Techniques for Velocity and Torque Control of RC Servomotors for a Humanoid Robot

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Abstract: **This paper proposes a general low-level control architecture for a small-size humanoid robot using on off-the-shelf technologies. The main features of this implementation are the distributed control approach and the relevance given to the sensorial information. Some practical issues on servomotor control are given since that turned out necessary before entering higher levels of control. Particular attention is given to the low-level control of RC servomotors and the enhanced performance achieved by software compensation. The distributed set of controller units is the key element towards a control system that compensates for large changes in reflected inertia and providing position and velocity control. Furthermore, an intermediate local-level controller is implemented based on force sensing, providing robust and adaptive behaviour to changes in a slope surface.**

Keywords: **Humanoid robotics; Biped locomotion; RC servomotors; Low-level control; Position/velocity control.**

I. Introduction

The field of humanoid robotics has stimulated an increasing interest in a wide community of researchers. As consequence, the number of research and development projects aimed at building bipedal and humanoid robots abound. The great success of Honda's robots [1,2] has inspired others to replicate the impressive design and skills [3]. On the other side, humanoid projects from academia, operating on a much smaller budget, aims at research on low-cost and easy-to-design robots, such as PINO [4], ESYS [5] and HanSaRam [6]. As robotics technology continues to progress, there will be a need for software and algorithms useful to improving the usability and autonomy of these complex machines.

The goal of this paper is to present the technical, technological and innovative controls aspects in building a small-size humanoid robot at reduced costs using off-the-shelf technologies. The work reported here has an experimental basis where our ideas and particular control algorithms have been tested and verified on a real robot to form a critical hypothesis-and-test loop. The paper begins by presenting the engineering solutions and the research results with a potential for application, such as the performance of servomotors, practical issues on their control and the test of the distributed control approach. Afterwards, the paper reports the development of the low-level control structure that is obtained by the addition of an outer position feedback loop to the servo's internal controller. The most relevant feature of this implementation is the distributed architecture where centralized and local control may co-exist to provide robust full monitoring and efficient control. The integration in simple local control units of a sensorimotor command layer that encapsulates useful combinations of sensing and action play a key role to allow for more advanced algorithms that go far beyond the classical control of robots. The paper reports on the development of force-driven actuation and control that are successfully applied to demonstrate the possibility of keeping the humanoid robot in upright balance position using the ground reaction forces. A more detailed explanation of the design considerations that governed this project, namely the distributed control architecture and the software development, can be found in previous publications [7][8]. Fig. 1 shows the humanoid robot at the current stage of development.

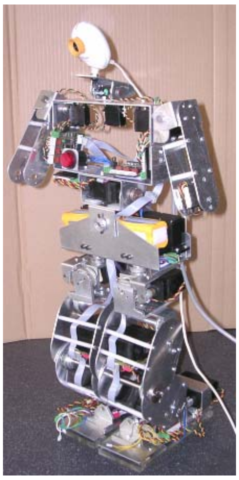

Fig. 1. Biped humanoid robot with 22 DOFs

The remainder of the paper is organised as follows. Section 2 describes the main technological issues, including the actuators and the sensorial requirements. Section 3 describes the implementation of the low-level controllers using a dynamic PWM generation with real feedback from the motor internal potentiometer. Section 4 gives an example of intermediate level control implemented as a local controller based on force sensing. Section 5 concludes the paper and outlines the perspectives towards future research.

II. Robotic System's Description

A. Actuators and their limitations

The complete system is conceived with 22 actuators of three different types according to torque requirements of the several joints: more power on legs and less power on neck and arms. For the dimensions involved, off-the-shelf actuation technologies do not offer significant alternatives other than the small RC servomotors, such as those from HITEC. The servomotor itself has a built-in motor, gearbox, position feedback mechanism and controlling electronics. Since these servos, even though the most powerful among their counterparts, offer torques not much higher than 2 Nm; gear transmissions had to be implemented in the mechanical structure.

The selected servomotors are practical and robust because the control input is based on a digital signal whose pulse width indicates the required position to be reached by the device. Its internal controller decodes this input pulse and tries to drive the motor up to the required position. However, the controller is not aware of the motor load and its velocity varies with the load. By design, servos drive to their commanded position fairly rapidly depending on the load, usually faster if the difference in position is larger. Additionally, which may be a critical concern, as the load increases, a steady-state error occurs, turning the device into a highly non-linear actuator upon variable loads on the shaft.

An entire system was set up to evaluate the actuator performance required for the servomotor advanced control; that includes a master and a slave unit controlling a servomotor properly fixed and loaded as described ahead. On the one hand, the master unit is connected to a computer through a RS-232 link, using MatLab software as the user's interface. On the other hand, the slave unit is connected to the servo mechanism in two ways: by sending the desired servo position command and by reading the potentiometer feedback signal. The experimental setup comprised several loads that were applied to the servo shaft through a linkage with 10 cm long. The servo was fixed in a mechanical lathe such that its zero position corresponds to the perpendicular between the link and the gravity vector. Finally, and this was the sole hardware intervention on the servomotor unit, in order to measure the servo position feedback signal, an extra output wire was connected to the servo internal potentiometer. Fig. 2 shows photos from this experimental arrangement where a calibrated weight is being lifted up.

Fig. 2. Experimental evaluation of the actuator's response using a HITEC HS805BB servomotor

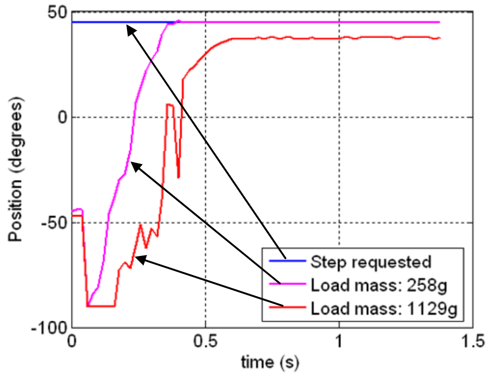

Fig. 3. Step response for two loads from -45º to +45º

After applying a step from -45º to +45º, the first notorious observation is the presence of steady-sate errors. For a low mass, the steady state error is negligible, but for the larger load (1129g) about 8º error remains after the transient phase (Fig. 3). Another observed anomaly in Fig. 3 is the unstable dynamic behaviour on position reading, which shows at the beginning a sudden jump to a position below -45º and some oscillations during the path up to the final set point. The interesting part of this observation is that the motor shaft did not show this behaviour; a continuous and a fast motion to the final position were observed without speed inversions or oscillations.

In order to implement some sort of velocity control, some experiments were then carried out in a manner that a variable position would be successively requested to the servo. The rate at which each new position was imposed settled some kind of velocity. Nonetheless, the only way to do it is still to impose (smaller) position steps to the servo controller; only their magnitude and rate will dictate some desired "average velocity". This approach will generate an approximately linear increase (slope) for the position, which is to say, some constant velocity. In addition, beyond the position control, velocity control is introduced by the definition of the ramp length. In Fig. 4 it can be seen that, although the transient response has a very improved behaviour, the steady state error still exists. This hard limitation had to be overcome by means of dynamic PWM generation with real feedback from the motor internal potentiometer.

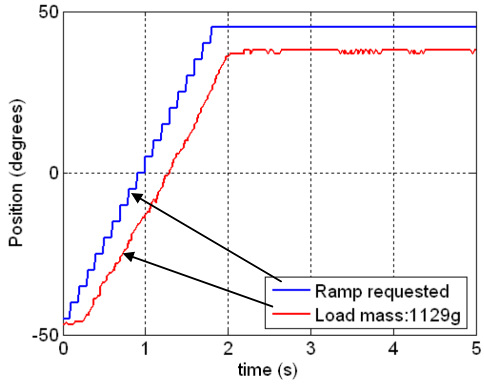

Fig. 4. Response to a slope input

B. *Servo potentiometers and motor current*

Joint position is currently read directly from the servomotor potentiometer. This was not as easy as initially expected due the complexity of the servos internal control unit. Indeed, the position reading only makes sense when duly synchronized with the PWM generation; doing otherwise will conflict with the servo own integrated controller (Fig. 2).

Having solved this initial difficulty, the need for an additional external potentiometer or encoder is now postponed *sine dia*. Related to this phenomenon is the electric current consumption which was initially expected to be measured indirectly by the voltage on a resistor (0.47 Ω) in series with the servo. Fortunately, after studying the servos potentiometer during operation, as observed in Fig. 5, current reading may be extracted from the potentiometer voltage level itself. All this has required elaborated low-level software development since PWM generation and sensor reading are synchronized and tuned with resolution of up to 1 μs for three simultaneous servos.

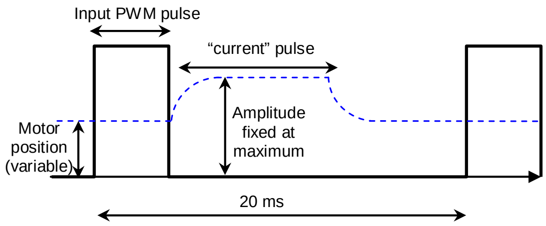

Fig. 5. PWM for motor control and position feedback potentiometer reading

C. *Force sensors*

The foot sensors are intended to measure the force distribution on each foot to further assist during locomotion or simply keeping upright. Four sensors on each foot allow evaluating balance. Commercial force sensors are expensive, so it was decided to develop a system based on strain gauges and amplify the deformation of a stiff material. The result is a kind of foot whose details can be viewed in Fig. 6 and is based on 4 acrylic beams located on the four corners of each foot that deform according to the robot posture. A Wheatstone bridge and an instrumentation amplifier complete the measuring setup. The electronics hardware lays on a piggy-back board mounted on the local control unit.

Due to the very small measurements involved, additional care in building the circuit for force measurement has been taken. Namely, to compensate for temperature variations and noise asymmetries, the bridges have been made with full symmetric components. Two strain gauges were used: one subjected to the force and a second one in the opposite arm of the bridge that does not suffer any strain, but ensures similar temperature and noise responses. Additionally, similar adjusting potentiometers have been installed on the other bridge arms to ensure the proper behaviour for temperature and noise. Results were quite satisfactory since they showed a large stability even for small forces.

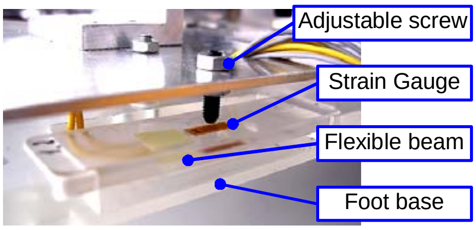

Fig. 6. Foot sensor details

III. LOW-LEVEL CONTROLLER

Among the major challenges in building low-cost and easy-to-reproduce humanoid robots, the performance of their control architectures and the constraints on actuator systems assume a special importance. In general, the control problem consists of: i) providing the adequate computational resources and, ii) using control laws and strategies to achieve the desired system response and performance. The first part of the problem has been extensively discussed in Section II.

Here, we concentrate on the second part with the emphasis being placed on the implementation of the low-level controllers to achieve an improved performance. The basic idea is to introduce suitable compensation control actions via the closure of an outer position control loop. In this work, procedures are described on how an external microcontroller can read the shaft position in order to evaluate intrinsic velocity by the motor.

A. *Servo control enhancement*

It is expected that enhanced performance can be achieved by software compensation, provided that position and/or torque measurements are available. In such cases, an effective strategy to improve the servo's operation is using an external controller, where an outer position control loop is closed around each slave unit. Fig. 7 illustrates the block diagram of the proposed servo controller.

The servo circuit has a very narrow input control range and it is difficult to control accurately, though it has adequate speed and torque characteristics. The outer position control loop is proposed as an effective tool to achieve good performance in terms of steady-state behaviour and enhanced trajectory tracking capabilities. That is achieved by a variable PWM throughout the full excursion o a joint. The algorithm is based on dynamic PWM tracking using the servo own potentiometer for feedback. In other words, the software tracks motor position with time and adjusts the PWM in order to accelerate or decelerate the motor motion.

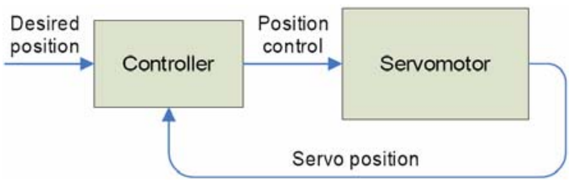

Fig. 7. Servo controller diagram

For that purpose, several control algorithms can be derived. The simplest approach that can be followed is to consider a digital PID-controller (or a particular combination of P, I and D cases). These requisites suggest that the control problem can be solved by an incremental algorithm in which the output of the controller represents the increments of the control signal. Hence, a digital PID controller was implemented following the control law as described, in the Z-domain, by equation (1):

$$U(z) = \frac{\left[K_I + K_P \cdot \left(1 - z^{-1}\right)\right] \cdot E(z) - K_D \cdot \left(1 - z^{-1}\right)^2 \cdot Y(z)}{1 - z^{-1}} \quad (1)$$

where $K_I = k_i \cdot T_S, K_P = k_p, K_D = k_d / T_s$ are constant positive gains, $Y(z)$ is the system position output and $E(z)$ is the error (difference between desired input and current output affected by a small dead-zone).

In this line of thought, this subsection focuses on the control and planning algorithms to generate smooth and stable motions, without requiring any modification of the servo internals. In the case of interest, the system to control is formed by a single joint axis driven by an actuator with pulse-width control.

B. Single-joint control

Several experiments were carried out in order to make a comparison between variations of the control scheme. The first experiment is aimed at verifying the effectiveness of the integral action. It is required to move the joint angle from an initial value q_i = -45º to a final value q_f = 45º in a given time t_f = 2 s, for a load of 924 g. Once again, the determination of the specific trajectory is given by position steps successively updated. The results are presented in Fig. 8 in terms of the desired and the measured angular positions. Significant differences occurring in the performance of the open-loop and the closed-loop system can be observed: the steady state error is eliminated and the delay time is reduced when applying this compensator. The additional curve (controller output) represents the real pulse-width control signal necessary to guarantee the effective conformity between input signal and output shaft position.

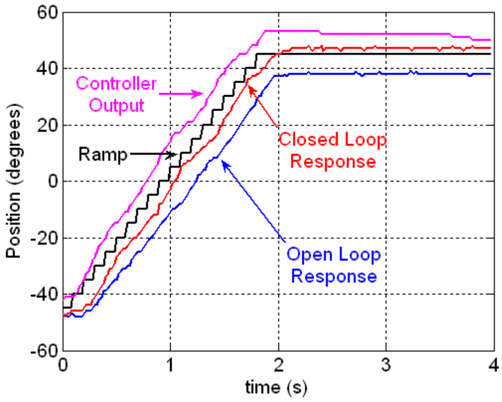

Fig. 8. Response to a slope input for integral action with K_I = 0.2

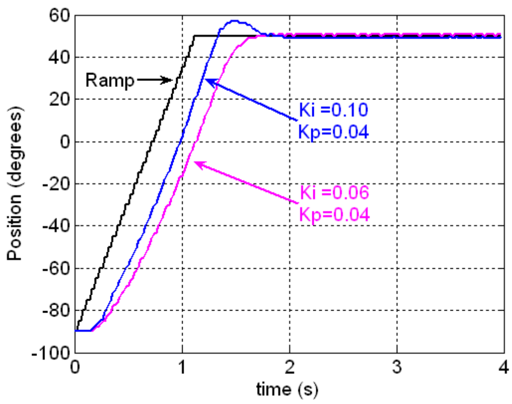

Fig. 9. Response to a slope input for proportional plus integral control

In the second experiment the proportional action is introduced in order to obtain a PI-controller that leads to improved speed response and damping. In this case, a more demanding specification for the desired slope is chosen. Each new step position is updated at the maximum rate of 50 Hz (corresponds to the PWM period) with an amplitude of 5 degrees. Let the desired initial and final angular positions of the joint to be -90 and +50 degrees, respectively, with time duration of 1.12 seconds. Although the PI control eliminates the steady-state error, it can be recognized that path tracking accuracy is still poor during execution (Fig. 9).

Improvement of the position tracking accuracy might be achieved by increasing the position gain constant K_P; however, this would give rise to larger overshoot and establishment times. To this purpose, a third experiment is conducted such that the control algorithm is rewritten to include the proportional, integral and derivative terms. Additionally, a planning algorithm is used to generate smooth trajectories that do not violate the saturation limits. In general, it is required that the time sequence of joint variables satisfies some constraints, such as continuity of joint positions and velocities. The choice of a third-order polynomial function to generate the joint trajectory represents a valid solution. The velocity has a parabolic profile, while the acceleration has a linear profile with initial and final discontinuities.

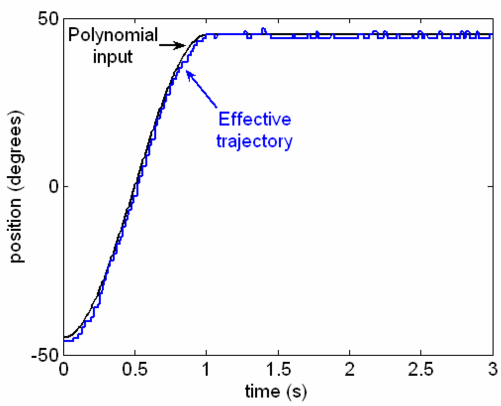

Fig. 10. Response to a slope input for PID control (K_P = 1.46, K_I = 0.39 and K_D = 0.15)

Fig. 10 illustrates the time evolution obtained with the following data: q_i = -45º, q_f = +45º, t_f = 1.12 s. The gains of the outer control loop have been tuned to limit the tracking errors. Significant improvements in the system's performance can be observed: zero steady-state error with no overshoot and limited tracking errors.

C. *Support-leg control*

It is now desirable to extend the previous results from the single-axis system to the humanoid robot. At the lower level in the control system hierarchy lay the local controllers connected by a CAN bus to a master controller. These slave control units generate PWM waves to control three motors grouped by vicinity criteria (entire foot up to knee and hip joints) and monitor the joint angular positions by reading the servo own potentiometer. In order to verify the effectiveness of the control scheme, a large number of experimental trials were carried out with the humanoid platform. The next step is to demonstrate the behaviour of a single-leg when performing some basic movements. More concretely, the desired movements to be performed consist of: (1) a vertical motion from an upright posture; and (2) a lateral motion in which the leg leans sideways (±27 degrees). In both cases, an additional load of 2.1 kg is attached to the upper part of the leg to emulate the mass of other segments.

There are two servo loops for each joint control: the inner loop consists of the servo's internal controller as sold by the vendor; and the outer loop which provides position error information and is updated by the microprocessor every 20 ms. We now compare the robotic system's behaviour when only the inner loop is present (hereinafter "open-loop control") and when the extra feedback loop is added (hereinafter "closed-loop control"). In the later case, the outer servo loop gains are constant and tuned to perform a well-damped behaviour at a predefined velocity. Further, the joint trajectories along the path are generated according to a third-order interpolating polynomial with null initial and final velocities.

The experimental results in Fig. 11 show the significant differences occurring in performance of the two control schemes (open-loop, and the cascading close-loop controller). The first observation is the usually poor performance of the open-loop control, particularly for steady-state conditions, which restricts the scope of its application. As a consequence of the imposed vertical motion, the limitations of the open-loop scheme are more evident when observing the temporal evolution of the ankle (foot) joint. On the other hand, an improved performance is successfully achieved with the proposed outer control loop, both in terms of steady-state behaviour and enhanced trajectory tracking.

IV. Force-Driven Local Control

The major problems associated with human-like walking results from the high centre of gravity (COG) with a small contact area to the ground. In other words, keeping balance is a central concern in order to engage useful tasks, from standing upright posture to motion goals. In what concerns control, the difficulty lies in the uncertainty of the environment and the limitations of the contact between the

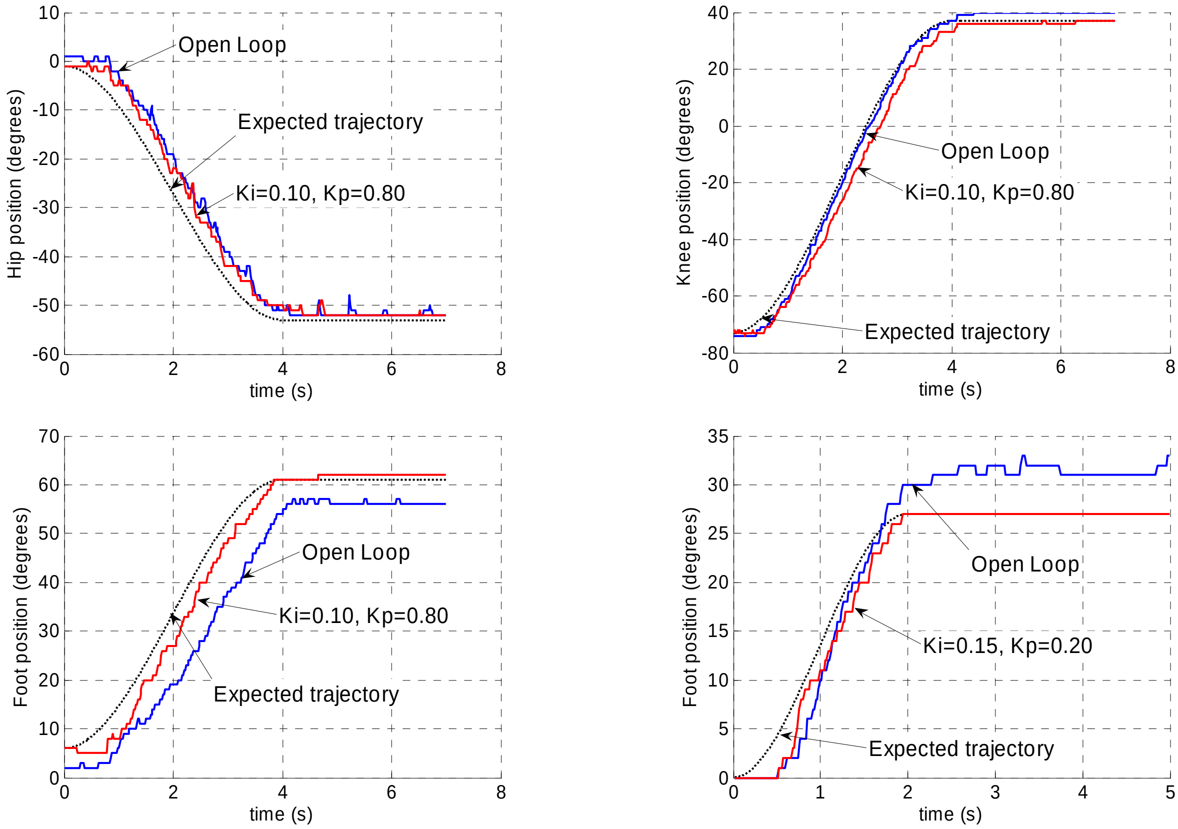

Fig. 11. Response to slope inputs for a PI controller. Top and left-bottom charts: behaviours of the 3 involved joints during up-down motion of legs. Bottom-right: behaviours of foot joint in lateral motion

robot and the environment.

This section shows an example that is being developed to demonstrate the possibility of achieving proper humanoid leg balancing using a local control approach. For this purpose, feedback control from several sensors is considered, including angular position in each joint and four force sensors inserted into the foot corners. The sensors in the feet provide information about the ground reaction forces and the location of the centre of pressure (COP), as well as about the full contact of the foot with the ground. This opens up new action lines and possibilities for distributed architecture approaches where centralised and local control co-exist and concur to provide robust full monitoring and efficient operation of such a complex systems.

A. Humanoid leg balancing

The ability to balance in single support, while standing on one leg, is an important requirement for walking and other locomotion tasks. In the previous section, the approach to balance control assumed the presence of explicitly specified joint reference trajectories and calculations based on static configurations to derive the necessary PWM input signal. The goal of this section is to present the developed control algorithm that provides enhanced robustness in the control of balancing by accounting for the ground reaction forces. Thus, the system is able to stand on an uneven surface or one whose slope suddenly changes. In a similar way, the control system senses that it has been pushed through the force sensors in the soles of its foot and reacts to maintain stability.

The open challenge is to allow local controllers to perform control based on sensor feedback and possibly a general directive. Here, the global order is to keep balance in a desired COP location and, although all actuators can intervene, the ankle joints have the relevant role to keep an adequate force balance on each foot. The controller presents the following key features. First, the force sensors are used to measure the actual COP coordinates and simplify control of abstract variables such as the centre of mass location. The controller is independent of the robot's model or nominal joint trajectory data by resorting to a solution scheme that accounts for the error between the desired and the actual COP. Second, the control system commands the joint actuators by relating the joint velocities to the above error using a proportional law. The resulting on-line motion planning constitutes one of the important aspects to achieve higher walking robustness, at the expense of an increased demand for computational resources. Third, a joint velocity saturation function is used to avoid abrupt motions while satisfying dynamic balance constraints.

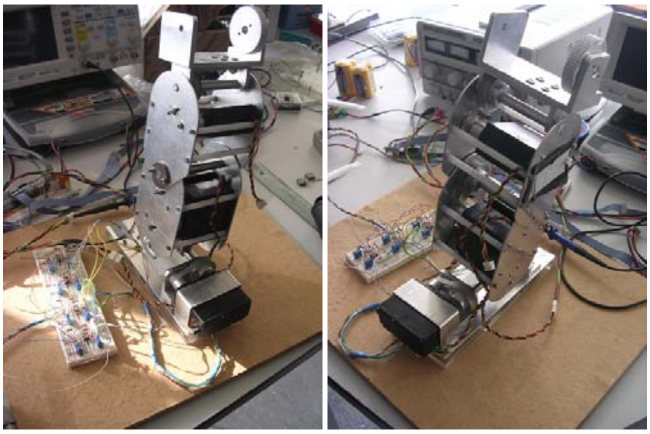

Fig. 12. Humanoid leg where balance experiments based on force were done

B. Experimental results

The following analysis illustrates the emergence of an appropriate behaviour when the system stands on a moving platform. The desired goal is to stand in an initial posture, while the control system relies on the reaction force data to estimate slope changes. As stated before, the emphasis in this work is on procedures that allow the robot to calibrate itself with minimal human involvement. Thus, after an initial procedure in which the humanoid leg is displaced to the desired posture, the control system generates online the necessary joint adjustments in accordance with the pre-provided goal. The joint velocity values are utilised in real time to modify dynamically the corresponding PWM signal. Fig. 13 illustrates the time history of the COP and the ankle joint angle obtained when imposing a motion on the platform that reveals the role of the ankle roll joint. On the other hand, Fig. 14 shows the results obtained when the humanoid leg adapts to unpredictable slope changes that reveal the main role of the ankle pitch joint. In both cases, the use of the proposed control algorithm gives rise to a tracking error which is bounded and tends to zero at steady state. This indicates that the posture was adjusted and the differences on the ground reaction forces become small.

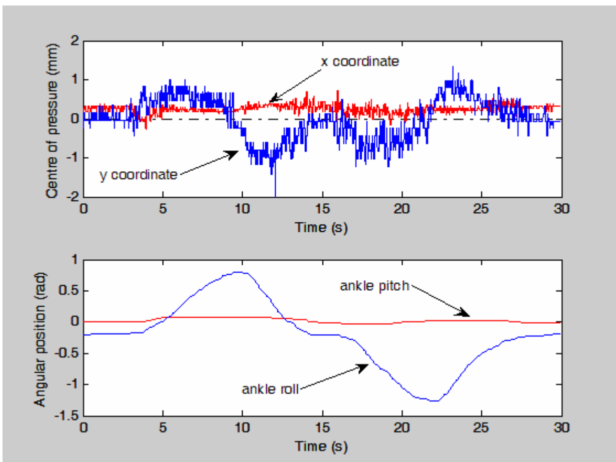

Fig. 13. Ankle roll joint predominance: temporal evolution of the centre of pressure (up) and joint angular positions (down)

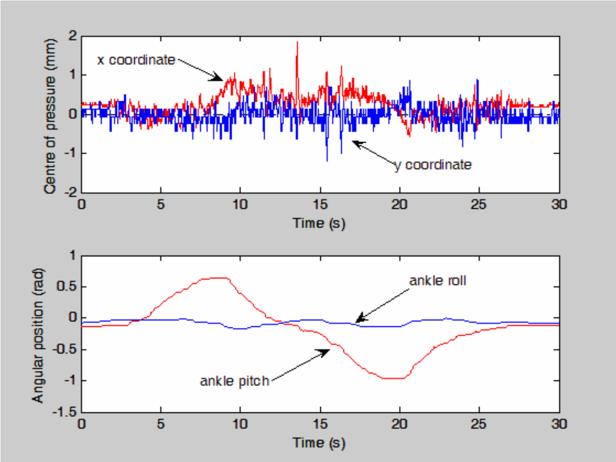

Fig. 14.Ankle pitch joint predominance: temporal evolution of the centre of pressure (up) and joint angular positions (down)

V. Conclusion and perspectives

This paper described the development and integration of hardware and software components to build a humanoid robot based on off-the-shelf technologies. The distributed set of microcontroller units is the key element towards a control system that compensates for large changes in reflected inertia and providing variable velocity control. Particular attention was given to the low-level control of RC servomotors as a relevant and abundant component of the humanoid system. Results with a closed-loop controller implemented with software show that motors' low-level velocity control has been made possible. The humanoid system reached a point where intermediate and high level control can now flourish. An example has been given for a kind of intermediate level control implemented as a local controller based on force sensing.

Most of the final platform hardware has been built and the results are very promising, mainly because many approaches and research issues suddenly opened and will provide opportunities to test distributed control systems.

Ongoing developments on the humanoid platform cover the remainder hardware components, namely the inclusion of vision and its processing, possibly with a system based on PC104 or similar. The future research, which has already started, will cover distributed control, alternative control laws and also deal with issues related to navigation of humanoids and, hopefully, cooperation. Force control techniques and more advanced algorithms such as adaptive and learning strategies will certainly be a key issue for the developments in periods to come in the near future.

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