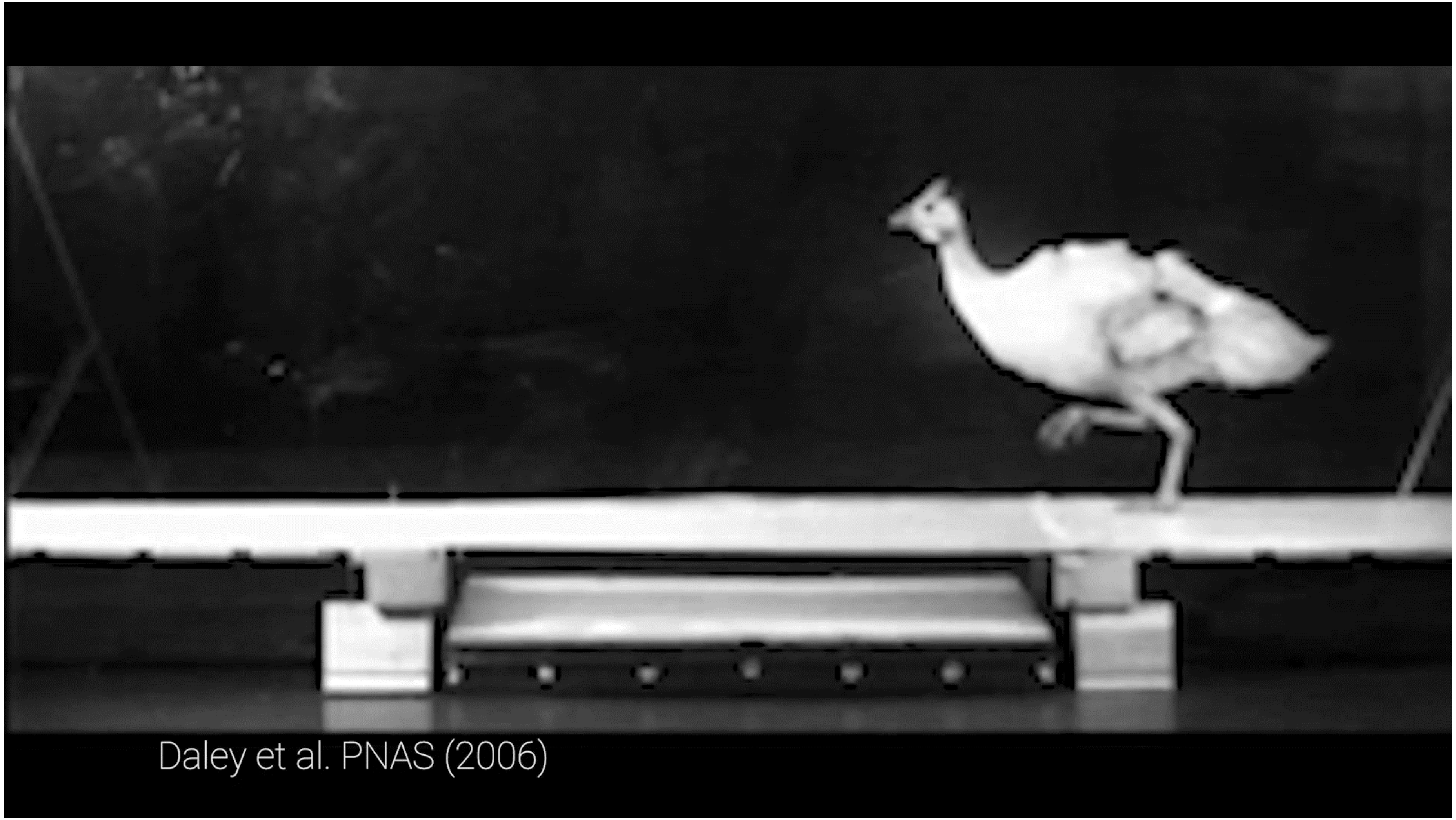
Fast Online Optimization for Terrain Blind Bipedal Robot Walking with a Decoupled Actuated SLIP Model

Ke Wang

Goal

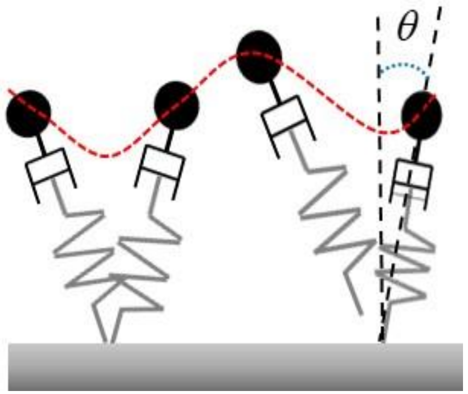
Let robots go anywhere, robustly, reactively

Perception fails sometimes …

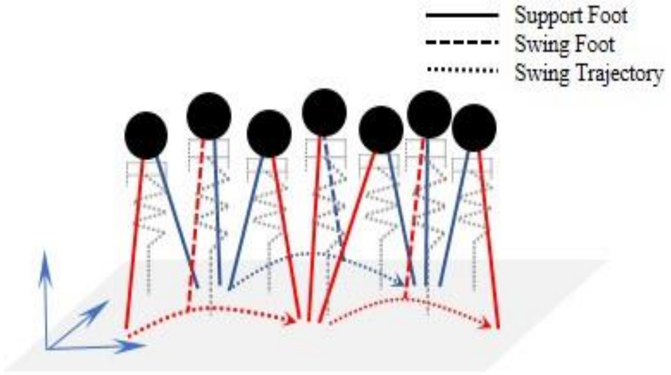


Navigating the unexpected with robust dynamic stability, Agility Robotics,
https://www.youtube.com/watch?v=mpxrnrR_Tsg&t=84s&ab_channel=AgilityRobotics

The actuated Spring Loaded Inverted Pendulum (aSLIP) Model

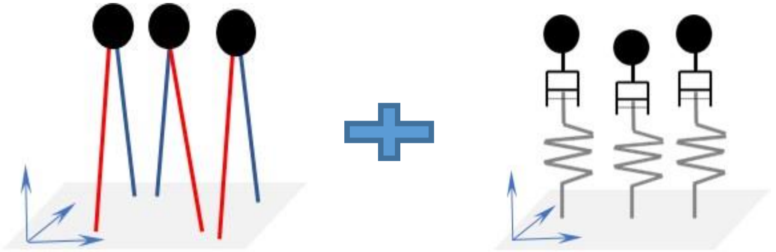


Small θ

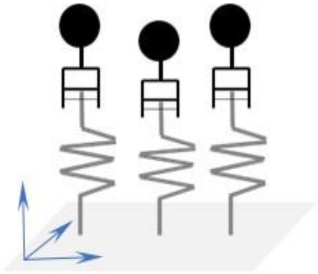


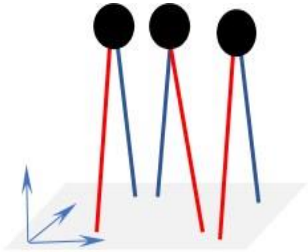
$$m\ddot{\boldsymbol{p}}_c = m\boldsymbol{g} + k(l - l_0)\hat{\boldsymbol{l}}$$

Actuated



$$\begin{bmatrix} m\ddot{l} \\ ml^2\ddot{\theta} \end{bmatrix} = \begin{bmatrix} ml\dot{\theta}^2 - k(l - l_0) - mg\cos\theta \\ -2ml\dot{l}\dot{\theta} + mgl\sin\theta \end{bmatrix}$$





$$m\ddot{z} = mg + k(z - r(t))$$

$$r(t) = r_0 + \frac{t}{T}(r_T - r_0)$$

$$\dot{\boldsymbol{Z}} = \begin{bmatrix} 0 & 1 \\ -\omega_z^2 & 0 \end{bmatrix} \boldsymbol{Z} + \begin{bmatrix} 0 \\ \omega_z^2 \end{bmatrix} \boxed{(r - \frac{g}{\omega_z^2})}$$

u_z

$$\ddot{x} = \frac{g}{z}(x - p_x)$$

$$\dot{X} = \begin{bmatrix} 0 & 1 \\ \omega_x^2 & 0 \end{bmatrix} X + \begin{bmatrix} 0 \\ -\omega_x^2 \end{bmatrix} u_x$$

QP Formulation

$$\min_{u_x, u_y, u_z} \quad \Gamma \qquad \text{(cost function)}$$

$$\text{s.t.} \quad \boldsymbol{X}_{k+1} = \boldsymbol{A}(T_s)\boldsymbol{X}_k + \boldsymbol{B}(T_s)u_k \qquad \text{(dynamics)}$$

$$h(\mathbf{p}_j) < 0 \qquad \text{(reachability)}$$

$$\Gamma_1 = ||\boldsymbol{X}_N - \boldsymbol{X}_N^{ref}||_{\boldsymbol{P}}^2 + \sum_{k=0}^{N-1} ||\boldsymbol{X}_k - \boldsymbol{X}_k^{ref}||_{\boldsymbol{Q}}^2$$

Reference Velocity Tracking

$$\Gamma_2 = \sum_{k=0}^{N-1} ||u_k - u_k^{ref}||_R^2$$

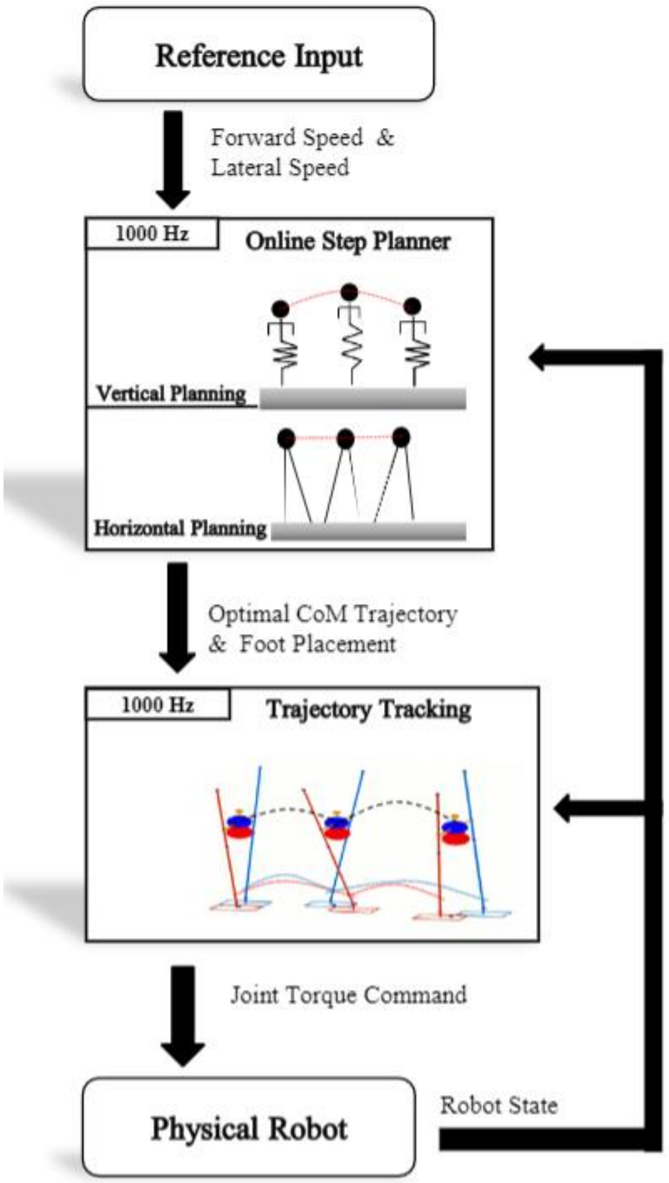
$$\bar{\boldsymbol{U}}_z^{ref} = \begin{bmatrix} r_0 I_{N_r} \\ 0_{N_s} \\ \dots \\ 0_{N_s} \end{bmatrix} + \begin{bmatrix} 1\,0 \dots 0 \\ 1\,1 \dots 0 \\ 1\,1 \dots 0 \\ 1\,1 \dots 1 \end{bmatrix} \begin{bmatrix} 0_{N_r} \\ \Delta r_1 I_{N_s} \\ \dots \\ \Delta r_{N_{steps}} I_{N_s} \end{bmatrix}$$

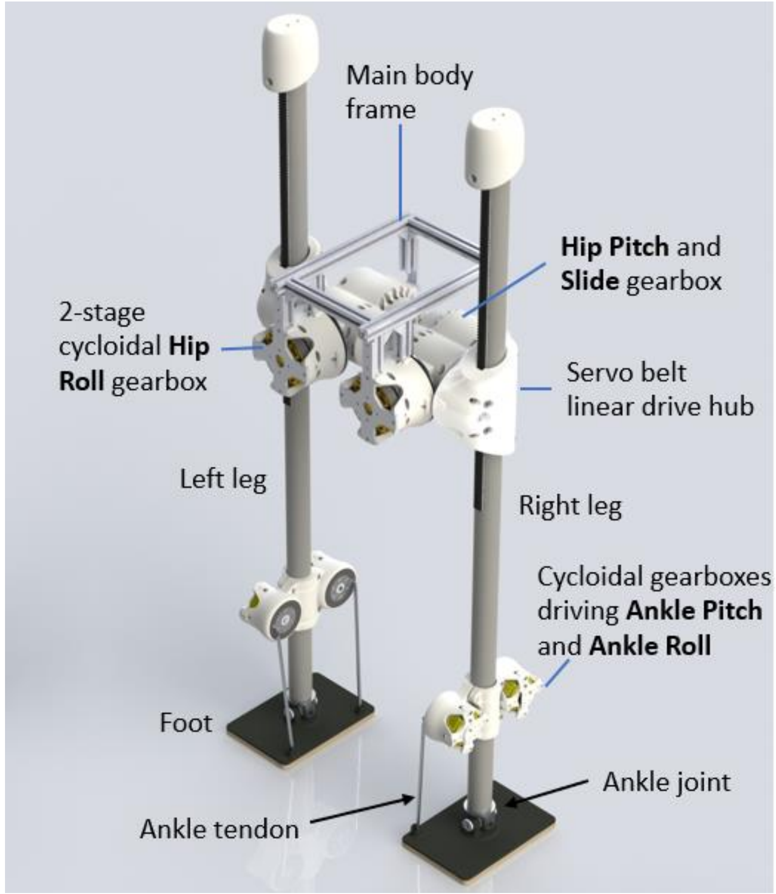
Reference Control Input Tracking

$$\Gamma_3^z = \sum_{i=1}^{N_{steps}} ||\Delta r_i - d_i^z||_W^2 = \sum_{i=1}^{N_{steps}} ||\Delta r_i||_W^2$$

$$\Gamma_3^{x,y} = \sum_{i=1}^{N_{steps}} ||\Delta P_i^{x,y} - d_i^{x,y}||_W^2$$

Control Change Regulation


Reference Input
Forward Speed &
Lateral Speed
1000 Hz
Online Step Planner
Vertical Planning
Horizontal Planning
Optimal CoM Trajectory
& Foot Placement
1000 Hz
Trajectory Tracking
Joint Torque Command
Physical Robot
Robot State


Main body
frame
Hip Pitch and
Slide gearbox
2-stage
cycloidal Hip
Roll gearbox
Servo belt
linear drive hub
Left leg
Right leg
Cycloidal gearboxes
driving Ankle Pitch
and Ankle Roll
Foot
Ankle joint
Ankle tendon

Different Designs of Bipedal Robot

Atlas

Cassie

SLIDER

Background – Bipedal Robot Design

Anthropomorphic Design

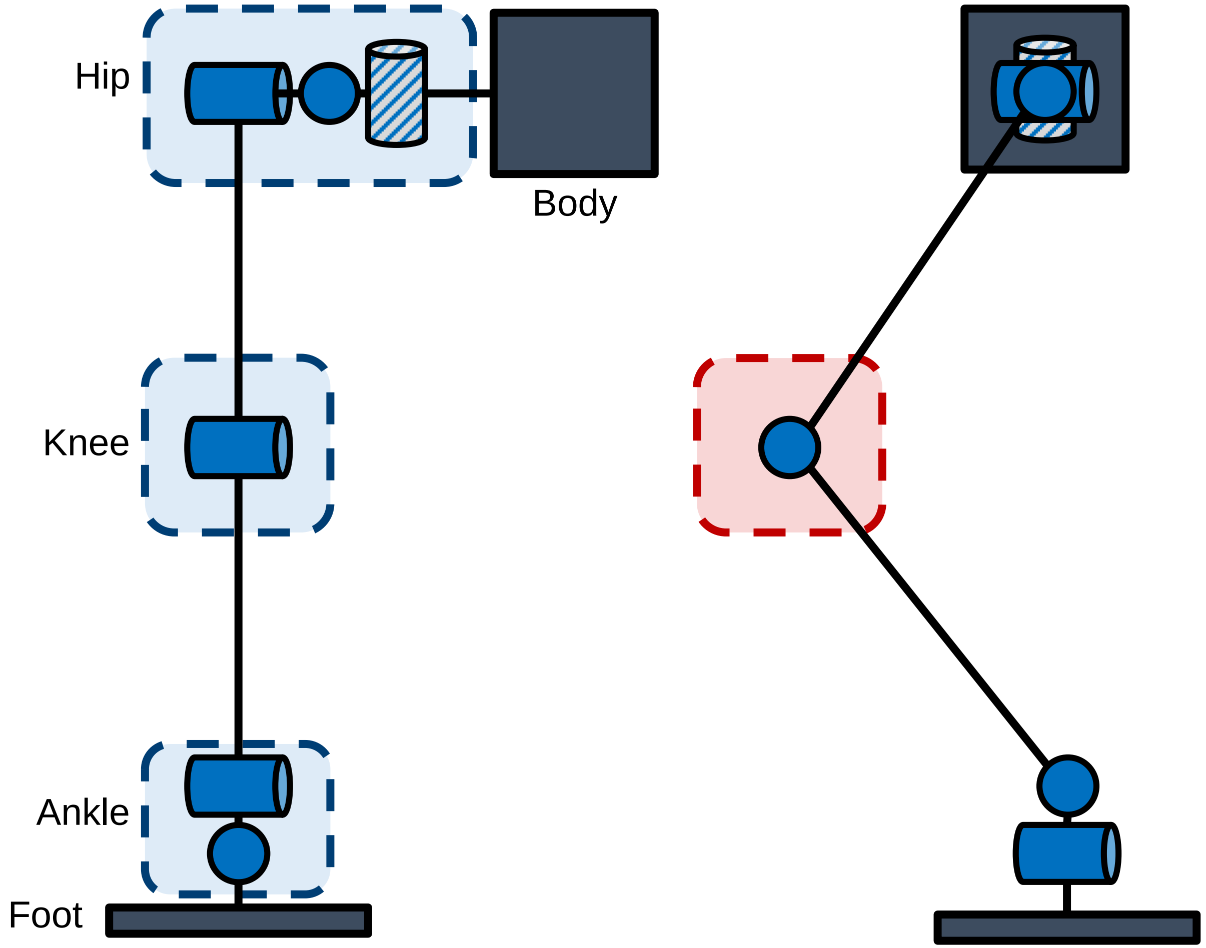
5/6 degrees of freedom in each leg:

- **Hip:** pitch, roll, and sometimes yaw
- **Knee:** pitch
- **Ankle:** pitch, roll

The knee joint has disadvantages:

- Bent knee walking is common
- Actuator must produce high torque
- Significantly proportion of leg mass
- Consumes excess power

Is it possible to design a walking robot without knees?



Kinematic Diagram
Coronal Plane

Kinematic Diagram
Sagittal Plane

Design and Control of SLIDER: An Ultra-lightweight, Knee-less, Low-cost Bipedal Walking Robot
Ke Wang, David Marsh, Roni Permana Saputra, Digby Chappell, Zhonghe Jiang, Bethany Kon, Petar Kormushev. IROS 2020

Background – Bipedal Robot Design

Non-Anthropomorphic Design

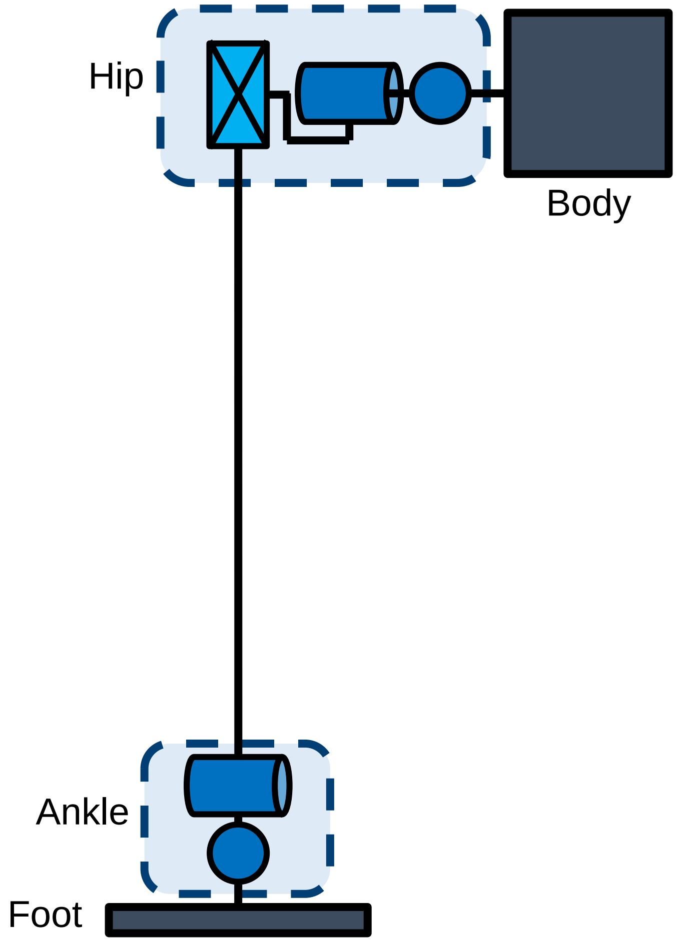
Replace the knee joint with a **prismatic joint** at the hip

Benefits:

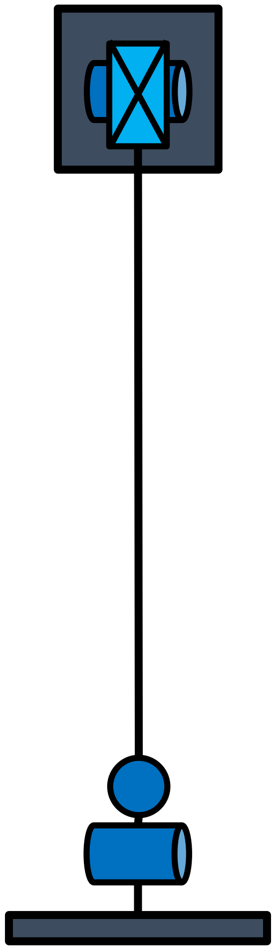
- Mass concentrated closer to the body, lightweight
- Excess power consumption from bent knee walking is eliminated

Drawbacks:

- Complicates the hip mechanism



Kinematic Diagram
Coronal Plane



Kinematic Diagram
Sagittal Plane

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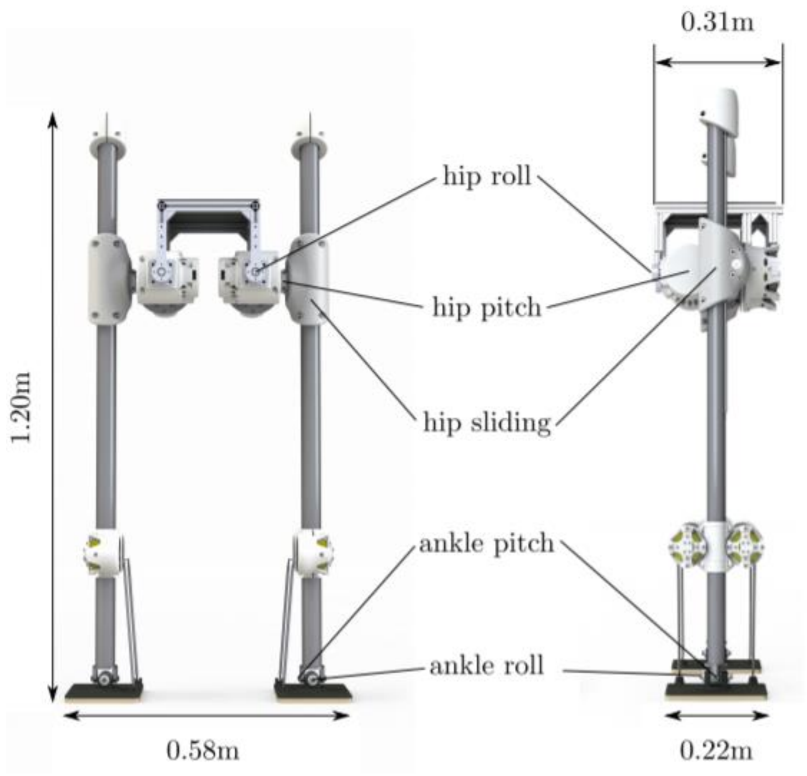
SLIDER: An Ultra-lightweight, Knee-less, Low-cost Bipedal Walking Robot

Goal of Design:

- Low cost (~£10k)
- Easy to manufacture
- Lightweight



Overview

- 1.2m tall and weighs 16kg
- Total cost £7k, most parts 3D printed
- 10 Degrees of Freedom with Knee-less legs. Capable of 3D walking
- Controlled through ROS, with 500Hz for low level controller

Sensors

- Encoders on motor side and output side (only for hip roll)
- IMUs on the pelvis and legs

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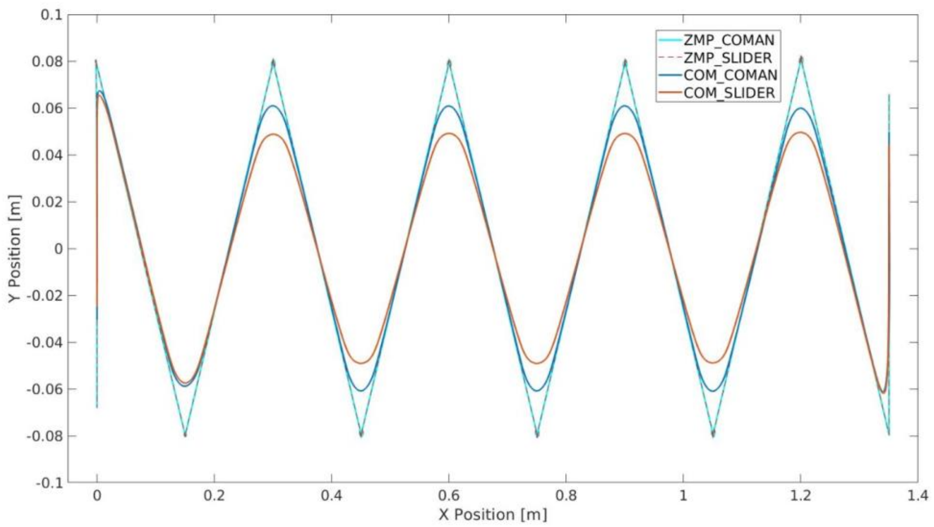
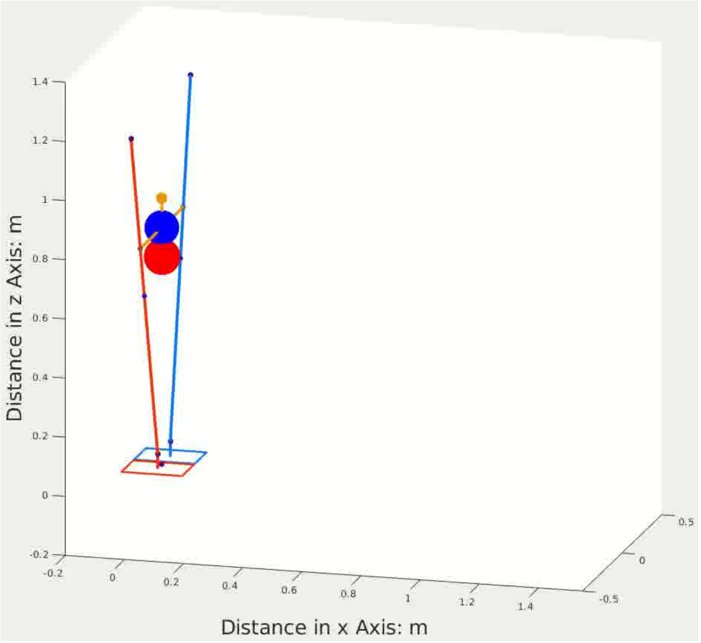
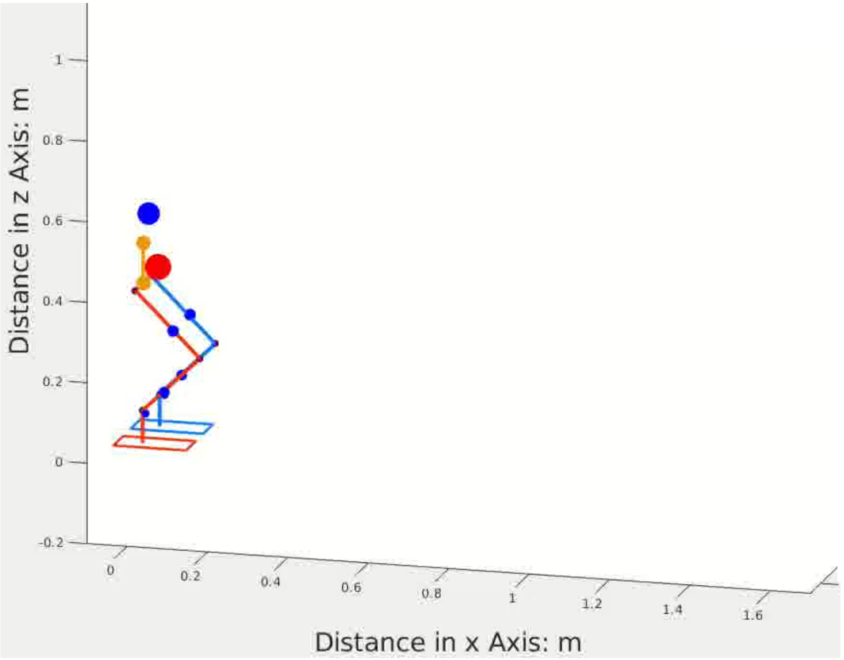
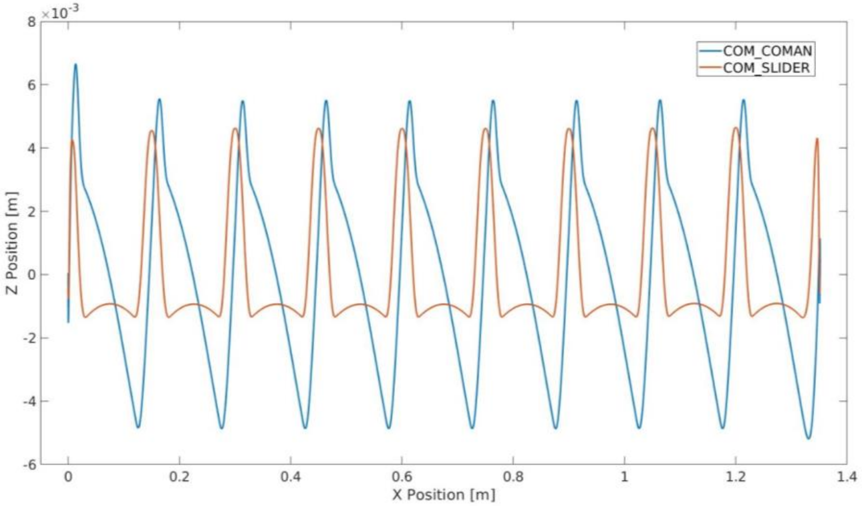
Robots Comparison: Centre of Mass Movement

- SLIDER exhibits less sway in the x-y plane
- SLIDER deviates from constant height less

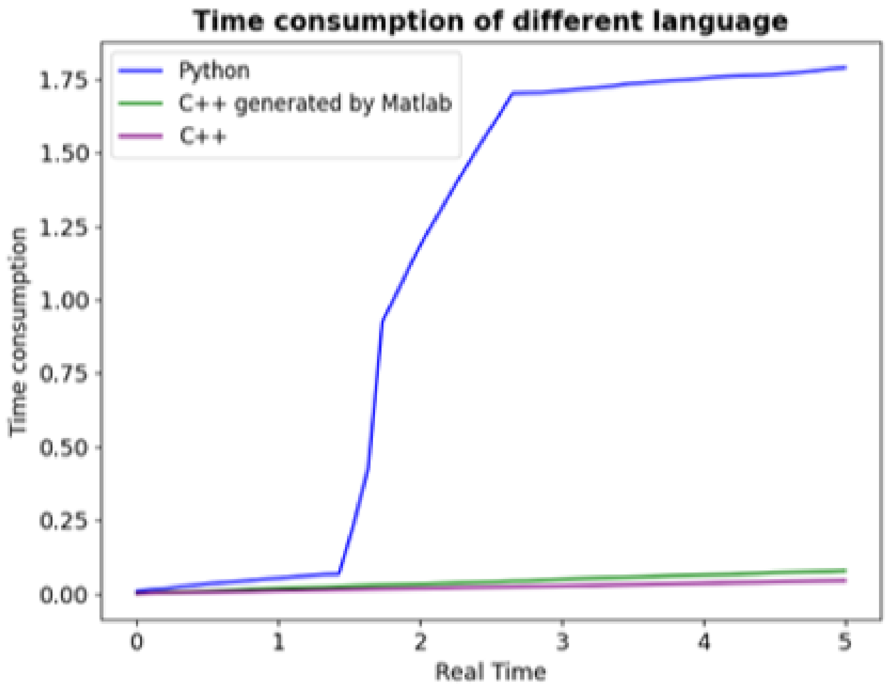


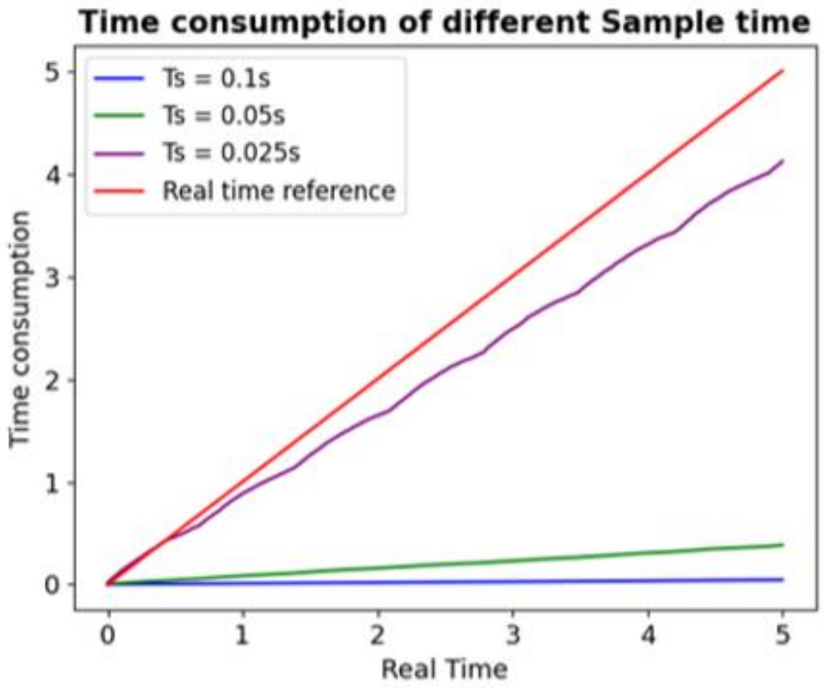


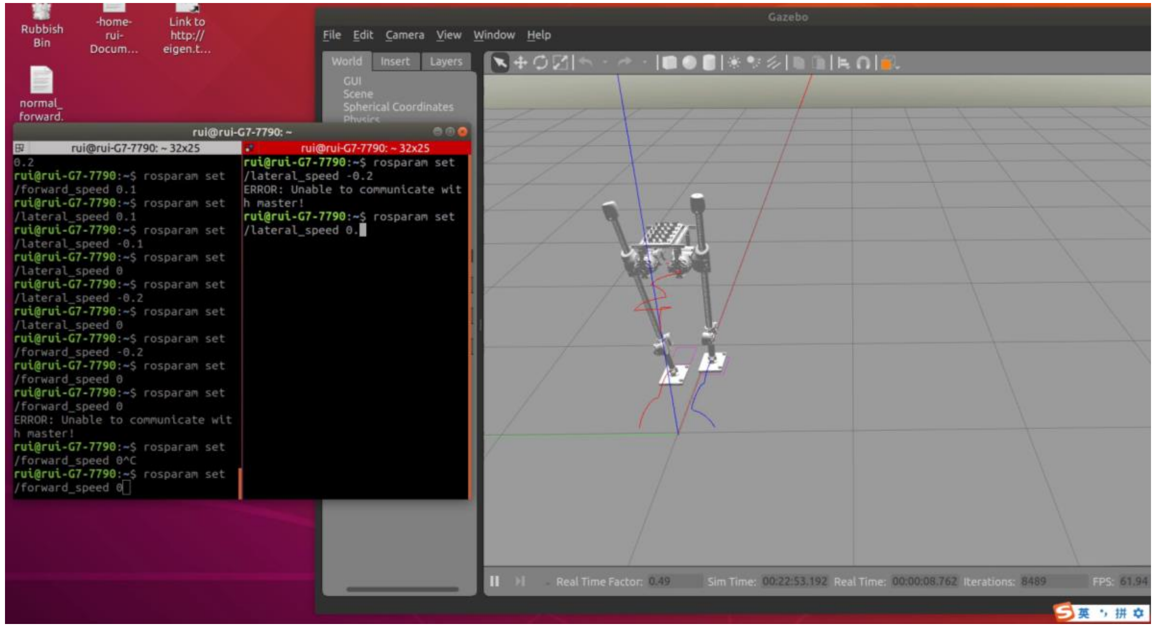


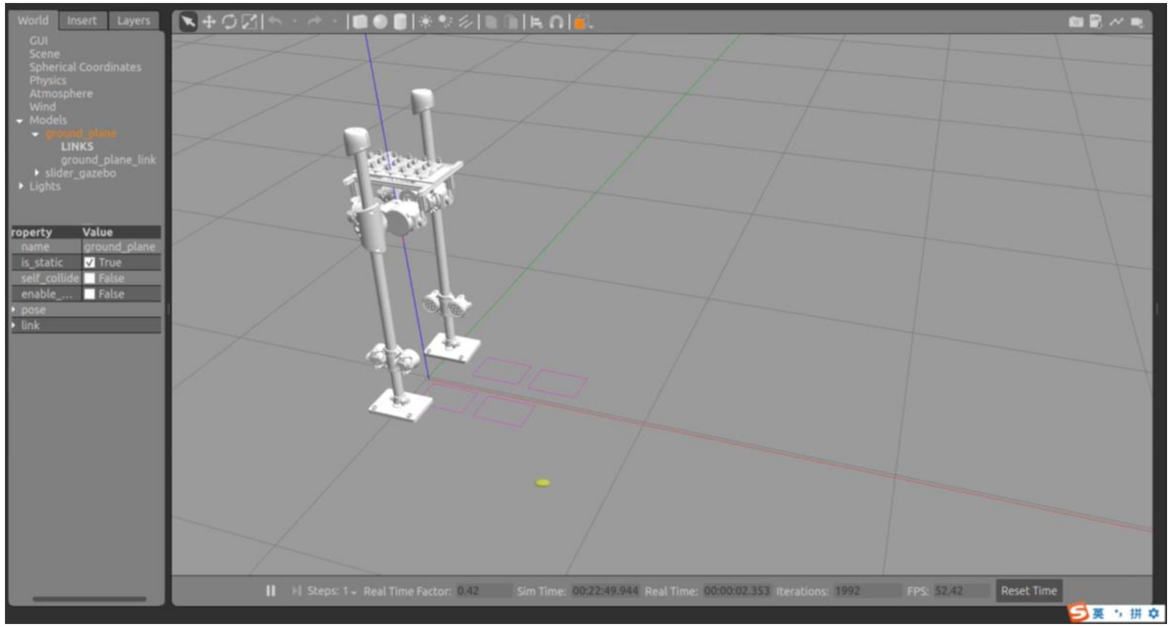


Implementation






Rubbish Bin
-home-rui-Docum...
Link to http://eigen.t...
normal_forward.
Gazebo
File Edit Camera View Window Help
World Insert Layers
GUI
Scene
Spherical Coordinates
rui@rui-G7-7790: ~
rui@rui-G7-7790: ~ 32x25
0.2
rui@rui-G7-7790:~$ rosparam set /forward_speed 0.1
rui@rui-G7-7790:~$ rosparam set /lateral_speed 0.1
rui@rui-G7-7790:~$ rosparam set /lateral_speed -0.1
rui@rui-G7-7790:~$ rosparam set /lateral_speed 0
rui@rui-G7-7790:~$ rosparam set /lateral_speed -0.2
rui@rui-G7-7790:~$ rosparam set /lateral_speed 0
rui@rui-G7-7790:~$ rosparam set /forward_speed -0.2
rui@rui-G7-7790:~$ rosparam set /forward_speed 0
rui@rui-G7-7790:~$ rosparam set /forward_speed 0
ERROR: Unable to communicate with master!
rui@rui-G7-7790:~$ rosparam set /forward_speed 0^C
rui@rui-G7-7790:~$ rosparam set /forward_speed 0
rui@rui-G7-7790: ~ 32x25
rui@rui-G7-7790:~$ rosparam set /lateral_speed -0.2
ERROR: Unable to communicate with master!
rui@rui-G7-7790:~$ rosparam set /lateral_speed 0.
Real Time Factor: 0.49
Sim Time: 00:22:53.192
Real Time: 00:00:08.762
Iterations: 8489
FPS: 61.94


World Insert Layers
GUI
Scene
Spherical Coordinates
Physics
Atmosphere
Wind
Models
ground_plane
LINKS
ground_plane_link
slider_gazebo
Lights
roperty Value
name ground_plane
is_static True
self_collide False
enable_... False
pose
link
Steps: 1
Real Time Factor: 0.42
Sim Time: 00:22:49.944
Real Time: 00:00:02.353
Iterations: 1992
FPS: 52.42
Reset Time

Imperial College London

Robot Intelligence Lab

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Ke Wang, Hengyi Fei and Petar Kormushev

SLIDER Website
http://www.imperial.ac.uk/robot-intelligence/robots/slider/

Contact: k.wang17@imperial.ac.uk

Thank you!