Bipedal robot description

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Erik V. Cuevas[1,2], Daniel Zaldívar[1,2], Raúl Rojas[1]

[1] Freie Universität Berlin, Institut für Informatik
Takustr. 9, D-14195 Berlin, Germany

[2] Universidad de Guadalajara
Av. Revolución No. 1500, C.P. 44430, Guadalajara, Jal., México

{cuevas, zaldivar, rojas}@inf.fu-berlin.de

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Abstract

This work report the electronic and mechanical for a bipedal robot prototype. The objective of this project is build a platform to study the dynamic walking and to prove some intelligent control techniques. This work highlighted the fact that mechanical design is equally, if not more important, than the control method used. All the electronic was implemented in a low cost PIC16F873 microcontroller. The robot designed has 9 degree of freedom (DOF) and each joint is driven by a DC servo motor. A gait program besides a control algorithm who read a gyroscope and force sensors are used to equilibrate the robot at walking.

1 Introduction

In recent years the interest to study the bipedal walking have grow also the demand for build biped robots has increase. However a search over the literature have show that there is little information about the bipedal robot design process. The goal in this work is to design the robot which would be used to investigate theories of bipedal walking. The design for the bipedal robot is rather different from conventional robots, there are limits in the amount on, actuators size, weight and in our case, since the funding for the project was limited a very cost effective design needed to be developed in order to succeed. The robot design was also required to withstand the rigorous of mechanical stress imposed upon it during experimentation. This work shows some important physical considerations during the walking, that should be know until begin the construction of a bipedal robot. In Section 2 an introductory study of the biped walking is presented, in Section 3 the mechanical considerations and specifications of the bipedal robot are described, in Section 4 the electronic and the sensors used are showed, finally in Section 5 the obtained results are reported and some future work are proposed.

2 Biped walking

In order to understand the mechanical bipedal robots mechanics design, is necessary first to understand the biped walking process or biped locomotion. This area has been studied for a long time, but it is only in the past years, thanks to the fast development of computers, that real robots started to walk on two legs. Since then the problem has been tackled from different directions.

First, there were robots that used static walking. The control architecture had to make sure that the projection of the center of gravity on the ground was always inside the foot support area. This approach was abandoned because only slow walking speeds could be achieved, and only on flat surfaces.

Then dynamics walking robots appeared [1]. The center of gravity (or center of mass) can be outside of the support are, but the zero momentum point (ZMP), which is the point where the total angular momentum is zero, cannot. Dynamic walkers can achieve faster walking speeds, running , star climbing [2], execution of successive flips, and even walking with no actuators [3].

2.1 Static walking

Static walking assumes that the robot is statically stable. This mean that, at any time, if all motion is stooped the robot will stay indefinitely in a stable position. It is necessary that the projection of the center of gravity of the robot on the ground must be contained within the foot support area (Fig. 1). The support area is either the foot surface in case of one supporting leg or the minimum convex area containing both foot surfaces in case both feet are on the ground. These are referred to as single and double support phases, respectively . Also, walking speed must be low so that inertial forces are negligible.

This king of walking requires large feet, strong ankle joints and can achieve only slow walking speeds. It has been abandoned by most researchers for dynamic walking, which provides more realistic and agile movements.

2.2 Dynamic walking

Biped dynamic walking allows the center of gravity to be outside the support region for limited amounts of time. There is no absolute criterion that determines whether the dynamic

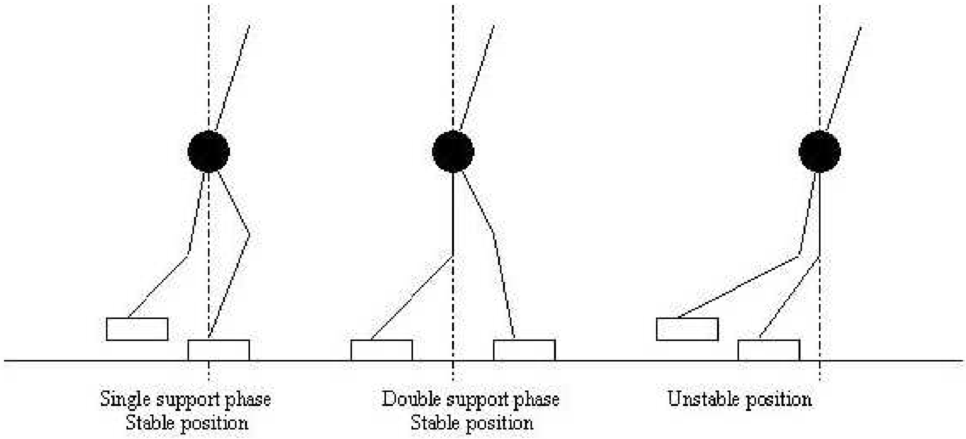

Figure 1: Static walking

walking is stable or not. Indeed a walker can be designed to recover from different kinds of instabilities. However, if the robot has active ankle joints and always keeps at least one foot flat on the ground then the Zero Momentum Point (ZMP) can be used as a stability criterion. The ZMP is the point where the robot's total moment at the ground is zero. As long the ZMP is inside the support region the walking is considered dynamically stable because is the only case where the foot can control the robot's posture. It is clear that for robots that do not continuously keep at least one foot on the ground or that do not have active ankle joints (walking on stilts), the notion of support area does not exist, therefore the ZMP criterion cannot applied.

Dynamic walking is achieved by ensuring that the robot is always rotating around a point in the support region (Fig. 2). If the robot rotates around a point outside the support region then this means that the supporting foot will tend to get off the ground or get presses against the ground. Both cases lead to instability. To draw an analogy with static walking, if all motion is stopped then the robot will tend to rotate around the ZMP

2.3 ZMP calculus

The position of the ZMP is computed by finding the point (X, Y, Z) where the total torque is zero. Since we are only interested in the ground plane we assume that $Z = 0$. To avoid confusion, torque and moment mean in this work the same thing. The robot has n links; each link is subject to a total force F_i applied at a point determined by the vector R_i relative to the center of gravity of the link. T_i determines the total motor torque applied to the link. R_z is the ZMP vector and T is the robots total torque. An example of the forces applied to a link is represented in Fig. 3.

The force, torque and position vectors have the following coordinates:

$$F_i : (F_{xi}, F_{yi}, F_{zi})$$

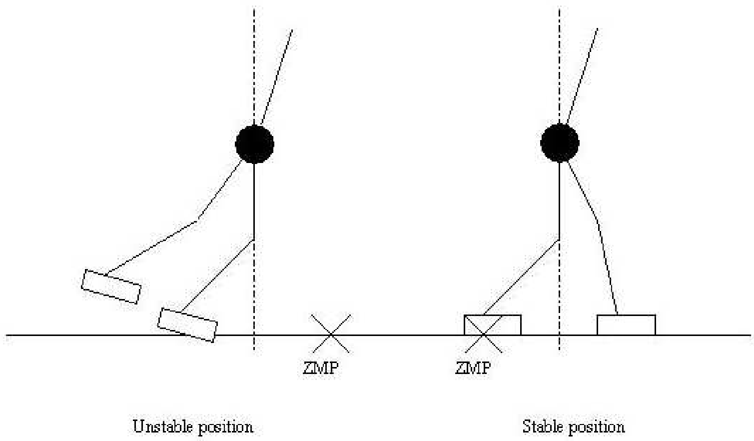

Figure 2: Dynamic walking

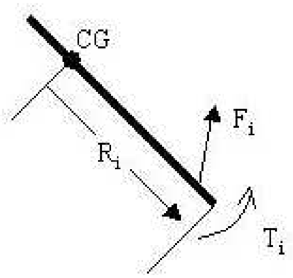

Figure 3: Forces applied to a link

$$T_i : (T_{xi}, T_{yi}, T_{zi})$$
$$R_i : (x_i, y_i, z_i)$$
$$R_z : (X, Y, Z)$$

Then the total torque is computed as:

$$T = \sum_{i=1}^{n} (R_i + R_z) x F_i + \sum_{i=1}^{n} T_i = 0 \qquad [1]$$

Where x represents the cross product. Equation 1 is then expanded as:

$$\sum_{i=1}^{n} (y_i + Y) F_{zi} - \sum_{i=1}^{n} (z_i + Z) F_{yi} + \sum_{i=1}^{n} T_{xi} = 0$$
$$\sum_{i=1}^{n} (z_i + Z) F_{xi} - \sum_{i=1}^{n} (x_i + X) F_{zi} + \sum_{i=1}^{n} T_{yi} = 0$$
$$\sum_{i=1}^{n} (x_i + X) F_{yi} - \sum_{i=1}^{n} (y_i + Y) F_{xi} + \sum_{i=1}^{n} T_{zi} = 0$$

Making Z=0 and solving these equations for Y and Y we obtain the ZMP coordinates:

$$X = \frac{\sum_{i=1}^{n} (z_i F_{xi} - x_i F_{zi}) + \sum_{i=1}^{n} T_{yi}}{\sum_{i=1}^{n} F_{zi}}$$

$$Y = \frac{\sum_{i=1}^{n} (z_i F_{yi} - y_i F_{zi}) + \sum_{i=1}^{n} T_{xi}}{\sum_{i=1}^{n} F_{zi}}$$

3 Mechanical considerations and specifications

The mechanical design process involves the creation of specifications such that the chosen walking model will succeed. This is not a trivial task, many considerations must be consider in order to ensure that the biped robot will be stable while walking.

The design chosen is formed by a biped robot configured of two legs, each having 4 degrees of freedom (DOF). Three of these are rotational on the pitch axis at the hip, knee and ankle. The fourth is also rotational an located at the hip on the yaw axis. The trunk (an inverted pendulum) has 1 DOF. Fig. 4 shows the robot structure.

The trunk is used to stabilize the robot during the walking gait. As the trunk is moved to the angle calculated by the controller, the centers of mass (COM) position will change to a point were the robot's structure is stable.

3.1 Stability

In traditional legged robots, stability is maintained by having at least three contact points with the ground surface at all time [4]. With biped machines, only two points are in contact with the ground surface for that reason algorithms to achieve balance most be implemented.

To intent resolve the biped robot stability at walking, a simplify model feet force sensors feedback can be used as an input to a controller thus, try to maintain stability at walking. Even so the mechanical design goal is to ensure that the robot at walking will achieve dynamic balance. Dynamic balance is in part provided by the control algorithm, however the mechanics design play a very important role at the robot's ability doing the correct movements.

A way to reach it, is finding a correct mass distribution at the robot, thus the robot will be eable to achieve the stability at walking. These movements can therefore be made rapidly without generating large moments which would further destabilize the robot. To achieve this, the COM should be placed in a location low enough to stabilize the robot inertially, but high enough so that it can be moved only small amounts to correct for undesired behavior [5].

The correct placing for the COM is the lower trunk, similar to humans. This provides for stability and allows the trunk to be moved, shifting the COM to archive desired accelerations to counteract existing undesired accelerations [6].

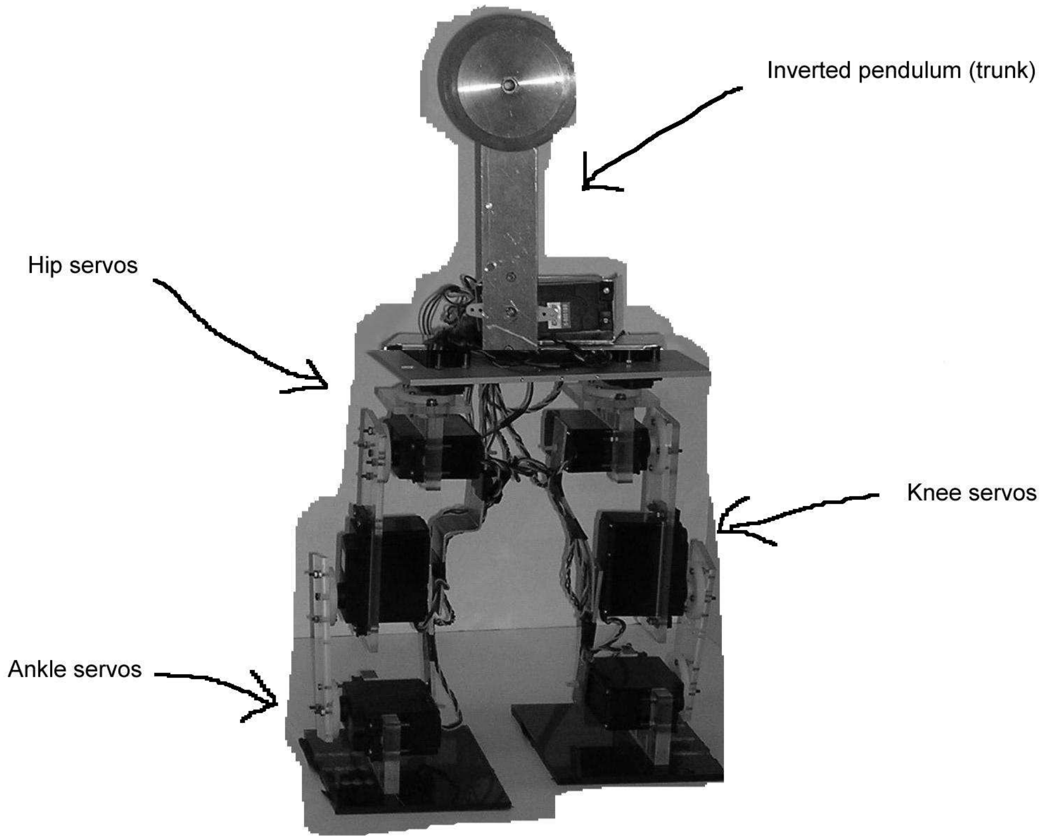

Figure 4: robot structure

Another important feature that helps to proveid biped's balance is the use of fast actuators. A good option are the electric motor devices, servos were chosen for this project. Conrad S-8051 servos were used. 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.

3.2 Dinamics of the robot's structure

Weight forces (mass), the motors momevents (torque) and inertias are an intrinsic part of a robot structure. In this sense the correct selection of each robot's part is very important likewise the electronic and the implement of a soft controll.

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 compensed at the robot's walking in order to achieve or maintain stability. Here a efficient controller and a good mechanical design (a correct mass distribution) are decisive. The controller will try to reach a stable position by moving the robot, changing its velocity and the acceleration.

A correct robot's design should provide enough strenght under its operation and be relaible to be controlled. To achieve this goal, some structure calculus must be done and an important value to be finded is the maximum torque required to be exerted by the servos.

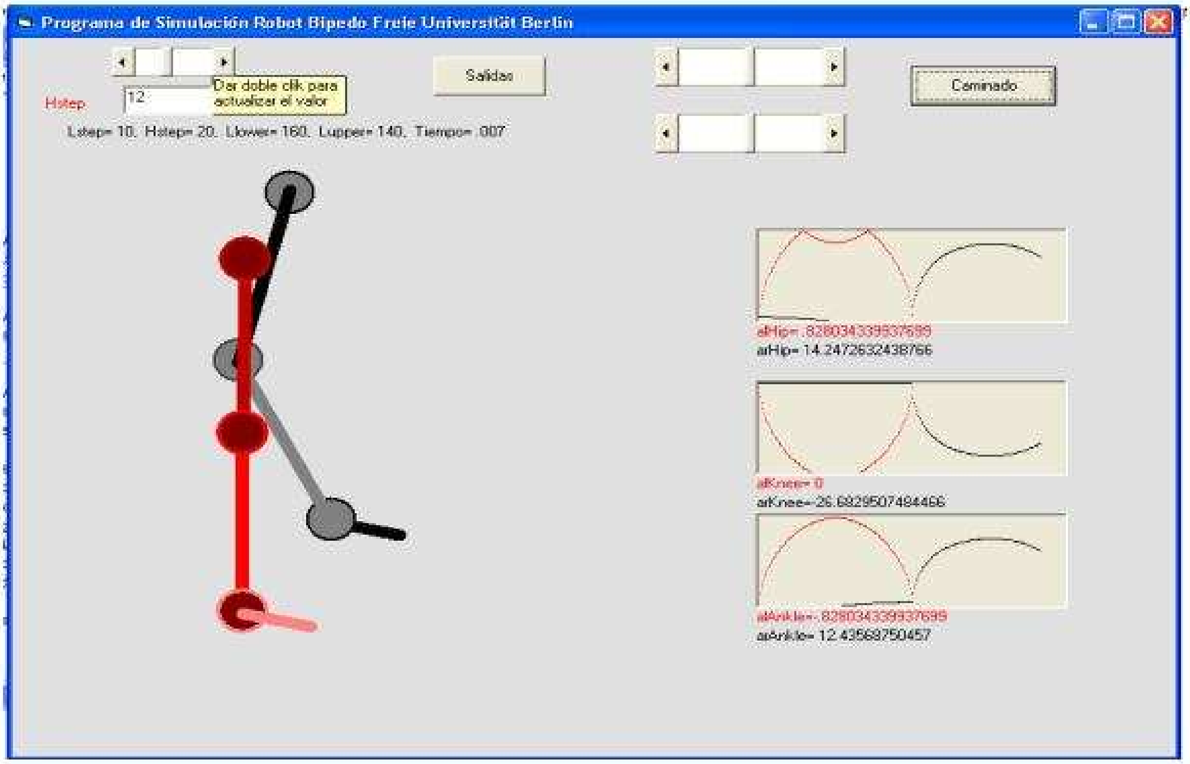

Figure 5: Robot's simulation program

This was calculated using the robot's mathematical model (a simulation program maded to resolve the robot's inversed kinematics and its estimated mass distributions). In this mathematical model the robot's weight values and its real measure should be considered. Fig. 5 shows the robot's simulation program.

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

Equation 2 can be an easy, option to resolve the torques needed by the robot in static equilibrium. These resolved torques represent a reasonable estimated of the torque required from the servos, and allows also a quick servo choice to be made.

$$\Gamma = Fl = Frsin(\theta) \qquad [2]$$

Were Γ is the torque or moment, 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 Fig. 6) The quantity l is the moment arm, and represents the perpendicular distance from the rotation axis to the vector F, or the reference axis.

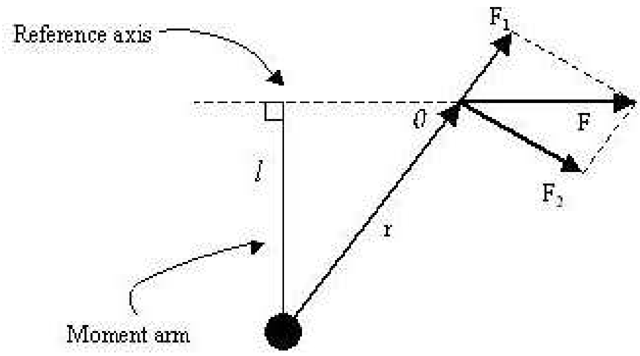

Figure 6: Torque's calculus

No gearing was used at the links to simplify the robot's construction. The servos were direct coupled to each link. Thus, the torque was directly transferred to the links movement. A high efficienty is achieve due to the absence of external gears.

Since the precise construction of the robot was not know in advance, this estimation was used to select the Conrad S-8051 servos that were used as the joint actuators. An estimated of the mass distribution was obtained from measuring material samples and weighing of components parts.

3.3 Mass distributions

McGeer [5] demonstrated that proportions can be more important than control by showing that dynamic walking can be achieved without actuation or control. In particular, mechanical parameters such as length and mass distributions may have a greater effect on the human gait than previously imagined. Therefore, considering the proportions of the robot such as leg link length and mass distribution throughout the body are imperative to success.

Some components of the robot were already pre-dimensioned, such as the servos, sensors, electronics, etc. Such inflexible parts hat to be incorporated, constraining the minimum dimensions for the robot. However, in order to keep the mass of the robot to a minimum, it was important to use as little material in the robot frame structure as possible. One further objective is to redesign the robot with proportions which will allow the robot to balance relatively easily while still allowing the research into dynamic walking to be accomplished. For this reason the mass and mass distribution play a large role in determining the designed dimensions of the robot.

The mass of the robot and the distribution of mass throughout the body of the robot is related to the forces operating on and within the robot. If the mass of the robot is too large, it will no be able to respond to the control system rapidly enough or even functioned incorrectly, especially if the servos chosen are not powerful enough. More importantly, the mass distribution within the robot also affects the balance of the robot, since this determines the location of the COM. In particular, the absolute mass distribution will vary as the robot links move relative to each other, meaning that the position of the COM within the robot will change during the walking gait. The movement of the COM will have a significant influence on the stability of the robot, therefore considering the mass distribution is also important to achieving dynamic walking.

In order to stabilize the robot as much as possible, we place the COM as low as possible while still allowing the trunk to be useful for compensating for the movements of the lower limbs. In order to achieving this goal leg links as short as possible were designed. Even so, we think that a better option could be coupling the servos directly to the link joins. Furthermore, we wold like to minimize and restrict the movement of the COM in a predictable manner, so we can control this as a method to balance the robot. To do this we make the ratio of the combined mass of the leg links to the combined mass of the upper body as small as possible. In this manner movements of the leg will affect the position of the COM marginally, and even only in the sagittal plane. We can control the side balance of the robot by swaying the trunk in the lateral plane. Since these planes are perpendicular, we need not be concerned about movements of the leg affecting the side balance of the robot.

3.4 Endurance

At walking the robot will be experiment normally strong forces expecially in certain points, this should be counsidered at the design. By the other hand a compromisse should be finded between the weight and the robot's resistence. Therefore only some parts of the robot must be strong enough to work appropiately. For these reason only some part of the robot's structure were constructed using 1.5 mm aluminium for the skeleton and others whith 2 and 5 mm plastic glass for the links and join brackets as shown in Fig. 7. A 4 mm was used for the lower trunk design, making the structure of the robot strong enough.

3.5 Construction

The distribution of mass of the constructed robot differed slightly from the estimated mass distribution due to two factors. The first reason was that the amount of aluminium required to make up the structure was underestimated. This increased the final mass of the robot above the estimated mass by approximately 5 Kg, making the final mass of the robot 5.7 Kg. The main reason for the underestimation was that heavier brackets were used around the servos to increase the strength at link joints, and to prevent unwanted forces occurring against the servo axis of rotation.

The second reason is that most of the heavier aluminium was added to the trunk to stabilize the COM there also the skeleton represent it self an increment in the amount of aluminium used , the entire plastic glass was it self quite weighty.

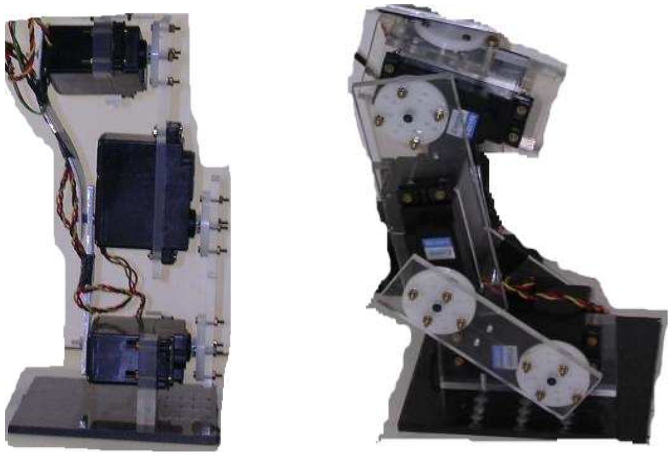

Figure 7: Skeleton

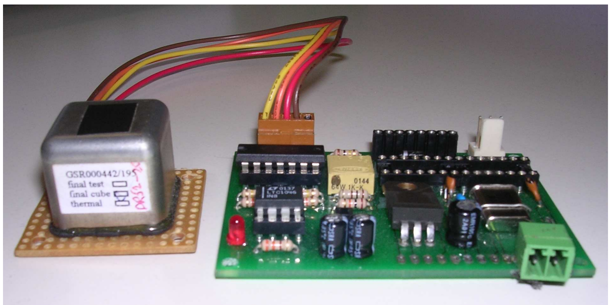

Figure 8: The designed electronic board based on the PIC16C783 microcontroller and the gyroscope

4 Electronic

The electronic is based on a PIC16C783 Microcontroller, it has A/D inputs, used to read the force sensors and a gyroscope. The Fig. 8 shows the electronic board designed for the PIC and the gyroscope. The Gyroscope used reads the angle to obtain the robots orientation. The gyroscope send a analog signal, and the PIC microcontroller should convert this signal in a angle value. This electronic also handle the 9 servo motors by sending a PWM signal to each of them. This signal represents the actual position to be achieve to the motor at that time. Those signals are calculated by a PC. For the 8 motors (the leg's motors) the signals represent the position to conform the walking sequence and for the pendulum motor, the signal represent the angle position sended by a fuzzy controller running at the PC. Finally the electronic is also able to read the 6 force sensors installed at the feet's bottom. Theses signals are processed to find the ZMP, who is used as an input to the Pendulum's control (or trunk control).

4.1 Force sensors

The force sensors are used to determine the load distribution of each foot. Each foot of the robot is constructed from plastic glass in square form, three strain gauges are attached to the foot forming a triangle. The force on each triangle's corner can be determined with the sensors and the ratio of the values to each other give the center of force in this triangle. A strain gauge is showed in Fig. 9

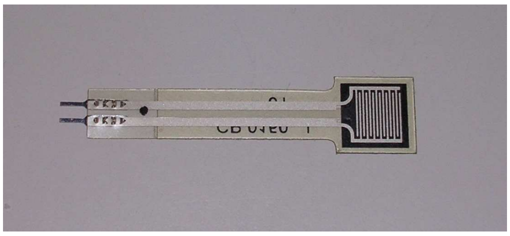

Figure 9: Strain gauge

5 Conclusions and future work

This work reports the development of a bipedal robot. This robot has features of small size and light weight. The light weight property could help to achieve a faster speed at walk. The robot's design includes the incorporation of a gyroscope and force sensors used in the walking control. A programm to simulate the robot's walking was used to find the position's sequences to implement the robot's walking at real time.

In order to improve the stability of the bipedal robot some modifications could be implemented:

The robot could be redesigned reducing the legs's mass in proportion to the trunk's mass. A problem in this modification is a possible servos overload due to a excessive mass addition to the trunk.

A second modification is to increase the degrees of freedom at the hip and ankle, allowing the body to have laterals movements to facility the control and even eliminate the pendulum.

This bipedal robot achieve successfully the static walking. Some walking videos of this robot and the actual state of the project are available at www.inf.fu-berlin.de/~zaldivar

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