CONTROL OF DYNAMIC GAITS FOR A QUADRUPEDAL ROBOT

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OVERVIEW

Motivations:

- Reproduce quadrupedal animal-like locomotion
- Implement a controller framework that dynamically chooses the right gait to match a target speed, as animals naturally do

Challenges:

- Unassisted navigation in 3D space
- Unperceived 3D obstacles on the ground
- Smooth transition between gaits
- Recover from external significant pushes and terrain variations

INTRODUCTION

Type of robot:
- StarlETH: quadruped robot

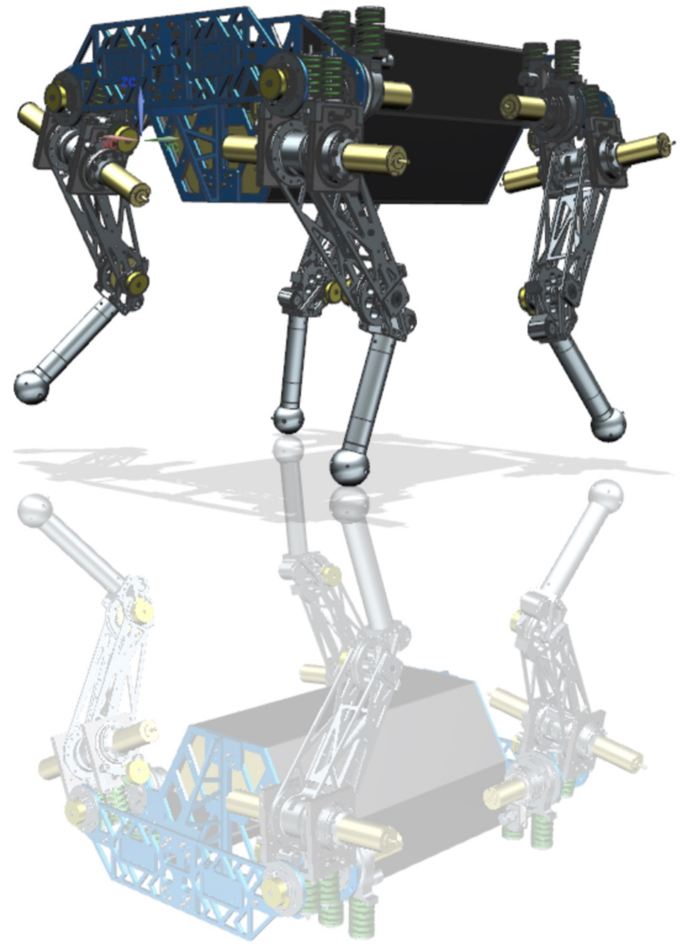
Type of control:
- Torque control for stance legs
- Position control for swing legs

Design method:
- Modular approach, based on biomechanical models (e.g., inverted pendulum for foot placement).

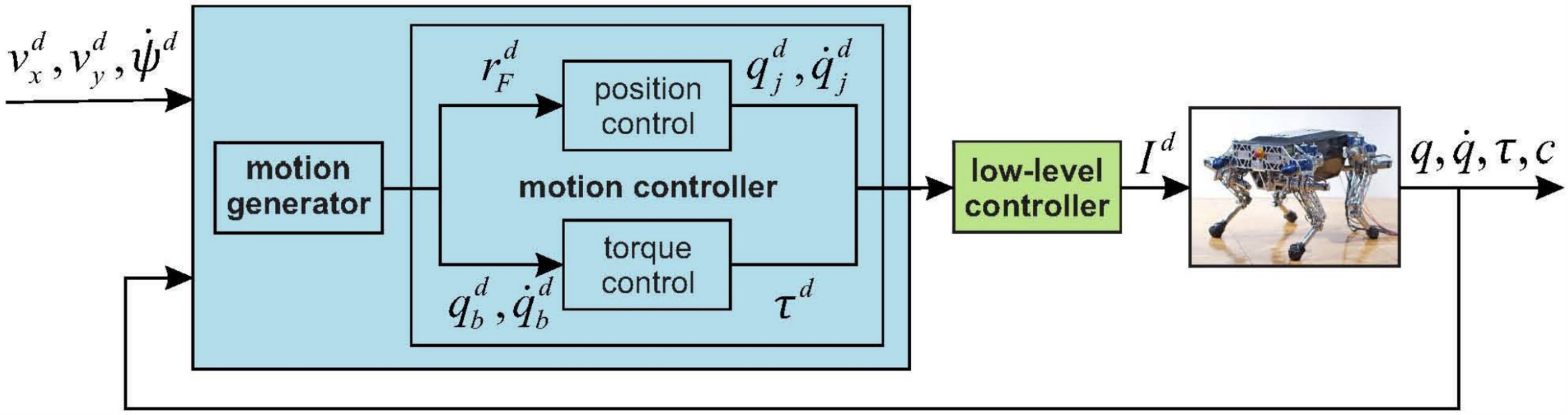
Type of gait:
- Static walking
- Walking trot

Main sensors:
- Inertial Measurement Unit (IMU) for orientation.
- Pressure sensors in feet to detect ground contact.
- Motor Encoders
- Spring Deflection Sensors

Main actuators:
- Series-Elastic Actuators (SEAs)

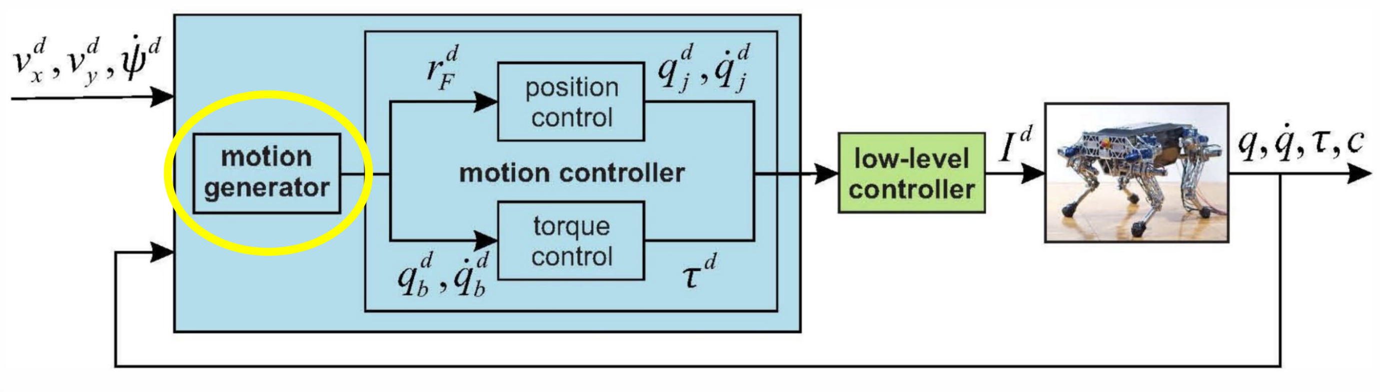


CONTROL FRAMEWORK



THE MOTION GENERATOR

- Terrain Estimation
- Swing Leg Configuration
- Stance Leg Configuration
- Main Body Configuration



TERRAIN ESTIMATION

No external sensors → Weighted average of two values:

- The vertical positions of the feet currently in contact with the ground
- The previous ground height estimate from the last time step

$$h_g(t) = \sum_{i=0}^{N=4} c_{\text{flag}\,i}\left({}_{I}r_{\mathrm{F_i,z}} \cdot \alpha + h_g(t - \Delta t) \cdot (1 - \alpha)\right)$$

SWING LEG CONFIGURATION

The target foothold: $${}_I\boldsymbol{r}_{\mathrm{HF}} = {}_I\boldsymbol{r}_{\mathrm{HF}}^{\mathrm{fb}} + {}_I\boldsymbol{r}_{\mathrm{HF}}^{\mathrm{ff}}$$

The feedback component:
It corrects the leg's movement in real time, especially for balance.

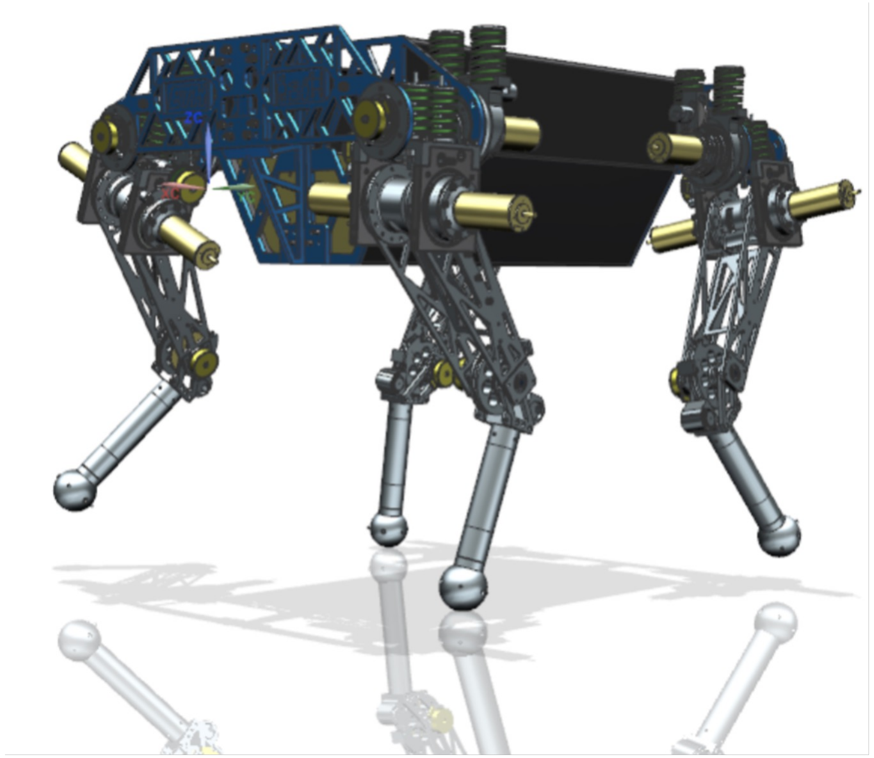
$${}_I\boldsymbol{r}_{\mathrm{HF}}^{\mathrm{fb}} = \eta({}_I\boldsymbol{v}_{ref} - {}_I\boldsymbol{v}^d)\sqrt{\frac{h}{g}}$$

The feedforward component:
It adjusts the foot placement to maintain smooth and stable motion during forward movement.

$${}_I\boldsymbol{r}_{\mathrm{HF}}^{\mathrm{ff}} = \frac{1}{2}{}_I\boldsymbol{v}^d \Delta t_{st}$$

STANCE LEG CONFIGURATION

When a leg is in stance mode but loses ground contact, it slightly lowers to regain contact.



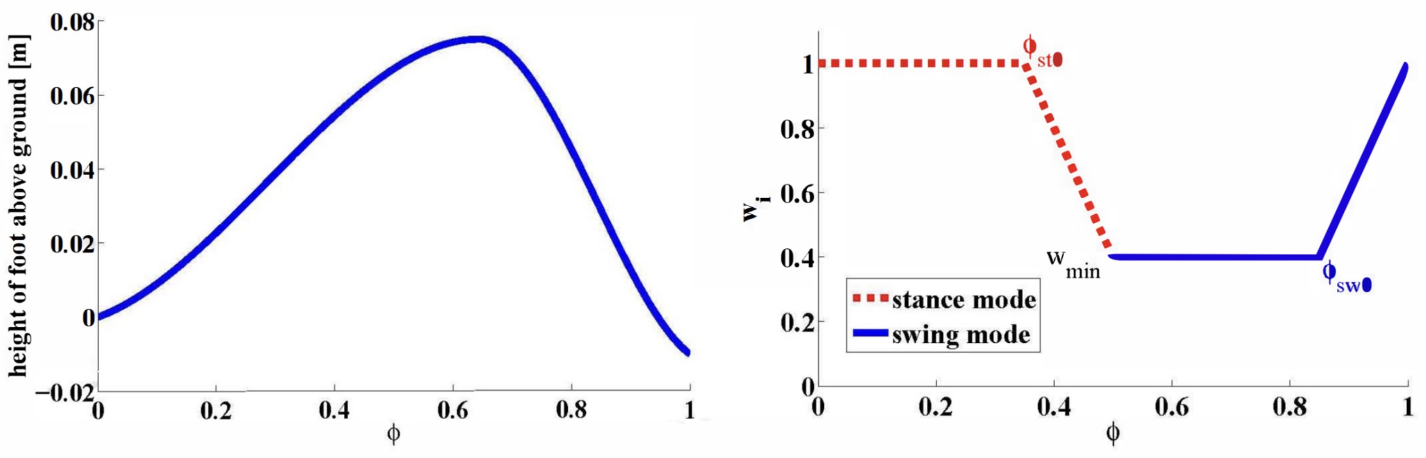
MAIN BODY CONFIGURATION

The robot's main body position depends on the location of its legs :

- Grounded legs
- Swing legs

Weighting functions help adjust the body's position, preparing it for transitions between leg phases. This design ensures the robot moves fluidly and maintains balance during complex actions.

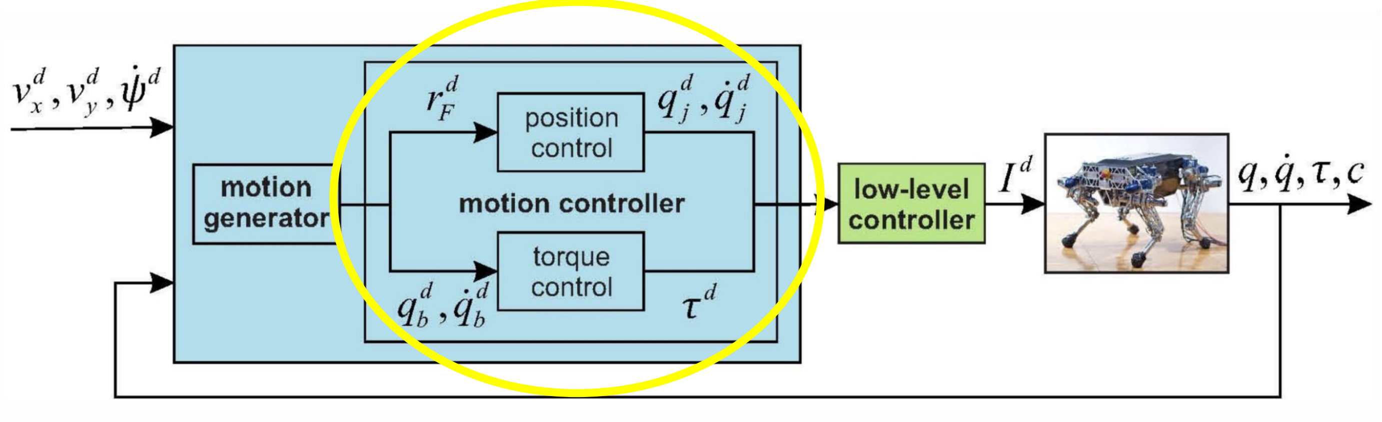
$$ {}_{I}\boldsymbol{r}_{\mathrm{B}}^{d} = \frac{\sum_{i=1}^{N} w_i(\phi)\, {}_{I}\boldsymbol{r}_{\mathrm{F_i}}}{\sum_{i=1}^{N} w_i(\phi)} $$



(a) Swing foot trajectory (b) Weights for balance control

THE MOTION CONTROLLER

- **Control Modes**
  - Position Control → Applied to swing legs
  - Torque Control → Applied to stance legs
- **Gait Transitions**



CONTROL MODES

Position Control:

- Applied to swing legs: ensure accurate tracking of desired joint trajectories.

  The desired joint angles are obtained from the desired foot positions through inverse kinematics

CONTROL MODES

Torque control:

- Applied to stance legs: generate the necessary forces for stability and body support.

1. Virtual force and torque computation for body stability: $$\begin{bmatrix} {}_B\boldsymbol{F}^d_{\mathrm{B}} \\ {}_B\boldsymbol{T}^d_{\mathrm{B}} \end{bmatrix} = \boldsymbol{k_p}(\boldsymbol{q}^d_b - \boldsymbol{q}_b) + \boldsymbol{k_d}(\dot{\boldsymbol{q}}^d_b - \dot{\boldsymbol{q}}_b) + \boldsymbol{k_{ff}} \begin{pmatrix} v^d_{\mathrm{x}} \\ v^d_{\mathrm{y}} \\ mg \\ 0 \\ 0 \\ \dot{\psi}^d \end{pmatrix}$$
2. Force distribution: $$\begin{aligned} \text{minimize} \quad & (A\boldsymbol{x} - \boldsymbol{b})^{\mathrm{T}} S (A\boldsymbol{x} - \boldsymbol{b}) + \boldsymbol{x}^{\mathrm{T}} W \boldsymbol{x} \\ \text{subject to} \quad & F^n_{\text{leg,i}} \geq F^n_{\min}, \\ & -\mu F^n_{\text{leg,i}} \leq F^t_{\text{leg,i}} \leq \mu F^n_{\text{leg,i}} \end{aligned}$$
3. Mapping to joint torques: $$\boldsymbol{\tau} = J^T \boldsymbol{F}_{leg}$$

GAIT TRANSITIONS

- Linear interpolation of the parameter sets
- Can be initiated at any point of the stride cycle
- Initiated either by an operator or as a function of the desired speed
- Change gait seamlessly → enhance agility + adaptability

RESULTS: PARAMETER SETS

TABLE I
PARAMETER SETS FOR DIFFERENT GAITS

Parameter	Symbol	Static Walk	Walking Trot	Running Trot
gait graph				
stride duration	$T_s[s]$	1.5	0.8	0.7
min. leg weight for support polygon	w_{min}	0.35	0.15	0.15
start of increasing the weight of a swing leg for support polygon	$\phi_{\mathrm{sw},0}$	0.7	0.7	0.7
start of decreasing the weight of the stance leg for support polygon	$\phi_{\mathrm{st},0}$	0.7	0.7	0.7
default left front swing leg offset	${}_B\boldsymbol{r}^d_{\mathrm{HF}}[m]$	$[0, -0.01, 0]^T$	$[0, 0, 0]^T$	$[0, 0, 0]^T$
default left hind swing leg offset	${}_B\boldsymbol{r}^d_{\mathrm{HF}}[m]$	$[0, 0.14, 0]^T$	$[0, 0, 0]^T$	$[0, 0, 0]^T$
height of middle of hip AA joints	$h_H[m]$	0.39	0.44	0.44
virt. force proportional gain	$\boldsymbol{k}_p$	$[500, 640, 600, 400, 200, 0]^T$	$[0, 640, 600, 400, 200, 0]^T$	$[0, 640, 2600, 400, 200, 0]^T$
virt. force derivative gain	$\boldsymbol{k}_d$	$[150, 100, 120, 6, 9, 0]^T$	$[150, 100, 120, 6, 9, 0]^T$	$[90, 60, 120, 6, 9, 0]^T$
virt. force feed-forward gain	$\boldsymbol{k}_{ff}$	$[25, 0, 1, 0, 0, 0]^T$	$[60, 0, 1, 0, 0, 0]^T$	$[25, 0, 1, 0, 0, 0]^T$
weights for matching the des. virt. forces	S	$\mathrm{diag}(1, 1, 1, 10, 10, 5)$	$\mathrm{diag}(1, 1, 0.2, 20, 20, 5)$	$\mathrm{diag}(1, 1, 0.2, 20, 20, 5)$
weights for reducing joint torques	W	$\mathrm{diag}(0.00001 \ldots)$	$\mathrm{diag}(0.00001 \ldots)$	$\mathrm{diag}(0.00001 \ldots)$

RESULTS: ROBUSTNESS

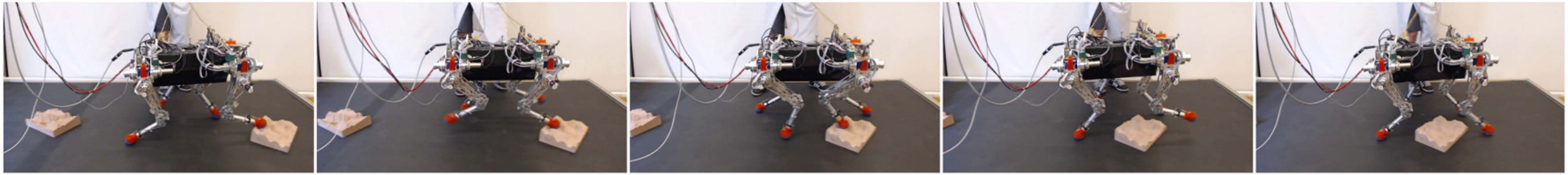


Fig. 5. StarlETH performs a walking trot while dealing with unperceived obstacles.

How to assess robustness ?

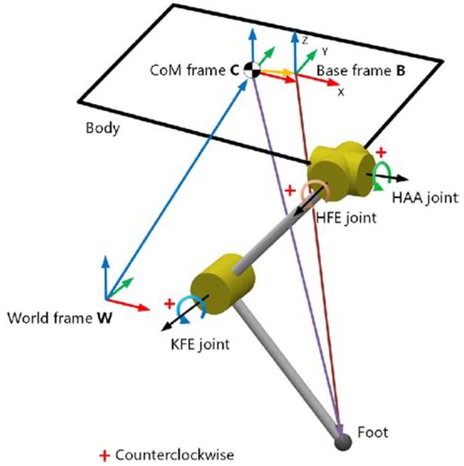
Run **experimental tests** while **varying** the configurations.

- Walk and trot gaits on flat ground
- 5cm high soft (foam) unanticipated obstacles
- Test recovery from external pushes

Maximum speed in walking trot: **0.7m/s**

Diagnose the source of failure:

- Limited HAA joint angle



RESULTS: PUSH RECOVERY

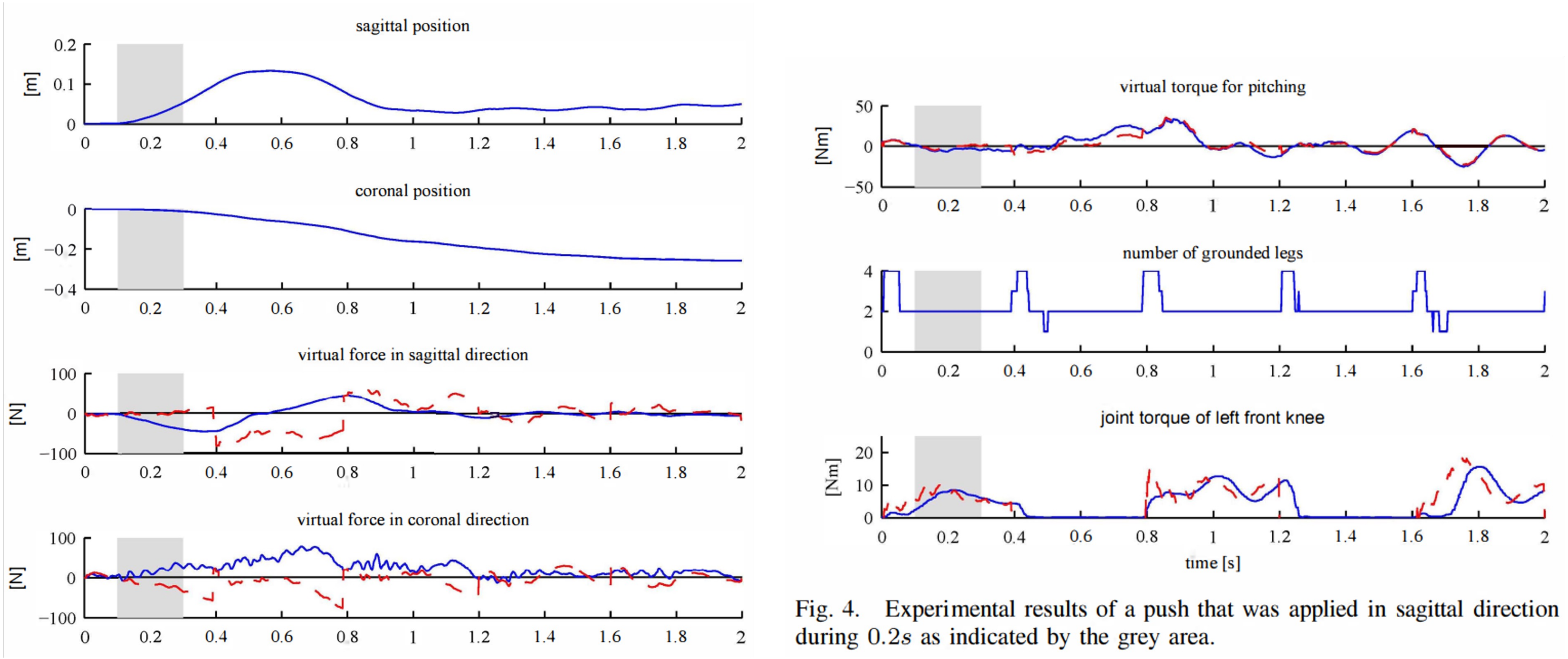


Fig. 4. Experimental results of a push that was applied in sagittal direction during 0.2s as indicated by the grey area.

StarlETH's INFLUENCE ON RESEARCH

242 citations

- *High speed trot-running: Implementation of a hierarchical controller using proprioceptive impedance control on the MIT Cheetah*, DJ. Hyun, S. Seok, J. Lee, S. Kim - The International Journal of Robotics Research, 2014

- *MIT Cheetah 3: Design and control of a robust, dynamic quadruped robot*, G. Bledt, MJ. Powell, B. Katz, J. Di Carlo… - IROS, 2018

- *High-slope terrain for locomotion for torque-controlled quadruped robots*, M. Focchi, A. Del Prete, I. Havoutis… - Autonomous Robot, 2017

- *Mechanism, actuation, perception, anc control of highly dynamic multilegged robots: a review*, J. He, F. Gao - Chinese Journal of Mechanical Engineering, 2020

PROS & CONS

Pros:

- Flexible Control System
- Smooth Transitions Between Gaits
- Robustness to Disturbances
- Real-World Implementation
- Building on Existing Research
- Modular and Intuitive Tuning

Cons:

- Limited Variety of Gaits
- Lack of Quantitative Evaluation
- Parameter Tuning Not Systematic
- Assumption of Flat Terrain

POSSIBLE EXAM QUESTIONS

- **Explain the solution used on StarlETH to achieve smooth gait transitions.**
  - The parameters such as controller gains and force distribution coefficients are tuned iteratively until the robot finds its balance. A set of those parameters can be established for each gait. Then, linearly interpolating between two gaits' parameter sets leads to a more or less smooth transition.

- **What are the main components of the control framework used on StarlETH ?**
  - Motion generator:
    - Terrain estimation
    - Swing/stance leg configuration
    - Main body configuration
  - Motion controller:
    - Position control for swing legs
    - Torque control for stance legs