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Trot Gait Based Feed-Forward Walking on Challenging Terrain: Case of High Step Climbing

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***Abstract*— For a quadruped robot, the crawl gait is commonly used on rough terrain environment where a pre-motion planing is required. However its walking speed is slower than other walking gaits and make it difficult to develop a practical legged robot. Among the various types of gaits, we consider that the trot gait is safety gait which can prevent complete falling by hitting its swinging leg on the ground. Therefore in this paper we propose a new feed-forward trot gait algorithm based on 3D sway compensation trajectory which can control footsteps and position of the center of gravity for rough terrain environment. The validity of the proposed algorithm is confirmed by step climbing experiment using a spawling-type quadruped robot TITAN-XIII. As a result, the robot climbed up the step of 120 mm height which is 40% of its height in 3 seconds and proved the feasibility of the trot gait on a difficult terrain.**

Fig. 1. Experimental sprawling-type quadruped robot, TITAN-XIII

I. INTRODUCTION

The most important feature of a quadruped robot is adaptability to rough terrain environment where a conventional wheeled and tracked robot cannot overcome. There are two types of walking strategies, the reactive walking strategy and the planned walking strategy. Generally, the reactive walking strategy is robust to sudden obstacles (good example is performed by StarlETH [1] and BigDog [2]). However, as a drawback it has limited terrain adaptability, e.g. difficult to overcome high steps or halls. Therefore, in the extremely difficult terrain, the planned walking strategy that generates a walking motion based on environmental data is preferable.

As a planned walking strategy, Hirose et al. presented the theoretical control method based on the crawl gait for a quadruped robot [3] in early stages of legged robots development. In real robots, Garcia et al. proposed a compliant adaptive gait based on the crawl gait and shows SILO4 walking on a inclined slope stably [4]. Defense Advanced Research Projects Agency (DARPA) held DARPA Learning Locomotion program. In this program several universities study walking strategy on rough terrain using a common robot platform, LittleDog developed by Boston Dynamics [5], [6], [7]. RoboSimian which participated DARPA Robotics Challenge also shows stable crawl gait on rough terrain using its own vision system [8].

Most of the previously mentioned robots use the crawl gait which always has three-point contact with the ground. The crawl gait is well known as a stable gait, thus it is appropriate for rough terrain walking. However the disadvantage of crawl gait is its slow moving speed due to its three-point contact constraint. Walking speed is a very important factor for making a legged robot useful in the real world. The practical solution for this problem is using both the reactive walking and the planned walking strategies, depending on the terrain difficulty. As a example, HyQ hydraulic quadruped robot succeeded to perform both the planned walking and reactive walking [9]. Even so, actual speed while using the planned walking strategy is still limited and should be improved.

In order to increase the walking speed, the use of the trot gait can be effective. By using the trot gait, the robot can walk much faster than using the crawl gait, considering their minimum duty factor (crawl gait: 0.75, trot gait:0.5). The trot gait is commonly used with the reactive walking strategy and there are few studies using trot gait with the planned walking strategy. One of the few researches is TITAN-VI developed by Yoneda et al. [10]. In their experiment, TITAN-VI stably walked over 105 mm step by using the proposed intermittent trot gait. However, considering the height of TITAN-VI: 1200 mm, the step is not so challenging and the reactive walking strategy can be used. Thus there is no research about a high step climbing by using trot gait to the best of our knowledge.

The purpose of this research is proving feasibility of the trot gait on a rough terrain environment and increase walking speed of a quadruped robot. First, we proposed new trot gait algorithm to maintain balance in difficult terrain based

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on the intermittent trot gait. To verify proposed algorithm, step climbing experiment is conducted by using the TITAN-XIII experimental quadruped robot shown in Fig.1. Finally experiment result and feasibility of the trot gait is discussed.

II. Body Motion Planning

As a walking strategy, we assume a similar walking strategy with the related researches which use the crawl gait[7], [9] as shown in Fig.2. First, a vision system perceives the environment and generates a map to localize the robot's position. Next, by using the given environment map, a possible footstep set is searched. Then appropriate footsteps, body's position and orientation are chosen from a footstep set. Finally by using this information, body motion is generated and joint angle command is sent to the robot. In this paper we focus on the body motion planner that is completely different from the one for a crawl gait.

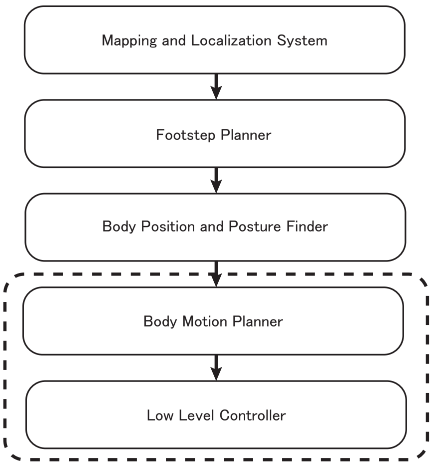


Fig. 2. Strategy for walking on rough terrain. Dashed line indicates our research focus on this paper.

A. Basic Walking Gait

First, we chose the intermittent trot gait [10] as a basic walking gait. The intermittent trot gait is a type of the trot gait where a diagonal leg pair of the robot moves synchronously, and has four-leg supporting phases in one walking cycle (see Fig.3). Because of this four-leg supporting phase, if the walking of the robot disturbed by any error or disturbances, the posture of the robot will be stabilized.

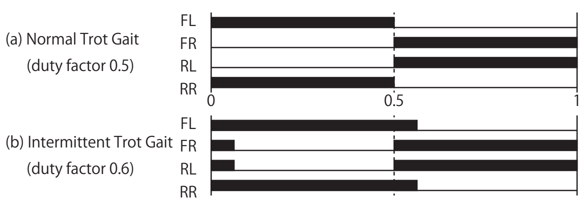


Fig. 3. Gait diagrams of trot gaits, characters indicate foot position as FL:Front Left, FR:Front Right, RL: Rear Left, RR:Rear Right

B. Conventional Sway Compensation Trajectory

In order to prevent falling, the robot has to keep dynamic stability which means keeping the Zero Moment Point (ZMP) on the diagonal supporting line. There are several ways to control the ZMP. In case of animals, they use their tail or arms like a reaction wheel. In this paper, we simply focus on using an acceleration and a deceleration of the body of the robot to control the ZMP, considering the robot as an inverted pendulum around the diagonal supporting line. Based on the idea above, previously Yoneda et al. proposed a control algorithm of the intermittent trot gait (sway compensation trajectory) [10], and Kurazume et al. extended the algorithm as the 3D sway compensation trajectory [11].

In this paper, we modify these sway compensation trajectories to specify positions of center of gravity (CG) at start and end of one step. By specifying CG positions, the range of motion in four-leg phase can be assured.

C. Position Specified Sway Compensation Trajectory

First, we assume that the robot's legs are mass-less, the position of the robot's CG is (x_{cg}, y_{cg}, z_{cg}). Additionally, in this paper we use the supporting leg coordinate to calculate all of the body trajectory. The supporting leg coordinate is defined as the midpoint between the left side foot and the right side foot touching the ground, and its x-axis direction is defined as moving direction given by an operator.

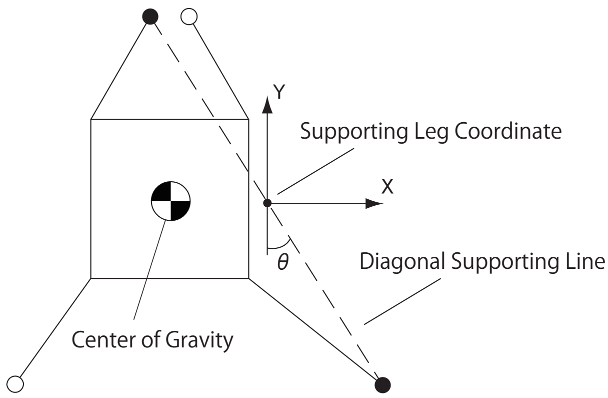


Fig. 4. Suppoting leg coordinate is placed at midpoint of current support feet and its orientation is given as walking direction by an operator

The position of the ZMP (zmp_x, zmp_y) is given by the equations below:

$$\begin{pmatrix} zmp_x \\ zmp_y \end{pmatrix} = \begin{pmatrix} x_{cg} \\ y_{cg} \end{pmatrix} - A \begin{pmatrix} \ddot{x_{cg}} \\ \ddot{y_{cg}} \end{pmatrix}, \qquad (1)$$

$$A = \frac{z_{cg}}{g}. \qquad (2)$$

We also define the diagonal supporting line as follows:

$$cos\theta x + sin\theta y = 0, \qquad (3)$$

where the θ is the angle of the diagonal supporting line from the supporting line coordinate (see Fig.4).

Then, to keep the ZMP on the diagonal supporting line, the position of CG has to fulfill the following equation.

$$cos\theta(x_{cg} - A\ddot{x_{cg}}) + sin\theta(y_{cg} - A\ddot{y_{cg}}) = 0 \tag{4}$$

Next, Eq.4 is decomposed into two equations for the x and y directions, and each solution is assumed to be given as follows:

$$\begin{cases} x_{cg}(t) = C_1^x e^{\frac{t}{\sqrt{A}}} + C_1^x e^{-\frac{t}{\sqrt{A}}} + a_2^x t^2 + a_1^x t + a_t^x \\ y_{cg}(t) = C_1^y e^{\frac{t}{\sqrt{A}}} + C_1^y e^{-\frac{t}{\sqrt{A}}} + a_2^y t^2 + a_1^y t + a_t^y \end{cases} . \tag{5}$$

Additionally, by substituting Eq.5 and second derivatives of Eq.5 into Eq.4, the following equation is derived,

$$\begin{aligned} 0 = a_0^x cos\theta - 2Aa_2^x cos\theta + a_0^y sin\theta - 2Aa_2^y sin\theta \\ + (a_1^x cos\theta + a_1^y sin\theta)t + (a_2^x cos\theta + a_2^y sin\theta)t^2. \end{aligned} \tag{6}$$

To fulfill Eq.6 regardless of variable t, the following equations are derived.

$$\begin{cases} a_2^x cos\theta + a_2^y sin\theta = 0 \\ a_1^x cos\theta + a_1^y sin\theta = 0 \\ 0 = a_0^x cos\theta - 2Aa_2^x cos\theta + a_0^y sin\theta - 2Aa_2^y sin\theta \end{cases} \tag{7}$$

Finally, by substituting following boundary conditions, Eq.5 is solved with two parameters a_1^x, a_2^x.

$$\begin{cases} x_{cg,t=0} = x_0 \\ x_{cg,t=T} = x_1 \\ y_{cg,t=0} = y_0 \\ y_{cg,t=T} = y_1 \\ \hat{\mathbf{v}}_{t=T} \cdot \hat{\mathbf{dir}} = 1 \end{cases} \tag{8}$$

Here, T is the period of one step, (x_0, y_0) is the initial position of CG, (x_1, y_1) is the position at T. $\hat{\mathbf{v}}_{t=T}$ is the unit vector of body velocity at T and $\hat{\mathbf{dir}}$ is the unit vector of the moving direction of the next step.

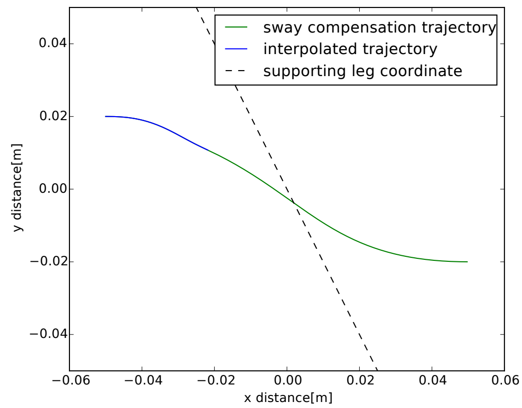
In the end, Eq.5 are solved analytically by using Mathematica Since the whole solution is too extensive to be shown here, it has been omitted.

Even when the end position of CG in current step and the start position of CG in next step is the same, each velocity and acceleration are not identical. In order to compensate this velocity and acceleration difference, we interpolate the two trajectories smoothly by using extended Ferguson-coons curve (Eq.9) in four-leg supporting phase ($0 < t < t_4$).

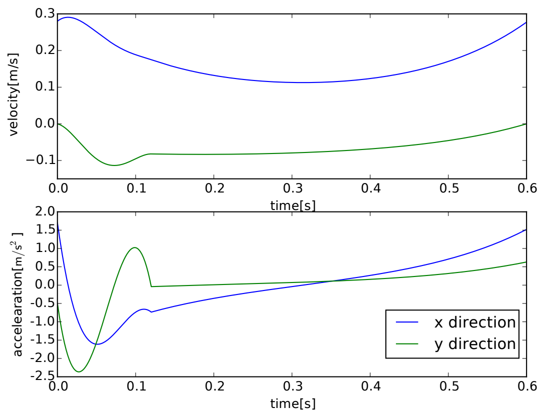
$$P(t) = \begin{pmatrix} (\frac{t}{t_4})^5 \\ (\frac{t}{t_4})^4 \\ (\frac{t}{t_4})^3 \\ (\frac{t}{t_4})^2 \\ \frac{t}{t_4} \\ 1 \end{pmatrix}^T \cdot \begin{pmatrix} -6 & 6 & -3 & -3 & -\frac{1}{2} & \frac{1}{2} \\ 15 & -15 & 8 & 7 & \frac{3}{2} & -1 \\ -10 & 10 & -6 & -4 & -\frac{3}{2} & \frac{1}{2} \\ 0 & 0 & 0 & 0 & \frac{1}{2} & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} P_0 \\ P_1 \\ \dot{P}_0 t_4 \\ \dot{P}_1 t_4 \\ \ddot{P}_0 t_4^2 \\ \ddot{P}_1 t_4^2 \end{pmatrix}, \tag{9}$$

where P_0 is the end position in previous step and P_1 is the end position of four-leg supporting phase in the current trajectory.

Example of the generated trajectory in continuous walking is shown in Fig.5. As shown in Fig.5(a), the generated trajectory is connected between the two specified points (-0.05, 0.02) and (0.05, -0.02), which is assumed as the end point of previous trajectory and the end point of current trajectory respectively . Since the dutyfactor is 0.6 and the period is 0.6 s, in one step period, from 0 to 0.12 s the interpolated trajectory is used, and from 0.12 to 0.6 s the position specified sway compensation trajectory is used.. In Fig.5(b), the velocity is connected smoothly. In case of the acceleration, although it is continuously connected, it cannot be differentiated at the switching point.



(a) Body position trajectory



(b) Velocity and acceleration trajectory

Fig. 5. Generated body position, velocity and acceleration trajectory with the following parameters: T (period):0.6 s, dutyfactor:0.6, z_{cg} (height of CG):0.2 m, θ:30 deg, a_1^x: 0.57, a_2^x: -0.004

III. STEP CLIMBING EXPERIMENT

In order to prove the feasibility of the proposed algorithm, we conducted an experiment by using the experimental sprawling-type quadruped robot, TITAN-XIII [12] (Fig.1, Table.I). The whole experiment was conducted with an on-board LiFePO4 battery.

TABLE I
SPECIFICATION OF TITAN-XIII

Characteristic	Value
Size (L x W x H)	220 x 550 x 345 mm
Weight(w/o battery)	5.3 kg
Weight(with battery)	5.65 kg
Max. walking velocity	1.36 m/s
Battery	LiFe 26.4V 1100mAh
Battery run time	approx. 20 min.

The experiment setup is shown in Fig.6. A simple wooden step, which is composed of stacked 12 mm wood plates, is chosen as the experimental terrain. The robot's body position and posture are measured by a motion capture system: OptiTrack Flex13, but the data was not used for controlling the robot. The height and position of the step and the initial robot's position are assumed to be known. The footsteps and the body position at each walking step are given heuristically as shown in Fig.7. The edge of the wooden step is located at 0.0 m in x direction and indicated by dashed line in Fig. 7. The target height of the footsteps on the step is defined as step height + 5 mm considering the tilting of the body while walking and the descending of the body after shifting from four-leg supporting phase to two-leg supporting phase. The robot's front legs are located at a distance of 60 mm from the edge of the step. Through the experiment, the duty ratio and one step period are 0.6 and 0.4 respectively and the step height was increased from 48 mm by 12 mm.

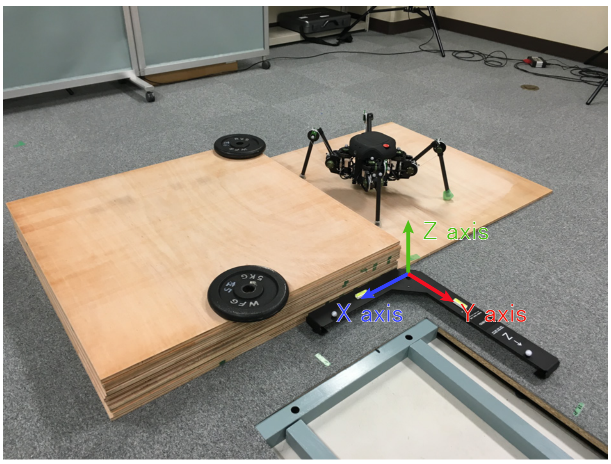


Fig. 6. Overview of experiment setup: The floor and the step are made of wood. The body position and orientation of the robot were measured by a passive optical type motion capture system.

We carried out the experiment and the robot successfully climbed up a step of 120 mm height as shown in Fig. 8. Fig.9 and Fig.10 show the x-y plot and x-z plot of the body position for the 120 mm step climbing experiment. As shown in Fig.9, the final reaching point of the body position differs from the planned body position especially for y-axis, which is as big as 0.105 m. On the other hand, in z-axis movement

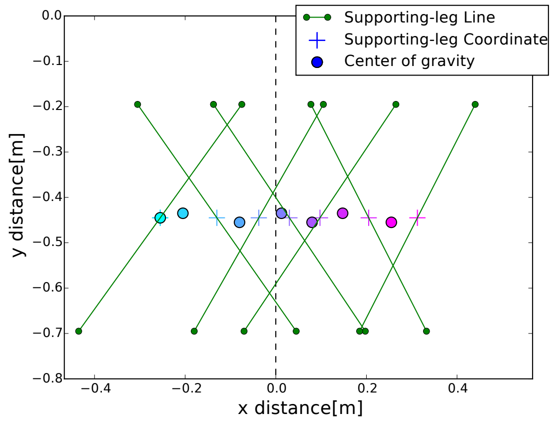


Fig. 7. Planned foot step for climbing up step. Green line shows diagonal supporting line and its tip of circle markers indicate footsteps. The circle marker shows the center of gravity of the robot. The plus markers indicate position of the supporting leg coordinate. The color of the marker changes from blue to purple along to the execution time.

a large error did not measured and its mean error is around 0.025 m as shown in Fig.10. We considered that the error in y-axis is not related to the step height, because in 48 mm step climbing experiment, the error is almost the same as 0.095 m. The main reason of this error is the yaw rotation which gradually increased while step climbing as shown in Fig.11. Carefully looking into the video, several slippages were observed while climbing. During the second step, when the FR foot is on the step and the RL foot is on the ground (both legs are a supporting leg), they slipped and bounced. However in the third step, only the FL foot slipped on the step, resulting in a yawing motion. In proposed algorithm, the maximum friction force which robot can receive, does not considered. Therefore at some moment the required friction force may overcome the actual friction force and it caused the slippage. Another reason for this slippages is thought to be the elasticity of the step caused by slight bending of the top wooden plate. Because of this elasticity, the foot on the step receives some extent of elastic force from the step and is accelerated upward. As a result, along with reducing the normal component of the ground reaction force, the friction force also decreased and caused slippage.

Pitching and rolling motion are also observed. Especially the pitching motion is increased up to $\pm 10deg$. However as we expected, the swinging legs hit the ground and the step, and prevented complete falling.

IV. DISCUSSION

By using proposed algorithm based on the trot gait, the robot can climb up a step of 120 mm height, which is about 40% of the robot's height.

What restricts the maximum climbable step is the z-axis velocity of the swinging leg. If one step walking period is able to be prolonged, the z-axis velocity of the swinging leg will not be a problem. However with the current algorithm, the period was set as 0.6 s (relatively short), otherwise the

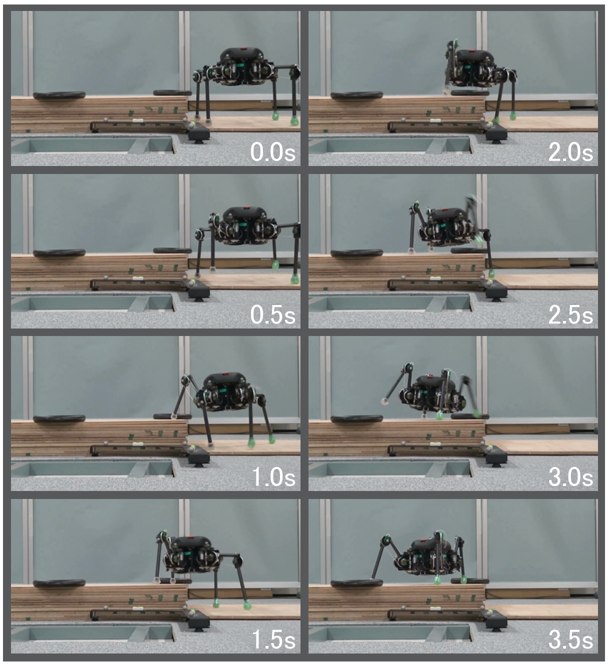


Fig. 8. Sequence of climbing up a 120 mm step climbing experiment.

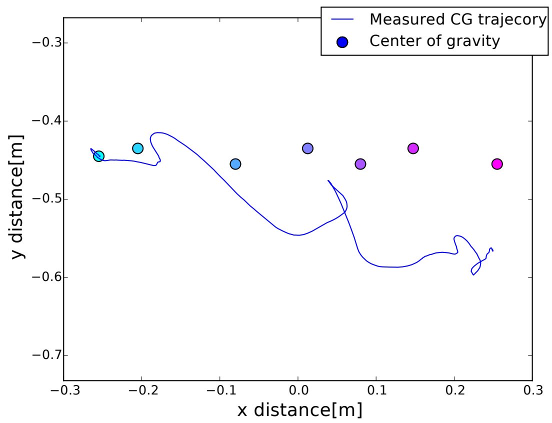


Fig. 9. x-y body motion trajectory while climbing up a step of 120 mm height. Circle markers indicate planned position of center of gravity.

robot will fail to climb a step because of over-tilting. Even though the proposed algorithm tries to keep the ZMP on the diagonal supporting line, there exists a modeling error, joint controller error and mechanical problems, and these errors cause tilting. Therefore, it is difficult to prolong the walking period.

Another solution is having a diagonal supporting polygon rather than the diagonal supporting line, which means having a sole and active ankle. One example of a quadruped robot which has active ankles is TITAN-XII [13]. TITAN-XII has 2 degree of freedom active ankle joint and succeeded to climb up 560 mm height of step(which is around 85% of its height) with crawl gait by using these extra diagonal supporting polygons. However equipping a such active ankle on a tip of

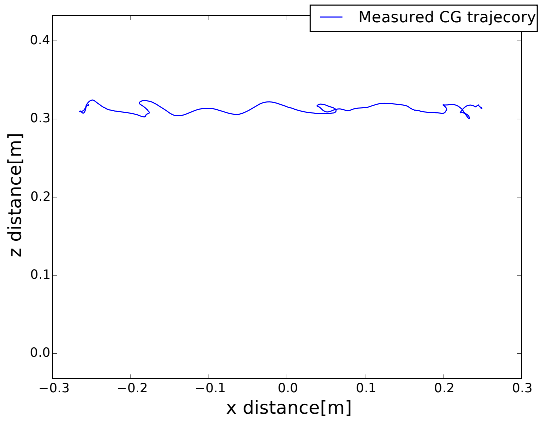


Fig. 10. x-z body motion trajectory while climbing up a step of 120 mm height

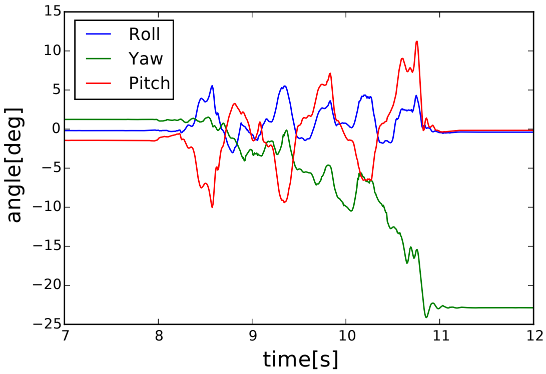


Fig. 11. Roll-Pitch-Yaw body angle while climbing up a step of 120 mm height.

legs will increase inertia of the legs greatly, and in case of executing the trot gait, light inertia of the leg is essential.

Although development of light active ankle is important, as a current practical walking strategy for a challenging terrain, both crawling and trotting gaits should be selected according to the difficulty of the terrain. As we discussed above the obstacle's height can be one criterion of terrain difficulty, but also the stability criterion such as the directional normalized energy stability margin (DNESM) [14] would be a better criterion.

V. CONCLUSIONS

In this paper we proposed to use the trot gait on rough terrain environment where pre-motion planning is required. To achieve this, a new walking algorithm based on the intermittent trot gait which can specify footstep and position of center of gravity at four-legged support phase is developed. In the experiment, step climbing is chosen as a difficult terrain As a result, by using the proposed algorithm, the robot climbed up a step of 120 mm height in 3 seconds. While climbing, the robot tilted around 10 degrees on the pitch axis, but still did not fall completely. Although the stability is lower than crawl gait, trot gait also can be effective for high step climbing, especially in terms of increasing walking speed. Practically, both crawling and trotting gaits should be used according to the difficulty of terrain. As a future work we will conduct walking experiment on more complex and difficult terrain by using proposed algorithm.

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