Ankle Variable Impedance Control for Humanoid Robot Upright Balance

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Abstract. Upright balance control is the most fundamental, yet essential, function of a humanoid robot to enable the performance of various tasks that are traditionally performed by human being in unstructured environments. Such control schemes were conventionally implemented by developing accurate physical and kinematic models based on fixed torque-ankle states, which often lack robustness to external disturbing forces. This paper presents a variable impedance control method that generates the desired torques for stable humanoid robot upright balance control, to address this limitation. The robustness of the proposed method was brought by a variable parameter approach with the support of the impedance model. The variable parameter of the ankle angle is able to describe the balance state of a humanoid robot, and the proper adjustment of such parameter ensures the effectiveness of the proposed model. The proposed control method was applied to a humanoid robot on a moving vehicle, and the experimental results demonstrated its efficacy and robustness.

Keywords: Impedance control, humanoid robot control, balance control, robotic control

1 Introduction

Humanoid robots have been widely used in training, manufacturing, medical services, transportation, and other fields, as either an intelligent replacement or an effective supporter of human experts [1]. A typical humanoid robot is naturally an unstable system due to two main reasons. Firstly, a humanoid is usually of a high centre of mass (CoM) and equipped with a relatively small base of support. Also, human robots often work in unstructured environments, which present various external disturbances. Effective control of humanoid robots to prevent them from falling, i.e. upright balance control, is therefore one of the main challenges in the research filed [2]. There exist three basic balance control strategies for humanoid robots, including the ankle strategy, the hip strategy, and the stepping strategy. The ankle strategy has been widely utilised in upright balance control [3], which enables humanoid robots keep balance by applying torques to the ankle joint in the case of relatively small disturbances. The majority of existing research on the ankle strategy concentrates on model-based and behaviour-based methods [4].

Zero moment point (ZMP) stability criterion was proposed by Vukobratovic proposed the in 1969 [5], which is defined as a point on the ground at which the equal moment of force of the humanoid robots in the upright state is zero. Based on this, the force or torque is used as feedback information to calculate the actual ZMP of the biped robot online. From this, a control law is applied to adjust the torque of each joint of humanoid robots, which continuously reduces the gap between the actual ZMP and the expected value, so as to achieve the humanoid robots upright balance control. The stability criterion ZMP has been utilised by a large number of humanoid robotic upright balance control theories, and some successful research results have been reported in the literature [6, 7]. Despite the large success, the update of the ZMP reference point feedback information calculated using sensor data lags behind the actual posture changes of the humanoid robots. This delay often causes controller response delay and even a system shock.

The adjustment of the centre of pressure (CoP) is another popular way to implement humanoid robot vertical balance control, through simultaneous actions on angular momentum and linear momentum, according to the law of conservation of momentum [9, 10]. The upright balance control method developed by Liu et al. [11] used the angular momentum inverted pendulum model to realize effective upright control of humanoid robot led by sudden changes of angular momentum. Hinata et al. [12] proposed a decomposition momentum control method that simultaneously deals with angular momentum and linear momentum, and incorporates its balance criterion into the whole body motion balance control framework. Given that the upright balance control of a humanoid robot using momentum balance relies on the dynamic model of the robot to evaluate the momentum information of the humanoid robot, any improvement on such control approach can be very challenging.

With the development of artificial intelligence and machine learning, intelligent learning algorithms are increasingly being used to solve complex problems. Yang et al. [13] established a multi-layer neural network, which captured the relationship between the human body's CoM, angular velocity and falls. This model was trained using a dataset captured through a large number of fall tests, and judged by evaluating whether there is posture imbalance in the balancing process through the learned relationship. Intelligent learning control methods usually rely on complex dynamics models and a large training and testing dataset, which both can be very difficult to develop practically [14]. In addition, this approach does not guarantee stability during actual operation subject to the coverage of the dataset and the generalisability of the developed dynamics models.

This paper proposes an ankle variable impedance control method for humanoid robot upright balance control. Note that the humanoid robots usually have a complex structure, with the characteristics of system nonlinearity and structural variability, which brings great challenges to the motion control [15]. This work ignores all the non-direct factors for upright balance control, and simplifies the ankle joint of a humanoid robot into a second-order impedance model composed of inertial, damping, and elastic units. Specifically, the ankle anti-disturbance torque is obtained by constructing a ankle variable parameter impedance model, and the ankle dynamic torque is calculated by constructing an inverted pendulum model of the humanoid robot, in combination with anti-disturbance, to estimate the expected ankle torque for humanoid robots upright balance control. The experimental results show that the control method improves the upright balance control performance of the humanoid robots.

The rest of this paper is organized as follows. Section 2 details the proposed ankle variable impedance control approach. Section 3 applied the proposed control method to a humanoid robot on a moving vehicle, and assessed the proposed control method with results analysed. The paper is concluded in Section 4.

2 Ankle Variable Impedance Control

The proposed ankle variable impedance control method generates the desired torque (τ_q) for humanoid robot upright balance control. It is comprised of three key components, including a dynamic model to calculate the dynamic torque (τ_r), an impedance model to estimate the ankle anti-disturbance torque (τ_e), and a parameters update component to update impedance model parameters (K, B, M) based on the humanoid robot ankle angle information (θ_{food} $\dot{\theta}_{food}$).

2.1 Overview

The framework of the proposed ankle variable impedance control method is illustrated in Figure 1. The data flow in the interconnected closed control loops guarantees strong robustness of the proposed control approach. The desired ankle torque is estimated through a joint effort of the dynamic model and impedance model. The inputs of the dynamic model are the angle (θ_{food}) and velocity ($\dot{\theta}_{food}$) of the robotic ankle, and the output is the dynamic torque (τ_r). Likewise, the inputs of the impedance model are the angle (θ_{food}) and velocity ($\dot{\theta}_{food}$) of the robotic ankle, based on the parameters provided by the parameter update components, and the output of the impedance model is the anti-disturbance torque (τ_e). The aggregation of the outputs of the two sub-models (τ_r and τ_e) forms the the desired ankle torque (τ_q). From this, the desired ankle torque is passed to the ankle torque actuator to drive the humanoid robot to maintain upright balance.

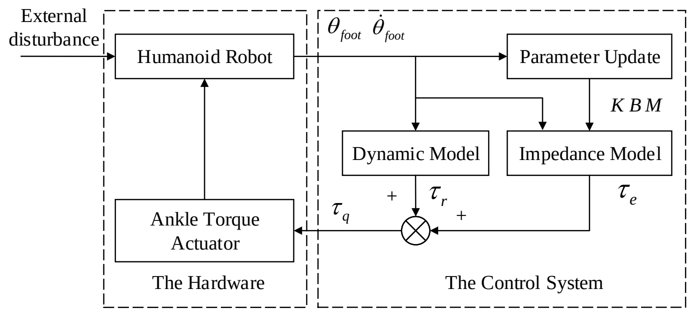

Fig. 1. The framework of ankle variable impedance control for humanoid robot upright balance

2.2 Impedance Model

The impedance model consists of a virtual spring-damping-mass system [16], which aims to make the robot joints present a "gloppy" or "springy" compliant control behaviour similar to human joints. By regarding the ankle joint of the humanoid robot as an impedance model, the humanoid robot ankle joint impedance model schematic diagram is shown in Figure 2.

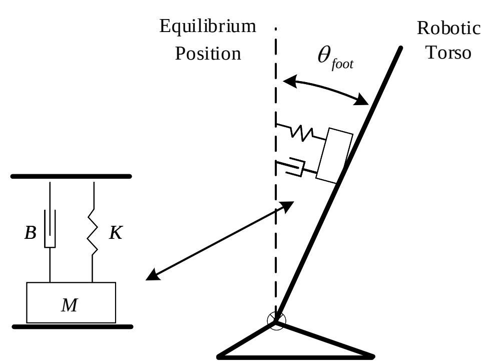

Fig. 2. The humanoid robot ankle joint impedance model schematic diagram

In the Cartesian coordinate system, the impedance model has the function of deriving the environmental force f_e from the input position error x_e[17], which is expressed as:

$$f_e = kx_e + b\dot{x}_e + m\ddot{x}_e, \tag{1}$$

where k, b, m denotes the stiffness, damping and inertia in the impedance model, respectively.

The Jacobi matrix $J(\theta_{foot})$ is defined as:

$$d_x = J(\theta_{foot})d\theta_{foot}, \tag{2}$$

where θ_{foot} is the humanoid robot ankle angle.

The anti-disturbance torque can be calculated based on impedance model, which is given by:

$$\tau_e = J(\theta_{foot})(kx_e + b\dot{x}_e + m\ddot{x}_e). \tag{3}$$

The kinematic relationship between the humanoid robot ankle joint Cartesian coordinates and the joint coordinates is:

$$x = l \sin\theta_{foot}, \tag{4}$$

where l is the vertical height of humanoid robot mass of centre.

For the task of humanoid robot upright balance control, the ankle angles θ_{foot}, i.e, the swing amplitudes, are usually small, that is $\sin\theta_{foot} \approx \theta_{foot}$. According to Equation 3, in the joint coordinates, the anti-disturbance torque can be expressed as:

$$\tau_e = J(\theta_{foot})(k\theta_e + b\dot{\theta}_e + m\ddot{\theta}_e), \tag{5}$$

where $\theta_e = \theta_{foot} - \theta_{ref}$ is the ankle tilt angle, and θ_{ref} stands for the ankle reference angle at robotic equilibrium position.

Since k, b, m are all constant coefficients, Equation 3 can be re-expressed as:

$$\tau_e = K\theta_e + B\dot{\theta}_e + M\ddot{\theta}_e, \tag{6}$$

where K, B, M denotes the target stiffness, damping and inertia value in the robotic ankle impedance model, respectively, and the following equations hold:

$$\begin{cases} K = J^T(\theta_{foot})kl \\ B = J^T(\theta_{foot})bl \\ M = J^T(\theta_{foot})ml \end{cases} \tag{7}$$

2.3 Parameter Update

In order to obtain good balance control performance, the target impedance parameters must be adjusted reasonably. Studies on the human body's upright balance have shown that under the control of the central nervous system, the human body can automatically adjust the mechanical impedance of the ankle joint to adapt to the motion state of the ankle joint during upright balancing. Inspired by the characteristics of the human ankle joint impedance parameters adjustment mechanism, this paper proposes a target impedance parameters updating method using the information of humanoid robot ankle joint angle. This work further proposes a feedback scheme to imitate the human body ankle impedance adjustment mechanical which was used to update the impedance parameters.

In particular, the target stiffness value is formed by the weighted summation of the ankle joint angle information ($\theta_{food}\ \ \dot{\theta}_{food}$), which is defined as:

$$K = k_p\theta_{food} + k_i\dot{\theta}_{food}, \tag{8}$$

where k_p and k_i represent the feedback gain of ankle angle and its velocity, respectively.

Biomechanics research shows that the square root of the mechanical stiffness of the joint is linearly related to the mechanical damping value of the joint. Therefore, the target damping value can be calculated by:

$$B = v\sqrt{K}, \tag{9}$$

where v is the preset constant coefficient.

In the process of humanoid robot upright balance control, the target inertia of the ankle joint only changes slightly; therefore this paper takes the target inertia value as a constant coefficient.

2.4 Dynamic Model

The ankle dynamic model describes the relationship between the motion of the humanoid robot and the dynamic torque (τ_r) of the ankle joint [18]. In order to study the ankle strategy of the humanoid robotic upright balance control, complex actions such as arm swing, footrest, curved body, step, and retreat can be ignored. Without loss of generality, the humanoid robot can be simplified as an inverted pendulum (IP) model swinging around the ankle joint. The proposed dynamic model takes the humanoid robotic upright balance process as an inverted pendulum swinging process that concentrates all weight on the centre of mass.

The position of the ankle joint in the initial state is marked as the origin of coordinates, the horizontal platform is marked as the x-axis, and the vertical direction is marked as the y-axis, thereby establishing a two-dimensional x-y coordinate system. The inverted pendulum model of the humanoid robot is shown in Figure 3.

Based on the established x-y coordinate system, after the humanoid robot is disturbed by external disturbances, the differential equation of the torso rotating around the ankle joint is:

$$F_y l \sin\theta - F_x l \cos\theta = \tau_r. \tag{10}$$

The horizontal movement of the humanoid robot center of mass (CoM) can be described as:

$$F_x = m\frac{d^2}{dt^2}(l\sin\theta), \tag{11}$$

that is:

$$F_x = ml(\ddot{\theta}\cos\theta - \dot{\theta}^2\sin\theta). \tag{12}$$

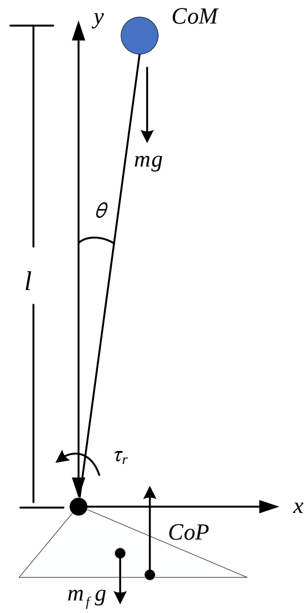

Fig. 3. The inverted pendulum model of the humanoid robot

The vertical movement of the humanoid robot center of mass (CoM) can be described as:

$$F_y = mg + m\frac{d^2}{dt^2}(l\cos\theta), \tag{13}$$

that is:

$$F_y = mg - ml(\ddot{\theta}\sin\theta + \dot{\theta}^2\cos\theta). \tag{14}$$

According to Equations 10, 12, and 14, the humanoid robot upright balance dynamic model can be expressed as:

$$\tau_r = I\ddot{\theta} - mgl\sin\theta. \tag{15}$$

The dynamic torque τ_r is combined with the anti-disturbance torque τ_e to obtain the desired ankle torque τ_q, as expressed below:

$$\tau_q = \tau_e + \tau_r. \tag{16}$$

According to Equations 9 and 15, Equation 16 can be re-expressed as:

$$\tau_q = (K - mgl)\theta_{foot} + B\dot{\theta}_{foot} + (M + I)\ddot{\theta}_{foot} + K\theta_{ref}. \tag{17}$$

Once this desired ankle torque is generate, it will be used by the ankle torque actuator to drive the humanoid robot to maintain upright balance.

3 Experimentation

The proposed ankle variable impedance control was applied to a humanoid robot upright balance control on a moving vehicle for system validation and robustness evaluation. The simulation platform was constructed using the OpenSim platform as shown in Figure 4, and all the data were processed using Matlab. The

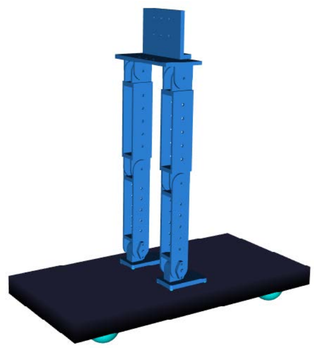

Fig. 4. Simulated humanoid robot on a moving vehicle

parameters of the humanoid robot module in this experimentation are listed in Table 1.

Table 1. The parameters of the humanoid robot module

Parameters	Mass/kg	Centre of Mass/m
Foot	0.5	0.02
Shank	0.7	0.23
Thigh	0.8	0.45
Haunch	0.5	0.5
Torso	1.0	0.6
Total	3.5	0.4

3.1 System Validation

In this experiment, the movement of the vehicle platform includes four states, including “stationary, acceleration, constant speed, and deceleration”. Among them, the vehicle platform only interferes with the humanoid robot upright balance during acceleration and deceleration. In this experiment, the acceleration of the vehicle platform was set to $0.5m/s^2$ as the disturbance; this was then utilised to verify the effectiveness of the ankle variable impedance control method for humanoid robot upright balance control.

During the upright balancing process of the humanoid robot, a counter-clockwise swing is defined as the negative direction, and a clockwise swing is defined as the positive direction. The results include humanoid robot body tilt angle and the desired ankle torque, as shown in Figure 5. The

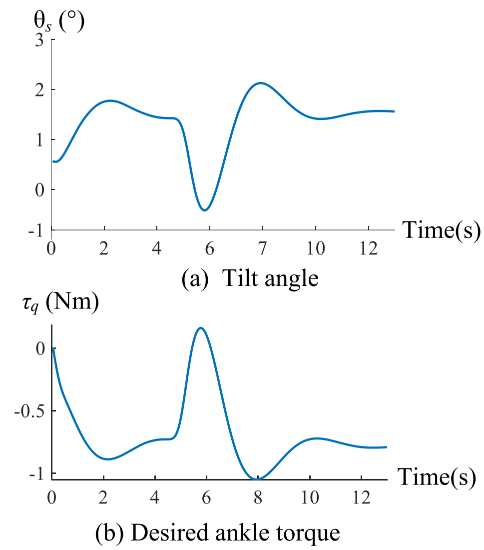

Fig. 5. The results of humanoid robot upright balance control ($0.5m^2$)

The vehicle stationary states: There is no external interference, and the humanoid robot can quickly adjust to an upright balance state. After the humanoid robot is adjusted to the balance position, it maintains an upright balance, and the desired ankle torque has not much change.

The vehicle acceleration states: The vehicle platform applies an acceleration of $0.5m/s^2$ at 5s time point, the humanoid robot body tilt angle θ_s as shown in Figure 5(a), after a lean forward to about $-0.5°$, and then lean backward to about $2.3°$, the humanoid robot gradually stabilized at around $1.8°$. The desired ankle torque presents a tendency to increase first and then decrease, as shown in Figure 5(b).

The vehicle constant speed states: The vehicle platform advances at a constant speed after the speed reaches 0.1m/s, the humanoid robot has no external interference and can quickly adjust to an upright balance state.

In summary, the proposed variable impedance control method can effectively estimate the desired torque of the humanoid robot ankle joint, and then drive the humanoid robot through the ankle torque actuator to complete the task of upright balance control.

3.2 Robustness Evaluation

The robustness of the proposed ankle variable impedance control method was evaluated by conducting multiple experiments with different vehicle platform acceleration. When the acceleration of the vehicle platform is $0.5m/s^2$, $1.0m/s^2$, and $1.5m/s^2$, the results of humanoid robot body tilt angle and the desired ankle torque, are shown in Figure 6.

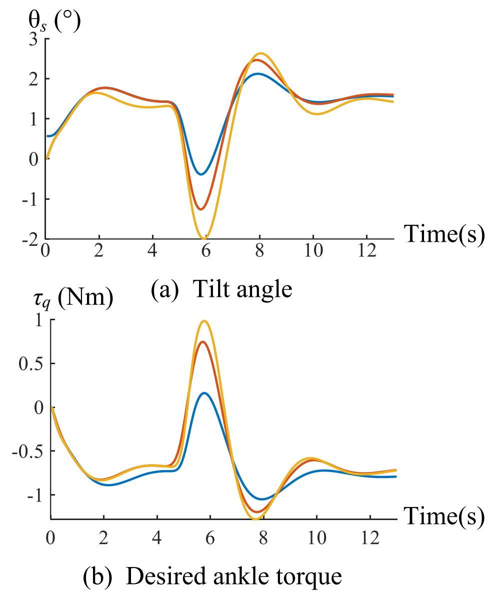

Fig. 6. The results of humanoid robot upright balance control as different vehicle acceleration

As the acceleration of the vehicle platform increases, the humanoid robot body tilt angle swing range θ_s increases. The anti-disturbance time of the biped robot is basically the same, respectively, specified as 4.8s, 4.8s, and 6.5s. After the upright balance control is completed, the humanoid robot returns to the basically consistent balance position within the range of $1.8 \sim 2.0°$.

When the vehicle acceleration of the vehicle is $0m/s^2$, the humanoid robot is in a stable upright equilibrium state without swinging, and the humanoid robot body tilt angle swing range is marked as $0°$. The angular range of the humanoid robot deviating from the equilibrium position after being disturbed is defined as the swing range θ_r. The swing range under different vehicle platform accelerations is shown in Figure 7. When the vehicle platform acceleration is within the range of $0 \sim 1.5m/s^2$, the upright balance control process of the biped robot is basically the same, with a relatively close anti-disturbance period. These experimental results demonstrated that the proposed ankle variable impedance control

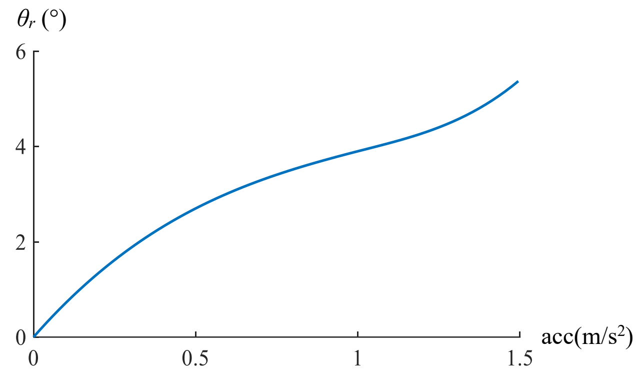

Fig. 7. The swing range under the vehicle platform different accelerations

has a comparative robust performance against the acceleration interference of the vehicle platform.

4 Conclusion

This paper studies and proposes an ankle variable impedance control method for humanoid robot upright balance control by generating the desired torque for the robotic ankle, aiming to mitigate the challenges of poor robustness led by commonly used humanoid robot control methods. Specifically, the ankle anti-disturbance torque is obtained by constructing the ankle variable parameter impedance model, the ankle dynamic torque is calculated by constructing an inverted pendulum model of the humanoid robot in combination with anti-disturbance to estimate the expected ankle torque for humanoid robots upright balance control. The experimental results based on the constructed humanoid robot upright balance control simulation platform shown the working and robustness of the proposed method for humanoid robot upright balance control. Although the proposed control method only targets humanoid robot balance control ankle strategy, the proposed approach is readily applicable to the other robot joint, which remains a piece of future work.

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