Considerations on Dynamic and Static Stability of a Biped Robot

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Abstract: - This paper describes the control of a biped robot, that uses an inverted pendulum for its balance.
A control method that consists of the balance of the gaits, through the correction of the lateral and longitudinal angles of the pendulum is proposed in this work. This method presents three phases: first the trajectory of the foot in movement is defined, applying the inverse kinematics to calculate the robot's internal angles, and the direct kinematics is used to obtain the positions and orientations of the robot's joints; then the linear and angular accelerations are obtained; last, the zero moment point (ZMP) is calculated as a verification parameter of the requested margin of stability.

Simulation of the robot gaits to walk in horizontal, sloping plans, and up and down stairs is also made.

In order to decrease the calculation time of the dynamic stability, the impact of using zero pendulum angles as starting points for the interactive process of achieving the desired stability is compared to the use of the starting angles given by the static model.

We also made a study to evaluate the necessary number of notable points to represent the gait to walk in horizontal plans. That evaluation demands to settle down a commitment between the stability quality and the computer effort, being therefore necessary to find a number of notable points that allows to reach that commitment, representing the gait satisfactorily.

Key-Words: - Biped robot, Control, Zero Moment Point, Dynamics, Statics.

1 Introduction

Legged robotics presents a great advantage face to wheeled robotics, the easiness the legged robots move in almost the totality of the terrestrial surface, while wheeled vehicles have serious difficulties in irregular lands, that is, in most of the terrestrial surface. But if legged vehicles present this important advantage, why are they so little used? The answer bases on the difficulty of controlling the legged robots, on the costs, and on the load capacity. Only recently, with the exponential increase of the power of computational calculation, associated to its low cost, was possible to control, in an efficient way, the locomotion with legs.

Nowadays, applications for these vehicles are coming up, being attended a growth phase in research and development (R&D) in this area. That is why it won't be a surprise if in the next years we come to live together, more easily, with legged robots.

2 The State of the Art

The biped robots' study has been waking up the scientific community's interest, due to its best mobility in hostile lands, characterized by the presence of obstacles and inclined plans.

Vukobratovic [9] was one of the famous researchers in the area of the biped robotics, who proposed a mathematical model and its method of control. Zerrugh and Radcliffe [11] have investigated the gait of a biped based on the data of the human kinematics. Mcgeer [4] presented a locomotion pattern generated by a passive interaction of the gravity and inertia in a descending inclined ramp.

With the objective of extending the application of the method "Energy-Optimal Walking" to the ascending locomotion in ramps, Rostomi and Bessonet

[6] and Roussel, Canudas-de-Wit, and Goswami [7] have proposed generation methods of gaits by minimizing the energy consumption. However, the investigation developed until this moment does not consider the robot' s stability. Since a biped robot is easily knocked down, it is necessary to take the stability into account for the determination of the gait. Zheng and Shen [12] have proposed a method of synthesis of the gait contemplating the static stability. Chevallerreau, Formal'sky, and Perrin [1] lifted the discussion concerning the dynamic stability through the analysis of the reaction force between the base of the foot and the soil; unhappily the defined reference trajectory doesn' t assure that the restriction of stability is satisfied.

To assure the dynamic stability of a biped robot, Shin, Li, Churng, Lee, and Cruver [8], Hirai, Hirose, Haikawa, and Takenaka [2], and Vukobratovic and Juricic [10] have proposed standard methods to gait synthesis based on zero moment point (ZMP). Basically this method contemplates two stages:

1. project of the desired ZMP trajectory;
2. variation of the torso and pendulum motion to sum up the defined trajectory.

However, since the change of ZMP due to the motion of the torso and pendulum is limited, not all the required ZMP trajectories will be realizable [5]. Besides, to sum up the wanted ZMP trajectory, the motion of the torso and pendulum can radically vary. As the biped robot' s torso is relatively voluminous, the consumption of energy will increase. Then, both the stability of the robot and the softness of the movement of the torso have to be taken in consideration.

For the biped robot be able to adapt its motion to the different characteristics of the soil, as inclination, rough ground and obstacles, it is imperative that it possesses several types of motions of the foot. For example, it is desirable that the biped robot can raise the feet to an enough height that allows it to go through obstacles.

3 Robot System Description

The robot's mechanical structure is a simple one, having just joints of the hip, knee, and ankle, for each leg. Another joint controlling an inverted pendulum is used in order to balance the structure.

Seven servomotors constitute the robot, the structure is made of acrylic and aluminum, with 1.7 Kg weight, and 50 cm height.

Figure 1 shows the implemented robot. It was totally designed and built at the Institute of System and Robotics, Department of Electrical Engineering and Computer Science of University of Coimbra, Portugal.

Fig. 1 - Implemented robot.

The robot was designed to walk in horizontal and inclined plans, to go up and down stairways, having a maximum speed of approximately 1 cm/s.

A battery is used to supply the power to the robot and is placed in the pendulum.

Shown in the figure 2 is the simplified diagram of the flow of data among the several components of the system.

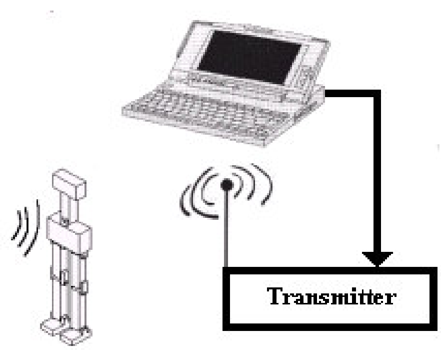

Fig. 2 - Main components of the robotic system.

4 Robot Modelling

4.1 Kinematics

The most used formalism for robot's kinematics is the of Denavit-Hartenberg method. The link's coordinate systems used to model the biped robot are illustrated in figure 3.

4.2 Dynamics

In this work the formulation described by Huang, Kajita, Kaneko, Yokoi, Komoriya, and Tanie [3] is used. This formulation is based on the calculation of ZMP through the dynamic and static models.

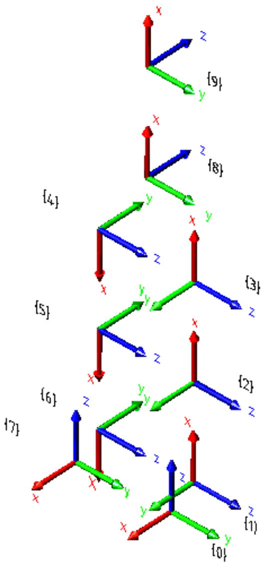

Fig. 3 - Model of the coordinate systems.

5 Gaits

A gait is the term used to designate a cyclic movement of the legs of an animal or robot. It can be said that the gait defines the form and the characteristics in the way a body moves; for this reason the study of the gaits is fundamental for legged robotics.

5.1 Gaits Conceived

In this work 8 different gaits were conceived, with the goal to approach the gaits that are considered to be the most frequent in the human being locomotion. Figure 4 represents the structure of conception of the gaits, as well as its denomination.

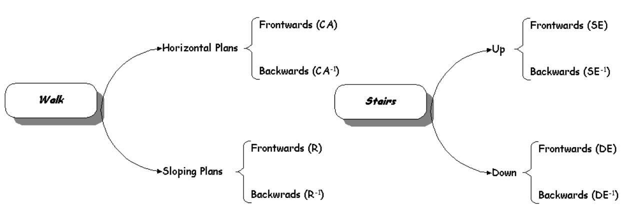

Fig. 4 - Structure conception of the gaits.

To project the gaits used in this work, a trajectory for the foot in movement was defined, trajectory that has the following characteristics:

- The robots walking must be like a human;
- At the beginning and at the end of the trajectory, the height of the foot is null, relative to the ground;
- At 50% of the trajectory the height of the foot is maximum (figure 5).

With these characteristics the following equation normalized for the trajectory of the foot was obtained:

$$y = 4 \cdot \left(x - x^2\right) \quad 0 \le y, x \le 1 \tag{1}$$

To obtain the final trajectory it is needed to know the height (A) and the length (C) of the trajectory, resulting

$$Y = A \cdot 4 \cdot \left(\frac{X}{C} - \left(\frac{X}{C} \right)^2 \right) \quad \begin{matrix} 0 \le Y \le A \\ 0 \le X \le C \end{matrix} \tag{2}$$

where $Y = A \cdot y$ and $X = C \cdot x$.

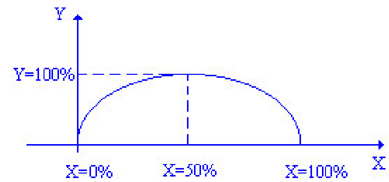

Fig. 5 - Normalized trajectory.

To walk in horizontal planes the trajectory given by the equation 2 is applied. With relation to walk in inclined plans the trajectory is determined through the rotation of the positions given by the equation 2, according to the inclination angle.

The trajectories used to go up and to go down stairs are obtained in the way shown in figure 6.

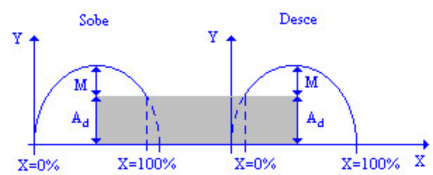

Fig. 5 - Trajectories to go up and to go down stairs.

Considering the width of the step (A_d) and safety' s margin (M), one can solve equation 2 with C = 1, A = A_d + M and Y = A_d, obtaining the percentage of relative length to the original gait. After that it is transformed into 0% or 100% when it goes down or it goes up stairs, respectively.

6 Trajectory

With the kinematics discussion and the robot' s dynamics the need to solve the problem of controlling the robot exists, with purpose that it follows the desired trajectory. The method of cubic spline offers several advantages: first because it uses the lowest degree of a polynomial function that allows continuity in speed and acceleration; second when using a polynomial of low degree the computation effort and the possibility of numeric instabilities are reduced. Although several base functions can be used, in this work, the polynomial interpolation, spline cubic, is used, corresponding to the use of the 3rd degree polynomial.

This is due to the fact that in this work it is necessary to use the 2^{nd} derivate to obtain the linear and angular accelerations.

7 Control Algorithm

In this work, a method that consists in a balance of the gait, through the correction of the angles of the haunches and pendulum is proposed. First, taking into account the characteristics of the step, the notable points of the trajectory is obtained and the trajectory of the falling foot is generated by an interpolation of 3rd spline order, being the trajectory of the remaining articulations generated using the direct and inverse kinematics. Last, ZMP will be compared with the center of the fixed foot in way to verify the margin of stability (K) chosen. If the margin of stability is not verified the angles of the hip and pendulum are corrected until it is obtained the wanted approach. Due to angular limitations of the servomotors of the pendulum and haunches, some gaits in that are not possible to obtain stability exist.

In case of the static model the need of the calculation of the spline doesn' t exist, what leads to a high reduction of the calculation needed; in the dynamic case it is necessary to calculate 4 splines for each link, what results in a high calculation needed, which turns impossible with actual computers, to consider the resolution of these equations on line.

8 Dynamic System vs Static System

In the characterization of robots' systems with legs, the problem of deciding if there is need to apply the dynamic system or the static exits. To decide, one must know if the system is fast or slow, that is to say, to know if the system is slow enough to the static system be considered. The computational calculation of the static model is, in this case, of about 110ms.

In the case of being necessary to use the dynamic model, being the calculation time higher (about 20 seconds), it results in the off-line use of the model.

The two models for the four gaits defined were compared: to walk in horizontal plans, to walk in inclined plans, and go up and down stairs. Each gait was considered separately, that is, won' t be kept in mind any gait that happened before. The comparison was done in order to evaluate the lateral and longitudinal variation of the pendulum. Due to lack of space we only present results for the gait to walk in horizontal plans for a margin of stability of 0.6 cm. Conclusions will be drawn for the other gaits.

8.1 Walking in Horizontal Planes

Variation in two ways will be analyzed, first varying the length of the gait and after varying the execution time.

The larger the length of the gait is, the greater the longitudinal correction of the pendulum is. This is due to the translation of the body to the front moving its ZMP.

With relationship to the lateral angle of the pendulum, it is not influenced, therefore ZMP y coordinate doesn' t vary with the length of the gait, it varies with the time of execution.

A gait of 5 cm is taking into analysis of the influence of the variation of execution time. The acceleration of the foot in movement is also presented because it is the variable that more contributes for the stability of the dynamic system.

The correction of ZMP decreases with the execution time of the gait, this is due to the increase of the acceleration component, which is reflected in the decrease of the pendulum correction.

For simulation of the dynamic system with this biped robot it is not possible to obtain stability for execution times of the gait below 0.6 s, this is due to the robot' s physical characteristics. Because the robot has a minimum time of execution of 1.6 s, there are no stability problems.

It is also possible to conclude that decreasing the margin of stability it is possible to use the static model, because the curve of the dynamic model for a execution time of 1.6 s will approach the curve of the static model.

8.2 Walking in Inclined Planes

Some inclination of planes were tested for walking. When the gait is to go up ramp, for the first phase it is necessary a larger longitudinal correction than when going down the ramp. This is due to the fact of ZMP in the first phase is behind the support foot. For the gait used to go down the ramp, as the distance between the projection of ZMP into the slope plan and the support foot is smaller along the X axis, the torque needed to achieve the desired margin of stability is minor, being obtained a smaller longitudinal angle. In the case of going up the ramp a larger longitudinal angle is obtained.

In the second phase it happens the opposite, resulting a smaller longitudinal angle for the gait to go up inclined plans and larger when it goes down.

With relationship to the lateral angle of the pendulum it is not influenced, once this only varies with the execution time of the gait, that is to say with the dynamic system. Without taking in account the sliding of the robot' s foot, stability can be reached even about 44º of inclination, for a gait of 7 cm of length.

A gait of 7 cm with an inclination of 5º was analyzed concerning the influence of the variation of the execution time.

Once again the correction of ZMP decreases with the time of execution of the gait, because the increase of acceleration component, which leads to the decrease of lateral and longitudinal pendulum corrections.

8.3 Going Up Stairs

The analysis of the variation is done in two ways, the first varying the height of the step and the second varying the execution time of the gait.

Three gaits for the analysis were considered, that is, gaits of 1, 2, 3 cm of height of the step for a fixed length of 12 cm. The length chosen for the analysis is due to the fact that Robot's foot is 11 cm.

The maximum point of the longitudinal angle of the pendulum happens in the situation when the robot places the foot in the step, which increases the robot's need for a larger longitudinal compensation of the pendulum.

The lateral angle of the pendulum doesn' t vary with the length of the gait.

A gait for a step height of 3 cm was analyzed for the influence of the variation of execution time in the lateral and longitudinal angles of the pendulum.

Once again the ZMP correction decreases with the execution time of the gait, due to the increase of the acceleration component, which is reflected in a decrease of the lateral and longitudinal pendulum corrections.

It is also verified that the lateral angle of the pendulum varies of quadrant, this is due to the change of fixed foot that is operated in this gait.

8.4 Going Down Stairs

The study will be similar to that of going up stairs, that is to say, it will be analyzed the variation in two ways, the first varying the height of the step and second varying the execution time of the gait.

Thee gaits were considered for the analysis, that is, gaits of 1, 2, 3 cm of height of the step for a fixed length of 12 cm.

When the robot places the foot in the ground, the maximum point of the longitudinal angle of the pendulum is verified, situation where the robot needs the largest longitudinal compensation of the pendulum. When the change of the fixed foot happens, it would be expected that the value in module of the longitudinal angle of the pendulum went similar to the previous situation in that the robot places the foot in the ground, however that is not verified because there is a displacement first to the front of the body, transferring the ZMP for the new fixed foot.

In respect to the variation of the lateral angle of the pendulum, the situation is the same verified for the previous gaits. The lateral angle is only influenced by the execution time of the gait. This gait has a maximum height of 3.3 cm for this robot, due to physical limitation, that is to say, one of the haunches reaches the 90º .

A gaits for a step height of 3cm is taken into analysis of the influence of variation of the execution time in the lateral and longitudinal angles of the pendulum.

The ZMP correction decreases with the execution time of the gait, because the component acceleration increases, which leads to a decrease of the lateral and longitudinal pendulum correction.

It is verified that the lateral angle of the pendulum varies of quadrant. This is due to the change of fixed foot that is operated in this gait.

9 Number of Notable Points

With this simulation the minimum number of notable points that are necessary to represent a satisfactorily gait was evaluated in order to decrease the time of calculation of the dynamic model. Once this biped robot executes the gait in 1.2s, we have just analyzed the gait for this time of execution.

The discretization of the gait was done with 3, 5 and 7 notable points, resulting in a calculation time of the dynamic model of 1.1 s, 3.5 s and 8.52 s respectively. The static model was used as a way of obtaining the initial pendulum angles.

Due to computer limitations it is required to settle down a commitment situation between the quality of the stability and the computer effort, being therefore necessary to find a number of notable points that allows to reach that commitment, representing a satisfactorily gait.

In the accomplished simulations that commitment situation is reached with 5 notable points. The angles of the pendulum with 3 notable points is quite different from those obtained with 5 and 7 notable points, so 3 notable points should not be used.

For 5 and 7 notable points the results are similar, not justifying the extra computer effort necessary to describe the gait with 7 notable points. So it can be concluded that the discretization of the gait with 5 notable points is enough to describe a satisfactorily gait to walk in horizontal planes.

10 Conclusions

With relationship to the hardware used it is verified that the robot' s autonomy is quite satisfactory compared to other robots presented until the moment. Also the implemented transmission system has a reasonable performance. The fact of not having endowed the robot with sensors takes it dependent of the imprecision, oscillations and linearity of the servomotors and of the constructed model.

The control of the biped robot through the formalism of ZMP leads to a decrease of the time of execution. But in this formalism it is not easy to include the control of torque, speed, or acceleration, turning it little reliable.

Simulations show that in this robot it is worth to apply the static system in the calculation of ZMP because it is verified that this robot is slow enough to make this approach and to maintain the stability. It is also concluded that the lateral angular correction of the pendulum is only affected when the dynamic model is applied, varying with the supposed time of execution of the gait The longitudinal angular correction is conditioned by the characteristics of the gait, that is to say, length, height, inclination and time of execution.

The use of dynamic ZMP implies the impossibility of real time control, because its calculation time is too high (3.52 s). However the use of the static ZMP as a starting angles reflects on a decrease of the dynamic stability's calculation time.

An off-line evaluating of the gait requests the consideration of only on 5 notable points for the verification of the biped robot' s dynamic stability, in order to decrease the computer effort.

In the practical execution of the gaits, it is verified that these result satisfactorily in horizontal and inclined plans. The gaits to go up and to go down stairs the feet slipping is verified.

The main difficulties found are concerned with model building and with robot' s calibration. The model of the biped robot required a lot of simplifications, such as the association of several parts of the body in just one, driving to an imperfect model. The robot' s calibration came as a difficulty due to the used servomotors non-linearity, but this difficulty can be solved with the servomotors substitution by more precise and linear motors.

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