Performance Assessment of a 3 DOF Differential Based Waist joint for the “iCub” Baby Humanoid Robot

W. M. Hinojosa, N. G. Tsagarakis, Giorgio Metta, Francesco Becchi, Julio Sandini and Darwin. G. Caldwell

Abstract— This work discusses the design and control approach of a recently developed 3 DOF waist joint for the “iCub” humanoid robot. “iCub” is child like crawling robot that resembles a 2 and a half year child. 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. The design of the mechanisms adopted for the waist joint is discussed. This is accompanied by discussion on the control scheme design and presentation of experimental results showing the performance of the mechanism.

I. INTRODUCTION

Anthropomorphic type robots combine many desirable features such as natural human like locomotion and human friendly design and behavior. As a result of this multi degree of freedom human like robots have become more and more common and many humanoid robots have been recently designed and fabricated.

The first biped humanoid robot was WABOT developed at Waseda University back in 1973. This biped which was able to perform simple static walking was followed by the development of WABIAN I and II. WABIN-RII[1]. Following these first prototypes a number of other human like robots were developed including the H6, H7 at the University of Tokyo [2], the impressive humanoid robots P2, P3 and ASIMO developed by HONDA [3-5] and some more recent prototypes as the JOHNNIE anthropomorphic autonomous biped robot [6] developed at University of Munich and the HRP, HRP-2 developed by METI in Japan [7-10].

Other less know medium and small size humanoids include SAIKA [11] and KENTA [12], the MK.5 a compact size humanoid robot constructed by Aoyma Gakuin University [13], the PINO platform constructed by ERATO [14] and the SDR-3X (Sony Dream Robot-3X) and SDR-4X developed mainly for entertainment [15, 16].

In the above humanoids examples the waist joint is usually implemented using a simple serial mechanism with 2 DOF. This waist configuration is adequate for these robots since the tasks that are usually perform are still limited in entertainment and amusement applications and in demonstrating walking capabilities.

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 will replicate a human-like robot with the size of a 2 and a half year old baby acting in a cognitive scenario, performing the tasks useful to learn, interacting with the environment and humans. In the early definition of the project two main tasks were considered from which the design requirements for the waist mechanism were derived. These are: crawling and manipulation [17]. Based on the requirements implied by these two tasks the design of the waist mechanism of the iCub was realized. A 3 DOF differential based mechanism was employed to provide not only increased stiffness but also increased range and flexibility of motion for the upper body.

This paper presents the design and control of this differential based waist mechanism of the iCub. The paper is organized as follows: Section II gives the general specifications of the waist joint in terms of DOF, range of motions and torque requirements. The following section describes the mechanical design adopted for the waist mechanism and highlights the advantages of this approach. Section IV introduces the system model used for the design of the control scheme while section V presents the control system design. Estimated performance measures of the control scheme are presented in sections VI and VII, by means of simulation and experimental result. Finally, section VIII introduces the conclusion of this work

II. WAIST SPECIFICATIONS

The kinematics specifications of the waist joint of the

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iCub include the definition of the number of D.O.F required and their actual location as well as the range of motions. These were defined with attention given to address the requirement for crawling and manipulation and in general to imitate the human baby form. As it has been mentioned the size of the iCub will have the approximate size of a two and a half year old child [17]. The D.O.F required for the waist was determined considering both the crawling and the manipulation prerequisite. Crawling simulation analysis showed that for effective crawling a 3 D.O.F waist is essential, Table I.

TABLE I
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 will offer 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 from 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 3 D.O.F enabling pitch, roll and yaw of the upper body.

Regarding the range of motion of the waist joints since the iCub is a human-like robot and will perform tasks similar to those performed by the human the range of motion of the standard human was used as a starting point for the selection of the movable range for the waist joints of the iCub.

Table II below introduces the range of motions specification for the joints of the waist mechanism in comparison with the corresponding ranges found in the human.

TABLE II
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

Looking at Table II it can be observed that range of motion in some joints has been extended or modified. 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 in front workspace for the robot. This extends the space of the robot where the iCub can reach and manipulate objects. The extended range in the waist makes the waist to act also as a redundant mechanism for the arm motions.

The last specification to be discussed is the required torques for the waist mechanism. This forms the starting point for the selection of the actuation groups. To optimize the selection of actuators and reduction ratios, iterations of the mechanical design of the waist and simulation analysis of the system were carried out.

Particularly the selection of the type of actuator to power the waist of the iCub involved various simulation of the robot model while performing crawling motions with different speeds and transitions from sitting to crawling pose and vice versa. From this simulation, the peak toque requirements of each joint of waist mechanism were identified and presented in Table III.

TABLE III
TORQUE REQUIRED FOR THE WAIST MECHANISM

Waist joint	**Torque Required(Nm)**
Roll	30.1
Pitch	45.8
Yaw	27.2

III. WAIST MECHANICAL DESIGN

The CAD model and the first prototype of the waist mechanism of the iCub baby humanoid robot is shown in Fig. 2. The iCub waist was designed using the 3D CAD software *Pro Engineer Wildfire 2 from PTC.*

In the previous section, the role of the waist joint in the flexibility of motion of the upper body has been highlighted. Such flexibility must be accompanied with high positional accuracy of the upper body that is required during manipulation. To satisfy these requirements the iCub's waist was realized using a mechanism where the torque and power of actuators is used for upper body pitch and yaw motions without respect of the desired direction of the two actuators. This is possible due to the realized cable based differential mechanism as seen in Figure 1 and 2.

For the pitch motion of the waist the two actuator groups that power the pitch and yaw motion apply a synchronous motion to the two differential input wheels using the torque of both motors. For the yaw the motors turn in contrary directions. This causes a yaw motion on the upper body again using the torque of both motors.

This differential mechanism has several advantages when compared with traditional serial mechanisms used in humanoids robots. These are:

i) Increased stiffness and accuracy.
ii) The sum of the torque generated by the two actuators that powered 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 implemented with the incorporation of a pulley shaft that is directly connected to the upper body frame. Torque is conveyed through a cable transmission system that provides also additional gearing to meet the torque requirements of the roll joint, Table III. For the first prototype DC motor actuators were employed to power the waist joints.

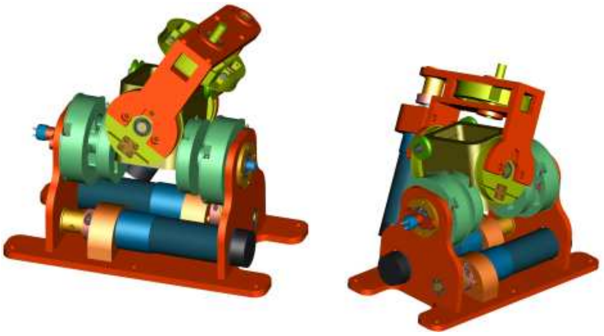

Fig. 1. CAD captures of the differential drive to be used as the robot waist.

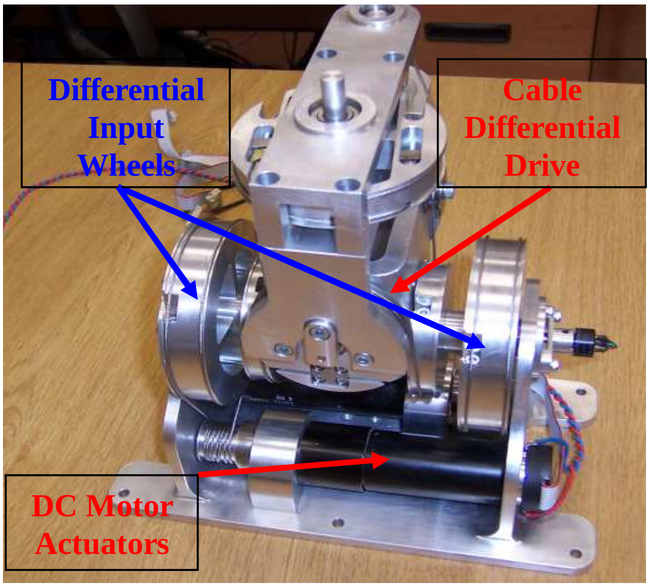

Fig. 2. Prototype of the differential based waist mechanism.

IV. SYSTEM MODEL

In order to achieve an effective control in waist motions an accurate model of the system has be developed and extensive simulations were performed.

A. Motor Actuator Model

For the development of this model a model of the motor actuator used to power the waist joints was required. Equations (1) and (2) characterize a general DC motor.

$$J\frac{d^2\theta}{dt^2}=T-B\frac{d\theta}{dt}\Rightarrow\frac{d^2\theta}{dt^2}=\frac{1}{J}\left(K_t i-B\frac{d\theta}{dt}\right)\qquad(1)$$

$$L\frac{di}{dt}=V-R\times i-e\Rightarrow\frac{di}{dt}=\frac{1}{L}\left(V-R\times i-K_e\frac{d\theta}{dt}\right)\qquad(2)$$

This mathematical model was implemented using MATLAB Simulink, Figure 3, and the results were cross-compared with the real system.

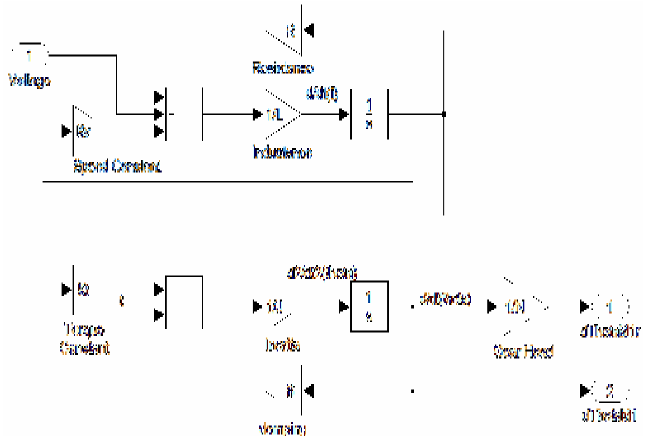

Fig. 3. MATLAB Simulink representation of the mathematical model of the two DC motors used to drive the differential waist mechanism.

B. Differential Mechanism Model

There are 2 motors controlling the pitch and roll motion of the robot waist, both located in parallel one in front of the other, but with its shafts pointing in opposite directions. From the kinematics analysis of the joints, the differential equations for the differential driver are:

$$R\times(\theta_{M1}+\theta_{M2})=\theta_{roll}\qquad(3)$$

$$R\times(\theta_{M1}-\theta_{M2})=\theta_{pitch}$$

(4)

Where R is the gear head reduction ratio for motor 1 and 2, θ_{M1} and θ_{M2} are the rotor angles for motor 1 and 2 respectively and θ_{roll} and θ_{pitch} are the waist roll and pitch rotation angles.

C. Waist Dynamics

In order to have an accurate mathematical description of the system the dynamics of the system must be included in the simulation; this includes the weights of the mechanical assembly, friction of the contact joints and motors, and ultimately the inertia of the system. For this, the waist dynamics block combines the waist kinematics (which combines the motion of the two DC motors in the differential scheme) and the dynamics of a generic limb. These two blocks represents the complete robot upper body which was estimated using an assumed weight that can be changed in order to perform a wide range of tests under different sets of conditions.

D. *Complete System Modelling*

In the simulations performed the position feedback is calculated by integrating the speed output from the DC motor model, in the real system, the speed is calculated using the derivative of the position output acquired from the incremental encoder readings. Figure 4 shows the final scheme including the differential equations block and the system dynamics for both motors, for a 2 DOF motion.

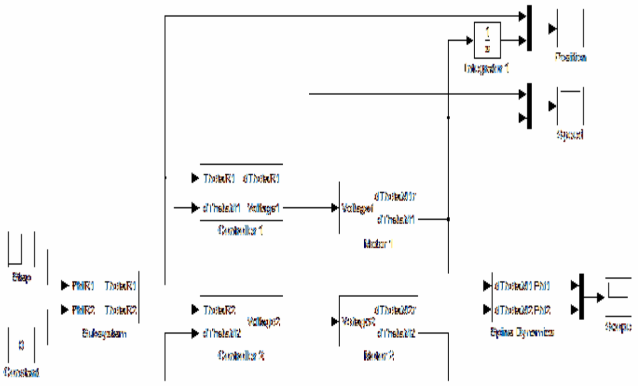

Fig. 4. Complete system for the 2 DOF differential joint. Speed and position control of 2 DC motors configured as a differential drive.

V. CONTROL SYSTEM

Presently different kind of approaches exist for control, each one with many advantages and disadvantages, but the classic PID control scheme is still implemented in about 90% of the real systems implemented [18]. In the present section, the design, model and simulation of a dual loop PID control system with a dynamic anti-windup scheme will be described.

A traditional PID controller uses the derivative and integral of the error signal; but when the reference input changes, the tracking error changes rapidly. The derivative signal of the tracking error can generate shock on the system [18]. To avoid this, the controller proposed uses the derivative of the output signal as shown in Figure 5.

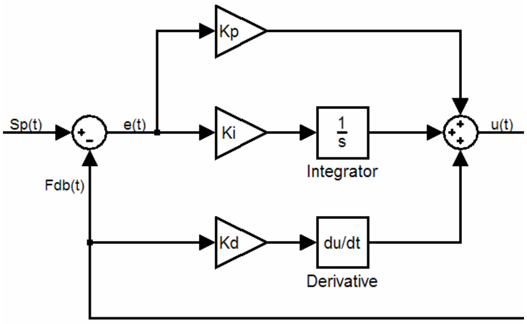

Fig. 5. Block Diagram of the classic three-term control scheme with derivative term using the feedback signal.

In order to perform a position and speed control, a cascade controller must be implemented, in the described system a dual loop controller is used to control both speed and position. As it is observed in Figure 6 a first inner loop is used to control speed, this loop uses the position controller (outer loop) output as a reference signal. The speed is then established by setting the maximum and minimum values of the output limiter of the position controller. The fact that the speed is to be adjusted by setting a maximum and a minimum value to the limiter implies that the system will saturate. A simpler limiter will limit the position control output to a maximum value, which represents the desired maximum rotor speed. If this speed is low enough, the rotor can take a considerable amount of time to reach its final position, which in turn will produce a high integral term value.

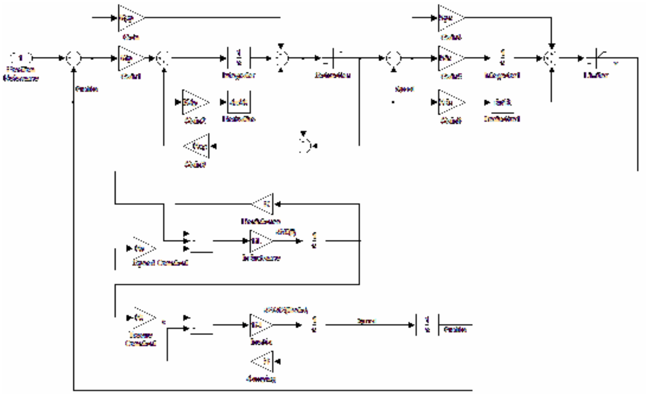

Fig. 6. Cascade control scheme for position and speed control, including the DC motor model.

In order to avoid this, a dynamic anti-windup scheme [18] was implemented; this scheme, Figure 7, takes the output of the system and compares it with a pre-saturated output to obtain a saturated error value, following, this value is multiplied by a previously set gain and then introduced to the integrator, reducing its value. Using this scheme it is possible to assure that the integral term wont have a high value so when the signals reaches its set point it will effectively reduce the steady state error, further more reducing the overshoot. Figure 6 shows the mentioned scheme.

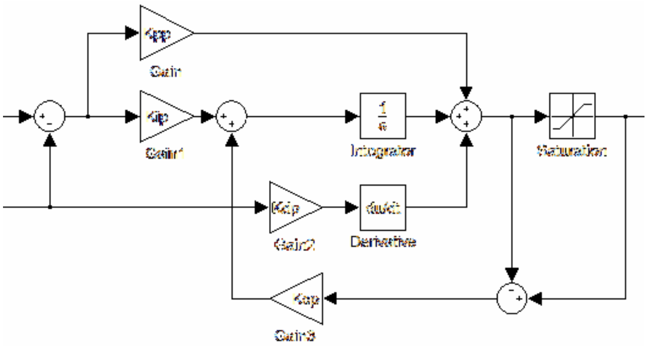

Fig. 7. Controller with dynamic anti-windup scheme, the integral term is effectively reduced, preventing overshoot and the saturation of the integral term.

VI. SIMULATION RESULTS

Testing of the control schemes were carefully evaluated and rigorously analyzed through simulations. For the following simulations, 2 types of reference signal where used: a step input signal and a sinusoidal signal with a set of different frequencies. In all cases, the solid lines represent the reference signals and the dashed lines the rotor position. In the next graphs, the only load considered was the weight of the limbs; the frictions in the joints were not considered.

A. *Speed Control*

The balance of the body of the robot is greatly affected by the motion speed due to inertial forces generated by the body weight. The following graphs show the simulation results of the speed controller, with a forced reference input signal (the actual speed reference is generated by the position controller). These simulations were performed using MATLAB Simulink. The actuator groups used for this test consist of two MAXON DC motors and gearboxes with a maximum output speed after the reduction of (2.1 rad/sec).

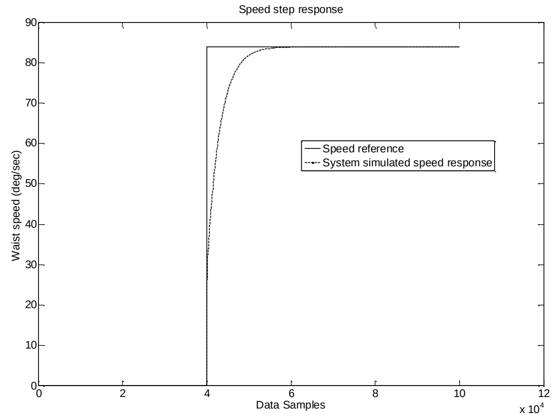

Fig. 8. Step response of the motor speed controller without load. This will help us evaluate the motor acceleration capabilities and the controller error margins.

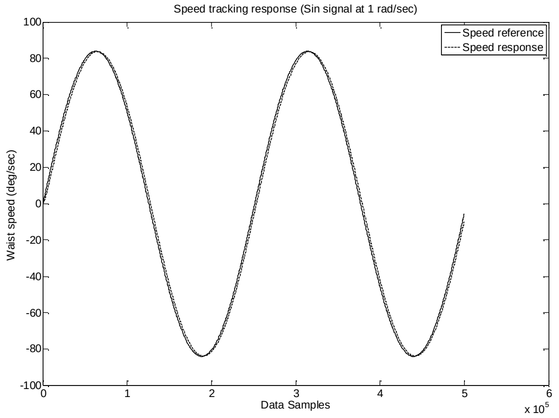

Fig. 9. With a 1 rad/s sinusoidal reference and a 1kg load over the joint.

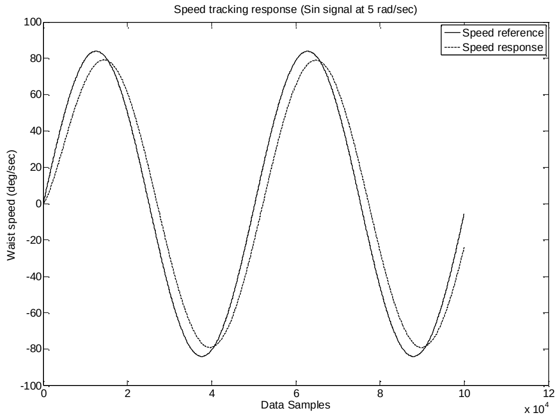

Fig. 10. With a 5 rad/s sinusoidal reference.

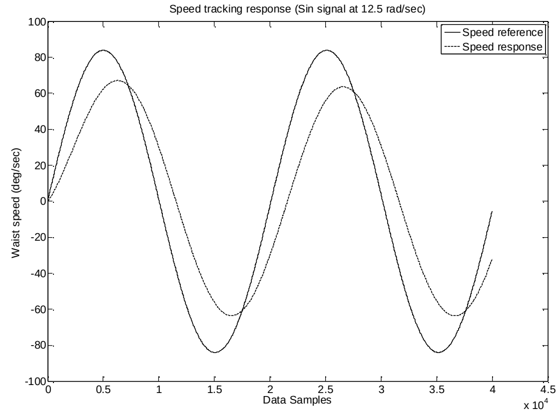

Fig. 11. With a 10rad/s sinusoidal reference.

For the simulations results presented, reference signals of 84 deg/sec (1.46rad/sec) were used and these represent the rotor speed for one of the motors.

This allowed us to evaluate the motor speed control capabilities under loaded and unloaded conditions and considering different motion directions (the load presented to the motor changes with the change of position of the gravity centre of the robot body)

The simulation results shows a good speed response time capable of moving the body of the robot at convenient speeds.

B. *Position Control*

The following graphs shows the simulation results of the position using the complete model (position and speed controller cascaded).

It can be seen the effect of the load in the tracking capabilities in the position control results using a 1Kg load; this load slows down the motion of the joint, even with a speed set near the motor maximum speed, though the position controller was able position the waist joints with errors around 0.03deg in steady state.

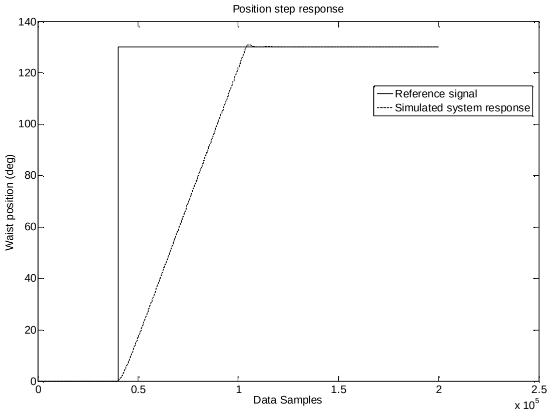

Fig. 12. Response for a square signal reference.

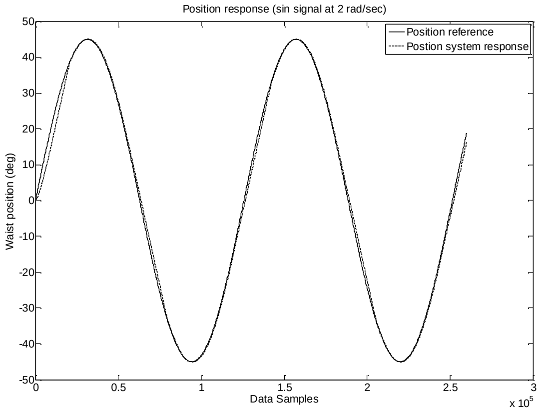

Fig. 13. Position tracking response with a 2 rad/s sinusoidal reference with a 90deg. of motion range.

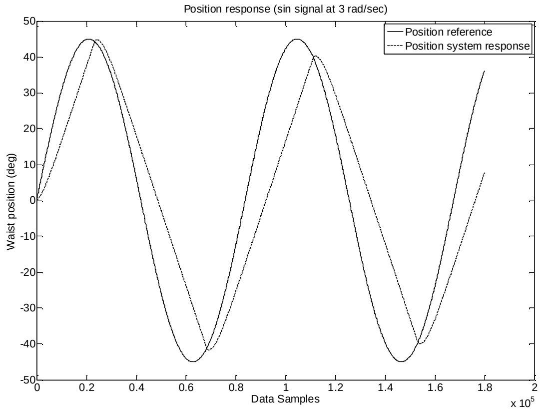

Fig. 14. Position tracking response with a 3 rad/s sinusoidal signal and 90deg of motion range.

Due to mechanical limitations, it can be observed from Figure 14 that the robot waist was able to follow accurately the reference signal at rates of change higher than 2rad/sec even setting the speed limit at its maximum.

VII. SYSTEM EXPERIMENTAL RESULTS

The following results were obtained by collecting measurements from the real system through the microcontroller (TMS320F2810, DSP from Texas Instruments) where the control system was implemented and its JTAG interface to a PC. Figures 15-17, show the results for the position control, when a step input is presented, with a previously set speed of 84 deg/sec in the joint. The joint is set to move forward and backwards between 22 and 65 deg.

After evaluating the results from the real system, different factors not considered in the simulation model like friction in the waist joints where notice to have little effect in the results.

From the graphs below, errors under 0.05deg in the position and under 1deg/s for the speed can be observed.

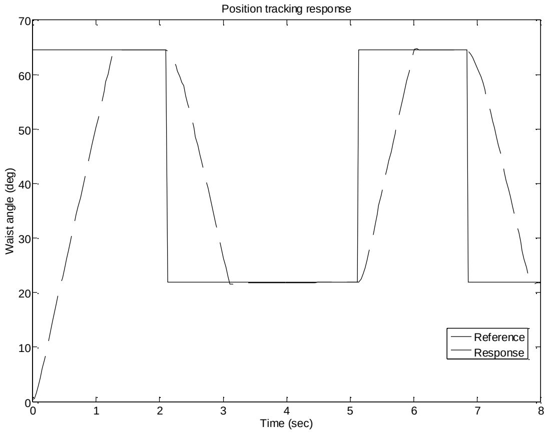

Fig. 15. Position Tracking Response of the real system. Reference signal in solid line, actual waist position in dashed line.

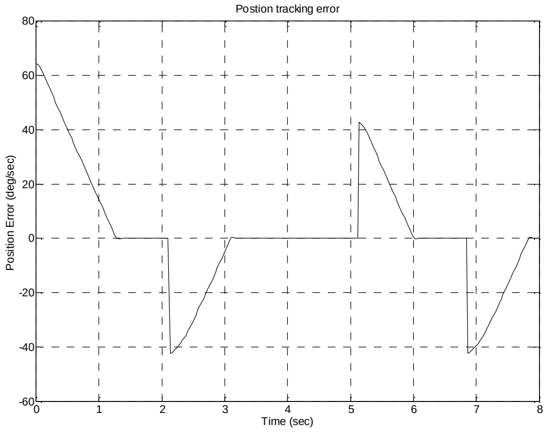

Fig. 16. Position tracking error of the real system.

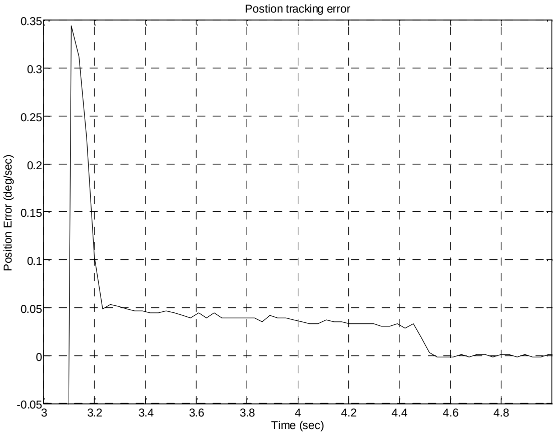

Fig. 17. Position tracking error. In this close up it is possible to observe the position error in steady state. Actual results show errors under 0.05deg in steady state with 0.35deg overshoot.

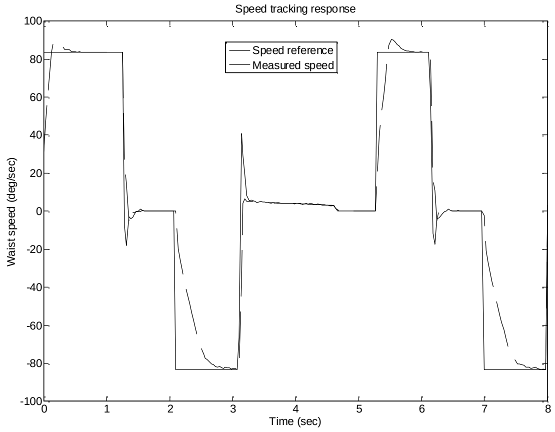

Fig. 18. Speed tracking response of the real system. Reference signal in solid line, actual waist speed in dashed line.

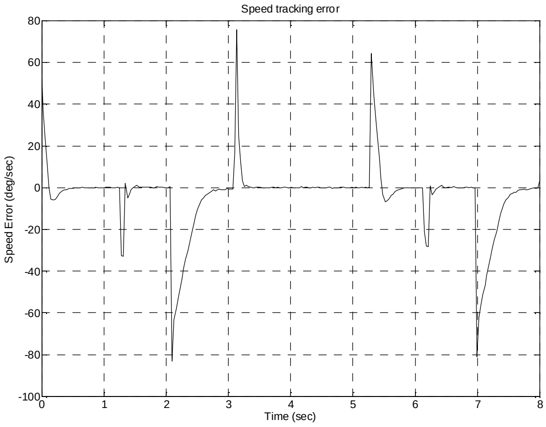

Fig. 19. Speed tracking error of the real system.

VIII. CONCLUSIONS AND FUTURE WORK

This work presented the design of a differential based mechanism developed to form the waist joint of a baby humanoid robot. A cascade PID based position and speed controller was optimally developed and its characteristics, such as overshoot, settling time and steady state error, have been evaluated through both experiment and simulation analysis. A control system consisting on a PID controller was established to achieve accurate position control of the joints.

It has been demonstrated through experimental implementation that the proposed control system can achieve control accuracy of 0.05 deg in step responses. In addition, a favorable speed control for sinusoidal and step trajectories was achieved. The control results presented in this study are quite self-explanatory, demonstrating that the proposed mechanism and control system can offer a desirable motion range with high position accuracy.

Future work includes a performance evaluation of the system using variable length and weight bodies to evaluate the effect of inertia over the system as well as mechanical (fatigue, maximum torques, etc.), electronic (current consumption, noise, etc.) and thermal effects.

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