

Measuring the distortion force over time by experimental methodology resulting in maintaining and improving the Stumble recovery on a humanoid robot

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1. Abstract

Humanoid robots movement without lying down in ground is of major importance. This thesis focuses on the hip-ankle strategy as a method to maintain balance when subjected to a large disturbance. This strategy is characterised by a large rotation of the hip joint which repositions the Centre of Mass (CoM). The hip-ankle strategy is compared to the ankle strategy which locks the hip joint and compensates for a disturbance by applying ankle torque. Various hip-ankle strategy controllers have been presented in literature of which three implementations on humanoid robots are known. However, none of the research provided experimental evidence that a humanoid robot can withstand larger disturbances by using the hip-ankle strategy compared to the ankle strategy.

The goal of this research was therefore to provide experimental evidence that a humanoid robot can maintain balance for larger disturbances by using the hip-ankle strategy than solely using the ankle strategy.

First, simple models were used to investigate the theoretical maximum allowable disturbance for the humanoid robot Bioloid.

The Inverted Pendulum Model (IPM) was used to simulate the ankle strategy where ankle torque was the

only control input. The hip-ankle strategy was simulated using the Inverted Pendulum plus Flywheel Model (IPFM) where flywheel served as an additional control input. The hip-ankle strategy was implemented by using bang-bang control input profile on the flywheel. Disturbances were applied in horizontal direction to the CoM of the model and measured in terms of applied impulse. In these simulations the hip-ankle strategy was able to maintain balance for disturbances 33.6% larger than the ankle strategy.

Key words : CoM, IPM, IPFM, Flywheel, Applied impulse, VMC, ICP

2. Control Algorithm

Next, a control algorithm was developed for the humanoid robot TULIP. In the control algorithm, the hip-ankle strategy was implemented by the application of virtual forces and torques on the trunk of the robot. These virtual forces were then transferred to joint torques by means of Virtual Model Control (VMC). [2, 3, 4] The Instantaneous Capture Point (ICP) of the robot was controlled to a desired location by modulating the Centre of Pressure (CoP) of the robot. If the CoP is sufficient to keep the ICP within the foot, the control algorithm will lock the hip joint and balance using solely the ankle torque. [6, 8, 10, 11].

The direction of the ICP which results in a rotational acceleration of the upper body. The ICP will then be pushed back into the foot and the application of ankle torque will then be sufficient again to maintain balance. In order to evaluate if it is physically possible for the humanoid robot Bioloid to maintain balance using the hip-ankle strategy control algorithm, a simulation was performed. The incorporation of Double Inverted Pendulum Model (DIPM) was used as a model for Bioloid and constraints in terms of maximum joint torque and range of motion were included. The ankle strategy and the hip-ankle strategy [11,13,15] were then subjected to horizontal impulsive disturbances to the back of the upper body of the robot and measured in terms of impulse. The hip-ankle strategy was able to withstand 16.6 % larger pushes than the ankle strategy. Finally the hip-ankle strategy was experimentally evaluated on the humanoid robot Bioloid [19,20]. Disturbances [16] were created by swinging a weight at the end of a pendulum to the back of the upper body of the robot.

The applied impulse was measured by measuring the disturbance force over time by using a load cell. [20,21] Experimental results showed that the hip-ankle strategy implemented on the humanoid robot can maintain balance for disturbances 19.3 % larger than solely using the ankle strategy. The main conclusion of this research is that the hip-ankle strategy can be used to improve the balance maintenance on a humanoid robot. This thesis provided the first experimental evidence that a humanoid robot can maintain balance. To properly build up the argument that the hip-ankle strategy outperforms the ankle strategy, the introduction of various key concepts is required.

Therefore, this research elaborates on the ankle and hip-ankle strategy in section 3-1. Additionally, it gives an explanation why the hip strategy should be used at all. Section 3-2 introduces the Instantaneous Capture Point (ICP) [21] as an important point on the ground that can be used to maintain balance on a humanoid robot.

This point will later be of great value in the analysis and synthesis of the balance control algorithm.

3-1 Strategies to maintain balance

Two strategies can be distinguished to maintain balance; the ankle strategy and the hip-ankle strategy. This section introduces both strategies and explains why the hip-ankle strategy should be used at all.

3-1-1 Ankle strategy

As explained by [3] M. Vukobratovic, A. A. Frank, and D. Juricic humans tend to use the ankle strategy.

In case of relative small disturbances. An example of this strategy is given in figure 3-1(a) where a disturbance pushes the CoM from its desired state. The ankle strategy is a relatively simple strategy and many applications of this strategy on humanoid robots are known [2, 4, 5, 8,12].

The hip joint is locked and ankle torque is used to bring back the CoM to its desired position.

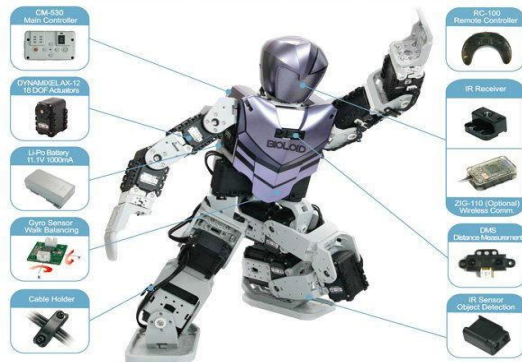
If we consider the hip joint as locked, the system in figure 3-1(a) can be considered to have one Degree of Freedom (DoF) with the ankle torque as commanded quantity.

The contact between the foot and floor is a unilateral constraint since no attractive forces exist between the two.

If the (required) ankle torque will become too large the foot will start to rotate.

This should be prevented at all times because the system then becomes underactuated.[19,20,21]

The limitation of this strategy is therefore the amount of ankle torque that can be applied without foot rotation to occur.



Bioloid Humanoid

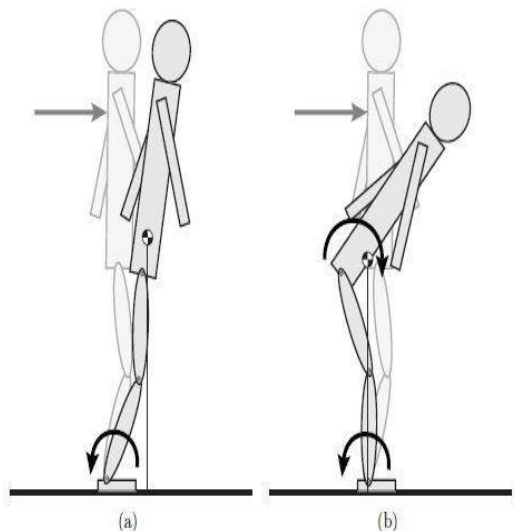


Figure 3-1: The ankle strategy and the combination of the hip and ankle strategy (hip-ankle strategy). In case of the ankle strategy (a), the hip joint is stiff and an ankle torque is applied to bring the CoM back to its desired position. In case of the hip-ankle strategy (a), a large torque on the hip joint is applied which creates forward angular acceleration of the upper body. This angular acceleration creates a large deflection at the hips and shifts the CoM backwards over the feet.[12,19]

3-1-2 Hip-ankle strategy

In case of a too large disturbance the ankle strategy will not be sufficient to prevent a fall Angular acceleration of the upper body can be generated in the direction of the disturbance by applying a torque on the hip joint as depicted in figure 3-1(b); the hip-ankle strategy.[5,10] In this figure a horizontal disturbance force is applied to the back of the robot, as a response a large

torque is applied on the hip joint and the upper body bends forward. This forward torque in combination with ankle torque results in a backward motion of the CoM to its desired position [1, 2, 4]. Limitations of this strategy are the amount of hip torque that can be applied, the range of motion of the joint that is accelerated and the inertia of the segment which is accelerated.

As introduced above, the hip-ankle strategy can be applied in case the ankle strategy is not sufficient. Another option would be to make a step, however, several situations might occur where stepping is not possible or where using the hip-ankle strategy is more beneficial. In this situation the robot is thus fully dependent on the hip-ankle strategy in order to prevent a fall. Three examples of these situations are illustrated by figure 3-2 and explained below:

3-1 Strategies to maintain balance

1. Stumble recovery See figure 3-2(a). A situation where the hip strategy is useful is when the swing foot hits the ground while walking. A sudden stop of the robot is required while the CoM might have large forward velocity y . By lunging forward in combination with applying ankle torque the robot might still be able to maintain balance. [18,19,20] A similar situation occurs when the robot intentionally makes the transition from walking to stopping.

To stop the robot the step length can be adjusted and a the CoM can be accelerated backwards by lunging forward. Using this strategy results in the robot having to take less steps in order to come to a stop.[12,13]

2. Requirement of a cross step See figure 3-2(b). Another situation that can occur is when the robot should take a step to maintain balance but the weight of the robot is incorrectly distributed.[The CoM of the robot is situated such that a cross step is required. For example if the robot balances on the left leg and a disturbance is applied to the left, the desired foot position for the right foot is on the left side of the stance foot. It is physically not possible to place the foot at that position and a lunge in that direction might prevent a fall [8].

3. Occurrence of an obstacle See fig 3-2(c). The final example where a step is not possible is the occurrence of an obstacle. In case of a large disturbance, when an obstacle is situated in the direction of that disturbance, a step cannot be taken but the hip strategy can be used to prevent a fall.

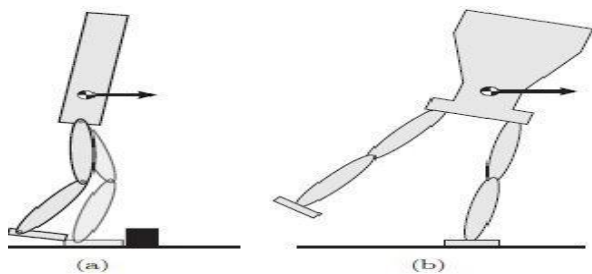


Figure 3-2: Situations in which using the hip strategy can be beneficial in order to maintain balance. In (a), the robot hits the floor or an obstacle while walking. By lunging forward, the forward CoM velocity of the robot can be compensated. Figure (b) shows a front view of the robot, it has a sideways CoM velocity or a disturbance in the direction of the arrow. In order to regain balance a step in the direction of the disturbance is required. However, this requires a cross step; the right leg should place its foot on the other side of the stance foot. This is physically not possible on the robot, the hip-ankle strategy will be of great value because it can still regain balance. In (c) a large disturbance is applied to the back of the robot. Because of an obstacle the robot can not make a step. However the hip-ankle strategy can still prevent a fall by lunging forward.

For a humanoid robot, the hip strategy will thus be useful in a variety of situations. This thesis will focus on balance maintenance in the sagittal plane with disturbances applied to the back of the robot (as shown in figure 3-2(c)).

3-2 Analysis and control using the Instantaneous Capture Point

As mentioned in section 3-1 a humanoid robot can maintain balance using the ankle strategy and in case of large disturbances the hip-ankle strategy can be used. In order to maintain balance on a humanoid robot it is therefore crucial to measure how close the system is to falling. Because a humanoid robot is a system with complex dynamics it is useful to approximate this dynamics by a simple model. The simple model used in this research is the Linear Inverted Pendulum Model (LIPM) [4, 8], introduced in section 3-2-1. It is used to analyse the CoM motion of the robot and calculate the Instantaneous Capture Point (ICP). The ICP, introduced in section 3-2-3, is a point on the ground which indicates how close the system is to falling and can be used to control the balance of a humanoid robot. The location of the ICP can be modulated by another point on the ground; the Centre of Pressure (CoP). This point is introduced in section 3-2-2.

3-2-1 Linear Inverted Pendulum Model

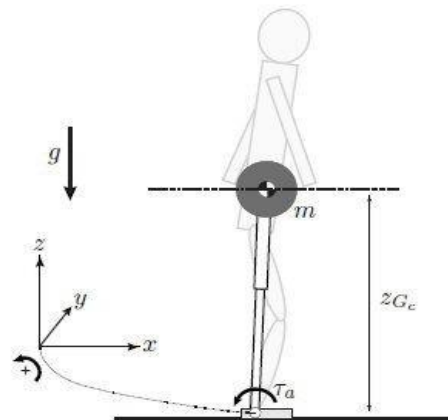


Figure 3-3: The LIPM consists of a point mass m and a massless telescopic leg. Ankle torque τ_a can be applied at the base of the pendulum. The equation of motion of this model is linearised by constraining the CoM to fixed height z_{Gc} .

The LIPM therefore simplifies the dynamics of the humanoid robot and can be used to derive an analytical solution for the ICP. The CoP is a point on the ground that indicates the amount of ankle torque applied. This point can be used to control the location of the ICP. The LIPM, depicted in figure 3-3, can be used to analyse and control a humanoid robot in order to prevent a fall. This model consists of a point mass and a massless telescopic leg. The point mass is situated at the CoM of the robot and has the same mass (m) as the robot. 3-2 Analysis and control using the Instantaneous Capture Point 13 telescopic leg is the dynamical equivalence of the force exerted by the legs of the robot on its CoM. On the LIPM of figure 3-3 torques τ_a can be applied at the base of the pendulum. The equations of motion for this model are linearised by constraining the CoM to a fixed height ($\ddot{z}_G = 0$).

This results in

$$\tau_a = -m\ddot{x}_G z_{Gc} + mgx_G \quad (3-1a)$$

$$\ddot{x}_G = \frac{g}{z_{Gc}} \left(x_G - \frac{\tau_a}{mg} \right) \quad (3-1b)$$

$$\ddot{x}_G = \omega_0^2 \left(x_G - \frac{\tau_a}{mg} \right) \quad (3-1c)$$

is the reciprocal of the time constant of a single pendulum where z_{Gc} is the constant height and g the gravitational constant [27]. Equation (3-1c) shows that the system is equivalent to a mass-spring system with negative spring stiffness, the farther away the location of the CoM from the

origin, the larger the force which pushes it away. The LIPM simplifies dynamics of the actual robot for a great deal as it reduces the number of Degrees of Freedom (DoF) compared to the actual robot and linearises the equations of motion. For the humanoid robot TULip this means a reduction from twelve to one DoF. Moreover, because (3-1c) is a second order linear differential equation it can be solved analytically.

3-2-2 Centre of Pressure

The derived equation of motion (3-1c) gives theoretical insight in the dynamical behaviour of a humanoid robot. A crucial feature in the maintenance of balance is the application of ankle torque. The CoP is the point on the ground that indicates the amount of ankle torque applied.

Equation (3-1c) can be rewritten as

$$\ddot{x}_G = \omega_0^2 (x_G - x_{CoP}) \quad (3-2)$$

The parameter x_{CoP} in equation (3-2) is the CoP of the robot,

$$x_{CoP} = \frac{\tau_a}{mg} \quad (3-3)$$

3-2-3 Instantaneous Capture Point

The ICP is the point on the ground where the CoP should instantaneously be placed and maintained in order to bring the system to a stop with the CoM above the CoP [2, 8, 9]. Once the ICP has left the support polygon the CoP cannot be placed at that position (due to the CoP constraint) unless a step will be taken or the hip- ankle strategy will be applied. The ICP can be derived by the “Linear Inverted Pendulum Orbital Energy” [35]. This is the Hamiltonian of the LIPM and consists of the total kinetic and potential energy. The kinetic energy is a function of the CoM velocity (\dot{x}_G),

$$T_{LIPM} = \frac{1}{2} m \dot{x}_G^2 \quad (3-4)$$

As (3-2) can be viewed as a mass-spring system, the stored elastic potential energy can be found by the work done by the system,

$$\begin{aligned} V_{LIPM} &= - \int F_{G_x} dx = - \int m \omega_0^2 (x_G - x_{CoP}) dx \\ &= - \frac{mg}{2z_{G_c}} (x_G - x_{CoP})^2 \end{aligned} \quad (3-5)$$

where $F_{G_x} = m \ddot{x}_G$ is the horizontal spring force and is derived from the equations of motion in equation (3-2). Note that this derivation is only valid for a constant x_{CoP} or a constant ankle torque. The total energy or Hamiltonian is given by

$$E_{LIPM} = T_{LIPM} + V_{LIPM} = \frac{1}{2} \dot{x}_G^2 - \frac{g}{2z_{G_c}} (x_G - x_{CoP})^2 \quad (3-6)$$

where the Hamiltonian E_{LIPM} is the orbital energy of the LIPM which is a conserved quantity and can therefore have a constant value. The orbital energy in the LIPM (E_{LIPM}) determines the behaviour of the system which is characterised by figure 3-4. If $E_{LIPM} > 0$ the CoM moves over the CoP, for $E_{LIPM} < 0$ the CoM does not reach the CoP and reverses direction. For $E_{LIPM} = 0$ the system has two eigenvalues, a stable and an unstable one. The eigenvalue for $E_{LIPM} = 0$ which brings the CoM to a stop over the CoP is of interest, this location is called the ICP. In equation (3-6) the CoP should be placed at such a location that the orbital energy becomes zero and the CoM comes to a stop over the CoP. In equation (3-6) the CoP can be placed at the ICP ($x_{CoP} = x_{ICP}$), which will result in zero orbital energy,

$$\frac{1}{2} \dot{x}_G^2 - \frac{g}{2z_{G_c}} (x_G - x_{ICP})^2 = 0 \quad (3-7)$$

with x_{ICP} the ICP location in x -direction. Solving equation (3-7) results in two solutions, as indicated by the saddle point in figure 3-4. The ICP is the solution for which the CoM moves towards the CoP,

$$x_{ICP} = x_G + \dot{x}_G \sqrt{\frac{2G_c}{g}} \quad (3-8)$$

which can also be written as,

$$x_{ICP} = x_G + \frac{\dot{x}_G}{\omega_0} \quad (3-9)$$

The ICP is thus a function of the CoM position and velocity as depicted by figure 3-5. It defines where the CoP should be placed in order to come to a stop.

3-2 Analysis and control using the Instantaneous Capture Point 15

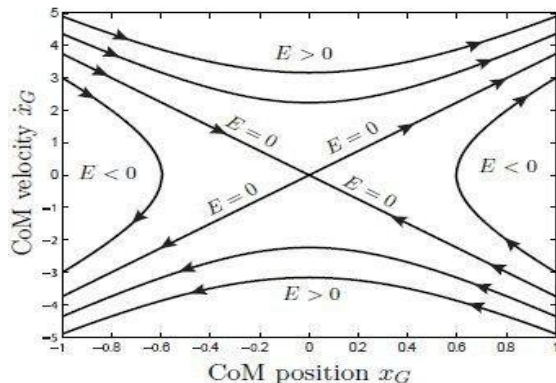


Figure 3-4: Phase portrait for the CoM of the Linear Inverted Pendulum Model. The CoP location is positioned at (0, 0). For $ELIPM > 0$, the CoM moves over the CoP. For $ELIPM < 0$ moves to the CoM but moves back before it reaches the CoP. For $ELIPM = 0$ the CoM comes to a stop over the CoP.

This knowledge can be used in order to maintain balance on the robot.

Placing the CoP in front of the ICP ($x_{CoP} > x_{ICP}$) will push the ICP backward, placing the CoP behind the ICP ($x_{CoP} < x_{ICP}$) will push the ICP forward. With this strategy the ICP can be controlled to a desired location.

This will be of later use in the application of the balancing control algorithm.

The desired location of the ICP is for this research defined in the middle of the support polygon as this location implies best robustness against disturbances for all directions.

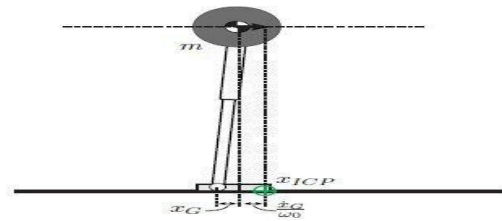


Figure 3-5: The location of the ICP x_{ICP} (in green) is calculated by the sum of the CoM projection on the ground and the CoM velocity \dot{x}_G divided by ω_0 .

3-3 Conclusion

A humanoid robot can use the hip-ankle strategy in case the ankle strategy is not sufficient in maintaining balance when subjected to a large disturbance. An important point on the ground that can be used to maintain balance on a humanoid robot is the Instantaneous Capture Point (ICP). The Linear Inverted Pendulum Model (LIPM) can be used to analytically derive the ICP for a humanoid robot. The ICP is composed of the CoM position and velocity of the robot and predicts how close the system is to a fall. The ICP is closely related to the Centre of Pressure (CoP), which is also a point projected on the ground. The CoP location indicates the amount of ankle torque applied and can be modulated to control the ICP to a desired location.

Future work

Now all preliminaries are introduced, a measure for the applied disturbance will be evaluated in future work.

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