

Balance Control of Biped Robot Running with One Arm in Task Motion

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Abstract: This paper proposes a control method for running biped robot with desired arm motion based on resolved momentum control. The focus is to maintain robot stability by using redundant degrees of freedom when running biped robot has desired arm motion. Motions for robot stability are calculated by predetermined the reference angular momentum keeping robot balance based on resolved momentum control. The reference angular momentum maintaining robot stability is determined by linear relationship with the angular momentum from constraint motions by a gradient optimization method. Under the assumption that the vertical center of mass (CoM) motion is simple hopping robot, trajectories of vertical and horizontal CoM are generated based on inverted pendulum model (IPM). A series of computer simulations of a 28-DOF biped robot showed that running of a biped robot with desired arm motions stably was successfully achieved with the proposed method.

Key-Words: angular momentum, biped robot, resolved momentum control, robot stability

1 Introduction

Many of the works on biped robots focus on walking as it is very fundamental and important. Lots of dynamically reliable algorithms for walking have been proved. Main algorithms for stable walking of biped robots are divided into two parts: stable leg and foot trajectory and stable locomotion control. For the trajectory, the CoM of robot is generated based on simple dynamic mode based on zero moment point (ZMP) such as the linear inverted pendulum model (LIPM) [1, 2] and the gravity-compensated inverted pendulum model (GCIPM) [3]. Moreover, lots of control methods have been researched for stable dynamic biped walking. Various analyses and researches on passive dynamic walking of biped robot have demonstrated this strategy is efficient for bipedal walking [4–7]. The computed-torque control and the hybrid impedance/computed-torque control have been proposed [3, 8]. An impedance control with impedance modulation strategy is proposed for biped robots to walk stably under the various locomotion conditions of the environment [9, 15]. Force controllers, sensory reflex motion, and intelligent controller are utilized to maintain robot stability in uncertain environments [10–13]. The 42 DOF humanoid robot HRP-4C successfully walks and turns by applying posture/force control [14].

Human beings use their arms freely while they run in order for performance or grabbing something

or whatever. For example, marathoners use their arms to grab water bottle while running. Based on this fact, our study focuses on maintaining stability for running biped robot with desired arm motions. Resolved momentum control [16] is used to maintain robot stability by using redundant degrees of freedom while the running biped robot has desired arm motions which could cause instability. The conventional resolved momentum control is the whole body motion is calculated from a given linear and angular momentum reference by using a pseudo-inverse of the inertia matrix. The reference linear momentum is determined by the trajectory generation and angular momentum is set to zero [16–18]. However, it is highly possible for some angles of joints to exceed the movable range if both linear and angular momenta are considered or angular momentum is set to some specific constant value if biped robot has numerous degrees of freedom. Therefore, several papers adopting resolved momentum control do not take care of the angular momentum around specific axes to prevent these problems, for example roll and pitch axes. However, the angular momentum around all axes is very important for robot stability.

This paper proposes how to take care of the angular momentum of all axes with joint limits without the use of linear momentum. The reason for not using the linear momentum is that only controlling angular momentum can keep the balance of robot suf-

ficiently [6]. While the reference angular momentum is set to a constant value in the conventional resolved momentum control, which is not good in keeping the balance of robot, especially in case of external disturbances such as uneven terrain or obstacles, this paper proposes to use variable angular momentum.

The proposed resolved momentum and the method of determining the reference angular momentum are presented in Section 2. The trajectory generation is presented in Section 3. A series of computer simulations of 28 DOF running biped robot with desired arm motions shows the reliability and performance of the proposed method in Section 4, followed by a few conclusions in Section 5.

2 Resolved Momentum Control

2.1 Resolved Angular Momentum Control

In this work, only the angular momentum is considered in applying resolved momentum control due to the fact that only controlling angular momentum can keep balance of biped robot and the limit of joint angles, unlike conventional resolved momentum control considering both angular and linear momenta [18]. The angular momentum $H \in \mathbb{R}^3$ of the whole mechanism are given by

$$H = \begin{bmatrix} \tilde{I} & H_{\dot{\theta}} \end{bmatrix} \begin{bmatrix} \omega_B \\ \dot{\theta} \end{bmatrix} \quad (1)$$

where $\tilde{I} \in \mathbb{R}^{3 \times 3}$ is the inertia matrix of whole body and ω_B is angular velocity of base link with respect to the ground. $H_{\dot{\theta}} \in \mathbb{R}^{3 \times n}$ is the inertia matrices which indicate how the joint speeds affect to the angular momentum and $\dot{\theta} \in \mathbb{R}^n$ is velocities of all joints as its element where n is the total number of joints. The target velocities of joints which is able to realize the reference angular momentum is calculated as the least square solution by

$$\begin{bmatrix} \omega_B \\ \dot{\theta} \end{bmatrix} = J^\dagger H + (E - J^\dagger J)\dot{\theta}_a \quad (2)$$

where $J = \begin{bmatrix} \tilde{I} & H_{\dot{\theta}} \end{bmatrix}$, J^\dagger is a pseudo-inverse (the least-square method) of J , E is an identity matrix and $\dot{\theta}_a \in \mathbb{R}^n$ is an arbitrary vector which does not affect the result, the reference angular momentum.

2.2 Reference Angular Momentum

Fig.1 shows an articulated biped robot. It is necessary to determined the reference angular momentum of this robot in advance. There are several researches

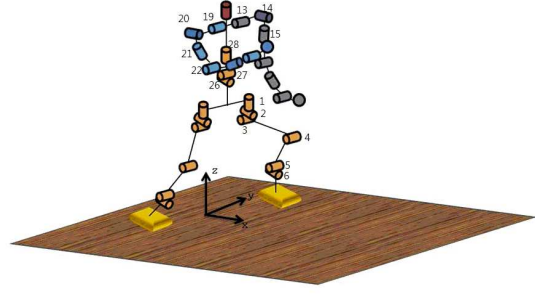


Figure 1: Configuration of the running biped robot

on momentum control, and usually the desired angular momentums of roll, pitch and yaw axis are all constant values, zero. The value the reference angular momentum could keep the stability of whole robot body. However, actually the angular momentum is not constant value during human running and if the reference angular momentum set to zero, it is highly possible for certain angles of redundancy degree of freedom to exceed joint range. Accordingly, two conditions should be considered in order to determine the reference angular momentum: robot stability and joint range. The robot stability means whether running biped robot with desired arm motion falls down or not, and joint range is whether calculated joint angles keeping balance is in movable range. In this paper, the reference angular momentum satisfying above two conditions is determined by linear relationship with the constraint angular momentum generated by the angular velocity of joints of legs and desired arm by a gradient optimization method.

Eq. (2) shows that all joints angles and the velocity of base body with respect to the ground could be calculated to satisfy the reference angular momentum. On the other hand, it is necessary to take into account several constraints in order that robot has desired motions such as running and wanted arm motions. Therefore, the joint speeds of all joints of two legs and arm having desired motion are constraints: $\dot{\theta}_{legs}$, $\dot{\theta}_{mo}$. In addition, if all components the vector $\omega_B \in \mathbb{R}^{3 \times 1}$ are set to zero and the null space is not considered, Eq. (2) results in following equation.

$$\dot{\theta}_{bal} = J_{bal}^\dagger (H - J_C \dot{\theta}_C) \quad (3)$$

where $J_{bal}^\dagger = H_{\dot{\theta}_{bal}}^\dagger$, $J_C = \begin{bmatrix} H_{\dot{\theta}_{legs}} & H_{\dot{\theta}_{mo}} \end{bmatrix}$ and $\dot{\theta}_C = \begin{bmatrix} \dot{\theta}_{legs} & \dot{\theta}_{mo} \end{bmatrix}^T$. To be specific, $\dot{\theta}_{bal}$ is joint speeds of the links of upper body which can keep the balance of body. $H_{\dot{\theta}_{bal}}$, $H_{\dot{\theta}_{legs}}$ and $H_{\dot{\theta}_{mo}}$ are the inertia matrices from each motion. If Eq.(3) is rewritten,

$$\dot{\theta}_{bal} = J_{bal}^\dagger (H_B - H_C) \quad (4)$$

where $H_C(\in \mathbb{R}^3) = J_C \dot{\theta}_C$. H_C indicates the angular momentum from leg and arm motions, constraint one. If only stability is considered when the reference angular momentum is determined, it would be obtained easily : zero or small constant values. If the reference angular momentum is set to zero or small constant values, calculated angles maintaining the balance of whole robot body could exceed the movable range. Therefore, it is significant to consider the range of joint angles.

This paper proposes the method to determine the reference angular momentum which is the similar tendency and small difference of the amplitude with the angular momentum from legs and desired arm motions. The reference angular momentum is determined by the linear relationship with the angular momentum from leg and upper body motions as shown in Eq.(5). The reason why defining the linear relationship with the angular momentum from legs and arm motions is joint angle range. Eq. (4) shows that the bigger the amplitude of $(H_B - H_C)$ is, the bigger calculated joint speeds are, which means angles of joints can exceed the movable range. By obtaining small and stable K , it is possible to find the reference angular momentum meeting conditions : joint range and stability.

$$[(H_B)] = [(1 + K) (H_C)] \quad (5)$$

2.3 Gradient Optimization Method

Determining K is a critical issue in this algorithm. These parameters have to satisfy two conditions, stability and joint range, because they control the reference angular momentum. Stability is determined by base body angles with respect to the ground measured by gyro-sensor as base body angles is one of the important indicators of robot stability.

$$F_{cost} = \sum \alpha_i \left(\frac{\psi_i - \bar{\psi}_i}{\Delta\psi_i} \right)^2 \quad (6)$$

where F_{cost} is the cost function to be minimized, $i = x, y, z$, α is weight value of cost function and ψ is the state value of each base body angle. Moreover, $\bar{\psi}$ is the center position around to minimize the movement and $\Delta\psi$ is the difference between the maximum and the minimum values of the joints. By minimizing the cost function, robot stability could be kept. What's more, angular momentum is highly related to the whole body angles of biped robot [19]. Based on this fact, K_i is determined considering this condition as shown in Eq. (7).

$$K_i = \begin{cases} -\frac{\partial F_{cost}}{\partial \psi_i} & \text{if } \text{sign}(H_C) = 1 \\ \frac{\partial F_{cost}}{\partial \psi_i}, & \text{otherwise} \end{cases} \quad (7)$$

where $i = x, y, z$. Fig.2 shows the proposed algorithm.

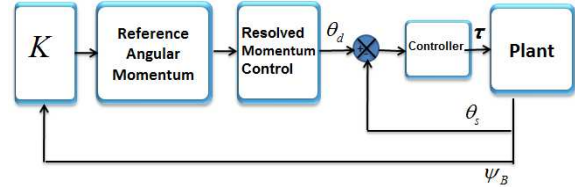


Figure 2: Block Diagram for Gradient Optimization Method

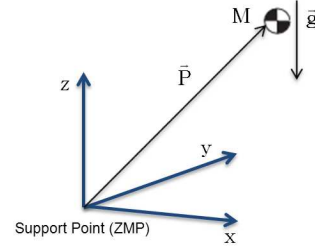


Figure 3: Inverted pendulum model

3 Trajectory Generation

Even though the motion at the center of mass (CoM) generated based on the IPM is not perfectly identical to human locomotion, lots of researches have been performed using IPM due to its simplicity. Fig. 5 shows that the articulated robot can be modeled as a single mass under the assumption that the ZMP is located in the middle of the support foot. Analyzing the angular moment about the ZMP yields

$$P \times (M\ddot{P}) = P \times (Mg) \quad (8)$$

or

$$M \begin{bmatrix} Y\ddot{Z} - Z\ddot{Y} \\ Z\ddot{X} - X\ddot{Z} \\ X\ddot{Y} - Y\ddot{X} \end{bmatrix} = M \begin{bmatrix} -gY \\ gX \\ 0 \end{bmatrix}. \quad (9)$$

where the vector P and g are represented by $P^T = [X \ Y \ Z]$ and $g^T = [0 \ 0 \ -g]$. M is total mass of the robot, X is reference locomotion trajectory in sagittal plane, Y is reference locomotion trajectory in frontal plane and Z is vertical trajectory. Note that above Eq. (9) is non-linear equation. Accordingly, it is necessary to linearize the moment equation. To

Table 1: Parameters of the Bodies of the Biped Robot

| Parameters | Mass [kg] | Length [m] |
|------------|-----------|------------|
| Whole Body | 33.24 | 1.15 |
| Torso | 13.71 | 0.4 |
| Leg | 8.17 | 0.75 |
| Arm | 1.57 | 0.52 |

linearize Eq. (9), the vertical trajectory is generated prior to determining horizontal trajectory assuming a simple hopping robot. To make a repetitive and symmetrical trajectory, a fourth interpolating polynomial is chosen to satisfy some conditions and constraints, which are that the velocity and position at landing-on and lift-off should be same. Based on the vertical trajectory, the horizontal one is easily obtained through the momentum equation of center of mass.

4 Simulation

This section is to evaluate the proposed control by simulating the running biped robot having desired upper body motions. More specific model information on biped robot, contact model and simulation results are introduced in this section.

4.1 Biped Robot Modeling

To simulate the dynamic biped locomotion, commercial software called RecurDyn is used. It is a computer program for a dynamic model analysis. It offers various kinds of contact models, joints, force and dynamic modeling tools: link length, mass, geometrical constraints, and etc. The size of the robot is similar to that of a typical toddler. The control of running biped robot with desired arm motion with running speed 0.6m/s was simulated with 28 DOF biped robot. Fig. 1 shows the structure of the biped robot consists of lower body and upper body. Table 1 shows the mass and length of whole robot body and the bodies of each link.

4.2 Contact Model

In the simulations, the contact force between the foot and the ground is modeled by

$$F_n = k\delta^{m_1} + c\frac{\dot{\delta}}{|\dot{\delta}|}|\dot{\delta}|^{m_2}\delta^{m_3} \quad (10)$$

where k and c are the spring and damping coefficients which are determined by an experimental method, respectively. Parameters m_1 , m_2 and m_3 are the stiffness, damping and indentation exponents. The δ and $\dot{\delta}$

Table 2: Friction coefficients

| Symbol | Parameters | Value |
|---------|------------------------------|----------|
| v_s | Static Threshold Velocity | 0.1 m/s |
| v_d | Dynamic Threshold Velocity | 0.15 m/s |
| μ_s | Static Friction Coefficient | 1 |
| μ_d | Dynamic Friction Coefficient | 0.8 |

are a penetration and time differentiation of the penetration, respectively. In this work, the coefficients are defined as $k = 0.9 \times 10^6$, $c = 0.5 \times 10^3$, $m_1 = 1.3$, $m_2 = 1$, and $m_3 = 2$. The friction force of contact elements is determined by

$$F_f = \mu(v)|F_n| \quad (11)$$

$$F_f = \text{sign}(F_f) \times \min(|F_n|, f_{max}), \quad (12)$$

where F_n , $\mu(v)$ and f_{max} are the contact normal force, the friction coefficient and the maximum friction force, respectively. The friction coefficient of coefficient of F_f is determined by a relative and tangential velocity on the contact point as shown in Fig. 4. Parameters of friction coefficients are shown in Table 2.

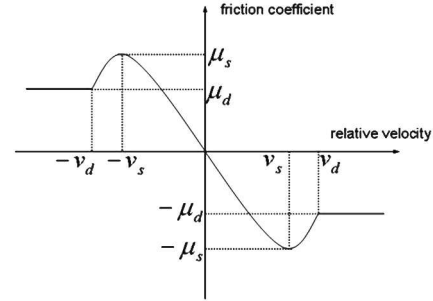


Figure 4: Relationship between relative velocity and friction coefficient

4.3 Simulation Result

4.3.1 Desired Swing Arm Motions

Various swing arm motions were simulated to prove that this algorithm is proper when running biped robot has the desired arm motions and introduce one of the various swing arm motions in this paper. Running biped robot swings its three joints of the right arm, two of them are same trajectory, at the time from 4 sec to 6 sec as shown in Fig. 5. The name of the each joint is shown in Fig. 1.

4.3.2 Reference Angular Momentum

To improve the stability of biped robot performing arm motions, the proposed algorithm is used. In this

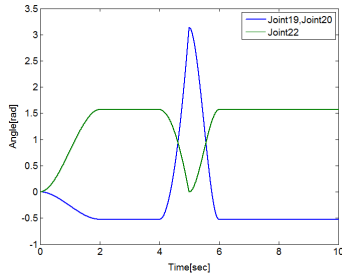
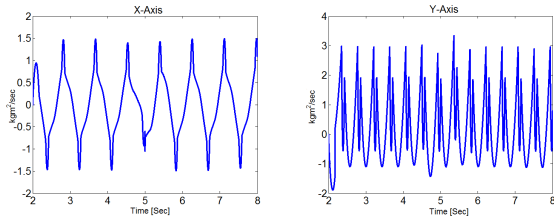


Figure 5: Joint trajectories for the desired arm-swing motion



(a) Momentum in the x -direction (b) Momentum in the y -direction

Figure 6: Reference angular momenta in the x - and y -directions

simulation, weight values α in cost function are all set to be 0.001. In addition, the reference angular momentum with respect to the base body (hip body) determined based on this study is shown in Fig. 6. At the time from 4 sec to 6 sec (desired arm motion), the amplitude of the reference angular momentum is changed according to the proposed algorithm: The yawing angular momentum is set to zero.

4.3.3 Joint Angle for Balance

Joint angles for robot balance are shown in Fig. 7. If the resolved momentum control is not applied, all the joints' angles are constant values. Even though the trajectory based on LIPM is proper to maintain balance of robot, to improve the robot stability, resolved momentum control is used for running motion as well as running with desired arm motion. Fig. 7 shows the angles of redundant degree of freedom to keep robot balance. In particular, it seems that joint 27 tends to exceed movable range of joint angle if simulation time is very longer. In this case, null-space can be used to make joint angle controllable range.

4.3.4 Snap Shots of Simulation

Fig. 8 shows that the proposed algorithm is proper for robot stability when running biped robot having desired arm motion through the dynamic simulation program. Fig. 8(a) shows that if the biped robot run-

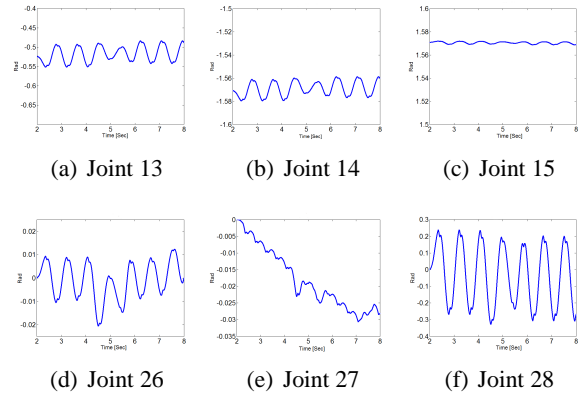


Figure 7: Joint trajectory for balancing the running robot

ning with the trajectory generated based on the LIPM swings its one arm, it falls down due to the instability due to the swing motion of the arm. On the other hand, Fig. 8(b) shows that the proposed algorithm works well in maintaining the stability of the running biped robot with the desired arm motion. Various arm motions were simulated in addition to this in order to prove the performance of the proposed algorithm. In these simulations, the robot was able to run stably in many cases with the proposed control, where its stability was not maintained without.

5 Conclusion

In this work, the algorithm which can maintain stability for a running biped robot with desired arm motions is studied. When a running biped robot has desired arm motions, stability of a biped robot cannot be kept. Resolved momentum control is applied to maintain balance of a robot in this paper. Resolved momentum control is to calculate angular velocity of each robot joint maintaining the balance of a robot based on the desired angular momentum. Not only robot balance but the amplitude of the robot angles of each joint keeping balance should be considered to determine the desired angular momentum. In this paper, the reference angular momentum satisfying above two conditions is determined by linear relationship with the angular momentum generated by the angular velocity of joints of legs and desired arm by a gradient optimization method. In the future work, the state-equation of the proposed algorithm will be used to verify the stability logically and the algorithm will be applied in uneven terrain.

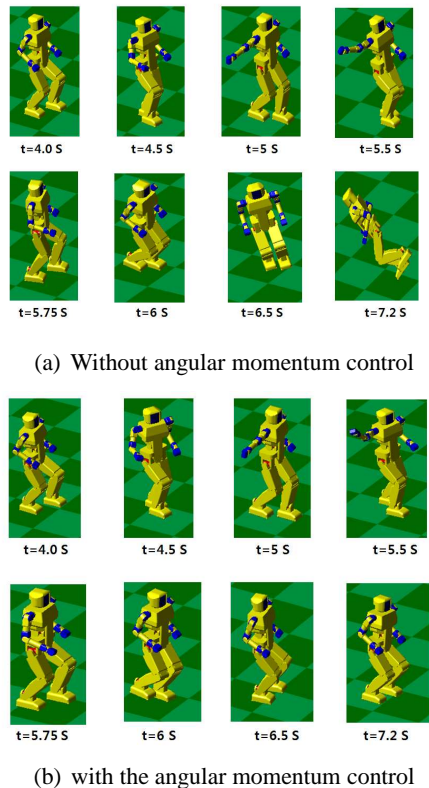


Figure 8: A series of snapshots with and without the proposed momentum control

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