Chapter 1

Introduction

1.1 Overview

The goal of this thesis is the design of a low-cost biped robot structure to investigate theories of bipedal walking and biped balance control. This thesis proposes a fuzzy PD incremental algorithm based on the ZMP criteria (Zero Moment Point criteria) to control the balance on a biped robot. The algorithm is quite economic computationally and for that reason more efficient than an adaptive control algorithm. The performance of the algorithm demonstrated a smooth balance control response and also a correct interaction between the robot's walking sequence algorithm.

An interesting thing on biped robots walking theory is that they can be allowed to walk in almost any type of terrain [1], [2], [3] [4], including those that are impossible for robots with wheels. For this reason, it is promising the use of biped robots in human environments as well as the development of biped robot's control algorithms [4], [5], [6] [7] [8].

In recent years, have been an increasing enthusiasm to study the bipedal walking. In private companies (Sony, Honda, etc.), research institutes and some universities, they have invested huge quantities of human and economic resources to develop sophisticated biped robots prototypes [9], [10], [11]. However, some others researchers have a low-cost biped robot's design philosophy. Such kind of biped robots are similar to his costly counterparts in the sense that they can offer the capacities to study and improve new biped walking algorithms, but they are more affordable. For that reason, the tendency to build low-cost biped robots has been worldwide increased [12], [13]. However, there's a lack of detailed information over the biped robot design process and control. This thesis intents to share the knowledge and experience acquired during the design process of a low-cost biped robot and the research of its control, to be a possible base for future biped robot designs.

Biped robot design is different from conventional robots since, there are restrictions and differences in the amount, type and size, response time of the actuators, sensors, parts-weight and even configuration, position, and distribution of the biped's robot structure. Thus, a correct robot's hardware design is a previous stage to come closer of a dynamic walk. Lastly, an efficient biped robot balance control and a smooth walking sequence can achieve dynamic walk. Also important are, simulators of the biped robot's cinematic and dynamics to adjust the biped robot's control algorithms.

A biped robot design also require to withstand the rigorous of mechanical stress imposed during experimentation. This thesis considers some important physical considerations presented at the walking process, that should be know until begin the design and control of a biped robot.

The robot designed in this thesis has 10 *degree of freedom* (*DOF*) and each joint is driven by a DC servo motor. A modular design was chosen to allow an easy assemble and even a different *DOF* easy-reconfiguration.

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

There are some techniques to implement a balance control for a biped robot, many of them are implemented using classic control techniques, but some others are implemented using soft computing or artificial intelligent techniques. In this thesis an incremental fuzzy PD controller to achieve balance in a biped robot is proposed.

In order to implement the balance control in this thesis, a feedback-force system at each foot was implemented to obtain the ZMP and feed it in to the incremental fuzzy PD controller to calculate the ZMP error. Then the controller adjust the lateral robot's positions (balance) to maintain always the ZMP point inside of the support region [14].

To control the biped robot's walking sequence a dynamic walking algorithm was implemented. The algorithm is based on cubic polynomial interpolation of the initial conditions for the robot's position, velocity and acceleration. This guarantee a constant velocity at each robot's link a smooth transition in the control of the walk trajectories and shows to be helpful to decrease the instability produced by violent transitions between the different walk phases [15]. Both algorithms (the fuzzy PD incremental algorithm for the biped robot's balance control and the cubic polynomial interpolation algorithm for the robot's walking sequence control) were programed using a C++ compiler running on two PIC16F873 microcontrollers and successfully tested on the bipedal robot "Dany walker" designed at the Freie Universität Berlin.

1.2 Related work

Next, a compact description of some previous and contemporary related work research is presented. Pointing out the contributions and their limitations. The biped robot related work exposed, was principally done on universities and labs on the hole word. Also, some relevant commercial biped robot projects are presented. Is hard to establishes a classification, but attending to the available resources some of the research can be classify as a low-cost biped robot approach. Such kind of biped robots are similar to his costly counterparts in the sense that they can offer the capacities to study and improve new biped walking algorithms, but they are more affordable.

Biped robot research on universities and labs

Shuuji Kajita [8] designed and developed an almost ideal 2-D model of a biped robot. Kajita supposed for simplicity that the robot's COG (Center of gravity) moves horizontally and he developed a control law for initiation, continuation and termination of the walking process. Figure 1.1 shows some kajita's earliest biped robots.

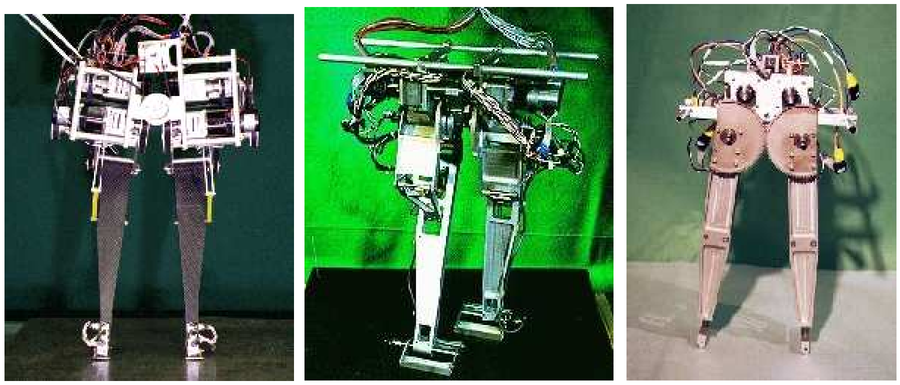


Figure 1.1: Biped robots used in earliest Kajita's experiments.

Zhen [1] proposed a scheme to enable the robot climb inclined surfaces. By force sensors placed in the robot's feet, the transition of the type terrain can be detected and then to compensate the inclination, the appropriately motors movements can be generated. Using other approach, Zhen, uses the inclination of the mechanical structure, as indirect measure of the COG to control the gait walking.

Cubic interpolation is used for many researchers as a biped robot's gait generation. Shih [18] and Huang [19] have used cubic polynomials to generate the hip and foot trajectory to walk on uneven terrains. The work of Shih discusses only the static walking, while the work of Huang proposes a method for dynamic walking.

Kajita and Tani [17] used the inverted pendulum model to accomplish the walking in rugged terrain. They conducted 2 experiments: the single leg support phase and the change of support leg and they found that to achieve a smooth exchange of support leg is necessary to maintain a vertical speed as well to maintain for some instants the double support phase. Figure 1.2 shows some biped robots used in the Kajita's experiments.

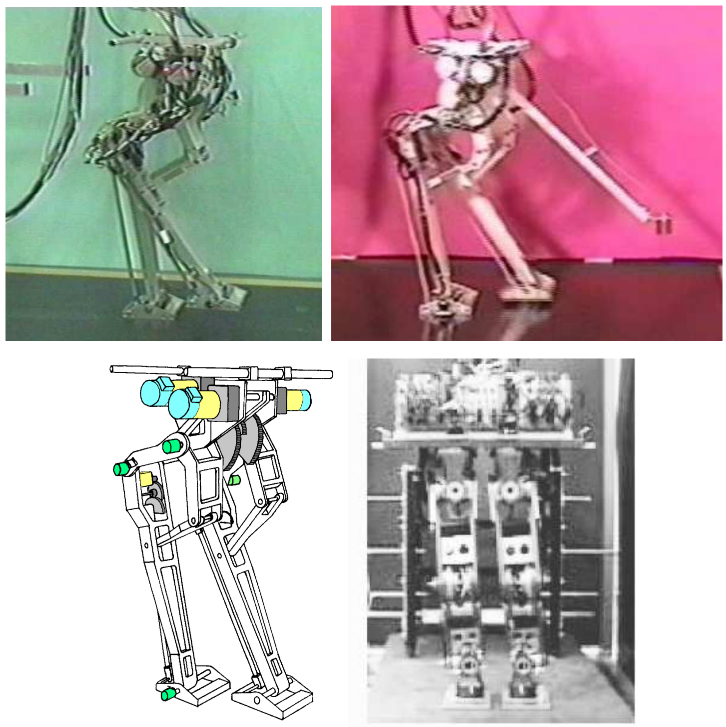


Figure 1.2: Biped robots used in Kajita's experiments.

Flamingo robot at Massachussets Institute of Technology (MIT)

Pratt [16] proposed the control of a seven link planar bipedal robot by natural dynamics. This is an algorithm based on human gait: the swing leg can swing freely once started; a kneecap can be used to prevent the leg from inverting; and a compliant ankle can be used to naturally transfer the center of pressure along the foot and help in toe. Each of these mechanisms helps make control easier to achieve and results in motion that is smooth and natural looking. The advantage of this algorithm is that don't require many sensors to allow the robot to walk and using natural mechanisms the robot requires very little computation. The necessary sensing consists of joint angles and velocities, body pitch and angular velocity, and ground reaction forces. Figure 1.4 shows the spring flamingo robot developed at MIT by Pratt. However, on the information is not clear if the balance problem was resolved on this planar biped robot.

Figure 1.3: Spring flamingo robot developed at MIT.

Dinosaur biped robot Troody

Peter Dilworth, a robotics researcher at MIT's Leg Lab, has built a 10-pound version of a dinosaur called Troody, the first two-legged dinosaur robot. Dilworth consulted with paleontologist to ensure that the dimensions are as true to the real thing as possible, based on fossils. Troody has 16 electric motors distributed among its hips, knees, ankles, feet, and tail. There are two sensors on each motor to feed joint angle and force readings to an on-board computer and a gyroscope to sense which way is up and in which direction the robot is moving.

Figure 1.4: Troody dinosaur biped robot developed at MIT.

Biped Robot WABIAN-2

WABIAN-2 is a robot built at Waseda Universities Japan (figure 1.5) for just research [[45]]. It has been designed accordingly in order to develop a humanoid robot with the height of 1500[mm] (figure), and the weight of 60[kg].

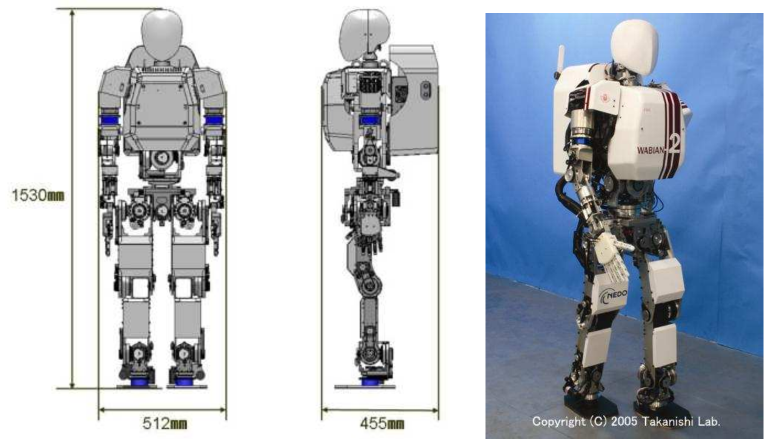


Figure 1.5: The Humanoid robot WABIAN-2, Takanishi Lab.

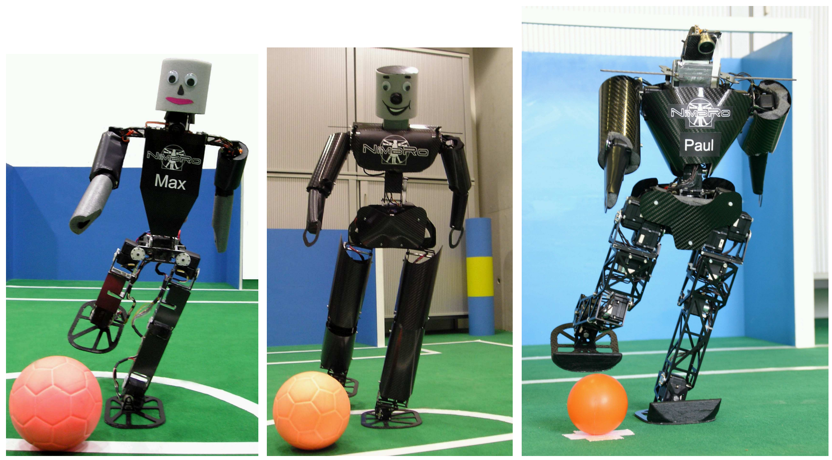
WABIAN-2 is controlled by a computer mounted on its trunk. The control computer consists of a PCI CPU board , which is connected to I/O boards through PCI bus. For I/O boards, a HRP Interface Board which has 16ch D/As, 16ch Counters and 16ch PIOs, and six axis force/torque sensor receiver board is used. Actuator system is equipped with an incremental encoder attached to the motor shaft, and a photo sensor attached to the joint shaft in order to detect the initial posture. (Also each ankle is equipped with a six axis force/torque sensor which is used to measure floor reaction force and ZMP.)

Low-cost biped robots

Biped robots at University of Freiburg

At University of Freiburg, NimbRo-Learning Humanoid Robots research group have developed some low-cost biped robots. All these robots are fully autonomous, servo-driven humanoid robots. They have a wide field of view camera, ample computing power, and wireless communication. They are controlled by a Pocket PC and use an electronic compass as a localization sensor. Also, they possesses basic soccer skills, walking dynamically in all directions (up to 20cm/s in forward direction) and are able to turn on the spot. They perceive the ball and the goals and localizes they self on the field. They can approach to the ball and dribble it. They are mainly used for the Robocup competition and are continuously improvement. For example, the Max biped robot shown in figure 1.6 a). It has 19DOFs, which are driven by servo motors. Max is 75cm tall and weighs 2.4kg. This robot had strong arms that help him to get up from the ground. Other biped robot developed at NimbRo is Robotinho. It is 100cm tall and weighs about 5kg. It has 21 joints which are driven by intelligent actuators. Figure 1.6 b) shows the Robotinho.

The last biped robot developed at NimbRo is Paul. It has 60cm high and has a total weight of 2,9kg. Its 20 joints are driven by intelligent actuators. Figure 1.6 c) shows the Paul robot.

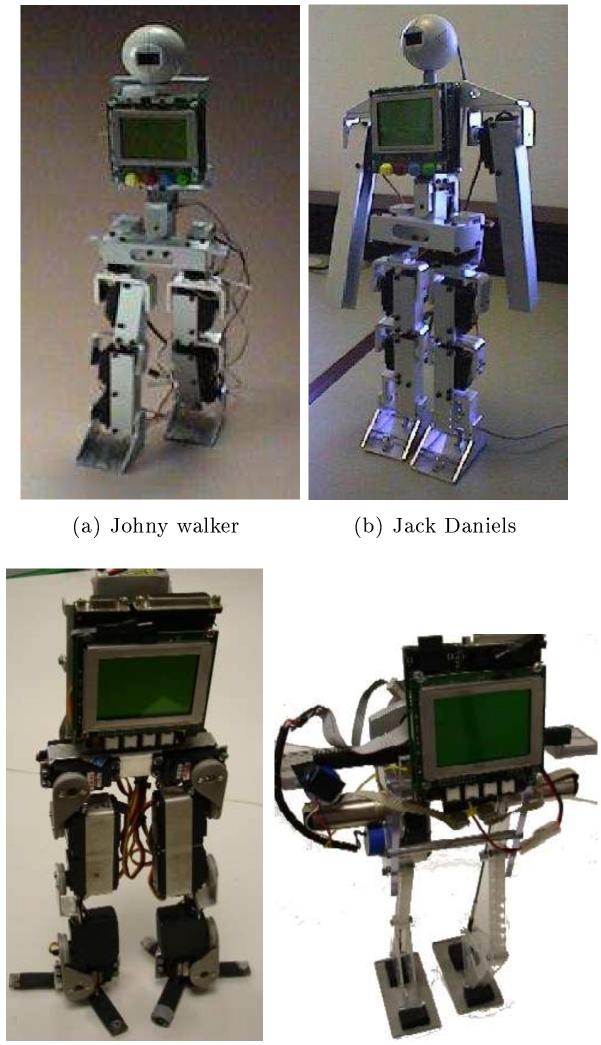


(a) Max (b) Robotinho (c) Paul

Figure 1.6: Biped robots, developed at Freiburg University.

Biped robots at University of Western Australia

Some low-cost biped robot's has been developed at University of Western Australia (CIIPS) [12]. For example, "Johnny Walker" (Figure a)) it has 9 degrees of freedom: each leg is bendable in its ankle, Knee, and hip and it can be rotated in the hip. An additional servo is situated in the torso allowing the robot to bend sideways. All actuators are servos and the upper body consists of an EyeBot-Controller and a digital camera. The torso servo is used to displace the center of mass to the left or right.



(a) Johny walker (b) Jack Daniels

(c) Andy Droid (d) Rock steady

Figure 1.7: Biped robot's developed at University of Western Australia.

It used an open-loop controlled walking that not bring the desired success, a modification of the "Johnny Walker" was developed. The next model had arms, which could only be moved forwards and backward. This brings two more degrees of freedom and now the center of mass could be shifted from the front to the back. The rest of the design of this new robot, named "Jack Daniels" (Figure 1.7 b)), was similar to the "Johnny Walker". In addition, the camera had been removed to lower the center of mass and stabilize the robot.

The next robots designs removed the torsos servo and the turning servos in the hip. The ankles obtained one more degree of freedom, allowing the robot to bend side wards. In total, this robot, Andy Droid (Figure 1.7 c)), was smaller than the first two designs and had 12 DOF.

All this robots until now were driven by servos. Rock Steady (Figure 1.7 d)) is driven by DC motors. Its mechanical structure is able to generate a gait in each leg driven by only one motor. A third motor is mounted behind the controller display to carry a weight from left to right and thereby relocate the center of mass. Thus, Rock Steady has only 3 degrees of freedom in total. The structure is made of light plastic, which makes this robot especially light.

Commercial projects

Honda biped robot ASIMO

As mentioned in the introduction, one of the most sophisticated biped robots is ASIMO (Figure 1.8), developed by Honda Motor Company. Is 1.2m tall and weight 52 Kg. ASIMO has 24 DOF, 5 in one arm, 1 in each hand and 6 per leg. The 6 DOF of one leg are a combination of the following joints: ankle front-back, ankle left-right, knee front- back, hip front-back, hip left-right, and hip rotate. The joints are driven by servos. ASIMO weights 43 kg and is controlled by an on-board controlling unit. It carries an autonomous power supply in this backpack. Each foot has a six-axis foot-area sensor and the torso contains gyroscopes and acceleration sensors [9]. The robot is able to walk, it has a wide operating angle with his arms and can imitate several human behavior to interact with humans directly. It also has a Japanese speech recognition system on-board. Honda refers, for instance, to the height of ASIMO as the minimum height which enables it to nonetheless manage operation of the human world. However, its principal inconvenient is it built and research cost (one copy off it, cost about 1 USD million (300 USD millions its research) [53].

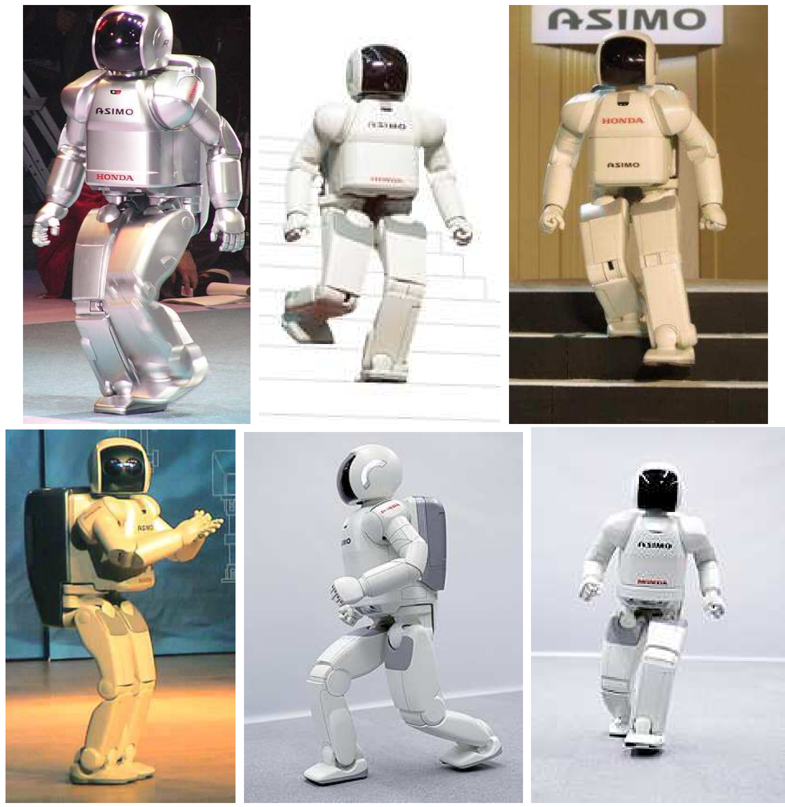


Figure 1.8: ASIMO (Honda Motor Company).

HUBO biped robot at Korea Advanced Institute of Science & Technology (KAIST)

The humanoid robot "HUBO," project at KAIST, has been getting attention in the robotics community worldwide. At a relatively inexpensive US$1 million, HUBO follows in the footsteps of Honda's robot dubbed "ASIMO," but using the latest control technologies, the KAIST team has made rapid progress by contrast, ASIMO took 15 years and cost US$300 million [53].

On the first generation, dubbed KHR-1 (Figure 1.9 a)), began in January 2002 and within a year the team had the prototype walking efficiently. Then, KHR-2 (Figure 1.9 b)) went through testing to improve the integration of the hardware and software and increase its stability.

HUBO last version, stands 120cm tall and weighs 55kg. It has 41 joints, enabling it to maneuver and walk at 1.25 km/h. It also has individually controlled fingers (Figure 1.9 c)) .

It's vision capabilities can recognize objects and the robot can respond to visual and auditory input using a voice recognition system.

(a) KHR-1 (b) KHR-2 (c) Least version

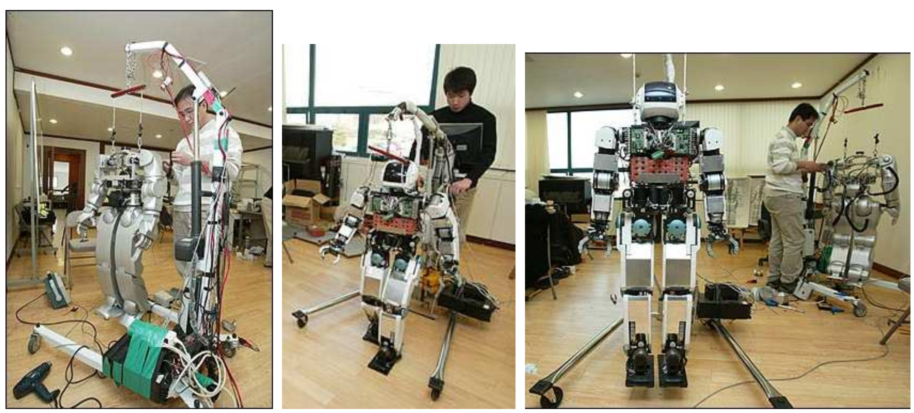


Figure 1.9: HUBO biped robot.

Sony biped robot SDR-4X II

The Sony robot SDR-4X II is shown in figure 1.10 . Since 1997, Sony is researching on this robot. The robot is conceived like an entertainment, and is able to dance and singing. This robot has 38 DOF and is equip with seven microphones for fine sound localization, image-based person recognition, on-board miniature stereo deph-map reconstruction, and limited speech recognition. Sony spent considerable effort designing a motion prototyping application system to enable their engineers to script dances in a straightforward manner. The robot measures 58 cm at standing and weight 6.5 kg.

Figure 1.10: The Sony SDR-4X II (Sony Company).

Shadow robot company "Shadow Robot"

A different design is the Shadow Robot (Figure 1.11 a)), developed by Shadow Robot Company Ltd. Its skeleton is made of wood to provide flexibility and its actuators are so-called air-muscles (figure 1.11 b)). In short, it is a flexible tube, which shortens when it is filled with air, similar to a balloon. The structure is closely orientated to the human skeleton, e.g. connecting the air-muscles to the joints by strings, which act as ligaments. The force of an air-muscle is detected by strain gauges at one end of the muscle. Under each foot, five pressure sensors detect the distribution of the robot's center of mass and a potentiometer determines the angle of each joint. Additional sensory data is gathered from mercury tilt sensors to provide information on the balancing state of the walker. However, this robot is only able to walk few steps.

(a) (b)

Figure 1.11: Shadow Robot Company Ltd. a)Shadow biped robot, b) Air-muscles.

Toyota humanoid robots

Toyota has introduced a suite of robots - one destined for health-care, one for factories, one for a human exoskeleton, and one for entertainment. (Figure 1.13). Their robots show significant advances over other robots, in particular dexterous hands and the ability to blow air through musical instruments.

Figure 1.12: Toyota's entertainment robots.

Toyota mountable, walking robot "i-foot"

This 2-legged, mountable robot was developed for three-dimensional mobility, with the ability to navigate staircases. The passenger climbs on and drives with a joystick. The egg-shaped design of the "i-foot" that wraps around the passenger is meant to express the dream of future three-dimensional mobility and the feelings of safety and reliability upon which that dream is built.

Main Features The ability to mount and dismount comfortably was of primary consideration in the design of the bird-like legs, which bend toward the rear. Steering and speed of the "i-foot" is controlled with a joystick.

Figure 1.13: Toyota's 2-legged biped robot "i-foot".

Commertial low-cost biped robots

Biped robot Andy DroidII

There also, low cost commercial robots, the Andy DroidII (Figure 1.14) is based around the EyeCon M4 mcu board and has 17 DOF's provided by 10 servos in the legs and 7 servos in arms and head. It also has the EyeCam C2 module mounted on its head bracket. The Andy DroidII is autonomous. It has an on-board CMOS Image Sensor along with the processing power of the EyeCon mcu board allow this humanoid to have a vision system.

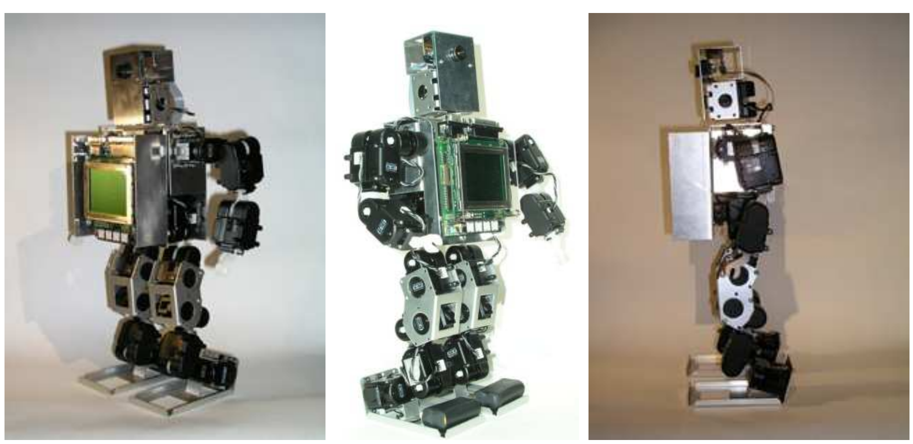


Figure 1.14: Andy DroidII.

Biped Robot CycloidII by Robotics

The CycloidII (Figure 1.15) biped robot is manufactured by Robotis and is based around the Dynamixel servo modules. They have the capacity to allows the robot to be used on applications with distributed control techniques and are capable of returning operational variables to the host controller. The control module used by the CycloidII is based around the 8bit Atmel ATMega128 mcu.

Figure 1.15: CycloidII (by Robotis).

Robot base, RoboSapien

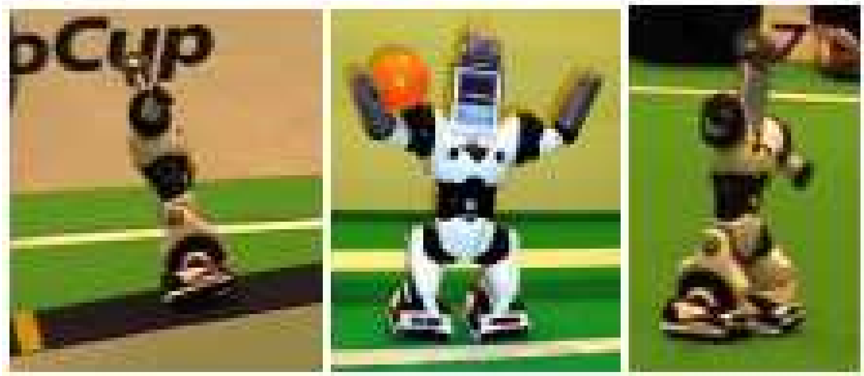
This robot base oriented to the toys market. Is used for some universities to enter on the biped research and make his first steps. The robot allows only passive walking and the structure is statically stable (big foots). The low center of mass makes RoboSapien very stable. It measures approximately 34cm in height and its weight is about 2.1kg. The robot has 7 DOF and is driven by seven small DC motors, see figure 1.17 a). One motor per leg moves two joints in the hip and the knee in the sagittal plane, keeping the foot orthogonal to the trunk. A trunk motor tilts the upper body laterally. One motor in each shoulder raises and lowers the arm and one motor in each elbow twists the lower arm and opens its grippers. RoboSapien has two gripper hands consisting of three fingers each. The new version RoboSapien v2 (Figure 1.17 b), it is provided with an infra-red vision sensor, plus a object-tracking vision system that lets the robot accept an item handed to it. In addition, this version has limited autonomy.

(a) Original

(b) Original v2

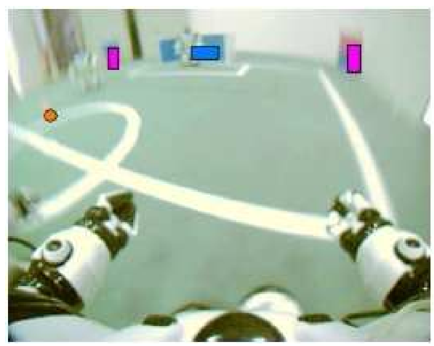
Figure 1.16: Original RoboSapien biped robot.

Some researchers had employ the RoboSapien biped robot base, but they augmented its capabilities. For example at Freiburg university (NimbRo) they add a Pocked PC with an integrated camera figure 1.17 c) to implement d). That allows, to implement self-localization and artificial vision and a behavior control 1.17 e) [[55]].



(a) Augmented by NimbRo

(b) Augmented by NimbRo



(c) Vison capabilities by NimbRo

Figure 1.17: Augmented RoboSapien biped robot.

Summary

Although the huge advances and encouraging results reached by international biped robot research groups and private companies, the overall performance of the biped robots, is not yet, comparable to its natural contra-parts, and is in a continuous process of improvement. Robust dynamic walking and realize other activities without loosing balance are not allowed by all robots. Even the best robots sometimes show instability while walking. Consequently, further research is needed. Within biped robots, the performance of smaller, servo-driven robots in general exceeded the performance of larger robots. The only two convincing larger robots so far are the Honda ASIMO prototype, and the WABIAN-2 at Takanishi Lab, out of reach for almost all researchers. On the other hand, the availability of low-cost robot bases, like RoboSapien, and construction kits, like

CycloidII and Andy DroidII, makes it possible to enter the biped robot research without the need for huge resources. The general research tendency is to improve the walking and balance robustness and increase the speed of dynamic bipedal walking.

1.3 Contribution of this thesis

In this thesis a biped robot structure is build to test walking and balance control algorithms. A list of associated publications accompanies the section. This thesis makes several significant contributions which are described in the following sections:

1. A biped robot structure based on modules is designed. The proposed modular design by its mechanical characteristics allows a quick and stable biped's robot configuration. It is designed following a low-cost philosophie. This philosophie, become such biped robot structures more affordable to a wide number of researchers. Likewise, this thesis describes the experiences gained during the construction of two previous biped robots structures.

2. A real-time biped walking based on a cubic polynomial interpolation algorithm is implemented. Real-time robust biped walking on the designed biped robot structure was achieve. The experimental results are presented in section 6.3.

3. A real-time biped balance control based on a fuzzy PD incremental algorithm is proposed. This algorithm, is based on the ZMP as a balance control criteria. The fuzzy PD incremental algorithm is quite compact. It allows a best computational efficiency than an adaptive control algorithm. Some experimental results of the algorithm presented in section 6.2 demonstrating a smooth balance control response and a correct interaction between the robot's walking sequence algorithm.

4. A hybrid approach dynamic biped robot model is proposed. It combine the inverted pendulum model approach to model the biped's walking and a back-propagation neural network system identification approach to model the biped's balance. The neural network, predicts the behavior of the ZMP during walking. Its behavior is reported in section 4.3.2.2.

a)"Dynamic control algorithm for a biped robot" *7th IASTED International Conference on CONTROL AND APPLICATIONS ~CA 2005~* May 18-20, 2005 Cancun, Mexico.

b)"Incremental fuzzy control for a biped robot balance" *IASTED International Conference on ROBOTICS AND APPLICATIONS ~RA 2005~* October 31 - November 2 , 2005 Cambridge, USA .

c)"Bipedal robot description" Technical Report B 04-19, *Freie Universität Berlin, Fachbereich Mathematik und Informatik,* 2004.

d)"Neural Network Model for the balance of a biped robot" *First International Conference on Neural Networks and Associative Memories, NNAM 2006.* November 21 to 24, 2006, Mexico City, Mexico

e) "Neural Network Model for the balance of a biped robot" *Journal Research in Computing Science, RCS,* ISSN 1870-4069, published by the National Polytechnic Institute, 2006, Mexico.

1.4 Thesis Organization

This thesis is organized as follow:

Chapter 1 establishes a biped robot research overview, then describes a previous and related works on research labs and universities and some commercial companies.

Chapter 2 present the robot's spatial localization. This chapter describes mathematical tools that allows the space localization of its points. In this section, the rotation matrix concept is introduced, also the homogeneous transformation matrix and its composition.

Chapter 3, describes the biped robot's design considerations and the implemented hardware. Those requirements are presented on the mechanical structure design and the electronic design. In this chapter, the modular-flexible design for an easy links robot's configuration is presented.

Chapter 4 explains the robot's mathematical model. In this chapter, the deduction of the kinematics by clasical methods and the dynamic model by neural networks are exposed. The mathematical robot's kinematic model is obtained to implement the simulation of the biped's robot kinematic. The kinematics is obtained by the handle of homogeneous transformation matrix applying the Denavit Hartenverg method. The robot's dynamic is obtained by the use of the inverted pendulum approach, to model the sagittal plane (walking sequence), an artificial neural network used as a system identification to model the ZMP robot's dynamic (balance).

Chapter 5 explains the biped's robot walking theory. The ZMP concept as a balance control criteria is described. In this chapter, the walking problem is divided on two themes: the *balance control* and the *walking sequence control.* A fuzzy PD Incremental algorithm is proposed as robot's balance controller, and *cubic polynomials algorithms* to control the *walking sequence control* are explained.

Chapter 6 shows the robot's performance during some experiments and tests accomplished on the balance controller and the walking sequence control. In this chapter, an adequate real-time experimental biped robot's response is demonstrated. Also, exposes some off-line adjustments (means a Matlab program) for the robot's walking sequence parameters to achieve stable trajectories. Some adjust are necessaries to guaranty initial and final velocities near to zero or even of zero.

Chapter 7 presents future work and a summary of the thesis. Some others controllers approaches to be implemented in the biped robot are suggested. Also, some hardware modifications and sensor fusion, ideas to improve and continuous the research on this field are proposed

Chapter 8 presents the conclusions of this thesis.