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Improvement of Humanoid Walking Control by Compensating Actuator Elasticity

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***Abstract*— The actuators in humanoid robots inevitably have compliance in their joint mechanisms. The joint elasticity often negatively affects static and dynamic performance of the robot. In the specific case of humanoid walking, the elasticity in the actuators can create problems not only on the performance but also on the stability, which is most critical for walking. In this paper, the joint deformation is modeled and its compensation method is proposed to improve walking control performance and stability. The proposed algorithm is implemented on our humanoid robot and its performance is demonstrated by improved stability of walking.**

I. Introduction

In recent years, many humanoid robots have been actively developed that can provide the capabilities of mobility and manipulation in industrial and social environments [1]. Especially, many researchers have focused on bipedal walking so that the humanoid robot can safely traverse various terrains without falling. In spite of a great deal of research, bipedal walking is still a very difficult task in the real situation, as shown at the DARPA Robotics Challenge (DRC) Finals 2015 [2].

The implementation of bipedal walking in real world environment is difficult because there are many uncertainties in the models of robot and environment. The uncertainties in the environment are from the uneven terrain, unknown disturbances, and other factors. The model of the robot also has many uncertainties in their dynamic and static parameters [3][4][5]. Among these many uncertainties, the joint compliance is quite often ignored in the model, which can cause degrade of performance and stability of bipedal walking. In this paper, the effect of joint compliance is investigated and a new compensator is proposed which can effectively account for the joint deflections due to the compliance.

One of the main sources of joint compliance is the gear transmission connecting between the motor and joint. This creates the discrepancy between joint angle and actuator angle [6], and the actual joint angle cannot be accurately measured when encoders are located only at the actuators. Therefore, the joint elasticity inhibits accurate tracking of the desired trajectory of the robot. Estimation of deflection due to elasticity and control for improved performance have been studied for manipulators [7][8][9]. Joint torque sensor is used to estimate deflection using elasticity model in [7]. Then, joint commands are modified to account for this deflection value. In [8], instead of joint torque sensor, gravity torque is computed and used to estimate the deflection. The system stability with these modified control input based on the elasticity model is analyzed in [9].

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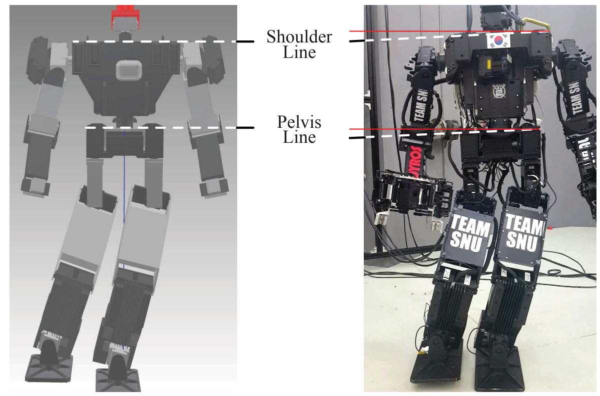

Fig. 1: The comparison of posture when the robot raised the right leg : (Left) commanded posture, (Right) posture of THORMANG in real.

However, this joint elasticity can create problems on the stability as well as the performance of control in humanoid walking. For example, as shown in Fig. 1, the pelvis of real robot hardware is tilted toward the direction of gravity from the horizontal line while that of the simulated robot maintains its pelvis orientation perfectly. This is because the simulation of the robot does not include the compliance of the joint. If the difference between desired and actual posture of the real robot is large, the swing foot cannot be exactly controlled and also the base frame of the robot cannot be accurately estimated.

The specific problem of compensating tilted pelvis angle has been investigated. Laser range finder (LRF) is attached to a hip joint to measure the deflection angle of the hip joint in [10]. Vision camera was used to measure the deformation of robot and variation of Zero Moment Point (ZMP) in [11]. Torque sensors are attached to each leg joints and the results are used to compensate all joints in [12]. These approaches, however, require additional extra sensors to measure the deflection. On the other hand, the deflections on each joint cannot be well estimated when the measurement is on the pelvis and/or feet in [10] and [11]. These previous works also did not analyze the after effect of the joint elasticity at walking in detail. It is only mentioned that elasticity is the reason of the complicated ZMP movements and it is

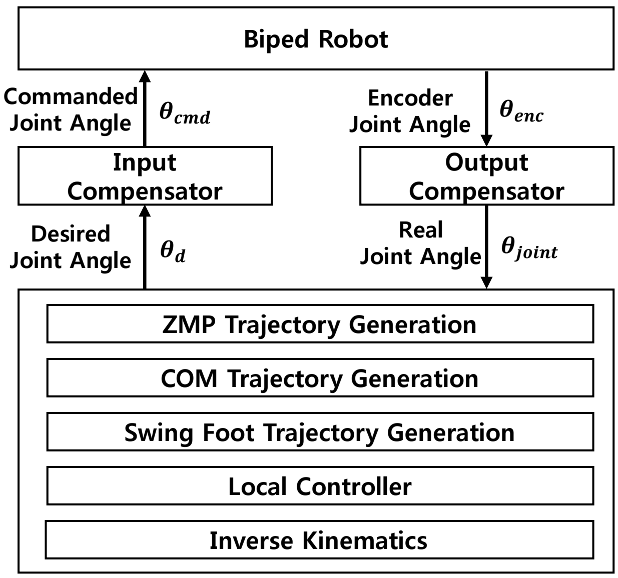

Fig. 2: System diagram for locomotion control with proposed compensator.

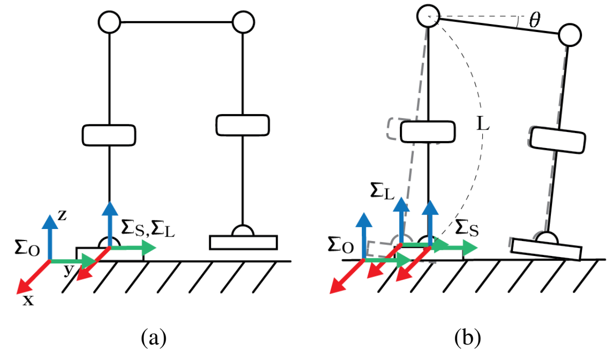

Fig. 3: Influence of joint elasticity at humanoid walking: (a) commanded posture and expected frames, (b) frame uncertainty caused by joint deflection at frontal plane.

too hard to track the desired ZMP trajectory in [10]. It is also mentioned that elasticity needs to be compensated for reducing erroneous foot displacement[12].

In this paper, we will first explain the problem of joint elasticity at walking focusing on not only the balancing and stability but also more detailed problems at walking control strategy. Next, a novel compensator is proposed based on the model of the robot as shown in Fig. 2 to overcome the aforementioned limitations. Linear elastic model of the joint is used to estimate joint deformation. The deflection due to gravity is compensated in the experiments of the paper. Input and output compensators are designed from the first-order linear approximation of the model. This compensator on the leg joints improves the performance of joint trajectory tracking and stability of bipedal walking. The effectiveness of the proposed compensator is demonstrated by applying it to a single actuator and then by implementing it on our humanoid robot.

This paper is organized as follows: Section II introduces the background of joint elasticity and the effects at humanoid walking. Section III presents our proposed joint elasticity model to estimate deflection of joint and proposes compensator for joint elasticity by using the linear elastic model. Section IV contains both the experimental setup and the results of the proposed compensator for joint elasticity, and the paper is concluded in Section V.

II. Problem Statement

A. Elasticity of Actuator

In general, the internal structure of actuator modules consists of two parts: a motor with an encoder and a speed reducer with several parts which can amplify the output torque. Since the encoder is directly attached to the motor, it only measures the input of the speed reducer, not the output. However, there is elasticity between the input and the output shaft because the speed reducer, such as *Harmonic Drive* or *cycloid*, is not completely rigid [13][14]. Therefore, gear elasticity induces the deflection of the joint, and this influences the static and dynamic behavior of the robot.

B. Influence of Humanoid Walking by Elasticity

Many typical walking control schemes based on ZMP and inverse kinematics consist of the following three parts: the Center of Mass (COM) trajectory generation using reference ZMP trajectory relative to global frame($\sum_O$), the swing foot trajectory generation relative to global frame($\sum_O$), and the robot controller with inverse kinematics, as shown in Fig. 2.

In order to represent the posture of the humanoid and trajectories for walking, the local reference frame($\sum_L$) is needed because the humanoids do not have fixed base. Local reference frame is typically chosen to be at the support foot position. It can be computed from the joint angles, and the orientation of the pelvis measured by Inertial Measurement Unit(IMU). However, this computed location of the local frame differs from the support foot position due to the joint deflections. As shown in Fig. 3(b), if the roll axis of the pelvis is tilted by the deflection of hip-roll joint, the position error vector from the support foot frame to the local reference frame, $\mathbf{e}$, is represented as

$$\mathbf{e} = \begin{bmatrix} 0 & 2Lsin\frac{\theta}{2}cos\frac{\theta}{2} & 2Lsin^2\frac{\theta}{2} \end{bmatrix}^T, \tag{1}$$

where L and θ are the leg length and the amount of the deflection at the hip roll joint, respectively. Fig. 3(b) assumed that the only hip roll joint torque is considered as the reason of joint deflection. But in real, the other joints are deflected too. Therefore, even small deflection of the joints cannot be ignored, because this causes a serious inconsistency between the local reference frame and support foot frame.

The inconsistency of the local reference frame with support foot frame can create problems on the stability of walking. First, the unknown difference between the local reference frame and support foot frame becomes the reason of unexpected humanoid motion. When humanoid is in walking sequence, every global trajectories are transformed to the local ones to control the robot. If there is a difference between the local reference frame and support foot frame, humanoid is going to move in a difference way from our intention. Especially in the single support phase, it cannot accomplish the proper COM trajectory tracking and the intended body configuration. As a result, humanoid cannot maintain stability.

Second, the problem is not only in the single support phase, but also during phase transition from single support to double support. As shown in Fig. 3, the contact between the swing foot and the ground which occurs earlier than expected is one of the biggest latent problem. Consequently, a disturbance due to line contact and unexpected contact force leads to the instability.

Third, the discontinuity of the analytical COM trajectory at the local reference frame transition triggers the instability while humanoid is in double support phase. Because of the difference between the expected swing foot landing and real landing position, COM trajectory planned from last local reference frame and next local reference frame has discontinuity at the frame transition point. The discontinuity of COM trajectory becomes the reason of unexpected motion during the double support phase. This motion has a negative influence for the stability of humanoid and it also diminishs the performance of feedback controller for COM tracking such as [15] and [16].

III. METHODOLOGY

In this section, the input and output compensator are discussed based on the proposed linear elastic model, as shown in Fig. 2. First, the linear elastic model is proposed to estimate the deflection of the joint without additional sensor such as external encoder and vision sensor. Next, the equation of motion for the robot in contact state is introduced to estimate the joint gravity torque while walking[17]. Finally, the input compensator is designed to compensate the deflection of the joint using the proposed linear elastic model and estimated joint torque. Thus, the input compensator generates a new input command to enhance tracking performance by compensating for the joint deflection. Also, the output compensator estimates the real joint angle from inaccurate joint value from an encoder by using first-order linear approximation of the model. The details of the linear elastic model, joint torque estimation, and the input and output compensator are described as follows.

A. Linear Elastic Model

The discrepancy between the actuator angle and joint angle is caused by many factors such as backlash, friction, and elasticity. In this paper, it is assumed that the major effect comes from the elasticity and the linear elastic model is used to estimate the joint deformation. That is, the joint deflection $\delta\theta = \theta_{enc} - \theta_{joint}$ is a function of the joint torque.

$$\delta\theta = f(\tau) = k_{joint}^{-1}\tau \tag{2}$$

The torque on the joint is not typically available unless joint torque sensor is used. Therefore, the gravity torque,τ_g, which can be calculated from the model, is used to compensate for the deflection at each joint.

$$\delta\theta = f(\tau) = k_{joint}^{-1}\tau_g \tag{3}$$

This compensation is not perfect when there are dynamic effects. However, the compensation of the deflection due to gravity only can greatly improve the performance of the robot. This has been experimentally verified and will be shown in the experimental section.

B. Gravity Torque Computation

In this paper, the deflection only due to the gravity is compensated. Estimated gravity torque is calculated by gravity compensation torque introduced in [18] as (4).

$$\tau_g = J_r^T F_r + J_l^T F_l \tag{4}$$

where $\tau_g \in \mathcal{R}^n$ is the estimated gravity torque, $J_r, J_l \in \mathcal{R}^{3\times n}$ are the Jacobian from COM to the right foot and left foot contact points respectively. And $F_r, F_l \in \mathcal{R}^3$ are the right foot, and left foot contact forces at the contact points respectively. The joint gravity torque during single support is uniquely determined. The gravity torque during double support is computed by distributing the contact forces depending on the relative COM position with respect to supporting feet as the following.

$$F_r = \mu F, \quad F_l = (1-\mu)F \tag{5}$$

$$\mu = \left|\frac{p_{COM} - p_l}{p_r - p_l}\right| \tag{6}$$

where F is the total weight of the humanoid, p_{COM}, p_r, and p_l are the position of COM, the position of right foot, and the position of left foot respectively. μ is 0 or 1 when humanoid is in left or right single support phase respectively. Also, when humanoid is in double support phase, μ is between 0 and 1.

C. Input Compensator

Input compensator computes the command value, which forces the joint angle, the output of speed reducer, to track the desired value by considering the deflection of speed reducer. This command value, θ_{cmd}, is then sent to the position motor.

For position-controlled robots, the encoder value θ_{enc} as actuator output, and the value that are commanded to actuator, θ_{cmd}, can be assumed approximately the same. And (3) is rewritten as

$$\delta\theta = k_{joint}^{-1}\tau_g(\theta_{joint}) = \theta_{cmd} - \theta_{joint}. \tag{7}$$

(7) can be re-expressed as (8)

$$\theta_{cmd} = \theta_{joint} + k_{joint}^{-1}\tau_g(\theta_{joint}). \tag{8}$$

To enforce θ_{joint} to follow the desired value, θ_d, the command value can be composed as follows

$$\theta_{cmd} = \theta_d + k_{joint}^{-1}\tau_g(\theta_d). \tag{9}$$

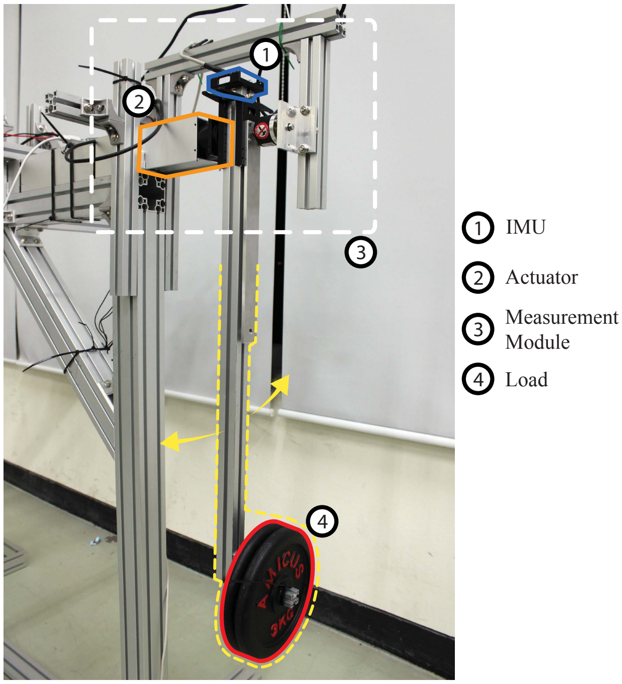

Fig. 4: Testbed for Experiment

D. Output Compensator

Output compensator calculates actuator output θ_{joint} using θ_{enc} and deflection value of the reduction gear estimated in elasticity model.

It can be expressed as

$$\theta_{joint} = \theta_{enc} - k_{joint}^{-1} \tau_g \left(\theta_{joint}\right), \tag{10}$$

where

$$\tau_g \left(\theta_{joint}\right) = \tau_g \left(\theta_{enc}\right) + \tau_g' \left(\theta_{enc}\right) \left(\theta_{joint} - \theta_{enc}\right). \tag{11}$$

Equation (11) is the 1st Taylor expansion about $\tau_g \left(\theta_{joint}\right)$ at θ_{enc}, and $\tau_g' \left(\theta_{enc}\right)$ is the partial derivative of τ_g at θ_{enc}. By substituting (11) into (10),

$$\theta_{joint} = \theta_{enc} - \frac{\tau_g \left(\theta_{enc}\right)}{k_{joint} + \tau_g' \left(\theta_{enc}\right)}. \tag{12}$$

Note that θ_{joint} can be calculated also by solving the nonlinear equation (10) using Newton-Raphson method with an initial value of θ_{enc}. This solution is more accurate than the value from (12) because (11) uses the first order approximation.

Equations (9) and (12) are the input and output compensators that account for the linear deformation model of reduction gear, respectively.

IV. Experimental Results

The proposed compensator is validated through several experiments. First, the experiment to find the stiffness of the joint elasticity model is implemented at the testbed with a single actuator. Then, we validated the proposed compensator in our humanoid, THORMANG. The subsections below explain the details of the systems configurations and experimental results of the proposed compensator.

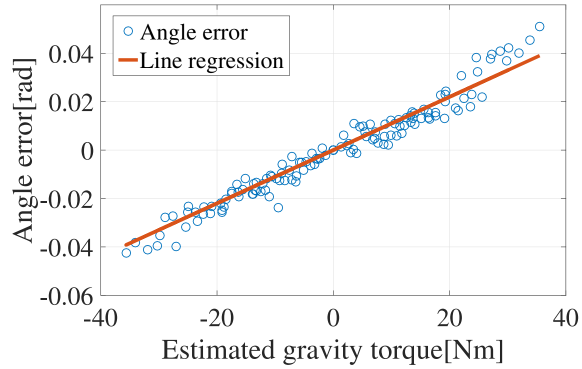

Fig. 5: Relationship between the estimated gravity torque and deformation angle using one joint testbed

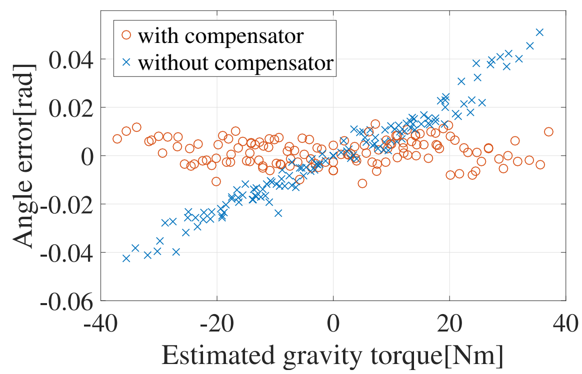

Fig. 6: Comparison between angle error with compensator and the result without compensator using one joint testbed

A. System Overview

As shown in Fig. 4, our testbed to determine the stiffness, k_{joint}, in (2) consists of single actuator module, a linkage with a pendulum, and the IMU (*Microstrain, 3DM-GX4-25*) to measure the deflection angle of the joint. The actuator module is Dynamixel PRO (*H54-200-S500-R*) developed by ROBOTIS as commercial products. The deflection of the joint by joint elasticity is calculated by comparing sensory data from the encoder in the actuator module and the angle data from IMU which is attached at the output of speed reducer.

THORMANG consists of 32 actuators: 8 in each arm (including gripper), 6 in each leg, 2 in the torso, and 2 for the head. The lower body of THORMANG uses the same actuators, Dynamixel PRO (*H54-200-S500-R*), as the one used in the testbed. The height and weight of THORMANG are 1.47 m and 57 kg, respectively. The IMU is attached at the pelvis in order to measure the deflection angle of the pelvis. There are four RS-485 communication lines between master controller and actuators. The control frequency is 250 Hz [19].

B. Experiments Using Testbed

The validity of our assumption in Section III-A is verified by experiments using the testbed. To obtain the relation

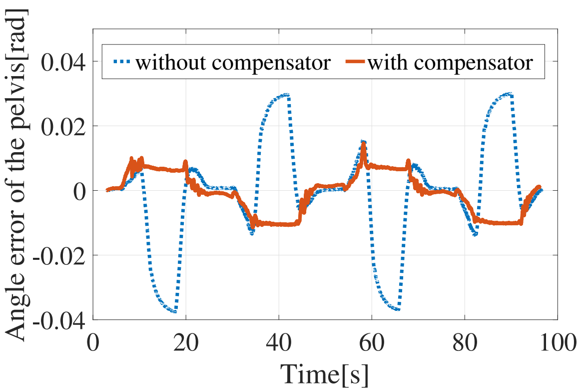

Fig. 7: Angle error of the pelvis, when the single step period is 24 seconds

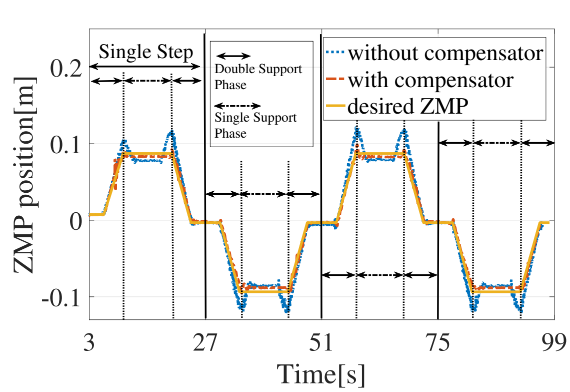

Fig. 9: Measured ZMP position, when the single step period is 24 seconds

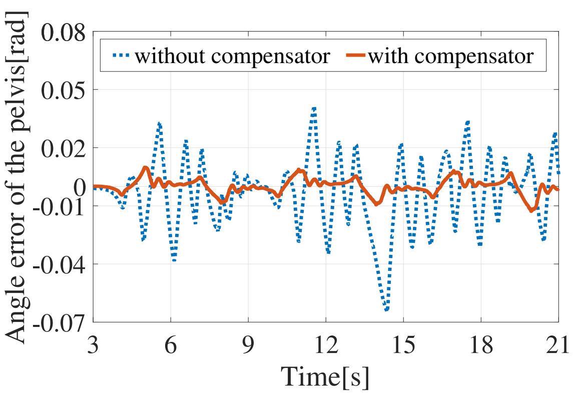

Fig. 8: Angle error of the pelvis, when the single step period is 3 seconds

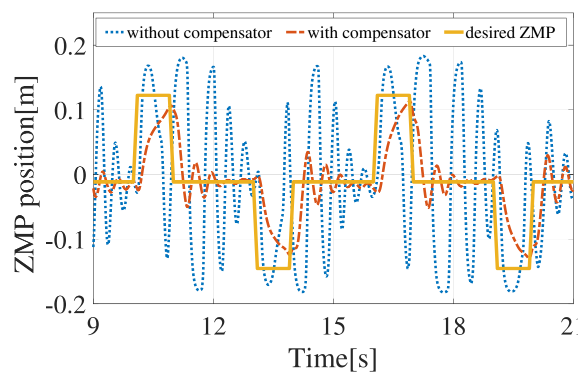

Fig. 10: Measured ZMP position, when the single step period is 3 seconds

between the amount of the joint deflection and the estimated gravity torque, we measured the deflection at different positions of the pendulum. Figure 5 shows that there is a strong and significant linear correlation between the joint deflection and the gravity torque (Pearson's $r = 0.9775$). Experimentally, k_{joint} of our actuator module is 1001 Nm/rad. Thus, the deflection of the joint can be represented as the linear model, as mentioned in (3).

We also conducted the experiment to validate our proposed compensator. In Fig. 6, the circle and the cross shows the result with the proposed compensator and without the compensator, respectively. As shown in Fig. 6, the distributed range of the joint deflection without the compensator is -0.0562 $\sim$ 0.0417 rad. Contrastively, the result range with the proposed compensator shows a narrow distribution as -0.0037 $\sim$ 0.0071 rad. Consequently, with our compensator, the actuator module could reduce the distribution due to the elasticity of joint.

C. Experiments Using Humanoid

The proposed approach is verified by using the humanoid, THORMANG. We implemented the compensator in our walking controller [19]. The compensator is implemented only at the lower body of humanoid which has 12 joints to demonstrate the improvement of walking stability. The computed value of the joint stiffness, k_{joint}, from the testbed is used because all the motors at the lower body of the humanoid are the same motors as the testbed. When the robot walks in place, firstly, we tested walking with 24 seconds single step period as a quasi-static motion. Next, we also tested walking with 3 seconds single step period as a faster walking. Single step in our experiment is composed of double support phase, single support phase, and double support phase sequentially. 24 seconds single step period is composed of 7 seconds double support phase and 10 seconds single support phase. Also, 3 seconds single step period is composed of 1.1 seconds double support phase and 0.8 seconds single support phase.

The pelvis angle was measured and monitored to assess the performance of the proposed compensators. Our walking controller commands the pelvis of the robot to be parallel to the ground. Therefore, the angular error of the pelvis indicates the performance of the compensators. Secondly, the ZMP values are measured by force/torque sensor to demonstrate the improved stability by implementing the compensators in the walking controller. As the robot tracks the desired joint trajectory better, the location of ZMP also remains closer to the desired values.

First, Fig. 7 and 8 show the angle error of the pelvis with two different single step periods. These angle errors are computed from the value of measured orientation by the IMU and the desired orientation of pelvis which is parallel to the ground. With the proposed compensator, the angle error of the pelvis is greatly reduced. In Fig. 7, the angle error is reduced from approximately 0.04 rad to less than 0.01 rad. Especially, as shown in Fig. 8, the compensator was effective even for faster walking with dynamic motion. The angle error of pelvis was suppressed to less than 0.01 rad and the oscillation was much reduced.

Second, Fig. 9 and 10 show the measured ZMP position with two different single step periods. In Fig. 9, the tracking performance of the ZMP position during quasi-static slow walking is greatly increased with the proposed compensator at the phase transition point and single support phase. Figure 10 shows the experimental results during the faster walking with 3 seconds single step period. We can observe that unintended ZMP oscillation and ZMP movement are aroused from the phase transition point and single support phase when humanoid walks without compensator. This unintended ZMP oscillation and movement are substantially removed by the proposed compensator.

The experimental results show that the overall stability of walking is greatly improved by the proposed compensator. It decreased the inconsistency between local reference frame and support foot frame, so that the physical robot much better tracks the desired behavior of the robot. Entire experimental result video is available at [20].

V. Conclusion

In this paper, a novel compensator for joint elasticity is designed based on the linear elastic model. The linear elastic model is proposed to estimate the deflection of the joint. Also, the input and output compensators are designed to account for joint deflections by using first order linear approximation. The main contributions of the proposed model and compensator are summarized as follows. First, the proposed linear elastic model can estimate the deflection without additional sensors. The validity of this model is verified by several experiments. Second, the walking stability is enhanced by our compensator. Especially, we designed the compensator for the torque caused by gravity and it works well not only in quasi-static walking with the 24 seconds single step period but also in faster walking with dynamic motion of 3 seconds single step period.

We mainly focused on the compensation of joint deflection due to gravity in this paper. Our future work will involve the extension of this compensator to be able to compensate for other joint torques during dynamic motion.

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