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Whole-Body Motion and Landing Force Control for Quadrupedal Stair Climbing

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***Abstract*— In this paper, we present a novel framework for quadrupedal stair climbing, which considers force interaction with stairs. For stable and robust climbing, a key issue is to avoid falling down on the stairs. From this point of view, control to minimize rate of change of angular momentum about Center of Mass (CoM) which is produced by ground reaction force (GRF) at contact of robot's foot is necessary. Using this approach, direct force-based Zero Moment Point (ZMP) for motion planning of the CoM and landing force control are implemented. The direct force-based ZMP method allows the robot to lift its foot with reduced possibility of tilting on the stairs, and the landing force control prevents instant increase of the moment by impact of the GRFs. In addition, terrain recognition to estimate parameters of the stairs and find proper footholds by vision system mounted on the robot is presented. Proposed framework is implemented to quadruped robot, AiDIN-VI, that has torque sensor at each joint, through experiments, capability of ascending several stairs including 3-step stairs which have 21cm height (31% of its maximum leg length) and 26.5° inclination is validated.**

Fig. 1. Force-controllable quadruped robot, AiDIN-VI, has torque sensor at each joint are ascending 3-step stairs without any support.

I. INTRODUCTION

Recently legged robots are receiving great attention as these have been showing remarkable performance in robot field. Atlas developed by Boston Dynamics can walk and run on real environment and even perform backflips [1]. ANYmal including Series Elastic Actuator (SEA) at each joint has shown walking on various terrains by its mechanical compliance and terrain mapping utilizing mounted vision system to replan its motion [2]. In addition, quadruped robot, Laikago, is able to overcome grassy slope($\approx 20°$) and uneven terrain during trot gait [3]. Like these robots, to fulfill diverse tasks for human in the future, it is important for legged robots to walk on the real environment, not on flat plane. Furthermore, locomotion in more challenging conditions have been researched. HyQ shows walking inside two high-slope (50°) V-shaped walls and a few quadruped robot perform obstacle avoidance during bounding or trot gait [4]–[6]. Among terrains existing in the real environment, stairs are one of the terrains which are difficult to be overcame by legged robots because it is possible to be fallen down when the robots miss its step or lose balance. Therefore, researching robust and stable control algorithms for stable stair climbing are definitely required.

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In previous research of humanoid stair climbing. THBIP-I can ascend the stairs by climbing gait and sensory control strategy with consideration of environmental and kinematic constraints [7]. Implemented stair climbing strategy for biped robot HRP-4 is that plane-segment is estimated in real time for integrating with humanoid motion planning and climbing motion generator [8]. In case of quadruped robot, Recently several research teams have been showing stair climbing controllers implemented to their quadruped robots. Locomotion planner which finds safe footholds based on terrain map and re-plans the motion, and pose optimization which finds proper position and orientation of the CoM for given contact situations are implemented to ANYmal [9]. Through this method, it was able to overcome diverse terrains including 17cm high stairs autonomously. Height reflex that is replanning strategy for foot trajectory was researched to redistribute swing-phase motion [10]. By this approach, HyQ can step down from a 24cm high platform which is 30% of its leg length. In addition, event-based blind locomotion on the stairs using accurate contact detection with 99.3% accuracy and a small 4-5ms delay is performed by MIT cheetah 3 [11]. Lastly, SpotMini has been showing stair climbing by trot gait using visual data from cameras mounted on the robot but there are no details about control methods to perform them [12].

In this paper, we present a novel framework for stable stair climbing which utilizes the GRFs for CoM motion planning and landing force control. Through intuitive approach with

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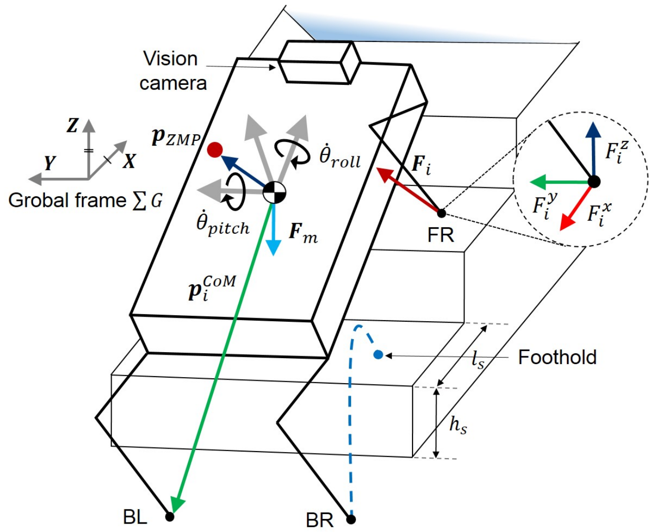

Fig. 2. A schematic drawing shows definition of parameters and vectors for stair climbing.

CoM dynamics model, required control methods are proposed for locomotion on the stairs. When the legged robots are walking on high height platforms, keeping its balance is a key issue to avoid falling down. In this context, minimizing the rate of change of angular momentum of the CoM which is generated by the GRFs is definitely important. To do this, the direct force-based ZMP method and landing force control are included in the framework. In spite of necessity to consider the force interaction during locomotion, almost legged robots were difficult to consider it because force or torque sensor are required to obtain exact force. Recently we developed quadruped robot, AiDIN-VI, which has torque sensor at each joint [13] as shown in Fig. 1. Therefore, AiDIN-VI is suitable to perform proposed control framework using force information. In addition, trajectory generation for swing phase, and terrain recognition to estimate geometrical parameters of the stairs are also discussed. Through implementation of proposed framework to AiDIN-VI, it was able to stably ascend the stairs up to 21cm which is 31% of its maximum leg length.

This paper is organized as follows. Firstly, approach for robust control of stair climbing is explained in section II. Overall our framework are presented specifically in section III. In section IV, experimental evaluations of proposed framework which is implemented to quadruped robot, AiDIN-VI, are explained. Lastly, conclusions are presented in section V.

II. Approach

In general, total mass of the legged robot system is assumed as a point (i.e., CoM) and its dynamics model is represented as

$$m\begin{bmatrix}\ddot{\mathbf{p}}_{CoM}-\mathbf{g}\\ \mathbf{p}_{CoM}\times(\ddot{\mathbf{p}}_{CoM}-\mathbf{g})\end{bmatrix}+\begin{bmatrix}\mathbf{0}\\ \dot{\gamma}\end{bmatrix}=\begin{bmatrix}\sum\mathbf{F}_i\\ \sum\mathbf{p}_i\times\mathbf{F}_i\end{bmatrix} \quad (1)$$

where $\mathbf{p}_{CoM}=\left[p_{CoM}^x,p_{CoM}^y,p_{CoM}^z\right]^T$ and $\ddot{\mathbf{p}}_{CoM}=\left[\ddot{p}_{CoM}^x,\ddot{p}_{CoM}^y,\ddot{p}_{CoM}^z\right]^T$ are location and acceleration of the CoM, respectively. $\mathbf{g}=\left[0,0,g\right]^T$ is gravitational acceleration, $\mathbf{p}_i=\left[p_i^x,p_i^y,p_i^z\right]^T$ is position of each foot-end, $\mathbf{F}_i=\left[F_i^x,F_i^y,F_i^z\right]^T$ is the GRFs, and $\dot{\gamma}$ is the derivative of the robot body‘s angular momentum, but it is ignored in this paper [15]. Required parameters for this dynamics model are expressed in Fig. 2. Our approach is control to minimize the moment to reduce possibility of falling down. Therefore, we are concerned with the angular momentum rate change more because it is related to balance of the robot. In other words, motion of the CoM about orientation is important for balance-critical tasks such as stair climbing. The rate of change of angular momentum in Eq.(1) is rewritten simply as

$$\mathbf{M}_{CoM}=(\mathbf{p}_i-\mathbf{p}_{CoM})\times\mathbf{F}_i \quad (2)$$

where $\mathbf{M}_{CoM}$ is the moment about the CoM. In Eq.(2), the rate of change of angular momentum depends on two kind of parameters: $\mathbf{p}_i^{CoM}$ and $\mathbf{F}_i$, where $\mathbf{p}_i^{CoM}=\mathbf{p}_i-\mathbf{p}_{CoM}$ is the foot location from the CoM. However, for locomotion on the real environment, it is desirable that the foot location is determined by recognition of vision system because environmental limits should be considered to find valid footholds. Therefore, if location of the foot is determined as a selected foothold in advance, moment of the CoM can be adjusted by control of the GRFs only even though $\mathbf{p}_i^c$ is still related to the angular momentum rate change. In previous research, the rate of change of angular moment is significantly considered for balance-based tasks [14]–[16]. However, almost researches presented indirect force control methods which mean utilizing virtual force calculated by position error and gain. We developed force-controllable quadruped robot, AiDIN-VI, and GRFs can be calculated using torque sensor as

$$\mathbf{F}_i=\begin{bmatrix}F_i^x\\ F_i^y\\ F_i^z\end{bmatrix}=\mathbf{J}_i^{-T}\tau_i \quad (3)$$

where $\mathbf{J}_i^{-T}$ is inverse transpose of jacobian matrix and τ_i is torque measured from torque sensor at i-th leg. Eventually, control objective is reducing the moment of the CoM using the GRFs calculated from torque sensor. To do this, the direct force-based ZMP and the landing force control are presented as below.

1) direct force-based ZMP: Many legged robots perform walking gait on the assumption that stable locomotion is possible if vertically projected CoM is existed on the support polygon. However, on rough terrain such as the stairs, shape and inclination of support polygon are possible to be changed significantly according to contact state of each leg. In other words, during stair climbing, shifting projection of CoM to somewhere on large space of the support polygon is able to make robot unstably even though this method is usually implemented for walking gait on normal plane. In case of support polygon-based locomotion, optimization method can

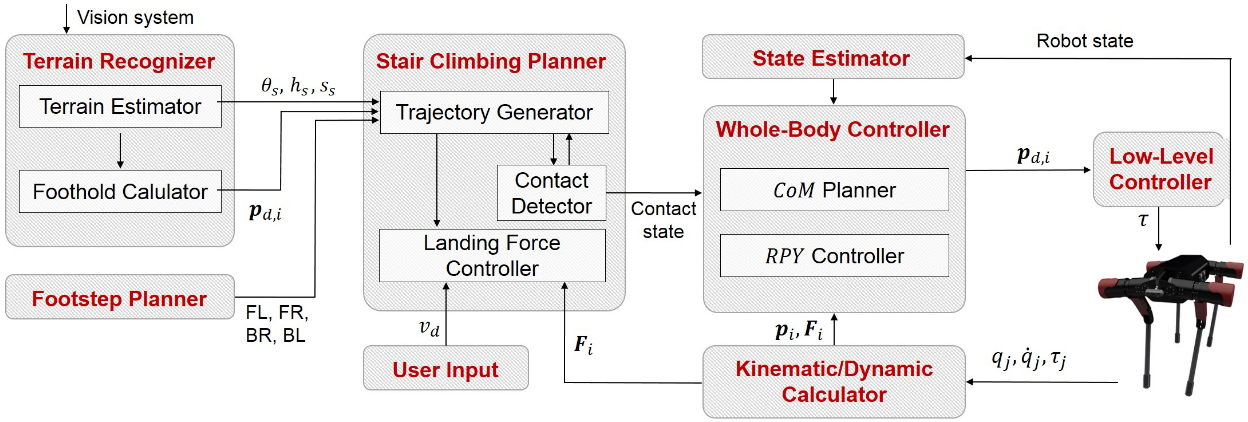

Fig. 3. Block diagram of framework for stair climbing. In terrain recognizer, proper footholds are detected and geometrical parameters for the stairs are estimated. The swing trajectory is generated considering contact state and landing force is adjusted to reduce impact force in stair climbing planner. The CoM is shifted to a computed point by the direct force-based ZMP, and roll-pitch-yaw angles of the robot body are controlled simultaneously in whole-body controller.

be one of the solution [9]. On the contrary, ZMP is more proper for the CoM motion planning because it is defined as a point does not produce any moment. Almost legged robots implement cart-table model for the ZMP using acceleration with robot‘s mass to obtain force [7], [17]. One characteristic of this method is that when the acceleration of the cart is zero, the ZMP corresponds to the projection of the CoM(i.e., $\mathbf{p}_{ZMP} = \mathbf{p}_{CoM}$). The characteristic that means robot‘s body have to be planned to obtain continuously CoM reference trajectory can cause instability during locomotion on the high height platform. On the other hand, the direct force-based ZMP can be calculated also in static state using measured force.

2) landing force control: Originally, locomotion is performed by force interaction with ground but many legged robot cannot know GRFs exactly because of absence of force/torque sensor. To absorb GRFs, alternatively, indirect force control, compliance mechanism, and event-based locomotion have been researched [2], [11], [14]. In addition, AiDIN-VI has quite stiff structure by using high ratio reduction gear (50:1) at each joint. Therefore, impact force cannot be absorbed if position-based control is employed. We implement landing force controller by utilizing torque sensor. Role of the landing force control is avoiding instantaneous increase of the moment by impact force.

III. Framework for Stair Climbing

In Fig. 3, overall control framework for stair climbing is represented, and detailed control methods will be explained in this section.

A. Terrain Recognizer

In terrain recognizer, geometrical parameters such as height, inclination of the stairs are detected and then proper foothold is estimated considering them. We used RANdom SAmple Consensus (RANSAC) algorithm, which detects multi-plane by point cloud obtained from the depth image assuming that terrains consist of several planes. It is one of the effective algorithm to exclude outlier data for the plane model. From this algorithm, equations of each plane can be acquired, through comparing these, height and length of the stairs, h_s and l_s, respectively, are estimated. In addition, the inclination is calculated as $\theta_s = tan^{-1}(\frac{h_s}{l_s})$. Fig. 4 shows recognized planes, valid footholds, and selected foothold using the depth camera which is mounted on the quadruped robot. Implemented algorithm is able to search multi-plane, resultantly, two planes on the stairs are detected. Within the planes, valid footholds are searched considering the walking direction, workspace of the robot and the order of stair. Walking direction is already known because desired velocity, v_d, is predefined by user. we set v_d to walk forward for climbing stairs in front of the robot. By kinematic calculation, the workspace is considered before searching of every footholds. In addition, if several planes are detected on the stairs, valid footholds are determined on a plane which have largest area compared to others. It is reasonable because

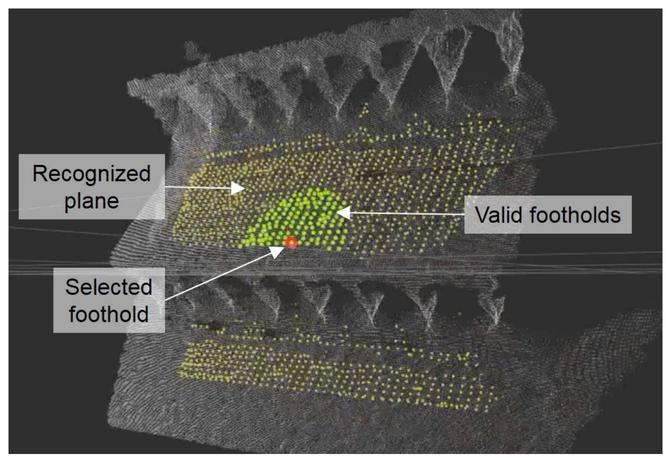

Fig. 4. Vision system mounted on the robot searches multi-plane and valid footholds within recognizable space, and one foothold is finally selected considering the walking direction, workspace of the robot, and tge order of stair.

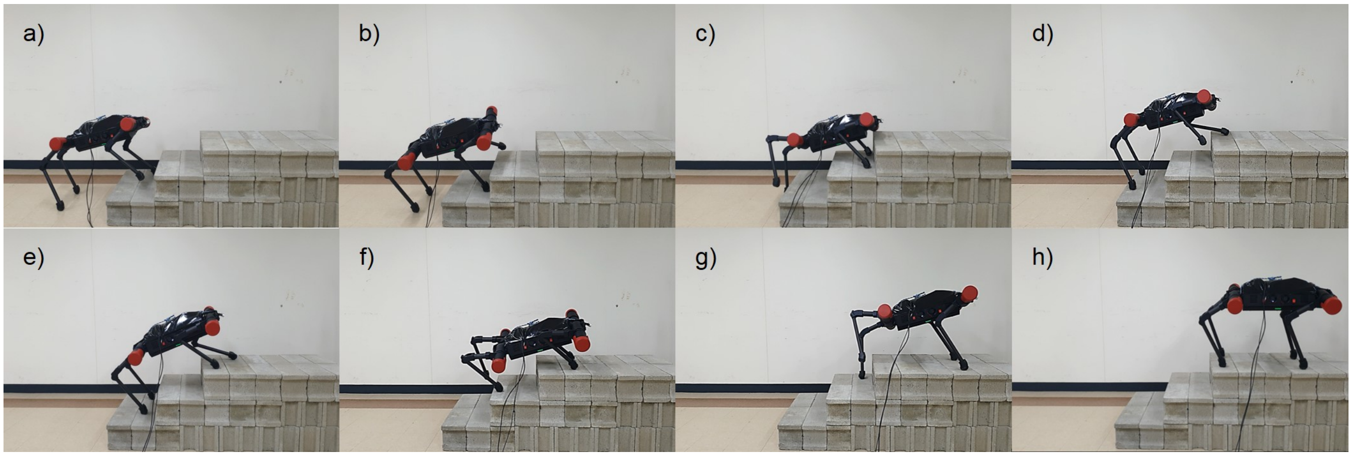

Fig. 5. Snapshots while quadruped robot, AiDIN-VI, are ascending 3-step stairs (height: 21cm, inclination: 26.5°).

it means a plane with largest area is most closed to the robot. Actually two planes are detected by the depth camera but valid footholds are located on a plane of more upper stair only. Among them, one foothold is selected finally at center of area of the valid footholds.

B. Stair Climbing Planner

During swing phase, foot-end position is shifted from initial position to desired foothold acquired in terrain recognizer. In the stair climbing planner, we use Non Uniform Basis Spline (NUBS) curve to generate swing trajectory on the stairs as well as the plane. NUBS curve has several advantages: 1) local modification, 2) tracking velocity control for each domain, and 3) low degree trajectory with a large number of control points, especially, third one is useful to avoid collision with the stairs. Its equation is represented as

$$\mathbf{C}_{sw}(t_{sw}) = \sum_{i=0}^{n} Q_{i,p}(t_{sw}) Z_i \tag{4}$$

where Z_i are control points, $Z_0, Z_1, ..., Z_n$, and $Q_{i,p}(t_{sw})$ are basis functions of degree p according to preset time of swing phase, t_{sw}. There are details in [5]. Designed trajectory is generated at transformed local frame, $\sum L$, which is parallel to global frame, $\sum G$. Desired position during swing phase is expressed as

$$\mathbf{P}_i^{sw} = \mathbf{P}_i^{init} + \mathbf{R}^T \mathbf{C}_{sw}(t_{sw}) \tag{5}$$

where $\mathbf{P}_i^{sw}$ is desired foot-end position during swing phase, $\mathbf{P}_i^{init}$ is initial position just before swing phase. $\mathbf{R} = Rot_z(\alpha^{yaw})Rot_y(\alpha^{pitch})Rot_x(\alpha^{roll})$ denotes the current rotation matrix of the robot body and $\mathbf{R}^T$ is its transpose matrix. At present, since AiDIN-VI has a camera on the front of the robot, finding footholds for hind legs is difficult. Therefore, the swing trajectory for hind legs is depending on kinematic calculation from two front feet and locomotion velocity.

During swing phase, contact is detected at each foot, simple compliance control is utilized to reduce the impact force which is similar in [18] but we implement it in the task coordinate. By errors of parameters related to foot-end, the GRFs can be defined as

$$\mathbf{M}\ddot{\mathbf{p}}_{e,i} + \mathbf{D}\dot{\mathbf{p}}_{e,i} + \mathbf{K}\mathbf{p}_{e,i} = \mathbf{F}_i \tag{6}$$

where $\mathbf{M}$, $\mathbf{D}$, and $\mathbf{K}$ are mass, damping, and stiffness matrices, respectively. Through this model, the velocity to reduce landing force can be calculated as

$$\dot{\mathbf{p}}_{l,i} = \mathbf{M}^{-1} \int (\mathbf{F}_i - \mathbf{D}\dot{\mathbf{p}}_{e,i} - \mathbf{K}\mathbf{p}_{e,i}). \tag{7}$$

Finally, $\dot{\mathbf{p}}_{l,i}$ is converted to positional parameter for use with swing trajectory as a final parameter of stair climbing planner.

C. Whole-Body Controller

Whole-body controller consists of CoM planner and PRY controller. Firstly, in the CoM planner, the robot's CoM trajectory is generated by the direct force-based ZMP. The computed ZMP from Eq. (3) is represented as

$$\mathbf{p}_{ZMP} = \begin{bmatrix} p_{ZMP}^x \\ p_{ZMP}^y \end{bmatrix} = \frac{\sum \mathbf{p}_i^{CoM} \times \mathbf{F}_i}{\sum \mathbf{F}_i} \tag{8}$$

and constraint of the ZMP to always lie in the support polygon is explained as

$$\mathbf{r}_l < \mathbf{p}_{ZMP} - \delta < \mathbf{r}_h \tag{9}$$

where $\mathbf{r}_l$ and $\mathbf{r}_h$ are limitation by space of the support polygon, and δ is offset for stability margin. We used modified preview control to generate the CoM reference trajectory. Implementation of traditional preview control is difficult since the direct force-based ZMP is utilized, not cart-table model [19]. However, previewing term of traditional method is still possible to be used for the direct force-based ZMP. The modified method is expressed as

$$\mathbf{u}(k) = -k_j \sum_{j=0}^{k} \mathbf{e}(j) - \sum_{r=1}^{N_L} G(r)\mathbf{p}_{ZMP,d}(k+r) - \mathbf{f}_c \tag{10}$$

where k_j and $G(r)$ are the gains, $\mathbf{e}(j) = \mathbf{p}_{ZMP}(j) - \mathbf{p}_{ZMP,d}(j)$ is error of the ZMP, N_L is samples future. $\mathbf{f}_c$ is additional term

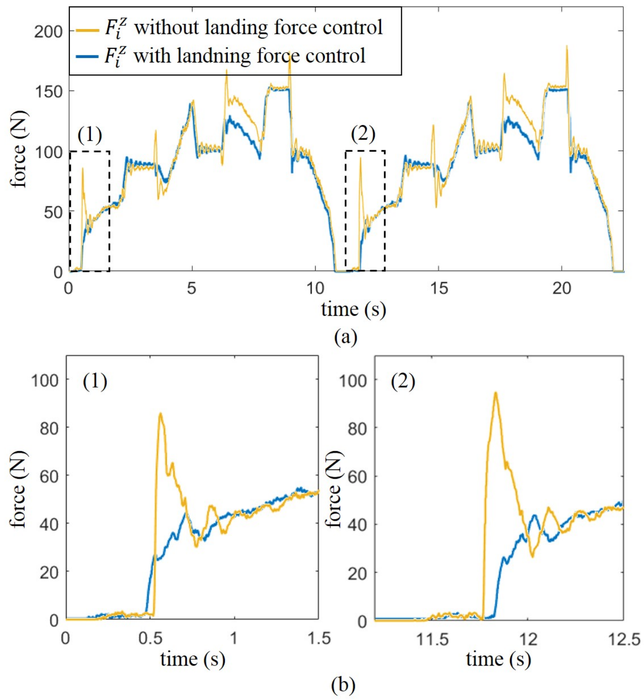

Fig. 6. Vertical force with and without landing force control during (a) two period of stair walking gait and (b) landing.

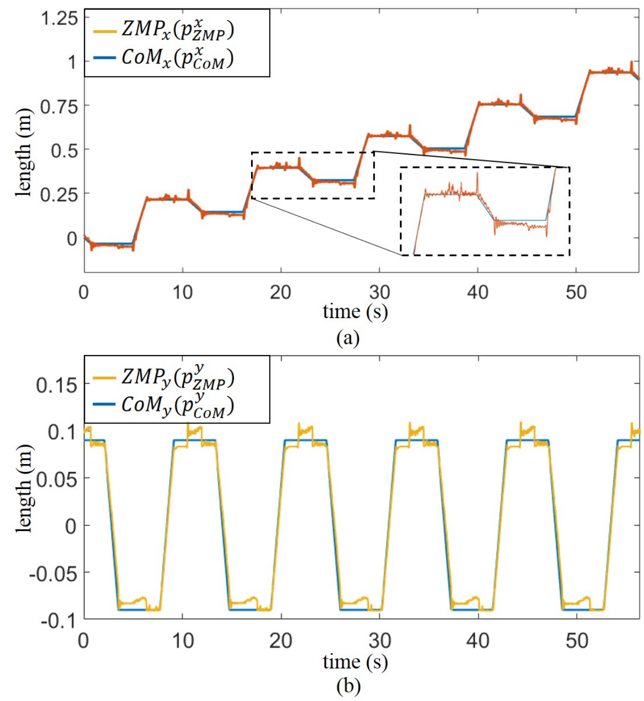

Fig. 7. Actual ZMP calculated by measured torque and CoM position on the (a) x-axis and (b) y-axis.

to decrease distance between the ZMP and CoM preference trajectory. In general, exact control of the ZMP is not performed like as $\mathbf{p}_{ZMP} = \mathbf{p}_{CoM}$. However, minimizing sum of error between $\mathbf{p}_{ZMP}$ and $\mathbf{p}_{CoM}$ causes reducing the rate of change of angular momentum during locomotion on the stairs. In addition, by $\mathbf{f}_c$, motion of the CoM is stopped during three-legged stance for more stable climbing. The reason that implementation of modified preview control with $\mathbf{f}_c$ even trough the CoM trajectory is constrained as a constant during three-legged contacts is for easy transition between stair climbing gait and other dynamic gaits. By removal of $\mathbf{f}_c$, the walking gait can be switched to other gaits simply after end of the stair climbing.

RPY angles of the robot body is adjusted by calculated error as

$$\mathbf{e}_i = (\mathbf{I} - \mathbf{R}^T\mathbf{R}_d)\mathbf{P}_i^{CoM} \tag{11}$$

where I is an identity matrix. The pitch and roll angle of the robot body, θ^{pitch} and θ^{roll}, are controlled to be equally located to estimated inclination of the stairs, θ_s, and close to 0, respectively.

IV. Experiments

To evaluate proposed stair climbing framework, it was implemented to the quadruped robot, AiDIN-IV and 3-step stairs which have 21cm height are set. Fig. 5 shows snapshots of performing stair climbing. In practice, standardized size of the stairs set on real environments is generally smaller than set platform for experimental validation but we believe trying to climb more bigger size‘s one can allow the robot to easily overcome diverse obstacles including stairs in real environment.

Fig. 6(a) show the vertical force with and without landing force control during the two period of stair walking gait. In case of walking without landing force control, there are four peak forces during one period. It means impact forces are generated by touchdown of each leg. Because high ratio reduction gear (50:1) is implemented to each joint of AiDIN-VI, simple position control cannot counteract it. On the contrary, smooth vertical force is represented during walking with landing force control. During landing, the vertical force are compared as shown in Fig. 6(b). Calculated ZMP from Eq.(6) and CoM position are expressed in Fig. 7. We try to perform exact control of the CoM motion closed to the calculated direct force-based ZMP. By this approach, minimizing angular momentum rate change is possible because of $\tau_{ZMP} = 0$ by definition of the ZMP. Actually, we can obtain small angular momentum rate change during locomotion as shown in Fig. 8. Moment of the CoM is calculated as

$$\tau_{CoM} = (\mathbf{p}_{ZMP} - \mathbf{p}_{CoM}) \times \mathbf{F}_i. \tag{12}$$

It is remarkable result compare to other researches which consider the angular momentum rate change during balance-critical tasks [14], [16]. Furthermore, the stair climbing is robustly and stably performed without a great change of the roll and pitch of the CoM as shown in Fig. 9.

V. Conclusions

In this paper, we propose a novel framework for quadrupedal stair climbing, which considers GRFs measured

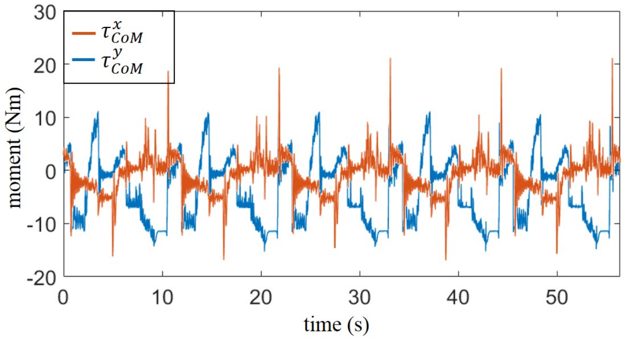

Fig. 8. Calculated moment of the CoM.

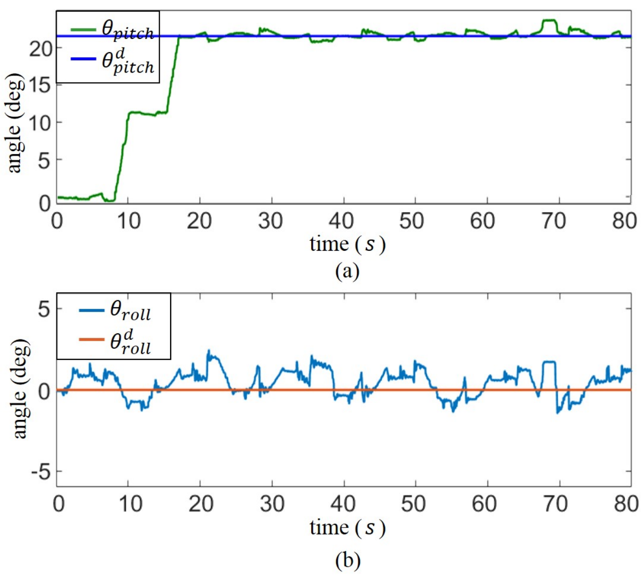

Fig. 9. Desired and actual roll and pitch angle of the robot body.

by torque sensors. Firstly, through intuitive approach with CoM dynamics model, required control methods are proposed for locomotion on the stairs: the direct force-based ZMP method and landing force control. Motion planning of the CoM is performed close to actual ZMP to decrease angular momentum rate change, and the peak force is reduced by landing force control. In addition, geometrical parameters are estimated by vision system. We implemented this framework to quadruped robot, AiDIN-VI, As a result, capability of ascending 3-step stairs which has 21cm height, and it is 31% of robot‘s maximum leg length is validated. As future works, framework for more high-speed climbing and descending on the stairs will be improved.

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