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YAW MOMENT COMPENSATION FOR BIPEDAL ROBOTS VIA INTRINSIC ANGULAR MOMENTUM CONSTRAINT

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This article is aimed at describing a technique to compensate undesired yaw moment, which is inevitably induced about the support foot during single support phases while a bipedal robot is in motion. The main strategy in this method is to rotate the upper body in a way to exert a secondary moment that counteracts to the factors which create the undesired moment. In order to compute the yaw moment by considering all the factors, we utilized Eulerian ZMP Resolution, as it is capable of characterizing the robot's rotational inertia, a crucial component of its dynamics. In doing so, intrinsic angular momentum rate changes are smoothly included in yaw moment equations. Applying the proposed technique, we conducted several bipedal walking experiments using the actual bipedal robot CoMan. As the result, we obtained 61% decrease in undesired yaw moment and 82% regulation in yaw axis deviation, which satisfactorily verify the efficiency of the proposed approach, in comparison to off-the-shelf techniques.

Keywords: humanoid; bipedal locomotion; yaw moment; angular momentum.

1. Introduction

In bipedal locomotion generation, one of the main restrictions is caused by the undesired yaw moment that is unavoidably induced about the support foot during single support phases. When this undesired moment reaches to a certain amount and exceeds the frictional moment, it may cause support foot rotation, which then leads it to slippage. This problem is accompanied with two major consequences.

- Support foot slippage may deviate the robot from its desired path in yaw axis and the robot could experience an unexpected vertigo¹. Depending on the amount of slippage, it may also cause the robot to be unable to maintain the dynamic balance and tip over. That being said, it is obvious that the yaw moment compensation is a crucial issue in generating feasible and dynamically-consistent bipedal motion patterns.

- Most of the real-time bipedal pattern generation algorithms are based on the simplified humanoid dynamics, in which the support foot is assumed to be stationary. If the support foot rotates, the accuracy of this assumption starts to scale down and floating-base effects become more dominant^{2,3}. Prevention of the support foot rotation is of importance for such practical methods to cover the dominant humanoid dynamics with hypothetically sufficient accuracy, unless twirling motion is aimed³.

Considering the discussions stated above, undesired yaw moment compensation appears to be an essential factor in bipedal motion generation. One of the straightforward realizations of this task could be performed via the utilization of upper body motion. For this purpose, two main strategies are introduced: i) Arm swinging strategy, ii) Yaw-axis waist joint rotation strategy.

In the first strategy, humanoid arms are simultaneously rotated through opposite directions, in a way to create a moment that can compensate the undesired yaw moment. This action is quite natural and can be observed during human walking⁴. Motivated by this fact, Fujimoto and Kawamura developed a yaw moment compensation method to improve robustness in bipedal walking⁵. Using a similar technique, Aoustin and Formal'skii considered optimal arm swinging⁶. As another approach, Yang et al. employed motion capturing techniques⁷. All these methods^{5,6,7} appear to be efficient in handling the undesired yaw moment problem; however, humanoids may be expected to realize grasping and object-carrying tasks while walking⁸. In such scenarios, humanoid robots are unlikely to use their hands specifically for the yaw moment compensation task.

To be able to overcome this difficulty, waist rotation strategy appears to be an appropriate choice. To this end, Hanamiya and Kawamura proposed a practical method to generate waist trajectories via experimentally tuned polynomial functions⁹. Yamaguchi et al. proposed a multi-mass method to compute the induced yaw moment^{10,11}. Nagasaka and his colleagues also followed a similar strategy and utilized optimal gradient algorithm, in which the undesired yaw moment is regulated by considering a specific cost function¹². Despite the fact that researchers demonstrated successful yaw moment compensation experiments using waist rotation, this strategy may influence sensory system; especially the ones that are deployed in the torso and head. In a vision control-based bipedal walking scheme, the head orientation should be adjusted in real-time to cancel the waist rotation influence. Such a problem does not exist in arm swinging strategy. What is more, arm swinging strategy is considered to be more powerful in creating compensation moment since the distance between humanoid arms and body rotation center is relatively farther.

It is obvious that both compensation strategies have pros and cons. Therefore, the best choice appears to be a synergetic combination of both methods, in which full-body legs-arms coordination can be implemented. In this specific study, we solely utilize waist rotation scheme due to the fact that our bipedal robot includes only lower body and torso with no arms. That being said, full-body legs-arms co-

ordination task is addressed as a future work.

Beyond the compensation strategies, yaw moment computation is of importance for a given bipedal trajectory scheme. In computing the undesired yaw moment, one alternative technique may be developed based on the analysis of swing leg motion. In doing so, Hirabayashi et al. mathematically related swing leg motion with undesired yaw moment, and generated waist joint trajectories using this model¹³. Even though their method is easily-applicable and efficient up to an extent, it only focuses on the swing leg motion. On the other hand, there are other factors which contribute to the undesired yaw moment, such as, forward body motion and intrinsic angular momentum rate changes¹².

Computation of yaw moment involves gravitational force, inertial forces and IAMR^a terms. Among these, IAMR terms appear to be critical components as they are associated with rotational inertia, a significant characteristics of robot dynamics¹⁴. Since it is comparatively difficult to include these terms in simplified bipedal motion generation methods, they are often omitted. However, ignoring IAMR terms may introduce severe problems, such as undesired stepping motions, body twists and torso angle fluctuations^{15,16,17}. Moreover, the motion interference between sagittal and lateral planes can no longer be included as IAMR terms carry rich information on this matter.

In order to handle these issues, we need to pay special attention to the rate change of angular momentum about the composite CoM (Center of Mass). For this cause, Kajita et al. developed Resolved Momentum Control in which joint velocities can be computed using the referential total momenta and feet velocities¹⁶. By the same token, Sugihara and Nakamura improved boundary condition relaxation method for bipedal hopping¹⁸. In their ZMP-based (Zero Moment Point¹⁹) method, angular momentum terms are firstly ignored then included in joint motion generation stage. The common ground in these methods is that angular momentum is related with joint motions. Dissimilarly, we hypothesize that angular momentum information could be included during trajectory generation stage. That way, we can enrich abstracted bipedal motion generation techniques, generate more feasible trajectories and compute joint motions by using simple inverse kinematics. In this matter, a similar strategy for this purpose is also pursued by Goswami¹⁴ as well.

While assessing IAMR terms in abstracted humanoid dynamics and motion generation techniques, a possibly misled approach is to sum up all individual links' centroidal torques^{20,21,22}. Such an addition may be performed for planar systems; however, in case of 3-D robots, individual links' torques are not additive unless they are projected to a common frame^{23,24}. Regarding this matter, a proper approach can be observed in Wael et al.'s and Buschmann's recent works^{25,26}.

^aIAMR (Intrinsic Angular Momentum Rate change) refers to the time derivative of inertia tensor $\cdot$ angular velocity multiplication²; $\frac{d}{dt} \{ \tilde{I} \cdot \vec{\omega} \}$.

In the light of these considerations, we composed a method to generate bipedal motions, which may ensure the overall dynamic balance. In our proposed method, motion equations are expressed in spherical coordinates, so that IAMR terms can be combined with inertial forces by using Euler's equations. Since these terms are included using Euler's equations, we name it Eulerian ZMP Resolution (EZR). We previously used this technique to generate ZMP-based bipedal walking trajectories^{17,27}. In these studies, the undesired yaw moment was not concerned as the main focus was generating ZMP-based feasible bipedal trajectories with intrinsic angular momentum information.

In view of the facts discussed above, the main focus in this article is to utilize Eulerian ZMP Resolution for calculating the undesired yaw moment via the characterization of the rotational inertia and associated angular momentum (IAMR) terms. Having obtained a thorough yaw moment computation method, our efforts are specifically aimed at remedying the undesired yaw moment issue using waist rotation, for the purpose of enhancing bipedal locomotion performance in humanoid robots. To this end, yaw-axis waist rotation trajectory is generated in a way to counteract to the undesired yaw moment to compensate its effects on the system. Despite the fact that waist rotation strategy is used, one can utilize this method for an arm swinging strategy as well. In order to validate the proposed method, several bipedal walking experiments are conducted on the actual robot CoMan²⁸. As the result, the method is observed to be efficient in compensating the undesired yaw moment as it shows superior performance over off-the-shelf methods.

This article is organized as follows. We briefly state the undesired yaw moment problem in section 2. Eulerian ZMP Resolution-based yaw moment computation is explained in section 3. The compensation action is disclosed in section 4. Experimental procedures and results are thoroughly discussed in section 5. Finally, the paper is concluded in section 6.

2. Problem Statement

As widely known, bipedal walking is a cyclic motion in which switching left and right leg single support phases are connected via double support phases. During single support phases, both CoM and swing leg moves forward in different levels, with respect to the support foot. This action, on the other hand, inevitably generates a moment about the support foot through yaw axis. Intrinsic angular momentum rate changes contribute to this undesired moment as well. Usually, the friction between the support foot sole and the ground supplies sufficient stiction to prevent the foot rotation which may occur due to slippage. However, depending on the foot contact conditions, aforementioned yaw moment may exceed the frictional moment. As a consequence, the support foot may slip and rotate, causing the whole robot body to deviate from its designated walking path. Depending on the amount of support

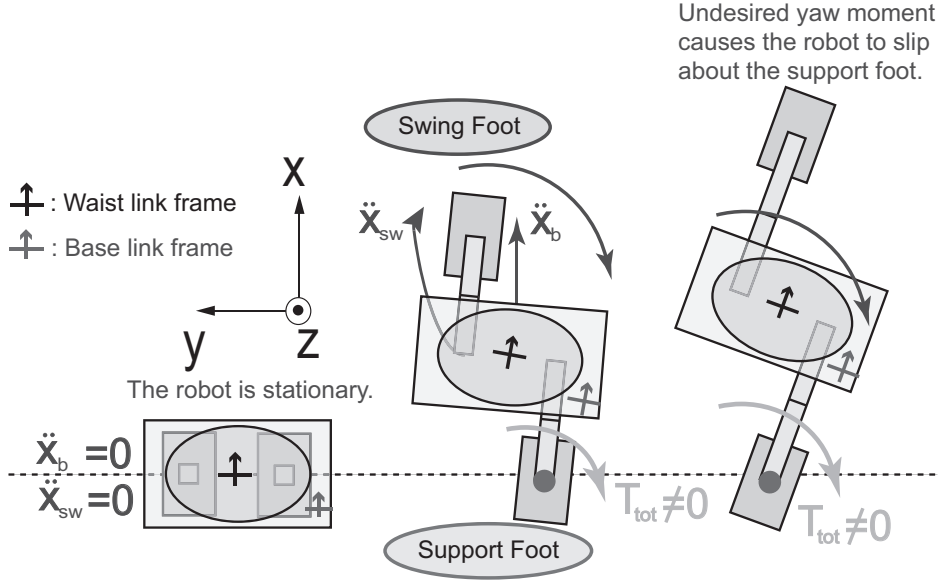


Fig. 1. Illustration of a single support phase in which the support foot slippage occurs due to the undesired yaw moment that is based on swing leg motion ($\ddot{x}_{sw}$), forward body motion ($\ddot{x}_b$) and intrinsic angular momentum rate changes. Note that the effect of intrinsic angular momentum rate change cannot be illustrated visually. If the undesired yaw moment exceeds the frictional moment as displayed, the overall torque (T_{tot}) about the pivot (support foot center) becomes non-zero and the robot rotates about the support foot. That may cause the robot start deviating from the designated walking path, and then it might even tip over.

foot rotation^b, the robot might not be able to maintain dynamic balance and tip over. Fig. 1 illustrates this scenario with no tipping over.

Being a severe limitation, undesired yaw moment could create unfavorable effects on the overall system performance. Therefore, compensating it via upper body rotation seems to be an essential task in generating feasible and dynamically-consistent bipedal motion patterns. As previously stated, waist rotation is chosen in this paper as the compensation action. In Fig. 2, waist rotation-based yaw moment compensation is illustrated for a single support phase.

3. Eulerian ZMP Resolution-based Yaw Moment Computation

In this paper, the main objective in compensating the undesired yaw moment is to obtain a mathematically rigorous model, which encapsulates all the factors related to the problem. Rather than focusing on individual factors, an overall look on this

^bFoot Rotation Indicator²⁹ (FRI) appears to be a useful tool on this matter; however, it indicates rotations about pitch and roll axes. In this paper, the main focus is yaw-axis foot rotations which may occur due to the undesired yaw moment.

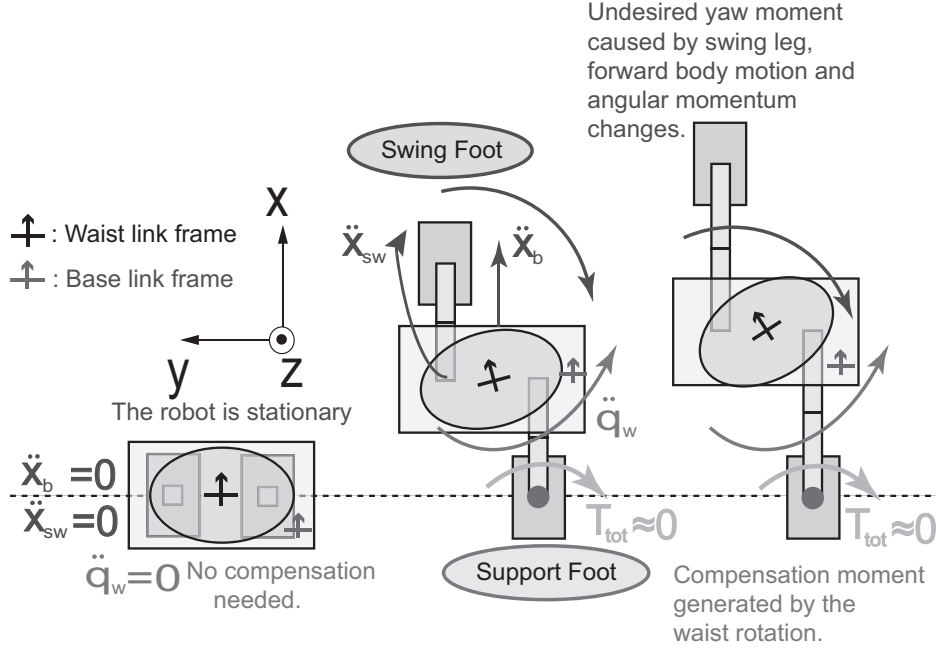


Fig. 2. Illustration of an identical single support phase as shown in Fig. 1, with additional yaw moment compensation. In this scenario, yaw axis waist joint motion ($\ddot{q}_w$) is utilized in a way to counteract to the undesired yaw moment. This action hypothetically makes T_{tot} zero and prevents the support foot rotation due to slippage.

issue might provide a relatively more efficient solution and enhance the system performance. Keeping this in mind, EZR appears to be a useful tool in which the rotational inertia, a key element in representing in humanoid dynamics, can be characterized.

3.1. A Brief Overview on Eulerian ZMP Resolution

As previously stated, EZR is a method to generate feasible ZMP-based CoM trajectories for bipedal motion generation task, without omitting the rotational inertia and associated angular momentum rate changes, namely IAMR terms^{17,27}.

Throughout single support phases, the robot is considered as a three dimensional composite rigid body, rotating about a fixed point (pivot frame's origin) and it is in contact with the floor through a rectangular foot as illustrated in Fig. 3. In this model, we assume that the frame which is attached to the CoM is oriented in an identical manner to the equivalent composite rigid body. In utilizing such a model, CoM configuration can be defined in the spherical coordinate frame.

The main reason for employing spherical coordinates is to yield the equivalent composite rigid body's CoM angular velocity in reduced forms, using θ and ϕ pa-

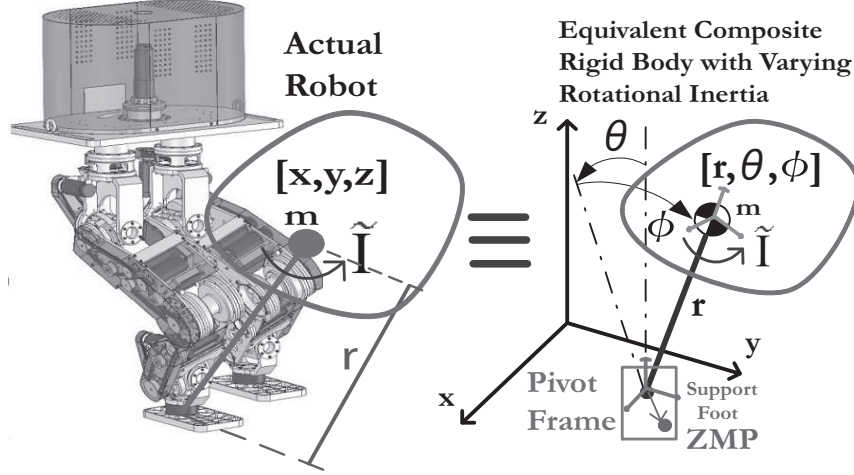


Fig. 3. Composite rigid body model and spherical coordinates on our bipedal robot CoMan²⁸. The actual robot is considered as a 3-D composite rigid body with variant rotational inertia. Its CoM is assumed to be oriented in an identical manner to the composite body. In order to mimic the physical robot, we computed the actual robot's composite rigid body inertia matrix³⁰ and utilized in this model. The origin of Cartesian frame and pivot frame are in fact coincided. The offset is left for illustrative purposes.

rameters, with the above-mentioned assumption in mind. Hence, it becomes quite appropriate to include IAMR terms which are always omitted in conventional ZMP-based methods. For our convenience, the spherical coordinate frame is defined as follows:

- (1) Translate the frame through r units along, the $+z$ -axis.
- (2) Rotate the frame through θ , about $+y$ -axis (sagittal).
- (3) Rotate the frame through ϕ , about $+x$ -axis (lateral).

In utilizing such a model, we are able to combine IAMR terms with inertial force terms that appear in yaw moment equations.

3.2. Yaw Moment Computation

Let us start with analyzing ZMP equations and yaw moment computation¹²:

$$X_{zmp} = \frac{x(\ddot{z} + g) - z\ddot{x}}{(\ddot{z} + g)} - \frac{\dot{L}_y}{m(\ddot{z} + g)} \quad (1)$$

$$Y_{zmp} = \frac{y(\ddot{z} + g) - z\ddot{y}}{(\ddot{z} + g)} + \frac{\dot{L}_x}{m(\ddot{z} + g)} \quad (2)$$

$$\tau_{yaw} = m(x - X_{zmp})\ddot{y} - m(y - Y_{zmp})\ddot{x} + \dot{L}_z \quad (3)$$

In (1) and (2), x , y and z stand for the composite CoM position in the Cartesian frame while L_x , L_y and L_z symbolize roll, pitch and yaw axes intrinsic angular momenta about the composite CoM. One dot and two dots represent first and second derivatives with respect to time. Moreover, m is the total mass and g is the gravitational acceleration.

In order to have a compact yaw moment equation without ZMP terms, we insert (1) and (2) into (3).

$$\tau_{yaw} = \dot{L}_z + \frac{\ddot{y}\dot{L}_y + \ddot{x}\dot{L}_x}{\ddot{z} + g} \quad (4)$$

As it may be observed in (4), one may not perform a thorough yaw moment analysis when IAMR terms are omitted. Indeed, these terms do play an active role in evaluating the overall yaw moment, together with acceleration terms. Henceforward, we are going to express both acceleration terms and IAMR terms by employing the spherical coordinate frame's parameters (θ and ϕ), in order to combine them in the final yaw moment equation.

Since the particular focus of this paper is yaw moment compensation, we mainly analyze (4). EZR-based bipedal walking trajectory is generated based on (1) and (2). For details about EZR-based bipedal walking planning, refer to Ugurlu and Kawamura's articles^{17,27}.

3.2.1. Mathematical Interpretation of IAMR Terms:

As previously stated, we may consider the single support phase as two successive rotations of a composite rigid body about a fixed point (origin of the support foot center). This situation is previously illustrated in Fig. 3. To this end, Euler's equations might provide us insights^{17,27}.

$$\begin{aligned} \dot{L}_x = & I_{xx}\dot{\omega}_x + I_{xy}(\dot{\omega}_y - \omega_z\omega_x) + I_{xz}(\dot{\omega}_z + \omega_x\omega_y) + \dot{I}_{xx}\omega_x + (I_{zz} - I_{yy})\omega_y\omega_z \\ & + I_{yz}(\omega_y^2 - \omega_z^2) + \dot{I}_{xy}\omega_y + \dot{I}_{xz}\omega_z \end{aligned} \quad (5)$$

$$\begin{aligned} \dot{L}_y = & I_{xy}(\dot{\omega}_x + \omega_y\omega_z) + I_{yy}\dot{\omega}_y + I_{yz}(\dot{\omega}_z - \omega_x\omega_y) + \dot{I}_{yy}\omega_y + (I_{xx} - I_{zz})\omega_z\omega_x \\ & + I_{xz}(\omega_z^2 - \omega_x^2) + \dot{I}_{xy}\omega_x + \dot{I}_{yz}\omega_z \end{aligned} \quad (6)$$

$$\begin{aligned} \dot{L}_z = & I_{xz}(\dot{\omega}_x - \omega_y\omega_z) + I_{yz}(\dot{\omega}_y + \omega_z\omega_x) + I_{zz}\dot{\omega}_z + \dot{I}_{zz}\omega_z + (I_{yy} - I_{xx})\omega_x\omega_y \\ & + I_{xy}(\omega_x^2 - \omega_y^2) + \dot{I}_{xz}\omega_x + \dot{I}_{yz}\omega_y \end{aligned} \quad (7)$$

In (5), (6) and (7), I_{xx} , I_{yy} and I_{zz} are moments of inertia and I_{xy} , I_{xz} and I_{yz} are products of inertia at composite CoM; $\vec{\omega} = [\omega_x \ \omega_y \ \omega_z]^T$ and $\vec{\dot{L}} = [\dot{L}_x \ \dot{L}_y \ \dot{L}_z]^T$ are angular velocity and IAMR vectors, respectively. Usually, Euler's equations are defined for rigid bodies with constant rotational inertia elements. Recently, Ugurlu and Kawamura presented a modification^{17,27} to this equation set in a way that it includes rotational inertia elements' time derivatives, as these terms are not constant in bipedal robots.

Evaluating (5), (6) and (7), we primarily need to express angular velocity, $\vec{\omega}$, and angular acceleration, $\vec{\dot{\omega}}$. Keeping the assumption that we stated earlier in mind, it is possible to express the equivalent composite rigid body's (see Fig. 3) CoM orientation by considering 2nd and 3rd rotational actions while defining the spherical coordinate frame.

$$Q_s = \begin{bmatrix} \cos \theta & 0 & \sin \theta \\ \sin \theta \sin \phi & \cos \phi - \cos \theta \sin \phi \\ -\sin \theta \cos \phi \sin \phi & \cos \theta \cos \phi \end{bmatrix} \quad (8)$$

Utilizing a tensorial approach²⁴, angular velocity can be expressed in skew-symmetric form ($\omega^\dagger$).

$$\omega^\dagger = \dot{Q}_s Q_s^T = \begin{bmatrix} 0 & -\dot{\theta} \sin \phi & \dot{\theta} \cos \phi \\ \dot{\theta} \sin \phi & 0 & -\dot{\phi} \\ -\dot{\theta} \cos \phi & \dot{\phi} & 0 \end{bmatrix} \quad (9)$$

Angular velocity vector can simply be extracted from (9) as expressed in (10). Differentiating this vector, we can obtain angular acceleration vector as well.

$$\begin{aligned} \omega_x &= \dot{\phi} & \dot{\omega}_x &= \ddot{\phi} \\ \omega_y &= \dot{\theta} \cos \phi & \dot{\omega}_y &= \ddot{\theta} \cos \phi - \dot{\theta} \dot{\phi} \sin \phi \\ \omega_z &= \dot{\theta} \sin \phi & \dot{\omega}_z &= \ddot{\theta} \sin \phi + \dot{\theta} \dot{\phi} \cos \phi \end{aligned} \quad (10)$$

As next step, we obtain $\dot{L}_x$, $\dot{L}_y$ and $\dot{L}_z$ by inserting (10) into (5), (6) and (7).

$$\dot{L}_x = I_a \ddot{\theta} + I_{xx} \ddot{\phi} + I_t \dot{\theta}^2 - 2I_c \dot{\theta} \dot{\phi} + M_a \dot{\theta} + \dot{I}_{xx} \dot{\phi} \quad (11)$$

$$\dot{L}_y = I_b \ddot{\theta} + I_{xy} \ddot{\phi} + I_a \dot{\theta}^2 \sin \phi - I_{xz} \dot{\phi}^2 + I_n \dot{\theta} \dot{\phi} \sin \phi + M_b \dot{\theta} + \dot{I}_{xy} \dot{\phi} \quad (12)$$

$$\dot{L}_z = I_d \ddot{\theta} + I_{xz} \ddot{\phi} - I_a \dot{\theta}^2 \cos \phi + I_{xy} \dot{\phi}^2 - I_n \dot{\theta} \dot{\phi} \cos \phi + M_d \dot{\theta} + \dot{I}_{xz} \dot{\phi} \quad (13)$$

For the purpose of easing our calculations, we utilized some subexpressions in (11), (12) and (13), as listed in the following.

$$\begin{aligned} I_a &= I_{xy} \cos \phi + I_{xz} \sin \phi; & M_a &= \dot{I}_{xy} \cos \phi + \dot{I}_{xz} \sin \phi; \\ I_b &= I_{yy} \cos \phi + I_{yz} \sin \phi; & M_b &= \dot{I}_{yy} \cos \phi + \dot{I}_{yz} \sin \phi; \\ I_d &= I_{yz} \cos \phi + I_{zz} \sin \phi; & M_d &= \dot{I}_{yz} \cos \phi + \dot{I}_{zz} \sin \phi; \\ I_c &= I_{xy} \sin \phi - I_{xz} \cos \phi; & I_n &= I_{xx} - I_{yy} - I_{zz}; \\ I_t &= I_{yz} \cos 2\phi - 0.5 (I_{yy} - I_{zz}) \sin 2\phi. \end{aligned} \quad (14)$$

3.2.2. Combining Acceleration and IAMR Terms:

In addition to IAMR terms, (4) includes acceleration terms as well. Therefore, a coordinate transformation between Cartesian frame and spherical coordinate frame is performed as follows.

$$[x \ y \ z]^T = Q_s[0 \ 0 \ r]^T \quad (15)$$

$$x = r \sin \theta \quad (16)$$

$$y = -r \cos \theta \sin \phi \quad (17)$$

$$z = r \cos \theta \cos \phi \quad (18)$$

Since the ZMP-based bipedal motion generation is an underconstrained problem in the general sense, one of the parameters should be predetermined. Conventionally, researchers usually supply z-axis CoM trajectory (z) in advance, then solve ZMP equations to obtain x-axis and y-axis CoM trajectories for a given set ZMP inputs (X_{zmp}, Y_{zmp}). The predetermined z-axis CoM trajectory is usually kept constant during walking, or optimized through reinforcement learning procedures for energy efficiency³¹. In case of running or jumping, it may be defined via polynomials to meet the jumping conditions. Because of these advantages, we also choose to predetermine z-axis CoM trajectory. Therefore, we perform mapping between (x, y) and (θ, ϕ) for a predetermined z parameter.

Using (18), r parameter can be expressed in terms of $(z, \theta$ and $\phi)$.

$$r = z \sec \theta \sec \phi \quad (19)$$

Considering (19), x, y , and their second time derivatives take the following form.

$$x = z \tan \theta \sec \phi \quad (20)$$

$$y = -z \tan \phi \quad (21)$$

$$\begin{aligned} \ddot{x} = & \tan \theta \sec \phi (\ddot{z} + (z\ddot{\phi} + 2\dot{z}\dot{\phi}) \tan \phi + z\dot{\phi}^2 (2 \sec^2 \phi - 1)) \\ & + (1 + \tan^2 \theta) \sec \phi (z\ddot{\theta} + 2\dot{\theta}(\dot{z} + z(\dot{\theta} \tan \theta + \dot{\phi} \tan \phi))) \end{aligned} \quad (22)$$

$$\ddot{y} = -(\ddot{z} \tan \phi + (1 + \tan^2 \phi)(z\ddot{\phi} + 2\dot{z}\dot{\phi}(\dot{z} + z\dot{\phi} \tan \phi))) \quad (23)$$

Having expressed both acceleration ($\ddot{x}, \ddot{y}$) and IAMR terms ($\dot{L}_x, \dot{L}_y, \dot{L}_z$) using spherical coordinate parameters (θ , and ϕ) with predetermined z parameter, we can combine them to obtain the mathematical model of the overall yaw moment. To this end, we plug (11), (12), (13), (14), (22) and (23) into (4) as follows.

$$\begin{aligned} \tau_r = & \left(z\mu_3\ddot{\phi} + \ddot{z}t_\phi + 2\mu_3\dot{\phi}(\dot{z} + z\dot{\phi}t_\phi) \right) \left(I_{xz}\dot{\phi}^2 - \dot{\theta}s_\phi(I_n\dot{\phi} + I_a\dot{\theta}) - \dot{I}_{xy}\dot{\phi} \right. \\ & \left. - M_b\dot{\theta} - I_b\ddot{\theta} - I_{xy}\ddot{\phi} \right) \end{aligned} \quad (24)$$

$$\begin{aligned} \tau_p = & \left(\ddot{z}t_\theta j_\phi + z(\ddot{\theta}\mu_1 + \ddot{\phi}\mu_2) + 2z\mu_1\dot{\theta}^2 t_\theta + (2\mu_3 - 1)z\dot{\phi}^2 t_\theta j_\phi + 2z\mu_1\dot{\theta}\dot{\phi}t_\phi \right. \\ & \left. + 2\dot{z}(\dot{\theta}\mu_1 + \dot{\phi}\mu_2) \right) \left(I_a\ddot{\theta} + I_{xx}\ddot{\phi} + M_a\dot{\theta} + \dot{I}_{xx}\dot{\phi} + I_t\dot{\theta}^2 - 2I_c\dot{\theta}\dot{\phi} \right) \end{aligned} \quad (25)$$

$$\tau_{yaw} = a_z(\tau_r + \tau_p) + \dot{L}_z \quad (26)$$

In (24), (25) and (26), s_ϕ , c_ϕ , t_θ , t_ϕ and j_ϕ respectively represent $\sin \phi$, $\cos \phi$, $\tan \theta$, $\tan \phi$ and $\sec \phi$. $\dot{L}_z$ can be computed using (13). Furthermore, following subexpressions are employed to ease the computation of τ_{yaw} .

$$\begin{aligned}\mu_1 &= \sec^2 \theta \sec \phi; & \mu_2 &= \tan \theta \tan \phi \sec \phi; \\ \mu_3 &= \sec^2 \phi; & a_z &= \frac{1}{\ddot{z} + g}.\end{aligned}\quad (27)$$

In Eulerian ZMP Resolution method, the bipedal trajectory generator block outputs θ and ϕ trajectories in real-time, for a given set of ZMP inputs, predetermined z trajectory and other walking parameters (single/double support phase periods, maximum foot height, stride length, etc.). Therefore, once the trajectory generation task is completed, we obtain z , θ and ϕ trajectories, together with their first and second derivatives. Subsequently, these trajectories can be inserted to (24), (25) and (26), so that we can compute τ_{yaw} variation in real-time, throughout the whole walking period. At this stage, we would like to highlight the fact that any feedback control action and/or walking parameter modification concurrently reflects on θ and ϕ trajectories. Therefore such actions also modify τ_{yaw} computation in real-time. We later discuss this fact in Section 5.

In addition, (24), (25) and (26) include rotational inertia elements and their time derivatives. These elements are computed in each control cycle via Balafoutis' composite rigid body inertia algorithm³⁰ through the utilization of Ugurlu and Kawamura's recursive calculation method¹⁷. Since IAMR terms are combined with acceleration terms in (4), we acquire a rigorous mathematical model in which the total yaw moment can be computed without omitting rotational inertia. For details about Eulerian ZMP Resolution based bipedal trajectory generation, refer to Ugurlu and Kawamura's previous works^{17,27}.

To sum up τ_{yaw} computation procedure, bipedal trajectory generator block firstly provides θ and ϕ trajectories in real-time. Together with the predetermined z trajectory and rotational inertia values, these variations are firstly inserted into (14) and (27) with their time derivatives, in order to obtain repeating subexpressions. As these subexpressions are encountered in the yaw moment equation several times, we compute them once and use when needed, so as to increase computational efficiency. As next step, $\dot{L}_z$, τ_p , τ_r are respectively calculated via (13), (24) and (25); finally leading us to computation of τ_{yaw} using (26). Note that no empirically-tuned parameter is required in this procedure.

4. Compensation Action: Waist Joint Trajectory Generation

As illustrated in Fig. 4(a), undesired yaw moment about the pivot, τ_{yaw} , can be regulated through the utilization of compensation moment exerted via upper body motion, τ_c . Frictional moment, τ_{fr} , appears to resist the difference between τ_{yaw} and τ_c . Usually, in a humanoid walking, τ_c cannot completely compensate τ_{yaw} ,

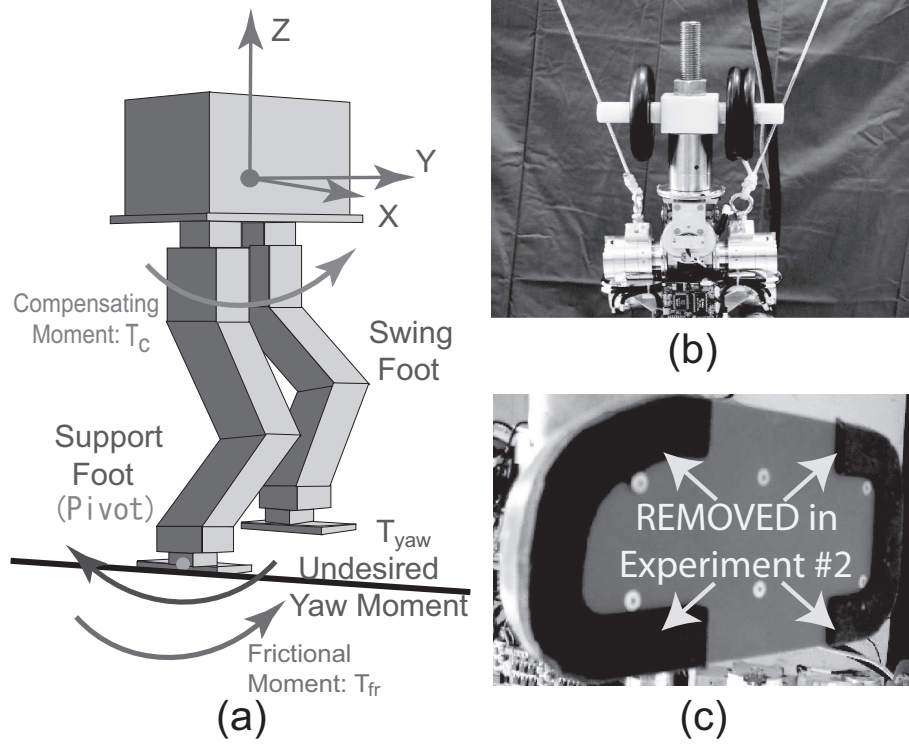


Fig. 4. a) Components of the yaw moment, induced about the support foot. Undesired yaw moment compensation task is realized via the utilization of waist rotation. b) Upper body weights are placed on top of the waist joint, in a way to create the compensating yaw moment. Note that dummy weights are placed symmetrically, so that their influence on mass distribution is negligible. c) In normal operation, custom-made pads are placed under the feet sole to provide sufficient friction. In Experiment #2, we remove these pads only from the right foot to illustrate the proposed method's efficiency.

so that τ_{fr} confronts the residual amount of undesired yaw moment. In case of overcompensating, which is unlikely to happen, τ_{fr} confronts the overcompensating torque.

$$\left| \tau_{yaw} - R_{wp} \tau_c \right| + \tau_{fr} = 0 \quad (28)$$

In (28), R_{wp} is the rotation matrix between waist joint and support foot (pivot) frames. It is included to project the torque generated by waist joint to the pivot.

Furthermore, the frictional moment depends on the material type of foot sole and the floor^{1,3}. Because of this fact, it is rather difficult to express it mathematically. What is more, humanoids are expected to walk and/or run on different types of surfaces; therefore, we prefer not to investigate frictional moment deeply. With this motivation in mind, we always try to compensate undesired yaw moment only by

using upper body motion planning.

$$R_{wp33}\tau_{cz} = R_{wp33}I_{uz}\ddot{q}_{13} = \tau_{yaw} \quad (29)$$

In (29), q_{13} symbolizes waist joint and I_{uz} indicates upper body's mass moment of inertia associated with yaw axis. Moreover, only the yaw axis waist joint is needed to be actuated, so that compensating torque can be expressed via Newton's torsional law. Because of this fact, only the third row - third column element of R_{wp} (R_{wp33}) and yaw-axis element of τ_c (τ_{cz}) are needed.

For a given bipedal motion planning, we are able to obtain τ_{yaw} for every instant through the utilization of (26). Upper body rotational inertia element, I_{uz} , is provided by the CAD data. Given these parameters, yaw axis waist joint trajectory, q_{13} , can be generated by numerically solving the following second order differential equation³².

$$\ddot{q}_{13} = \frac{\tau_{yaw}}{R_{wp33}I_{uz}} \quad (30)$$

Having derived the yaw axis waist joint trajectory, following actuator limitations should be considered.

$$q_{13}^- \leq q_{13} \leq q_{13}^+; \quad \dot{q}_{13}^- \leq \dot{q}_{13} \leq \dot{q}_{13}^+; \quad \tau_{13}^- \leq \tau_{13} \leq \tau_{13}^+. \quad (31)$$

In (31), τ_{13} is the yaw-axis waist joint torque command that is needed to drive the joint through the designated trajectory, generated via the numerical solution of (30). Superscripts + and - stand for upper and lower limits, respectively. If the desired yaw axis joint motion is not within the actuator limits, yaw moment compensation task may not be realized in a complete manner. Therefore, joint actuator limitations should be carefully considered in advance.

Even though we adopted yaw-axis waist rotation scheme as the compensation action, one may utilize arm swinging strategy as well. Having computed the undesired yaw moment via (26), one may generate symmetrical arm swinging motions through opposite directions, in a way to compensate its influence on the system, as performed by Fujimoto and Kawamura⁵. We will investigate this technique in our future studies.

5. Experimental Results and Discussions

In this section, we firstly provide a brief presentation regarding the mechatronic hardware of the bipedal robot CoMan. Afterwards, experiment procedures and real-time implementation scheme are explained. Having described the overall background in conducting experiments, results from two distinct experimental studies (Experiment #1 and Experiment #2) are disclosed. In the last subsection, experimental results and limitations are discussed thoroughly.

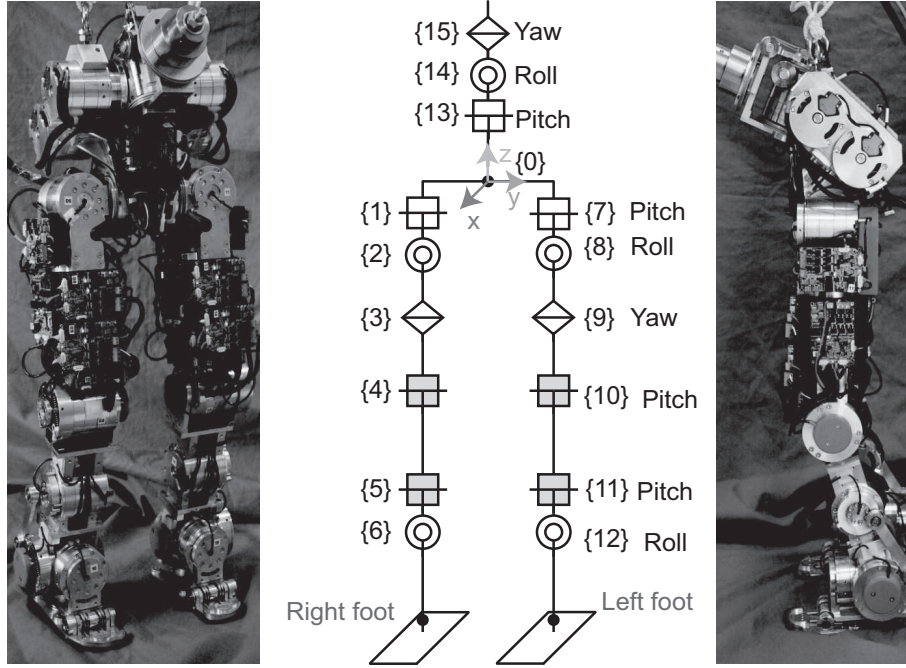


Fig. 5. The mechanical assembly of CoMan and its joint configuration.

5.1. Bipedal Robot CoMan

In order to explore compliant humanoid characteristics, we developed a bipedal robot called CoMan (**C**ompliant **Hu**Manoid). The robot has a total of 15 active DoF (degrees of freedom); 6 DoF in each leg, and 3 DoF at the waist to be able to obtain greater motion flexibility. Each joint incorporates three position sensors (2 absolute and 1 relative) and one torque sensor. Knee joints and pitch axis ankle joints have passive compliant elements to provide elasticity²⁸. The robot is also equipped with 6-axis Force/Torque sensors at the ankles and five 1-axis load cells on the foot sole. Moreover, CoMan has a 3-axis rate gyro sensor and a 3-axis accelerometer, located at the pelvis. In its electronic hardware structure, the main controller is an Intel Core Duo 1.5 GHz dual processor with 3.0 GB RAM, running on a 32-bit GNU/Linux operating system that includes real-time Xenomai extension. Data communication is performed via real-time Ethernet protocol called RTnet. Fig. 5 displays the actual robot and the joint configuration. Refer to Tsagarakis et al.'s article²⁸ for more details.

As displayed in Fig. 5, CoMan does not have an actual upper body at the present time. Keeping this in mind, we slightly modified the upper body. A T-profile structure is assembled on top of the waist joint, on which we can hang dummy weights to both sides. Fig. 4(b) displays this hardware modification.

5.2. Experiment Procedures

In both Experiment #1 and Experiment #2, identical dynamic bipedal walking experiments are conducted four times for benchmarking purposes:

- Case 1: No yaw moment compensation, i.e., waist joint is not rotated.
- Case 2: With yaw moment compensation method introduced by Hirabayashi and his colleagues¹³.
- Case 3: With yaw moment compensation method described by Yamaguchi and his colleagues¹¹.
- Case 4: With the proposed yaw moment compensation method.

In all experiments, walking parameters are kept the same; single support time, double support time, maximum swing foot height, stride length, lateral distance between legs, constant CoM height are substituted as 0.5 [s], 0.1 [s], 2.5 [cm], 6 [cm], 8.21 [cm], 36.2 [cm], respectively. Moreover, all the experiments (both benchmarking and EZR-verification experiments) are conducted on our actual bipedal robot CoMan. Sampling time is substituted as 1 [ms]. The average computation time for the whole process (real-time walking motion generation and control, yaw moment computation and compensation) is realized online and handled within 1 [ms] in each cycle.

In Experiment #1, we analyzed the induced yaw moment throughout the whole walking period. In this experiment, custom made pads are placed under the feet soles to provide sufficient foot contact, in order to acquire the induced yaw moment correctly. Yaw moment response variations are compared in four distinct cases to examine the efficiency of the proposed method.

In Experiment #2, we removed custom made pads only from the right foot sole as displayed in Fig. 4(c). Thus, during right leg single support phases, frictional moment is greatly reduced, so that we are able to evaluate the proposed method under this condition. Without yaw moment compensation, the robot body rotates about the support foot during right leg single support phases, even though the designated walking path is a straight line. Depending on the efficiency of the yaw moment compensation method, deviations (yaw-axis disorientations) are expected to be minimized. Therefore, in this study, deviations in yaw-axis orientation give us insights in evaluating the efficiency of the proposed yaw moment compensation methods comparing to off-the-shelf-techniques^{11,13}.

5.3. Real-time Implementation

In Fig. 6, an overall block diagram during a possible real-time implementation scenario can be observed. In this diagram, *Bipedal Motion Planning and Control* is composed of a trajectory generator and real-time stabilizer. It is responsible for generating feasible lower body motion to realize dynamically-equilibrated walking. Primarily, the trajectory generator evaluates the designated walking parameters (single/double support phase periods, maximum foot height, stride length, etc.)

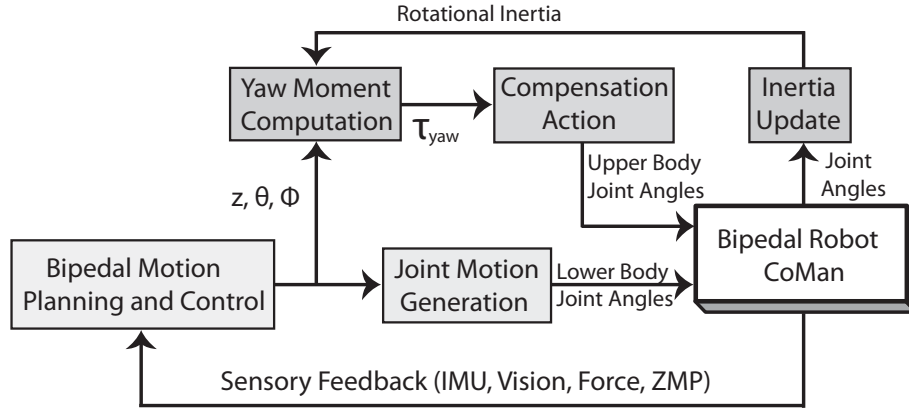


Fig. 6. Overall block diagram during a general case of a real-time implementation.

and synthesizes the motion pattern accordingly. Walking parameters can be adjustable in real-time to alter the bipedal motion online. Subsequently, real-time stabilizer processes sensory information, so that dynamic balance under varying environmental conditions can be achieved. Sensory information could vary depending on the real-time control architecture; it could make use of vision sensing, IMU unit, force/ZMP measurements, or combination of these measurements. Having synthesized dynamically-consistent lower body motion, joint angles are generated and then inserted to local servo blocks to compute necessary joint torques.

As previously stated, the undesired yaw moment is inevitably induced while the robot is in motion. Keeping this in mind, lower body motion that is generated by the *Bipedal Motion Planning and Control* block is processed in *Yaw Moment Computation* block; so that we can obtain the real-time variation of the undesired yaw moment, despite the changes in walking parameters and/or environmental conditions. Since these aforementioned changes are handled in *Bipedal Motion Planning and Control* block, any modification is reflected on the undesired yaw moment calculation in real-time. Afterwards, *Compensation Action* block generates necessary upper body motion (waist rotation or arm swinging) accordingly, in a way to cancel out the undesired yaw moment.

In this specific work, we utilized Ugurlu and Kawamura's real-time bipedal motion synthesis technique^{17,27}. In order to compute yaw moment, we need to insert z , θ and ϕ trajectories into (26), along with their time derivatives. These trajectories are supplied by the bipedal motion planning and control unit. Moreover, rotational inertia elements are updated in each control cycle via Balafoutis' method²⁴ and used in yaw moment computation. Having computed the undesired yaw moment, compensating yaw-axis waist trajectory is generated by using (30). Note that any real-time changes (altering walking parameters, feedback control action) reflect on the undesired yaw moment compensation in real-time.

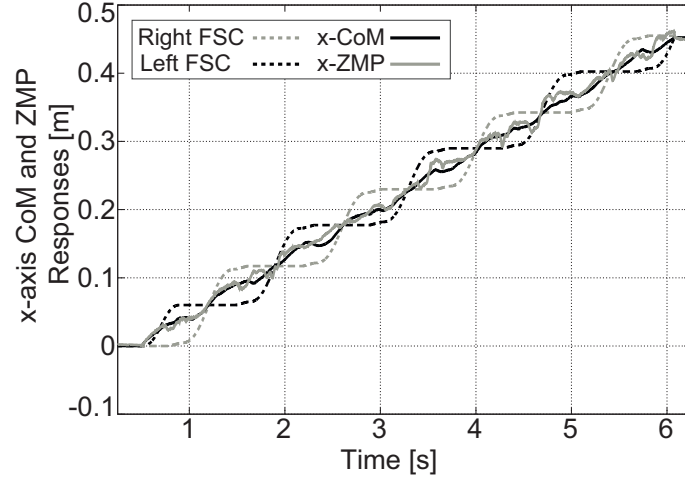


Fig. 7. x-axis CoM and ZMP.

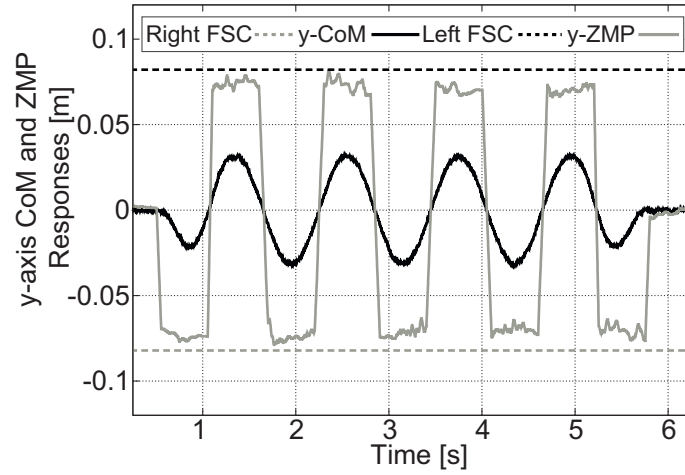


Fig. 8. y-axis CoM and ZMP.

5.4. Experiment #1

As previously explained, we firstly conducted dynamic bipedal walking experiments. Results can be examined from Fig. 7 to Fig. 13.

CoM and ZMP response trajectories are displayed in Fig. 7 and Fig. 8, for x-axis and y-axis. In these figures, solid black and gray lines depict CoM and ZMP trajectories while dashed black and gray lines symbolize left FSC (Foot Sole Center) and right FSC positions. Throughout the whole walking period, ZMP responses are

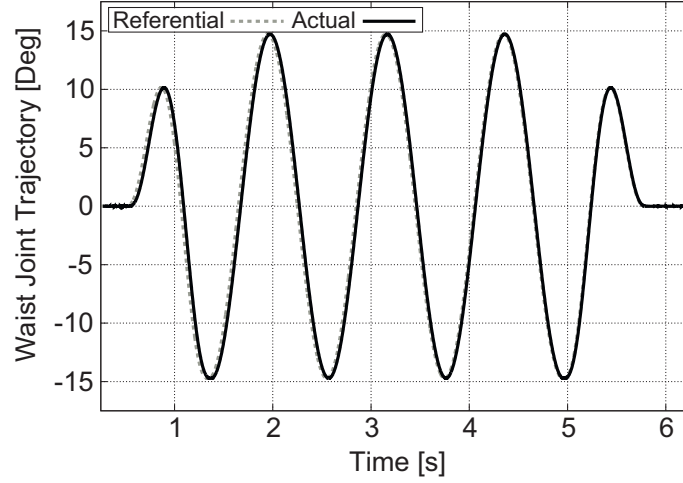
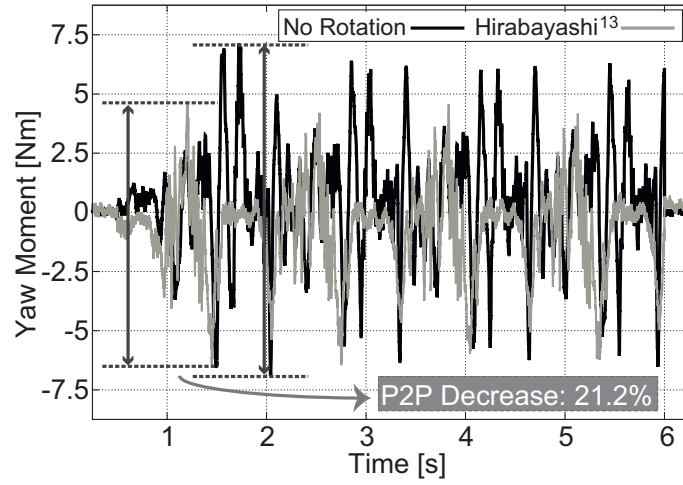


Fig. 9. Yaw-axis waist joint trajectory.

Fig. 10. Case 2: Hirabayashi et al.'s method¹³, Experiment #1.

observed to be within the support polygon boundaries, indicating that we obtained dynamically-equilibrated walking cycles. Moreover, CoM trajectories appear to be continuous and smooth, indicating that sequential double and single support phases are tied seamlessly.

Yaw-axis waist joint trajectory is exhibited in Fig. 9, in which dashed gray and solid black lines denote referential and response trajectories. The referential trajectory is computed via eq. (26), in accordance with the planned bipedal trajectory.

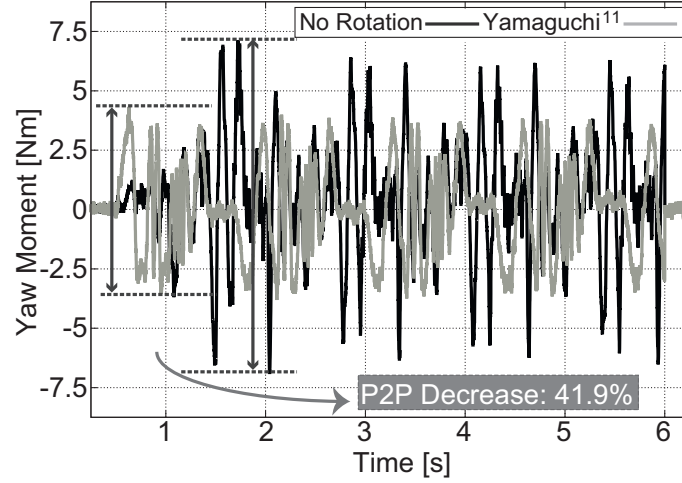
Fig. 11. Case 3: Yamaguchi et al.'s method¹¹, Experiment #1.

Table 1. Yaw Moment Measurements, Experiment #1

	No Compens.	Hirabayashi et al. ¹³	Yamaguchi et al. ¹¹	Proposed
P2P	13.99 [Nm]	11.03 [Nm]	8.13 [Nm]	5.59 [Nm]
RMS	2.26 [Nm]	1.76 [Nm]	1.67 [Nm]	0.88 [Nm]

Table 2. Yaw Moment Decrease Percentages, Experiment #1

	Hirabayashi et al. ¹³	Yamaguchi et al. ¹¹	Proposed
P2P	21.2%	41.89%	60.02%
RMS	22.15%	26.06%	61.04%

In Fig. 10, Fig. 11 and Fig. 12, yaw moment response variations are plotted with solid gray lines while employing yaw moment compensation, respectively for Case 2, Case 3 and Case 4. Each figure additionally includes yaw moment response variations for Case 1, i.e., while the waist joint is locked. This variation is illustrated with black color. All measurements are summarized in Table 1, including peak-to-peak (P2P) and root mean square (RMS) values. What is more, peak-to-peak decrease percentages with respect to 'No Compensation' case are indicated in each figure.

Specifically, Fig. 13 illustrates RMS value decrease percentages with respect to 'No Compensation' case, namely Case 1. In Case 2, Case 3, and Case 4, RMS value of yaw moment response is reduced for about 22.15%, 26.06% and 61.04%,

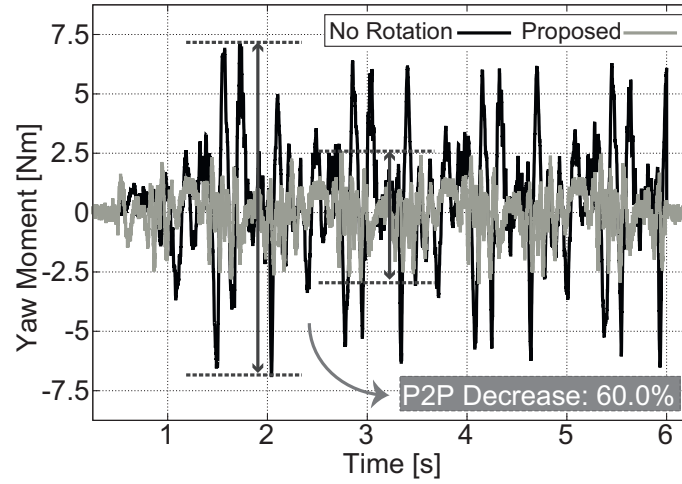


Fig. 12. Case 4: Proposed method, Experiment #1.

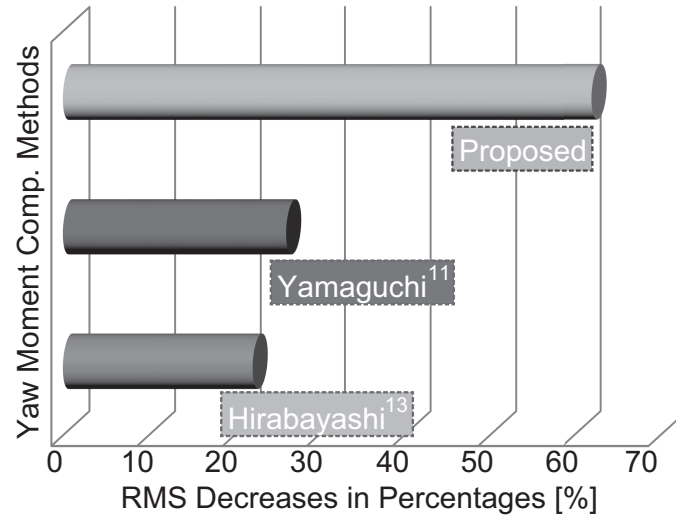


Fig. 13. RMS Decreases with respect to Case 1, Experiment #1.

respectively. Both peak-to-peak and RMS value decrease percentages are provided in Table 2.

5.5. Experiment #2

In this experimental study, we removed the custom-made pads only from the right foot sole (see Fig. 4(c)), as explained earlier. In doing so, the frictional moment

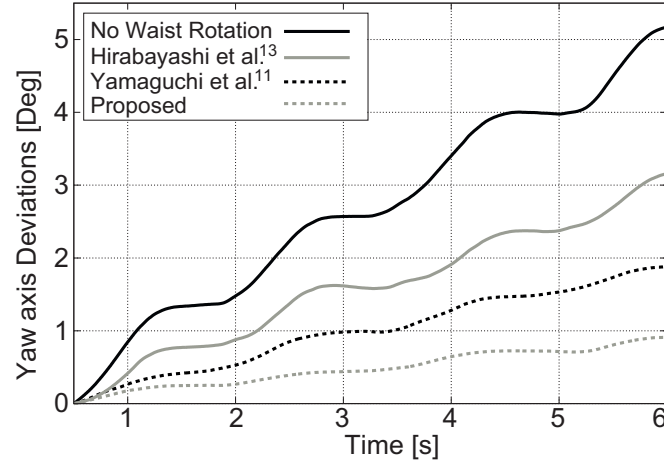


Fig. 14. Yaw-axis Disorientations, Experiment #2.

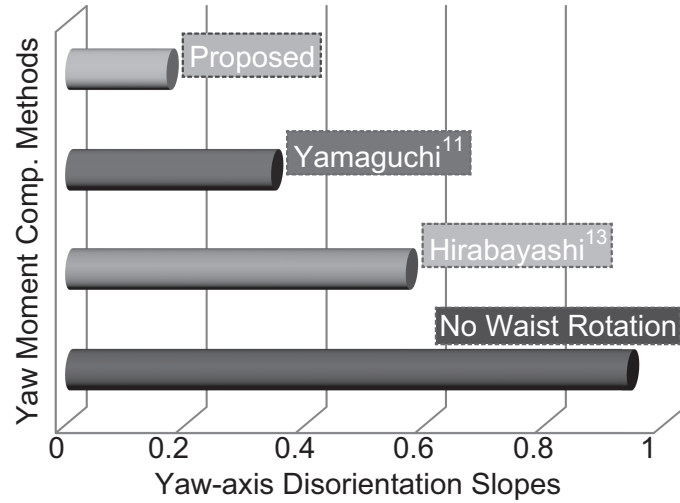


Fig. 15. Disorientation slope values, Experiment #2.

acting on the right foot sole is reduced, causing the robot body to rotate inevitably in yaw axis when the left leg is swinging, i.e., during right leg single support phase. Utilizing a proper yaw moment compensation technique, such deviations in yaw axis can be regulated. Depending on the efficiency of the yaw moment compensation technique, yaw axis disorientations can be minimized as the designated walking path is a straight line.

Having conducted this experiment for four distinct cases, we recorded yaw axis

Table 3. Yaw Axis Disorientation Decrease Percentages, Experiment #2

Hirabayashi et al. ¹³	Yamaguchi et al. ¹¹	Proposed
39.36%	63.82%	81.9%

deviations in Fig. 14, using the IMU sensor located on the robot body. Solid black, solid gray, dashed black and dashed gray lines indicate yaw axis deviations for Case 1, Case 2, Case 3, and Case 4, respectively. After walking for 8 consecutive steps, the robot body deviated for about 5.18 [Deg], 3.15 [Deg], 1.9 [Deg] and 0.97 [Deg], respectively for Case 1, Case 2, Case 3, and Case 4.

Yaw axis deviations measured in this experiment can simply be modeled using lines with constant slope values. These slope values appear to be a regulation performance metric; smaller slope value indicates a better performance. As indicated in Fig. 15, slope values are computed as 0.94, 0.57, 0.34 and 0.17, for Case 1, Case 2, Case 3, and Case 4, respectively. Comparing to Case 1, we obtained 81.9% regulation in yaw axis deviation when using the proposed method (Case 4). Same decrease percentages for Case 2 and Case 3 are computed as 39.36% and 63.82%. This result is summarized in Table 3.

Note that swing leg motion during Experiment #2 is adjusted in a way that it does not cause any dynamic instability while the support foot (right) is rotating due to slippage.

5.6. Discussions on the Results and Potential Limitations

As it may be observed in experimental results, the proposed method shows a superior performance over off-the-shelf yaw moment compensation techniques^{11,13} in compensating the undesired yaw moment and in regulating yaw axis disorientation. Therefore, the proposed method appears to be an efficient solution for the undesired yaw moment problem.

In Hirabayashi et al.'s method¹³, undesired yaw moment is computed solely based on swing leg motion. On the contrary, swing leg motion alone is not the only responsible factor for the undesired yaw moment. Forward body motion and intrinsic angular momentum rate changes contribute to this issue as well. With this in mind, Yamaguchi et al.'s method¹¹ appears to be a better solution as they attempt to compute the overall undesired yaw moment using a multi-mass model. Indeed, our comparative experimental studies indicate that Yamaguchi et al.'s method exhibits better results in comparison with Hirabayashi et al.'s method.

Even though Yamaguchi et al.'s method escalates the efficiency, it has its own limitations. One of the main issues in their method is that rotational inertia is not characterized as all individual links are considered as point masses. Therefore, IAMR terms cannot be included in yaw moment computation. Depending on the inertial parameters of the target robot, IAMR terms can have significant effects on

the overall yaw moment induced about the support foot. Especially, in biped robots with significant inertial characteristics (mass and rotational inertia of links, mass distribution, etc.), IAMR terms may have dominant characteristics²⁷.

To this end, the proposed method seems to be a better alternative. Utilizing Eulerian ZMP Resolution, we are able to characterize the rotational inertia and the related angular momentum terms (IAMR terms) at the composite CoM. That enables us to obtain a yaw moment computation with relatively higher precision. This fact naturally reflects on the experimental results as well. While using the proposed method, we obtained improved and enhanced results in handling the undesired yaw moment issue. What is more, comparison of experimental results indicate that it shows a superior performance over off-the-shelf methods^{11,13}.

Inevitably, the proposed method has its own drawbacks. To mention one, yaw moment compensation is firstly computed via (26), then the compensation moment (τ_c) is generated via waist rotation by solving the differential equation in (30). Equation (26) appears to be somewhat complicated, making (30) quite difficult to be solved analytically. Furthermore, it has rotational inertia elements which must be recursively computed in each cycle. That being the case, we implement a numerical method to solve this equation. For this purpose, we make use of Runge-Kutta with Adaptive Stepsize Control³². This method handles 'the precision-computation time tradeoff' smoothly in real-time, via adjusting the stepsize. Hence, the method does not suffer from rounding error accumulation or expensive computational burden. On the other hand, the algorithm becomes slightly more complex. As the result, this fact appears to be a disadvantage of the proposed method.

Another limitation is directly addressed in waist joint actuator capabilities. As explained earlier, the compensating yaw moment is exerted solely by the waist joint. If the required compensation action is beyond the actuator limits (see eq. (31)), undesired yaw moment cannot be regulated completely. What is more, arm swinging strategy seems to be more promising when it comes to generating more powerful compensation moments. Since CoMan has no upper body at the moment, this issue remains as a future task. In our next investigations, we are planning to overcome this potential drawback via the utilization of full-body legs-arms coordination.

We also would like to highlight the fact that this paper focuses on straight walking motion without yawing (cornering) motion. Generally, necessary trajectory for this yawing motion, let us call it ψ , is generated by a high-level bipedal motion planning unit, via assessing vision sensing information or such like³³. In other words, ψ trajectory is given in advance. Keeping this in mind, one can re-formulate yaw moment computations (eqs. (8)-(13)) in a way that they include ψ and its time derivatives. Subsequently, the same procedures are followed and yaw moment regulation is performed. Therefore, this fact is not a drawback; however, it is required to perform additional modifications when it comes to yaw moment compensation for bipedal walking motion with cornering.

6. Conclusions and Future Work

To summarize, we proposed a systematic way of generating waist trajectories in a way to compensate the undesired yaw moment within a relatively more dynamically-consistent manner. Instead of focusing on the individual factors, the proposed method provides a thorough computation method, in which the overall yaw moment can be calculated for a given bipedal motion planning scheme. In this matter, Eulerian ZMP Resolution technique enables us to characterize the rotational inertia and associated angular momentum rate change (IAMR) terms, rather smoothly.

In order to validate the proposed method, several dynamic bipedal walking experiments are conducted. As the result, the method provides 61% decrease in undesired yaw moment response throughout the whole dynamic walking period. Moreover, we obtain 82% decrease in yaw-axis deviations as well. Considering these results, the method shows a superior performance in yaw moment compensation problem, in comparison to off-the-shelf methods. Therefore, the proposed method appears to be a promising solution in handling the undesired yaw moment problem which may be faced during bipedal motion planning.

Currently, there is an ongoing process in finalizing the upper body of the bipedal robot CoMan. After completing the overall humanoid body, the proposed method will be expanded and improved in a way to consider full-body legs-arms coordination. In addition, we will also investigate yaw moment compensation techniques through the direct utilization of yaw axis hip joints.

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