Towards an Efficient Running Quadruped that Handles Slopes

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I. MOTIVATION

Humans and animals have incredible motion capabilities in terms of speed, energy efficiency and transversing capabilities of environments with rough terrain, extreme slopes, and obstacles, such as off-road and mountainous areas, earthquake ruins, volcanoes, or even cities and complex building interiors. These capabilities are due mainly because of their legged locomotion system that allows them to use discrete footprints to handle discontinuities. Also, they change the stiffness of their muscles and the distance between their CoM and the ground to preserve their desired motion in an efficient way despite ground inclination and obstacles. In addition, humans and animals are able to perform a dynamically stable motion in order to achieve higher speeds.

We seek to extend our understanding of the dynamics of straight-ahead running on sloping ground, and hence to integrate such capabilities into the NTUA Quadruped, aiming at an increase in its performance in handling terrains with positive or negative slope. It is expected that these capabilities will enhance the locomotion qualities of autonomous legged robots handling real-life challenges.

II. STATE OF THE ART

A number of approaches aiming at quadruped robots capable of sloping ground locomotion have been presented up to date. To name a few, a normalized energy stability criterion has been presented in [1] and used as a tool to design the “intermittent crawl gait”. A gait planning to generate appropriate trajectories of the body to handle concave and convex slopes has been proposed in [2]. These approaches realize static walking with high stability and steep slope handling, but with low speed.

A controller based on the Central Pattern Generator (CPG) that alters its active phase based on sensory feedback was developed in [3] and used to make a quadruped robot walk dynamically on irregular terrain, but without having success in handling slopes. In [4], it was discussed how the limb length affects joint torque requirements when a gorilla-like robot is walking on a slope. Divergence between simulation results and experimental values were caused due to slip negligence.

Boston Dynamics’ BigDog has performed well in open-field experiments in rough, sloped terrain with its forward speed to be controllable using four hydraulic actuators for each leg [5]. Although it moves with static stable gaits, it can achieve a dynamically balanced trot gait when moving at human walking speeds. A decomposed control architecture was presented in [6] for fast quadruped locomotion over rough terrain. Although the controller achieved to guide the robot through unknown terrain with obstacles and discontinuities, the speed was rather low due to static stable motion while the ground was level in general.

A novel energy transfer mechanism (ETM), presented in [7], ensures the proper regulation of energy transfer between the unactuated and actuated degrees of freedom for a running quadruped robot with only one actuator per leg. The controller was able to handle slopes up to 20^{o}, both uphill and downhill. In simulations of a detailed three-dimensional robot model, uncompressed length and spring stiffness for both rear and front legs were considered fixed and even. The ground inclination was constant.

III. OWN APPROACH

In our current work, we investigate the influence of leg length and spring stiffness over the overall motion characteristics and study the actuator torque requirements of a quadruped robot running with dynamically stable gaits on sloped ground. To this end, simulations have been performed for different slopes and initial experiments have been conducted with the physical prototype performing pronking and bounding gaits with the desired characteristics at level ground.

The NTUA Quadruped has legs with springs and only one actuator per each hip joint. The total mass of the robot is 11 kg, including motors, gearboxes, sensors, electronics, batteries and onboard computer. All robot design parameters have been selected following a systematic methodology and are optimal according to specific criteria.

At first, simulations were performed with the robot’s design parameters constant on sloping ground of inclination -10^o to 10^o. The robot is left to fall from 0.35 m initial height and with 0.4 m/s initial forward speed, while the controller achieves and maintains the desired motion characteristics that include a forward speed of 1.1 m/s and an apex height of 0.325 m. Results prove that when inclination is approximately -5^o the torque requirement is kept to a minimum and is increased both for -10^o and 10^o. Also, torque variation, especially in transient state, is grater while inclination is increased.

Next, simulations were conducted using different values of uncompressed leg length between 0,26 to 0,31 m while initial and desired conditions remain as before. Again, ground inclination was between -10^o to 10^o. Although torque requirements are greater with shorter legs, their distance from the ground is also greater at the desired apex height. A robot the size and weight of the NTUA Quadruped with uncompressed leg length of 0.29 m can achieve dynamically stable gait at the speed of 1.1 m/s on ground with inclination between -10^o to 10^o, while its legs are at least 0.035m above the ground with maximum torque requirement of 6 Nm.

Finally, simulations were conducted using different values of leg stiffness with values between 1500 to 4500 N/m. Results have shown that as leg springs become stiffer, torque requirements increase. However, the use of softer springs leads to larger variations of robot's body pitch angle, especially when inclination is around -10^o or 10^o. The NTUA Quadruped can achieve a stable gait with the desired characteristics on sloping ground while keeping pitch angle at a minimum with maximum torque requirement of 6 Nm.

Initial experiments with the NTUA Quadruped were conducted on level ground. Pronking and bounding gaits were realized and captured by a high-speed camera running at 500 Hz. Evaluation of captured frames and data from robot's sensors (full quadrature encoders and a 6 DoF inertial measurement unit) verify that the desired values tend to be achieved. Further experiments will be conducted on a new treadmill capable of inclinations above 15^o. Also, a PhaseSpace MoCap system will be used for more accurate evaluation of robot's motion characteristics.

IV. Discussion Outline

Key questions that emerge during the design of legged robots that can handle slopes include:

1. Which is the ideal uncompressed leg length?
2. Which is the ideal leg stiffness or compliance?
3. How these two design parameters affect a robot's ability to handle slopes?
4. Which values of these parameters minimize actuator torque requirements?

At Dynamic Walking 2011, we will present latest results and conclusions towards answering these questions. Overall, no single ideal value for every terrain exists, but instead a region can be identified that provides self-stabilizing characteristics against external perturbations, such as leg-slopped ground interactions and motor control. Using the multipart controller in [7], the forward speed and apex height, are maintained constant. Results show that larger leg lengths lead to smaller torque requirements; however the distance from the ground becomes smaller and hence, large leg lengths are more appropriate to level terrains without vertical obstacles. On the other hand, when vertical obstacles or slopes are detected, e.g. using onboard optical sensors, the uncompressed leg lengths are decreased so that collisions that can start a tip-over are avoided, with the result of requiring higher torques to maintain the desired motion. Similarly, legs can have variable compliance with a range defined by values appropriate for level ground and low torque requirements, and by those that keep the pitch angle almost zero. It is expected that the results of this work will contribute towards allowing legged robots transverse rough environments, expanding their usage in areas unreachable by wheeled robots.

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