The 2009 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 11-15, 2009 St. Louis, USA

The Mechanical Design of the New Lower Body for the Child Humanoid robot 'iCub'

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Abstract—**The "iCub" is a robotic platform that was developed within the RobotCub European project to provide the cognition research community with an open "child-like" humanoid platform for understanding and development of cognitive systems [1]. In this paper we present the mechanical realization of the new lower body developed for the "iCub" child humanoid robot in order to keep up with the latest technology and solve mechatronic problems found in the previous version. The new lower body assembly demonstrates significant improvements over the old prototype including higher modularity, full joint state sensing and improved range of motion and torque capabilities. In particular the new leg and waist mechanisms to match the size and physical abilities of a 3½ year old human child are introduced.**

I. Introduction

Anthropomorphic design, natural and adaptive locomotion and human like behavior and performance are some of the intrinsic features that have driven the rapid growth of humanoid robots during the past decade. The development of such a humanoid platform that has the physical capacity of a human being poses many challenges from the mechatronic point of view. These must be addressed in a methodical and concurrent manner in order to co-ordinate and integrate the various components that form the complete mechatronic platform. There is clearly a requirement for many iterations of the design process before reaching the final prototype. These are usually guided by the experience gained from previous prototypes, as well as the advances in actuation, materials, sensor technologies, the increasing computational power and other supporting technologies such as electronics and ICT.

The first humanoid developed back in 1973 [2] formed the basis for all subsequent designs with all current successful humanoids being produced as part of a process of continuous improvement from their predecessors. Hence, the current ASIMO humanoid developed from E0 (1986), E1-E2-E3 (1987-1991), E4-E5-E6 (1991-1993), P1-P2-P3 (1993-1997), through to the original ASIMO (2000) and the new Asimo (2005) [3, 4]. The Humanoid Robot Platform (HRP) started with an adapted Honda P3 and subsequently HRP-2L, HRP-2P, HRP-2, HRP-3 were released [5]. Soon HRP-4 will be introduced which reportedly looks like a woman with a realistic geometry. QRIO was originally named Sony Dream Robot or SDR with prototype models SDR-3 and SDR-4X [6], while the TUM humanoid LOLA is an enhancement over Johnnie [7]. Similarly KAIST built KHR-1, KHR-2 and KHR-3 (Hubo) [8]. Waseda built different models from their first humanoid ever in 1973 to Wabian-2R [9].

The RobotCub project [10] is a research initiative dedicated to the realization of embodied cognitive systems and the creation of an advanced robotic platform for neuroscientific study. The two main goals of this project 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.

The "iCub" platform has as its aim the replication of the physical and cognitive abilities of a 3½ year old child. This "child" robot will act in a cognitive scenario, performing the tasks useful to learning, and interacting with the environment and humans. The OPEN approach of the "iCub" combined with the small size (104cm tall), low weight (<23kg) and very compact structure (fitting within the volume of a child) and high number (53) of degrees of freedom form fundamental differences with the many excellent humanoids already developed. It is evident that the OPEN nature of the "iCub" platform induces high needs for robustness and easy maintenance. This paper reports on the design of the new lower body modules for the "iCub". The new lower body assembly was designed and built based on the knowledge gained from the first successful prototype. It demonstrates significant improvements over the old

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prototype including higher modularity, reduced complexity, better quality full joint state sensing, and improved range of motion and torque capabilities.

The paper is organized as follows: Section II gives the specifications of the new lower body. Sections III and IV introduce the enhancements/modifications done on the mechanical design, the actuation and the sensing of the lower body. Section V presents experimental results from joint tracking performance experiments and characteristic measures of the new design in terms of joint range of motion, and output torque. These are compared with those of the original prototype. Finally, section VI addresses the conclusions.

II. Lower body specifications

An extensive description of the first prototype of the lower body design of "iCub" is provided in [11]. The size of the "iCub" approximates the dimensions of a 3½ year old child. In the new lower body design the total length and mechanical interface mechanism with the upper body remained unchanged so the new legs can be added to the current upper body without any modifications. The number of degrees of freedom in the lower body also remained unchanged.

The initial functional specification for the "iCub" legs was to have a capacity to sit, squat and crawl. These actions were rigorously simulated and it was determined that a 5 D.O.F leg could achieve these goals. However, subsequent study suggested that standing and childlike walking would be appropriate further goals and an additional D.O.F at the ankle to support standing (supported and unsupported) and walking formed a new upgraded specification. Therefore, each leg consists of 6 D.O.F: 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 and equals the design approach chosen in many other bipedal robots.

For the waist most humanoids usually have a relatively simple 2 D.O.F. mechanism, however humanoids trying to replicate the functionally of the human spine have also been developed [12]. For the "iCub" a 3 D.O.F waist was considered as this implementation offers greater motion flexibility than that of the conventional 2 D.O.F waist mechanisms. This extra functionality is needed as very young children typically reach for objects from a seated position and flexibility at the waist increases their workspace. At the same time the complexity is kept low in line with the requirements of the OPEN platform for robustness, easy maintenance and manufacturing. Based on above, the "iCub" waist provides pitch, roll and yaw motions for the upper body.

The range of motion for the joints of the lower body was defined considering human ergonomic data, data from other successful humanoid platforms and simulation studies. The range of motion of a "standard" human was used as a starting point. Table 1 depicts the range of motion of the "standard" human [13] and the "iCub" and it can be seen that in some joints the robot joint range specifications exceed those of the "standard" human. Wherever possible this greater range was deliberate to enhance the motion capability of the robot.

In particular, the range of the waist joint has been extended/modified to increase the manipulation workspace of the child-like robot. 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. This effectively improves the workspace for the iCub's arms while the robot is in a sitting position.

In some joints the specified range of motion of robot is smaller compared to that of the "standard" human, Simulation studies have confirmed that for these joints the range of motions provided in the specification is sufficient to ensure that the "iCub" can perform the basic exploratory and manipulation procedures required for the "child".

TABLE I
SPECIFICATIONS FOR THE RANGE OF MOTION OF THE LOWER BODY JOINTS.

	Human [13]	iCub
LEG	Range of motion (°)	
Hip Flexion/Extension	+45, -147	+45,-120
Hip Abduction/Adduction	+45, -40	+45,-31
Hip Rotation	+45.5, -43.5	+31,-91
Knee	+127.5, 0	+130,-5
Ankle Flexion/Extension	+34, -51.5	+30,-40
Ankle Abduction/Adduction	+58, -44.5	+25,-25
Ankle Twist	+36.5,-34	Not Implemented
WAIST		
Waist roll	+35, -35	+60,-60
Waist pitch	+70, -30	+90,-10
Waist yaw	+40, -40	+60,-60

The torque requirements used were identical to those specified for the first prototype. These torque requirements, Table II, were obtained from crawling simulations using Webots [14] at different gait speeds (0.5Hz cycles and 1Hz cycles) and with transitions from sitting to crawling pose and vice versa [11]. Ankle abduction/adduction does not contribute much during crawling motions and was omitted in these simulations.

TABLE II
SPECIFICATIONS OF THE PEAK TORQUES OF THE LOWER BODY JOINTS.

JOINT	Peak Torque (Nm) at 0.5 Hz	Peak Torque (Nm) at 1 Hz
Hip Flexion/Extension	38.5	46.3
Hip Abduction/Adduction	15.1	37.1
Hip Rotation	23.2	36.8
Knee	28.0	27.4
Ankle Flexion/Extension	11.3	12.4
Waist Roll	26.5	27.2
Waist Pitch	34.3	45.8
Waist Yaw	13.7	30.1

III. Enhancements of the new lower body

The new lower body assembly was designed and built based on the knowledge and experience gained from the design and testing of the first successful prototype. To improve the performance of the original system a number of modifications and/or enhancements were incorporated.

A. High Fidelity Robot Sensing

By evaluating walking motions produced by a trajectory generator based on the preview control [15], it was found that for dynamic motions the 12-bit resolution (0.088°) of the absolute rotary position sensor (Hall effect sensors of AS5045 from Austria Microsystems) used in the first prototype and positioned on the joint after the reduction drive was insufficient. Problems had arisen as the original angular velocity data based on encoder signals isn't ideal with the fidelity of the signal affected by the quality of the position sensor and the method used to generate the velocity signal, e.g. pulse counting or pulse timing. With the initial design the smallest detectable angular velocity obtained using the pulse count method (pulse timing was not possible) is $\Delta q/T_s$=0.088°/0.001s=88°/s which is unacceptable, To both improve the angular accuracy and velocity signal in the new prototype an additional 11bit incremental encoder is mounted inside the motor housing before the reduction drive, Fig. 1.

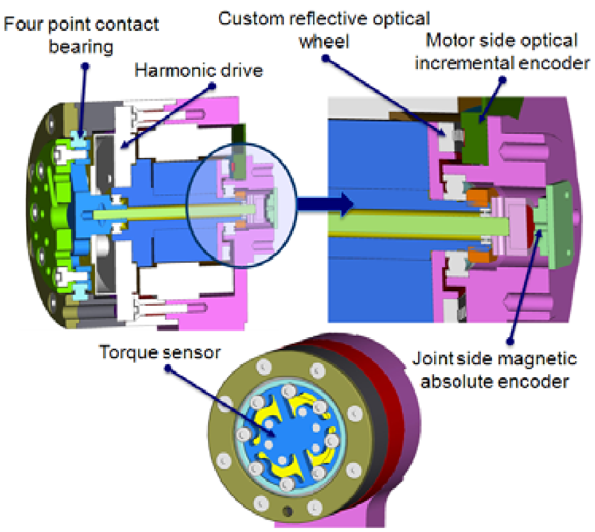


Fig.1 Section of the mechanical assembly of the motor group.

With the new design the encoder disk and emitter-receiver with the integrated electronics were placed inside the motor housing without the need to increase the size of the motor. Considering the 100:1 gear ratio provided by reduction drive the positional accuracy at the joint side is improved to 0.0017°. The minimum detectable angular velocity using the pulse count method now becomes $\Delta q/T_s$=0.0017°/0.001s=1.7°/s. Results showing how these improvements affect the tracking performance of the system are discussed in section V. Since the new encoder is relative the original absolute encoder at the joint side is retained for system initialization.

In addition to the enhanced position sensing, torque sensing was integrated within the new motor group. As stated by [15] force control and not position control is the key technology for natural physical interaction for robots. However, most humanoids, as the former design of the lower legs of "iCub", are position controlled with high gain PD.

Six axis force/torque sensors are often implemented in the feet of humanoids to stabilize walking using the ZMP concept. Recent research has focused on the use of individual joint torque control using software controlled active compliance [16] or passive compliance [17].

To achieve this in the upgraded "iCub" the new lower body integrates two types of force/torque sensors, Fig. 2; a 6 D.O.F F/T sensor integrated at the foot and torque sensors at each joint. Since commercial motor torque sensors are both expensive and often not mechanically compatible (size, mechanical interface) with high D.O.F. robots where space is limited customized torque sensor with additional advantage of dimensional optimization were developed.

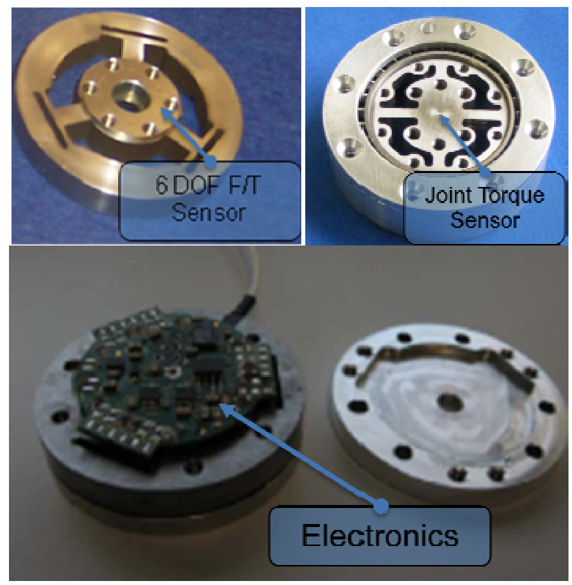


Fig. 2 The structures of the 6 D.O.F force/torque and the joint torque sensors.

The 6 D.O.F force/torque sensor is based on a three spoke structure which is machined from a solid stainless steel block to reduce hysteresis and increase the strength and repeatability. The signal conditioning, the data acquisition electronics and the communication interface (CAN) of the sensor are tightly integrated within the sensor module, Fig. 2. The sensor can provide force and torque measurements in the range of 500N and 20Nm respectively with 16bit resolution.

The joint torque sensor l, Fig. 2 is based on a four spoke structure mounted between the harmonic drive output and the output link. In both the 6 D.O.F force/torque and the joint torque sensor the strain is measured with semiconductor strain gauges and customized design electronics mounted within the joint.

B. Improved Modularity and Robustness and Enhanced Joint Range and Torque Output

To ease the manufacturing, assembly and maintenance as well as to improve the robustness of the robot the mechanical realization of the new lower body incorporates significant alterations on the implementation of the various modules. These modifications/improvements are listed below.

i) Redesign of the hip module to eliminate cable stages and reduce mechanical complexity.
ii) Rearrangement of the waist/lower torso to improve the compactness and maximize the hip range of motion.
iii) Redesign of the knee to eliminate cable stage, improving robustness and range of motion.
iv) Redesign of the ankle section to reduce complexity and improve the torque output capability in order to support standing and walking.

Details of these modifications follow.

IV. DETAILED DESCRIPTION OF LOWER BODY MECHANICS

The mechanical realization of the new lower body of the "iCub" child humanoid robot and an overview of its kinematics with the location of the degrees of freedom is illustrated in Fig. 3. From the kinematic perspective the new lower body includes the lower torso (housing the waist module) and the two leg assemblies. The height of the new "iCub" lower body from the foot to the waist is 671mm, with a maximum width and depth (at the hips) of 176mm and 110mm respectively. The weight of the lower body is 12.7kg with each leg weighing approximately 4.35kg and the waist section including the hip flexion motors weighing 4kg. The total weight of the "iCub" robot including the upper body is 23kg.

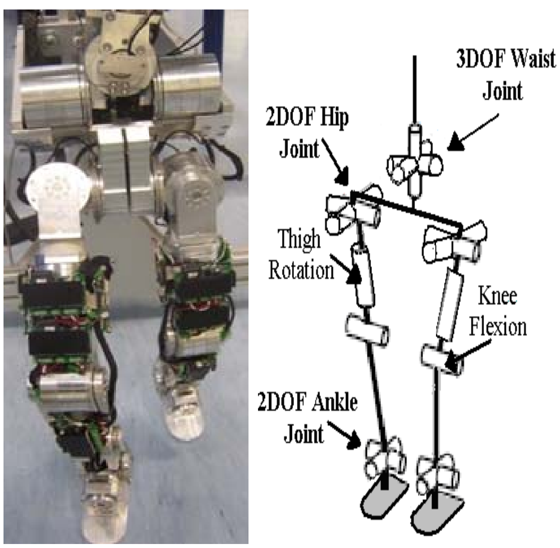


Fig. 3 Kinematic configuration and the mechanical assembly of the new "iCub" lower body.

The actuation solution adopted for the new lower body is the same with that adopted in the first prototype using a combination of a harmonic drives(CSG series, 100:1 ratio for all joints) and a Kollmorgen RBE series brushless frameless motor (BLM) . To improve modularity and reduce fabrication cost the number of the different actuator groups used in the new lower body was reduced from three (in the original prototype) to two. These are:

i) The **high** power actuator group delivers 40Nm at the output shaft and has a diameter of 60mm and a length of 53mm (Kollmorgen RBE1211 + Harmonic drive CSD17-100:1).
ii) The **low** power motor group provides up to 20Nm with a diameter of 50mm and a length of 48mm (Kollmorgen RBE1210 + Harmonic drive CSD14-100:1).

Motor gears, joint relative and absolute sensing have been highly integrated to optimize weight and dimensions of the lower body joints, Fig. 3. The use of frameless motors enables the mechanical integration of the motor and harmonic system within an endoskeleton structure that minimises size, weight and dimensions with the immediate benefit of the freedom in shaping the actuator housing, see Fig. 3 and Fig. 4.

The components of the new prototype that are considered as low stressed parts were fabricated in Aluminum alloy Al6082 with the medium/highly stressed components (load bearing sections of the housing) made of Aluminum alloy 7075 (Ergal) which has an excellent strength to weight ratio. The joint shafts were fabricated from Stainless steel 17-4PH which delivers an excellent combination of good oxidation and corrosion resistance together with high strength.

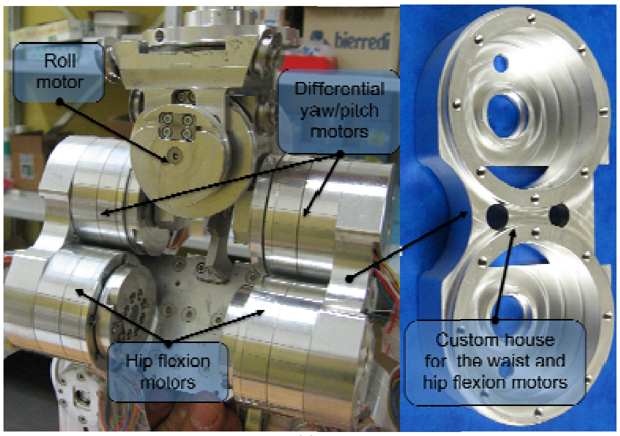
Fig. 4 Spare parts of the "iCub" motor/gearbox actuator group.

A. Waist Mechanism

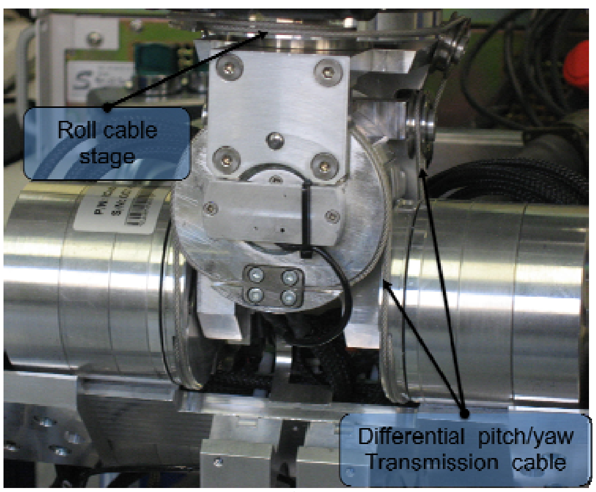
The iCub's waist was based on the core mechanism used in the original prototype. The torque and power of the two actuators used for body pitch and yaw is transferred using a cable based differential mechanism, Fig. 5.

For the waist pitch motion the two high power actuators assemblies (40Nm each) that drive 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. Roll is achieved through a pulley shaft 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. 5a. 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 II.

Compared to the original prototype, the new waist assembly exhibits greater integration due to the redesign and rearrangement of the motor housing. The relocation of the two motors powering the two hip flexion joints allowed the integration of these motors with the two motors actuating the waist differential mechanism resulting in a 23% volume reduction, Fig. 6.



(a)



(b)

Fig. 5 (a) Back view of the waist module and the custom motor house, (b) Front view of the waist module and the cable routing.

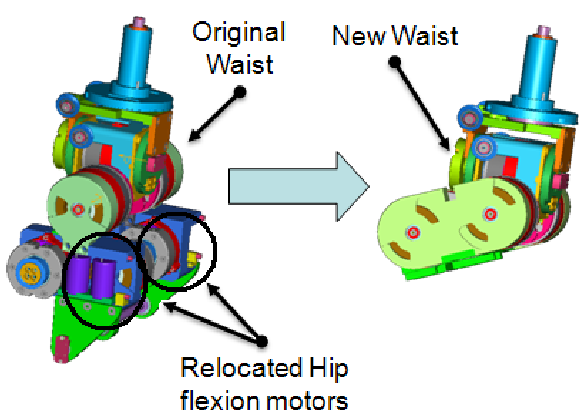


Fig. 6 The original and the new wait assembly.

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B. Leg Module

The new leg has a more modular structure allowing for easy assembly and maintenance. In general the leg has an anthropomorphic kinematic form consisting of; the hip, the thigh with the knee joint, the calf with the ankle joint and the foot, Fig 7. All these sections were radically redesigned in the new leg assembly.

The hip module, Fig. 7 provides 2 D.O.F to enable the thigh flexion/extension, abduction/adduction. Compared to the differential hip mechanism used in the first design [11] the hip joint of the new leg module is a simpler more easily assembled mechanism having a greater range of motion. It is a one side supported serial cantilever based structure with a typical roll-pitch-roll configuration. The single side supported hip provides a large range of motion, maximizes robustness (number of cables stages is reduced to one compared to four of the differential mechanism) and reduces the assembly complexity and cost. The hip abduction is directly driven by the motor placed in the centre of hip joint while torque to the hip flexion is transmitted from the hip flexion motor placed in the lower torso (see Fig. 5a) through a cable stage that also provide additional secondary gearing of (1.5:1).

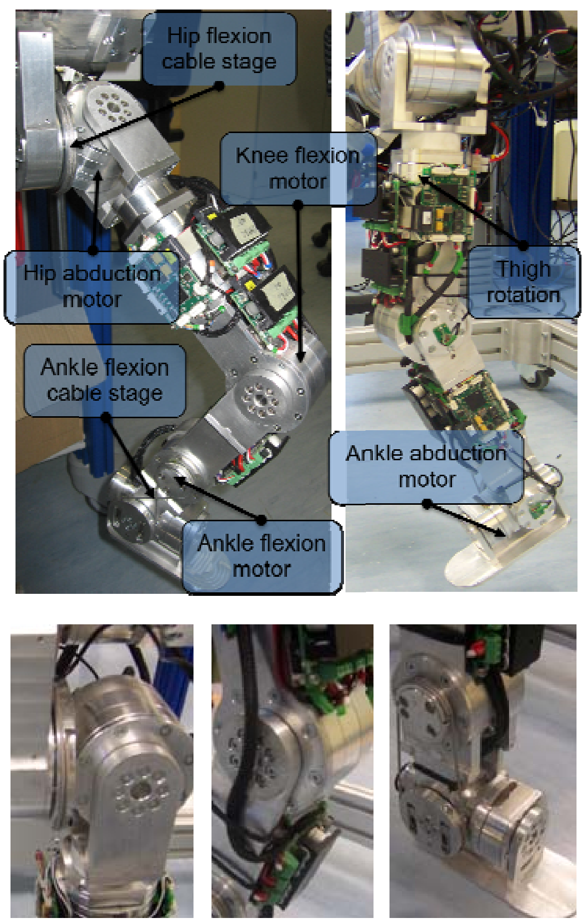


Fig. 7 The mechanical realization of the "iCub" leg modules.

The thigh rotation is implemented similarly to the first design along the thigh section with the actual thigh shell forming the housing of a high power (40Nm) actuator group that drives this joint.

The knee joint was radically redesigned to improve robustness. In the old design [11] the actuation was provided by a low power motor group (20Nm) housed within the calf conveying torque to the knee joint through a cable transmission. In the new design the knee joint is directly driven by a high power motor group (40Nm) at the centre of the knee joint, eliminating the need of the cable drive.

The calf section forms the housing of a low power actuator group (20Nm) associated with ankle flexion joint, Fig. 7. Torque to this joint is transferred through a cable transmission system that also provide additional secondary gearing of 1.5:1. The last D.O.F which produces ankle abduction/adduction uses a low power actuator (20Nm) located on the foot plate and directly coupled to the ankle ab/adduction joint, Fig 7. Torque output in both ankle joints has been increased compared to the original design, Table III, to support standing and walking.

In general, for the selection of the actuator groups a conservative approach was adopted. This means that the torque/speed margins of the actuator groups far exceed the torque/speed requirements obtained by simulation and experimental data from the first prototype. The main reason for this conservative selection comes from the OPEN character of the robot. As a wide range of experimentation with high level of uncertainly in terms of joint performance is the expectation from such an OPEN platform the simulation results from the crawling locomotion were only used as a guide to define the minimum performance capabilities of the new lower body joints.

V. TRAJECTORY TRACKING PERFORMANCE AND CHARACTERISTIC MEASURES

The performance of the new lower body was also evaluated against the original prototype using both walking trajectories based on preview control [15], Fig. 8 and sinusoidal inputs, Fig. 9.

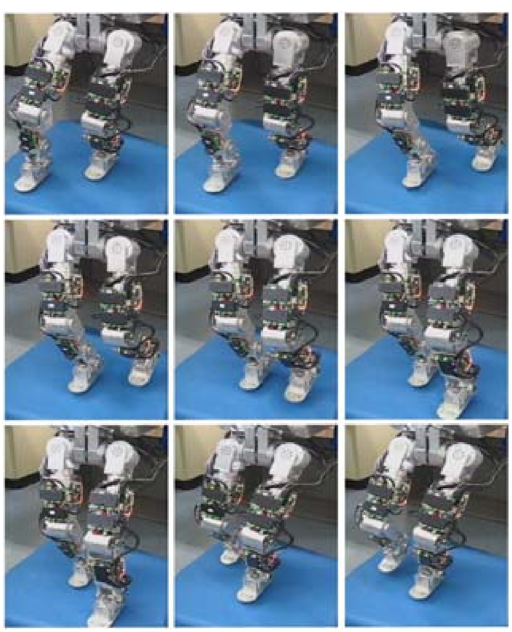
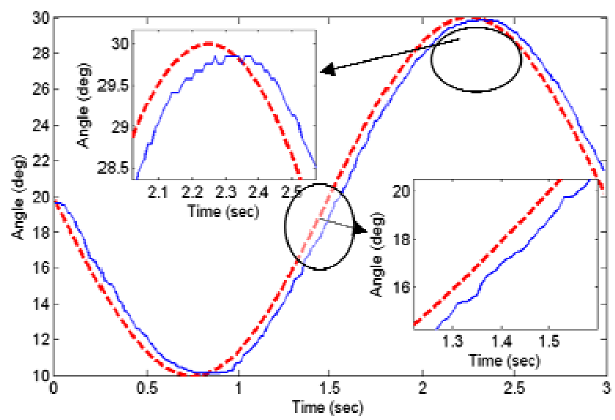
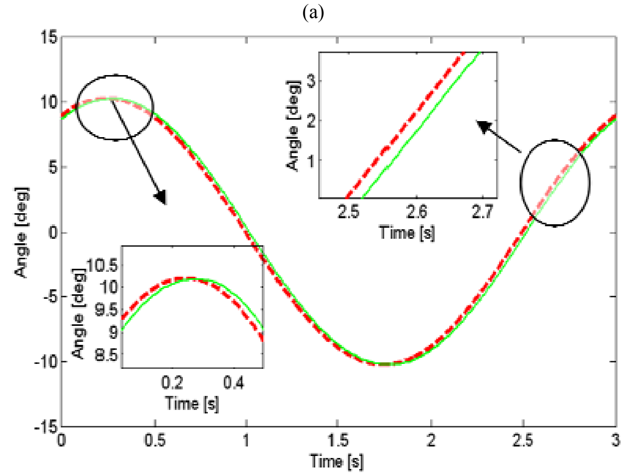


Fig. 8 Walking gait used in the joint tracking performance tests.

These experiments particularly aimed to evaluate the effect of the joint sensing improvements as discussed in section II. Two scenarios were evaluated. In the first case the low level joint control loop is closed on the joint side using the 12bit absolute magnetic encoder (first prototype). In the second scenario the joint control loop is closed using feedback from the incremental encoder which is mounted on the motor side (new design). The tracking performance of one of the joints for a low frequency sinusoidal input (0.3Hz) is illustrated in Fig. 9. This low frequency signal was selected to show the inability of the old prototype to accurately track low velocity profiles. Fig. 9a shows significant fluctuations in the output trajectory both in the line and peak regions which were even visually evident when the robot was walking as in Fig. 8. The main cause of these fluctuations is the friction in the harmonic drive gear which cannot be removed by increasing the damping gains due to the low quality of the velocity signal. In the second case (new prototype), Fig. 9b shows that the output trajectory is much smoother without any obvious fluctuations due to the increased damping permitted by the higher resolution sensing.



(a)



(b)

Fig. 9 Joint tracking performance improvement.

Finally, the motion range and torque of the new lower body prototype are compared with the first prototype in Table III. Clearly the range of most joints has been increased, while in terms of torque output the new leg design gives significantly higher values while the waist joints have equal performance.

TABLE III
CHARACTERISTIC MEASURES OF THE ICUB COMPARED TO THOSE OF THE ORIGINAL PROTOTYPE.

Leg	Range of motion (°)		Torque (Nm)		New Lower body Joint Drives	
	Original Prototype	New Prototype	Original Prototype	New Prototype	Motor Type	Gear Reduction
Hip Flex/Ext	+50, -100	+45, -134	Sum of the differential drive torques = 84Nm	60Nm	RBE1211 (200W)	CSD17-100:1 + 1.5:1 cable stage
Hip Abd/Add	+17, -35	+18, -120		40Nm	RBE1211 (200W)	CSD17-100:1
Hip Rotation	+65, -35	+80, -80	40Nm	40Nm	RBE1211 (200W)	CSD17-100:1
Knee	+115, -10	+126, -24	30Nm	40Nm	RBE1211 (200W)	CSD17-100:1
Ankle Flex/Ex	+70, -50	+43, -22	24Nm	30Nm	RBE1210 (140W)	CSD14-100:1 + 1.5:1 cable stage
Ankle Abd/Add	+25, -25	+25, -25	11Nm	20Nm	RBE1211 (200W)	CSD17-100:1
Waist						
Roll	+70, -70	+70, -70	30Nm	30Nm	RBE1210 (140W)	CSD14-100:1 + 1.5:1 cable stage
Pitch	+90, -15	+90, -15	Sum of the differential drive torques = 80Nm	Sum of the differential drive torques = 80Nm	RBE1211 (200W)	CSD17-100:1 + 1:1 cable stage
Yaw	+45, -45	+45, -45			RBE1211 (200W)	CSD17-100:1 + 1:1 cable stage

Comparing the achieved joint ranges and torques with the specifications given in Table I and II it can be seen that in most of the joints the achieved joint specifications satisfy the requirements. Some small deviations were due to the hard mechanical constrains raised from the child size of the robot.

VI. CONCLUSIONS

Humanoids robots are high complexity mechatronic machines build on a process of test and revision. Therefore, there is clearly a necessity for many iterations of the design process before reaching a final prototype.

This paper presented the structure of the new lower body of the "iCub" child humanoid robot. Built from the knowledge obtained by the first prototype an improved version of the lower body was designed, fabricated and fully assembled. Specific deficiencies of the first design were addressed resulting in the realization of the new lower body platform that exhibits significant improvements over the old prototype including higher modularity, highly integrated actuator modules with full joint state (improved resolution and torque) sensing, improved joint range and torque capabilities, simpler construction, easier assembly and maintenance and improved joint trajectory tracking.

ACKNOWLEDGMENT

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

REFERENCES

[1] N.G.Tsagarakis, G.Metta3, G.Sandini, D.Vernon, R.Beira, F.Becchi, L.Righetti, J.S.Victor, A.J. Ijspeert, M.C.Carrozza and D.G.Caldwell, "iCub –The Design and Realization of an Open Humanoid Platform for Cognitive and Neuroscience Research", International Journal of Advanced Robotics, Special Issue on "Robotic platforms for Research in Neuroscience", Vol.21, No.10, pp, 1151-1175, 2007.

[2] J. Yamaguchi, E. Soga, S. Inoue, and A. Takanishi, "Development of a Bipedal Humanoid Robot – Control Method of Whole Body Cooperative Dynamic Biped Walking," Proc. of IEEE ICRA 1999, pp. 368-374.

[3] K. Hirai, M. Hirose, Y. Haikawa, and T. Takenaka, "The Development of Honda Humanoid Robot," Proc. of IEEE ICRA 1998, pp. 1321-1326.

[4] M. Hirose, Y. Haikawa, T. Takenaka, and K, Hirai, "Development of Humanoid Robot ASIMO" Proc. IEEE/RSJ IROS 2001, Workshop2

[5] K. Akachi, K. Kaneko, N Kanehira, S. Ota, G. Miyamori, M. Hirata, S. Kajita and F. Kanehiro, "Development of humanoid robot HRP-3P", Proc. of IEEE-RAS Int. Conf. on Humanoid Robots, pp. 50-55.

[6] T. Ishida, Y. Kuroki, J. Yamaguchi, M. Fujita, and T.T Doi, "Motion entertainment by a small humanoid robot based on OPEN-R", Proc. of IEEE IROS 2001, pp 1079-1086.

[7] S. Lohmeier, T. Buschmann, H. Ulbrich, and F. Pfeiffer, "Modular Joint Design for Performance Enhanced Humanoid Robot LOLA", Proc. of IEEE ICRA 2006, pp. 88-93.

[8] I.W. Park, J.Y. Kim, J. Lee, and J.H. Oh, "Mechanical design of the humanoid robot platform HUBO", Journal of Advanced Robotics,vol.21,no. 11, pp. 1305-1322, 2007.

[9] Y. Ogura, H. Aikawa, K. Shimomura, A. Morishima, H. Lim, and A. Takanishi, "Development of a New Humanoid Robot WABIAN-2", Proc. of IEEE ICRA 2006, pp. 76-81.

[10] G. Sandini, G. Metta, and D Vernon, "RobotCub: An Open Framework for Research in Embodied Cognition", International Journal of Humanoid Robotics, November 18, 2004 8:2.

[11] N.G. Tsagarakis, F. Becchi, L. Righetti, A. Ijspeert, and D.G. Caldwell. "Lower body realization of the baby humanoid - 'icub'", Proc. of IEEE IROS 2007, pp. 3616-3622.

[12] I. Mizuuchi, R. Tajima, T.Yoshikai, D. Sato, K. Nagashima, M. Inaba, Y. Kuniyoshi, and H. Inoue, "The Design and Control of the Flexible Spine of a Fully Tendon-Driven Humanoid "Kenta", Proc. IEEE/RSJ IROS 2002, pp. 2527-2532.

[13] "The measures of Man and Woman, Human factors in Ergonomic design", John Willey & Sons, New York, 2002.

[14] O. Michel, "Webots: Professional mobile robot simulation," International Journal of Advanced Robotic Systems, vol. 1, no. 1, pp. 39-42, 2004.

[15] S. Kajita, F. Kanehiro, K. Kaneko, K. Fujiwara, K. Harada, K. Yokoi, and H. Hirukawa, "Biped walking pattern generation by using preview control of Zero-Moment Point", Proc. of IEEE ICRA 2003, pp. 1620- 1626.

[16] S.H Hyon, "Compliant Terrain Adaptation for Biped Humanoids Without Measuring Ground Surface and Contact Forces", IEEE Transactions on Robotics, Vol. 25, issue 1, pp. 171-178, 2009

[17] R. Van Ham, S. Thomas, B. Vanderborght, K. Hollander, and D. Lefeber, "Review of actuators with passive adjustable compliance / controllable stiffness for robotic applications," IEEE Robotics and Automation Magazine 2009 (accepted).