2012 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 7-12, 2012. Vilamoura, Algarve, Portugal

Impedance Control of Quadruped Robot and Its Impedance Characteristic Modulation for Trotting on Irregular Terrain

Jaehwan Park[1] and Jong Hyeon Park[2]

***Abstract*— Trotting on irregular terrain is a difficult task as undesirable impulse force by collision between robot foot and an obstacle makes the robot unstable. To cope with the problem, in this paper, variable impedance control algorithm changing leg impedance parameters according to the change of finite trot states is proposed. The state of quadruped trot is divided into five phases and the impedance parameters are changed to generate adequate response to the contact force in each locomotion phase. Simulation of trotting on irregular terrain with half-ellipsoidal trajectory has been performed with the control groups. The simulation has verified that the proposed control method shows outstanding performance and better stability for trotting on the highly irregular terrain.**

I. INTRODUCTION

Among a number of animal-like robots being developed at this moment, some quadruped robots are showing possibility of realizing practical robot. Big Dog is a representative quadruped robot that can walk on irregular terrain with heavy duty load [1]. Since quadruped robot is more stable then biped robot and is faster than six-legged robot, it is regarded as a good solution of the trade-off problem between stability and mobility of the legged robots.

Quadruped animal has many walking patterns and each of them shows different performance on a specific walking condition. Schematically, types of straight-driving locomotion of quadruped can be classified into walking, trotting, and galloping. Among them, trotting is a middle-speed locomotion, which is 5–10 km/h speed of a dog. When a dog trots, diagonal feet are placed in pairs at the same time. The first quadruped robot which has ability of trot was developed by MIT Leg Laboratory. Raibert used a pair of virtual-hopping legs for modeling quadruped locomotion [2]. In his research, a finite state machine is used to control different leg situations, which can be divided into stance and flight phase. Meanwhile, instead of using a finite state machine, simple and continuous control algorithm with ellipsoidal foot trajectory was proposed by Kim [3] and the consequent simulation done by Chae [4] proved effectiveness of genetic algorithm for optimizing ellipsoidal trajectory of quadruped robot galloping.

It has been an issue for the walking robots to control both desired leg force and position. Controlling both requirements is not an easy task as one of them is an input and the other one is output for the conventional controllers. For manipulators, setting impedance characteristic of force and position between a robot and the environment was introduced [5]–[7]. Impedance control made it easy to arrange interaction characteristic of a manipulator by simplifying behavior of robot end effector into 2nd-order system, which are mass, spring and damper. Adjusting impedance characteristic of a robot arm to satisfy varying task requirement was proposed by Ikeura [8]. He proposed variable impedance control, which can select optimized interaction characteristic in a specific operating environment. Recently, reinforcement learning algorithm was implemented to the variable impedance control by Buchli [9].

Impedance characteristic of a high-mobility robot leg is very important as the behavior of a fast-running animal leg can be characterized by a spring. The spring characteristic of a leg plays an important role for saving energy and reducing impulse force generated by high-speed leg contact. In other words, a leg should have compliance to contact force and it can be modeled as a spring inverted pendulum. In the former research on biped robots in [10], it was shown that impedance control is superior to position-oriented control methods in impact regulation during foot landing and adaptation to some ground irregularity.

In this paper, variable impedance control of quadruped robot trot is proposed and simulations to certify the advantage of the proposed method have been processed. At first, a half-ellipsoidal foot trajectory is proposed. Then, trot is finitely divided into number of phases. Impedance modulation method according to the states are proposed in the following section and the effect of variable impedance control is verified by the simulations with the control groups.

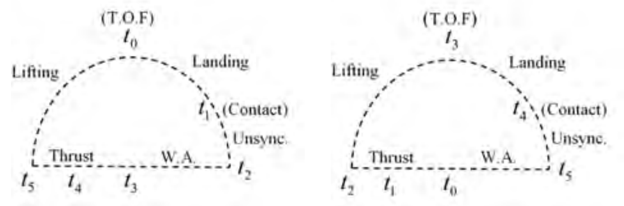
II. HALF-ELLIPSOIDAL FOOT TRAJECTORY

Basically, desired trajectory of a quadruped robot foot with respect to the robot body is a half-ellipsoid. It is desirable for trot as a robot can move forward consistently without changing body height. A pair of supporting legs and flight legs move the same path with time phase difference, which is a half of the walking period T. The displacement of foots with respect to the center points of the foot trajectory are

$$\bar{p}_{fore,left} = \bar{p}_{hind,right} = \begin{cases} \begin{bmatrix} x(t) & 0 & z(t) \end{bmatrix}^T & \text{if } nT \le t < (n+0.5)T \\ \begin{bmatrix} x(t) & 0 & 0 \end{bmatrix}^T & \text{if } (n+0.5)T \le t < (n+1)T \end{cases} \tag{1}$$

[1]Jaehwan Park, Department of Mechanical Engineering, Hanyang University, Seoul, Korea. (Email: jaehwanv@gmail.com)

[2]Jong Hyeon Park (the Corresponding Author), Department of Mechanical Engineering, Hanyang University, Seoul, Korea. (Email: jongpark@hanyang.ac.kr)



(a) Phases of leg pair1 (FL, HR) (b) Phases of leg pair2 (FR, HL)

Fig. 1: Finite states along the foot trajectory

TABLE I: Finite states of quadruped trot

	t_5-t_0	t_0-t_1	t_1-t_2	t_2-t_3	t_3-t_4	t_4-t_5
FL	Lift	Landing	Unsync.	W.A.	Thrust	Thrust
FR	W.A.[a]	Thrust	Thrust	Lift	Landing	Unsync.
HL	W.A.	Thrust	Thrust	Lift	Landing	Unsync.
HR	Lift	Landing	Unsync.	W.A.	Thrust	Thrust

[a] Weight acceptance

$$\bar{p}_{fore,right} = \bar{p}_{hind,left} = \begin{cases} \begin{bmatrix} x\left(t+0.5T\right) & 0 & 0 \end{bmatrix}^T & \text{if } nT \le t < \left(n+0.5\right)T \\ \begin{bmatrix} x\left(t+0.5T\right) & 0 & z\left(t+0.5T\right) \end{bmatrix}^T & \text{if } \left(n+0.5\right)T \le t < \left(n+1\right)T \end{cases}, \tag{2}$$

where the number of steps is n.

The equations of the ellipsoid are

$$x\left(t\right) = \frac{l_{step}}{4}\cos\left(\frac{2\pi}{T}t\right) \tag{3}$$

$$z\left(t\right) = h_{step}\sin\left(\frac{2\pi}{T}t\right), \tag{4}$$

where l_{step} is length of a foot step and h_{step} is height of the foot flight.

Since the half-ellipsoidal trajectory is a 2D trajectory on the x-z plane, lateral motion of legs cannot be generated. Yawing motion of the robot can be controlled by adjusting step length of inner leg and outer leg of a turning curve. The step length of left foot and right foot should be changed by yawing error of the body.

$$l_{step,l} = l_{step} + K\left(\theta_{yaw} - \theta_{yaw,d}\right) \tag{5a}$$

$$l_{step,r} = l_{step} - K\left(\theta_{yaw} - \theta_{yaw,d}\right), \tag{5b}$$

where θ_{yaw} is yaw angle of the robot body with respect to the ground, $\theta_{yaw,d}$ is desired yaw angle, and K is rate of turning.

III. FINITE TROT PHASES

Fig. 1a and Fig. 1b shows location of five phases along the trajectory and Table I shows time division of phases in each leg. Leg lifting and landing phases are the states where a pair of feet are on the air. In the leg lifting phase, legs take off the ground heading toward the top of the flight position. During the landing phase, the foot heads toward the ground and contact occurs when one foot hits the ground in advance to the other foot. In those states before the contact, no ground contact force affects robot locomotion. On the other hand, unsynchronized, weight acceptance, and thrust phases are the states where ground contact forces affect the robot body. These three phases are important for controlling body stability and momentum.

Unsynchronized phase is the state when one foot hits the ground though a pair of feet should contact the ground at the same time. In this state, large impulse force is generated by collision between the foot and the ground. This is critical for the robot on the ground where terrain irregularity is high. For example, impact by collision of the robot and an obstacle can push the robot backward and increase undesirable body angular momentum.

During the weight acceptance phase, the robot settles down to the steady-state, where the robot body momentum is eliminated excepting the linear momentum heading forward the robot path. In this state, robot position should be statically stable to keep body angular momentum from being changed by the large moment generated by the external forces.

Thrust phase is the kinetic energy generating state. Existence of flight phase should be reflected on when the amount of the kinetic energy is determined. Thrust force is also important when a robot trots on irregular ground where a slope makes robot slip on the surface. Moreover, in this situation, large normal force should be generated to increase the friction force between the foot and the ground.

TABLE II: Main issue in each state

Phase	Issue
Unsynchronized	Impulse force reduction
Weight Acceptance	Balancing on irregular terrain
Thrust	Generating thrust force

Table II is summery of the issues mentioned above. To resolve the listed problems, both position and force control are necessary. However, this research introduces practically effective and simple way, which can be realized with the least number of sensors and position controlled actuators. The detailed method is introduced in the next section.

IV. VARIABLE IMPDEANCE CONTROL OF QUADRUPED ROBOT TROT

Each leg of the robot is designed as linear combination of mass, spring, and damper, which has characteristic of a simplified linear 2nd order system. In the impedance controlled legs, as the steady-state of the system without load is the desired trajectory, the compliance of the leg shows 2nd order system characteristic. As shown in the block diagram Fig. 2, input of the impedance controller is force $\bar{f}$ and output is compliance $\bar{\delta}$. In other words, the controller is an

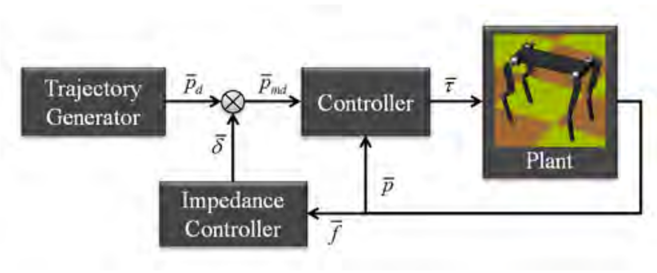


Fig. 2: Impedance control block diagram

admittance controller.

$$\ddot{\bar{\delta}} = \frac{1}{M_i}\left(\bar{f} - B_i\dot{\bar{\delta}} - K_i\bar{\delta}\right) \tag{6}$$

M_i, B_i, and K_i are the impedance parameters of the ith state. After integrating $\ddot{\bar{\delta}}$ twice, $\bar{\delta}$ is added to the desired trajectory $\bar{p}_d$. Then, the modified trajectory, the steady state of the system with load, is

$$\bar{p}_{mod} = \bar{p}_d + \bar{\delta}. \tag{7}$$

The impedance modulator changes impedance parameters by the phases, which are defined finitely in the previous section. When the robot is set on the ground with four legs, default values of impedance parameters are

$$K_0 = \frac{mg}{2\delta_{z,o}} \tag{8}$$

$$M_0 = \frac{K_0}{(2\omega)^2} \tag{9}$$

$$B_0 = 2\sqrt{M_0 K_0}, \tag{10}$$

where $\delta_{z,0}$ is the target steady-state compliance of the leg in z-coordinate and m is total weight of the robot. Steady-state compliance is the steady-state response of compliance when a leg contacts the ground. The stiffness is defined supposing the situation that two legs support the body and mass is defined to make the system have the same natural frequency as the supporting phase frequency, which is double of the walking frequency ω. Damping parameter is set as the critical damping ratio, so that the robot can reduce the overshoot of the response.

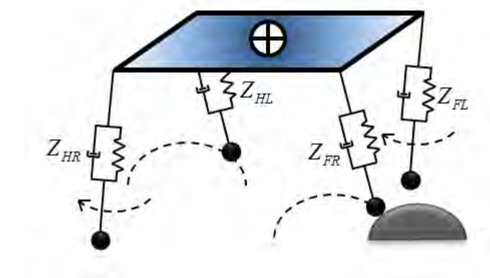
A. Impdeance Modulation for an Unsynchronized Foot

When a leg touches irregular ground without synchronizing with the pair leg as shown in Fig. 3a, unexpected impulse force makes the robot body unstable. To minimize the influence of the contact force to the body, low-stiffness impedance parameters are set for the unsynchronized contact leg as shown below.

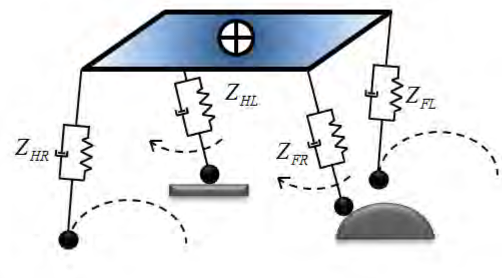
$$K_1 = A_1\frac{mg}{2\delta_{z,o}} \tag{11}$$

$$M_1 = \frac{k_i}{\omega^2} \tag{12}$$

$$B_1 = 2\sqrt{M_1 K_1} \tag{13}$$



(a) Unsynchronized foot



(b) Weight acceptance

Fig. 3: Leg impedance model and contact situations on irregular terrain

To reduce stiffness of the leg, a gain A_1, smaller than 1, is multiplied to the default stiffness. When ground irregularity is high, this state can occur several times. To minimize the effect of short responses, mass is also modulated to have the system show slow natural frequency response, which is half of the trot frequency. The system is set as a critically damped system to reduce overshoot of the response, which makes the system vibrate.

B. Impdeance Modulation for Weight Acceptance

In the weight acceptance phase, the response of the robot leg compliance sets to the steady-state and it is largely influenced by the static stability of the robot. On the irregular terrain, altitude irregularity can make robot unstable. To cope with this problem, steady state compliance of the pair of feet should be set differently, so that the robot can be stably supported as shown in Fig. 3b.

The altitude difference can be estimated by measuring orientation information of the body and foot displacement from the body center. The offset of steady state between foreleg and hind leg is

$$\delta_{z,off} = \begin{bmatrix} 0 & 0 & 0.5 \end{bmatrix} \cdot \left({}^L_B R \cdot \bar{p}_f - {}^L_B R \cdot \bar{p}_h\right), \tag{14}$$

where ${}^L_B R$ is rotation matrix of robot body orientation and $\bar{p}_f$, $\bar{p}_r$are displacement of the foreleg and hind leg with respect to the body center. The stiffness parameters of foreleg and hind leg are defined as below.

$$K_{2,f} = \frac{mg}{2\left(\delta_{z,o} - \delta_{z,off}\right)} \tag{15}$$

$$K_{2,h} = \frac{mg}{2\left(\delta_{z,o} + \delta_{z,off}\right)} \tag{16}$$

To keep stiffness from diverging as $\delta_z \simeq \delta_{z,off}$, a certain limitation of the stiffness should be set. The rest of the parameters are set to have the same natural frequency as the supporting phase frequency and set to show critically damped response.

$$M_{2,f} = \frac{K_{2,f}}{(2\omega)^2} \tag{17}$$

$$M_{2,h} = \frac{K_{2,h}}{(2\omega)^2} \tag{18}$$

$$B_{2,f} = 2\sqrt{M_{2,f}K_{2,f}} \tag{19}$$

$$B_{2,h} = 2\sqrt{M_{2,h}K_{2,h}} \tag{20}$$

C. Impdeance Modulation for Thrust

In this state, robot thrust force can be decided by existence of the flight phase. Thrust force is also important when a robot trots on irregular ground where a slope makes robot slip on the surface. The amount of potential energy and contact force can be changed by modulating the stiffness. Modulation of stiffness in the thrust phase is

$$K_{3,f} = \frac{A_2 mg}{2\left(\delta_{z,o} - \delta_{z,off}\right)} \tag{21}$$

$$K_{3,h} = \frac{A_2 mg}{2\left(\delta_{z,o} + \delta_{z,off}\right)}, \tag{22}$$

where $A_2$is a gain, which is larger than 1, for generating thrust energy. The rest of the parameters are set to have the same natural frequency as the supporting phase frequency and set to show critically damped response.

V. SIMULATION

A. Dynamics Model

The simulation is processed by a dynamics simulator with a 3D animation engine and by the control logic simulator Simulink. The numerical calculation time of each sampling step is set as 1 ms. Ground contact model of the simulation is an nonlinear spring-damper model. Contact force is calculated by an equation of penetration between two contact objects and the equation is

$$f_c = K_c {\delta_p}^{1.2} + B_c \frac{\dot{\delta}_p}{\left|\dot{\delta}_p\right|} \dot{\delta}_p {\delta_p}^2, \tag{23}$$

where δ_p is penetration depth, K_c is a spring property and B_c is a damping property. K_c is set as 2000 kN/m and B_c is set as $1\,\mathrm{kN \cdot s/m^3}$ as the response of the model is similar to the impact of a rubber attached to the robot foot and a wooden ground.

In the friction model of this simulation, friction coefficient is a haversine formula of relative speed between the contact objects. Static threshold speed v_s is set as 0.1 m/s and static threshold speed v_d is set as 0.15 m/s. In this simulation, assuming the material of the robot foot is rubber, high friction coefficients are set. Dynamic friction coefficient μ_s is set as 0.6 and static friction coefficient μ_d is set as 0.9.

When it comes to the robot model, size of the robot is 0.5 m height, 0.35 m width and 0.6 m length. Weight of the robot is 24 kg including weight of frames, actuators and controllers.

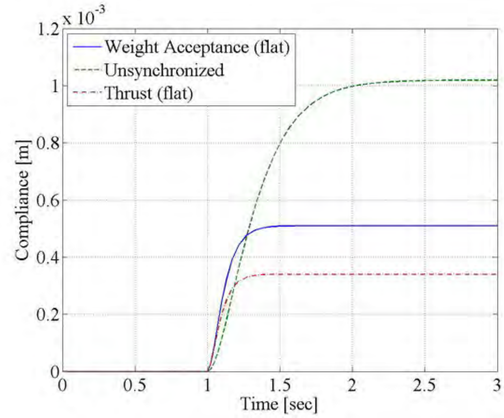


Fig. 4: 1 N step response of leg compliance in each phase

TABLE III: Parameter settings for the simulations

	l_{step}	h_{step}	$\delta_{z,o}$	h_{body}	A_1	A_2
Without Impedance	0.1734 m	0.1 m	-	0.45 m	-	-
Fixed Impedance	0.2 m	0.16 m	0.06 m	0.45 m	1	1
Variable Impedance	0.2 m	0.16 m	0.06 m	0.45 m	0.5	1.5

B. Control Parameter Settings

This simulation aims to simulate mid-speed trot on irregular terrain. Thus, the simulation is processed on the ground, where the height of the cylindrically modeled obstacles are 2.5 cm. Step length of the robot l_{step} is 0.1 m and frequency of trot is 1.3 Hz. Therefore, the desired forward speed of the robot is 0.94 km/h, which is mid-speed considering size of the robot.

To verify the benefit of the variable impedance control algorithm, two control groups are simulated with the same simulation model. One is the simulation without impedance control and the other one is the simulation with fixed impedance control. The fixed impedance control does not change impedance parameters and fix the parameters as the default values. Since impedance controller adds compliance to foot trajectory, the step height $h_{step,imp}$ and step length $l_{step,red}$ of simulation with impedance control should be modulated as shown below $h_{step,o}$.

$$h_{step,imp} = h_{step,o} + \delta_{z,o} \tag{24}$$

$$l_{step,red} = l_{step} \frac{h_{body} - \delta_{z,o}}{h_{body}}, \tag{25}$$

where h_{body} is height of the robot body.

Trajectory parameters of different simulations are summarized in the Table III. Fig. 4 shows step response of each impedance on the flat surface. The response of the unsynchronized foot shows the slowest response and has the largest compliance. All the step responses are critically damped, which has no overshoot.

C. Simulation Result: Trot on highly irregular terrain

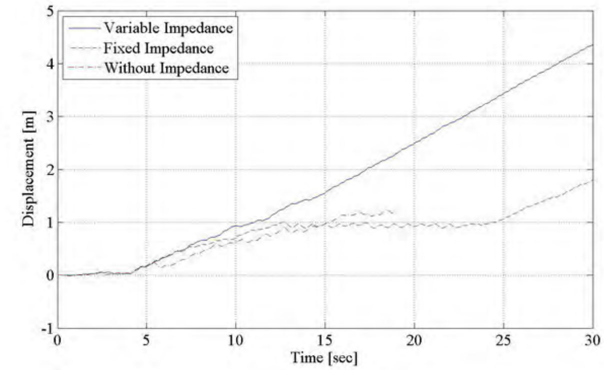
The simulation was operated on the terrain with 2.5 cm height irregularity. At the beginning of the simulation, the robot makes the initial pose. After then, the robot starts trotting on the irregular zone whose distance is 1 m. The robot walks on the flat terrain after passing through the irregular area.

As shown in Fig. 5a and Fig. 8, variable impedance control has shown the best speed performance. In the simulation with variable impedance control, during the time from 4 s to 15 s, when the robot passes through the irregular terrain, the robot was able to keep going ahead though trot speed has decreased little bit by the disturbances from the obstacles. On the other hand, in the simulation with fixed impedance control, when the robot passes through the irregular terrain, during the time from 4 s to 25 s, the robot was stuck between the obstacles for 12 seconds. The problem has been brought about by an unsynchronized foot and lack of thrust force. The robot was pushed backward by the contact impulse force between the unsynchronized foot and an obstacle and slip was occurred on the sloped surface because of the lack of the normal force thrusting the body. The trot of the robot without impedance control was the most unstable. Finally, it was collapsed on the irregular terrain at 18 s.

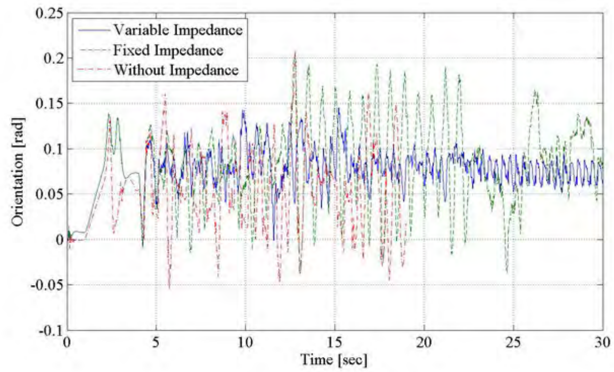
In regard to stability, pitching, rolling, and yawing of the variable impedance control robot is the smallest on the irregular terrain as shown in Fig. 5b–5d. Fig. 6 and Fig. 7 shows the original trajectory and the modified trajectory by impedance controller. Variable impedance controller has made more moderate trajectory than that of fixed impedance controller. This shows variable impedance controller is more feasible than fixed impedance controller for trotting on the terrain with high irregularity.

VI. CONCLUSION AND FUTURE WORK

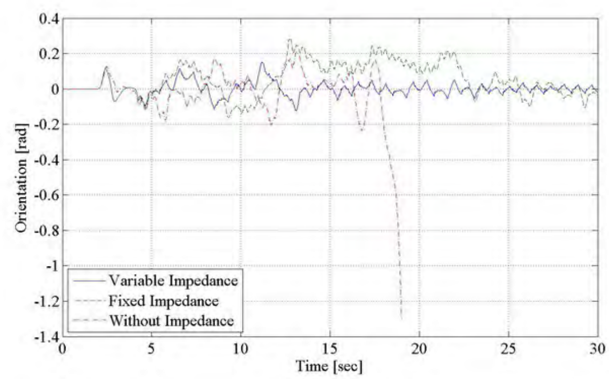
In this research, variable impedance control method for quadruped robot trot has been proposed and simulations to verify the merit of the proposed method has been processed. Impedance parameters of robot leg can be derived by the heuristic knowledge based on the characteristic of 2nd order



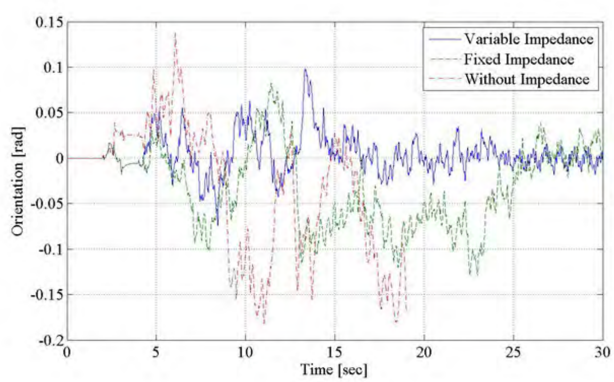
(a) Forward displacement



(b) Body pitching



(c) Body rolling



(d) Body yawing

Fig. 5: Simulation Data

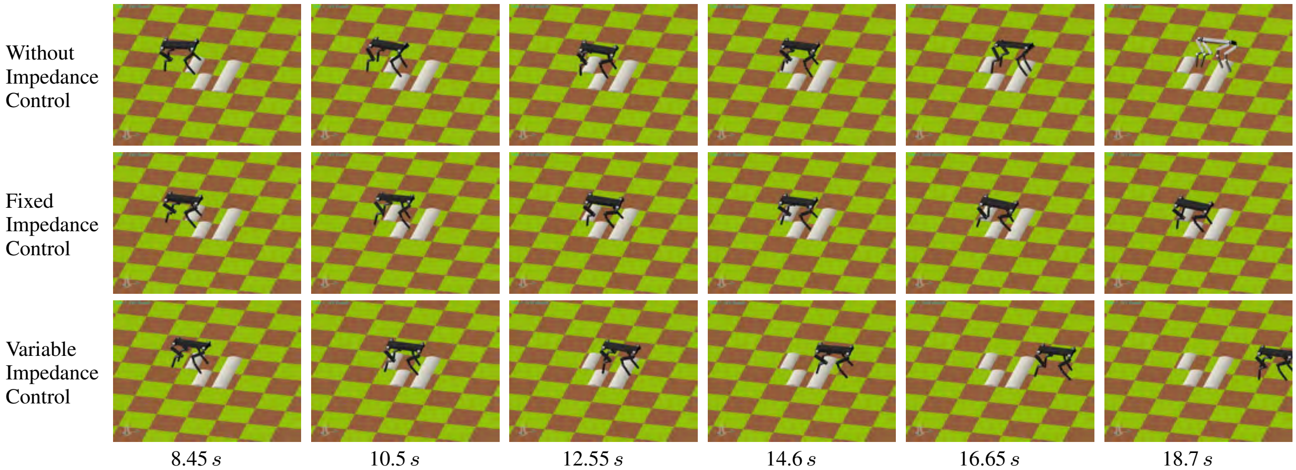
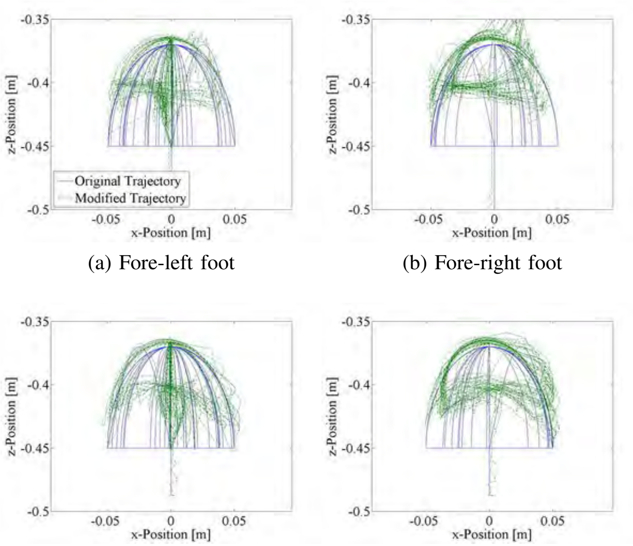


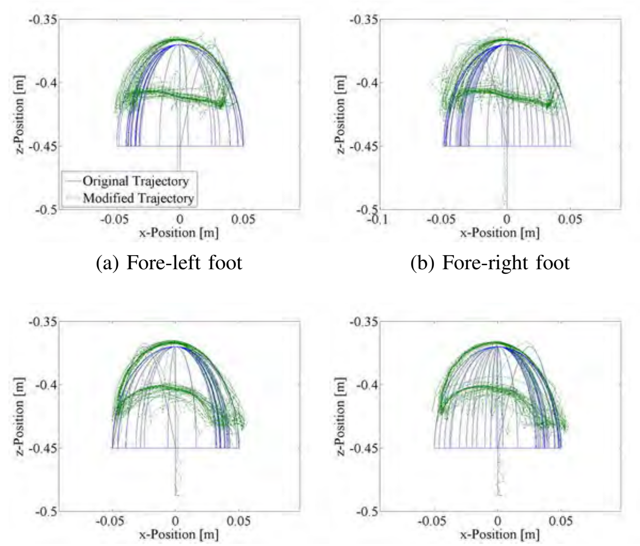
Fig. 8: Animation of trot sumulations



(a) Fore-left foot (b) Fore-right foot

(c) Hind-left foot (d) Hind-right foot

Fig. 6: Foot trajectory of simulation with fixed impedance



(a) Fore-left foot (b) Fore-right foot

(c) Hind-left foot (d) Hind-right foot

Fig. 7: Foot trajectory of simulation with variable impedance

system. Variable impedance control changing impedance parameters according to the change of finite states of quadruped trot has shown better performance and stability than fixed impedance control in trotting on irregular terrain.

In the future, to show the algorithm is practically useful, hardware experiment should be performed. Moreover, optimization should be processed to find the best impedance parameters in each trot phase.

REFERENCES

[1] R. R. Playter, M. Buehler, and M. H. Raibert, "BigDog," in *Proceedings of SPIE*, vol. 6230, 2006, pp. 62 302O–1–62 302O–6.

[2] M. H. Raibert, M. Chepponis, and H. B. Brown Jr., "Running on Four Legs As Though They Were One," *IEEE Journal of Robotics and Automation*, vol. 2, no. 2, pp. 70–82, 1986.

[3] K. Y. Kim, O. Kwon, J. S. Yeon, and J. H. Park, "Elliptic Trajectory Generation for Galloping Quadruped Robots," in *Proceedings of IEEE International Conference on Robotics and Biomimetics*, 2006, pp. 103–108.

[4] G. J. Chae and J. H. Park, "Galloping Trajectory Optimization and Control for Quadruped Robot Using Genetic Algorithm," in *Proceedings of IEEE International Conference on Robotics and Biomimetics*, 2007, pp. 1166–1171.

[5] N. Hogan, "Impedance Control: An Approach to Manipulation: Part I-Theory," *Journal of Dynamic Systems, Measurement, and Control*, vol. 107, no. 1, pp. 1–7, 1985.

[6] ——, "Impedance Control: An Approach to Manipulation: Part II-Implementation," *Journal of Dynamic Systems, Measurement, and Control*, vol. 107, no. 1, pp. 8–16, 1985.

[7] ——, "Impedance Control: An Approach to Manipulation: Part III-Applications," *Journal of Dynamic Systems, Measurement, and Control*, vol. 107, no. 1, pp. 17–24, 1985.

[8] R. Ikeura and H. Inooka, "Variable Impedance Control of a Robot for Cooperation with a Human," in *Proceedings of IEEE International Conference on Robotics and Automation*, vol. 3, 1995, pp. 3097–3102.

[9] J. Buchli, F. Stulp, E. Theodorou, and S. Schaal, "Learning Variable Impedance Control," *International Journal of Robotics Research*, vol. 30, no. 7, pp. 820–833, 2011.

[10] J. H. Park, "Impedance Control for Biped Robot Locomotion," *IEEE Transactions on Robotics and Automation*, vol. 17, no. 6, pp. 870–882, 2001.