# Metastable Walking of the Five-Link Biped on Stochastically Rough Terrain

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## 1. Motivation for Metastable Analysis

Studies on walking often concentrated on constant slopes or flat ground, whereas the obvious advantage of walking over wheels is on rough terrain with discontinuities, such as rocky obstacles, ditches, or stairs. In order to make use of this advantage, stochastic terrains should be considered, on which, a black-white stability notion is not adequate.

## 2. Motivation for Switching

What is very intuitive but has lacked sufficient attention is that humans do not walk the same way on every ground type. They modify their walk depending on various conditions, such as whether the surface is pavement or clay, whether the ground is triangular (slopes), or rectangular (stairs), whether it’s uphill or downhill, and whether there are obstacles on the way, just to name some. It is not possible or necessary to design a fixed controller for all cases.

## 3. Approach

We created a mesh that captures the step-to-step dynamics of walking. Then, we accurately represented the ten dimensional system dynamics of metastable walking as a Markov process. As a results we were able to calculate the Mean First Passage Times (MFPT), which are useful measures of stability on rough terrain.

Using the state transition matrices obtained, we also examined the effect of switching between controllers.

## 4. Results

We were able to verify the success of the mesh capturing the dynamics of walking by sample tests as shown in Table I.

Table 1 - Sample Cases

| | (Mean, St. Deviation) | | | Mean |
|---|---|---|---|---|
| Controller | Slope | Simulation | $\text{Estimation}_1$ | $\text{Estimation}_2$ |
| 1 | (0,3) | (20.9,20.5) | (21.4,20.9) | 21.5 |
| 1 | (-1,2) | (746.6,741.1) | (712.2,713.4) | 700.9 |
| 1 | (0,2) | (140,141.8) | (141.7,139.6) | 139.2 |
| 2 | (0,1.5) | (515.1,509) | (471,461.1) | 468.4 |
| 2 | (1,3) | (15.1,14.5) | (15.5,15) | 15.4 |
| 2 | (-1,1.5) | (73.5,73.1) | (64,62.7) | 63.9 |
| Random | (0,0.5) | (137.6,132.9) | (146.8,148.1) | 145.6 |
| Random | (-1,2) | (5.1,3.9) | (5,4) | 4.6 |

Figure 1 illustrates the MFPT of two different controllers and the effect of switching between them.

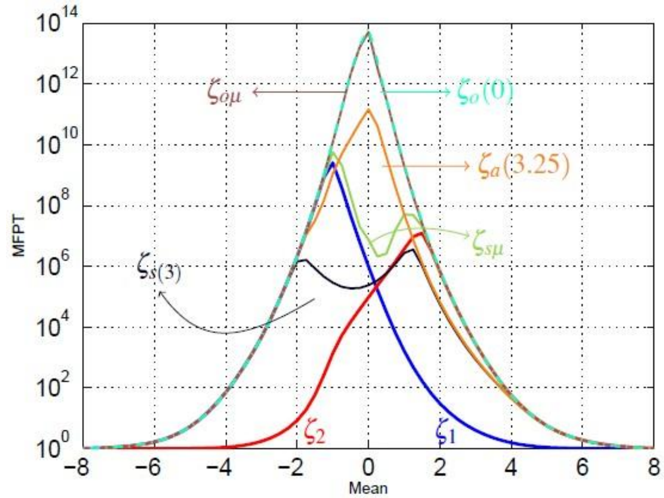

Figure 1 - Mean First Passage Times

By switching between two qualitatively different controllers, we show that the number of steps before failure can be increased dramatically compared to using either one of the controllers only.

## 5. Best Possible Outcome

While the results seems promising, we suspect the robustness of switching is still an issue.

It would create a great impact if we were able to show applicability of these ideas to a high DOF walker.

Finally we are hoping to use these ideas not just to analyze, but also to design controllers.

## Note

This work includes parts from the papers presented at ICRA'13 [1] and submitted to CDC'13 [2].

## Acknowledgements

This work was supported by the Institute for Collaborative Biotechnologies through grant W911NF-09-0001 from the U.S. Army Research Office. The content of the information does not necessarily reflect the position or the policy of the Government, and no official endorsement should be inferred.

## References

[1] C. O. Saglam and Katie Byl. "Stability and Gait Transition of the Five-Link Biped on Stochastically Rough Terrain Using a Discrete Set of Sliding Mode Controllers", in *Proc. IEEE Int. Conf. on Robotics and Automation (ICRA)*, 2013.

[2] Cenk Oguz Saglam and Katie Byl. "Switching Policies for Metastable Walking". Submitted to *IEEE Conference on Decision and Control (CDC)*, 2013.