Lower Body Design of the 'iCub' a Human-baby like Crawling Robot

N.G.Tsagarakis
Center of Robotics and Automation
University of Salford
Salford , M5 4WT, UK
n.tsagarakis@salford.ac.uk

M. Sinclair
Center of Robotics and Automation
University of Salford
Salford , M5 4WT, UK

F. Becchi
TELEROBOT
Advanced Robotics
16128 Genova, Italy

G Metta
LIRA-Lab, DIST
University of Genova
16145 Genova, Italy
pasa@liralab.it

G. Sandini
LIRA-Lab, DIST
University of Genova
16145 Genova, Italy
sandini@unige.it

D.G.Caldwell
Center of Robotics and Automation
University of Salford
Salford , M5 4WT, UK
d.g.caldwell@salford.ac.uk

***Abstract* – The development of robotic cognition and a greater understanding of human cognition form two of the current greatest challenges of science. Within the RobotCub project the goal is the development of an embodied robotic child (iCub)with the physical and ultimately cognitive abilities of a 2 ½ year old human baby. The ultimate goal of this project is to provide the cognition research community with an open human like platform for understanding of cognitive systems through the study of cognitive development.**

In this paper the design of the mechanisms adopted for lower body and particularly for the leg and the waist are outlined. This is accompanied by discussion on the actuator group realisation in order to meet the torque requirements while achieving the dimensional and weight specifications. Estimated performance measures of the iCub are presented.

Index Terms – Lower body, Humanoid, Crawling, Legs.

I. INTRODUCTION

In the past decade the need for human friendly robots to interact with humans and assist them in the execution of daily activities has been increasingly recognized. Anthropomorphic robots combine many desirable features needed to satisfy such a goal including natural human like locomotion and human friendly design and behaviour. As a result, multi degree of freedom human like robots have become more common and an increasing number of humanoid robots have been designed and fabricated.

One of the first bipedal humanoid robots, WABOT-I, was developed at Waseda University back in 1973. This biped which was able to perform simple static walking was followed by a long and distinguished series of robots leading to the most current developments of WABIAN I and II. WABIN-RII which weights 131.4kg forms a complete human like figure [1]. At the University of Tokyo which also has a long history of humanoid development, research efforts on human like robots has led in recent times to the development of H6 and H7. H6 has a total of 35 degrees of freedom (D.O.F) and weighs 55Kg [2]. Within the commercial arena there were also robots of considerable distinction including those developed by HONDA. Their second prototype, P2, was introduced in 1996 and provided an important step forward in the development of full body humanoid systems. This was the first humanoid robot, which could go up/down stairs [3]. P2 had a height of 1820 mm a width of 600mm and its weight was 210kg. P3 introduced in 1997 was a scaled down version of P2 (1600mm height, 600mm width, 130kg weight) with 6 D.O.F./Leg, 7 D.O.F./Arm, 1 D.O.F./Hand) [4]. ASIMO (Advanced Step in Innovative Mobility) a child sized robot (1200mm height, 450mm width, 43kg weight) appeared in 2000. ASIMO has 6 D.O.F./Legs, 5 D.O.F./Arms, 1 D.O.F./Hand, 2 D.O.F./Head) and new walking technology (i-WALK) [5] which allowed it to walk continuously while changing directions.

A more recent research effort in Europe and in particular at the Technical University of Munich has led to the development of JOHNNIE, an anthropomorphic autonomous biped robot with 17 D.O.F. Its overall weight is about 40kg and the height is 1.80m [6]. HRP is another humanoid robotics project, coordinated by METI [7] in Japan resulting in the development of two humanoid platforms HRP [8] and HRP-2[9-10]. HRP-2 has 30 D.O.F in total, a height of 1539mm, a width of 621mm and weights 54.1Kg. HRP, HRP-2 showed abilities to work with human, to cope with uneven surface, to fall over safely and to stand-up again [11]. Other more recent medium size humanoids include SAIKA [12] a low cost 30 D.O.F robot and KENTA [13] that employs a flexible spine structure and is powered by pneumatic muscles.

In addition to the above examples of adult or medium sized anthropomorphic robots a number of smaller prototypes have been also constructed. MK.5 is a compact size humanoid robot constructed by Aoyma Gakuin University. It has 24 D.O.F. a height of 356mm and weighs 1.9kg [14]. The PINO platform constructed by ERATO [15] is designed to be a humanoid that can be built by everyone, using cheap, off-the-shelf components. The idea of PINO development is to provide a platform that will accelerate the research and development of humanoid robots by providing the technical information of PINO open to the public. Other compact size humanoid robots are the SDR-3X (Sony Dream Robot-3X) and SDR-4X developed mainly for entertainment [16, 17]. These robots have a height of 500mm, a width of 220mm and weigh 5kg. They have the ability not only to walk but also to perform synchronized choreography.

Although, nowadays the application areas for most humanoid robots is still limited to the entertainment and amusement applications it is expected that as more humanoids robots are developed several new applications will be identified in all areas of domestic robotics such as offices, homes and hospitals.

The 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. In the early definition of the project two main tasks were considered from which the design requirements were derived. These are: 4 limbed crawling with the capacity to develop through learning to sitting, standing and walking and manipulation [18, 19]. Based on the requirements implied by these two tasks the design of the lower body of the iCub was realized

This paper presents current progress on the design of the lower body modules of the iCub. The paper is organized as follows: Section II gives the general specifications of the system in terms of size and D.O.F. The kinematics and the motion requirements are presented in section III. The following section describes in details the mechanical design, the actuation and the sensing adopted for the lower body. This includes the proposed waist and leg designs and the selection of the actuators. Estimated performance measures of the current design in terms of joint range of motion and output torque are introduced in section V. Finally, section VI addresses conclusion and future work.

II. LOWER BODY SPECIFICATIONS

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. These were defined with attention given to addressing the requirement for crawling and manipulation and in general the need to imitate the human baby form. As already mentioned, the size of the iCub will approximate all the dimensions of a two and a half year old child, Fig 1 [19]. Regarding the number of D.O.F 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. However, it was decided to incorporate an additional D.O.F at the ankle to support not only crawling but also standing (supported and unsupported) and walking, Table I. As different research groups may also 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(flexion/extension and abduction/adduction). The foot twist rotation was not implemented.

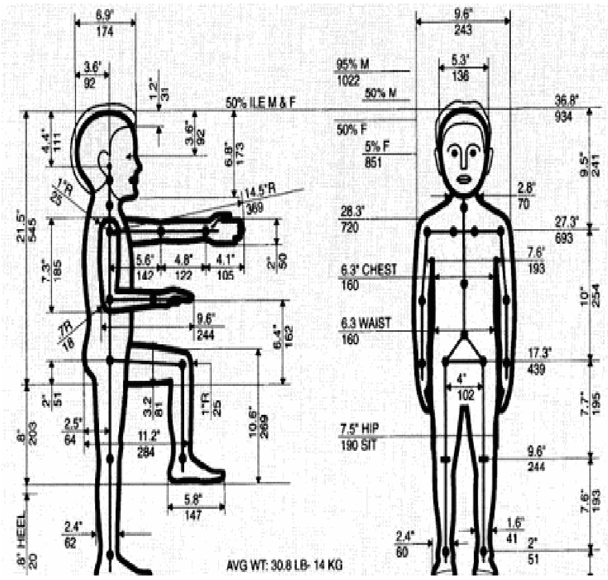

Fig. 1 Size specification for the iCub.

TABLE I
LEG MECHANISM NUMBER OF DOF

	Degrees of Freedom (°)	
Joint	Human	iCub
Hip	3 Flexion/Extension Abduction/Adduction Rotation	3 Flexion/Extension Abduction/Adduction Rotation
Knee	1 Flexion/Extension	1 Flexion/Extension
Ankle	3 Flexion/Extension	2 Flexion/Extension

	Abduction/Adduction Rotation	Abduction/Adduction -
		2 x 6DOF =12DOF

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, Table II.

TABLE II
WAIST MECHANISM NUMBER OF DOFS

	Degrees of Freedom (°)	
Joint	Human	iCub
Waist	3 Roll Pitch Yaw	3 Roll Pitch Yaw
		=3DOF

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 and 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.

III. LOWER BODY KINEMATIC DESIGN AND RANGE OF MOTION SPECIFICATIONS

Figure 2 shows an overview of lower body kinematics with the location of the degrees of freedom reported in tables I and II.

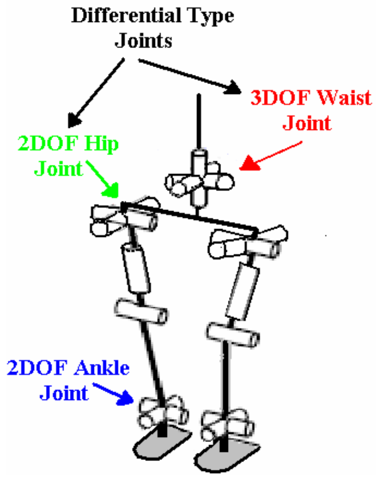

Fig. 2 Lower body kinematic configuration of iCub.

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

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

ii) Two of three D.O.F in the iCub's waist (pitch, yaw) are also implemented using a cable differential mechanism. As a result the increased flexibility of the upper body and the ensuing larger working space of arms are combined with increased stiffness due to the differential mechanism also adopted for this joint.

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

TABLE III
RANGE OF MOTION OF THE LEG JOINTS

Leg X 2	**Range of motion (°)**	
Joint	Human	iCub
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	x

TABLE IV
RANGLE OF MOTION OF THE WAIST JOINT

Waist	**Range of motion (°)**	
Joint	Human	iCub
Waist roll	-35, +35	-90,+90
Waist pitch	-30, +70	-10,+90
Waist yaw	-40, +40	-60,+60

Considering Table III, IV 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.

IV. Overall Mechanical Design Actuation and Sensing

The CAD model (*Pro Engineer Wildfire 2*) of the lower body of the iCub baby humanoid robot with its dimensions is shown in Fig. 3. The height of the iCub lower body from the foot to the waist is 611mm while the width of the lower torso from left to the right is 186mm. The weights of the lower body are as follows: the total weight is estimated 11.2Kg with the weight of each leg being 3.2Kg and the weight of the lower torso including the waist being 4.8Kg.

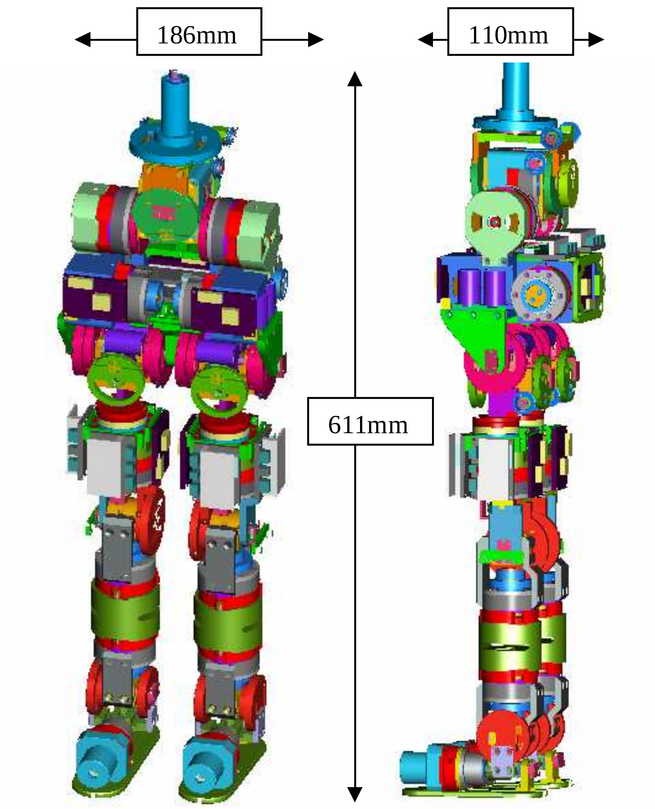

Fig. 3 CAD model of the lower body of the iCub baby humanoid robot.

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

When considering the actuation of the individual joints, the selection of motor actuator and any gear reduction ratio is critical in the design of a humanoid robot. To optimize the selection of actuators and reduction ratios, iterations of the mechanical design and simulation analysis of the system were necessary. The selection of the type of actuator to power the lower body of the iCub involved various simulations of the robot model while performing crawling motions with different speeds and transitions from sitting to crawling pose and vice versa, Fig 4. From these simulations the peak torque requirements of each joint of the lower body were identified and presented in Table V.

TABLE V
TORQUE 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. 4 View of the iCub crawling and sitting simulation.

These results provide the guidelines to decide hardware specifications such as type of motor and reduction ratio. Another factor that also steered the selection of the actuator was the dimensional and weight prerequisites of the robot. Various combinations of motor and gearbox were considered to satisfy the above and the torque requirements as derived from the simulation model of the iCub. The solution finally adopted is based on a combination of a harmonic drive reduction system (100:1 ratio) and a brushless motor (BLM) from the Kollmorgen RBE series. This combination was found to meet the requirements of compactness accompanied by a high power to weight ratio. A view of such an actuator group is introduced in Fig 5

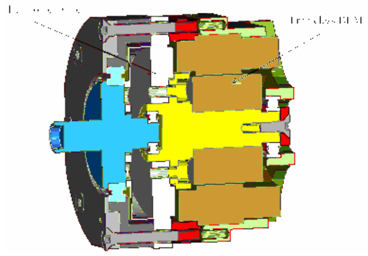

Fig. 5 View of the iCub motor/gearbox actuator group.

To reduce further the size of the actuators, the frameless version of the motor was selected which has certain benefits to the overall design. It enables the integration of the motor and harmonic system within an endoskeleton type structure that minimises weight and dimensions with the immediate benefit of the freedom in shaping the actuator housing. Three different power actuators models are used for the lower body. The high power actuator model 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 10Nm 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. 6.

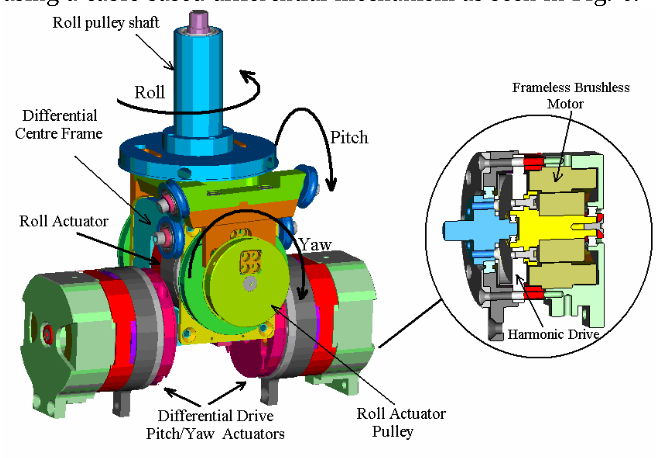

Fig. 6 The compact mechanical design of the 3DOF iCub waist.

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 humanoids robots. These are:

i) Increased stiffness .
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 6. 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 V.

B. *Leg*

For the leg design, particular attention was paid to satisfy the dimensional and weight requirements while at the same time maximising 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 7. The hip module provides 2 D.O.F to enable the thigh flexion/extension and abduction/adduction. Its design 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 though a cable transmission system that also provides a (2:1) gear ratio in order to satisfy the torque requirements of the hip module.

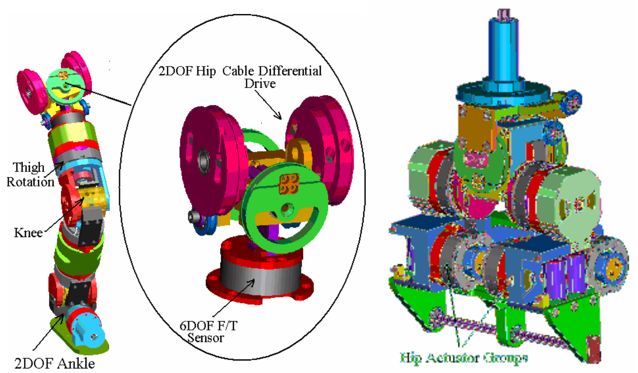

Fig. 7 Leg CAD model of the iCub and Lower torso with the housing of the hip actuators.

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 thigh rotation is implemented along the thigh with the actual thigh shell forming the housing of the actuation group.

The calf section forms the housing for the two medium power actuator groups (20Nm) associated with knee and ankle flexion. Torques to these joints are transferred through cable transmission systems that also provide additional gearing of (1.5:1 and 1.25:1) for the knee and the ankle joint respectively. The last D.O.F which produces ankle ab/adduction is implemented using a low power actuator (10Nm) located on the foot plate and directly coupled to the ankle ab/adduction joint.

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) used for system initialization and calibration.

In addition to motion sensing a 6 D.O.F F/T sensor was integrated within each leg. This F/T sensor which is located at the level of the hip between the hip differential module and the thigh was integrated to enable active compliance control to be implemented at the lower limbs of the iCub.

The body of the 6 D.O.F F/T torque sensor is shown in Figure 8. It is based on a three spoke structure where the strain generated is measured by semiconductor strain gauges that are mounted on the 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 steel block to reduce hysteresis and increase the strength and repeatability.

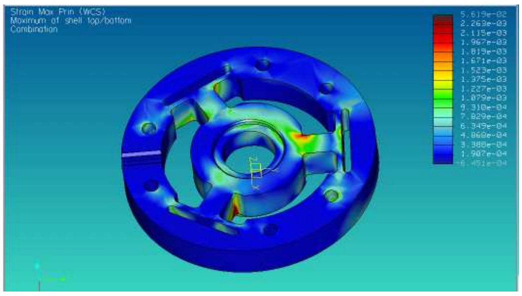

Fig. 8 The strucure of the 6DOF force/torque sensor

V. Estimated Performance Measures

This section introduces the estimated performance measures in terms of torque and motion range of the individual lower body joint of iCub as they derived from the proposed design solution, Table VI. 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 estimated 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 will be addressed in the next iteration of the design and are considered not significant issues.

TABLE VI
Estimated Performance Measures of the Proposed Design

Leg	**Estimated Torque (Nm)**	**Range of motion (°)**
Hip Flexion/Extension	Sum of Flexion + Abduction Torques of the differential drive = 84Nm	+50 , -110
Hip Abduction/Adduction		+47 , -35
Hip Rotation	40Nm	+65, -65
Knee	30Nm	+115, 0
Ankle Flexion/Extension	24Nm	+70, -50
Ankle Abduction/Adduction	11Nm	+35, -35
Waist		
Roll	30Nm	+90,-15
Pitch	Sum of Pitch + Yaw Torques of the differential drive = 80Nm	+45, -45
Yaw		+90,-90

VI. Conclusions

This paper discussed the concepts adopted for the design of the lower body of a biped humanoid robot named the iCub. iCub will have the size of a 2 ½ year old baby with the ultimate project goal of providing the cognition research community with an open human like platform for understanding of cognitive systems. 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 with the benefits of reduced size and high power to weight ratio. Estimated performance measures depict the ability of the proposed design solution to meet the iCub simulation torque and motion requirements. We are currently on the stage of commencing the assembly of the first iCub prototype that is planned to be completed in mid 2006.

Acknowledgment

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

References

[1] 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. IEEE Int. Conference on Robotics and Automation, pp. 368-374, 1999.
[2] K. Nishiwaki, T. Sugihara, S. Kagami, F. Kanehiro, M. Inaba, and H. Inoue, "Design and Development of Research Platform for Perception-Action Integration in Humanoid Robot: H6," Proc. Int. Conference on Intelligent Robots and Systems, pp. 1559-1564, 2000.
[3] K. Hirai, "Current and Future Perspective of Honda Humanoid Robot", Proc. IEEE/RSJ Int. Conference on Intelligent Robots and Systems, pp. 500508, 1997.
[4] K. Hirai, M. Hirose, Y. Haikawa, and T. Takenaka, "The Development of Honda Humanoid Robot," Proc. IEEE ICRA, pp. 1321-1326, 1998.
[5] M. Hirose, Y. Haikawa, T. Takenaka, and K, Hirai, "Development of Humanoid Robot ASIMO," Proc. Int. Conference on Intelligent Robots and Systems, Workshop2 (Oct.29, 2001), 2001.
[6] M. Gienger, K. Löffler, and F. Pfeiffer, "Towards the Design of Biped Jogging Robot," , Proc IEEE ICRA, pp. 4140-4145, 2001.
[7] H. Inoue, S. Tachi, Y. Nakamura, K. Hirai, N. Ohyu, S. Hirai, K. Tanie, K. Yokoi, and H. Hirukawa, "Overview of Humanoid Robotics Project of METI," Proc. the 32nd Int. Symposium on Robotics, pp. 1478-1482, 2001.
[8] K. Kaneko, F. Kanehiro, S. Kajita, K. Yokoyama, K. Akachi, T. Kawasaki, S. Ota, and T. Isozumi, .Design of Prototype Humanoid Robotics Platform for HRP,. Proc. IEEE/RSJ Int. Conference on Intelligent Robots and Systems, pp. 2431-2436, 2002.
[9] K. Kaneko , F. Kanehiro, S. Kajita, H. Hirukawa, T.Kavasaki, M. Hirata, K. Akachi, and T. Isozumi, "Humanoid Robot HRP-2", Proceedings of the 2004 IEEE ICRA, New Orleans, LA • April 2004
[10] N. Kanehira, T. Kawasaki, S. Ota, K. Akachi, T. Isozumi, F. Kanehiro, and K. Kaneko, and S. Kajita, "Design and Experiment of Advanced Leg Module (HRP-2L) for Humanoid Robot (HRP-2) Development," Proc. Int. Conference onIntelligent Robots and Systems, 2002.
[11] K. Yokoyama, J. Maeda, T. Isozumi, and K. Kaneko, "Application of Humanoid Robots for Cooperative Tasks in the Outdoors," Proc. Int. Conference on Intelligent Robots and Systems, Workshop2 , 2001
[12] Satoru Shirata, Atsushi Konno, and Masaru Uchiyama,"Design and Development of a Light-Weight Biped Humanoid Robot Saika-4", Proc. IEEE/RSJ IROS, pp148-153 ,2004, Sendai, Japan,.
[13] 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", IEEE/RSJ IROS, pp2527-2532, 2002, Lausanne, Swizerland.
[14] T. Furuta, Y. Okomura, and K. Tomiyama, "Design and Construction of a Series of Compact Humanoid Robots and Development of Biped Walk Control Strategies," Proc. IEEE-RAS Int. Conf on Humanoid Robots, 2000.
[15] F. Yamasaki, T. Matsui, T. Miyashita, and H. Kitano, "PINO The Humanoid that Walks", Int.Conference on Humanoid Robots, 80.pdf, 2000.
[16] Y. Kuroki, T. Ishida, J. Yamaguchi, M. Fujita, and T. Doi, "A Small Biped Entertainment Robot," Proc. IEEE-RAS Int.Conference on Humanoid Robots, pp. 181-186, 2001
[17] Masahiro Fujita, Yoshihiro Kuroki, Tatsuzo Ishida, and Toshi T. Doi. Autonomous Behavior Control Architecture of Entertainment Humanoid Robot SDR-4X. In *Proc. of IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS 2003)*, pp. 960–967, 2003.
[18] 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
[19] Giorgio Metta, David Vernon, Giulio Sandini," D8.1 Initial Specification of the CUB Open System" , http://www.robotcub.org