Position Control and Variable-Height Trajectory Tracking of a Soft Pneumatic Legged Robot

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Motivations

Soft Robotic heXapod (SoRX) [1] :

Previous work introduced a novel soft pneumatic legged robot SoRX, able to traverse rough, steep and unstable terrain

Playback Speed: 1x

Playback Speed: 1x

Playback Speed: 1x

[1] Z. Liu *et al*. in IEEE ICRA, 2020

Objectives & Challenges

Objectives:

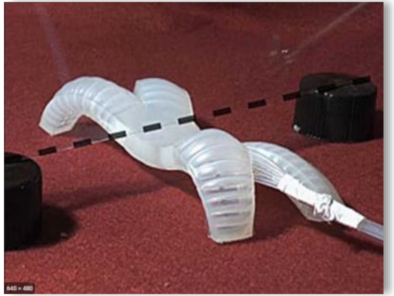
- ❖ Extending motion capabilities: feedforward position control and closed-loop trajectory tracking
- ❖ Preliminary feasibility test for outdoor operations (remote-controlled)

Challenges:

- ❖ Model-based motion control
- ❖ Feedback pressure control
- ❖ Closed-loop trajectory tracking

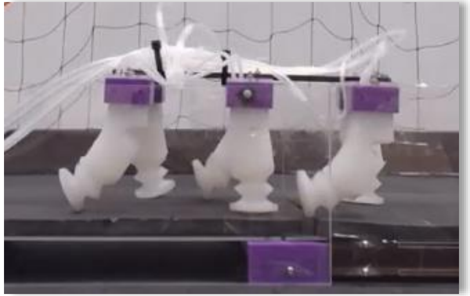
Related Work

Existing work on soft pneumatic legged robots:



R.F. Shepherd *et al.*, 2011

D. Drotman *et al.*, 2017



Z. Liu *et al.*, 2020

D. Drotman *et al.*, 2021

Limitation: relying on empirically hand-tuned input sequences for open-loop control.

Related Work

Existing work on model-based motion control for pneumatically-actuated robots :

- Piecewise constant curvatures & variable curvature models
  e.g., A. D. Marchese et al. 2016, T. Mahl et al. 2014

- Cosserat rod, mass-damper-spring-based, finite-element-method-based
  e.g., P. E. Dupont et al. 2019, Y. Guo et al. 2015, T. M. Bieze et al. 2018

- PID, sliding mode control, MPC and learning-based methods
  e.g., T. M. Bieze et al. 2018, E. H. Skorina et al. 2015, C. M. Best et al. 2016, T. G. Thuruthel et al. 2018

Methods are limited in the application to the control of soft pneumatically-actuated legged robots.

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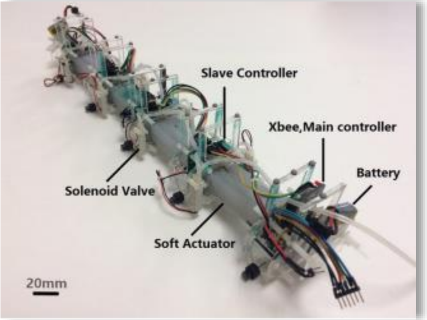
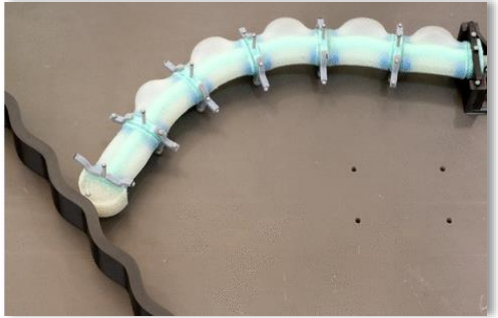
Related Work

Existing work on motion control of soft pneumatic mobile robots (soft robotic snakes):

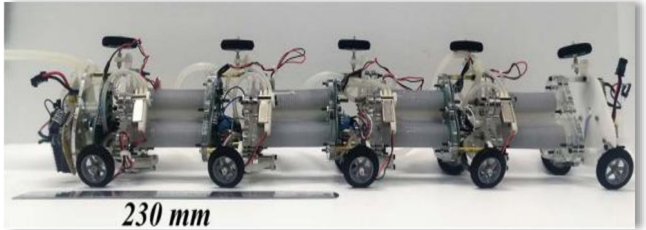
C. D. Onal *et al.*, 2013



M. Luo *et al.*, 2020



C. Della Santina,*et al.*, 2020



Y. Qin *et al.*, 2018

Limitations:

- Rigid parts for contacting with the surface
- Planar movements

Summary

In this work, we develop:

- ❖ A static model based on geometric constraints for feedforward position control (body height and orientation).
- ❖ A pressure feedback controller based on a custom low-cost pneumatic regulation board.
- ❖ A closed-loop trajectory control method to track variable-height trajectories.
- ❖ An experimental study on the robot's position control and trajectory tracking performance.

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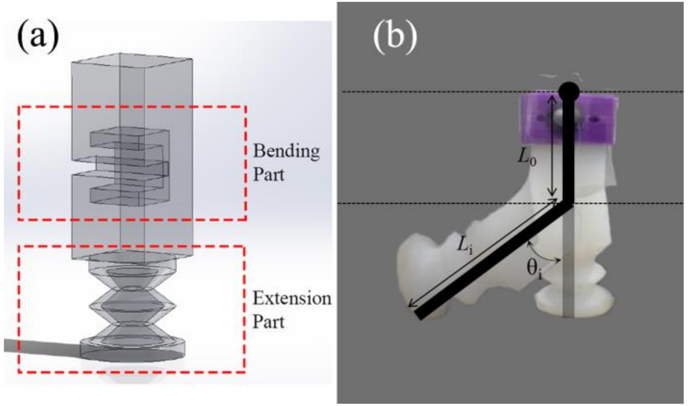
Static Model

Each leg consists of two actuation parts: bending and extension parts.

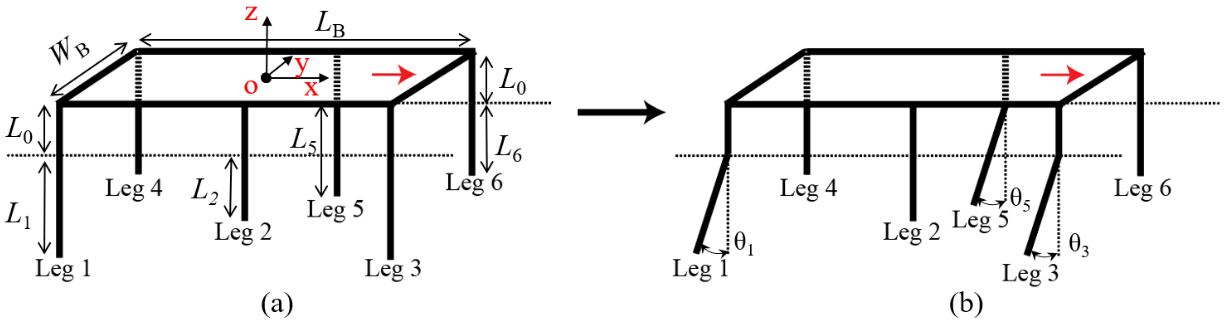
We use one revolute θ_i and one prismatic joint* L_i to model the bending and extension parts.



Playback Speed: 1x

* Includes both the length of the extension part and the distance to the cut of the bending part.

Static Model



- Two steady states for a tripod gait*:

(a) only the extension part actuated
(b) both parts actuated

- The height of the robot:

$$h = L_0 + \frac{L_1 + L_5}{2}$$

- The robot's roll angle along x axis:

$$\phi = \mathrm{atan}(L_5 - L_1, \frac{W_B}{2})$$

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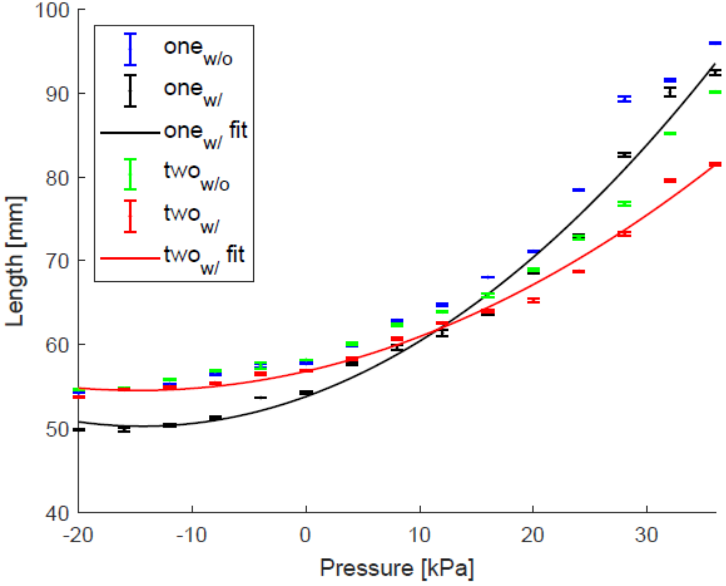
* The robot employs an alternating tripod gait.

Pressure Model



TEST CASES FOR EXTENSION PART MODELING

$\text{one}_{w/o}$	Single-leg tripod side actuated, other side not actuated
$\text{one}_{w/}$	Single-leg tripod side actuated, other side pressurized (30 kPa)
$\text{two}_{w/o}$	Double-leg tripod side actuated, other side not actuated
$\text{two}_{w/}$	Double-leg tripod side actuated, other side pressurized (30 kPa)

POLYNOMIAL COEFFICIENTS FOR MODEL FITTING

Models	Polynomials	Units	Ranges
$\text{one}_{\text{w/}}$	$0.017p^2 + 0.492p + 53.801$	mm	[-20, 36] kPa
$\text{two}_{\text{w/}}$	$0.010p^2 + 0.309p + 56.821$	mm	[-20, 36] kPa
θ	$0.010p + 0.0153$	rad	[-20, 50] kPa

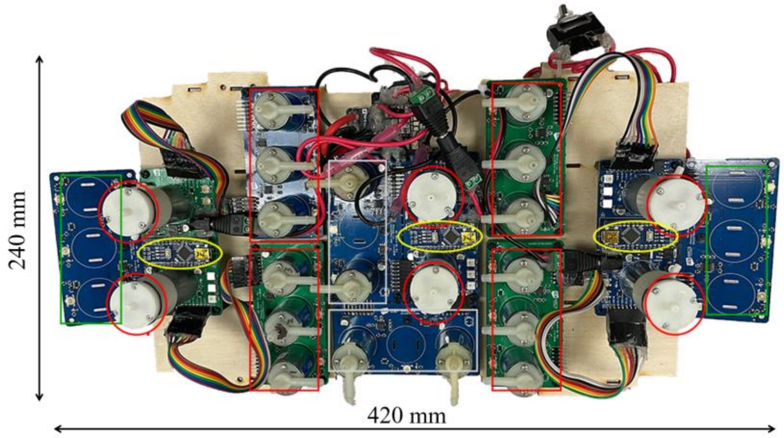
Bending angle model

$$R^2_{\text{one}_{\text{w/}}} = 0.9877 \quad R^2_{\text{two}_{\text{w/}}} = 0.9878 \quad R^2_{\theta} = 0.9691$$

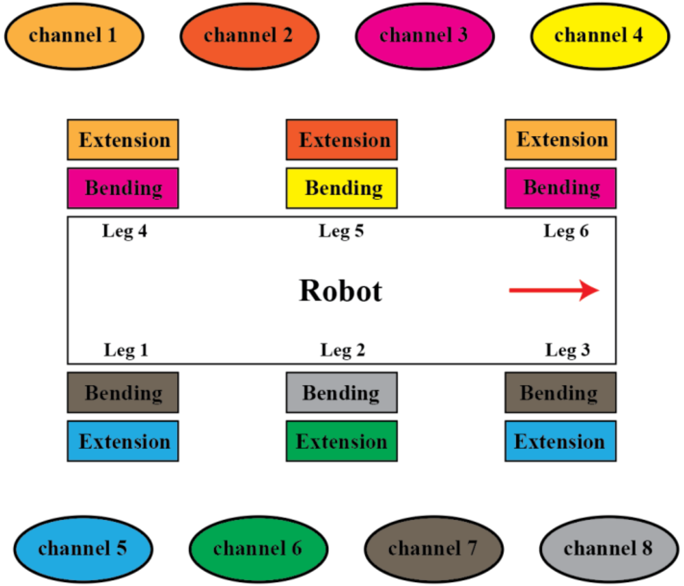
* Extension parts have higher risk to break when input pressure exceeds 36 kPa.

[1] Z. Liu *et al*. in IEEE ICRA, 2020

Pneumatic Regulation



❖ A custom low-cost pneumatic regulation board* that powers up to eight channels of pressurization / depressurization with pressure feedback.



❖ A diagram of eight air output channels to drive 12 actuation parts. Actuation parts and air output channels of the same color are connected.

* https://github.com/Programmable-Air

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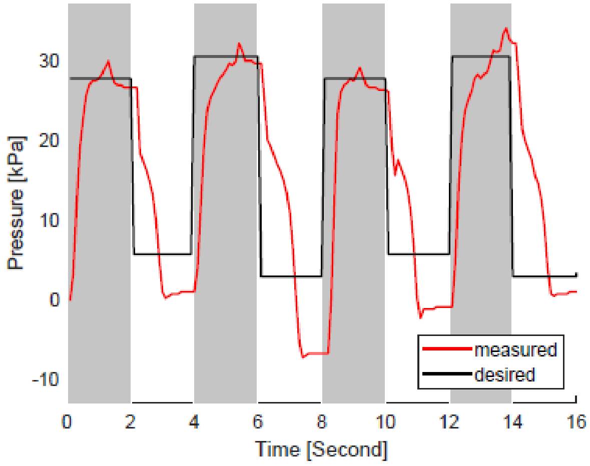
Pneumatic Regulation

Algorithm 1: Pressure Feedback Controller

Given: total time T, threshold ϵ;
Input: the desired trajectories (mode$_t$, desired$_t$), pressure feedback values real$_t$ at time t;
while $t \leq T$ **do**
  if $mode_t$ == *pressurize* **then**
    if $real_t < desired_t - \epsilon$ *and* $Valve_1$ == *closed* **then**
      Valve$_1$ $\leftarrow$ open;
      Pump$_1$ $\leftarrow$ on;
    if $real_t \geq desired_t$ *and* $Valve_1$ == *on* **then**
      Valve$_1$ $\leftarrow$ closed;
      Pump$_1$ $\leftarrow$ off;
  else
    if $real_t > desired_t + \epsilon$ *and* $Valve_2$ == *closed* **then**
      Valve$_2$ $\leftarrow$ open;
      Pump$_2$ $\leftarrow$ on;
    if $real_t \leq desired_t$ *and* $Valve_2$ == *on* **then**
      Valve$_2$ $\leftarrow$ closed;
      Pump$_2$ $\leftarrow$ off;



❖ Step response for the proposed pressure feedback controller.

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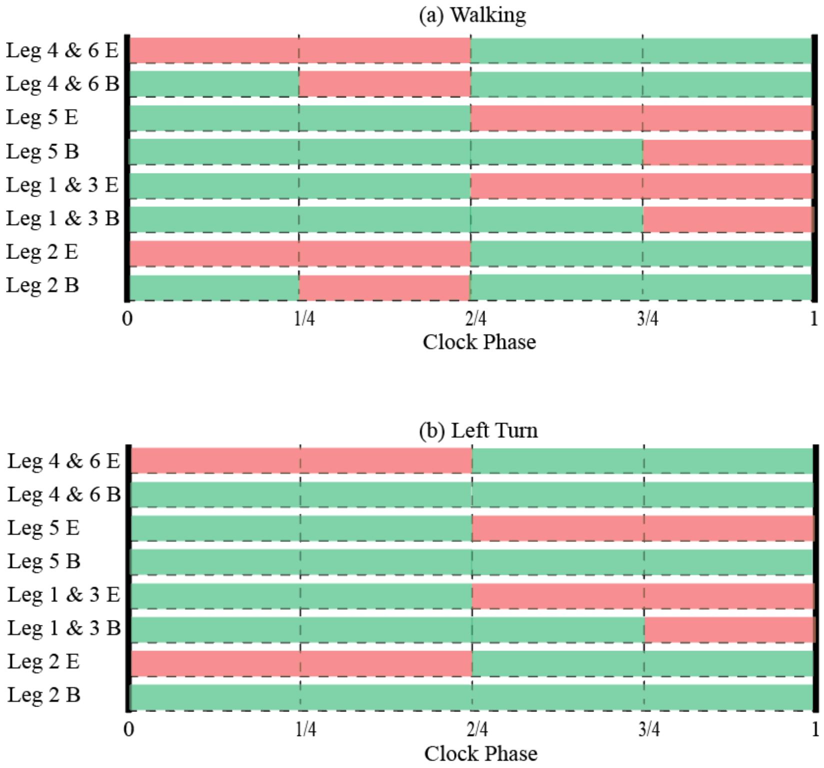
Walking & Turning



Playback Speed: 4x

- ❖ Actuation sequences for (a) walking and (b) left turn.
- ❖ Notations E and B represent extension and bending parts, respectively.
- ❖ Red boxes are used to represent pressurization, while the green ones stand for depressurization
- ❖ A full actuation sequence enables the robot to turn by approximately 10◦.

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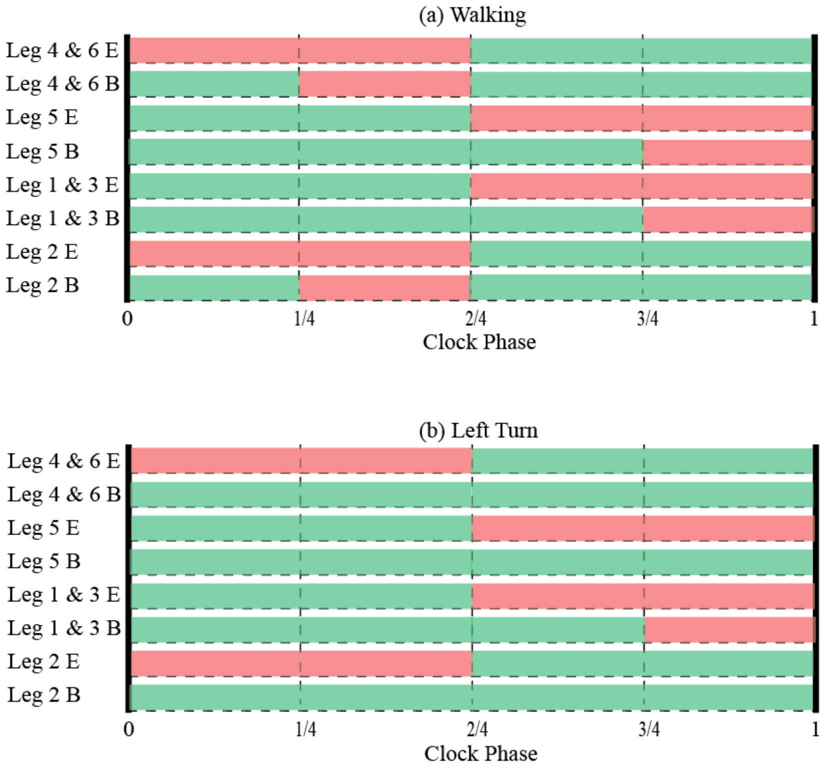
Velocities



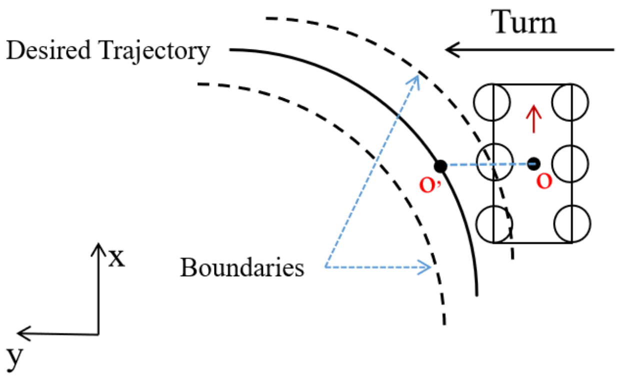
	Clock Phase [s]	Velocities [mm/s]	Velocities [BL/s]
Open-loop pressure control[1]	1.6	101	0.44
Closed-loop pressure control	6.6	24	0.11

❖ When turning, the speed of the robot is further slowed down as the robot moves forward during only half of the clock phase.

[1] Z. Liu *et al*. in IEEE ICRA, 2020

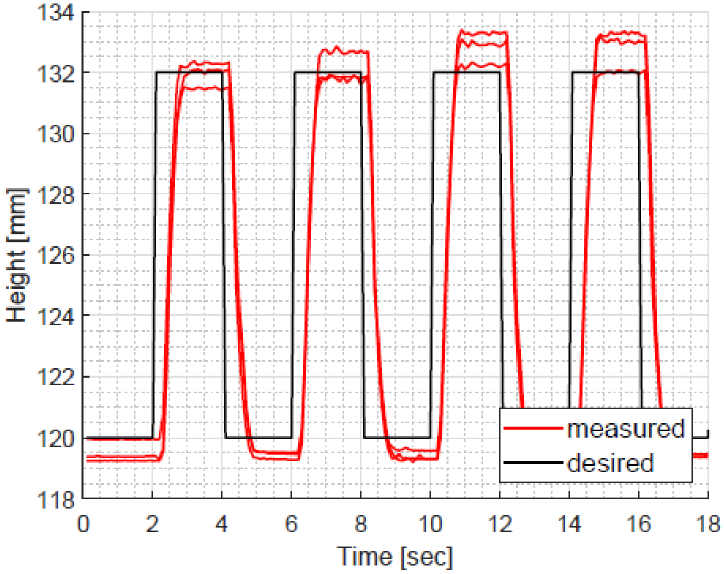
Trajectory Tracker

- Inputs: 3D position from motion capture and desired one.
- A 2D corridor (black dashed lines) with user-defined distance from the desired trajectory.
- Turning gaits triggered when the robot's center lies outside the corridor.
- Desired height (z values) is tracked for variable-height trajectories.



Experiment

Position Control - Height



Playback Speed: 1x

❖ Desired heights: 132 and 120mm

❖ Desired pressures:

- Double-leg side: 19.75 and -8.11 kPa
- Single-leg side: 16.93 and 2.26 kPa

❖ 3 consecutive trials

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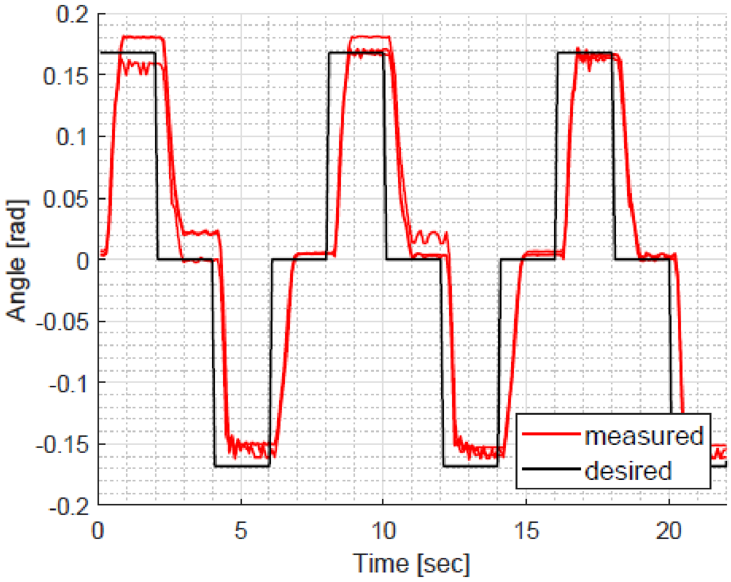
Experiment

Position Control - Orientation

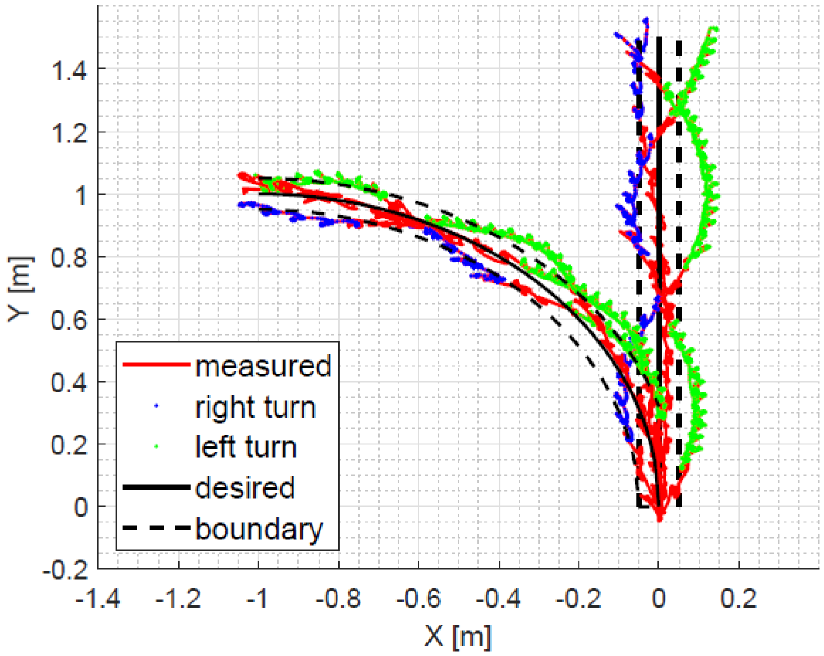


Playback Speed: 1x

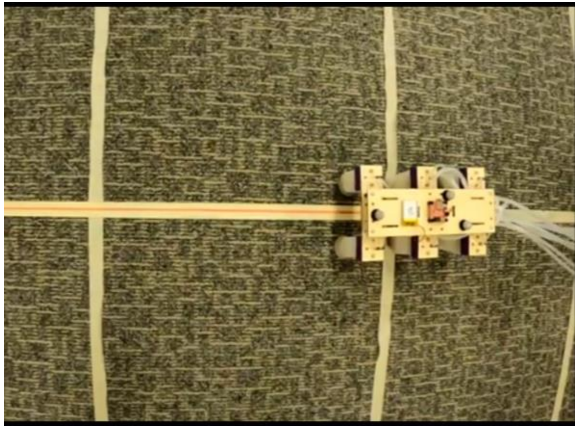
- Applied same desired pressure inputs to two side of one tripod
- Desired height different: $\mathrm{h} = \pm(L_5 - L_1) = \pm 12\text{mm}$
- Desired roll angle: $\phi = \pm \arctan(\frac{2(L_5 - L_1)}{W_B}) = \pm 0.17$ rad
- 3 consecutive trials

Experiment

2D Trajectories - Lines



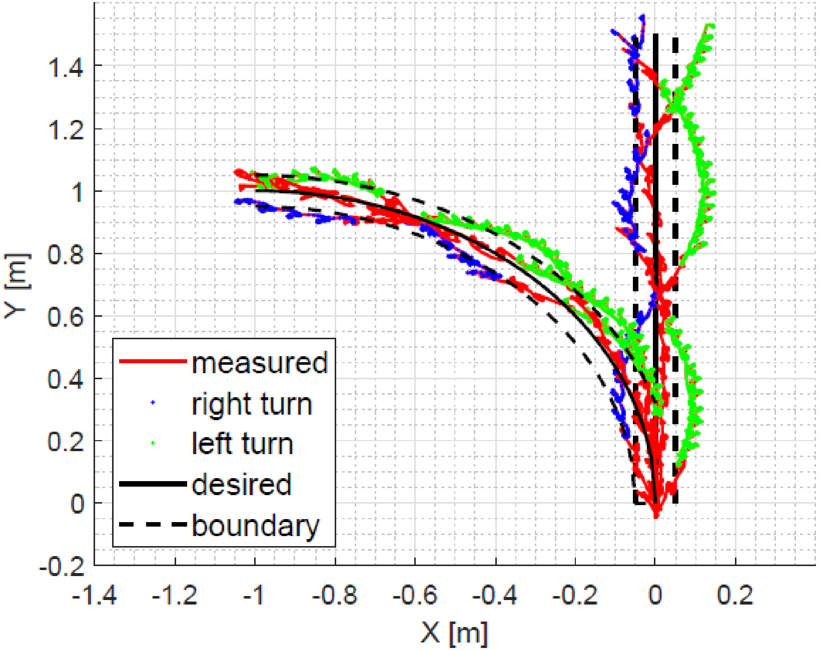
Playback Speed: 8x, starting angle 0



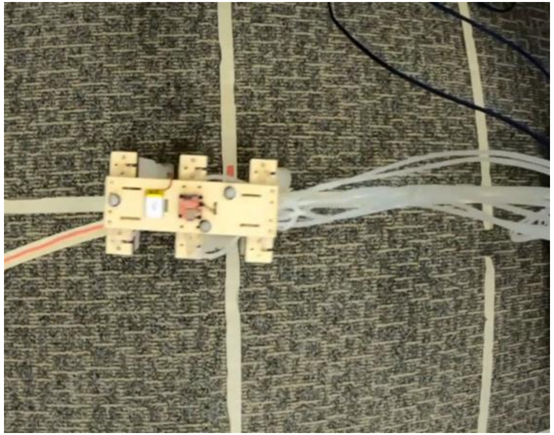
- Start: (0,0) Goal: (0,1.5) m
- Desired trajectory: Line $x = 0$
- Robot stops after passing the line $y = 1.5$ m
- 2D corridor set as $x = \pm 0.05$ m
- 3 trials with different starting angles $0, \pm 15^{\circ}$

Experiment

2D Trajectories - Curves



Playback Speed: 8x, starting angle 0



- Start: (0,0) Goal: (-1,1) m
- Desired trajectory: Quarter circle of $(x+1)^2+y^2=1$
- Robot stops after passing the line $x=-1$ m
- 2D corridor set as quarter circles of $(x+1)^2+y^2=(1\pm 0.05)^2$
- 3 trials with the same starting angle 0

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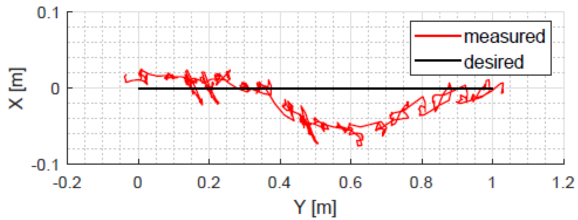
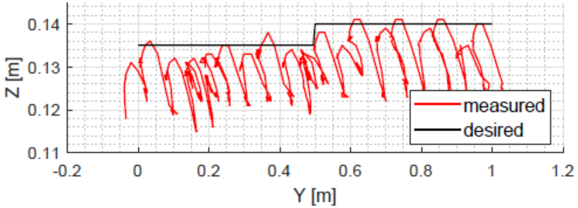
Experiment

Variable-Height & Analysis



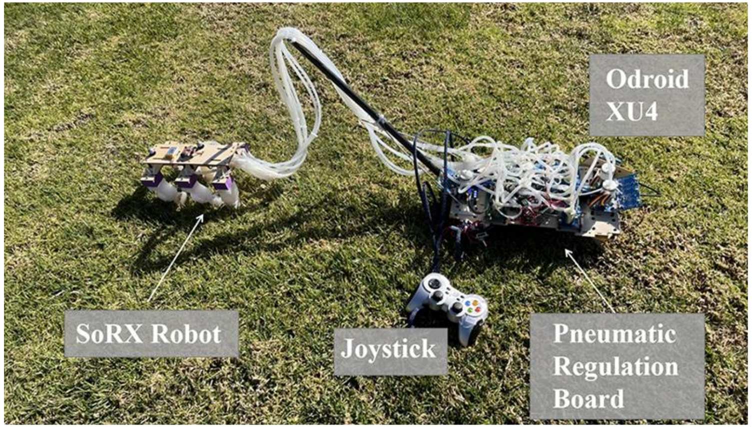


- Repeat the line tracking test
- Desired trajectory: Line $x = 0$
- Desired maximal height switching from 0.135 to 0.140 m after the line $y = 0.5$

Tracking Performance for all tests

Variables	Tracking Errors	Units
Step Response p	-0.737 ± 11.198	kPa
Position Control Height h_1	-0.263 ± 4.910	mm
Position Control Angle ϕ	0.006 ± 0.073	rad
Trajectory Tracking Line d_1	0.029 ± 0.019	m
Trajectory Tracking Curve d_2	0.045 ± 0.020	m
Trajectory Tracking Variable-Height d_3	0.024 ± 0.020	m
Trajectory Tracking Variable-Height h_2	-1.474 ± 2.245	mm

Outdoor Field Tests



- ❖ SoRX can operate in outdoor environments, thanks to the compact and portable pneumatic regulation board.
- ❖ Walking and steering is remote-controlled.
- ❖ Motivate research on autonomous soft legged robots in outdoor environments.

Playback Speed: 3x

- ❖ Powered by the untethered board, SoRX operates on various types of natural rough terrain, including creeks and gravel.

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Discussion

Limitations:

- Tethered
- Nonconverging tracker
- Relying on motion capture for feedback

Future Work:

- Fully untethered soft legged robot
- More involved trajectory trackers
- Autonomous operations in outdoor environment

Acknowledgement

The authors wish to thank Dr. Elia Scudiero for offering access to outdoor experimental fields for testing.

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Thank you!

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