**Review 1**

Major Contribution of the Paper:

This study divide it into high level controller and low level controller. Because they want to deal with the reactive balance and full body inverse dynamics control problem. And they want to react the robot robust.

Organization and Style:

Very good.

Technical Accuracy:

The formulas are difficult, so I cannot understand them correctly, but I can understand them in detail about the expressions.

Presentation:

I think you have a good presentation skill. But when presenting, it would be better to look at the audience rather than just looking at the professor.

Adequacy of Citations (List possible additions if needed):

**Review 2**

Major Contribution of the Paper:

- The controller is divided into two, and the robot is proposed to maintain the posture in any situation. The high-level controller sets the drift compensation, and the low-level controller sets the motion tracking and joint torque. The two controllers are appropriately coordinated to derive robust attitudes of the robot. It describes how each controller solves the problem with an algorithm and can be confirmed in the video.

- In the introduction section, the wheeled robots and UAV have some limitations due to irregular terrain and obstacles and the climate problem and energy charge. So, this paper suggested the legged robot is a better solution. In terms of sustainability, UAV is considered to be inefficient, and I agree, but in a disaster situation where no obstacles or terrain may exist, I think UAV which is flying freely in the air is more efficient than a wheeled or legged robot moving in contact with the ground. Therefore, it seems that it is necessary to use a suitable robot according to the disaster situation, and the walking robot will not be the best in all situations.

Answer: We consent to the point that a legged robot is not suited for all the disaster situations. Yet, we emphasized in the paper that the legged robot is a better choice than the other in case of the robot has to interact directly with its surroundings in tandem with human counterparts. For instance, in a case that a robot is required to perform manipulation tasks such as opening/closing a door, picking up a fire hose and securely attaching it to a pipe, and so on. Since a UAV has limited payload capabilities and energy autonomy, it is difficult to attach a manipulator on it to perform manipulation tasks as mentioned earlier. (Since a UAV can fly fast around and can capture the terrain information from up top very quickly and efficiently, we can use a UAV and a legged robot to perform collaborative surveillance and inspection tasks utilizing their different abilities to create a bigger framework.)

Organization and Style:

- It is judged to have achieved good research process and results with fewer team members than other teams.

Technical Accuracy:

- It is assumed that the z-direction is constant when the CoM moves based on the ZMP in the high-level controller. It is expected to move in the arc shape by the pendulum movement. When applied to an actual robot, the difference is expected depending on the length of the leg and the angle of the movement.

Answer: Linear Inverted Pendulum Model is a simplified model that consists of CoM with a constant height, ZMP, and a massless telescopic leg between them. Since we used this model to construct our high-level controller, the desired motion of the z-component of CoM will be a constant value in order to make the dynamics of the robot behave like a LIPM model. And the low-level controller outputs a set of optimal torque command for each of the actuated joint to control the height of CoM remain in a constant value.

- Figure 3 and 4 show drift without correction and vice versa. This result seems to be a good way to solve the drift. However, the “CoM- y” graph (red line) in Fig. 4 shows that the error is about 0.01 m from the median. Since the size of the robot is not specified, it isn’t known whether this error is a large or small.

Answer: The size and inertial information of the robot we used in the simulation can be seen in the table 1. We can know that the error (about 0.01m) is about 6.25% of the base width (0.16m) of the robot. We can further reduce the magnitude of the error by increasing the gain of the controller for CoM drift compensation.

Table 1. Specifications of quadruped robot

|  |  |  |  |
| --- | --- | --- | --- |
| Link Mass | Value [kg] | Link Dimension | Value [m] |
| Base | 34 | Base (x, y, z) | (0.4, 0.16, 0.08) |
| Upper-Leg | 1.6 | Upper-Leg | 0.25 |
| Lower-Leg | 0.2 | Lower-Leg | 0.22 |

- In Figure 6, does the bended slope and maximum height of the Z-axis graph (Yellow line) match the slope and height of the actual simulation?

Answer: Yes, it is.

- There is no indication of the degree of inclination of the slope used in the simulation. It would be better to give information about topography of obstacle. Also, conducting simulations in various angles and bends (irregular shapes) is needed. Thus, it would be necessary to simulate about ability for passing through the specific obstacles.

Answer: The slope of the terrain used in the simulation was 18 degrees and we will specify the slope of the terrain in the paper. To verify the performance of the proposed controller, we will conduct an experiment that a quadruped robot walks across an uneven terrain consists of irregular shapes.

Presentation:

- This team presented about their introduction, contribution point, solution and results well. However, because of it’s complexity, it is hard to present all of the contents of this study in a short time, it would be difficult to understand people who are not engaged in this field.

Answer: Due to the paper count limit, we wasn’t able to present detailed contents thoroughly. But we will try to make the content of the final presentation as understandable as possible for whom are not engaged in the legged robotic field can understand our controller framework.

Adequacy of Citations (List possible additions if needed):

- This paper cited the necessary content to suit the flow. And plagiarism will also not be occur a problem.

Additional:

- In case of hardware research, the result of simulation and application to actual robot could be different. Therefore, it is recommended to apply actual test to applied robot in future research.

Answer: As you mentioned, there is a big gap between a simulation and a real world implementation due to the modelling error, state estimation error, and sensor noises. Although each of the mentioned difficulty is a field of research itself, we will do research on them and combine our controller to overcome the difficulties mentioned above and to work well on a real robot.

- In this paper, only the information about CoM is presented. It is expected that there will be a relationship (link structure, length, weight, etc.) with connected part constituting the leg of the robot in actuality.

Answer: The process of the controller is as follows:

1. User specify the desired CoM velocity of the robot in Cartesian/Euclidian space.
2. High-level controller takes as input, and recalculate the compensating the drift of the CoM. By using the dynamics of LIPM, high-level controller outputs the next step position of the swing leg (the leg in the air) towards the direction while maintaining its body balance if there exists disturbance.
3. Low-level controller takes all the desired motion including the swing leg, stance leg, position and velocity of CoM expressed in Cartesian space as input. By using the full-body inverse dynamics, which uses all the robot joint and link information including the state of the joint, link mass, link inertia, link length to calculate the , , and , and outputs a set of optimal torque commands considering the dynamic and kinematic constraints to track the desired motions specified by the user.

So all the relationship (link structure, length, weight) with connected part constituting the leg of the robot are considered in low-level controller.

**Review 3**

Major Contribution of the Paper:

In this paper, authors suggest a control logic to reliably control the quadruped locomotion robot under without-map situations. Especially, they have implemented QP along contact-force based low level controller to efficiently and robustly estimate the optimal output torque. And also for high level controller, the authors have implemented a Linear Inverted Pendulum Model to alter the fixed based models, which yields a more simplified and linear control.

Organization and Style:

The authors suggest that their method could provide high compliancy, reactiveness, and energy efficiency. However, in the results and conclusion, the aimed goal is barely mentioned. Since this is an engineering paper, the form of suggesting the main goal in introduction, and proving it in the conclusion will more easily read by the reviewers.

Answer: We will verify all the features via a set of experiments in the remaining time, and will include the results in the paper.

Technical Accuracy:

The LIPM assumes CoM as in the end point of the rig. However, the overall system is quadruped robot, and CoM does not locate itself on the end of the pendulum but somewhere else. We can model the robot leg as an inverted pendulum in 2d as the assumption itself is valid, but proper reasoning to prove the validity of modeling should be presented for more feasible explanation.

Answer: Linear Inverted Pendulum Model is a simplified model that consists of CoM with a constant height, ZMP, and a massless telescopic leg between them. Since we used this model to construct our high-level controller, the desired motion of the z-component of CoM will be a constant value in order to make the dynamics of the robot behave like a LIPM model. And the low-level controller outputs a set of optimal torque command for each of the actuated joint to control the height of CoM remain in a constant value.

Since the mass of each leg is much smaller than that of base of the robot (about 1/10), we can sufficiently approximate the whole robot as a Linear Inverted Pendulum Model in 3d.

Presentation:

The presentation focuses on explaining the logic and control details of the robot, which was logical and straightforward. However, in my opinion, the presentation should show the improvements done over the prior control logics and systems in other papers. More comparison over prior researches and performance of achievements on the main goal, which is to control body over challenging terrain, should be demonstrated more specifically.

Answer: We consent to aforementioned points. We will compare the performance of the proposed controller with prior researches.

Adequacy of Citations (List possible additions if needed):

Fast, Robust Quadruped Locomotion over Challenging Terrain, Mrinal K, 2010 ICRA should be presented as a comparison of performance, since the paper aims for the same goal.

Answers: We will read this paper carefully, and will examine whether or not can compare the results fairly with it.