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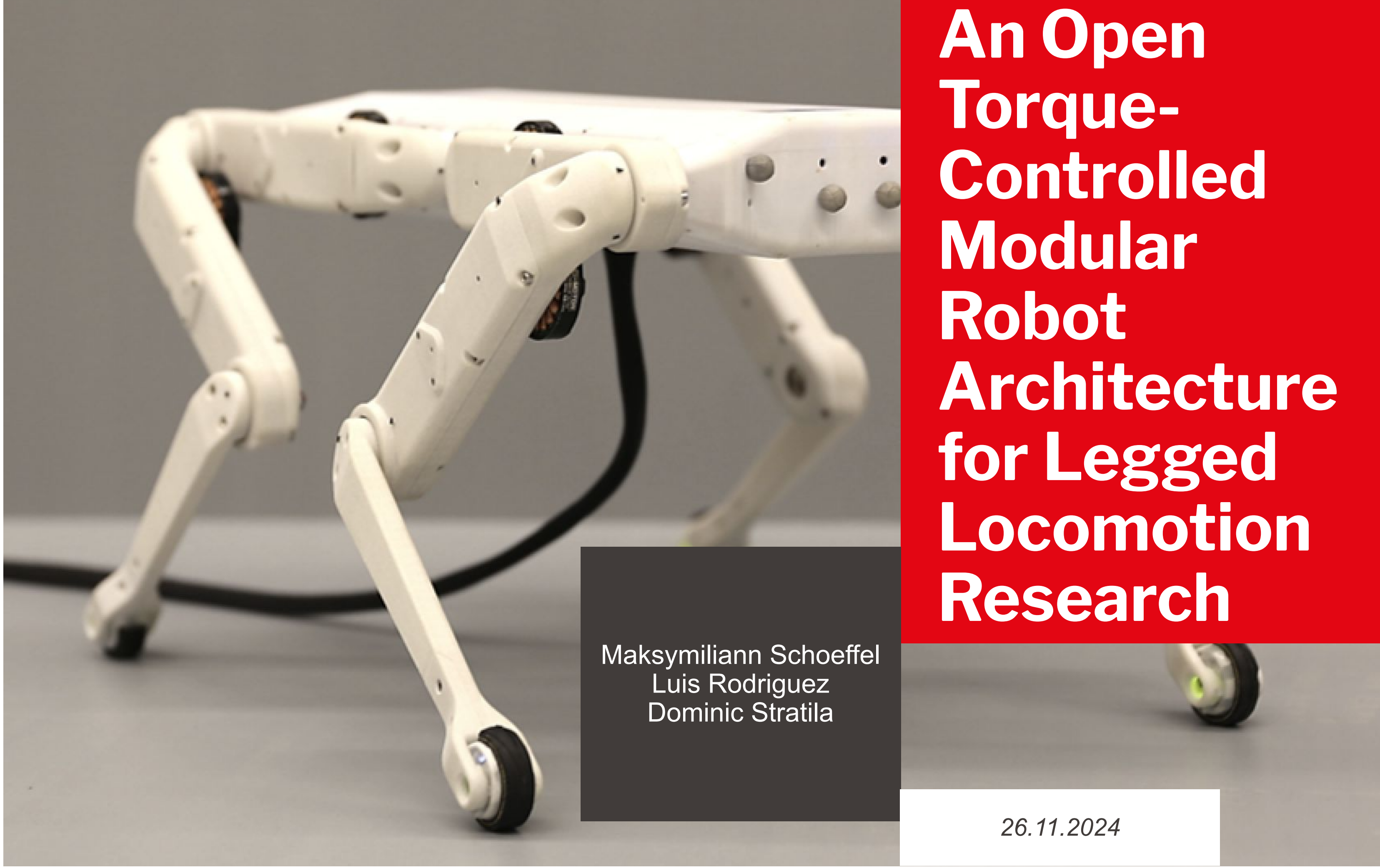

An Open Torque-Controlled Modular Robot Architecture for Legged Locomotion Research

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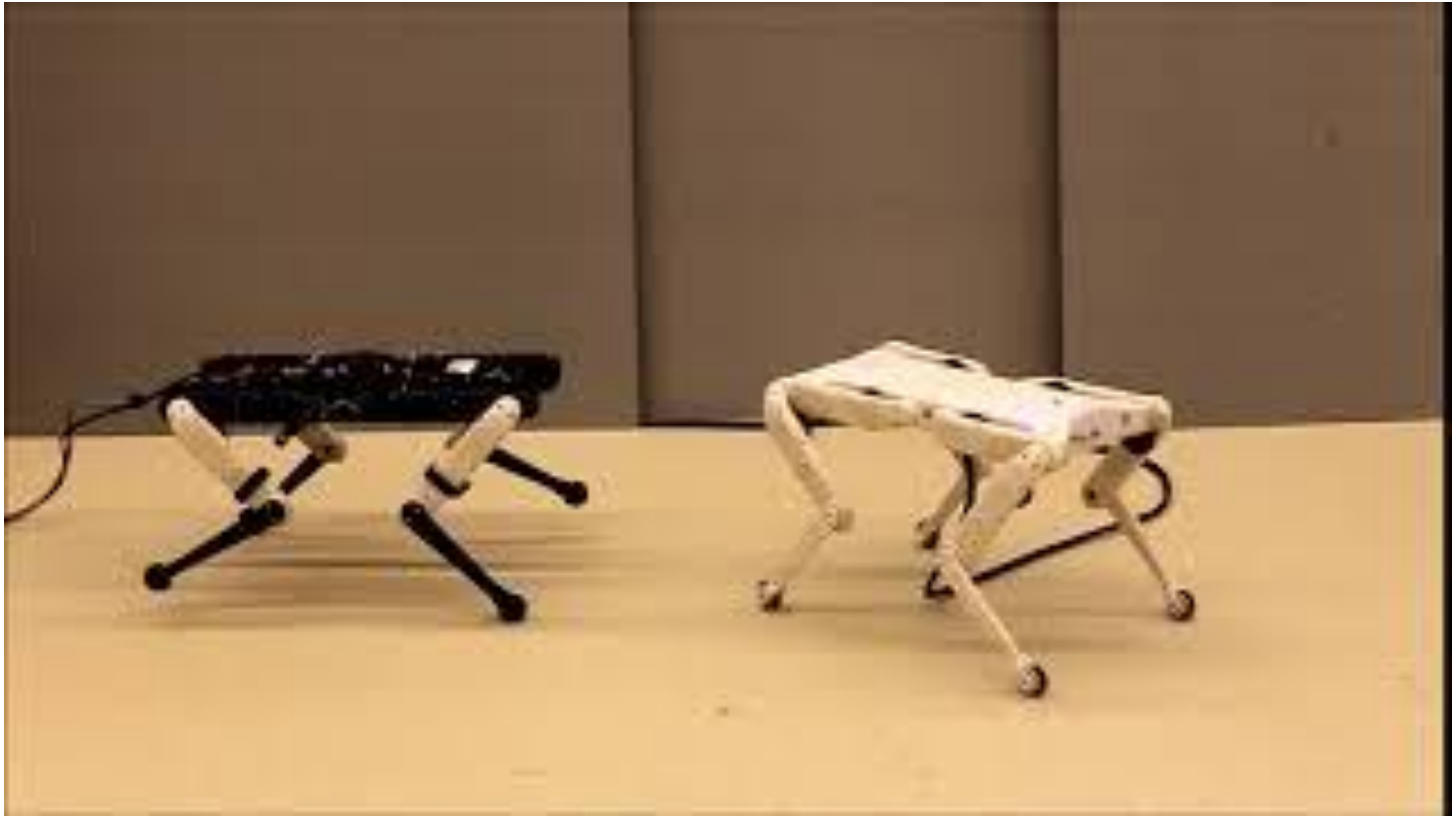
MICRO-507

Introductory Video

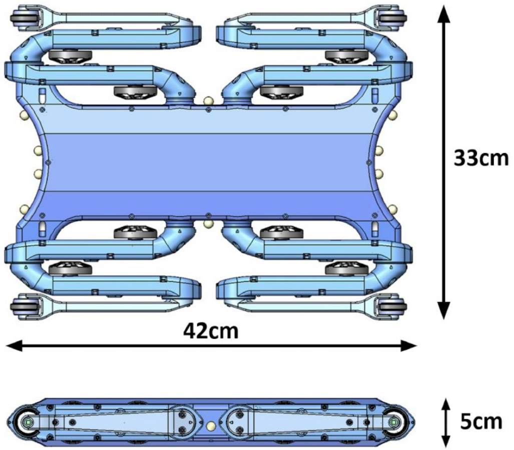


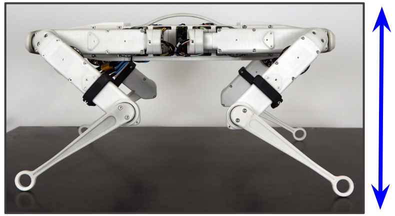
Platform And Robot Overwiew

This article introduces the SOLO robot, designed to advance research in legged robot locomotion. The creators developed a lightweight, low-cost, and versatile robot with human-like leg stiffness, making it manageable by a single researcher. The article also discusses the robot's main mechanical components and presents experiments evaluating its performance.

- Weight: 2.2 kg
- Hip height: 24 cm
- Maximum hip height: 34 cm
- Body length: 42 cm
- Type of legged robot: quadruped
- Communication: Wired communication via a CAN port, along with a master board that facilitates interaction between the robot’s motors and the off-board control computer.

Maximum hip height



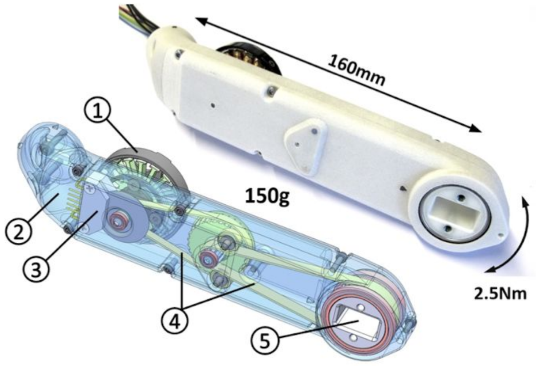


Hip height

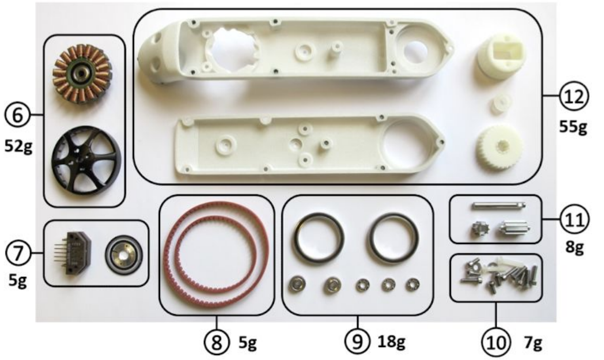
Actuator Concep

Lightweight BLDC motors with 9:1 low gear ratio:

- high performance
- low friction
- precise proprioceptive force control
- no additional torque sensors
- motor current measurements for torque estimation.



(a) Actuator module



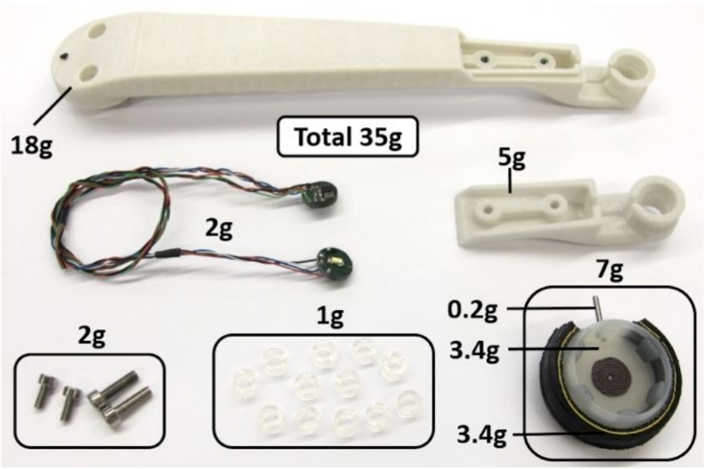
(b) Component overview

1. *BLDC motor*
2. *Two-part 3D printed shell structure*
3. *High-resolution encoder*
4. *Timing belts*
5. *Output shaft*
6. *Brushless motor*
7. *Optical encoder*
8. *Timing belts*
9. *Bearings*
10. *Fasteners*
11. *Machined parts (motor shaft and pulleys)*
12. *3D printed parts*

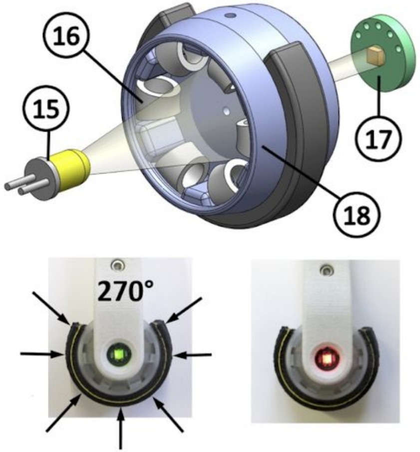
Foot Contact Sensor

Spring-loaded touch sensor at the distal:

- robust
- detects foot impacts
- effectively handling high dynamic loads
- reliability on rough terrain, even under peak forces exceeding twice the robot's body weight.



(c) Lower leg component overview



(c) Foot contact switch

15. Light-emitting diode (LED)

16. Elastic silicone element

17. Light sensor

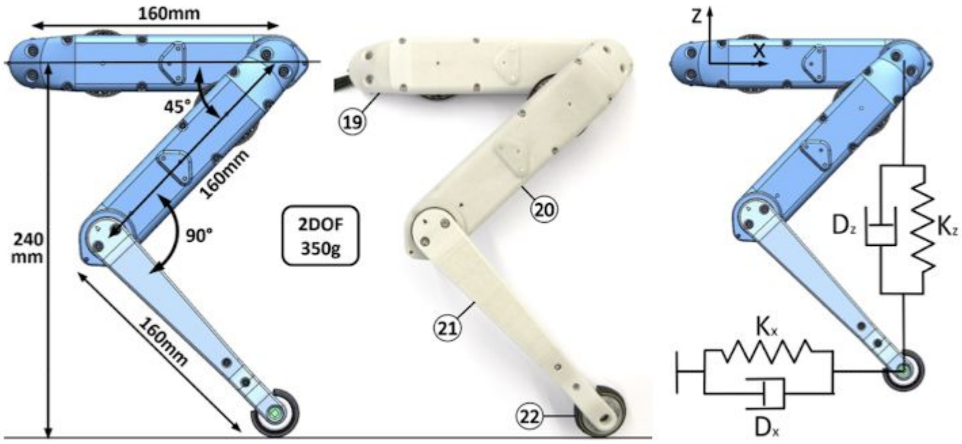
18. Spring-loaded mechanical aperture

2-DOF Leg and Quadruped Robot Solo

The 2-DOF leg features a modular design:

- low-weight
- high torque capabilities
- supporting dynamic motion
- precise impedance control
- efficient, agile locomotion
- self-righting capabilities.

Impedance control is a method to manage the interaction forces between a robot and its environment by adjusting stiffness, damping, and compliance. This allows the robot to adapt dynamically, ensuring smooth and stable movements during locomotion or manipulation tasks.



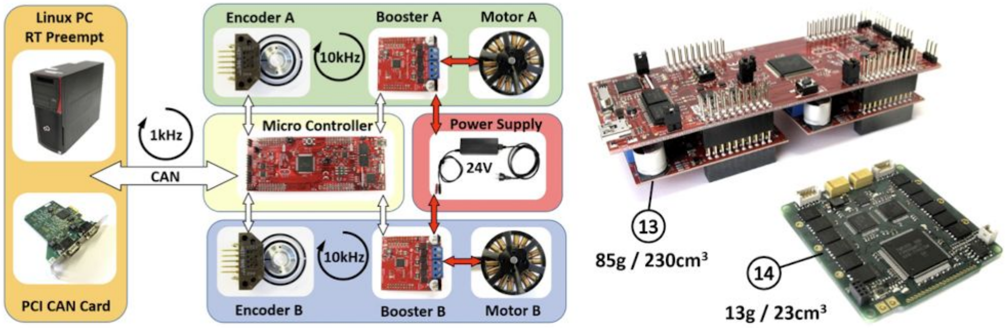
(a) 2-DOF leg (b) Impedance control

19. Hip Actuator Module:
20. Upper Leg
21. Lower Leg
22. Foot Contact Switch

Communication and Control Software

The system employs efficient, real-time communication and control software, enabling seamless operation of the quadruped's modular architecture. This facilitates:

- dynamic motion generation
- torque regulation
- integration with kino-dynamic optimizers for complex movements.



(a) Brushless system overview (b) Brushless motor driver boards

13. TI Evaluation Board:
Controls two BLDC motors with 10 kHz torque control and encoder feedback, used for initial testing.

14. MPI Micro-Driver Board:
A compact custom board replacing the TI board, integrating a TI microcontroller and motor drivers, reducing size and weight significantly.

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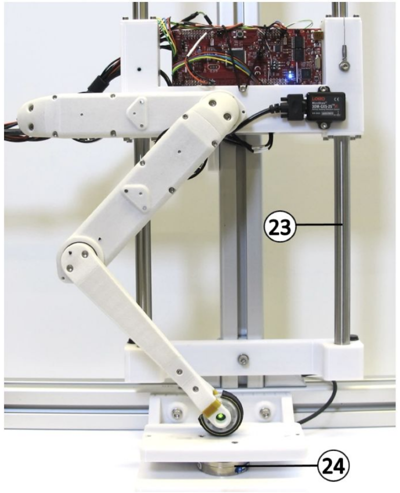
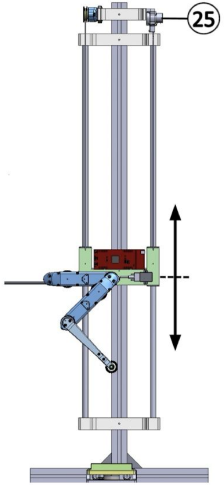
Impedance control of the 2-DOF leg

The aim of the experiments is to test the impedance control of the 2-DOF leg of the robot and validate its performance under various conditions. Torque control is only based on the internal motor current and motor position measurements without any force feedback.

- Quasi-static experiment
- Drop experiment
- Jumping experiments
- Contact sensor validation



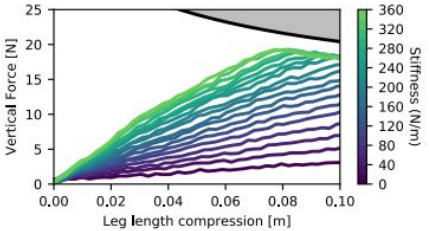


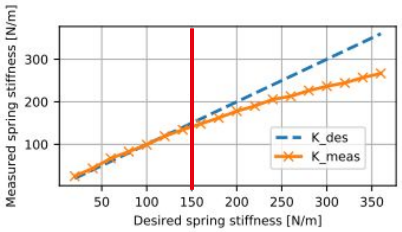
23. Linear Guide
24. 6-Axis ATI Mini40 Force Sensor
25. String Potentiometer

Experiments

Quasi-static Stiffness Regulation

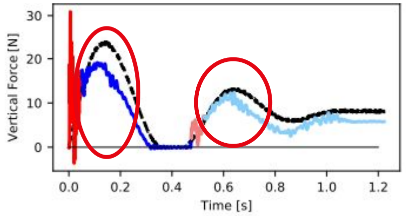
- Objective: characterize the robot's ability to regulate stiffness in quasi-static conditions
- Method: The leg was pushed slowly, and the ground reaction force and leg displacement were measured using external sensors
- Results:
  - The leg's stiffness can be regulated between 20 N/m and 360 N/m
  - Above 150 N/m stiffness, there is a discrepancy due to limitations like friction and transmission flexibility
- Key Takeaway: the system can regulate stiffness accurately within limits and works without the need for force sensors, demonstrating the effectiveness of impedance control

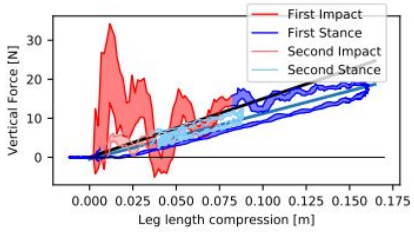




Drop Test

- Objective: test the robot's impedance control during high-impact scenarios
- Method: the leg is dropped from a height of 0.24 m. The desired stiffness is set to 150 N/m with low damping
- Results:
  - During impact, large oscillations in force were observed, followed by settling at a stable force (6 N)
  - The leg's behavior demonstrated good repeatability, with hysteresis effects due to friction and structural deformation
- Key Takeaway: The leg is capable of absorbing impacts and maintaining a stable force, but friction and hysteresis must be accounted for in dynamic tasks

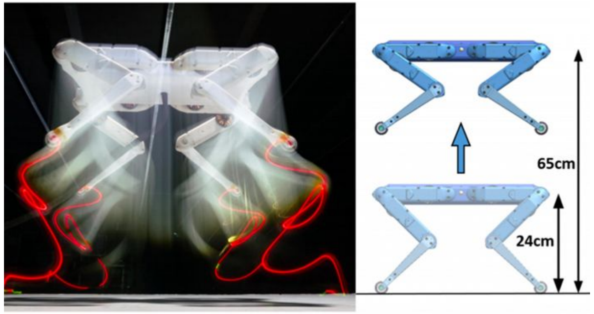




Experiments

Jumping Capability

- Objective: evaluate the dynamic motion capabilities of the leg
- Method: a simple vertical motion is implemented to test the robot's jumping capability
- Results:
  - The robot was able to jump to a height of 0.65 m (approximately twice its leg length)
- Key Takeaway: The system’s ability to perform dynamic actions like jumping shows the versatility and robustness of the design



Contact Sensor Validation

- Objective: test the performance of the contact sensor against external force measurements
- Method: the robot's foot contact was monitored using both motor curren estimations and a direct force sensor
- Results:
  - The contact sensor showed a delay of about 3 ms, while using motor currents resulted in a delay of 31 ms, which could cause issues in fast dynamic tasks
- Key Takeaway: the contact sensor is lightweight and effective for most tasks but may require more advanced algorithms for high-speed applications

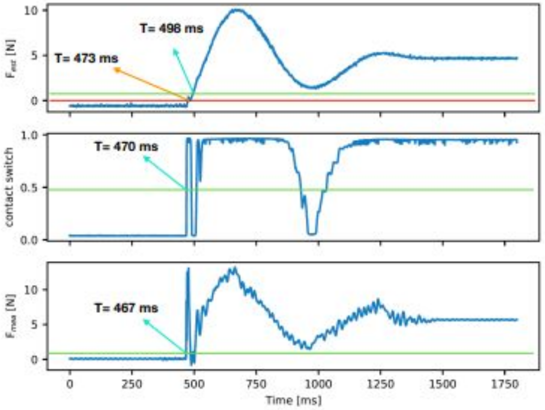


Fig. 8: Drop test experiment. We notice a sharp contact detection with the contact sensor (middle) compared to force contact prediction from motor current (top). The bottom plot shows the ground truth from a high resolution force sensor.

Dynamic behavior of the quadruped robot

Demonstrate the capabilities and dynamic behavior of the quadruped robot in real-world scenarios using advanced motion planning techniques based on centroidal dynamics and kino-dynamic optimization

- Kino-dynamic motion optimizer and controller
- Solo motion capabilities
- Tracking kino-dynamic plans

Kino-Dynamic Motion Optimizer and Controller

The kino-dynamic optimizer balances centroidal dynamics (center of mass motion and contact forces) with the full-body kinematics (joint configurations) to produce feasible and efficient motion trajectories. The planner solves two interconnected optimization problems iteratively

- Optimize centroidal dynamics to find the center of mass trajectory and contact forces.
- Refine the robot's kinematics to ensure that joint-level motions are achievable

Centroidal Dynamics:

$$\mathbf{f}_{\text{ext}} + m\mathbf{g} = m\ddot{\mathbf{c}}, \quad \tau_{\text{ext}} = \dot{\mathbf{k}}$$

- $\mathbf{f}_{\text{ext}}$ = sum of external forces (contact forces).
- τ_{ext} = net external torque.
- $\mathbf{g}$ = gravitational acceleration vector.
- $\mathbf{c}$ = position of the center of mass.
- $\mathbf{k}$ = angular momentum.

Kino-Dynamic Motion Optimizer and Controller

Motion Controller Design:
The controller is designed to track the planned motions by regulating forces and wrenches at the center of mass and distributing contact forces across the robot's feet.

$$W_{\text{CoM}} = \begin{bmatrix} \mathbf{f}_{\text{CoM}} \\ \tau_{\text{CoM}} \end{bmatrix} = \begin{bmatrix} W_{\text{ref, CoM}} + K_c(\mathbf{x}_{\text{ref},c} - \mathbf{x}_c) + D_c(\dot{\mathbf{x}}_{\text{ref},c} - \dot{\mathbf{x}}_c) \\ K_b(\mathbf{q}_{\text{ref},b} \ominus \mathbf{q}_b) + D_b(\mathbf{k}_{\text{ref}} - \mathbf{k}) \end{bmatrix}$$

- $\mathbf{x}_c$ and $\dot{\mathbf{x}}_c$: current CoM position and velocity.
- $\mathbf{x}_{\text{ref},c}$ and $\dot{\mathbf{x}}_{\text{ref},c}$: reference CoM position and velocity.
- $\mathbf{q}_b$: current base orientation (quaternion).
- $\mathbf{q}_{\text{ref},b}$: reference base orientation.
- $\ominus$: quaternion difference.
- K_c, K_b, D_c, D_b: feedback gains for position and angular momentum tracking.
- $\mathbf{k}$: current angular momentum, and $\mathbf{k}_{\text{ref}}$: reference angular momentum.

Optimal Foot Force Allocation:
The robot allocates forces to each foot to achieve the desired while satisfying frictional constraints. This is formulated as a quadratic program

$$\min_{\mathbf{F}_i, \boldsymbol{\eta}, \zeta_1, \zeta_2} \sum_i \mathbf{F}_i^2 + \alpha(\boldsymbol{\eta}^2 + \zeta_1^2 + \zeta_2^2)$$

$$\text{s.t.} \quad \mathbf{W}_{CoM} = \sum_{i \in \mathcal{C}} \begin{pmatrix} \mathbf{F}_i \\ \mathbf{r}_i \times \mathbf{F}_i \end{pmatrix} + \boldsymbol{\eta}$$

$$F_{i,x} < \mu F_{i,z} + \zeta_1, \quad F_{i,y} < \mu F_{i,z} + \zeta_2 \qquad \forall i \in \mathcal{C}$$

- $\mathbf{F}_i$: force at foot i.
- $\mathbf{r}_i$: vector from foot i to the CoM.
- C: set of feet in contact with the ground.
- μ: friction coefficient.
- η, ζ_1, ζ_2: slack variables for robustness.

Low-Impedance Leg-Length Controller:
To complement force control, a low-impedance leg-length controller adjusts the leg's position

$$\tau_i = J_i^T \left(\mathbf{F}_i + K(\mathbf{l}_{\text{ref},i} - \mathbf{l}_i) + D(\dot{\mathbf{l}}_{\text{ref},i} - \dot{\mathbf{l}}_i) \right)$$

- J_i: Jacobian matrix for leg i.
- $\mathbf{l}_i$ and $\dot{\mathbf{l}}_i$: current leg position and velocity.
- $\mathbf{l}_{\text{ref},i}$ and $\dot{\mathbf{l}}_{\text{ref},i}$: reference leg position and velocity.
- K, D: leg stiffness and damping gains.

Solo motion capabilities

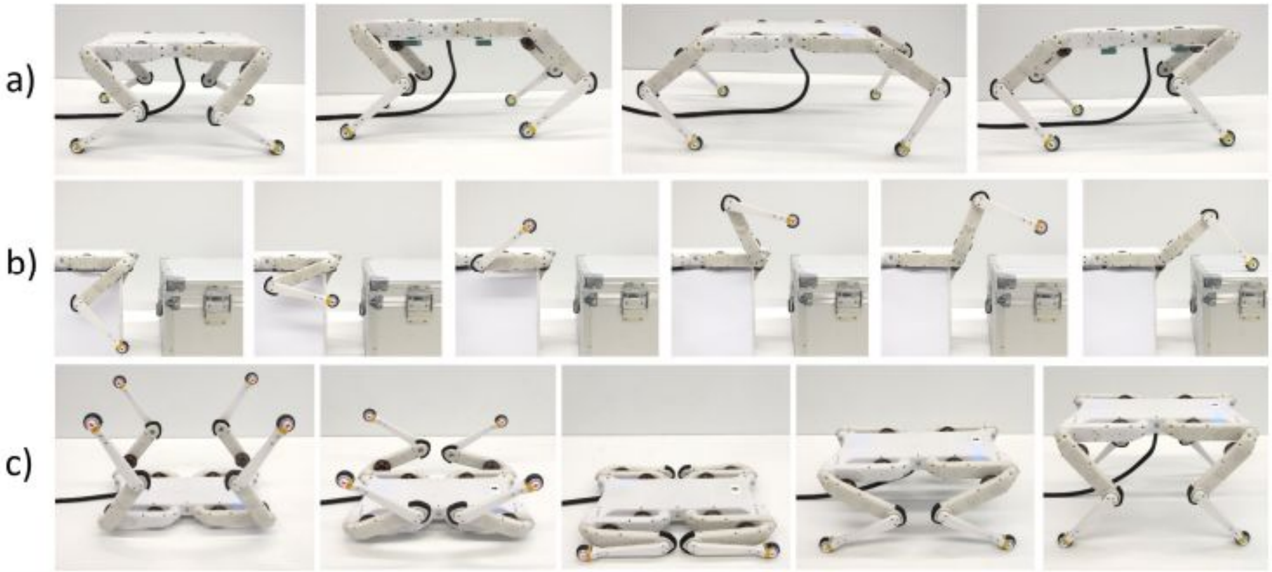


Fig. 9: Example motion sequences: a) Legs can switch between all the four knee configurations, b) with more than 360° hip joint rotation capability, and little space to navigate, legs can be rotated first backwards, and then onto a step, c) in case the robot falls onto its back, it can re-orient its legs, and stand up without rotating the trunk.

Tracking Kino-Dynamic Plans

Experimental Setup

- *Various scenarios tested, including balancing on moving platforms, walking over uneven terrain, and jumping*

Results

- *The robot balances effectively on dynamic platforms without prior knowledge of the environment*
- *It adapts to unexpected obstacles, such as a seesaw during a walking sequence, demonstrating robustness to uncertainties*
- *Executes a vertical jump, achieving a base height of 65 cm, landing safely without damage*

Key Takeaway

- *The experiments confirm that kino-dynamic plans generated in simulation transfer well to the real robot, bridging the gap between theoretical models and real-world dynamics*

Citations

135 citations on Scopus

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- Bogdanovic M., Khadiv M., Righetti L. “Learning variable impedance control for contact sensitive tasks" IEEE Robotics and Automation Letters, 5(4),9146673, pp. 6129-6136
- Badri-Spröwitz A., Sarvestani A.A., Sitti M., Daley M.A. “BirdBot achieves energy-efficient gait with minimal control using avian-inspired leg clutching” Science Robotics, 7(64), abg4055

Influenced other labs because the modularity and ability to 3D print parts make it an attractive option, allowing others to avoid the resource-heavy process of developing similar systems from scratch

- Lab LAAS-CNRS
- Research group at NYU
- Max Planck Institute For Intelligent Systems

No apparent criticism

PROS AND CONS

Pros

- low-cost robot (i.e. off-the-shelf components, 3D printed pieces)
- weight
- controller robust to uncertain environments
- knee-joints versatility
- reusability, low-complexity

Cons

- Limited (in comparison to more specialized tasks)
- Possible compensation of motors for slow-precision tasks

Questions

1. **How does the impedance control enhance the 2-DOF leg's performance?**
    a. Impedance control adjusts stiffness and damping for smooth terrain interactions, precise foot positioning, and force application, crucial for tasks like jumping or walking. It replicates human-like stiffness and adapts to challenges without torque sensors.

2. **What trade-offs were made to balance cost, weight, and performance?**
    a. The robot uses low-cost BLDC motors with a 9:1 timing belt, reducing complexity and cost while relying on motor currents for torque measurement. Lightweight 3D-printed parts cut costs, with minimal precision machining needed, ensuring affordability and versatility.