-2 [8] KHR-2 [9] and LUCY [10], while the HRP, HRP-2 [11, 12], SAIKA [13] and KENTA [14] are examples of medium size humanoid robots. In addition to the above examples of adult or medium sized anthropomorphic robots a number of smaller prototypes have been also constructed including MK.5 [15], PINO [16], the SDR-3X, SDR-4X developed mainly for entertainment [17, 18] and the humanoid-gorilla robot developed by [19].

However, despite the big number of humanoid platforms, at the present time the application of most of these well mechanically developed robots is still limited to the entertainment and amusement applications. This is believed to be due to lack of brainpower capabilities that prohibits these systems to learn and safely interact and cooperate within the human environment. From this rationale the RobotCub project started. The RobotCub concept behind the development of iCub is to provide the cognition research community with an open human like hardware/software platform for understanding of cognitive systems through the study of cognitive development. The iCub has as its aim the

replication of the physical and cognitive abilities of a 2½ year old baby. This “baby” robot will act in a cognitive scenario, performing the tasks useful to learning, interacting with the environment and humans [20]. Based on these requirements the design of the lower body of the iCub was realized. The development of such a structure that aims to have the embodied capacity of a human child poses many significant and important challenges and requires careful design, co-ordination and integration of the various components that form the complete mechatronic structure.

This work reports on the design of the lower body modules for the iCub. The paper is organized as follows: Section II gives the general specifications of the lower body. Sections III and IV describe the mechanical design concepts, the actuation and the sensing adopted for the lower body. Section V concludes with the introduction of characteristic measures of the current design in terms of joint range of motion, and output torque. Finally, section VI addresses the conclusions.

II. LOWER BODY SPECIFICATIONS

Among the most important questions to be addressed when considering the hardware design is the fundamental layout, to enable a natural, stable, robust actions found in the early years development of a child. The kinematic specifications of the lower body of the iCub include the definition of the number of D.O.F required and their actual location as well as the actual size of the legs and lower torso. The size of the iCub will approximate all the dimensions of a two and a half year old child, Fig 1 [20]. For the definition of the number of D.O.F for the legs and the waist joint of the lower body, several iCub simulation models were developed and analysed. For the legs these simulations have indicated that for crawling, sitting and squatting a 5 D.O.F leg is adequate. It was decided though to incorporate an additional D.O.F at the ankle to support not only crawling but also standing (supported and unsupported) and walking, Table I. As different research groups may also be interested in walking and balance research the incorporation of the additional D.O.F to support the ankle lateral motion was considered as an advantage for the iCub in terms of the open platform nature of the system. Therefore, each leg consists of 6 D.O.F: that include 3 D.O.F at the hip, 1 D.O.F at the knee level and 2 D.O.F at the level of the ankle. Despite the fact that the foot rotation was observed in baby subjects to be active during crawling the twist rotation was not implemented at the foot as was found from simulations not necessary for executing crawling motion patterns.

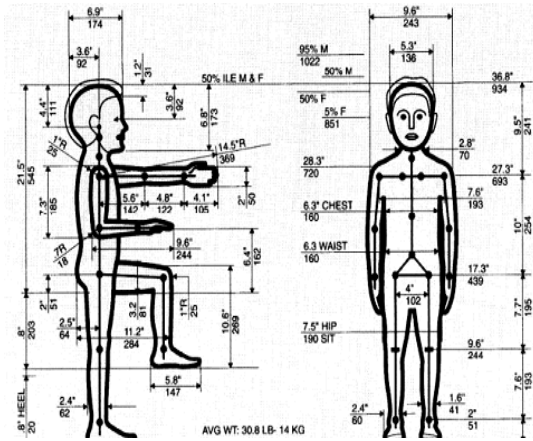


Fig. 1 Size specification for the iCub.

TABLE I
NUMBER OF DOF OF THE LOWER BODY

Degrees of Freedom		
Joint	Human	iCub
LEG		
Hip	3 Flexion/Extension Abduction/Adduction Thigh Rotation	3 Flexion/Extension Abduction/Adduction Thigh Rotation
Knee	1 Flexion/Extension	1 Flexion/Extension
Ankle	3 Flexion/Extension Abduction/Adduction Rotation	2 Flexion/Extension Abduction/Adduction -
		2 x 6DOF = 12DOF
WAIST		
Waist	3 Roll Pitch Yaw	3 Roll Pitch Yaw =3DOF

The D.O.F required for the waist was determined by considering both the crawling and the manipulation prerequisites. Crawling simulation analysis showed that for effective crawling a 3 D.O.F waist is essential.

An additional advantage that a 3 D.O.F waist offers is the increased range and flexibility of motion for the upper body. This increased flexibility results in an amplified workspace for the iCub when performing manipulation tasks using its hands while in a sitting position. As manipulation is directly related to learning which is an essential task for the iCub the 3 D.O.F waist will provide significant benefits. Based on above, the iCub waist needs to provide pitch, roll and yaw in the upper body, Table I.

Regarding the range of motion of the individual joints 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 in the iCub. Table II shows the range of motions specification for the

joints of the lower body in comparison with the corresponding ranges found in a human baby.

Considering Table II, it can be observed that range of motion in some joints has been increased while others are slightly reduced. The range of the waist joints has been extended to increase the manipulation workspace of the baby-like robot while the robot is in a sitting position.

In particular the range of the waist yaw and roll has been increased while the range of the pitch motion was modified to increase the upper body forward tilting to provide improved access to the workspace in front of the robot. This extends the vital space in front of the iCub where it can reach and manipulate objects. In addition, the extended range in the waist allows the waist to act as a range amplification mechanism for the arm motions. After studying simulations of the performance of basic crawling activities and transitions to baby-style sitting positions, the range of motion of the leg joints were also modified to provide enhanced performance. Consequently, the range of motion in some joints of the leg was reduced or increased accordingly.

TABLE II
RANGE OF MOTION OF THE LOWER BODY JOINTS

LEG	Human	iCub
Range of motion (°)		
Hip rotation	-43.5, +45.5	-91,+31
Hip Abduction/Adduction	-40, +45	-31,+45
Hip Flexion/Extension	-147, +45	-120,+45
Knee	0, +127.5	0,+130
Ankle Flexion/Extension	-51.5, +34	-60,+70
Ankle Abduction/Adduction	-44.5, +58	-25,+25
Ankle Twist	-34, +36.5	Not Implemented
WAIST		
Waist roll	-35, +35	-90,+90
Waist pitch	-30, +70	-10,+90
Waist yaw	-40, +40	-60,+60

For the purpose of actuator selection to power the lower body of the iCub various simulations of the robot model were carried out. In these simulations the robot performed crawling motions Fig. 2, with different speeds. Two examples of the simulated joint torque curves corresponding to the hip flexion/extension and the waist pitch joints are shown in Fig. 3 while the peak torque requirements of each joint of the lower body depicted in Table III.

III. LOWER BODY DESIGN

The mechanical realization of the lower body of the iCub baby humanoid robot and an overview of its kinematics with the location of the degrees of freedom is illustrated in Fig. 4. The height of the iCub lower body from the foot to the waist is 611mm, the width of the lower torso from left to the right is 186mm while the depth from front to back is 110mm. The weights of the lower body are as follows: the total weight is 12.7Kg with the weight of each leg being

3.5Kg and the weight of the lower torso including the waist being 5.7Kg.

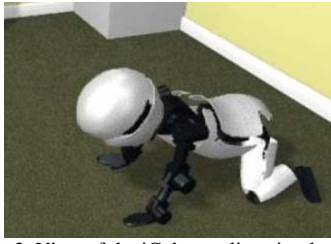


Fig. 2 View of the iCub crawling simulation.

TABLE III
TORQUES REQUIRED FOR THE LOWER BODY

LEG	Torque Required(Nm)
Hip Flexion/Extension	46.3
Hip Abduction/Adduction	37.1
Hip Rotation	36.8
Knee	27.4
Ankle Flexion/Extension	12.4
Ankle Abduction/Adduction	-
WAIST	
Roll	30.1
Pitch	45.8
Yaw	27.2

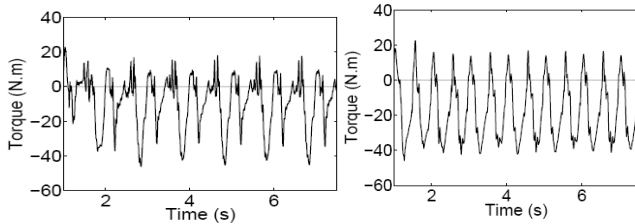


Fig. 3 Typical examples of 1Hz crawling simulation torque curves for the hip flexion/extension and waist pitch joint.

The realisation of the kinematic structure of the iCub's lower body incorporates a number of features that are listed below.

- i) The implementation of the hip joint of iCub and particularly for the hip flexion/extension and abduction/adduction motions is based on a cable differential mechanism to maximize stiffness on this level of the leg.
- ii) Two of three D.O.F in the iCub's waist (pitch, yaw) are also implemented using a cable differential mechanism.
- iii) As a result the increased flexibility of the upper body and the ensuing larger working space of arms due to the 3DOF waist are combined with increased stiffness that is an inherent feature of the differential mechanism also adopted for this joint.



Fig. 4 Kinematic configuration and CAD model of iCub lower body.

IV. ACTUATOR SELECTION AND MECHANICAL MECHANICAL REALIZATION

The actuation principle of most existing humanoid robots is a combination of Harmonic Drive gears and DC brush [6, 9, 10] or brushless motors [5, 7], mostly coupled with secondary gearing using timing belts or cables. This is because this combination meets the requirements of compactness accompanied by a high power to weight ratio.

The selection of the actuator for the lower body of the iCub was steered both from the dimensional and weight prerequisites of the robot as well as the torque requirements as derived from the simulation model of the iCub. Various combinations of motor and gearbox were considered. The solution finally adopted is based on a combination of a harmonic drive reduction system (CSG series, 100:1 ratio for all joints) and a brushless frameless motor (BLM) from the Kollmorgen RBE series. Advantages of harmonic drives include no-backlash, high reduction ratios on small space with low weight while brushless motors exhibits desired properties such as robustness, higher power density, and higher torque and speed bandwidths when compared with conventional DC brushed motors..

The selection of the actuator group of each joint was optimised through several iterations of the mechanical design and further simulation analysis of the revised system. These results provided the guidelines to decide hardware specifications such as type of motor and reduction ratio. To optimize further the size of the actuators, the frameless versions of the Kollmorgen RBE motor series were selected which have certain benefits to the overall design. It enables the integration of the motor and harmonic system within an endoskeleton type structure that minimizes weight and dimensions with the immediate benefit of the freedom in shaping the actuator housing. Three different power actuator groups are used for the lower body. The high power actuator group is capable of delivering 40Nm at the

output shaft which has a diameter of 60mm and a length of 53mm, the medium power motor group provides up to 20Nm with a diameter of 50mm and a length of 48mm, and the low power motor group delivers up to 11Nm with a diameter of 40mm and a length of 82mm.

A. 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. 5.

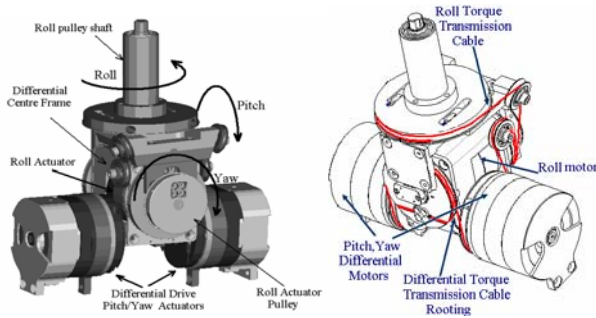


Fig. 5 The compact mechanical design of the differential 3DOF iCub waist.

For the pitch motion of the waist the two high power actuators assemblies (40Nm 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 humanoid 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 through a pulley shaft that is directly connected to the upper body frame. The actuator

assembly of the roll pulley (20Nm) is located within the square centre element of the differential, Fig. 5. 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 III.

B. Leg

For the leg design, particular attention was paid to satisfy the dimensional and weight requirements while at the same time maximizing the range of motion 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, the hip, the knee and the ankle, Fig 6.

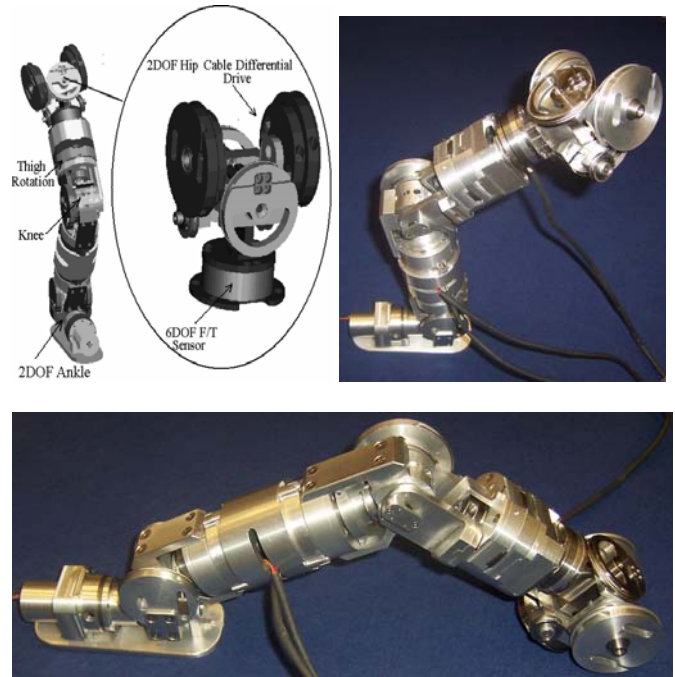


Fig. 6 CAD model and mechanical realization of the iCub leg.

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 (20Nm) located in the lower torso are used to drive the two input pulleys of the differential through a cable transmission system that also provides a secondary (2:1) gear ratio in order to satisfy the torque requirements of the hip module, Fig. 7.

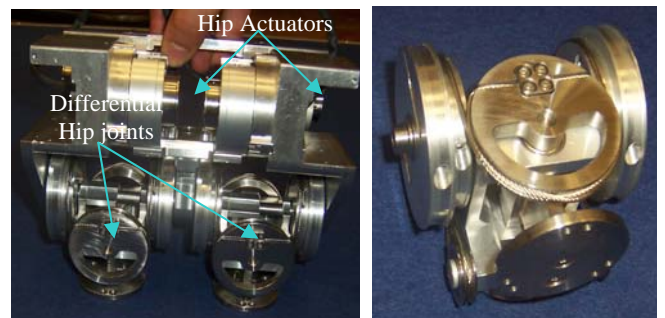


Fig. 7 Mechanical realisation and torque transmission cable rooting of the differential hip joints

This makes the design of the hip section quite uniform with the design of the waist joint providing increased stiffness at this level of the leg. The third DOF 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 groups (20Nm) associated with knee and ankle flexion, Fig. 8.

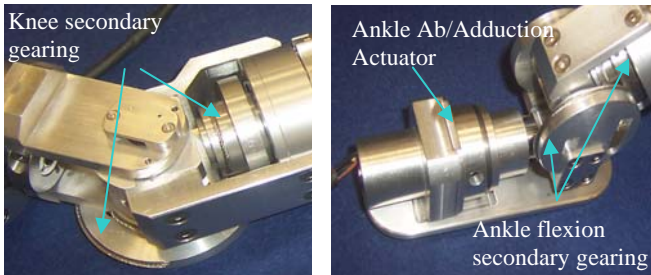


Fig. 8 Mechanical realisation and torque transmission cable rooting for the knee and ankle joints.

Torque to these joints is transferred through cable transmission systems that also provide 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 (10Nm) located on the foot plate and directly coupled to the ankle ab/adduction joint.

For the first lower body prototype the material chosen for most of the mechanical components is Aluminum alloy Al6082. This is a structural alloy having a medium strength and excellent corrosion resistance. Some parts were fabricated from steel (shafts) and Ergal70 (actuator housing).

C. Sensing

As far as the sensing is concerned all joints of the lower body are equipped with relative position sensing (Hall effect sensors integrated within the motors) and miniature 12bit absolute magnetic encoders (AS5045 from Austria Microsystems). In addition to motion sensing a 6 D.O.F F/T sensor was integrated within each leg. In contrast to most of the humanoid robots where the F/T sensors are usually found at the foot level the F/T sensor in the iCub is placed at the level of the hip between the hip differential module and the thigh. The fixation of F/T sensor at this level of the leg is justified from the fact that during crawling the contact of the leg with the ground occurs at the knee level. In addition, force/torque sensing at the hip level enables the implementation of active compliance control at the lower limbs of the iCub. Additional F/T sensors may require though 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. 9. 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. Because 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.

Fig. 9 also shows the developed signal conditioning and data acquisition electronics of the sensor which is based on a TMS320F2812 150MHz DSP processor. Each electronic unit with dimensions of 45[mm] x 45[mm] x 5[mm] can handle two 6DOF load cells.

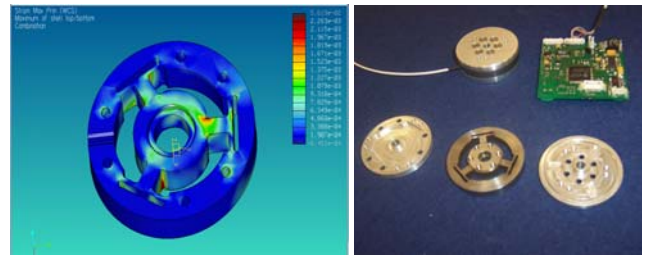


Fig. 9 The structure of the 6DOF force/torque sensor

V. PRELIMINARY ACTUATION TESTING AND PROTOTYPE CHARACTERISTIC MEASURES

Currently initial point to point motion trails of the joints on the lower body prototype have been performed to evaluate the performance of the Kollmorgen + HD actuator groups. A typical experimental position step response from the knee joint is shown in Fig. 10.

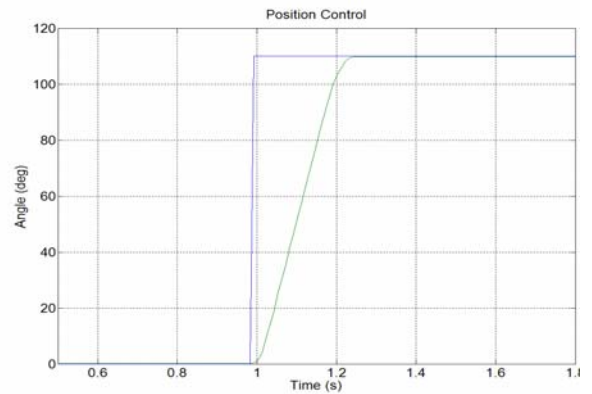


Fig. 10 Experimental step motion response of the knee joint.

The motion range and torque measure of the first prototype of the individual joints of iCub lower body are introduced in Table IV. As can be seen in this table and as far as the torque requirements of the iCub are concerned these are fully satisfied by the proposed design and actuator selection.

In some joints significantly higher torques are achieved. Regarding the range of motion of the individual joints these in general also meet the specified requirements of the 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 considered not significant issues.

VI. CONCLUSIONS

This paper presented the mechanical design adopted for the the lower body of a biped humanoid robot named the iCub. The design of the lower body mechanisms were introduced including the design of the 3 D.O.F waist that provides increased upper body flexibility and manipulation workspace accompanied with maximised stiffness due to the differential type mechanism adopted. In a similar way the hip module of the legs is also based on a differential mechanism making the design of the lower body quite uniform. An actuator assembly consisting of a harmonic drive and a frameless brushless motor forms the base of the lower body actuation. This combines lightness and compactness with high power to weight ratio. Performance measures depict the ability of the first prototype to meet the iCub simulation torque and motion requirements.

VII. ACKNOWLEDGMENT

This work is supported by the European Commission FP6, Project IST-004370.

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TABLE IV
CHARACTERISTIC MEASURES OF THE ICUB

Leg	Range of motion (°)	Actuator (Kollmorgen series)	Gear	Secondary Cable Gearing	Torque (Nm)
Hip Flex/Ext	+50 , -110	RBE 1210	HD-CSG14_100:1	2:1	Sum of the differential drive torques = 84Nm
Hip Abd/Add	+47 , -35	RBE 1210	HD-CSG14_100:1	2:1	
Hip Rotation	+65, -65	RBE 1211	HD-CSG17_100:1	-	40Nm
Knee	+115, -10	RBE 1210	HD-CSG14_100:1	2:1	30Nm
Ankle Flex/Ex	+70, -50	RBE 1210	HD-CSG14_100:1	1.5:1	24Nm
Ankle Abd/Add	+35, -35	RBE 0513	HD-HFUC11_100:1	-	11Nm
Waist					
Roll	+90,-15	RBE 1210	HD CSG14_100:1	2:1	30Nm
Pitch	+45, -45	RBE 1211	HD CSG17_100:1	-	Sum of the differential drive torques = 80Nm
Yaw	+90,-90	RBE 1211	HD CSG17_100:1	-	

