ECCOMAS Thematic Conference on Multibody Dynamics
June 29 - July 2, 2015, Barcelona, Catalonia, Spain

Towards an Enhanced Controller for Slope Climbing

Athanasios S. Mastrogeorgiou[*], **Evangelos G. Papadopoulos**[#]

[*] School of Mechanical Engineering
National Technical University of Athens
Heroon Polytechniou 9,
15780 Zografou, Greece
amast@mail.ntua.gr

[#] School of Mechanical Engineering
National Technical University of Athens
Heroon Polytechniou 9,
15780 Zografou, Greece
egpapado@central.ntua.gr

ABSTRACT

This paper presents simulation results obtained with a 3D model of the NTUA quadruped robot in the Webots simulation environment during slope climbing. Initially, the robot is controlled to perform pronking on level ground in order to validate the simulation environment. Gradually, the inclination is increased and simulations are conducted to discover the maximum value of positive slope the quadruped can cope with. Finally, disturbances are introduced and it is shown that the robot's forward deceleration mainly depends on the front leg touchdown angles.

Keywords: quadruped, control, event driven, slope.

1 INTRODUCTION

In recent years, there has been an increasing interest in legged robots. A great deal of research for moving quadrupeds on uneven terrains, utilising observations of animals, has been carried out with significant results [1], [2]. Quadruped robot locomotion is a difficult task due to the high system complexity and the rough environment. In addition, critical stability issues emerge when considering multibody systems such as quadruped robots. Legged robots have complex dynamics and many degrees of freedom that must be well orchestrated for achieving a robust and dynamically stable locomotion pattern. Handling positive or negative slopes enhances the locomotion qualities of legged robots, but demands more from its actuation system. However, higher torque requirements have an adverse impact on a robot's total mass, due to the need for bigger motors, which also require bigger batteries.

Legged robots have an advantage in dealing with various terrain types, or in handling terrain discontinuities with the use of accurate foot placement. Such systems have hybrid dynamics that are described by different sets of differential equations, according to the phase at which the robot is in (flight phase, double stance phase, etc.). Up to now, enhanced controllers, e.g. by means of computer vision [3], have been implemented for trotting on rough terrain. However, legged robots are difficult to control and as a result, they are subject to dangerous tipover instabilities.

Tipover prevention criteria have been introduced aiming at prevention of dangerous situations for mobile manipulator systems [4]. The most influential tipover stability measures are based on two criteria; the robot's centre of mass (CM) and the support polygon defined by the convex area spanned between the ground contact points. The zero-moment point (ZMP) [5], originally derived for stabilizing bipedal robots, defines a point on the ground where the moment of total external forces (inertial plus gravity force) becomes zero. The Force-Angle algorithm measures stability by the angle of the total force applied to the centre of mass. The angles are referenced to the convex support polygon derived from the outer ground contact points of the robot. Building on this idea, Moosavian and Alipour proposed the Moment Height Stability (MHS) measure [6]. These criteria take into account tipover or rollover when operating over uneven terrain, and/or when exerting large forces or moments [7]. In past research, these tipover criteria have been validated in real-world scenarios [8].

In our current work, we investigate stability issues of quadruped robots on positive slopes subject to various disturbances. For this purpose, a 3D quadruped robot model has been implemented in Webots 8 [9] and the equations of motion of a simpler passive 2D model have been calculated analytically. The Webots model is equipped with the necessary sensors (gyros, accelerometers, force sensors, laser range finder etc.) for state estimation and accurate phase triggering. The control algorithm uses sensor measurements to calculate the necessary torque and touchdown leg angles for stable pronking. Initially, the robot is controlled to perform pronking on level ground. Gradually, the inclination is increased. The quadruped's performance is validated to be similar to [10]. We analyse how stable dynamic running can be performed as terrain morphology changes, how the quadruped's gaits can be rearranged in order to carry out these tasks, and what makes a gait more persistent to disturbances compared to alternative ones.

In this work, we seek to enhance the controller in various ways by answering the previously stated questions. We examine the different support situations for quadrupeds. Firstly, during the double stance phase, the legs are in contact with the ground and form a support polygon. Experiments with the NTUA quadruped show that, during dynamic running, tipover may occur when the robot rotates around the (front) left toe – right toe axis (or back left and right toes respectively). In this case, we seek solutions in which the total force acting on the CoM is pointing towards the side of the robot with a leg about to contact the ground. Overall, no single approach for every terrain or inclination exists, but instead stable running also depends on friction constraints between the tow and the ground as well as on ground compliance.

Simulations will be performed for level ground and for a maximum slope of 20°. In the conducted experiments the quadruped model in Webots 8, performed pronking or bounding using a controller previously developed [11]. With this controller, forward velocity on lift-off and apex height, are maintained within desired limits, (Figure 4). In these simulations, by enhancing the controller with the use of events when a disturbance is sensed we show that the quadruped is able to cope with a sudden increase in the forward velocity and dangerous tipovers do not occur.

2 SIMMULATION SETUP

A 3D model of the NTUA quadruped was created in Webots 8 Simulation Environment, see Figure 1. The simulation setup can be seen in Figure 2.

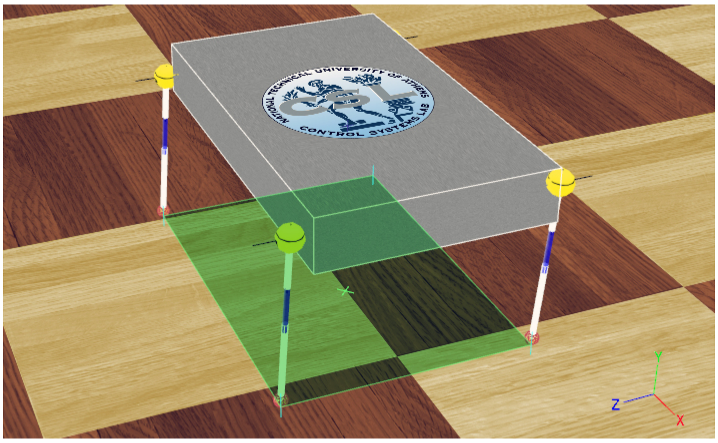

Figure 1: The 3D model of the NTUA quadruped in Webots 8 Simulation Environment during dynamic running. The legs are compliant and the projection of the body's CoM is within the robot's support polygon. Pronking on a 20° slope has been achieved.

A control algorithm previously presented in [11] has been extended in order to be connected to the Robot Model in Webots. A Physics plugin for Webots 8 was created so that the controller could communicate with the Open Dynamics Engine [12]. During the flight phase, the Matlab controller calculated the touchdown angles for the front and rear legs and the torque to be applied by the hip servos during the next stance phase in order to maintain the desired apex height and forward velocity.

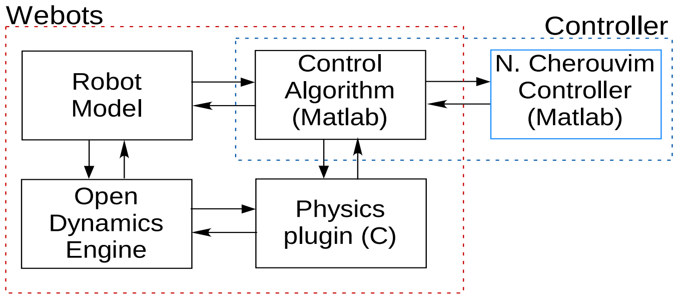

Figure 2: High Level flowchart of the Webots Simulation.

2.1 Description of the controller

The small footprint and the control on the apex height are important for transversal of rough terrain since overcoming sudden obstacles such as rocks or handle discontinuities requires the foot to maintain a specific clearance from the ground. Thus, the MP controller [13] tries to maintain a passive gait with desired characteristics by applying proper actuation to compensate for energy losses. This approach results in minimum energy consumption, but requires an estimation of the leg compliance and system losses.

On liftoff the controller calculates a touchdown angle to achieve the desired apex height, and applies a constant torque during stance to achieve the desired forward velocity. As a result, the touchdown angle γ_{td} to achieve a desired apex height is calculated as a function of the robot's state at lift off [14]:

$$\gamma_{td} = f_1\left(\overbrace{\mathrm{m,k,L,d,I,b,g}}^{\text{robot parameters}},\ \underbrace{\dot{x}_{des},\ h_{des}}_{\text{gait parameters}}\right) \tag{1}$$

where $\dot{x}_{des}$ and h_{des} are respectively the desired forward velocity and apex height. During the flight phase, a simple proportional derivative (PD) controller is used to position rear (b) and front (f) legs at the desired touchdown angles. The control torque applied by the actuator is then,

$$\tau_{b/f} = k_p \cdot \left(\gamma_{td,b/f} - \gamma_{b/f}\right) - k_d \cdot \dot{\gamma}_{b/f} \tag{2}$$

where k_p and k_d are controller gains. The values of k_p and k_d are selected in the Webots simulation in order for the controller to be both fast enough to change the leg angle during the flight phase, while avoiding overshooting and unwanted oscillations. The necessary control torque (τ_s) that must be applied during the stance phase, is also calculated at lift off as a function of the robot's state:

$$\tau_s = f_2\left(\overbrace{\mathrm{m,k,L,d,I,b,g}}^{\text{robot parameters}},\ \dot{x}_{des},\ h_{des},\ \gamma_{td}\right) \tag{3}$$

2.2 The Webots 3D model

The Webots 8 simulation environment was used to create a detailed model of the NTUA quadruped (Figure 3 & 6). The model consists of the main body, containing the electronics and the sensors needed for the controller, and four identical legs consisting of five individual parts that can be seen in Figure 3. The body can rotate at an angle (θ) around the z-axis of its CoM. The rotation servo allows positioning of the legs at angle (γ) at the sagittal plane. Each leg has a passive prismatic joint modelled as a linear compression spring of constant (k) and viscous dumping coefficient (b). The prismatic joint allows changes of the front or rear legs length ($l_{b/f}$) and energy accumulation during locomotion. Table 1 summarizes model and motion parameters. It should be noted that front and rear legs are modelled to have the same uncompressed length (l_0), spring constant k and viscous damping coefficient b. The model parameters have been selected such as to obtain similar results to [10].

Table 1: Nomenclature

Symbol	Description	Webots / Real model Value	2D model Value
(x, y, z)	CoM coordinates	-	-
θ	body pitch angle	-	-
b	as index: back leg	-	-
f	as index: front leg	-	-
γ_b, γ_f	leg absolute angle	-	-
φ_f, φ_b	leg relative angle	-	-
l_f, l_b	current leg length	-	-
$x_{body} \cdot y_{body} \cdot z_{body}$	robot body dimensions	$0.6m \cdot 0.8m \cdot 0.35m$	$0.6m \cdot 0.8m$
K_b, K_f	leg spring stiffness	3400 N/m	$6800\, N/m$
b	viscous friction coefficient	8 N·s/m	16 N·s/m
d	hip joint to CoM distance	0.27m	0.27m
l_0	leg rest length	0.3m	0.3m
l_{ul}	upper leg length	0.075m	-
l_{ll}	lower leg length	0.15m	-
m	body mass	10.5kg	10.91kg
J	body inertia w.r.t. z-axis	0.8 kg·m^2	0.8 kg·m^2
J_l	leg inertia w.r.t. z-axis	0.0019 kg·m^2	-
l_m	leg mass	0.41/4 kg	-
m_{total}	total robot mass	10.91kg	10.91kg

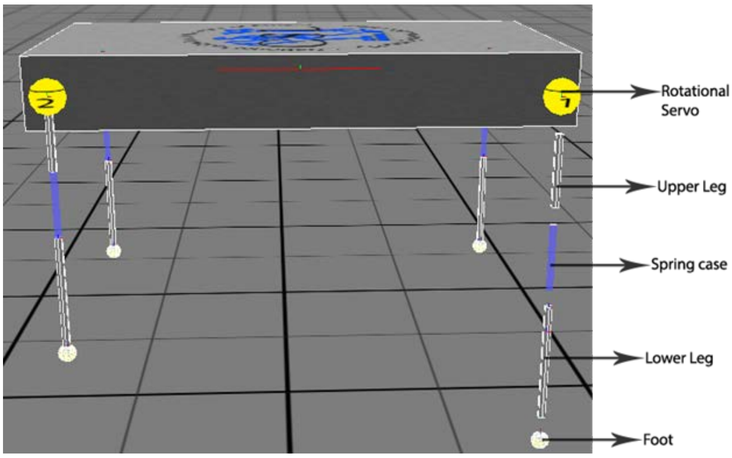

Figure 3: The 3D model of the NTUA quadruped in Webots 8 Simulation Environment. The 4 legs are identical and consist of five individual parts (the rotational servo, the upper leg, the spring, the lower leg and the foot).

2.3 The Analytical 2D model

To obtain a better insight into the dynamics of the quadruped, the equations of motion of a 2D lumped parameter model of a quadruped were derived with a Lagrangian approach, using body Cartesian coordinates, x, y, and pitch, θ. The model consists of two compliant virtual legs (VLegs) respectively. The Vlegs are indicated as rear (b) or front (f). A VLeg, front or rear, models the two respective physical legs that operate in pairs when a gait is realized and exerts equal torques and forces on the body as the set of the physical ones [15]. The planar model is valid for gaits that have symmetry about the plane of the forward motion, like pronking and bounding.

The planar quadruped robot model can be seen in Figure 5. It should be noted that front and rear legs are modelled to be massless linear springs. The 2D analytical lumped parameter model of a quadruped is shown in Figure 5.

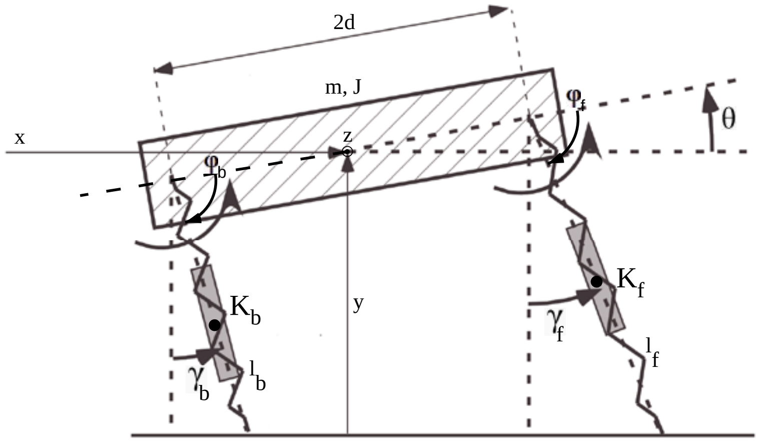

Figure 4: Planar quadruped robot model.

The equations of motion for the double stance and flight phase were developed and are presented here. Front and back stance equations of motion can be derived from the double stance ones, by cancelling the terms that do not appear in the front or back stance respectively. All symbols in the equations are described in Table 1.

Double Stance

$$m\ddot{x} + K_b\left(L - l_b\right)\sin\gamma_b + K_f\left(L - l_f\right)\sin\gamma_f = 0 \quad (4)$$

$$m\ddot{y} - K_b\left(L - l_b\right)\cos\gamma_b - K_f\left(L - l_f\right)\cos\gamma_f + mg = 0 \quad (5)$$

$$I\ddot{\theta} + dK_b\left(L - l_b\right)\cos\left(\gamma_b - \theta\right) - dK_f\left(L - l_f\right)\cos\left(\gamma_b - \theta\right) = 0 \quad (6)$$

Flight Phase

$$\ddot{x} = 0, \ddot{y} = 0, I\ddot{\theta} = 0 \quad (7)$$

Front Stance | **Back Stance**

$$m\ddot{x} + K_f\left(L - l_f\right)\sin\gamma_f = 0 \qquad m\ddot{x} + K_b\left(L - l_b\right)\sin\gamma_b = 0 \quad (8)$$

$$m\ddot{y} - K_f\left(L - l_f\right)\cos\gamma_f + mg = 0 \qquad m\ddot{y} - K_b\left(L - l_b\right)\cos\gamma_b + mg = 0 \quad (9)$$

$$I\ddot{\theta} - dK_f\left(L - l_f\right)\cos\left(\gamma_f - \theta\right) = 0 \qquad I\ddot{\theta} + dK_b\left(L - l_b\right)\cos\left(\gamma_b - \theta\right) = 0 \quad (10)$$

To evaluate the model, initial experiments have been carried out on level ground. As it can be seen in the phase plane diagram in Figure 5 and the forward velocity in Figure 7 the quadruped can perform stable dynamic running.

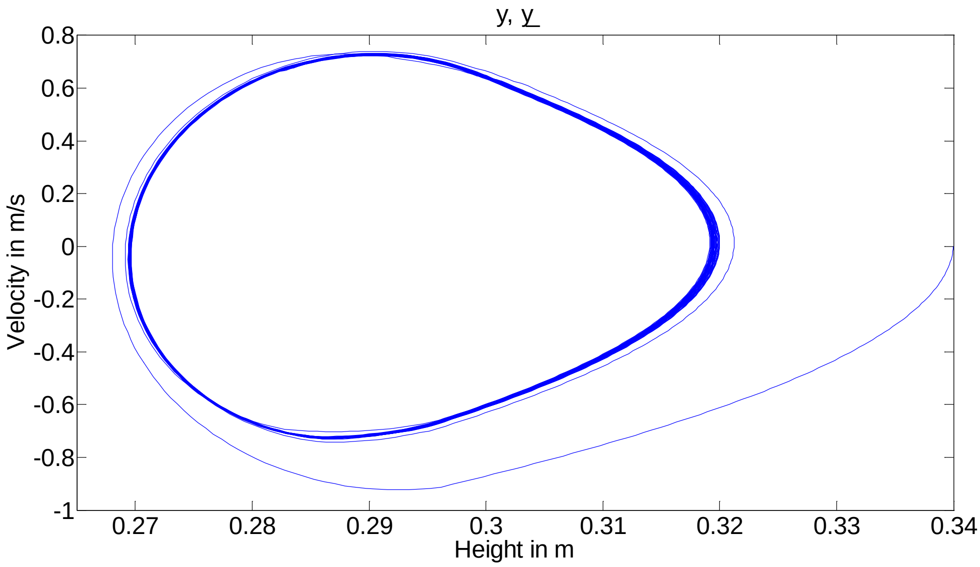

Figure 5: Phase plane diagram of the vertical position and acceleration of the robot's CoM while performing dynamic running on level ground.

The Webots model of the robot in comparison to the real robot is shown in Figure 5.

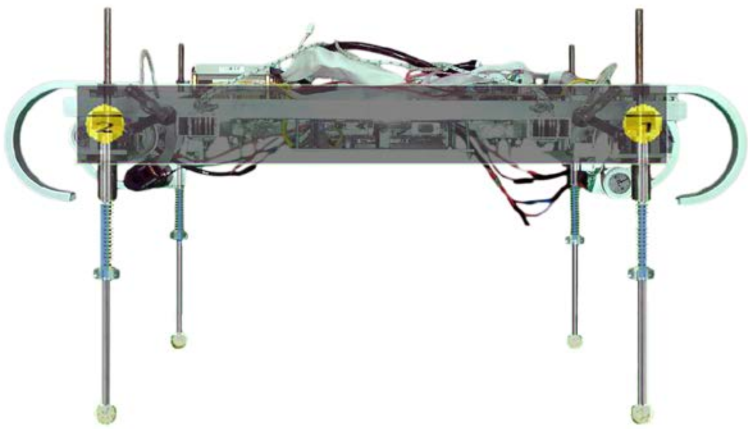

Figure 6: Constrast of the NTUA quadruped and the simmulated robot model in Webots 8.

3 RESULTS

The controller can achieve stable dynamic running on inclinations ranging from 0 to 20 degrees. In Figure 7 simulation results for 10 degrees slope climbing are presented. The quadruped can perform repeatable motions (steady state) in all these cases.

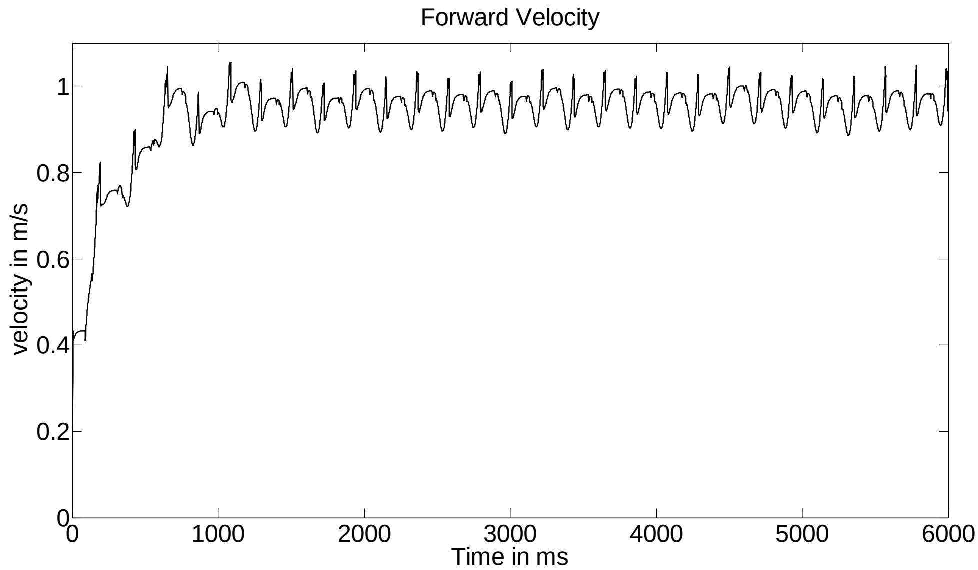

Figure 7: Quadruped's forward velocity on a 10 degree slope.

The controller has been also tested on various disturbances while the quadruped performs dynamic running. In Figure 8, a horizontal force of 1200 N (in the same direction of the robot's motion) is applied at the CoM of the body for 4ms tending to increase the forward velocity instantly. The controller overcomes this disturbance and the system reaches again a steady state.

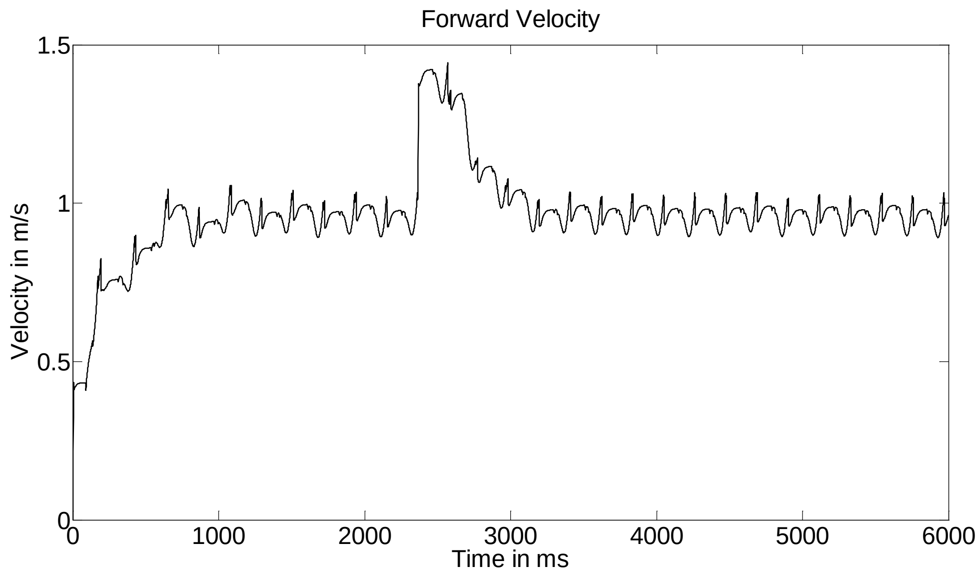

Figure 8: The system reaches a steady state after a disturbance on flight phase

If the disturbance applied is two times greater than the previous case, the controller fails to retain the robot in its standing position. As the forward velocity increases instantly when the front feet contact the ground, the pitch angle also starts to increase due to the frictional forces. Eventually, the robot falls since the front legs cannot prevent it.

In Figure 9, the body pitch angle over time is depicted. This time the robot falls because of the applied disturbance. An enhancement of the controller (which can also be extended for 3D motions) in order to overcome such disturbances is developed. Since the controller is robust enough to handle disturbances such as those in Figure 8, an event that is triggered for higher values of the forward velocity is introduced.

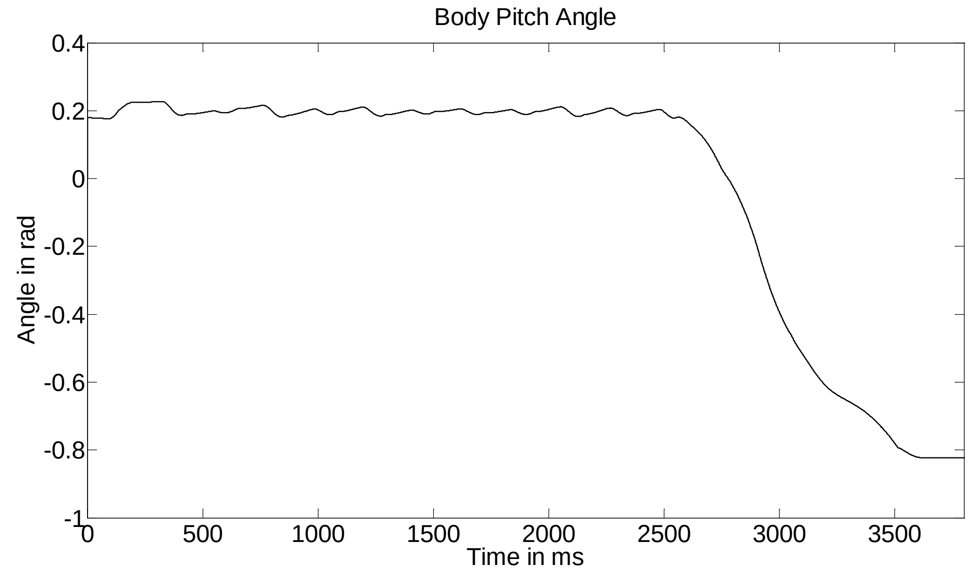

Figure 9: Pitch angle over time. The disturbance is applied at time t=2363ms

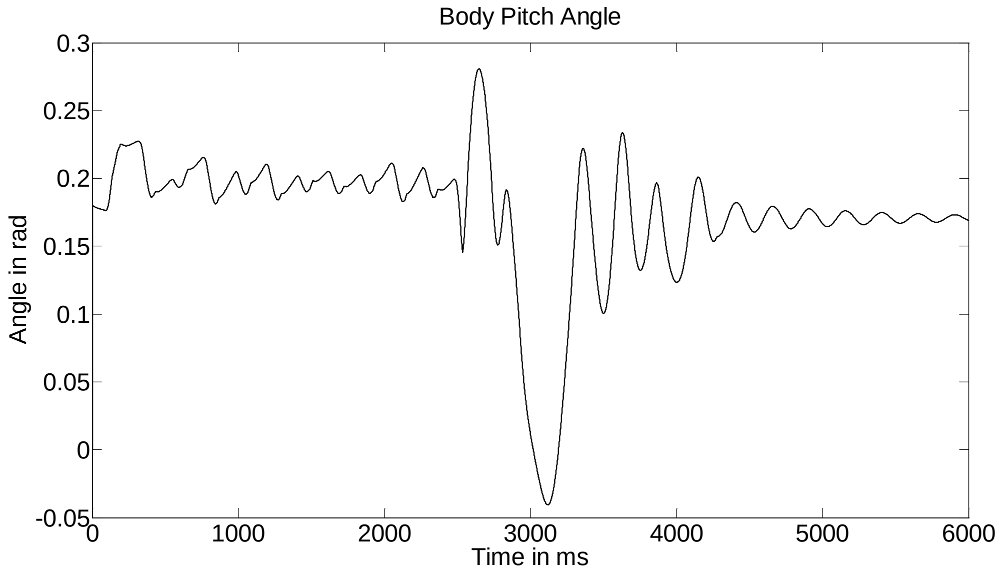

Figure 10: The robot remains in standing position despite the disturbance. When a rapid change in the forward velocity (in this case from 1m/s to 2.7m/s) is sensed the controller reacts by increasing the front legs touchdown angle (in this case from 0.19rad to 0.39rad).

The front leg hip joint is able to move from -0.43 rad to 0.43 rad. At the first stage, experiments using the maximum angle that the front hip joint can reach (0.43 rad) were carried out. As a result, the robot was able to overcome the applied disturbance as shown in Figure 10. Because of the fact that, the quadruped reaches a steady state, the duration of the flight phase and stance phase can be estimated. The stance phase lasts for about 0.1s. As a result, the disturbance has to be cancelled out, or as shown in Figure 8, reach a value that the controller can handle, in less than 0.1s. Using the equation of motion of the simplified 2D model for the front stance phase, it can be seen that the forward acceleration of the model depends on the touchdown angle of the robot's front legs (γ_f).

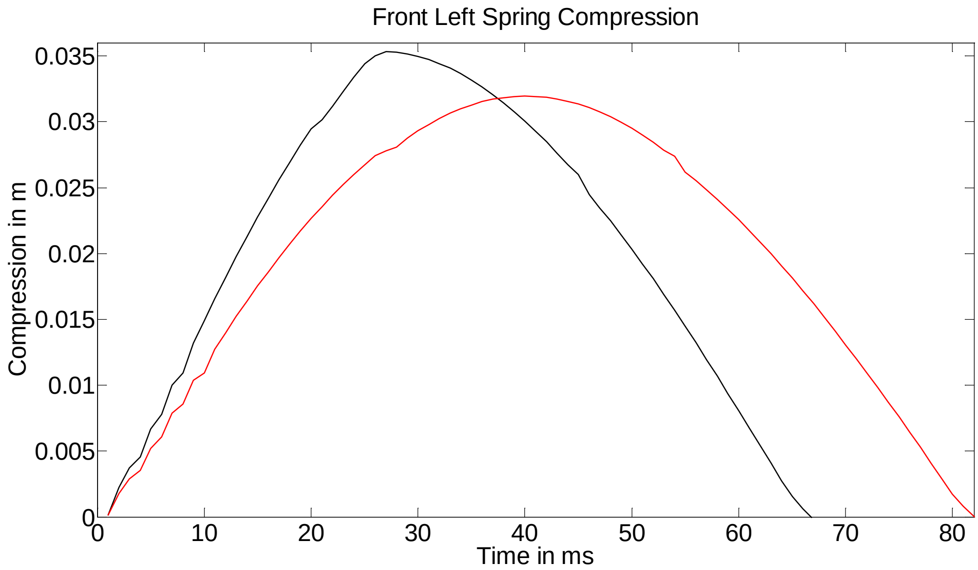

Figure 11: Front leg spring compressions for two disturbances. The black line is the spring compression for an instant increase in the forward velocity from 1m/s to 2.7m/s and the red line for a smaller disturbance from 1m/s to 2.3m/s.

The touchdown angle of the front legs in the steady state (for 1 m/s desired forward velocity) is ~0.19 rad. The introduced disturbance increases the forward velocity of the quadruped from the desired 1 m/s to 2.3 m/s. In Figure 8 it is shown that for minor disturbances there is no need to take action while for situation such as the one in Figure 9, it is needed.
According to the equations of motion for the front stance $\ddot{x}$ depends on $\sin\gamma_f$ ranging from $\sin -0.43 = -0.417$ to $\sin 0.43 = 0.417$ and $(L - l_f)$ ranging from 0 to 3.5cm. If it is needed to increase the forward deceleration because of a disturbance the term, $(L - l_f)$, has a minor impact in that. According to Figure 11, the spring compression, $(L - l_f)$, in two different cases is similar. As a result, experiments have shown that by increasing the touchdown angle of the front legs from 0.19rad to 0.29rad (from $\sin 0.19 = 0.189$ to $\sin 0.29 = 0.286$ is enough to decelerate the robot from 2.3m/s to 1.5 m/s and retain the quadruped in standing position. In addition, by increasing the front leg touchdown angle by 0.2 rad, the quadruped can handle disturbances 4 times the one shown in Figure 8 (from 2.7m/s to 1.5 m/s).

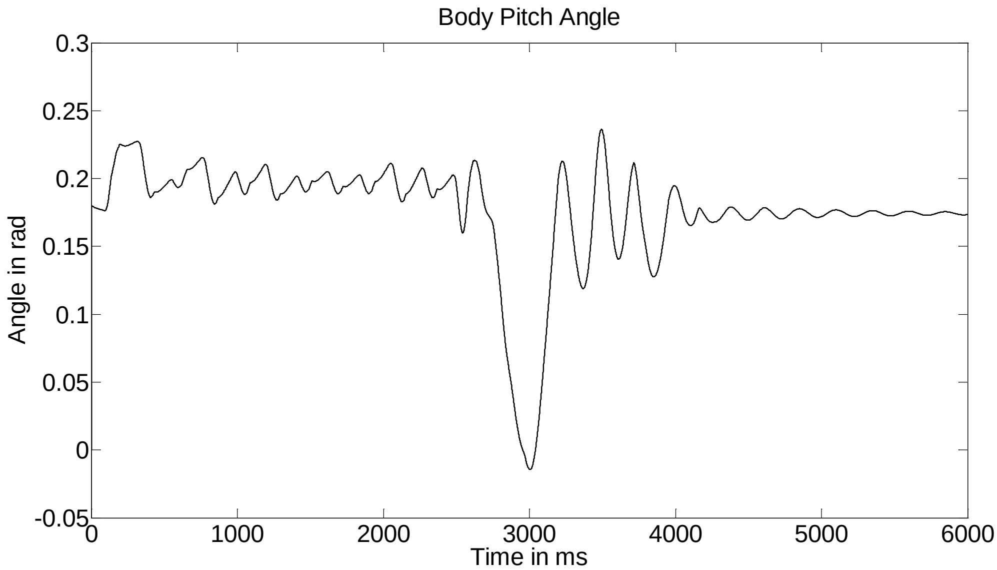

Figure 12: The robot remains in standing position despite the disturbance. When a rapid change in the forward velocity (in this case from 1m/s to 2.3m/s) is sensed the controller reacts by increasing the front legs touchdown angle (in this case from 0.19rad to 0.29rad).

In conclusion, since ~0.19 rad is the touchdown angle of the front hip joints in the steady state and the controller is robust to handle disturbances up to 0.5 m/s higher than the desired forward velocity (1 m/s) we can use the addition 0.23 rad (0.43 rad is the mechanical limit of the joint) to enhance stability.

4 CONCLUSIONS

This paper presented simulation results obtained with a simulated quadruped robot on sloping ground in Webots. It has been shown that in situation such as those presented, events can be introduced and dangerous tipover subject to disturbances can be prevented. In the first stage, experiments were conducted in order to find out how robust the controller is. In the second stage, an event was introduced. The whole range of the robot's joint was used in order to keep the robot in standing position. In the end, this approach was enhanced since from our analysis it is shown that despite the various disturbances the spring compression and decompression remains almost the same. As a result, we can benefit only from the touchdown angle of the front legs in order to decelerate the robot. Finally, intermediate steps where introduced according to the intensity of the disturbance.

5 ACKNOWLEDGEMENTS

This research has been co-funded by the European Union (European Social Fund –ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF) – Research Funding Program: Thalis. Investing in knowledge society through the European Social Fund.

6 REFERENCES

[1] P. D. Neuhaus, J. E. Pratt, and M. J. Johnson, "Comprehensive summary of the Institute for Human and Machine Cognition's experience with LittleDog," *Int. J. Robot. Res.*, vol. 30, no. 2, pp. 216–235, Feb. 2011.

[2] J. Buchli, M. Kalakrishnan, M. Mistry, P. Pastor, and S. Schaal, “Compliant quadruped locomotion over rough terrain,” in *Intelligent Robots and Systems, 2009. IROS ’09., Proceedings of the 2009 IEEE/RSJ International Conference on*, 2009, pp. 814–820.
[3] S. Bazeille, V. Barasuol, M. Focchi, I. Havoutis, M. Frigerio, J. Buchli, C. Semini, and D. G. Caldwell, “Vision enhanced reactive locomotion control for trotting on rough terrain,” in *Technologies for Practical Robot Applications (TePRA), 2013 IEEE International Conference on*, 2013, pp. 1–6.
[4] E. G. Papadopoulos and D. A. Rey, “A new measure of tipover stability margin for mobile manipulators,” in *Robotics and Automation, 1996. Proceedings., 1996 IEEE International Conference on*, 1996, vol. 4, pp. 3111–3116 vol.4.
[5] M. Vukobratović and B. Borovac, “Zero-Moment Point - Thirty Five Years of its Life,” *Int. J. Humanoid Robot.*, vol. 01, no. 01, pp. 157–173, Mar. 2004.
[6] S. Ali, A. Moosavian, and K. Alipour, “Stability Evaluation of Mobile Robotic Systems using Moment-Height Measure,” Bangkok, Thailand, 2006, pp. 1–6.
[7] D. A. Rey and E. G. Papadoupoulos, “Online automatic tipover prevention for mobile manipulators,” in *Intelligent Robots and Systems, 1997. IROS ’97., Proceedings of the 1997 IEEE/RSJ International Conference on*, 1997, vol. 3, pp. 1273–1278 vol.3.
[8] P. R. Roan, A. Burmeister, A. Rahimi, K. Holz, and D. Hooper, “Real-world validation of three tipover algorithms for mobile robots,” in *Robotics and Automation (ICRA), 2010 IEEE International Conference on*, 2010, pp. 4431–4436.
[9] O. Michel, “Webots: Professional Mobile Robot Simulation,” *Int. J. Adv. Robot. Syst.*, vol. 1, no. 1, pp. 39–42, 2004.
[10] Kontolatis I. and E. Papadopoulos, “Dynamic Running Quadruped for Crater Exploration,” in *11th International Symposium on Artificial Intelligence, Robotics and Automation in Space, (i-SAIRAS)*, Turin, 2012.
[11] N. Cherouvim and E. Papadopoulos, “Use of a novel multipart controller for the parametric study of a trotting quadruped robot,” in *Robotics and Automation, 2008. ICRA 2008. IEEE International Conference on*, 2008, pp. 805–810.
[12] E. Drumwright, J. Hsu, N. Koenig, and D. Shell, “Extending Open Dynamics Engine for Robotics Simulation,” in *Simulation, Modeling, and Programming for Autonomous Robots*, vol. 6472, N. Ando, S. Balakirsky, T. Hemker, M. Reggiani, and O. von Stryk, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2010, pp. 38–50.
[13] A. Nikolakakis, I. Kontolatis, N. Cherouvim, P. Chatzakos, and E. Papadopoulos, “Implementation of a Quadruped Robot Pronking/Bounding Gait Using a Multipart Controller,” presented at the Proceedings of the ASME 2010 Dynamic Systems and Control Conference, Cambridge, Massachusetts,USA, 2010, pp. 149–156.
[14] V. Vasilopoulos, I. S. Paraskevas, and E. G. Papadopoulos, “Compliant terrain legged locomotion using a viscoplastic approach,” 2014, pp. 4849–4854.
[15] M. H. Raibert, *Legged robots that balance*. Cambridge, Mass.: MIT Press, 1986.