Central Pattern Generator with Inertial Feedback for Stabilized Locomotion in Unstructured Terrain

Samuel Shaw, Guillaume Sartoretti, Matthew Travers, and Howie Choset

Introduction

Legged animals of varying sophistication subconsciously navigate extreme terrain with ease. In an effort to match this performance, bio-inspired control mechanisms have been widely studied, but have most commonly been used for open-loop gait generation. To improve locomotion in unstructured terrain, we present a method for incorporating body stabilization into a Central Pattern Generator (CPG) by adapting CPG parameters using inertial feedback.

Results

Locomotive speed greatly improves when robot body orientation is strictly controlled.

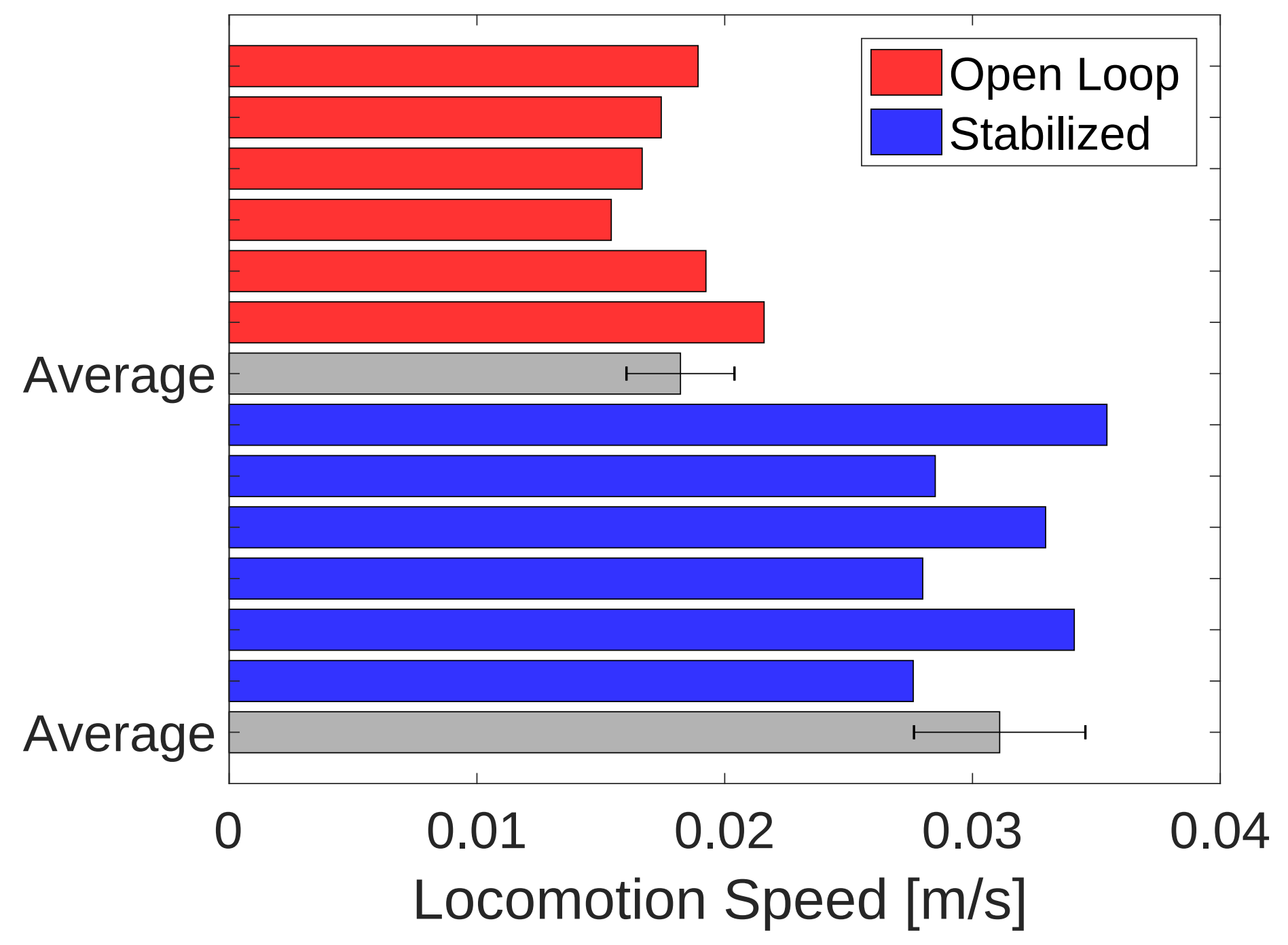

Figure 1: *Performance of stabilized trials (blue) and open-loop trials (red); average values are shown in gray with overlaid standard deviations.*

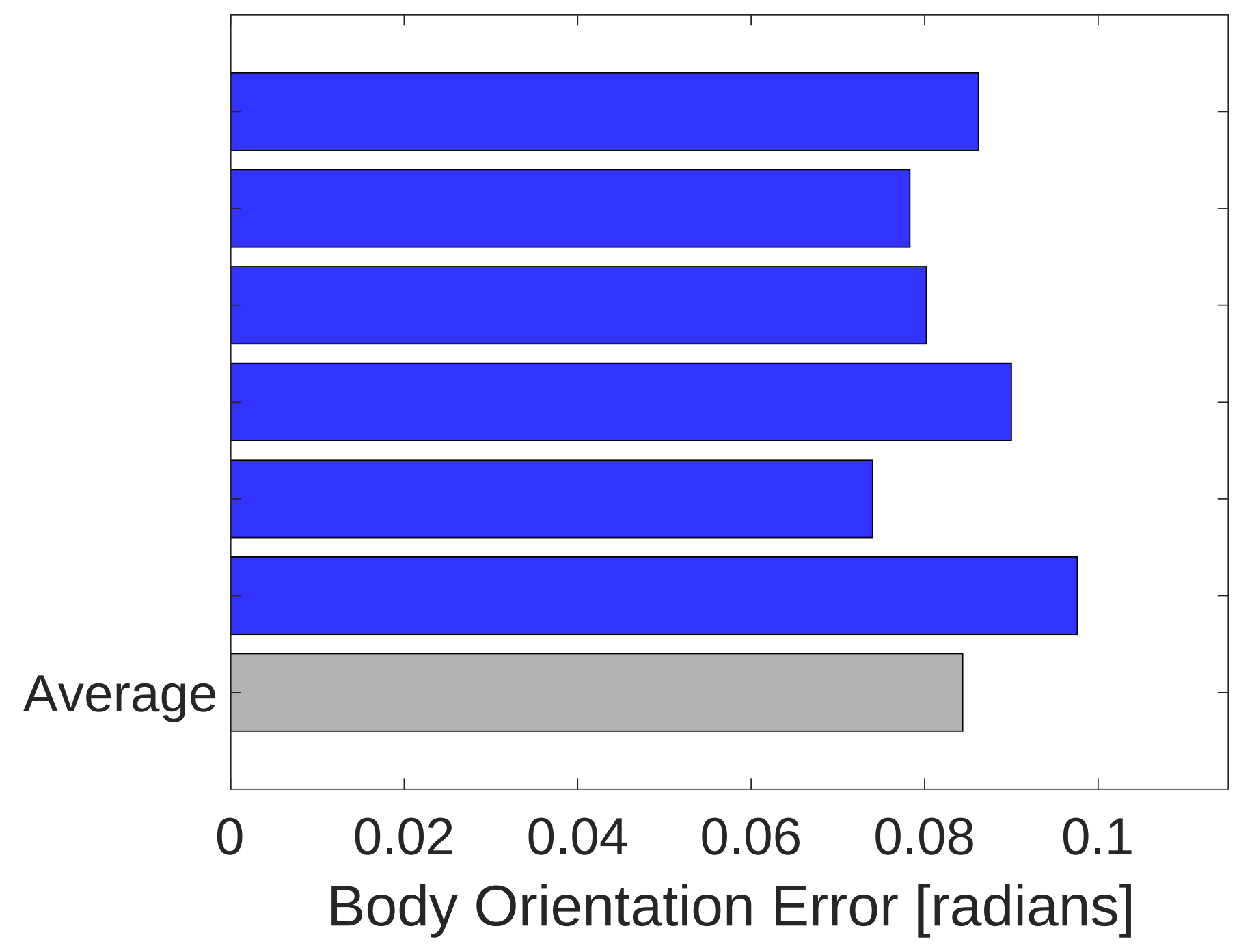

Figure 2: *Body orientation error for each stabilized trial (blue), and average across all trials (gray) (shown in radians, $\sim 5^\circ$).*

Conclusion

We show that inertial body stabilization improves blind locomotion by smoothing out sudden perturbations due to end-effector slip and increasing locomotive speed in unstructured terrain. Additionally, we conclude that stabilization can allow a robot to traverse steeper and more challenging terrains, where open-loop locomotion would otherwise fail. Using a CPG framework generalizes the method so that it may serve as a fundamental tool for future research on legged locomotion or a potential building block for vision-based applications.

References

[1] Ludovic Righetti and Auke Jan Ijspeert. Pattern generators with sensory feedback for the control of quadruped locomotion. In *Robotics and Automation, 2008. ICRA 2008. IEEE International Conference on*, pages 819–824. IEEE, 2008.

Hexapod Robot

Figure 3: *Experimental Platform: modular, series-elastic hexapod robot aerial view (left); hexapod robot leg joint configuration (right).*

Central Pattern Generator Model

We model the CPG as a dynamical system of linked oscillators in the joint space, where $x = [x_1, ..., x_n]$ represents the angles of the proximal, lateral joints and $y = [y_1, ..., y_n]$ represents the angles of distal, vertical joints:

$$\begin{cases} \dot{x_i} = \gamma(1 - \frac{(x_i - c_{x,i})^2}{a^2} - \frac{(y_i - c_{y,i})^2}{b^2}) \cdot (x_i - c_{x,i}) - \omega \frac{a}{b} \cdot (y_i - c_{y,i}) \\ \dot{y_i} = \gamma(1 - \frac{(x_i - c_{x,i})^2}{a^2} - \frac{(y_i - c_{y,i})^2}{b^2}) \cdot (y_i - c_{y,i}) - \omega \frac{b}{a} \cdot (x_i - c_{x,i}) + \lambda \sum K_{ij}(y_i - c_{y,i}) + \Delta\theta_{e_{2,i}}. \end{cases} \tag{1}$$

Inertial Stability

By examining the orientation of the robot's body, we obtain $e \in \mathbb{R}^{3 \times n}$, the error in end-effector position in Cartesian space for each leg:

$$e = \begin{bmatrix} x_1 & \cdots & x_n \\ y_1 & \cdots & y_n \\ z_1 & \cdots & z_n \end{bmatrix}. \tag{2}$$

Rearranging the kinematics equation,

$$\dot{x} = J\dot{\theta}, \tag{3}$$

where $\dot{x}$ is the end effector velocity, J is the Jacobian, and $\dot{\theta}$ is the angular speed of the joint, we obtain:

$$\Delta\theta_e \approx J^{-1}e. \tag{4}$$

In order to ensure that joint angle correction does not diverge, we add a constant dissipation to the origin:

$$\Delta\theta_e = \Delta\theta_e - \alpha \cdot \theta_e, \tag{5}$$

where $\alpha \in \mathbb{R}$ governs the dissipative term.

By integrating the error in joint angle, denoted $\Delta\theta_e$, with respect to time,

$$\theta_e = \int_0^t \Delta\theta_e dt, \tag{6}$$

we obtain joint offsets, θ_e, that correspond to the desired corrections in the orientation and height of the robot's body.

The second row of $\Delta\theta_e$ gives offsets for the distal, vertical joints, which are used to set c_y to obtain stability:

$$c_{y,i} \equiv \theta_{e_{2,i}}. \tag{7}$$

Experimental Setup

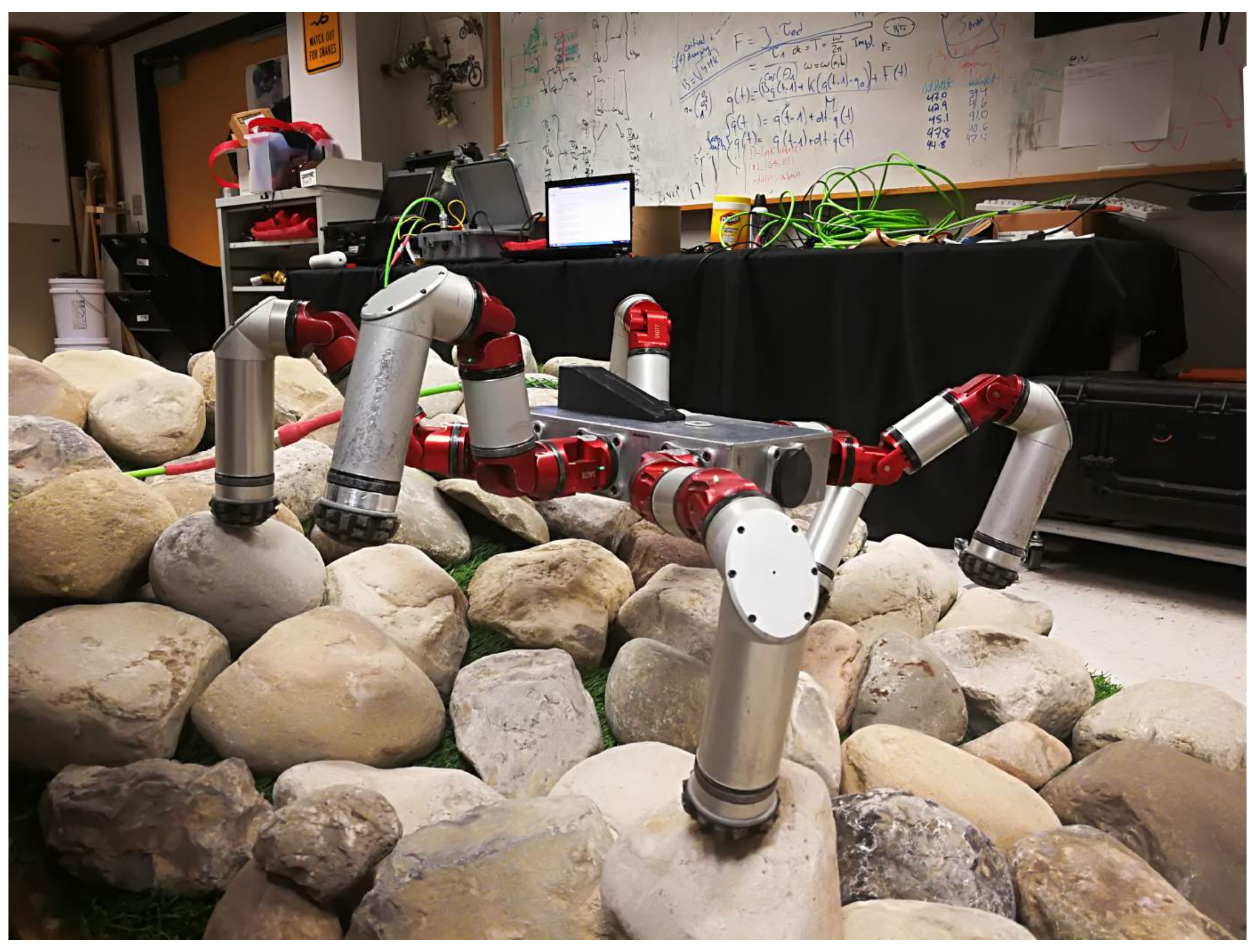

Figure 4: *Hexapod robot on experimental unstructured terrain.*

Experiments were conducted on a twelve-degree slope, featuring randomly-placed and -oriented rocks that varied in elevation from approximately 5cm to 20cm.

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Contact

Samuel Shaw, Tufts University
samuel.shaw@tufts.edu
215-910-2171