Chapter 3

Robot's hardware design

3.1 Introduction

The robot's hardware design have a huge influence in order to obtain a reliable biped robot. It is an arduous process and some times with not "written rules". In the robot's hardware design process many requirement and conditions must be care for to ensure a stable biped robot walking. Those requirements are presented on the mechanical structure design and the electronic design.

The mechanical structure design must always attempt an adequate robot's proportions. For that reason, mass distributions, CM (Center of mass) location and the actuators selection are important stage on the mechanical structure design and have a direct impact on the robot's performance. In this thesis, also a modular-flexible design for an easy links robot's configuration is proposed, allowing quick changes on the structure.

The electronic design must mainly assure be fast enough to perform the control algorithms, handle some sensors, intercommunication to a PC and finally a portable electronic is recommendable.

In general, the robot's hardware design must keep on mind add less weight as possible and been "low cost" since a low-cost biped robot's design philosophy is been applied.

3.2 Mechanical structure

First than a biped robot can achieve static or dynamic walking a mechanical stable robot's structure must be guaranteed. The mechanical structure has such importance, that even a non-controlled biped robot with correct mechanical proportions can achieve dynamic walking [50]. In this sense, proportions, length and distributions of the robot's body mass have a huge influence on the gait performance.

The key of the mechanical stability of a biped robot is an adequate CM (Center of mass) location. The CM (also called centroid) is the point in a system of bodies or an extended body at which the mass of the system may be considered to be concentrated and at which external forces may be considered to be applied. The CM is determined during the mass distribution process.

The correct placing for the CM is the lower waist, similar to humans. This provides for stability and allows the waist to be moved, shifting the CM to achieve desired accelerations to counteract existing undesired accelerations [11] [12].

Naturally, the position of the CM change during the walking gait. In this sense, the robot's mechanics design must facilitate, that the controller compensate theses changes. By the other side, a high enough CM contributes to an easier modification of its position bia actuators.

Also, other phenomenon intervene on the walking process, like the inertias generated by the actuators movements and the gravity force. A lower CM is recommendable in order to increase the robot's stability for the inertial phenomena.

Thus, the CM should be placed in a location low enough to stabilize the robot inertially, but high enough so that it can be moved by the actuators, needing small changes positions to correct it (to avoid biped robot unstability).

For the final biped robot prototype, two biped's previous designs were needed. In the next section, the previous designs are briefly described, then a description of the mechanical structure design for the final prototype is exposed.

3.2.1 Previous prototypes

In this thesis, a first biped robot design experience was earn with the MEX-Biped [13]. Its mechanical structure was compound by 8 DOF and was designed with plastic and aluminum parts (Figure 3.1). Each part was designed especially

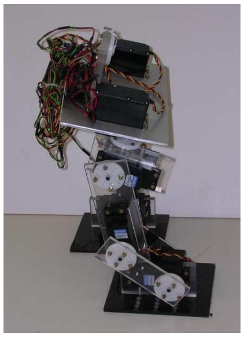

Figure 3.1: First prototype, the "MEX-biped".

and were not interchangeable. This, difficult significantly any change to be made on the CM location (the only possibility to change the CM was adding extra weight to the robot). The MEX-biped was able to be stand and perform static walking. Some balance control intents were implemented on it, for example with simple inverted pendulum. This robot also bring some experiences for the walking sequence means periodic function approach [12] and CPG central patterns generators [33]. and was the base of the final biped robot prototype of this thesis.

Then a second biped robot prototype was designed, the "Dany walker V1". Its mechanical structure was compound by 10 DOF links designed with low-density aluminum (Figure 3.2). Each link was redesigned applying a modular philosophy (explained at 3.2.2.1) allowing the interchange and easy modification of its structure. This, feature facilitate changes on the CM location without add extra weight to the robot. In this prototype, a balance control means an inverted pendulum add to its structure was implemented. But, the pendulum complicate the dynamic system since the delay time between the controller response and the robot's at walking was to large. As a result, the designed system was to complex and the balance control was unstable. For that reason, the pendulum, used as an actuator for the balance control was abandoned.

3.2.2 Final prototype

The final biped robot "Dany Walker" is composed by 10 low-density aluminum links rotational on the pitch axis at the hip, knee and ankle. Each link consists of a modular structure designed to allow an effective torque transmission and low deformation [13]. The links are connected forming a biped robot of 10 degrees

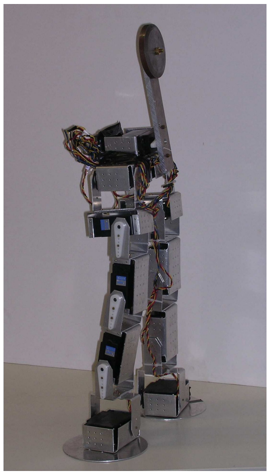

Figure 3.2: "Dany Walker V1" biped robot with inverted pendulum.

of freedom as shown in figure 3.3. Figure 3.4 shows the CAD design using the inventor program.

The "Dany walker" had a correct CM location for standing but at walking the CM was to high, generating unstability. In order to stabilize the robot as much as possible (static and mechanically), the CM was placed as low as possible while still allowing the waist to be useful for compensating by the movements of the lower limbs. To achieve this goal leg links as short as possible were designed and also a short leg's position was adopted (figure 3.5).

The ratio of the combined mass of the leg links to the combined mass of the upper body was as small as possible. In this manner movements of the leg will affect the position of the CM marginally, and even only in the sagittal plane. Thus, is possible to control the lateral balance of the robot by swaying the waist (by 4 motors, two at waist and two at the ankles figure 3.6) in the lateral plane. Since these planes are perpendicular, movements of the leg affecting the sagittal plane of the robot are ignore.

Since the precise construction of the robot was not know in advance, an estimated of the mass distribution was obtained from measuring material samples and weighting of components parts. Finally the distribution of mass of the constructed robot differed slightly from the estimated mass distribution due to two factors. The reason was that the amount of aluminum required to make up the structure and the electronic was underestimated. This increased the final mass of the robot above the estimated mass by approximately 710 g, making

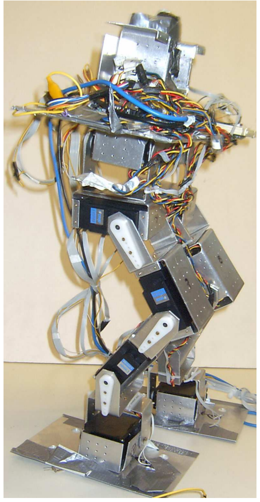

Figure 3.3: "Dany walker" biped robot.

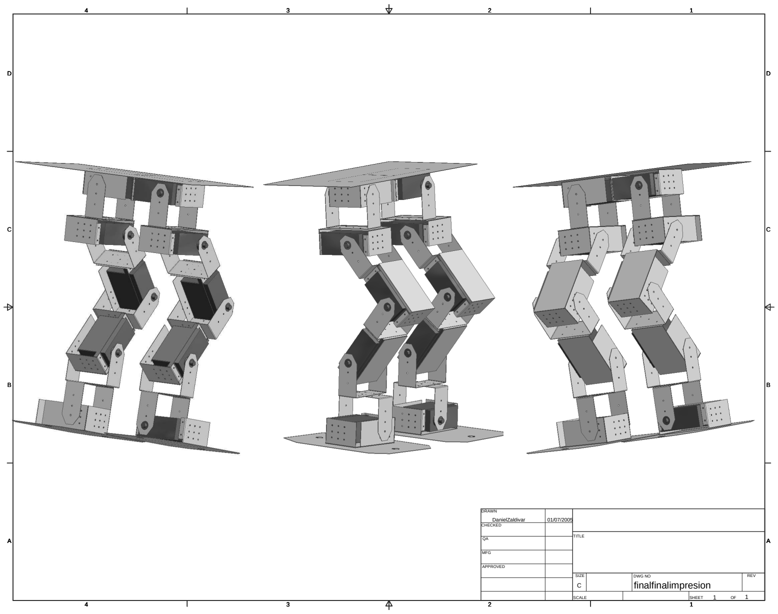

Figure 3.4: "Dany walker" biped robot CAD design.

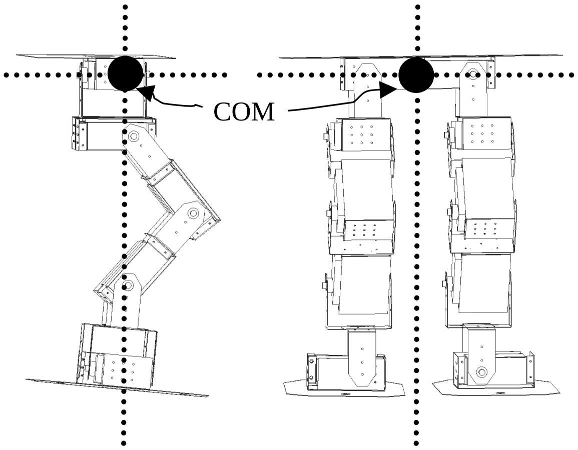

Figure 3.5: CM location on "Dany Walker" biped robot.

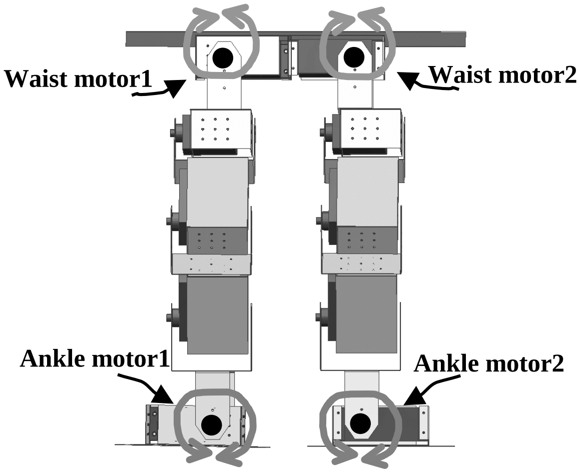

Figure 3.6: Lateral movements (four lateral motors).

the final mass of the robot 3.1 Kg. Most of the heavier aluminum was added to the waist to stabilize the CM. The table 5.1 shows the final robot's parts weighs.

Part	Weight
Each module	202g
Feet	185g
Waist+Electronic	710g
Total weight	3100g

Table 5.1 robot's final weights

3.2.2.1 Modular Design

At walking the robot will be experiment normally strong forces especially in the joint points, this should be considered at the design. By the other hand a compromise should be find between the weight and the robot's resistance. Thus, as a result from the first biped robot experience [13] all the robot's modules were redesigned using the CAD tool "inventor" (figure 3.7) and then constructed using 1.5 mm low-density aluminum as shown in figure 3.8, this modules reinforce the contact axe by adding an extra contact axis in the aluminum structure. This redesign has increase notably the robot's joint resistance and reduce the energy demand at the joint. Also, this modules allow to construct rapidly different robot's configurations, by adding modules or changing its positions, simplifying likewise the robot's design because is not necessarily to create a special piece for each part of the robot, only the feet and the waist were especially design for this project.

No extra gearing were used at the module design and each servo was mounted and coupled to each module. Thus, the torque was directly coupled to the "u" part (figure 3.7) of each module simplify the robot's construction. The mechanical efficiency of the torque transmission was significantly improved with the addition of an extra axe (Figure 3.7).

Finally a 4 mm aluminum was used to construct the lower waist design, making the structure of the robot strong enough and with a low gravity center.

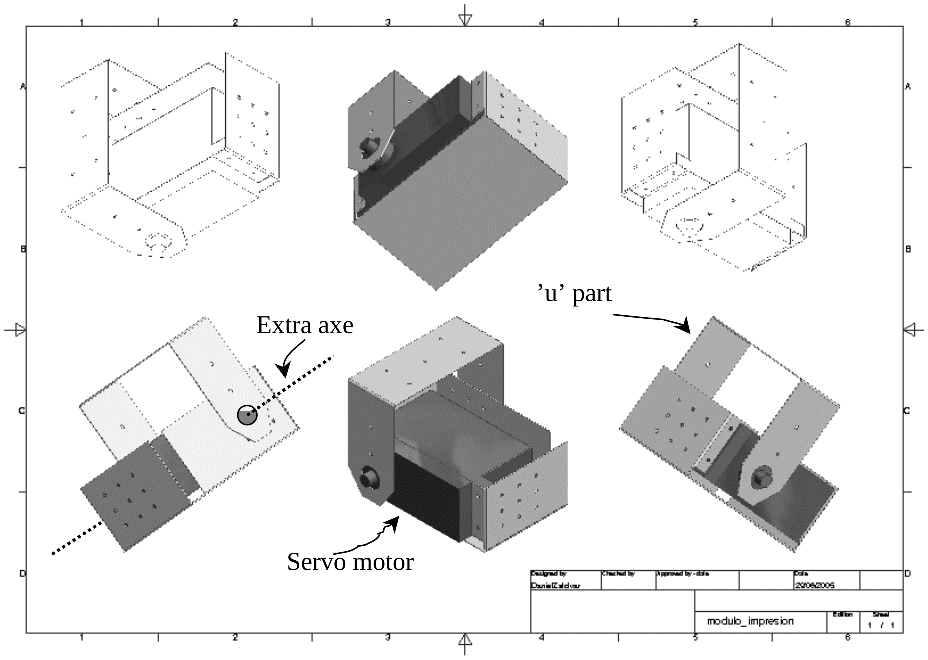

Figure 3.7: Robot's modules CAD redesign.

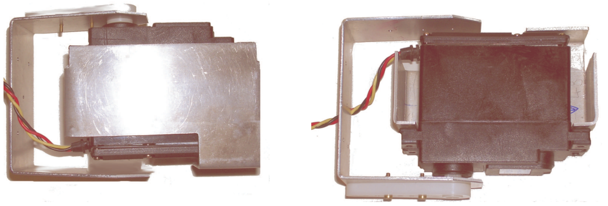

Figure 3.8: Real robot's modules.

3.3 Electronic

The developed electronic hardware for the robot, is composed by, the microcontrollers boards, the actuators and force sensors. But only the first two will be explained, since the force sensors are trivial.

3.3.1 Actuators

They must be strong enough to carry out the robot's weight and maintain a good relationship between its weight and torque.

For a first approximation, is very recommendable to have more than enough actuator's capabilities (velocity, torque, a good weight/torque relationship, etc). Since, the total mass of the robot and the mass allocation during the hardware design process can drastically change in order to increment the robot's stability. Thus, in case of the robot's mass were increase, the control system time-response is guaranteed.

Also, weight forces, inertias and the motors movements are an intrinsic part of a robot structure. In this sense the correct selection of the robot's actuators is very important for the soft performance of the controller.

For bipedal robots, there not only exist forces due to the acceleration field of the earths gravity, but forces produced by the robot itself. All theses forces must be compensate at the robot's walking in order to achieve or maintain stability. In this sense, not only a efficient controller, a good mechanical design and a correct mass distribution are important, also a reliable actuators selection can be decisive. That is because the controller will try to reach a stable position by moving the robot, changing its velocity and the acceleration and this will be executed directly from the actuators.

The robot's structure should provide enough endurance under its operation and be able to be controlled. The robot movements should be achieved by the actuators. To guaranty this, structure calculus must be done (at each part of the robot) and an important value to be find is the maximum torque required to be exerted by the actuators.

An option to resolve the torques needed by the robot in static equilibrium is [5.1]. These resolved torques represent a reasonable estimated of the torque required from the actuators [12].

$$\Gamma = Fl = Fr\sin(\theta) \ [5.1]$$

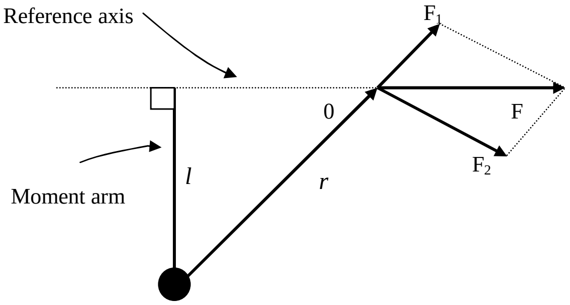

Figure 3.9: Torque graphic representation.

Figure 3.10: Servo motor.

Were Γ is the torque, F is the magnitude of the applied force, r is the radius of the applied force from the axis of rotation and θ is the angle of the applied force to the reference axis (the axis where F acts Figure 3.9) The quantity l is the moment arm, and represents the perpendicular distance from the rotation axis to the vector F or the reference axis.

The calculations revealed that the maximum torque that would be experimented at the ankle and the knee joint, would be approximately 173 Nm.

An important feature that helps to provide biped's balance is the use of fast actuators. A good option for these case are the electric motor devices, servos were chosen for this project.

This estimation and the torque calculus was used to select the Conrad S-8051 servos that were used as the joint actuators. Theses motors are high torque servo motors 198 Ncm with a speed of 0,19 sec/60 Degrees, a dimension of 66x30x58 mm and a mass of 152 g. Figure 3.10 shows the servo motor.

3.3.2 Microcontroller boards

Two interconnected electronic boards based on a PIC16C783 Microcontroller were developed in this project. One electronic board had implemented basically the *balance controller algorithm* ("balance controller board"). Figure 3.11 shows

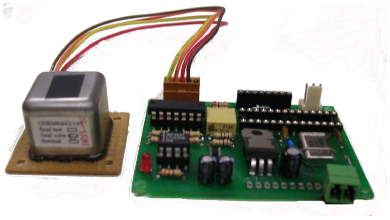

Figure 3.11: "Balance controller board".

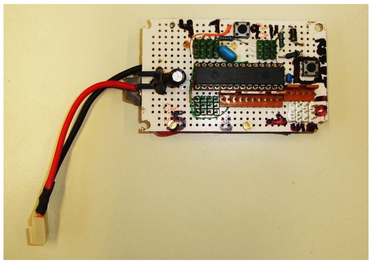

Figure 3.12: "Walking sequence board".

the balance controller board and the gyroscope). The other electronic board had the *walking sequence algorithm* ("walking sequence board", Figure 3.12). Both were programmed using a C compiler for PIC's microcontrollers.

In the "balance controller board", the balance controller and the ZMP calculus algorithm were implemented. When the ZMP was near to the support polygon boundary an alarm signal was send ("walking sequence attenuator") to the walking sequence board to decrease the acceleration and velocities of the walking sequence. For the balance controller board, A/D inputs from the microcontroller were used to read the force sensors, a gyroscope, and an inclinometer as a sensors for the *balance controller algorithm*. Finally, force sensors were used to calculate the ZMP. The gyroscope is plane to be used in the robot's localization (when the robot change its orientation).

In the "walking sequence board", the *walking sequence algorithm* and a program to handle efficiently the 10 servo motors (by sending a PWM signal to each motor) was implemented [51] [52].

In this board, six PWM signals represents the wakings actual position calculated by the *walking sequence control*, (explained in section 5.6). The other four signals (waist and feet motors) are calculated by the *balance controller* (the *incremental fuzzy PD controller*, explained in section 5.5.4) for the lateral

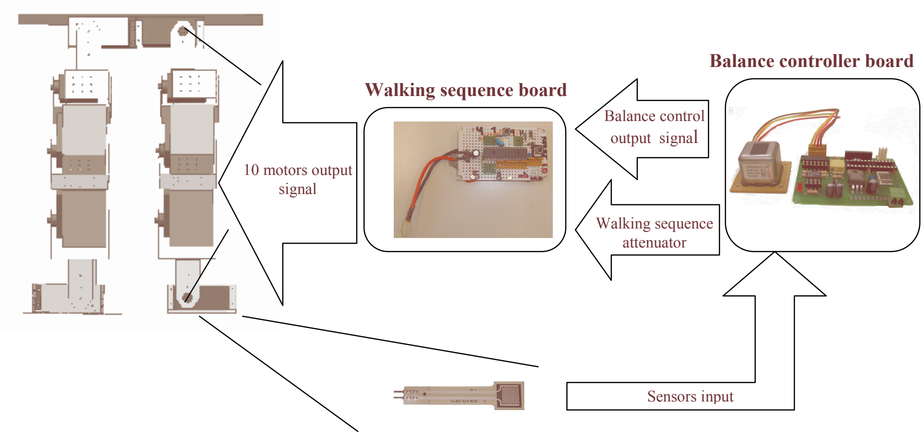

Figure 3.13: Interconnection between both boards.

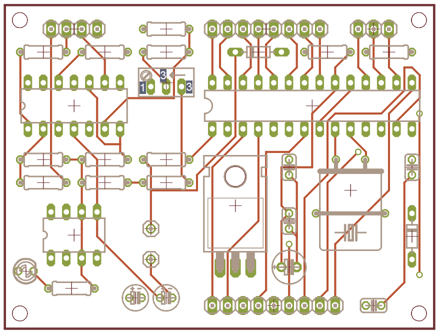

Figure 3.14: Electronic board's PCB design (top).

movements. Those signals represent the positions to balance the robot. A serial communication between the to PIC's boards was implemented for its communication. Figure 3.13 shows a diagram to explain the interconnection between both boards and the robot's modules.

The electronic board for the balance was designed on a CAD program to obtaining its PCB, the PCB have a PIC16C873 as a microcontroller and was designed on two layers . Figure 3.14 shows the electronic board's PCB design at top and Figure 3.15 shows the electronic board's PCB design at bottom.

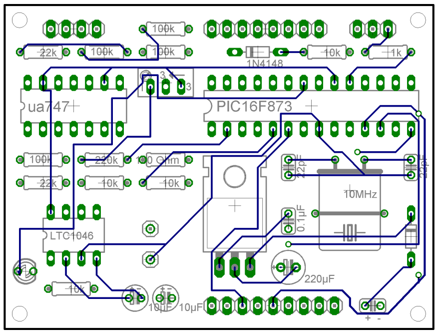

Figure 3.15: Electronic board's PCB design (bottom).