Improved Standing Balancing For Legged Robots With Unified Balancing Model

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Motivation

Improve balance control of legged robots by extending existing reduced order models to include additional balancing strategies.

Balancing Strategies

Human and robotic standing balancing can be broken into three distinct strategies [1].

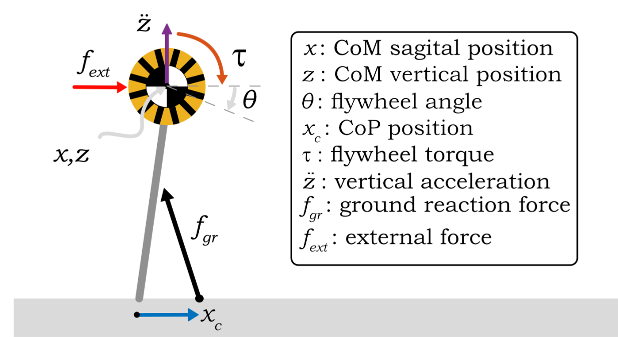
- **Ankle**: position center of pressure (CoP) within the base of support
- **Hip**: generate angular momentum about the center of mass (CoM) to regulate restoring sheer force at support
- **Toe**: utilize vertical motion to increase ground reaction force (GRF) to increase magnitude of restoring force

Existing standing reduced order models capture up to two of the above strategies

- **Linear Inverted Pendulum** (LIP) [2] : ankle
- **Linear Inverted Pendulum Plus Flywheel** (LIPPFW) [3]: ankle + hip
- **Variable Height Inverted Pendulum** (VHIP) [4] : ankle + toe

Unified Model

Variable Height Inverted Pendulum Plus Flywheel Model



Here we extend the existing balancing models to include **ankle**, **hip** and **toe** balancing strategies. We call this model the **variable height inverted pendulum plus flywheel model** (VHIPPFW).

Dynamics $\ddot{x} = \frac{(g+\ddot{z})}{z}(x-x_c) + \frac{\tau}{mz}$, $I\ddot{\theta} = \tau$

State $\mathbf{x} = [x, \theta, z, \dot{x}, \dot{\theta}, \dot{z}]^T$

Control $\mathbf{u} = [x_c, \tau, \ddot{z}]^T$

Methods

We used a non-linear model predictive controller (NLMPC) for each reduced order model.

$$\min_{\mathbf{u}} \sum_{i=1}^{p} (\mathbf{x}_i - \mathbf{x}_0)^T Q (\mathbf{x}_i - \mathbf{x}_0) + \mathbf{u}_i^T R \mathbf{u}_i$$

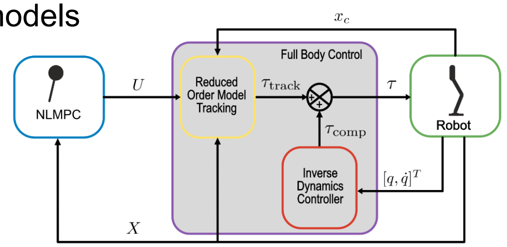
subject to $\mathbf{x}_{k+1} = \boldsymbol{f}(\mathbf{x}_k, \mathbf{u}_k)$ model dynamics

$\mathbf{x}_{\min} \le \mathbf{x}_k \le \mathbf{x}_{\max}$ actuation limits

$\mathbf{u}_{\min} \le \mathbf{u}_k \le \mathbf{u}_{\max}$ control limits

Push recovery simulations were conducted on a simple 4 link balancing robot.

A full body controller was constructed for the robot to track the reduced order models



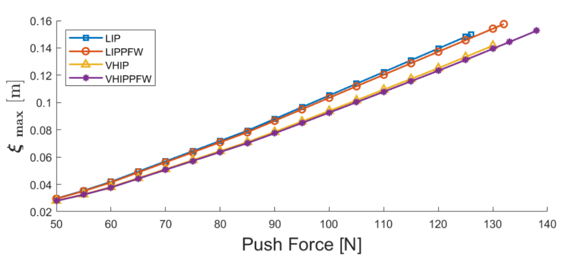
Push disturbance modeled as constant force applied at the CoM for 0.1 seconds

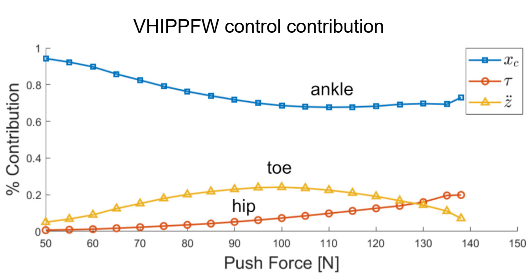
Performance was evalutated on maximum **capture point**: $\xi = x + \sqrt{\frac{z}{g}}\dot{x}$

- represents point for CoP to be placed for LIP dynamics to bring system to rest
- smaller $\xi \rightarrow$ more stable

Results

Reduced order model simulations





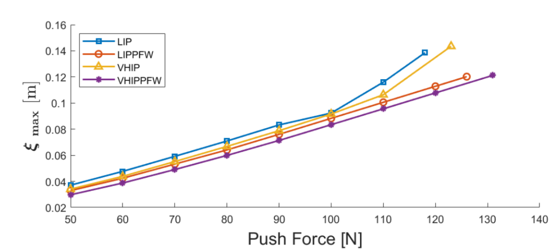
Maximum recoverable push force

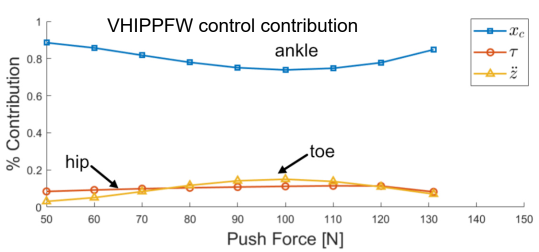
LIP: 126 N LIPPFW: 132 N

VHIP: 133 N VHIPPFW: 138 N

- Models that used toe strategy Reduced $\xi_{\max}$ by 9.7%

Robot simulations



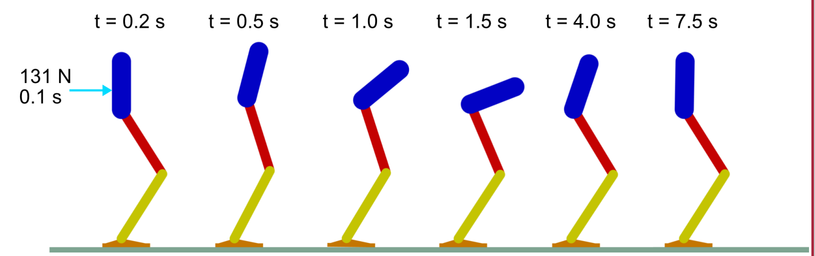


Maximum recoverable push force

LIP: 117 N LIPPFW: 126 N

VHIP: 123 N VHIPPFW: 131 N

- Hip more effective on robot than toe base models



push recovery simulation of simple balancing robot using VHIPPFW NLMPC

With access to **more balancing strategies** the standing **balance improves** with the use of VHIPPFW NLMPC controller.

VHIPPFW NLMPC can recover from 3.7% (model) and 3.9% (robot) greater disturbances compared to the next best reduced order model.

VHIPPFW has lowest $\xi_{\max}$ for all of tested disturbances

Ongoing & Future Work

Construct simple legged robot with torso to implement the controls based on the reduced order balancing models on hardware

Acknowledgements

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Refrences

[1] McGreavy et al. (2020)
[2] Kajita et al. (2001)
[3] Pratt et al. (2007)
[4] van Hofslot et al. (2019)