CONCEPTUAL AND MECHANICAL DESIGN OF AN ANTHROPOMETRIC-SCALED BIPED ROBOT FOR REPRODUCING NORMAL AND PATHOLOGICAL HUMAN GAIT

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Abstract. *This paper presents some preliminary results concerning the conceptual and mechanical design, as well as the primary hardware and software development, of a biped robot able to reproduce human gait patterns as recorded from a gait analysis laboratory. Robot dimensions followed the same mean proportions between the segments observed in human subjects. In this way, geometrical and kinematical similarity between the robot and humans were sought, although the kinetical parameters of the robot (weight and moment of inertia) were kept as light as possible, minimizing the nominal torque requirements of the servo-actuators. The robot was designed and built using 10 PWM-controlled servo-actuators. For the ankle and hip joints, parallel three-dimensional mechanical linkages were used, with the advantage of almost doubling the nominal torque-generation capacity of the servoacutators, as the two servos are employed in the generation of the movements. However, this linkage has a complex kinematics, and it was necessary to derive a mathematical model to find the servo input angles that generates the desired joint angles for the gait cycle. The control of the robot is performed by MS-Windows dedicated software, that controls the PWM (Pulse Width Modulation) signals to the servo actuators.*

Keyworks. *biped robot, biomechanics, control, human gait*

1. Introduction

The reproduction of human gait by means of a robot has been one of the most interesting challenges for engineers (Duysens et al., 2002). Several prototypes have been developed in the last years and can be found in the literature. Most of these prototypes, however, attempted to reach some kind of functional gait, regardless of more strict kinematical and anthropometrical similarities with real human body and gait. In most of these projects, heavy, expensive and sophisticated robots have been built (Hirai et al., 1998), able to reach autonomous gait patters, not necessarily similar to human real walking. At the same time, dimensional parameters, specially the relative lengths between the limbs, had not been constrained to real anthropometrical measures.

This paper shows some design ideas that are being used to build a biped robot with some specific features: anthropometrical based sizes and proportions between the limbs, low weight, low cost and the greatest possible kinematical similarity with real human gait. Stability and autonomy of the gait were not taken into account in this stage of the project. These issues will be addressed latter, by using specific sensors and control strategies.

The availability of biped robots with these biomechanical characteristics may lead to new applications of such devices. One of them is the reproduction of real gait patterns, previously acquired in gait study laboratories, since a kinematical correspondence between the gait lab model and the robot can be established. Not only normal gait should be reproduced, but also pathological patterns, usually observed in cerebral palsy, hemiplegy, basal ganglia syndromes etc. This should increase the comprehension of the phenomenon by the physician and the chance of success of the therapy.

2. Conceptual design

As the robot shall reproduce real human gait patterns, the relative dimensions among the limbs must follow proportions usually found in humans. The scheme presented by Winter (1991) has been used to find robot's segments lengths, by fixing a total height of the body. In spite of the fact that the height was fixed in 'childish' value, around 1 meter, the joint angle variations along the gait cycle, as well as the gait pattern, have geometrical similarity with real gait. The main geometrical parameters as well as the DOFs are shown in Figure 1.

Actually, the human locomotor apparatus has a great number of degrees of freedom (DOF). It is virtually impossible to reproduce all of them in a robot, and only the most important ones have been considered in the device design (Table 1). With these DOFs, it is supposed that the robot can walk straight forward. The non-planar DOFs are still important for this task. In the middle stance, for example, the support limb has to perform an inversion of the foot and the adduction of the hip, in order to stabilize the projection of the center of mass within the basis of support. On the other hand, walk to the right or to left side should require the internal or external rotation of the support limb, performed by any joint.

Table 1. Joints and DOFs of the robot.

Joint	Movements	Number of DOFs
Hip	adduction/abduction, flexion/extension	2
Knee	Flexion/extension	1
Ankle	Inversion/eversion, plantar flexion/dorsiflexion	2

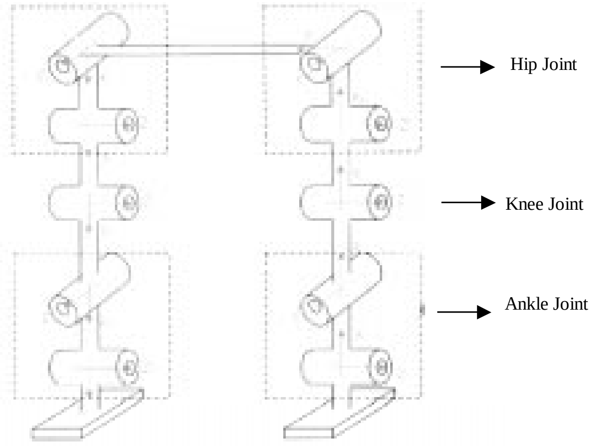

Figure 1: Reference frames, joints and degrees of freedom of the robot

A fundamental issue in the conceptual design of the robot is the choice of the joints mechanisms. Some solutions have been considered, and the parallel mechanisms shown in Figure 2 have been chosen for the ankle (left) and for the hip (right). The “A” bars indicated are connected to the servomotors. In the ankle, If both bars rotate upward, the foot makes a plantar flexion. If they rotate downward, the foot does a dorsiflexion. If one bar rotates up and the other down, the foot may perform an inversion or an eversion. In the case of the hip, a similar behavior is achieved, and the expected movements are the flexion/extension of the hip, as well as the adduction/abduction. This class of linkages has an important advantage of using simultaneously the torque of two servo-actuators to perform the same movement. On the other hand, the relation(? Não entendi) between the servos and the joints angles is not trivial, and requires a kinematical model of the linkage. This issue will be discussed in the next section. For the knee, a simple hinge joint was used. The overall view of the robot is shown in Figure 3. Low-weight, laminated aluminum profiles were chosen as the material of the robot. Spherical joints manufactured by Termicon S.A. (São Paulo, Brazil) have been used to assemble the ankle and hip joints.

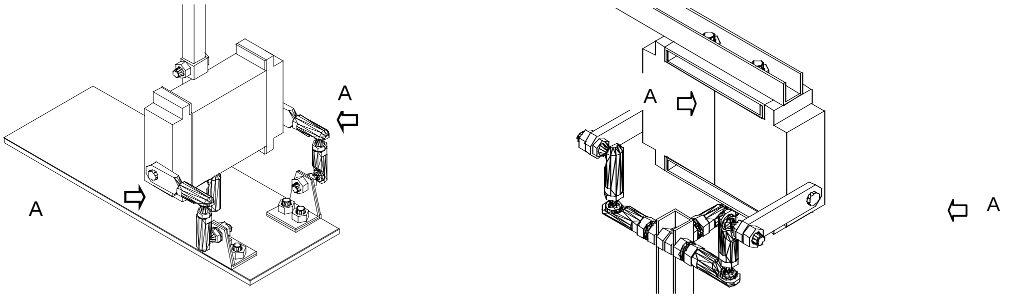

Figure 2: Detailed view of the ankle (left) and hip (right) joints

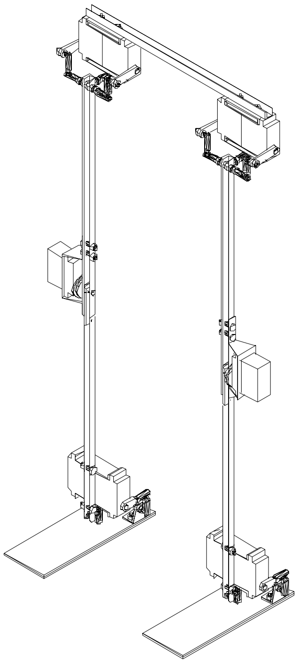

Figure 3: Overall view of the robot

3. Mechanical design

The first step in the specification of robot dimensions and actuator devices is to estimate the maximum torques performed by each joint along the gait cycle. This information was addressed by verifying in several gait lab reports (Vaughan et al. 1992; CGA, 2003) the peaks of the joint moment curves. It has been observed a direct correspondence among the weight of the body and the peak ankle torque, which is usually highest among all joints. This peak torque appears in the ankle of the stance limb in the beginning of the double support phase. In order to verify this relation, a static model of the robot was formulated (Soares and Le Diagon, 2002). The static model, derived by applying Newton equations, comprises 23 equations and 22 unknowns, as in the double support phase the lower limbs forms a closed kinematic chain. The solution of the redundant linear system was performed by two ways: the first, using the pseudo-inverse matrix and the second eliminating the shear equation (the relation between normal and shear force) of the stance foot. For a 2kg total mass, the maximum torque obtained by the first and the second methods were, respectively, 1.78 N.m and 2.35 N.m. These values follows approximately the relation of 1:1 between the peak torque (in N.m) and the body weight (in kg), that has been observed in the gait lab reports. Static models of ankle and hip linkages were also formulated, and the maximum torque that should be delivered by the servo-actuator was determined. This information was then used to specify the model of the servo-actuator as well as the maximum weight allowed for the robot.

A kinematical model of the joint linkage was developed (Piñero-Valle and Pagnota, 2002). The hip and ankle joints used the same linkage design, although some bar dimensions were different. For this reason, the same methodology was used for both joints. The problem consists in obtaining the flexion/extension (ϕ_2) and eversion/inversion (ϕ_1) angles of the foot (adduction/abduction for the hip) as a function of the angles of the servos (α_1 and α_2). Two highly nonlinear equations are obtained, that can be solved numerically with Matlab fsolve function, to find the α_1 and α_2 angles that corresponds to the joint angles imposed by the gait kinematics. The numerical solution is not fast enough for real-time implementation. For this reason, the kinematical equations were solved off-line for the allowed range of servos angles, and the solutions were fitted into simple polynomial expressions of the kind:

$$\alpha_1 = a_1 + a_2 \cdot \phi_1 + a_3 \cdot \phi_2 + a_4 \cdot \phi_1^{\ 2} + a_5 \cdot \phi_2^{\ 2} + a_6 \cdot \phi_2 \cdot \phi_1$$

$$\alpha_2 = b_1 + b_2 \cdot \phi_1 + b_3 \cdot \phi_2 + b_4 \cdot \phi_1^{\ 2} + b_5 \cdot \phi_2^{\ 2} + b_6 \cdot \phi_2 \cdot \phi_1$$

where the a_i and b_i *,i=1,..6,* parameters were estimated using a least-squares method. These expressions were incorporated in the software described bellow.

4. Actuators and control

The servos angular positions are controlled open-loop by means of a PWM signal, generated by a microcontroller-based card Sb Servo Control (Solbet LTDA., Campinas, Brazil) connected to the RS-232 interface of a PC. Each card can control up to 8 servos, and hence two cards are used, connected to PC's COM1 and COM2 ports. The PWM control signals, as well as the DC power supply are transmitted to the robot by cables. A MS-Windows Visual Basic software was developed to read the joint angles from a gait data-base, calculate the angles of the servos applying the fitting polynomial expressions and control the serial interface. A typical screen of the software developed is shown in Figure 4. At the same time, a graphical routine shows the walking robot in real-time, using a Denavit-Hartenberg derived kinematical model (Villar et al., 2002). The gait lab data was generated by AACD (Associação de Assistência à Criança Defeituosa, São Paulo), for normal and cerebral-palsy children.

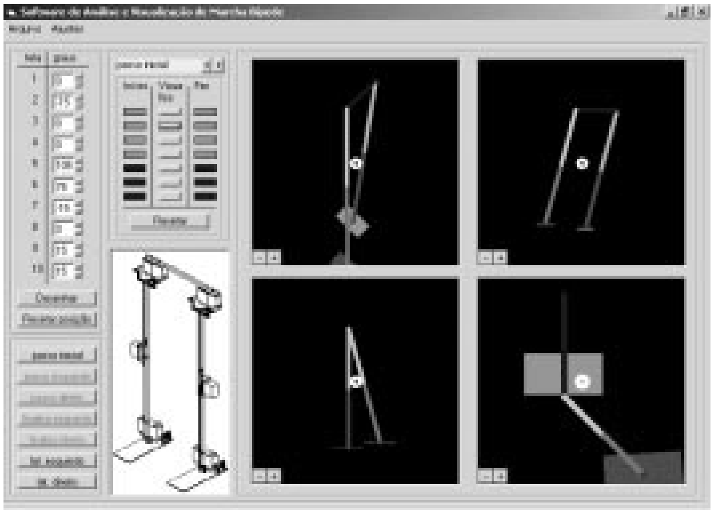

Figure 4: Sample screen of the Windows control software.

5. Discussion and research directions

This paper describes the main features and design concepts of a biped robot that is being developed at IPT. Preliminary tests were carried out, and the results led to reviewing of some features on the original project. The dimensions of the limbs are being reduced, by applying a smaller scale factor for the robot. The knee joint is being remanufactured, as the first version didn't meet the tolerance requirements. A system of sensors, based on the digitizing of the servos internal potentiometer signals to estimate joint angles, as well as tilt sensors, is also being developed.

Further work is also being carried-out for finding an overall dynamical model of the robot walking. This model will be useful for finding optimal control based trajectories for stable gaits. Those devices and control techniques will allow the design of signal generation strategies that should lead to autonomous gait patterns for the robot.

6. Acknowledgements

The authors are gratefully acknowledge to IPT, to the Department of Telecommunications and Control and to the Department of Mechanical Engineering of Escola Politecnica, University of Sao Paulo, for financial support of the project, as well as the use of the manufacturing facilities. We also thank Prof. Tarcísio Coelho (PMR-EPUSP) for discussing the design and modeling of the joint linkages, and Termicon S.A. for the donation of the spherical joints. The scholarships of CNPq and CAPES for some of the authors are also deeply appreciated.

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