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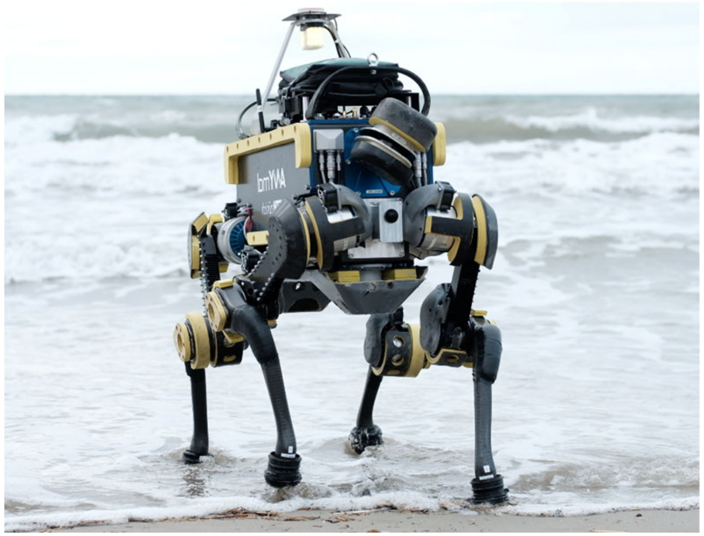

Lecture «Robot Dynamics»:

Case Study ANYmal

151-0851-00 V

Marco Hutter, Roland Siegwart, and Thomas Stastny

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17.09.2019	Intro and Outline	Course Introduction; Recapitulation Position, Linear Velocity			
24.09.2019	Kinematics 1	Rotation and Angular Velocity; Rigid Body Formulation, Transformation	25.09.2019	Exercise 1a	Kinematics Modeling the ABB arm
01.10.2019	Kinematics 2	Kinematics of Systems of Bodies; Jacobians	02.10.2019	Exercise 1a	Differential Kinematics of the ABB arm
08.10.2019	Kinematics 3	Kinematic Control Methods: Inverse Differential Kinematics, Inverse Kinematics; Rotation Error; Multi-task Control	09.10.2019	Exercise 1b	Kinematic Control of the ABB Arm
15.10.2019	Dynamics L1	Multi-body Dynamics	16.10.2019	Midterm 1	Programming kinematics with matlab
22.10.2019	Dynamics L2	Floating Base Dynamics	23.10.2019	Exercise 2a	Dynamic Modeling of the ABB Arm
29.10.2019	Dynamics L3	Dynamic Model Based Control Methods	30.10.2019	Exercise 2b	Dynamic Control Methods Applied to the ABB arm
05.11.2019	Legged Robot	Dynamic Modeling of Legged Robots & Control	06.11.2019	Midterm 2	Programming dynamics with matlab
12.11.2019	Case Studies 1	Legged Robotics Case Study	13.11.2019	Exercise 3	Legged robot
19.11.2019	Rotorcraft	Dynamic Modeling of Rotorcraft & Control	20.11.2019		
26.11.2019	Case Studies 2	Rotor Craft Case Study	27.11.2019	Exercise 4	Modeling and Control of Multicopter
03.12.2019	Fixed-wing	Dynamic Modeling of Fixed-wing & Control	04.12.2019		
10.12.2019	Case Studies 3	Fixed-wing Case Study (Solar-powered UAVs - AtlantikSolar, Vertical Take-off and Landing UAVs – Wingtra)	11.12.2019	Exercise 5	Fixed-wing Control and Simulation
17.12.2019	Summery and Outlook	Summery; Wrap-up; Exam			

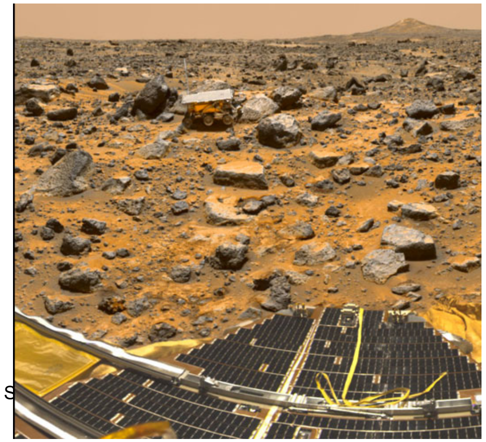
Questions from Piazza

- Difference u and q_dot

Make Robots that can go Anywhere

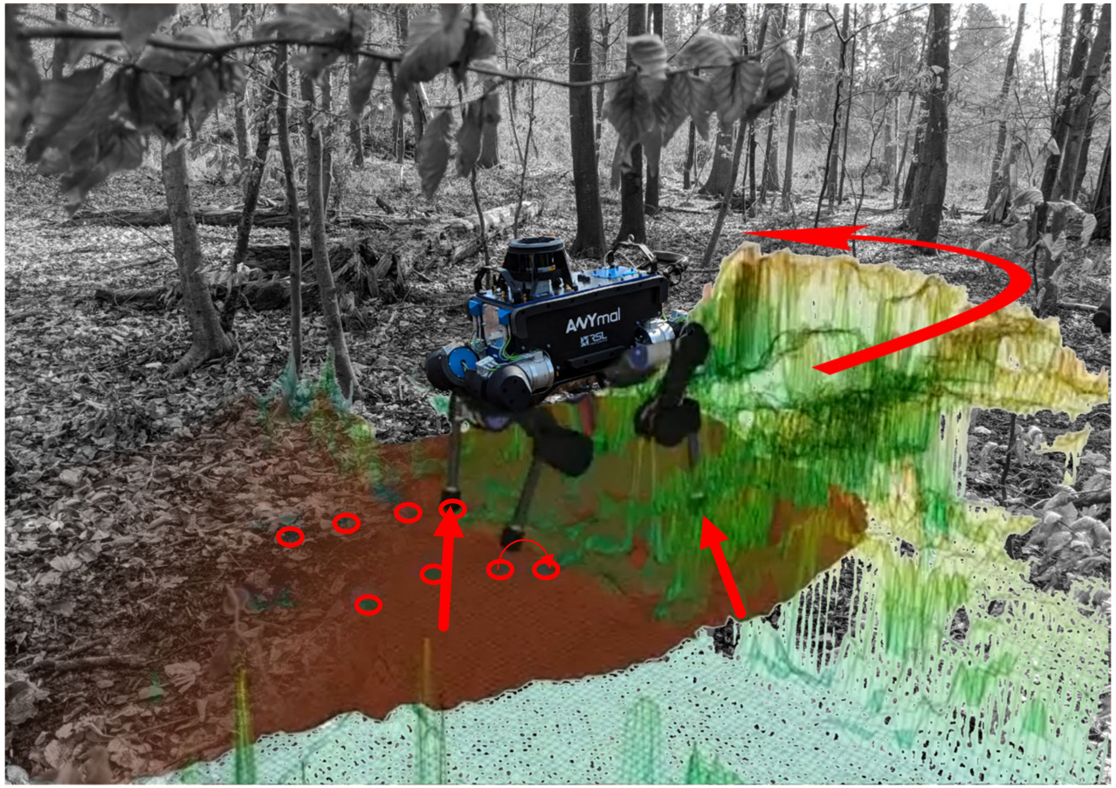
… to do the dirty and dangerous jobs

Mobility & Interaction Capabilities with Uncertain Environments

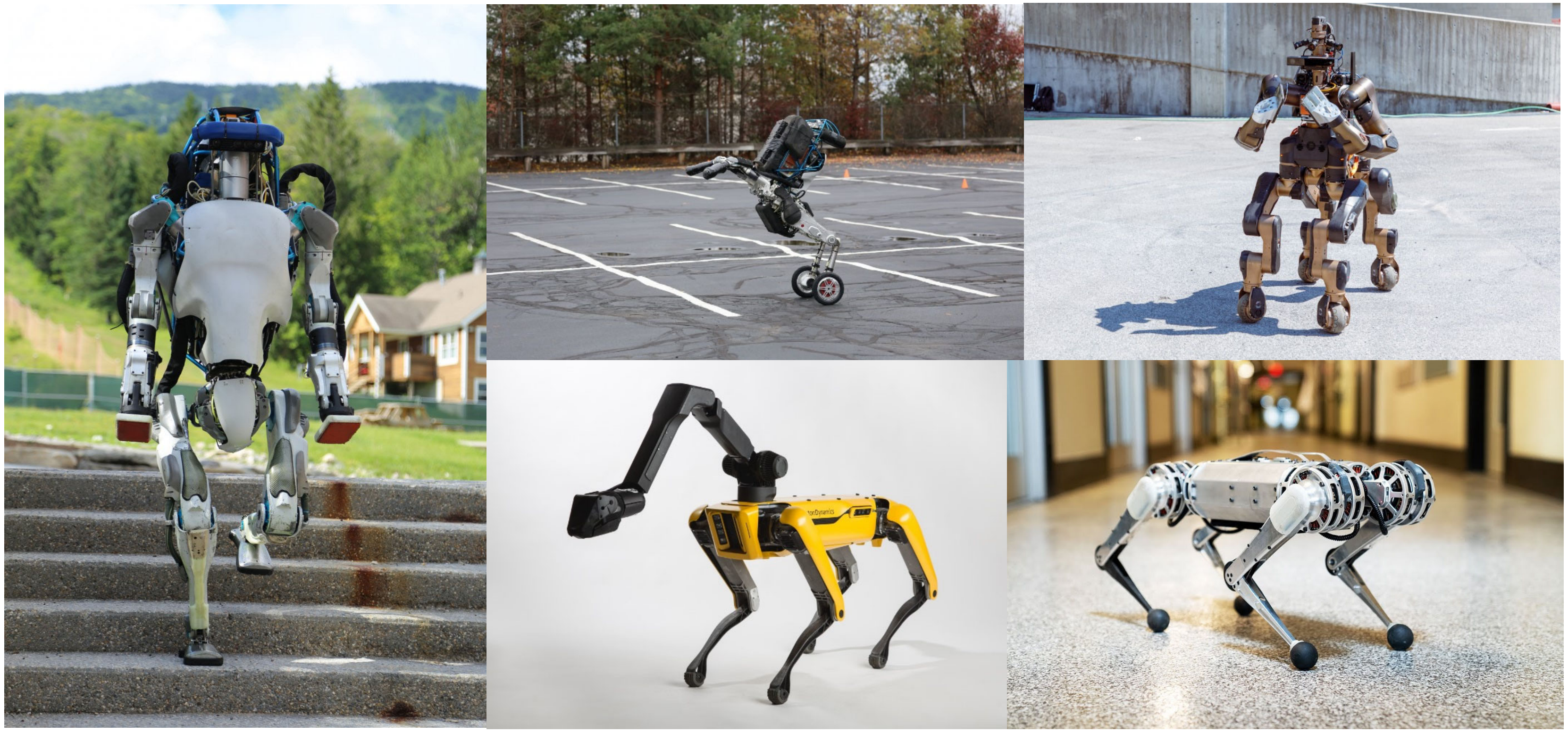


Challenges of autonomous legged locomotion

- **See** and understand the environment
- **Estimate** the location and motion
- Find a feasible **navigation** path
- Figure out where and when to **step**
- **Interact** with the uncertain environment



State of the Art in Legged Robotics



MIT Mini Cheetah

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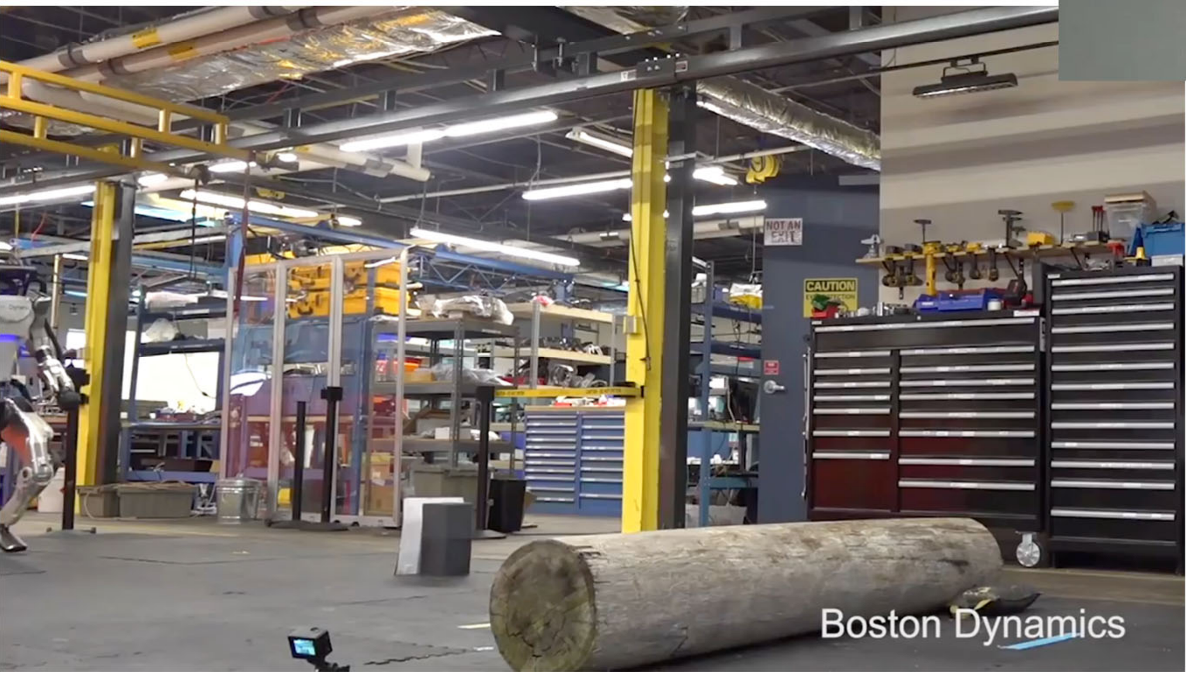
Boston Dynamics
Spot mini and Atlas



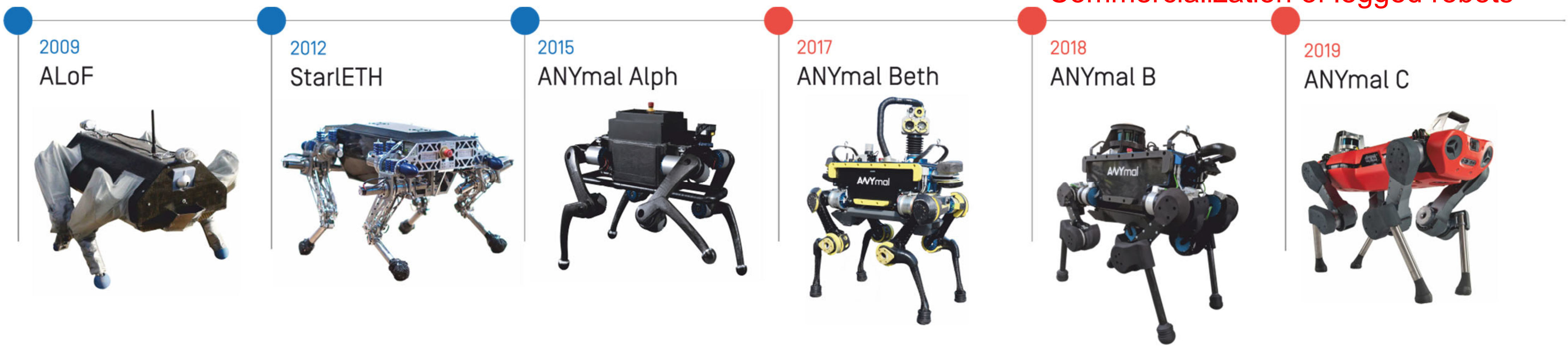
ICRA 2019 Workshop

From simple prototypes to market ready solutions – in 10 years

RSL Robotic Systems Lab

ANYbotics

- Founded 2016, ~40 people
- Commercialization of legged robots



Legged Robotics Research at ETH

Since 2018

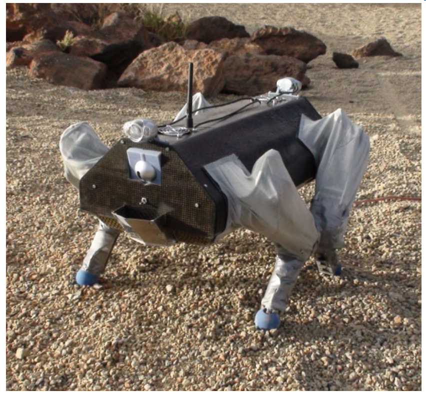
ANYmal

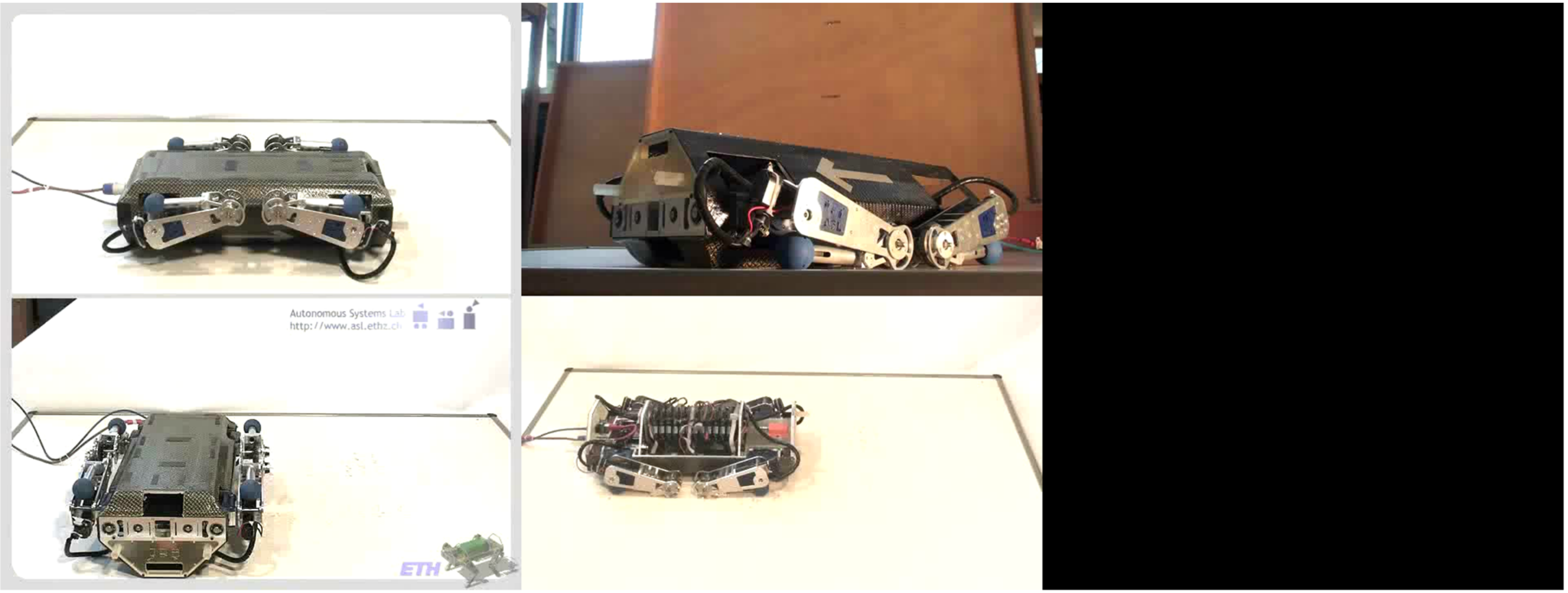
ANYmal on wheels

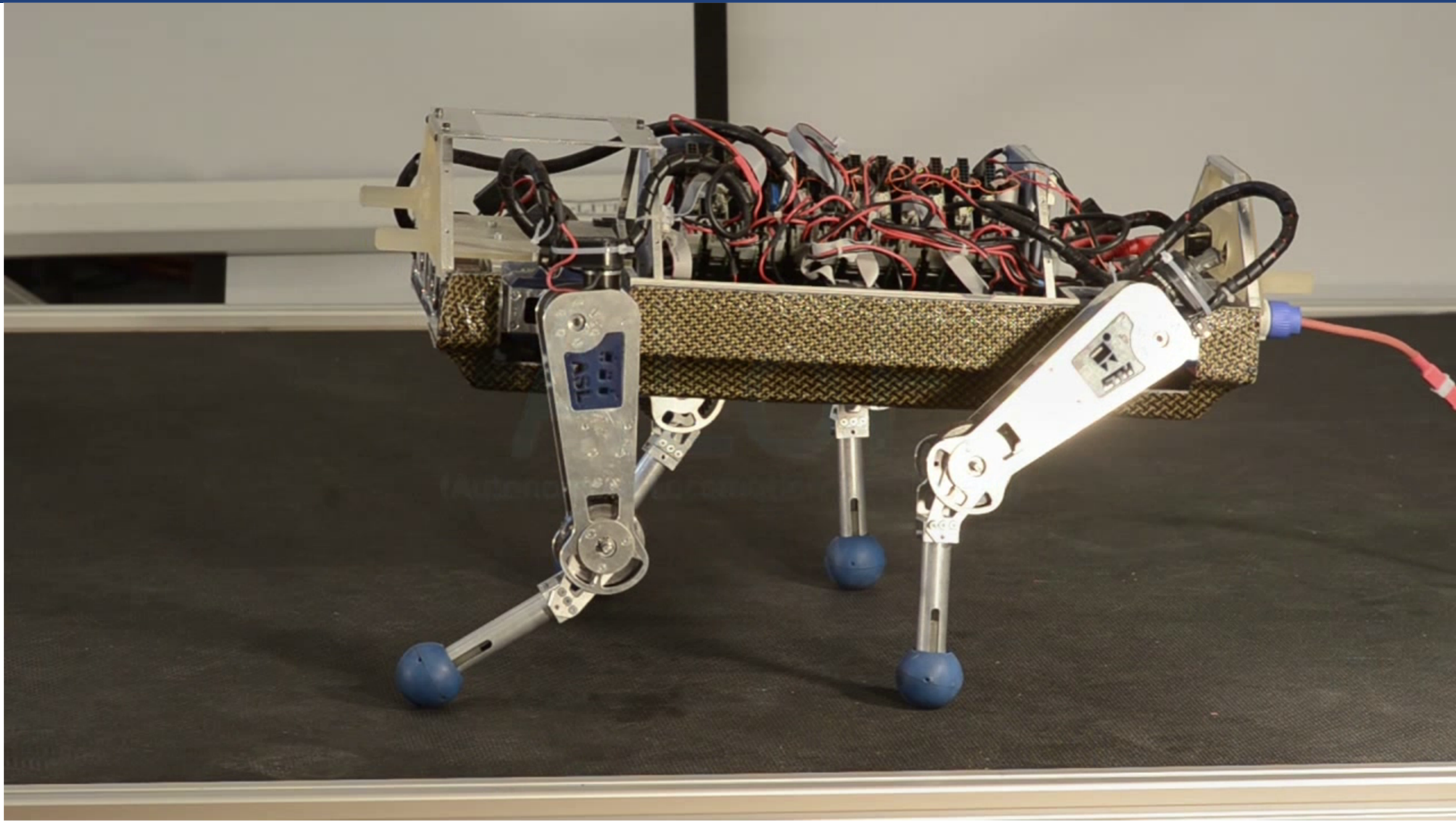
ANYmal with an arm

ALOF
a versatile quadruped robot

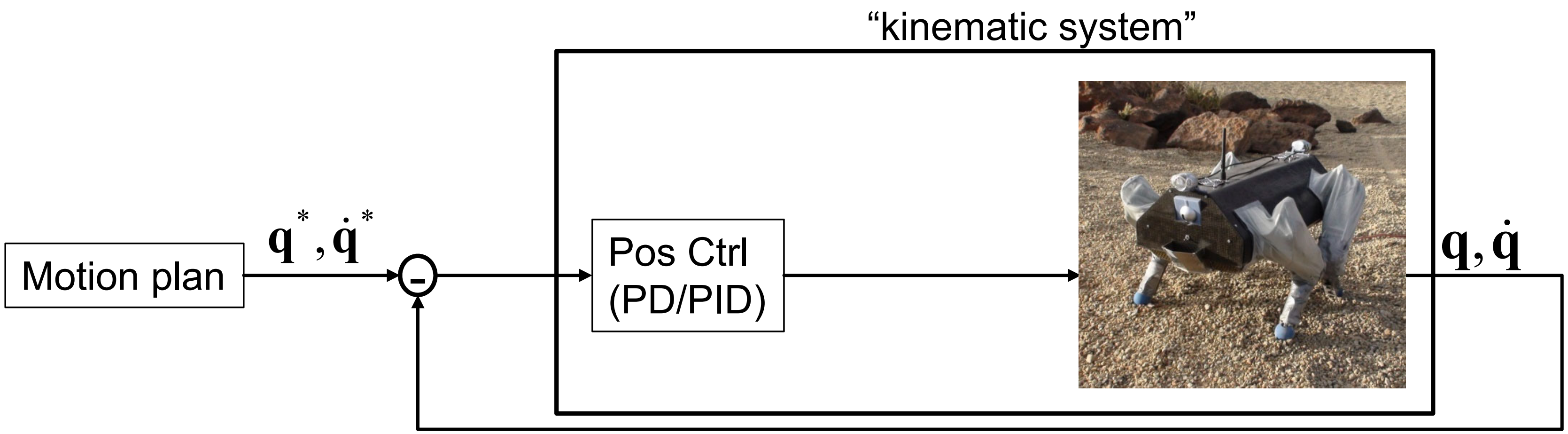
- High mobility
  - Clever design
  - Precise kinematic planning







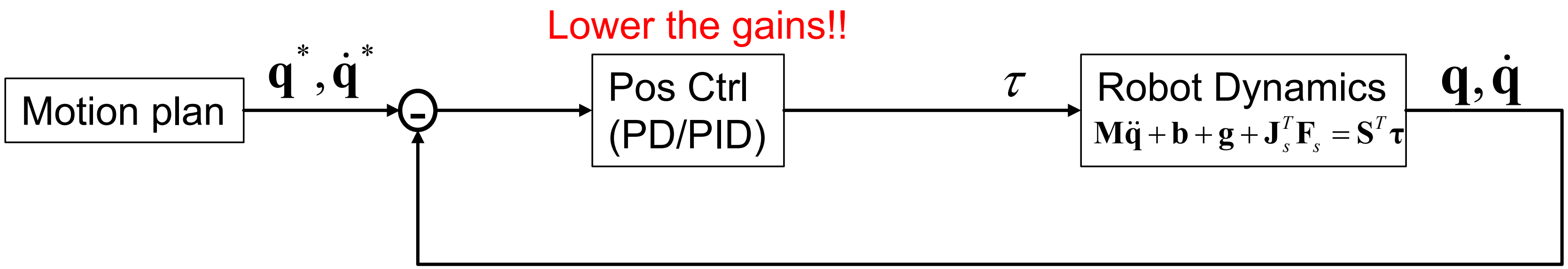
Classical Position control for locomotion



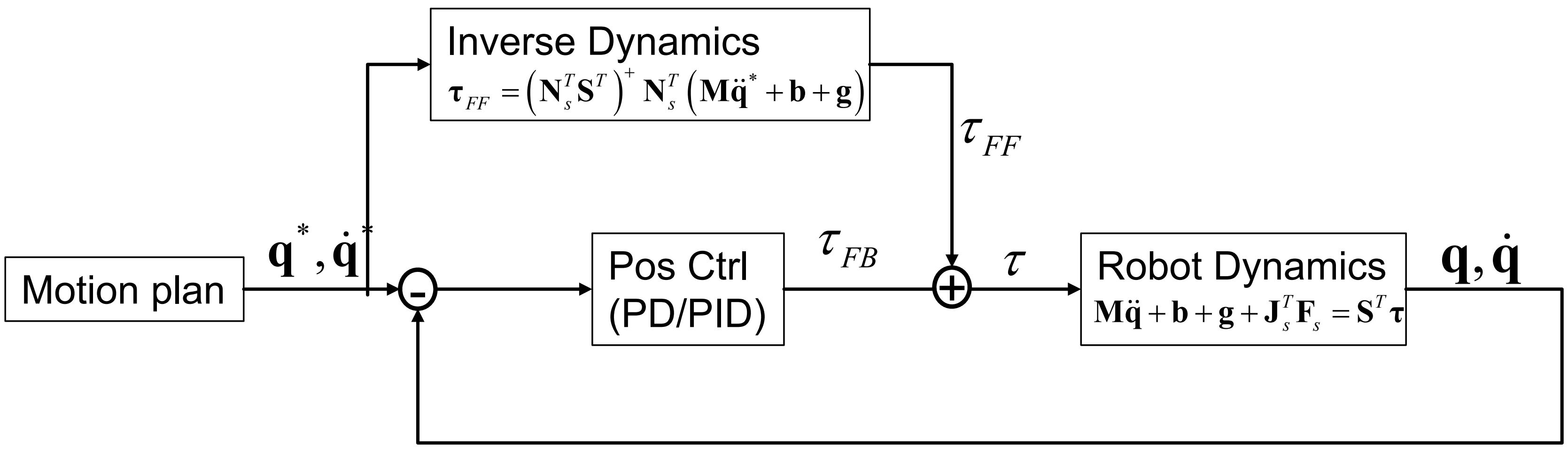
Little Dog Challenge

Motion planning and high-gain kinematic trajectory following
Unperceived/unplanned obstacles

Low-gain joint control with model compensation



Low-gain joint control with model compensation



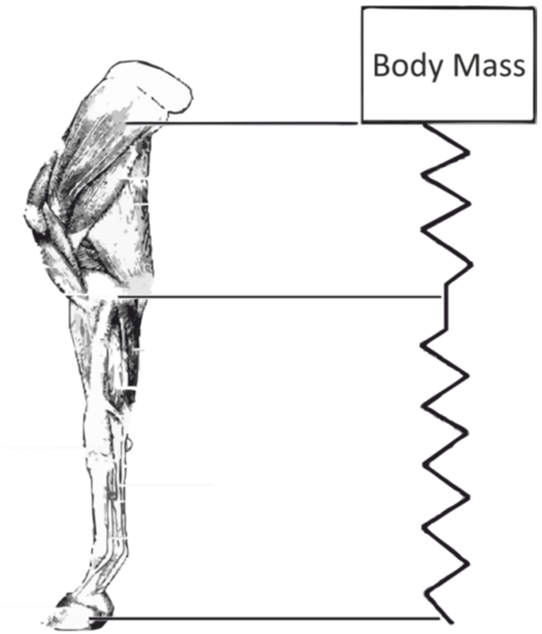
Low-gain kinematic trajectory following + Inv. Dynamics

Unperceived/unplanned obstacles

Biomechanics of Animals
Compliance in muscles and tendons

- Muscle/tendon (mech. compliance)
  - Robustness
  - Energy storage
  - Power/speed amplification
  - Force control instead of position

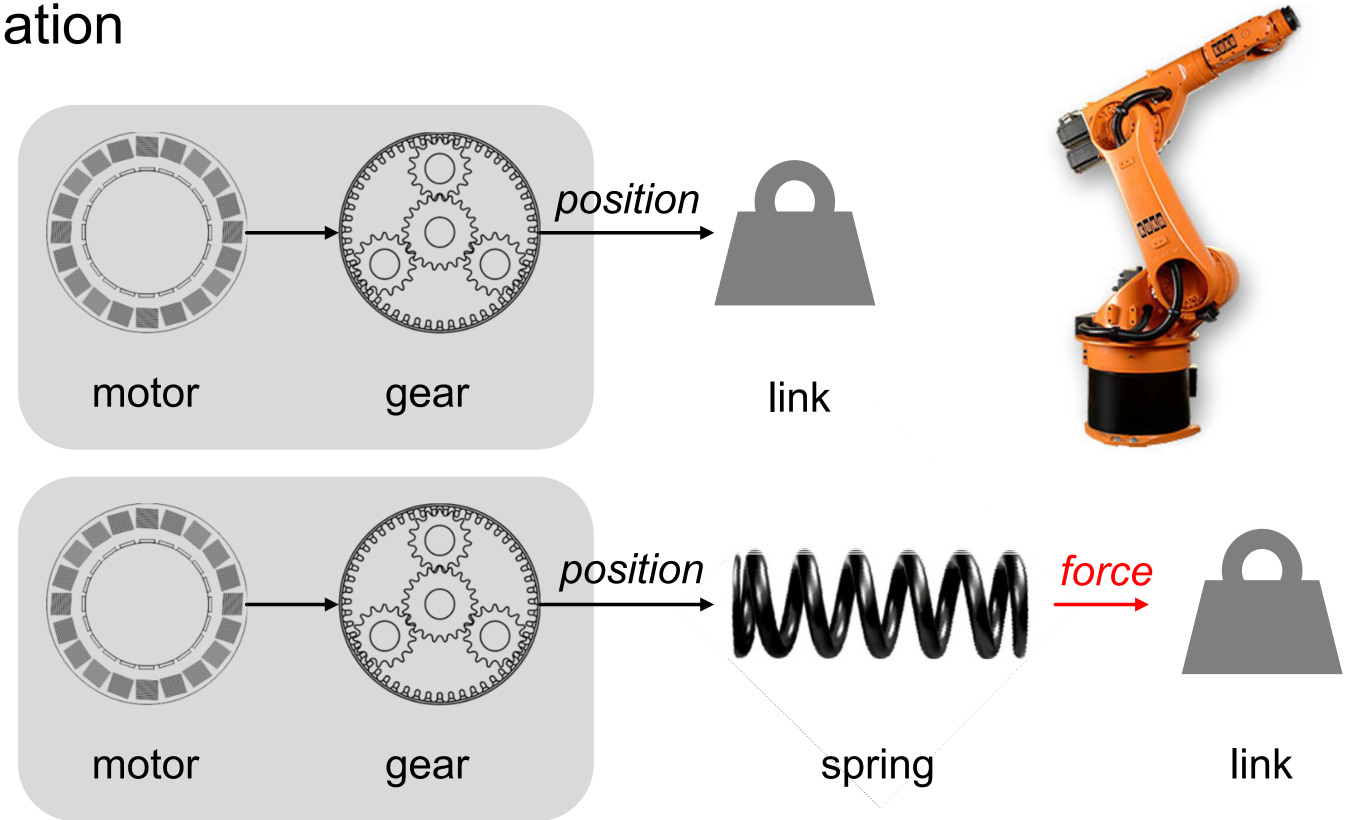
  [Alexander 1988,1990,2002,2003]



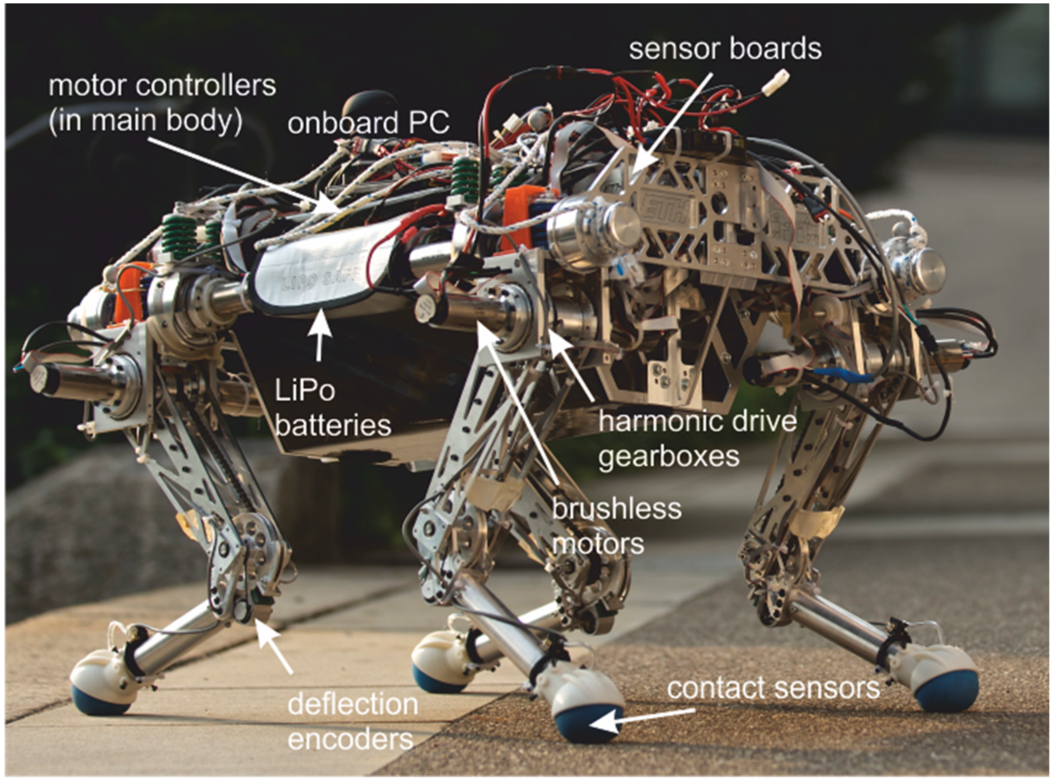
From Position to Force Controlled Systems

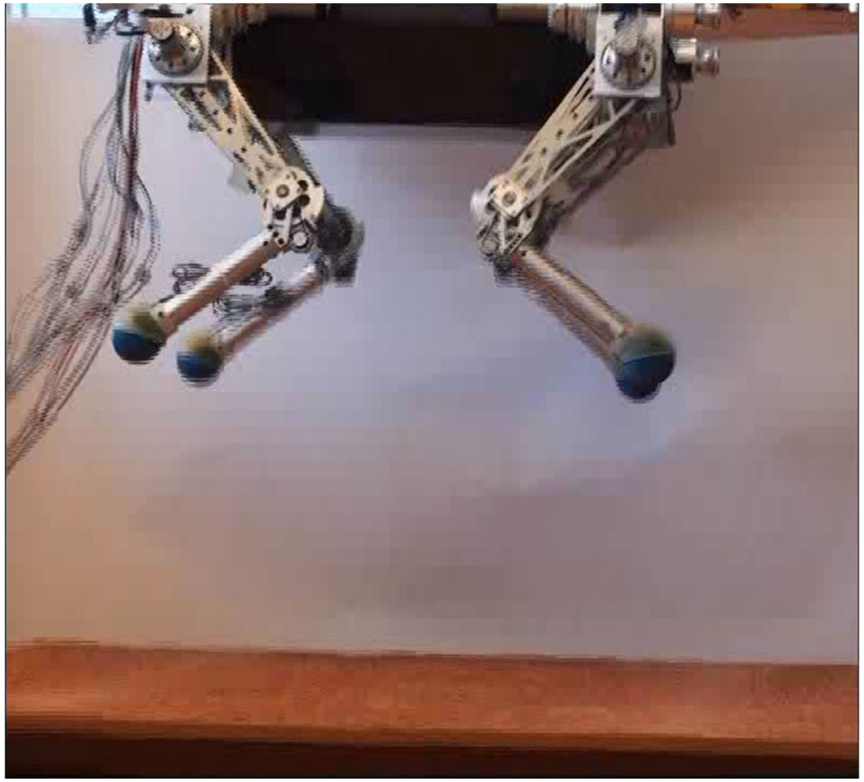
Compliance in robotic actuation

- Kinematic, position control
- Dynamic, force control



StarlETH
A compliant quadrupedal robot

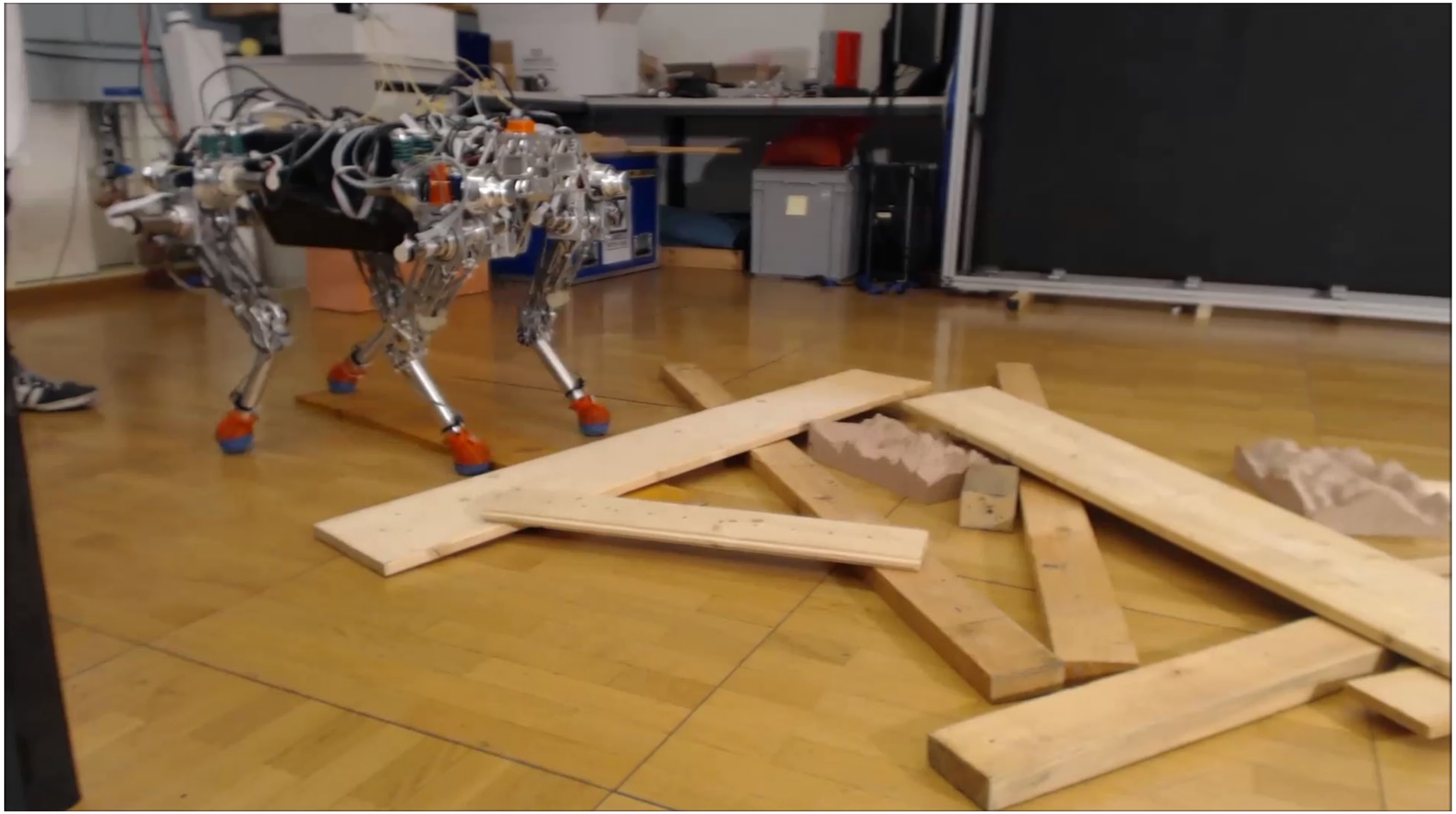




[Gehring et. al., ICRA 2013, RAM 2015]

StarlETH – a Compliant Quadrupedal Robot

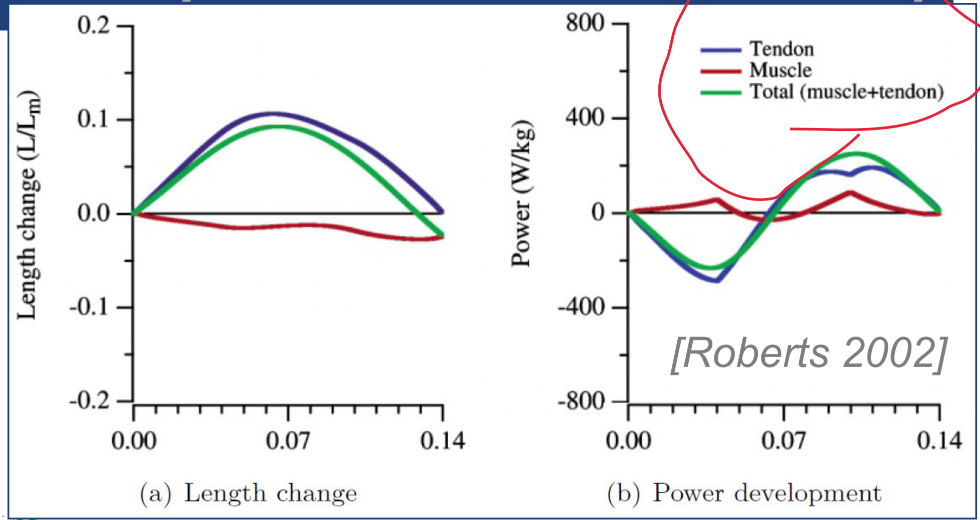
Towards autonomous running and climbing



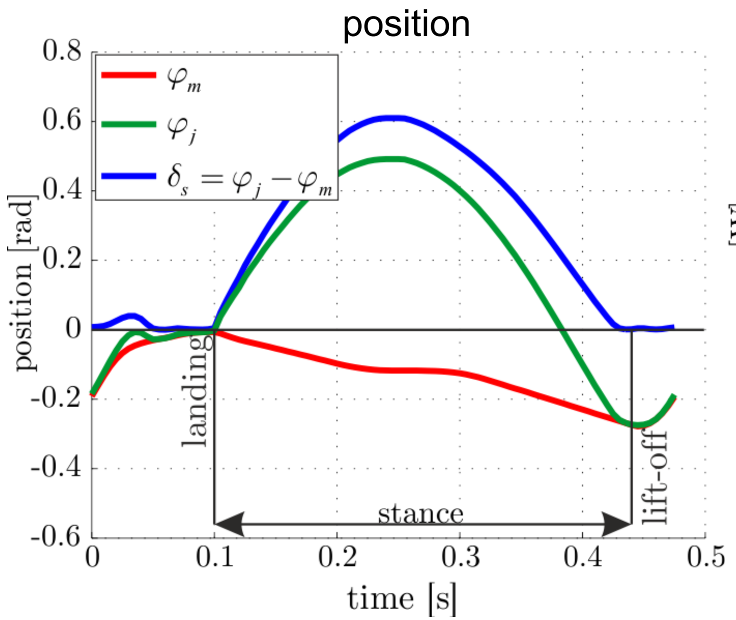
[Hutter et. al., TMECH 2011, TRO 2014]

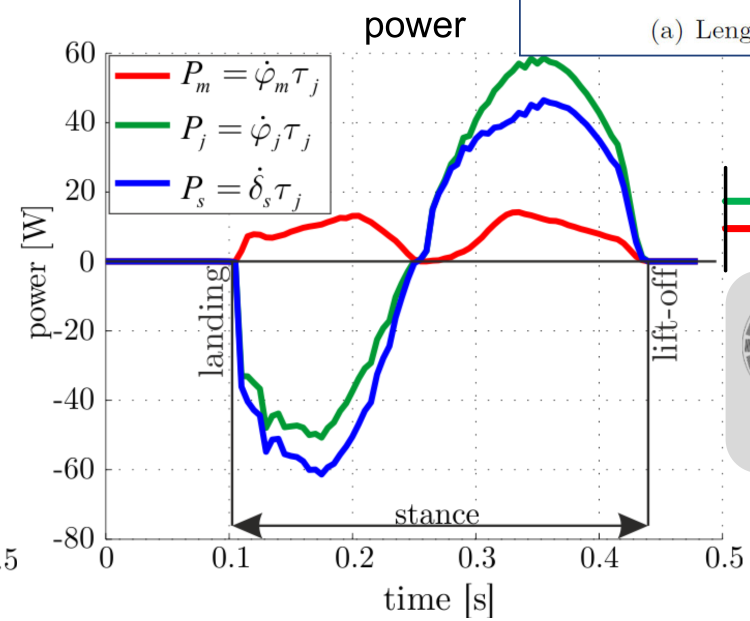
Exploitation of Passive Dynamics

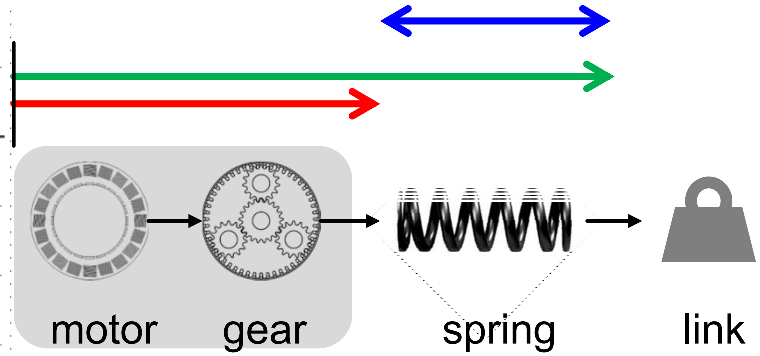
- 64% passive energy recovery
- Speed amplification 4.7, power amplification 4.1



[Roberts 2002]



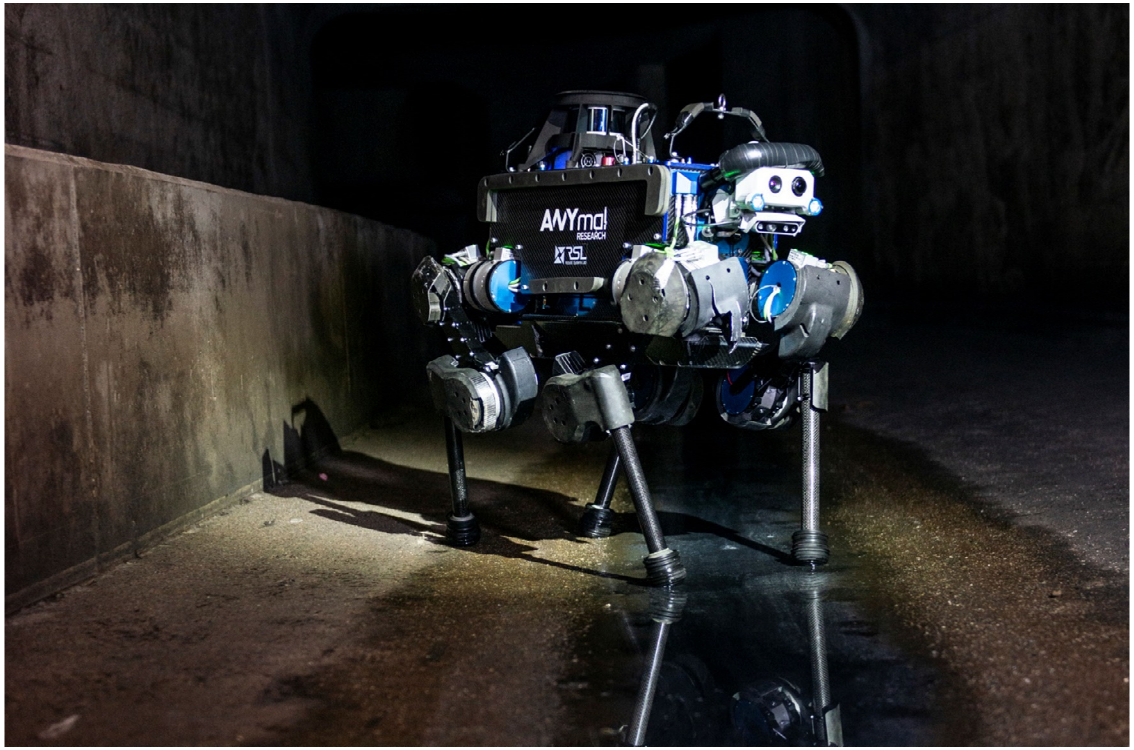




ANYdrive
A robust and force controllable robot joint unit

- Fully integrate SEAs
  - Custom motor control and sensing (no communication delay)
  - EtherCAT and power interface
  - Precise absolute output position and torque control
  - Hollow shaft for cabling
  - Large output load bearing
  - IP67

ANYmal - a field-ready, torque controllable quadruped



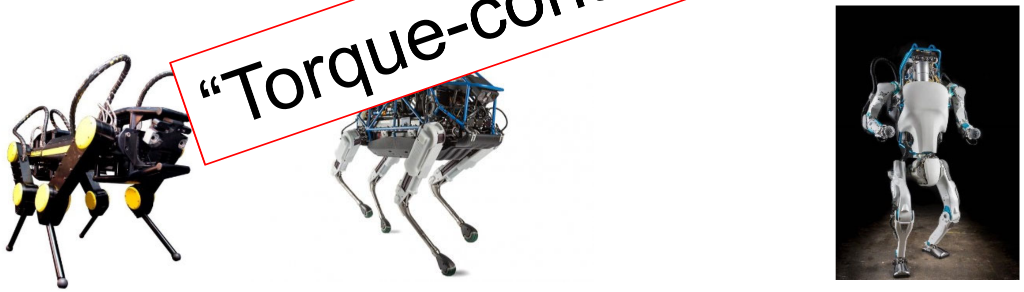
- ANYmal
  - Modular, simple maintenance
  - Fully autonomous
  - 1.5 m/s speed
  - 2-3h endurance (280W avg power)
  - 30kg-35kg weight
  - Falls safe
  - IP67
  - ATEX compliance possible
  - Docking station for aut. charging

State of the Art Legged Robots – and their actuation

- High-gear system with elasticity or torque sensor

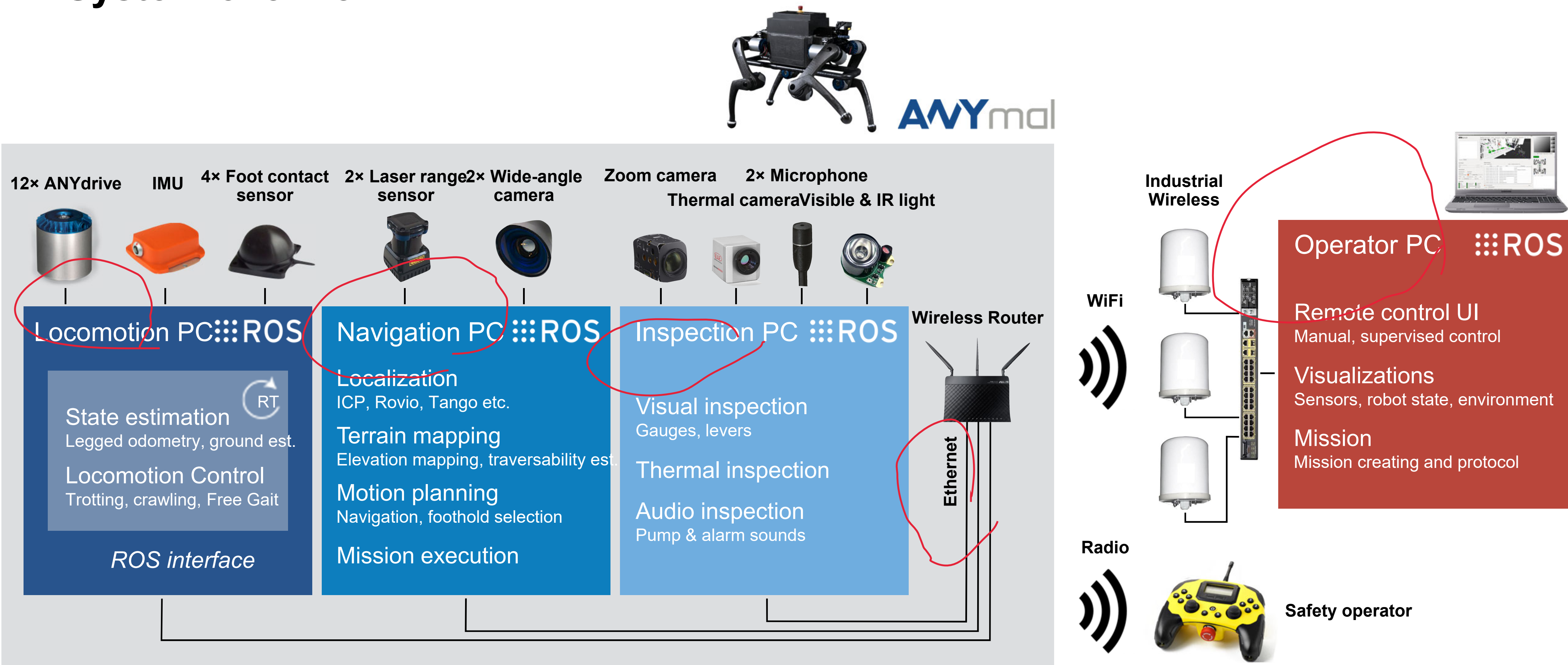
- Low gear system with current control only

- Hydraulic (pressure a



"Torque-controllable, multi-articulated system"

System overview



Legged Locomotion Control

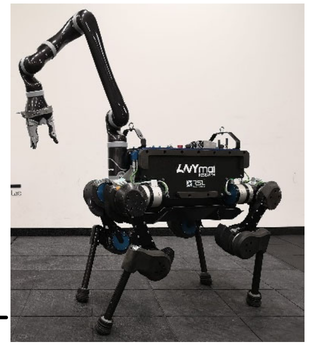
"Torque-controllable, multi-articulated system"

Navigation
…

Planning
- Motion
- Foothold
- Reference torque

Tracking
- Follow the plan
- Satisfy constraints
- Reactive behaviour

Joint Control
- Joint torque
- Joint position



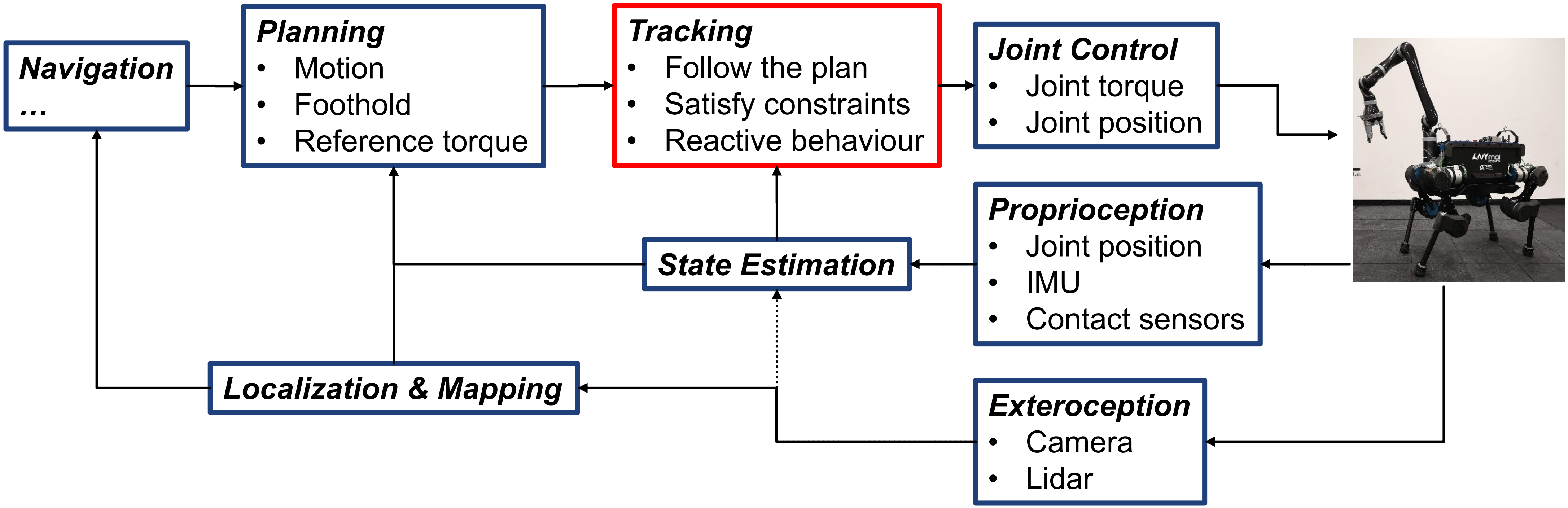
State Estimation

Proprioception
- Joint position
- IMU
- Contact sensors

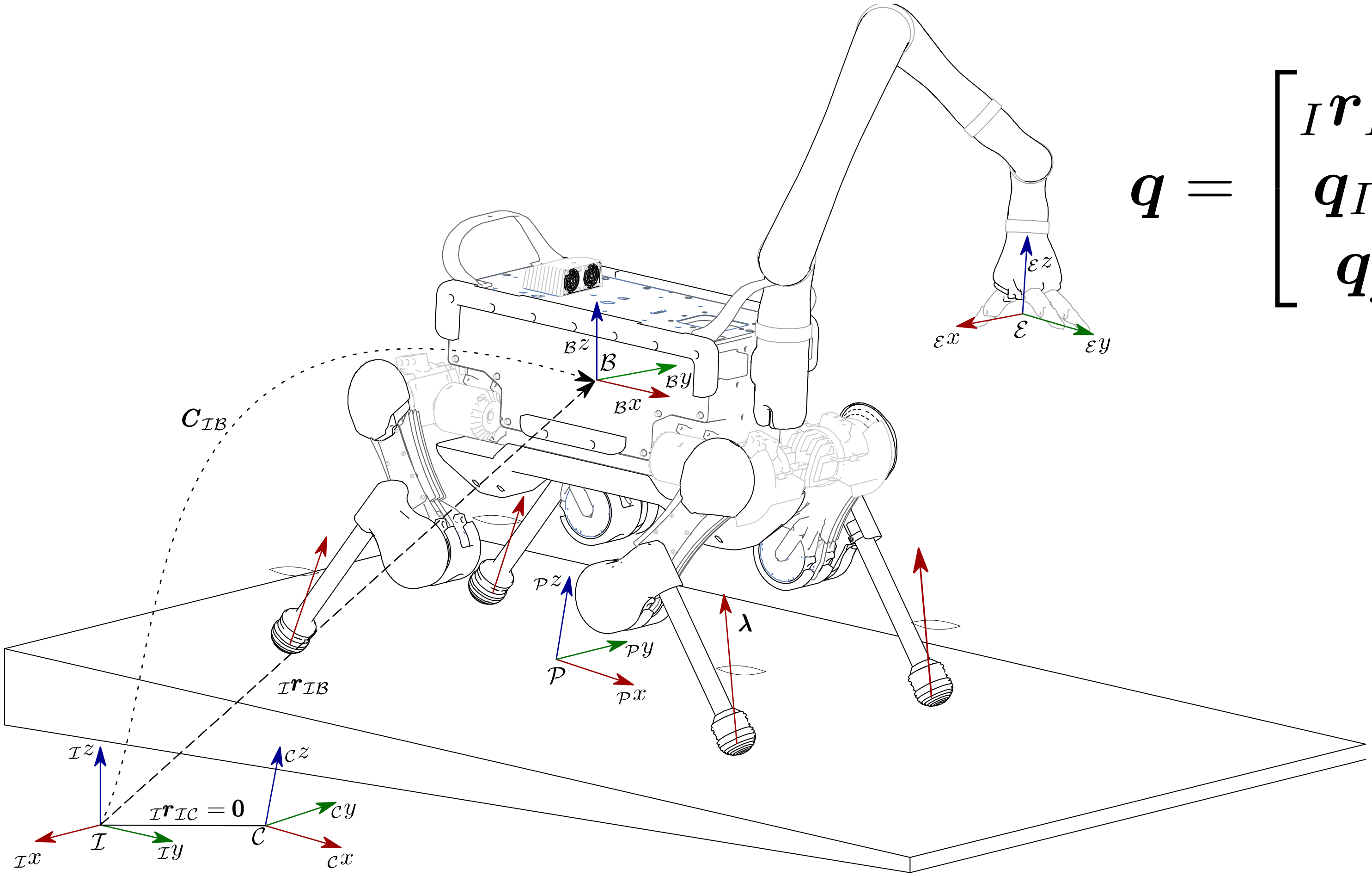
Localization & Mapping

Exteroception
- Camera
- Lidar

Legged Locomotion Control



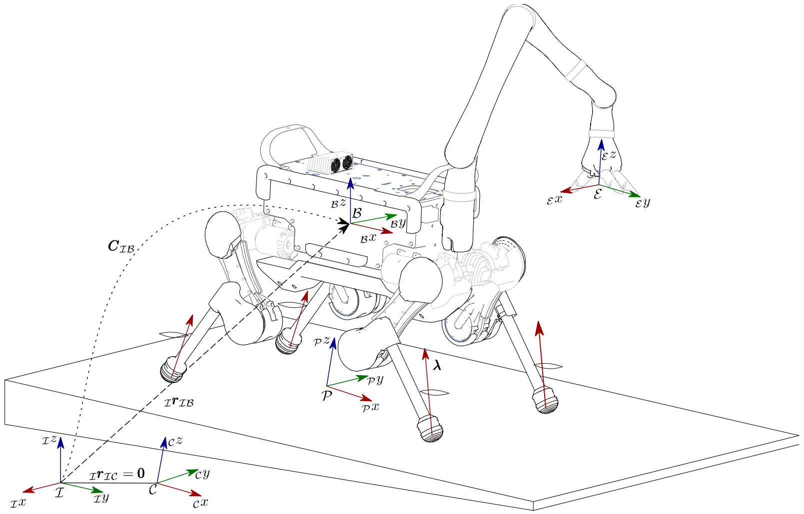
Floating-Base model



$$\boldsymbol{q} = \begin{bmatrix} {}_{I}\boldsymbol{r}_{IB} \\ \boldsymbol{q}_{IB} \\ \boldsymbol{q}_{j} \end{bmatrix}, \boldsymbol{u} = \begin{bmatrix} {}_{I}\boldsymbol{v}_{B} \\ {}_{B}\boldsymbol{\omega}_{IB} \\ \dot{\boldsymbol{q}}_{j} \end{bmatrix}$$

$$\boxed{\dot{\boldsymbol{q}} \neq \boldsymbol{u}}$$

Floating-Base model

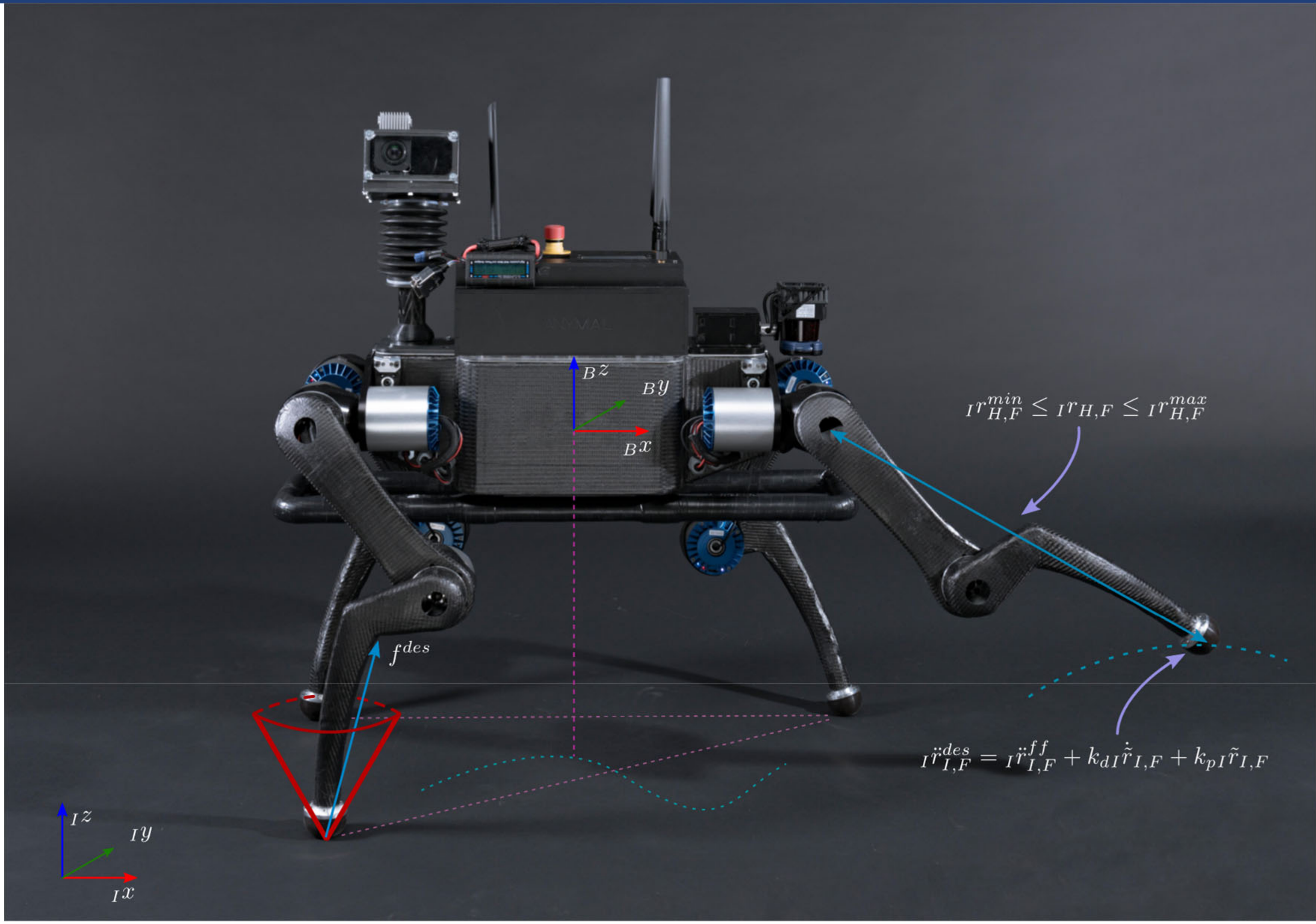


$$\boldsymbol{q} = \begin{bmatrix} {}_I\boldsymbol{r}_{IB} \\ \boldsymbol{q}_{IB} \\ \boldsymbol{q}_j \end{bmatrix}, \boldsymbol{u} = \begin{bmatrix} {}_I\boldsymbol{v}_B \\ {}_B\boldsymbol{\omega}_{IB} \\ \dot{\boldsymbol{q}}_j \end{bmatrix}$$

$$\boldsymbol{M}(\boldsymbol{q})\dot{\boldsymbol{u}} + \boldsymbol{h}(\boldsymbol{q}, \boldsymbol{u}) = \boldsymbol{S}^T\boldsymbol{\tau} + \boldsymbol{J}_S^T(\boldsymbol{q})\boldsymbol{\lambda}$$

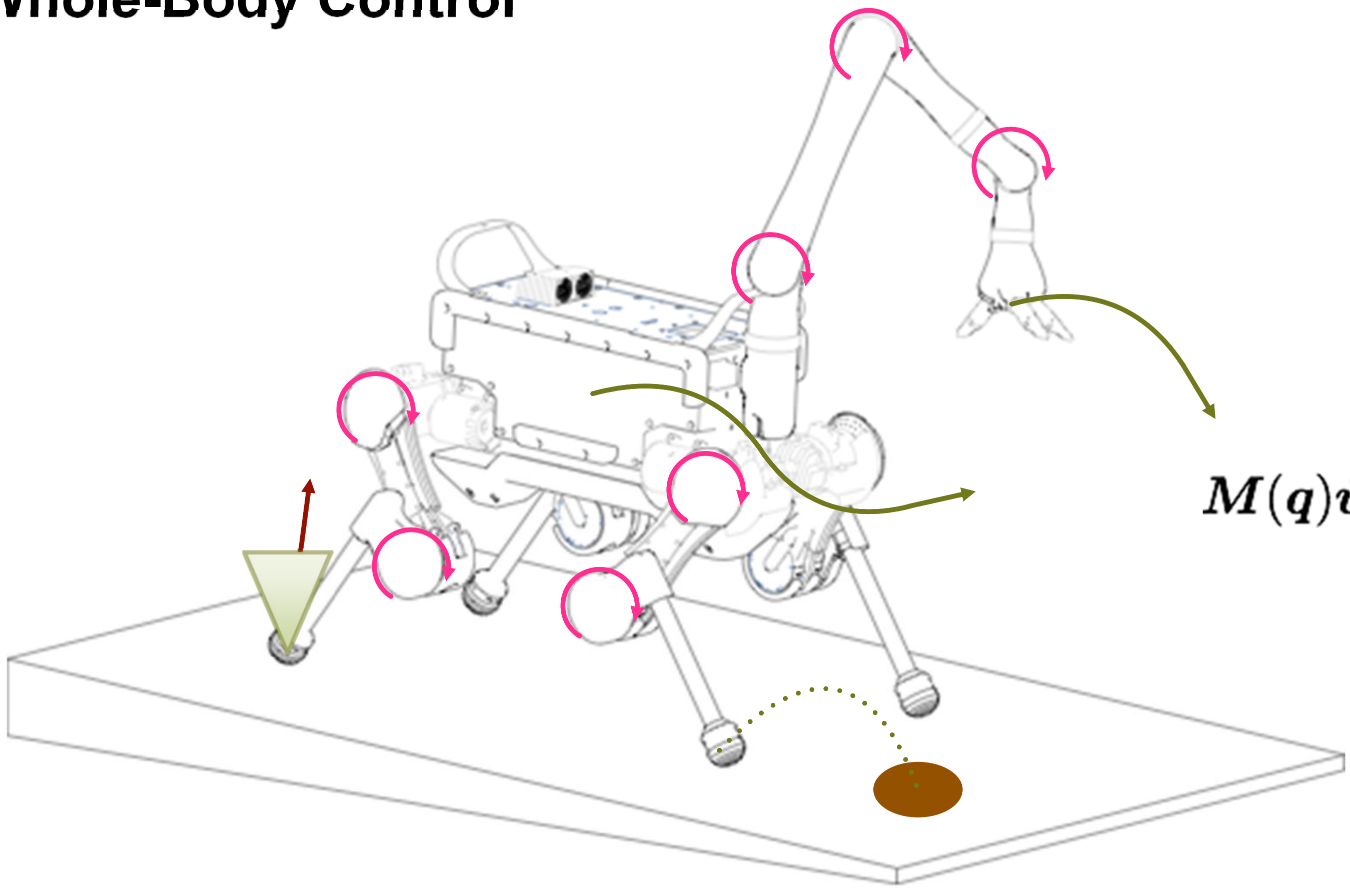
$$\boldsymbol{\lambda} = \begin{bmatrix} \boldsymbol{\lambda}_1 \\ \vdots \\ \boldsymbol{\lambda}_{n_c} \end{bmatrix} \quad \boldsymbol{J}_S = \begin{bmatrix} \boldsymbol{J}_{E_1} \\ \vdots \\ \boldsymbol{J}_{E_{n_c}} \end{bmatrix}$$

$${}_I\boldsymbol{J}_{E_k} = \begin{bmatrix} \boldsymbol{I} & -\boldsymbol{C}_{IB} \cdot {}_B\boldsymbol{r}_{BE_k}^{\times} & \boldsymbol{0} & \cdots & {}_I\boldsymbol{J}_{BE_k} & \cdots & \boldsymbol{0} \end{bmatrix}$$



$_Bz$
$_By$
$_Bx$
$_Ir^{min}_{H,F} \leq {_Ir_{H,F}} \leq {_Ir^{max}_{H,F}}$
f^{des}
$_I\ddot{r}^{des}_{I,F} = {_I\ddot{r}^{ff}_{I,F}} + k_{dI}\dot{\tilde{r}}_{I,F} + k_{pI}\tilde{r}_{I,F}$
$_Iz$
$_Iy$
$_Ix$

Whole-Body Control



$$\boxed{\boldsymbol{\tau} = ?}$$

$$\boldsymbol{M}(\boldsymbol{q})\dot{\boldsymbol{u}} + \boldsymbol{h}(\boldsymbol{q},\boldsymbol{u}) = \boldsymbol{S}^T\boldsymbol{\tau} + \boldsymbol{J}_S^T(\boldsymbol{q})\boldsymbol{\lambda}$$

$$\boldsymbol{\lambda} = \begin{bmatrix} \boldsymbol{\lambda}_1 \\ \vdots \\ \boldsymbol{\lambda}_{n_c} \end{bmatrix} \quad \boldsymbol{J}_S = \begin{bmatrix} \boldsymbol{J}_{E_1} \\ \vdots \\ \boldsymbol{J}_{E_{n_c}} \end{bmatrix}$$

Whole-body Control of a Legged Robot

- Define a vector of quantities used for control
  - Solve for generalize accelerations and contact forces

$$\boldsymbol{\xi} = \begin{bmatrix} \dot{\boldsymbol{u}} \\ \boldsymbol{\lambda} \end{bmatrix}$$

- Break down the locomotion problem into simpler tasks
  - Equations of motion
  - Contact constraints
  - Force and torque limits

$$\boldsymbol{T}_p : \begin{cases} \boldsymbol{W}_{eq,p}(\boldsymbol{A}_p\boldsymbol{\xi} - \boldsymbol{b}_p) = \boldsymbol{0} \\ \boldsymbol{W}_{ineq,p}(\boldsymbol{D}_p\boldsymbol{\xi} - \boldsymbol{f}_p) \leq \boldsymbol{0} \end{cases}$$

- Solve the tasks hierarchically
  - Project the constraints into the nullspace of higher priority tasks

Whole-Body Controller
Prioritized Tasks

- Equations of motion $$\begin{bmatrix}\boldsymbol{M}_b(\boldsymbol{q}) & -\boldsymbol{J}_{s,b}^T(\boldsymbol{q})\end{bmatrix}\boldsymbol{\xi} = -\boldsymbol{h}_b(\boldsymbol{q},\boldsymbol{u})$$
- Contact constraints $$\begin{bmatrix}\boldsymbol{J}_s & \boldsymbol{0}\end{bmatrix}\boldsymbol{\xi} = -\dot{\boldsymbol{J}}_s\boldsymbol{u}$$
- Contact force limits $$\begin{aligned}({}_I\boldsymbol{h} - {}_I\boldsymbol{n}\mu)^T {}_I\boldsymbol{\lambda}_k &\leq \boldsymbol{0}\\ -({}_I\boldsymbol{h} + {}_I\boldsymbol{n}\mu)^T {}_I\boldsymbol{\lambda}_k &\leq \boldsymbol{0}\\ ({}_I\boldsymbol{l} - {}_I\boldsymbol{n}\mu)^T {}_I\boldsymbol{\lambda}_k &\leq \boldsymbol{0}\\ -({}_I\boldsymbol{l} + {}_I\boldsymbol{n}\mu)^T {}_I\boldsymbol{\lambda}_k &\leq \boldsymbol{0}\end{aligned}$$
- Motion tracking $$\begin{bmatrix}\boldsymbol{J}(\boldsymbol{q}) & \boldsymbol{0}\end{bmatrix}\boldsymbol{\xi} = \ddot{\boldsymbol{x}}_{ref} - \dot{\boldsymbol{J}}(\boldsymbol{q})$$
- Contact force minimization $$\begin{bmatrix}\boldsymbol{0} & \boldsymbol{I}\end{bmatrix}\boldsymbol{\xi} = \boldsymbol{0}$$
- Compute the actuation signals: inverse dynamics $$\boldsymbol{\tau}^d = \boldsymbol{M}_j(\boldsymbol{q})\dot{\boldsymbol{u}}^* + \boldsymbol{h}_j(\boldsymbol{q},\boldsymbol{u}) - \boldsymbol{J}_{s,j}(\boldsymbol{q})\boldsymbol{\lambda}^*$$

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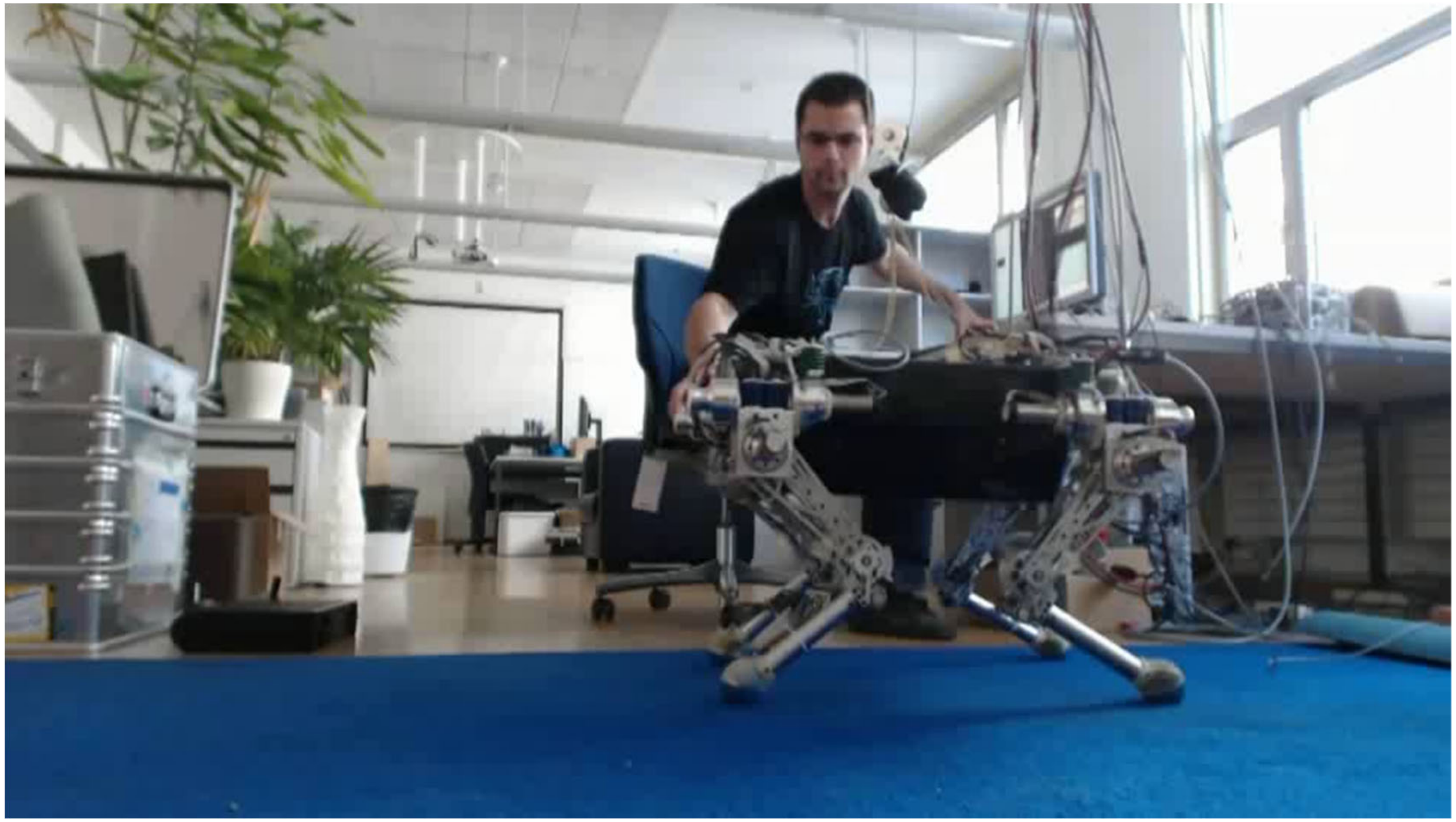
Static Walking with Compliant Behavior



Static Walking – Force/Torque Optimization

- Different force and torque optimization strategies:
  - Reduced energy consumption by torque minimization
  - Reduction of risk of slippage by contact force alignment

20%

			Torque minimization	Tangential force minimization
Energy consumption	$E_\tau = \int \boldsymbol{\tau}^T \boldsymbol{\tau} \mathrm{d}t$	$[N^2 m^2 s]$	4701	5544
Risk of slippage	$\overline{\mu} = \mathrm{mean}\left(\frac{F_{tan}(t)}{F_{norm}(t)}\right)$	[-]	0.2	0.04
Average tracking error	$\overline{\Delta r} = \mathrm{mean}\, \lVert r(t) - r_{des}(t) \rVert$	[mm]	7.7	3.3

Contact Force Alignment

1. Measure surface normal with IMU in the feet.
2. Formulate tasks in local contact frame.

Friction pyramid constraint

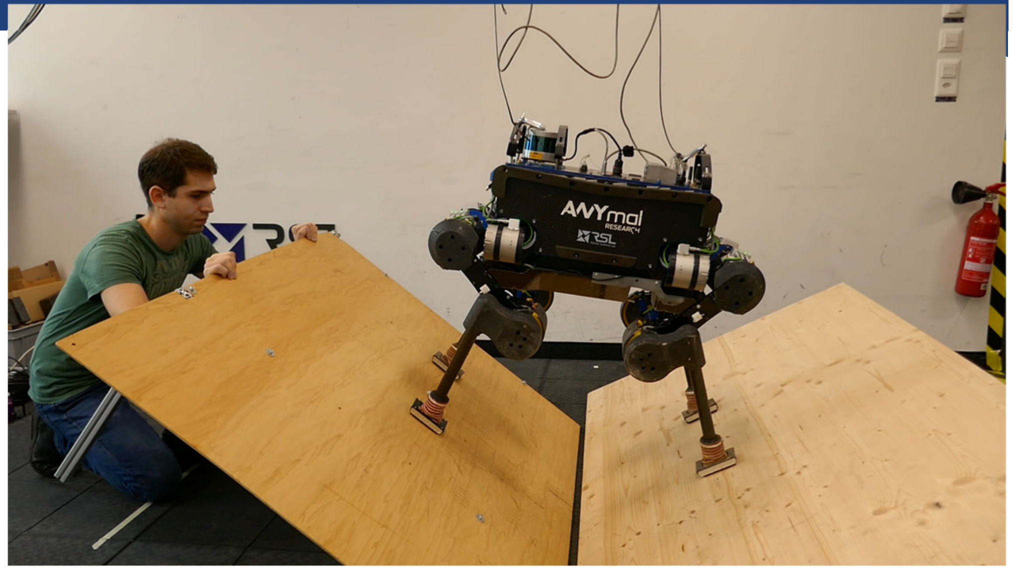
$$(\pm \mathbf{t}_{i,h} - \mu\, \mathbf{n}_i)^T \boldsymbol{\lambda}_i \leq 0,$$
$$(\pm \mathbf{t}_{i,l} - \mu\, \mathbf{n}_i)^T \boldsymbol{\lambda}_i \leq 0,$$
$$-\mathbf{n}_i^T \boldsymbol{\lambda}_i \leq -\lambda_{\text{min}}$$

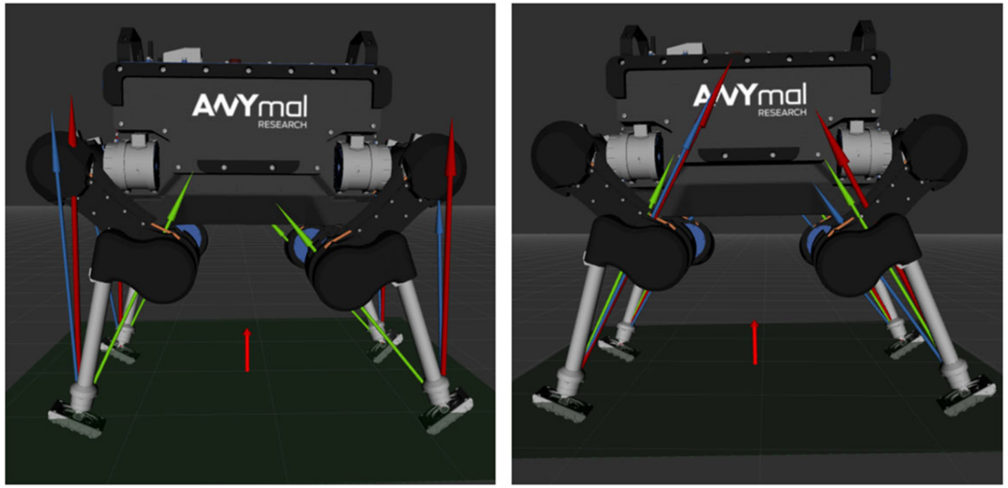
Optimize contact force direction

$$\min_{\boldsymbol{\lambda}_i} \quad \|\mathbf{T}_i^T \boldsymbol{\lambda}_i\|_2^2 + \gamma^2 (\mathbf{n}_i^T \boldsymbol{\lambda}_i)^2$$

3. Integrate into hierarchical whole-body control framework

Priority	Task	Dim.	Type
0	Floating base equations of motion.	6	Eq.
	Torque limits.	12	Ineq.
	Friction cone constraint.	$5n_c$	Ineq.
	No motion at the contact points.	$3n_c$	Eq.
1	Center of mass linear motion tracking.	3	Eq.
	Base angular motion tracking.	3	Eq.
	Swing leg position tracking.	$12 - 3n_c$	Eq.
2	Contact force optimization.	$3n_c$	Eq.





Surface normal, desired forces, measured forces.

[Giorgio Valsecchi et al. "Tactile feedback enhanced locomotion for quadrupedal robots". Submitted to: IEEE Robot and Automation Letters (RA-L) (2020)]

Contact Force Alignment

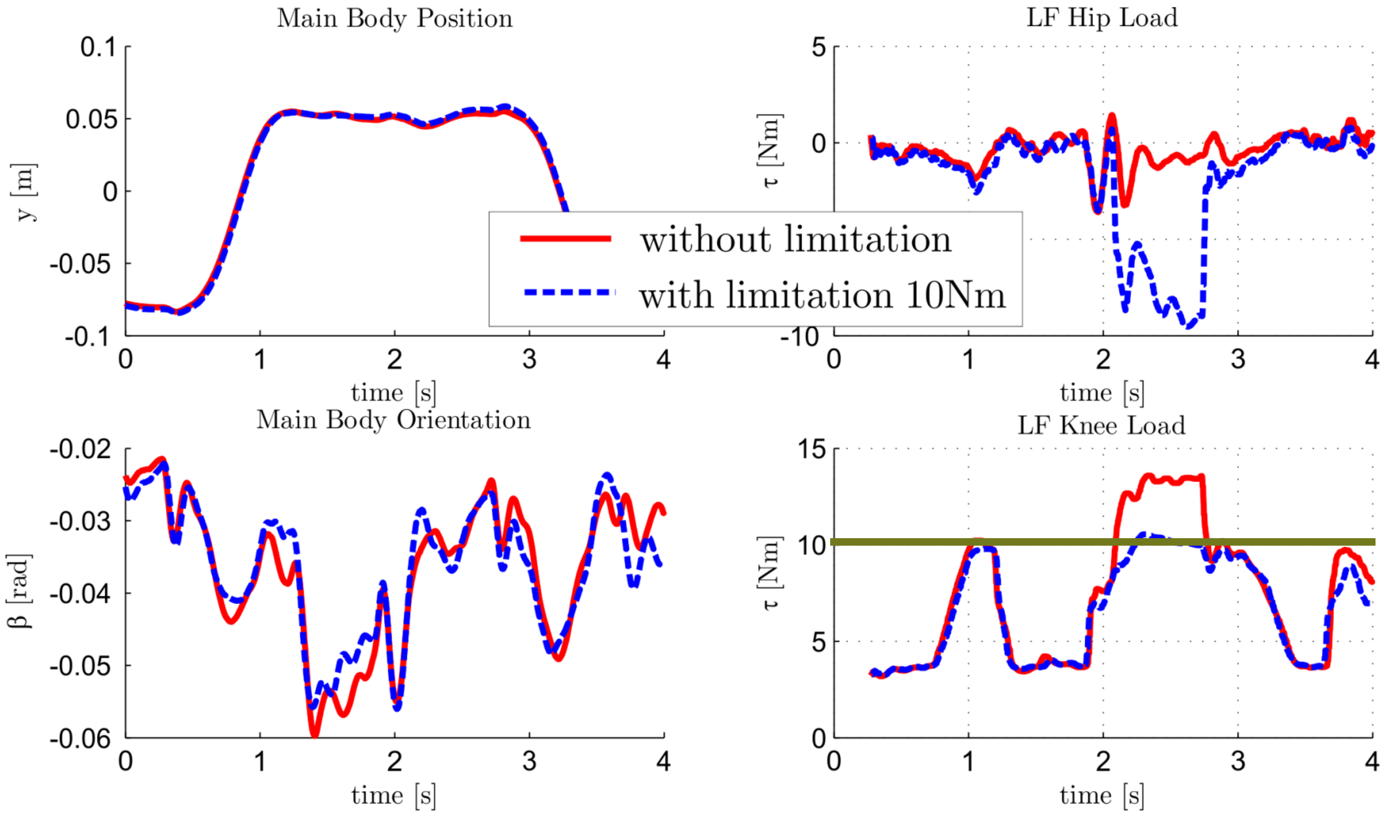
Without haptic terrain perception

With haptic terrain perception

[Giorgio Valsecchi et al. “Tactile feedback enhanced locomotion for quadrupedal robots”. Submitted to: IEEE Robot and Automation Letters (RA-L) (2020)]

Joint Torque Limitations

- Inequality tasks

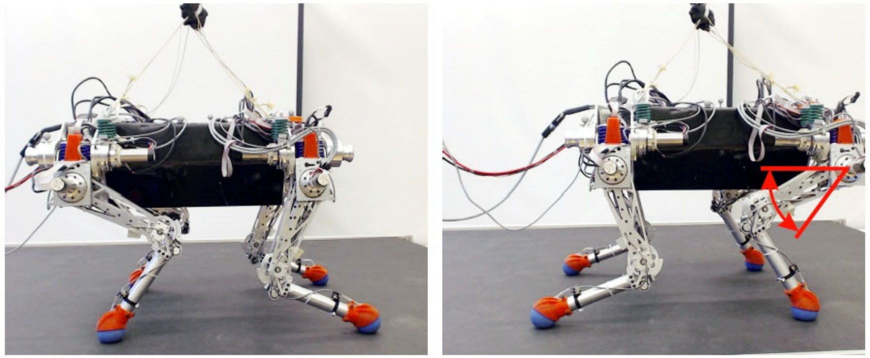


Joint Position Limitation

$$\boxed{\mathbf{A}_i \mathbf{x} \leq \mathbf{b}_i}$$

- Base shifting
- Joint Limitation = Inequality constraint

P_1^q : contact constraints
P_2^q : angle limitation
P_3^q : xy body position
P_4^q : body orientation
P_5^q : ground clearance



(a) Start configuration (b) No joint limitation

Task Prioritization (Bellicoso, Humanoids 2016)

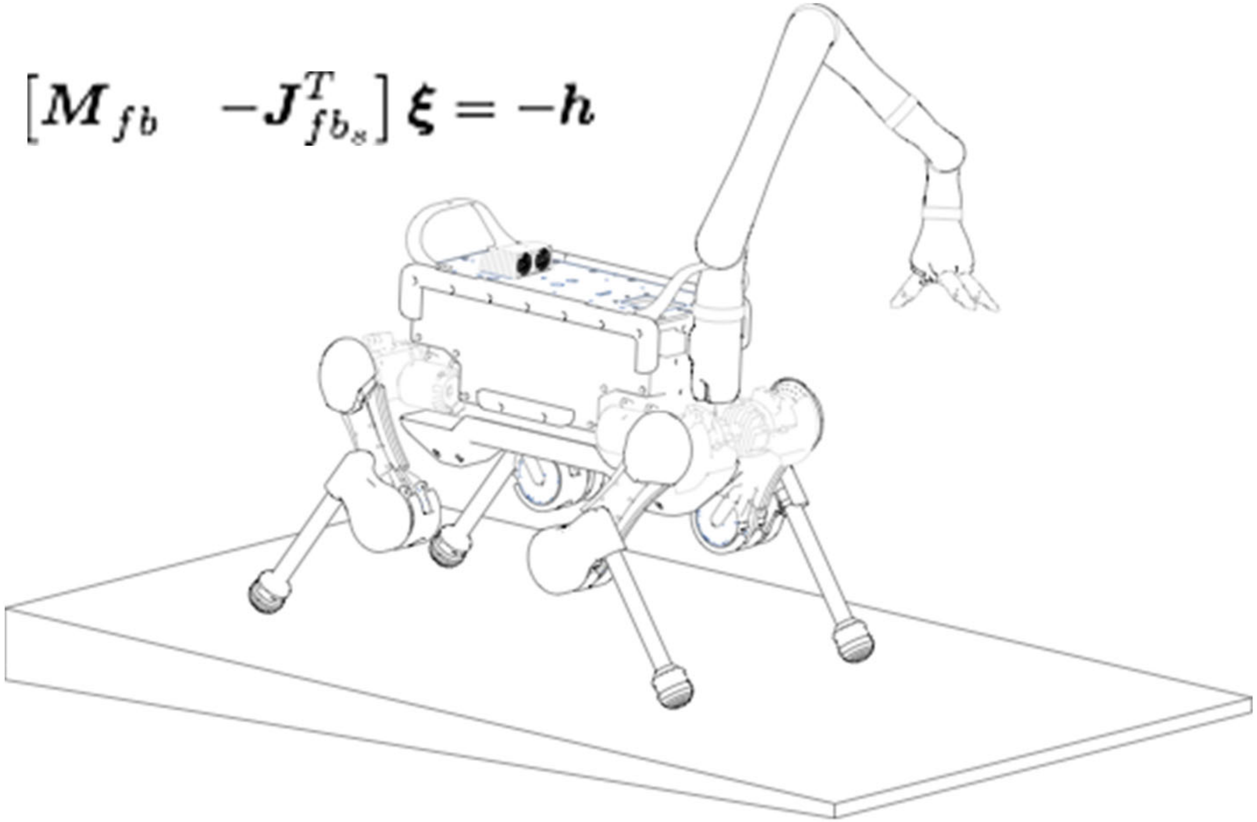
Priority	Task
1	Equations of Motion
2	No contact motion
3	Torque limits
4	Friction cone and $\boldsymbol{\lambda}$ modulation
5	Desired torso x, y position
6	Swing foot motion tracking
7	Limb kinematic limits
8	Main body yaw
9	Main body height
10	Main body roll and pitch
11	Contact force minimization

Whole-Body Control – Mobile Manipulation

Whole-Body Control - Prioritized tasks

1	Equations of Motion
1	Force/torque limits
1	No motion at contact points
2	CoM motion tracking
2	Torso angular motion
2	Foot motion tracking
2	End-effector motion tracking
2	End-effector force tracking
2	Torso orientation adaptation
3	Contact force minimisation

$$\begin{bmatrix} \boldsymbol{M}_{fb} & -\boldsymbol{J}_{fb_s}^T \end{bmatrix} \boldsymbol{\xi} = -\boldsymbol{h}$$

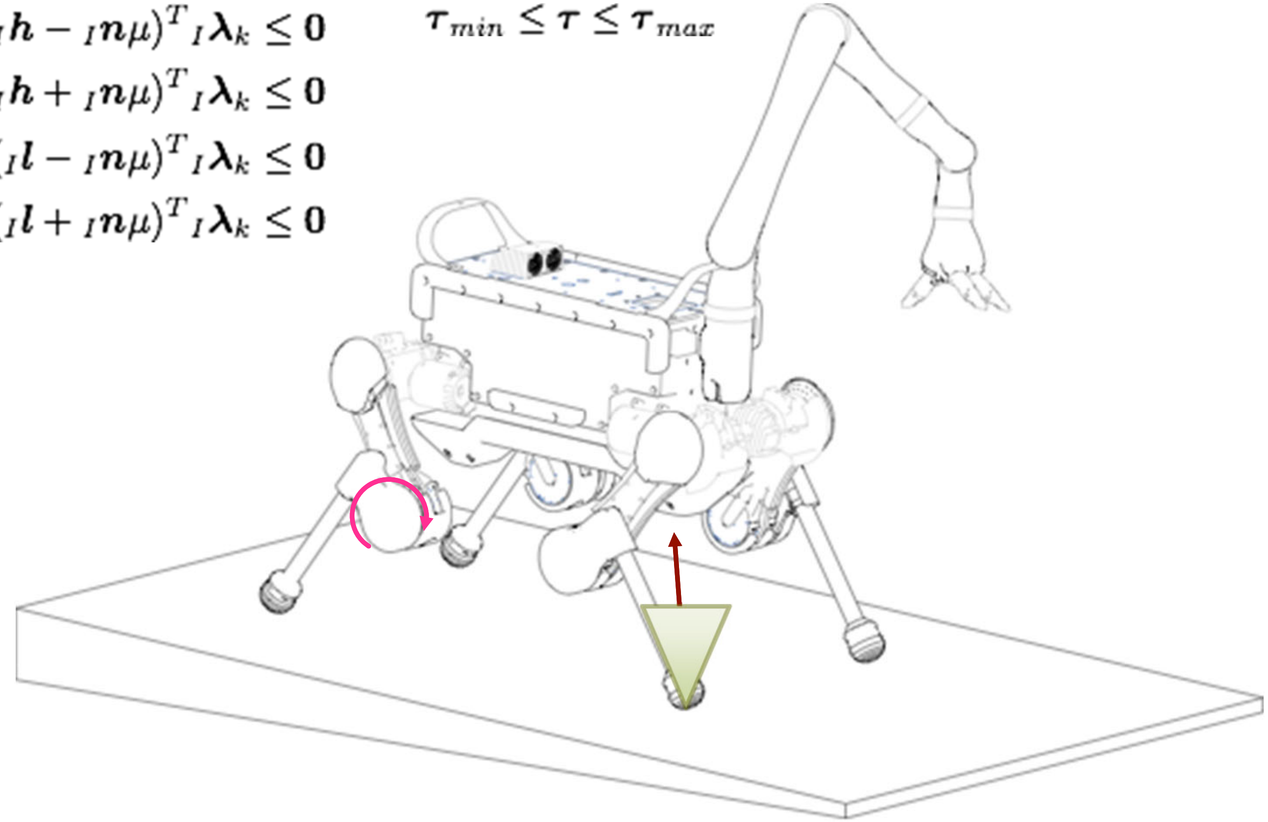


Whole-Body Control - Prioritized tasks

1	Equations of Motion
1	Force/torque limits
1	No motion at contact points
2	CoM motion tracking
2	Torso angular motion
2	Foot motion tracking
2	End-effector motion tracking
2	End-effector force tracking
2	Torso orientation adaptation
3	Contact force minimisation

$$({}_I\boldsymbol{h} - {}_I\boldsymbol{n}\mu)^T {}_I\boldsymbol{\lambda}_k \leq \mathbf{0}$$
$$-({}_I\boldsymbol{h} + {}_I\boldsymbol{n}\mu)^T {}_I\boldsymbol{\lambda}_k \leq \mathbf{0}$$
$$({}_I\boldsymbol{l} - {}_I\boldsymbol{n}\mu)^T {}_I\boldsymbol{\lambda}_k \leq \mathbf{0}$$
$$-({}_I\boldsymbol{l} + {}_I\boldsymbol{n}\mu)^T {}_I\boldsymbol{\lambda}_k \leq \mathbf{0}$$

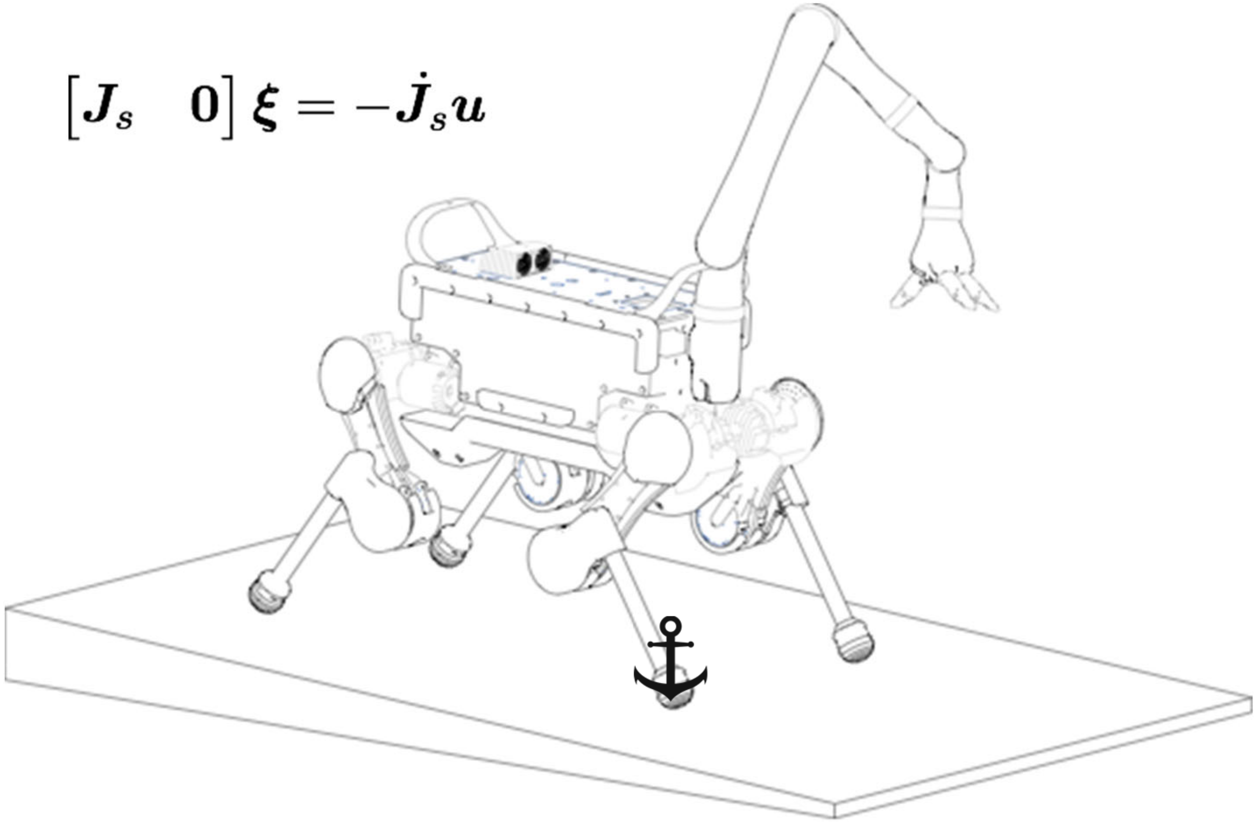
$$\boldsymbol{\tau}_{min} \leq \boldsymbol{\tau} \leq \boldsymbol{\tau}_{max}$$



Whole-Body Control - Prioritized tasks

1	Equations of Motion
1	Force/torque limits
1	No motion at contact points
2	CoM motion tracking
2	Torso angular motion
2	Foot motion tracking
2	End-effector motion tracking
2	End-effector force tracking
2	Torso orientation adaptation
3	Contact force minimisation

$$[\boldsymbol{J}_s \quad \boldsymbol{0}]\,\boldsymbol{\xi} = -\dot{\boldsymbol{J}}_s \boldsymbol{u}$$



Whole-Body Control - Prioritized tasks

1	Equations of Motion
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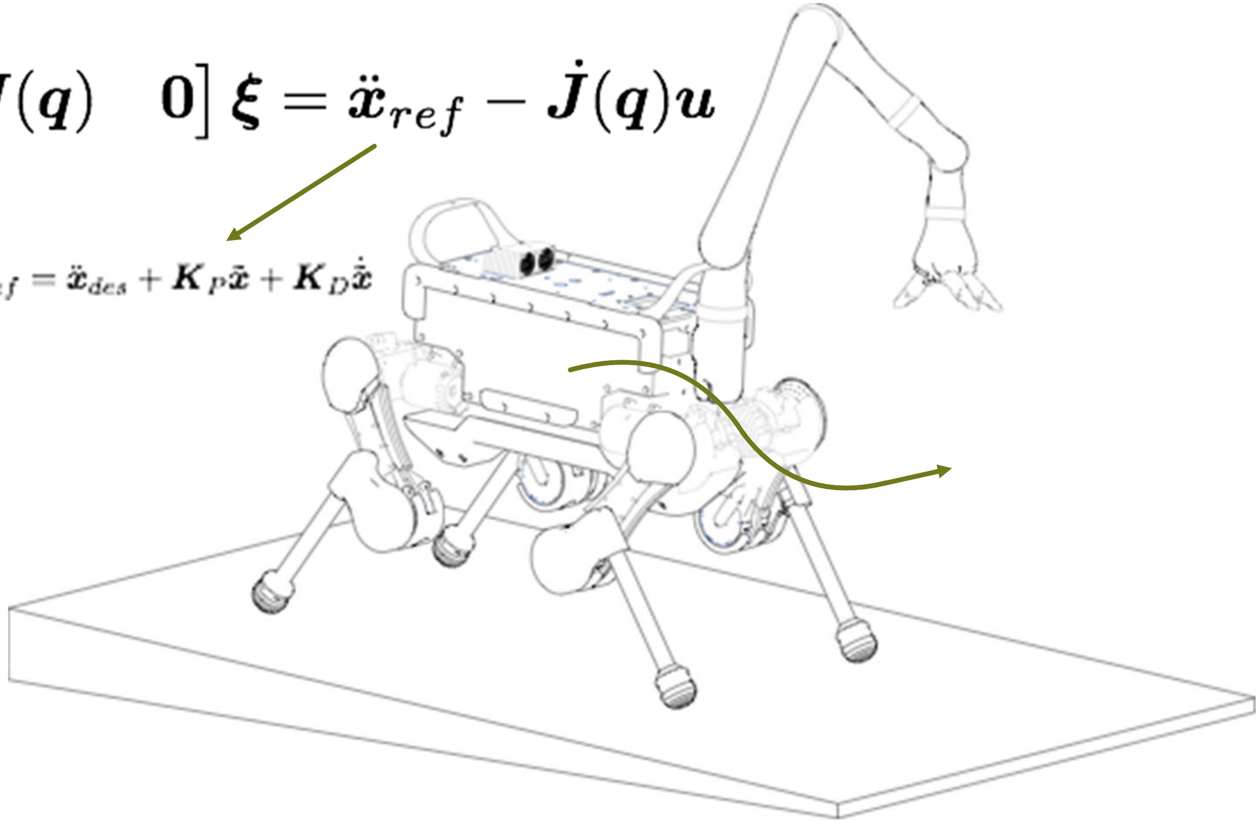
2	Torso angular motion
2	Foot motion tracking
2	End-effector motion tracking
2	End-effector force tracking
2	Torso orientation adaptation
3	Contact force minimisation

$$[\boldsymbol{J}(\boldsymbol{q}) \quad \boldsymbol{0}]\, \boldsymbol{\xi} = \ddot{\boldsymbol{x}}_{ref} - \dot{\boldsymbol{J}}(\boldsymbol{q})\boldsymbol{u}$$

$$\ddot{\boldsymbol{x}}_{ref} = \ddot{\boldsymbol{x}}_{des} + \boldsymbol{K}_P \tilde{\boldsymbol{x}} + \boldsymbol{K}_D \dot{\tilde{\boldsymbol{x}}}$$



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2	End-effector force tracking
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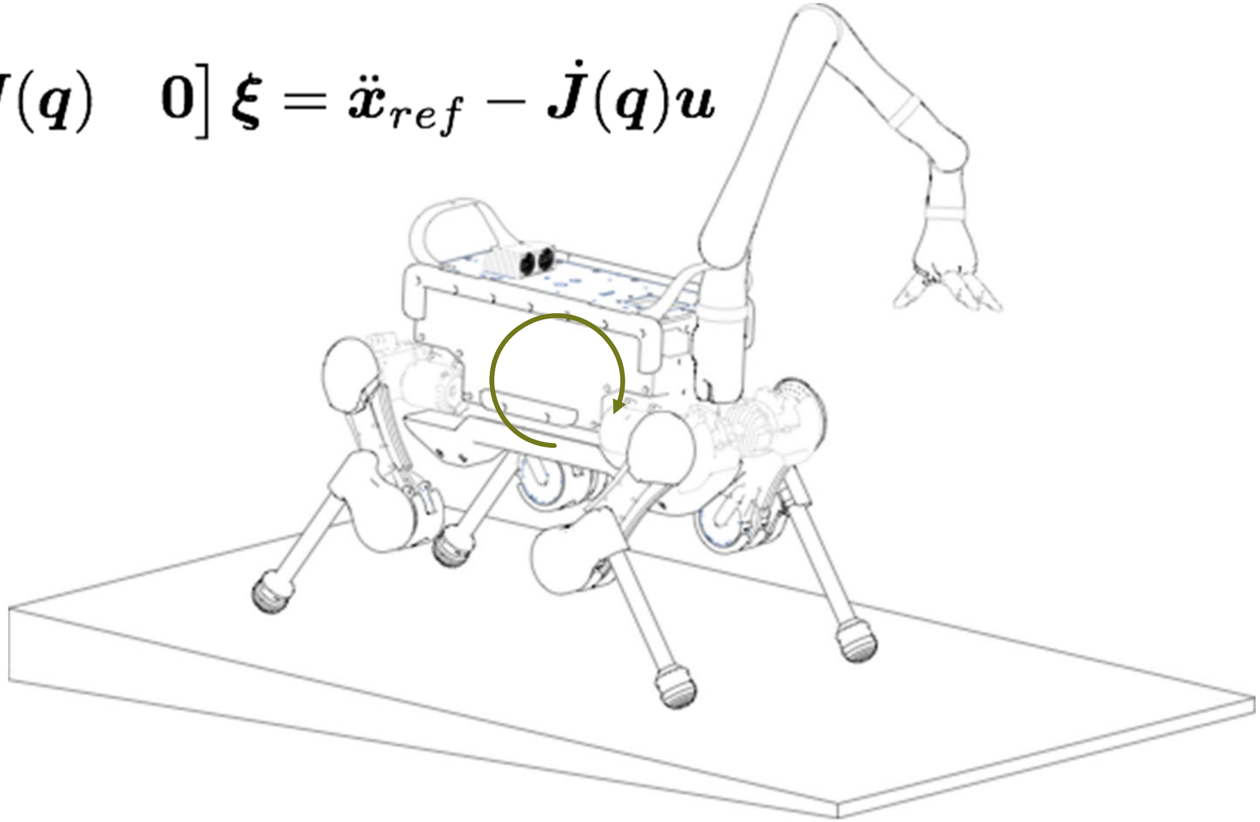
3	Contact force minimisation

$$\begin{bmatrix} \boldsymbol{J}(\boldsymbol{q}) & \mathbf{0} \end{bmatrix} \boldsymbol{\xi} = \ddot{\boldsymbol{x}}_{ref} - \dot{\boldsymbol{J}}(\boldsymbol{q})\boldsymbol{u}$$



Whole-Body Control - Prioritized tasks

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2	Torso angular motion
2	$\boxed{\text{Foot motion tracking}}$
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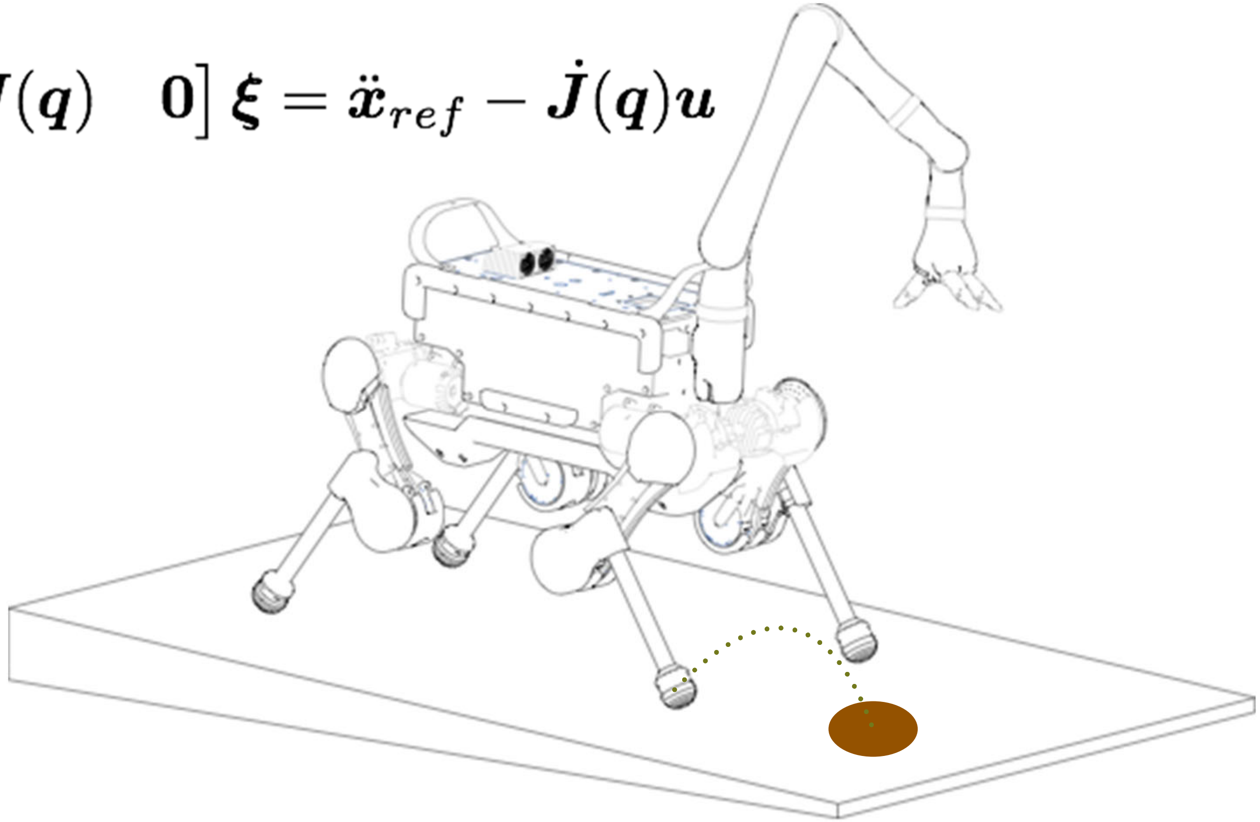

Whole-Body Control - Prioritized tasks

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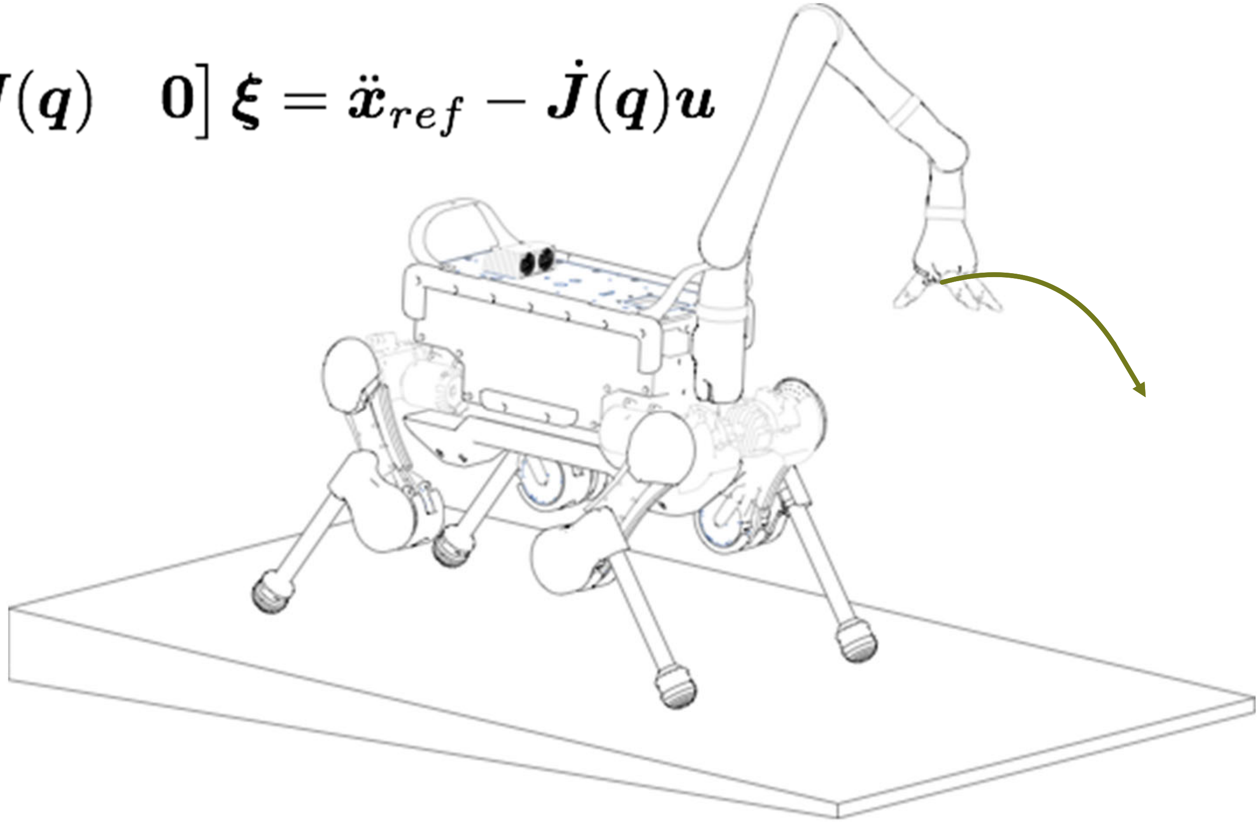

Whole-Body Control - Prioritized tasks

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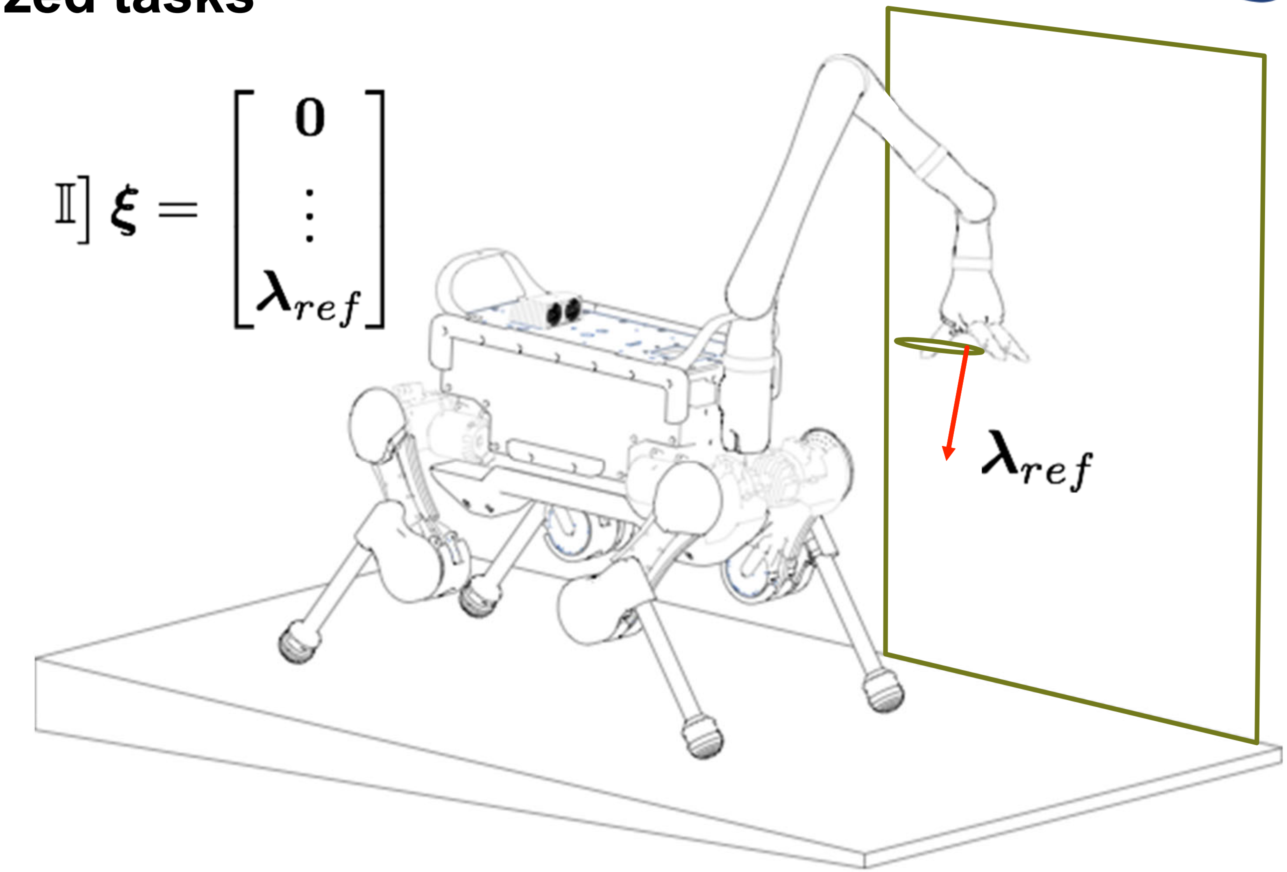
$$[\mathbf{0} \quad \mathbb{I}]\,\boldsymbol{\xi} = \begin{bmatrix} \mathbf{0} \\ \vdots \\ \boldsymbol{\lambda}_{ref} \end{bmatrix}$$



Whole-Body Control - Prioritized tasks

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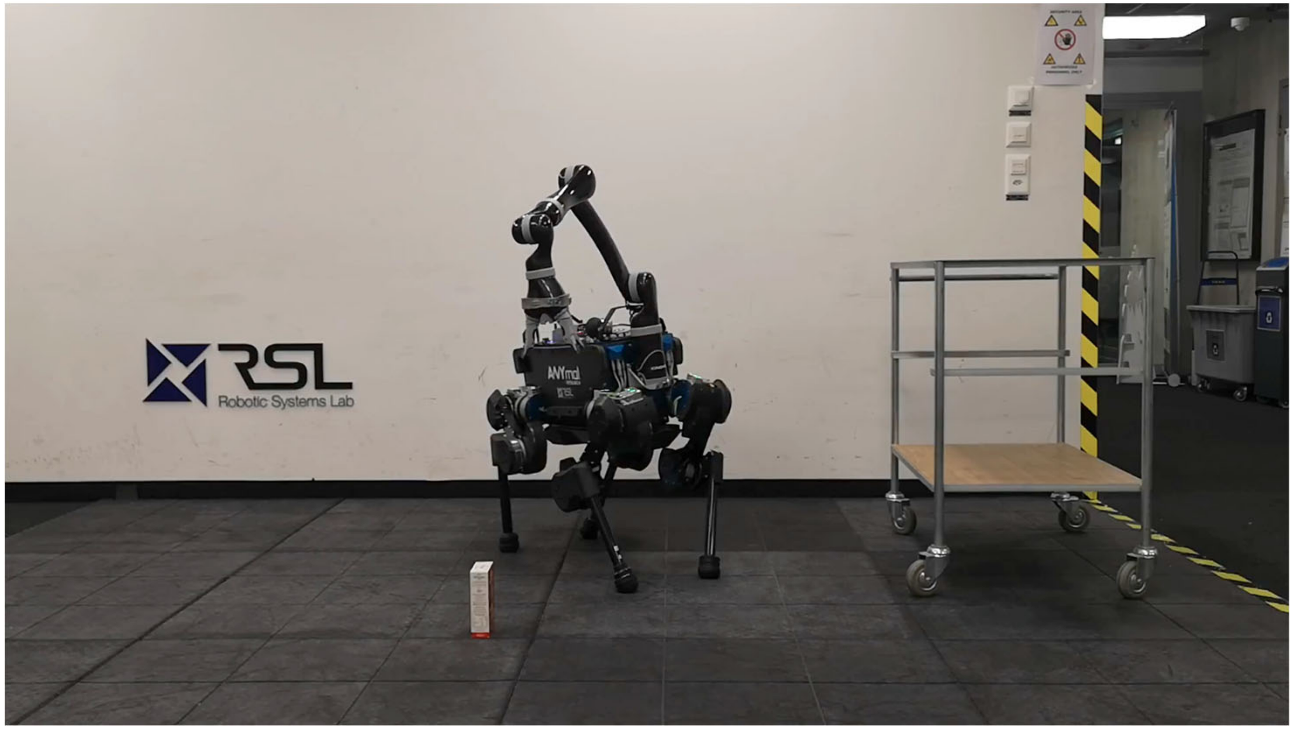

Whole-Body Control - Prioritized tasks

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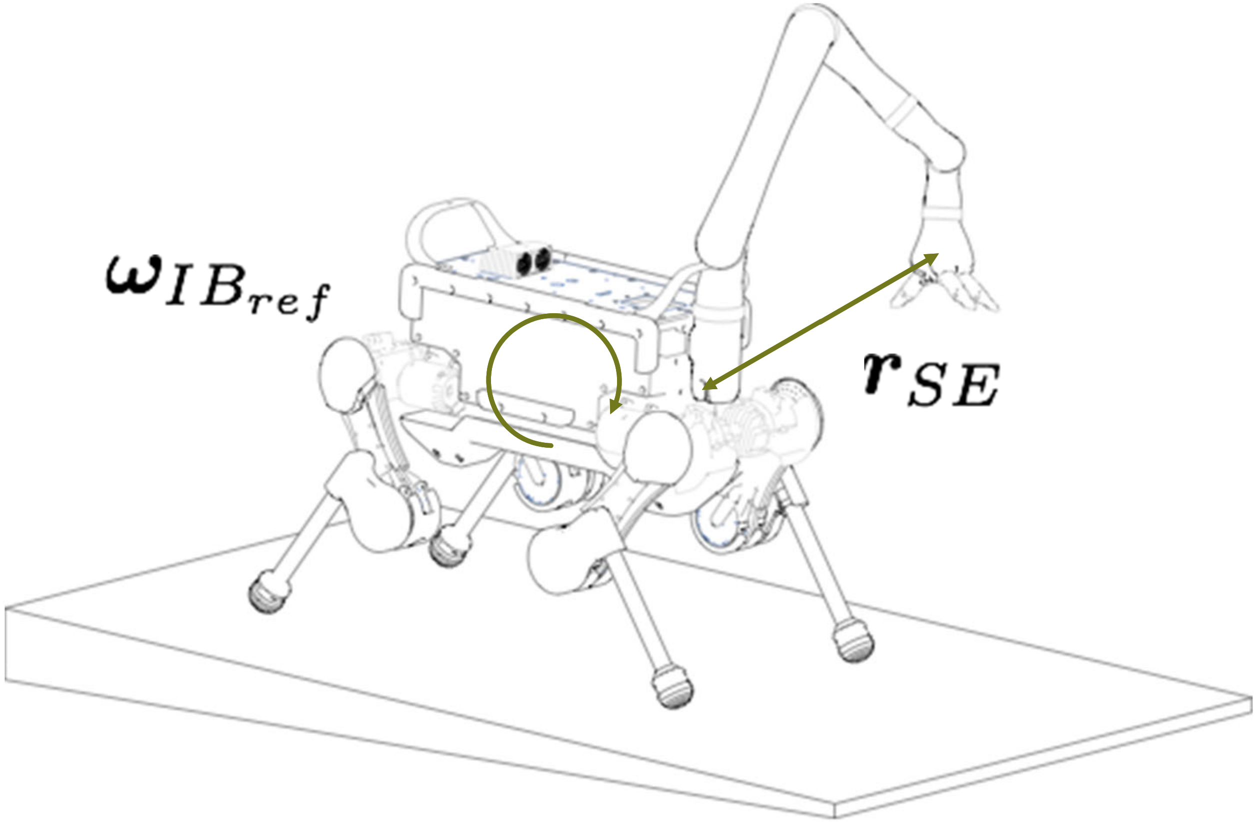

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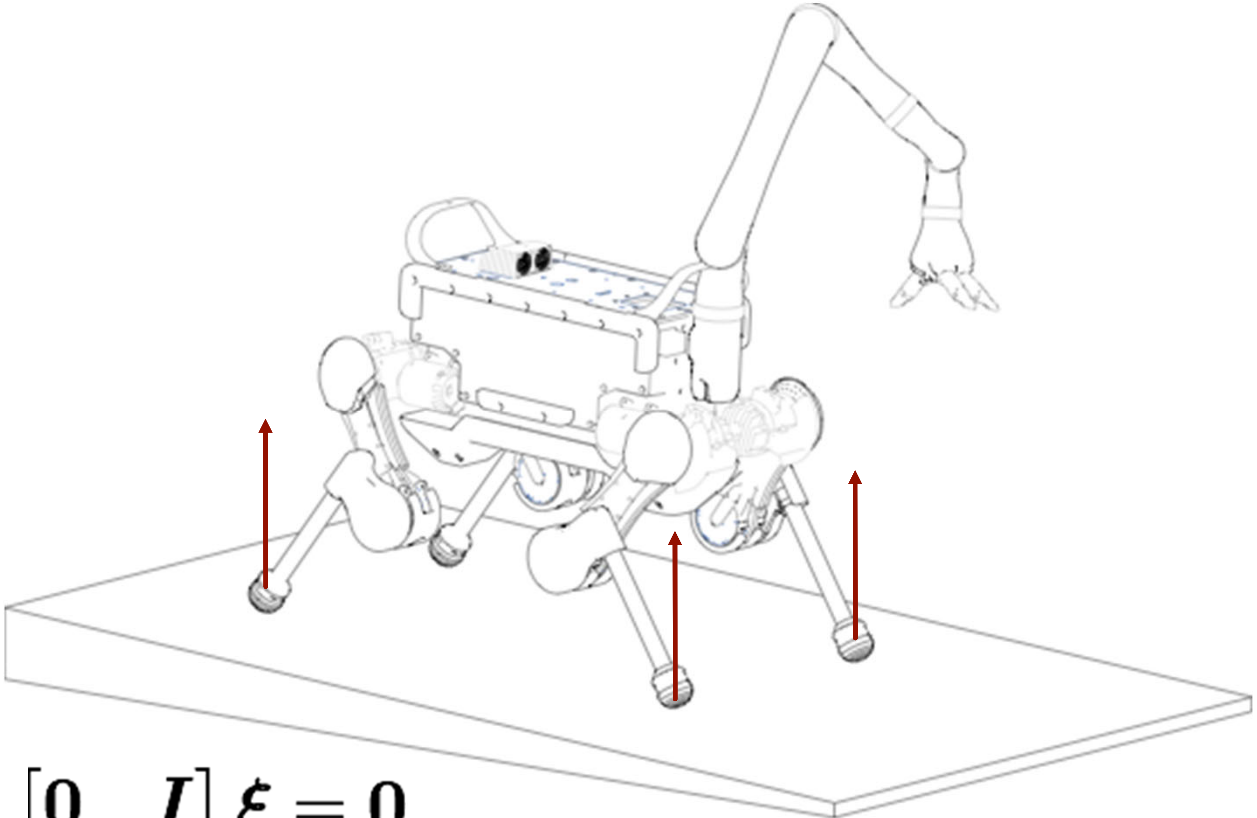
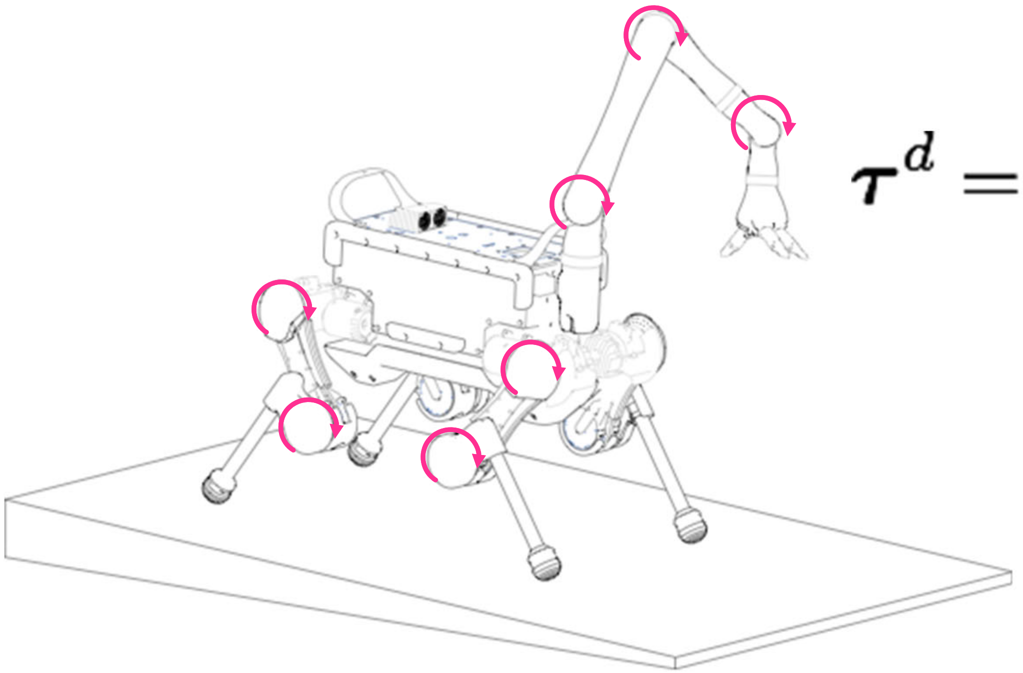


$$\begin{bmatrix} \mathbf{0} & \boldsymbol{I} \end{bmatrix} \boldsymbol{\xi} = \mathbf{0}$$

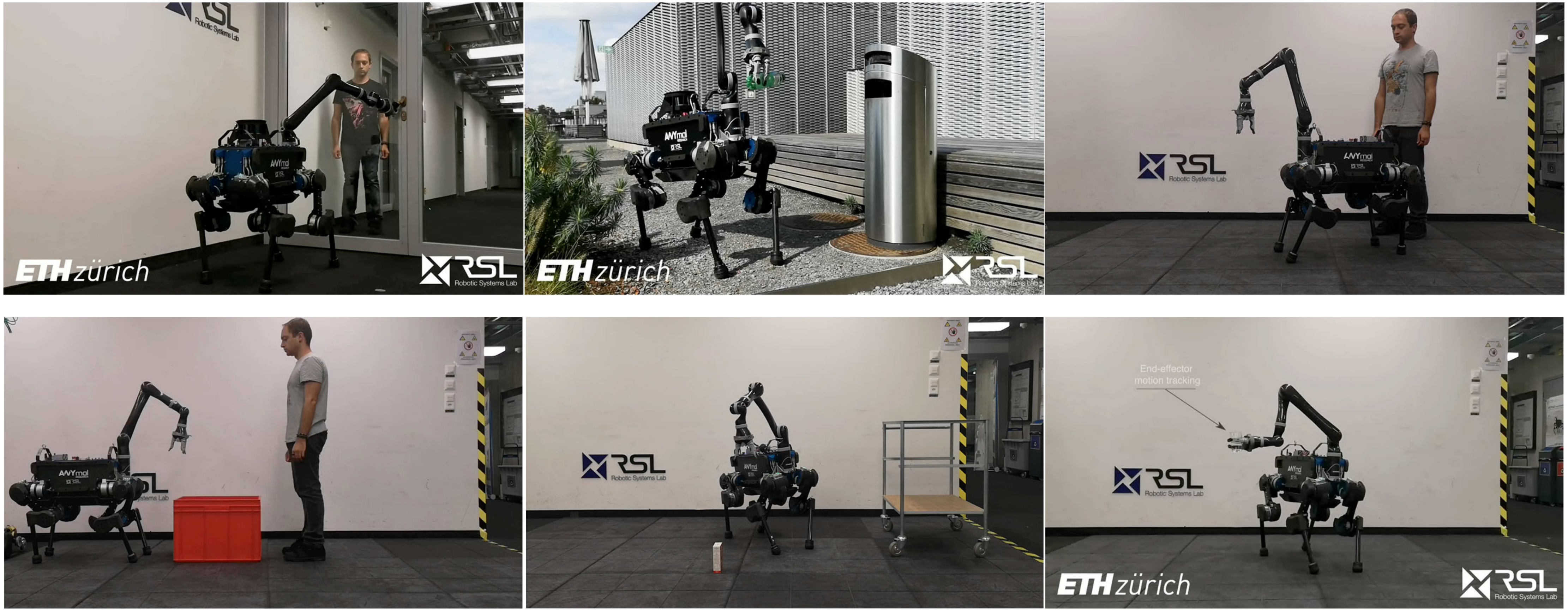
Whole-Body Control - Actuation signals



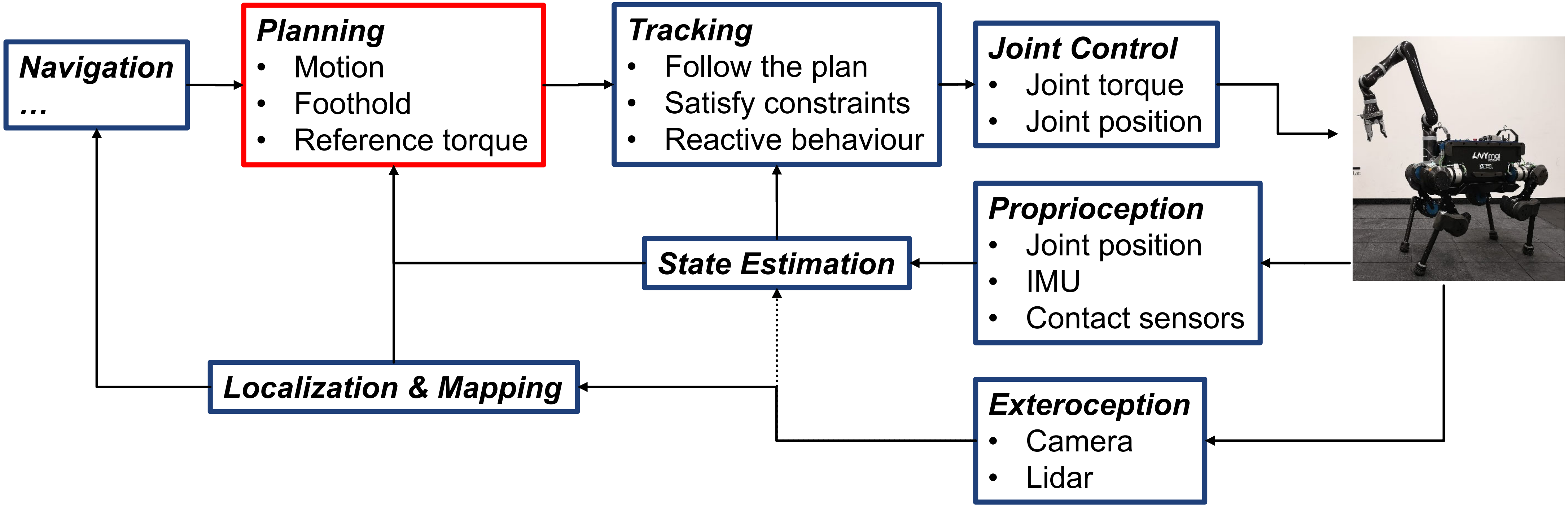
$$\boldsymbol{\tau}^d = \boldsymbol{M}_j(\boldsymbol{q})\dot{\boldsymbol{u}}^* + \boldsymbol{h}_j(\boldsymbol{q},\boldsymbol{u}) - \boldsymbol{J}_{s,j}(\boldsymbol{q})\boldsymbol{\lambda}^*$$

$$\boldsymbol{\tau}^{ref} = \boldsymbol{\tau}^d + \boldsymbol{k}_P\tilde{\boldsymbol{q}} + \boldsymbol{k}_D\dot{\tilde{\boldsymbol{q}}}$$

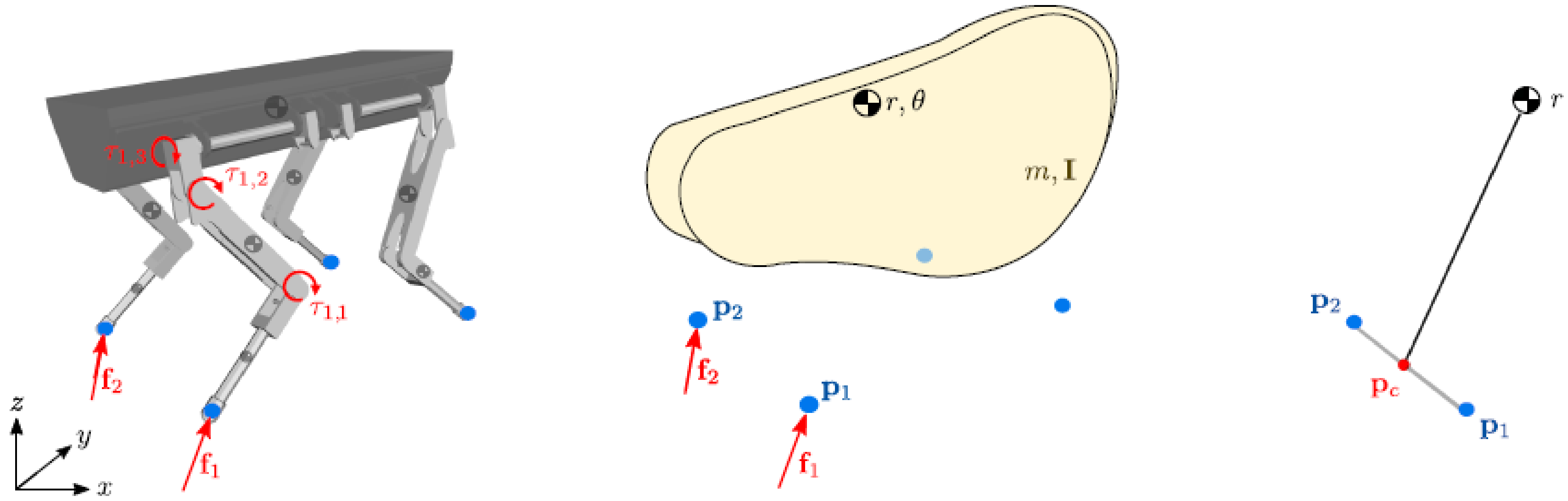
Coordination of Locomotion and Manipulation



Legged Locomotion Control



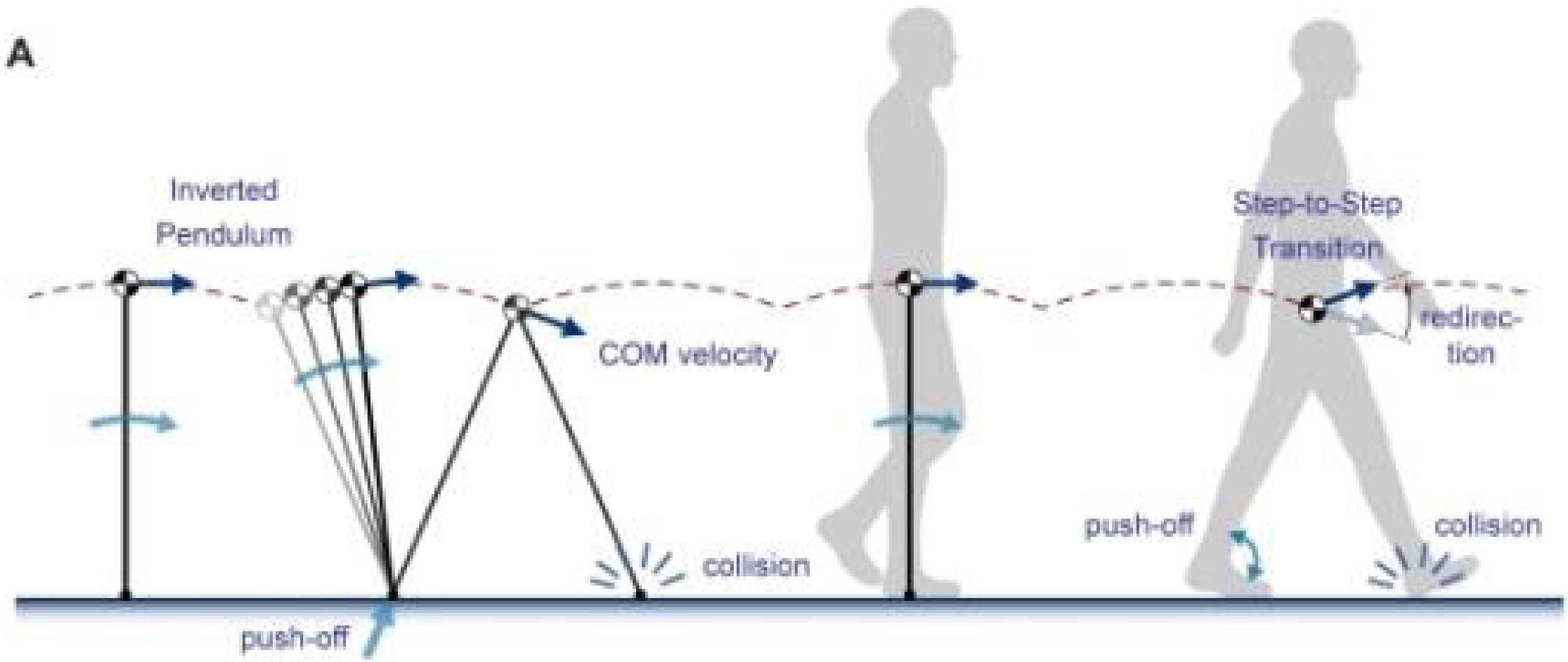
Various models for real-time TO / MPC



- Different levels of complexity used for trajectory optimization
- Integrated or sequential optimization for timing and foothold locations

Static walking principles
Inverted Pendulum

- Static walking can be represented by inverted pendulum

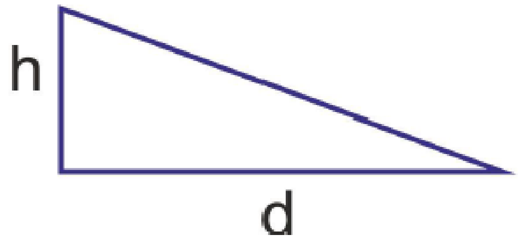


Static walking principles
Inverted Pendulum

- Static walking can be represented by inverted pendulum
- Exploit this in so-called passive dynamic walkers

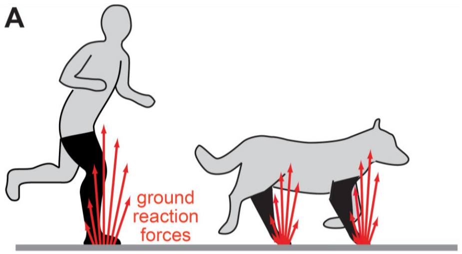
Energetically very efficient

$$COT = \frac{E_{used}}{m \cdot g \cdot d} = \frac{m \cdot g \cdot h}{m \cdot g \cdot d} = \frac{h}{d}$$

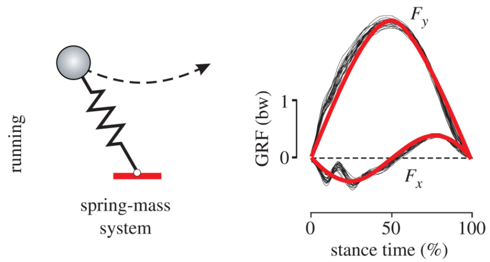


Foot Placement Control
Balance from stepping

- Biomechanical studies suggest SLIP models to describe complex running behaviors



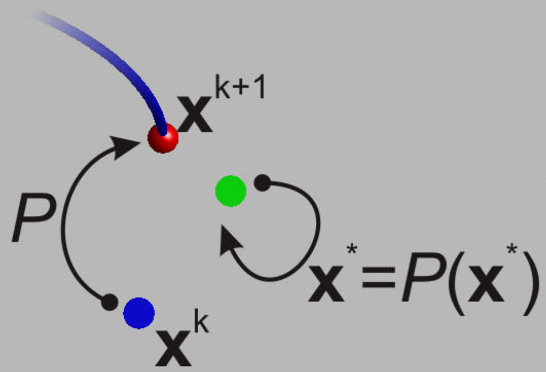
[Dickinson, Farley, Full 2000]

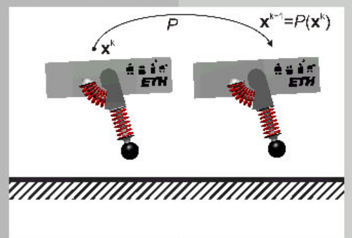


[Geyer 2006]

Analyzing Stability through Limit Cycles

- Poincaré Map $\mathbf{x}_{k+1} = P\left(\mathbf{x}_k\right)$
- Fix-Point $\mathbf{x}^* = P\left(\mathbf{x}^*\right)$
- Linearization of mapping $\Delta\mathbf{x}_{k+1} = \dfrac{\partial P}{\partial \mathbf{x}} \Delta\mathbf{x}_k = \mathbf{\Phi}\Delta\mathbf{x}_k$
- The system is stable iff: $\lambda_i\left(\mathbf{\Phi}\right) < 1$

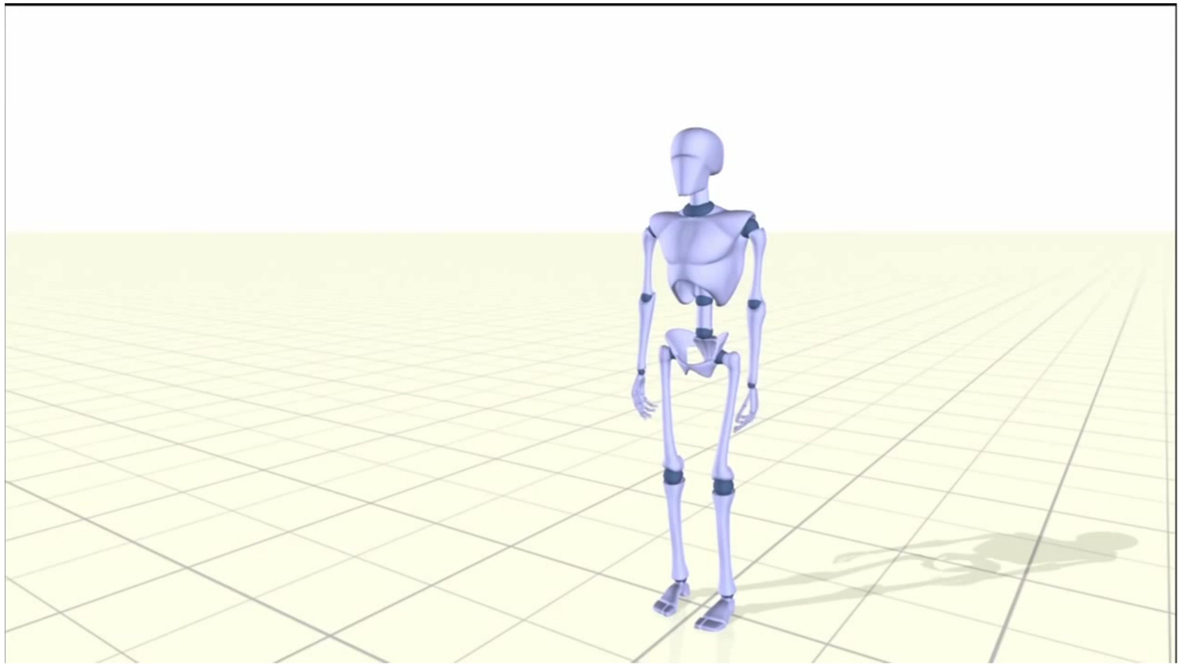




[C. David Remy, 2011]

Stability and Control of Locomotion
Example of a biped

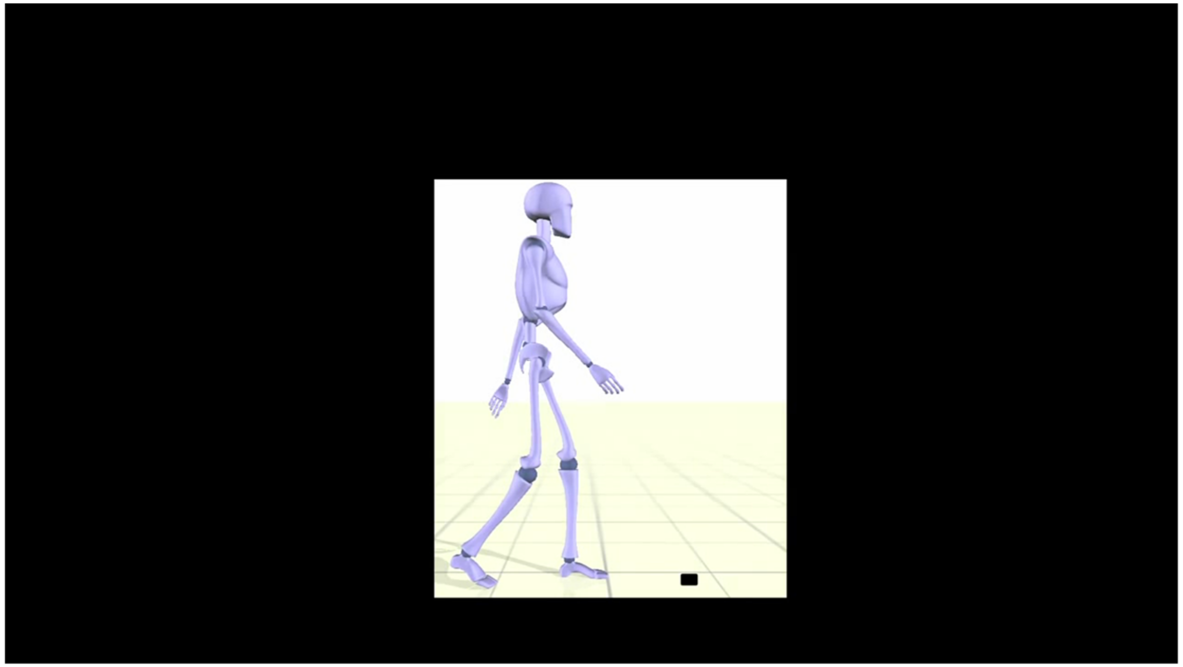
- External disturbances lead to instability



[Coros 2012]

Stability and Control of Locomotion
Example of a biped

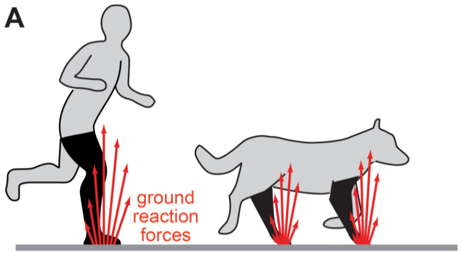
- External disturbances lead to instability
- Foot step control for fall recovery



[Coros 2012]

Foot Placement Control
Balance from stepping

- Biomechanical studies suggest SLIP models to describe complex running behaviors



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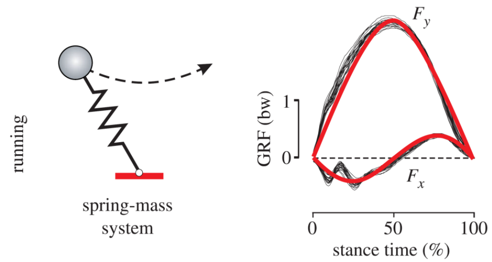
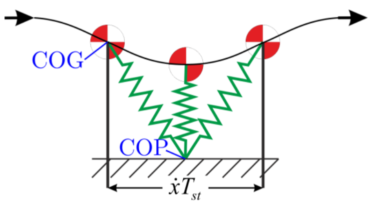
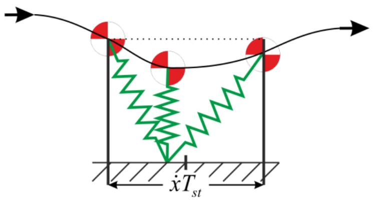


[Geyer 2006]

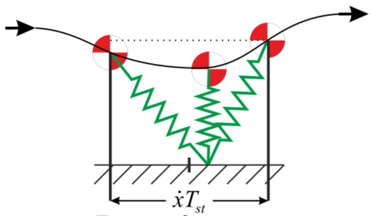
- Simple step-length rule to adjust the velocity $\mathbf{r}_F = \frac{1}{2}\dot{\mathbf{r}}_{HC,des}T_{st} + k_R^{FB}\left(\dot{\mathbf{r}}_{HC,des} - \dot{\mathbf{r}}_{HC}\right)\sqrt{h_{HC}}$ *[Raibert 1986]*



Constant speed



Accelerate

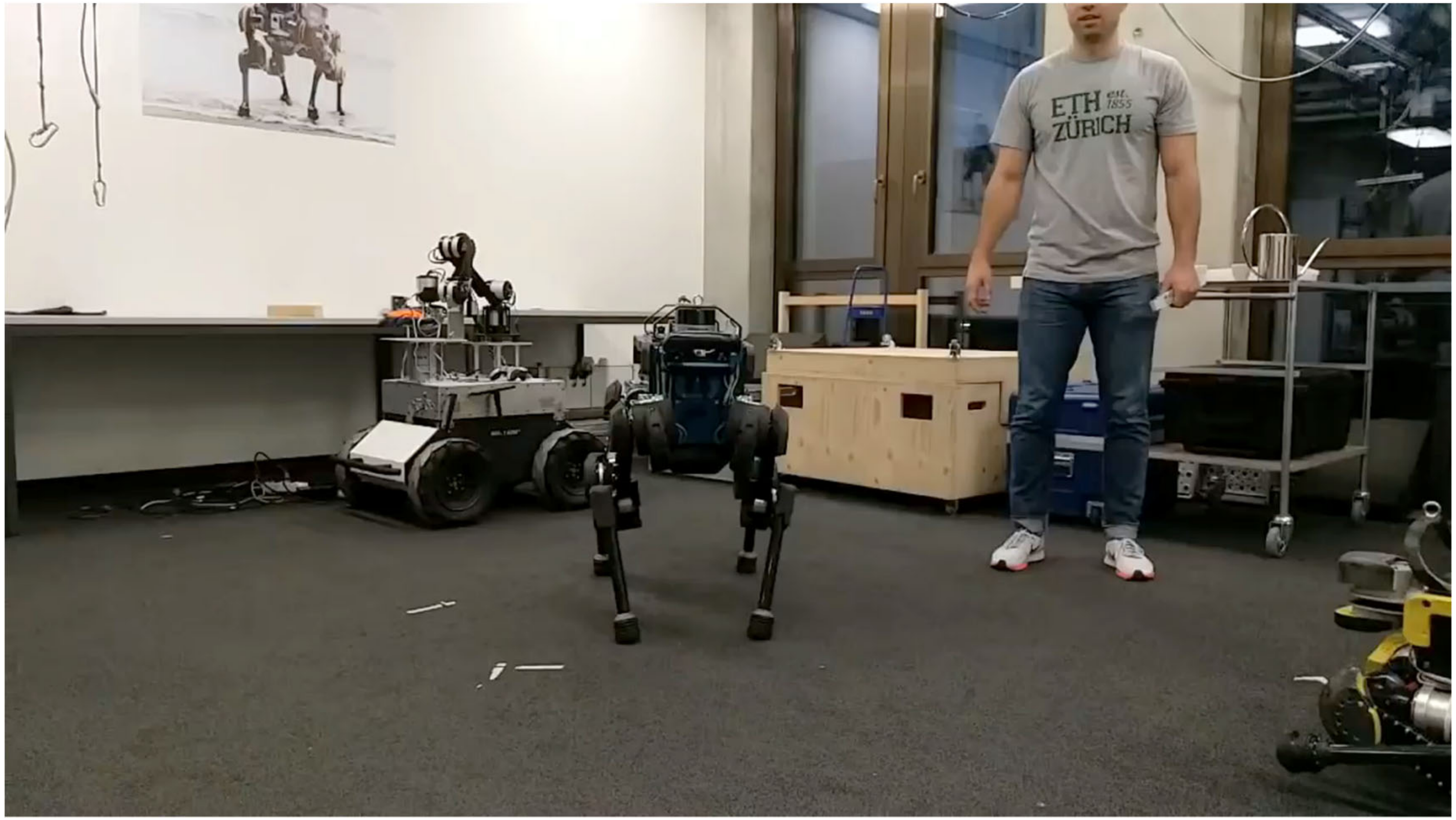


Decelerate

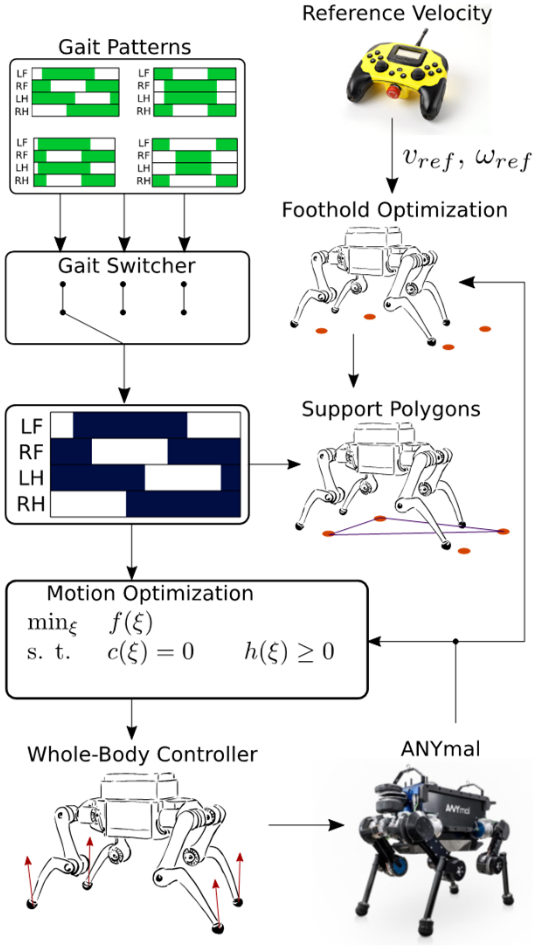
Locomotion control
Foot-point planning

- Dynamic gaits
  - Inverted pendulum

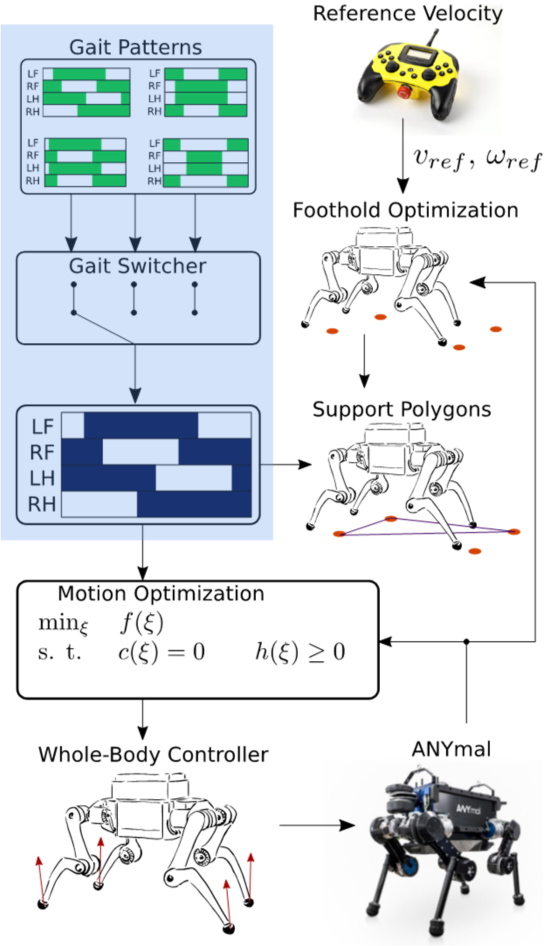
[Raibert 1986]



Control Structure

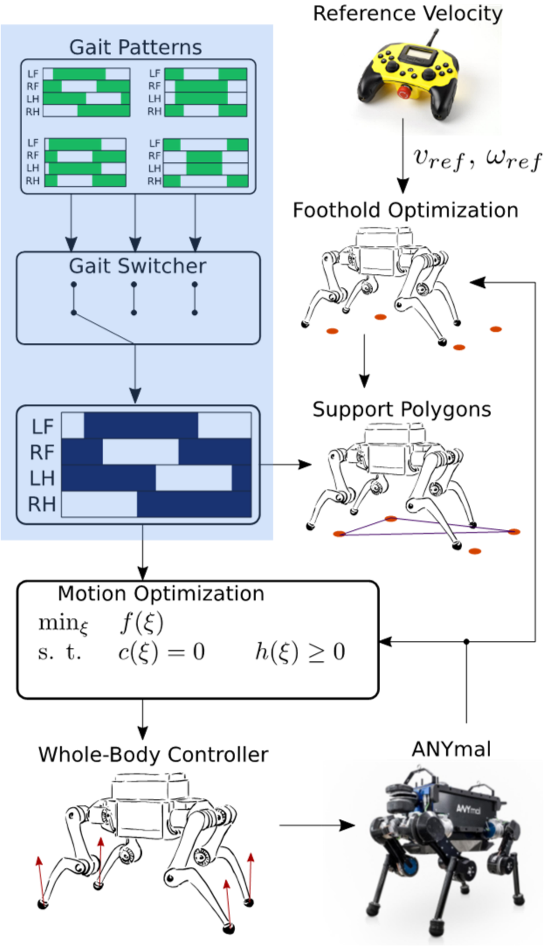


Contact Schedule



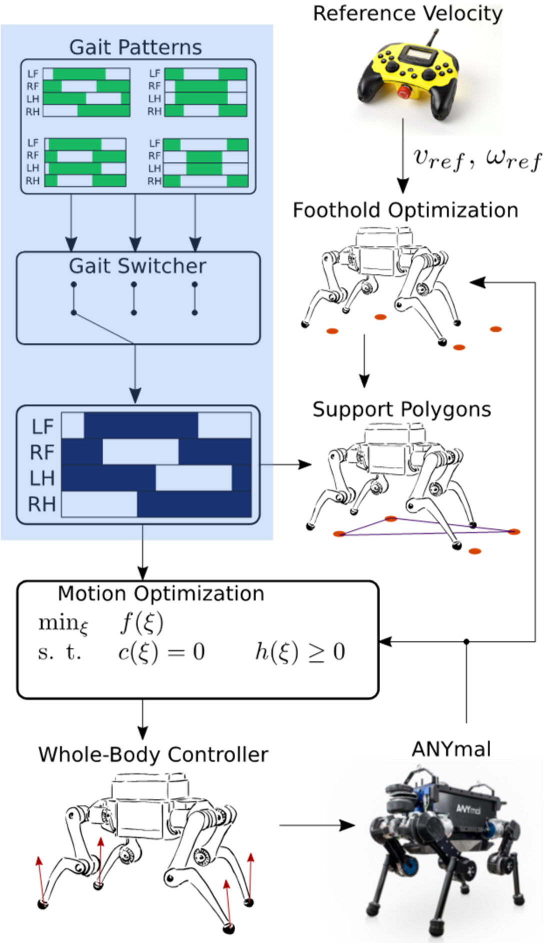
- Gait fixed in phase domain

Contact Schedule



- Gait fixed in phase domain
- Triggers Lift-off and Touch-down events
- Transition by appending desired gait to active gait
- Stride duration controlled by velocity error

Contact Schedule



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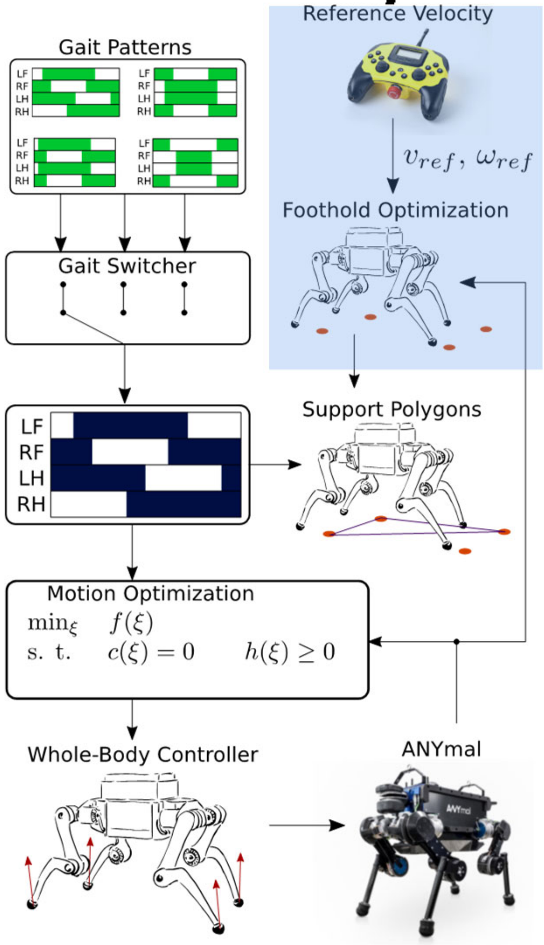
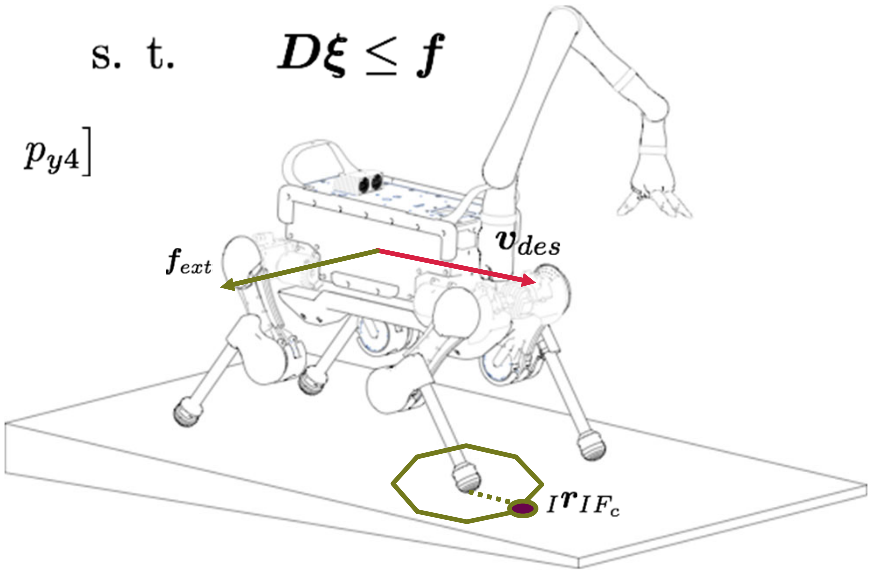
Foothold Optimization



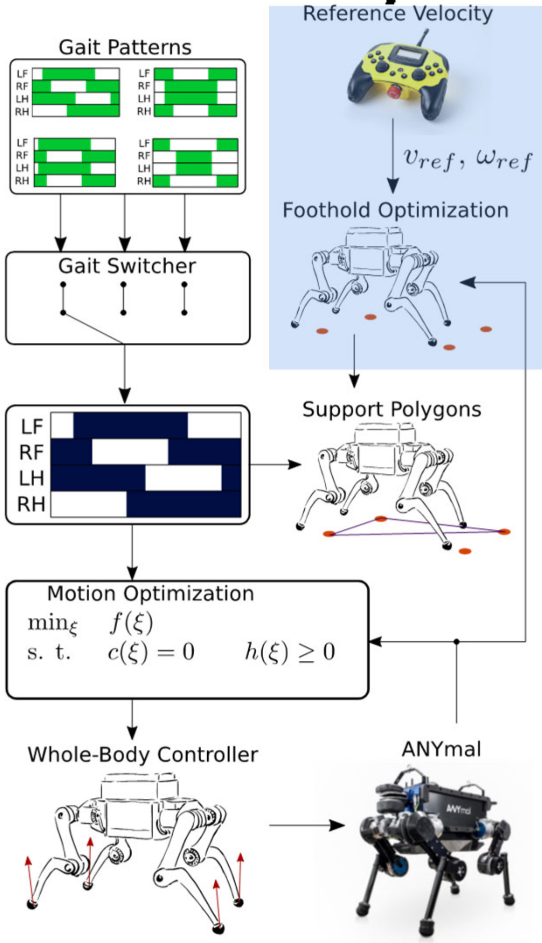
- Reference velocity by joystick/ high-level controller
- Footholds centered around COG
- Objective: Approach to inverted pendulum footholds
- Hard constraints: Avoid leg over-extension and self-collision
- Optimization time 0.25ms

$$\min_{\boldsymbol{\xi}} . \quad \frac{1}{2}\boldsymbol{\xi}^T\boldsymbol{Q}\boldsymbol{\xi} + \boldsymbol{c}^T\boldsymbol{\xi} \qquad \text{s. t.} \qquad \boldsymbol{D}\boldsymbol{\xi} \leq \boldsymbol{f}$$

$$\boldsymbol{\xi} = \begin{bmatrix} p_{x1} & p_{y1} & \dots & p_{x4} & p_{y4} \end{bmatrix}$$



Foothold Optimization



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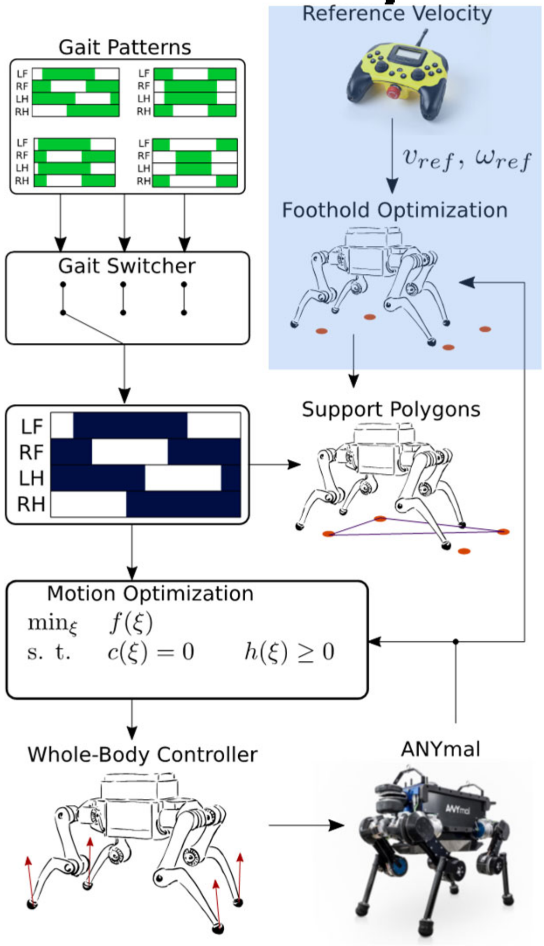
Cost function
Velocity projection
Inverted pendulum [1]
Deviation from previous solution

Inequality constraints
Kinematic limits

Foothold Optimization



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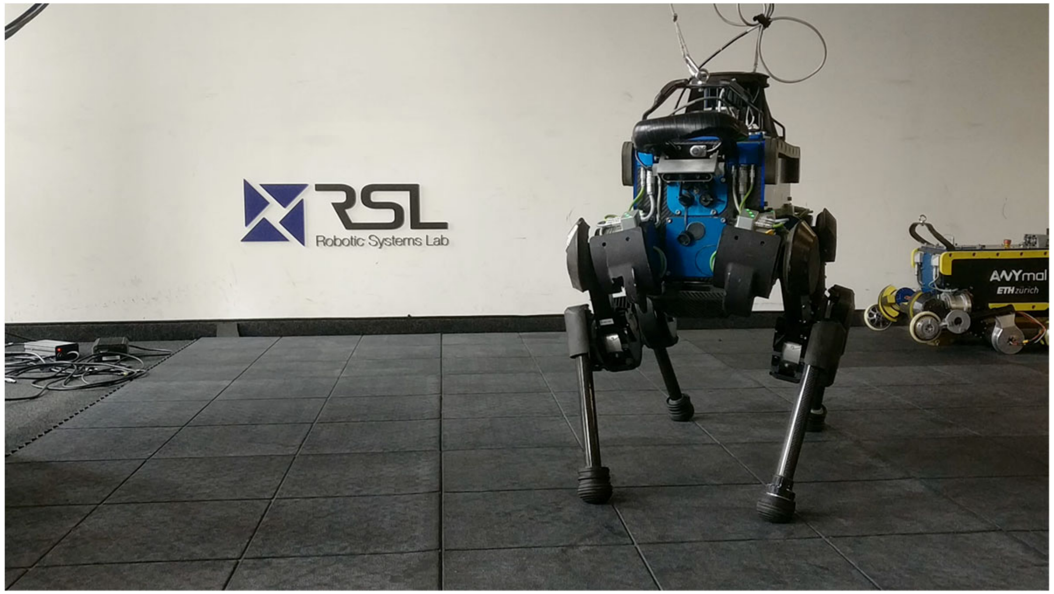
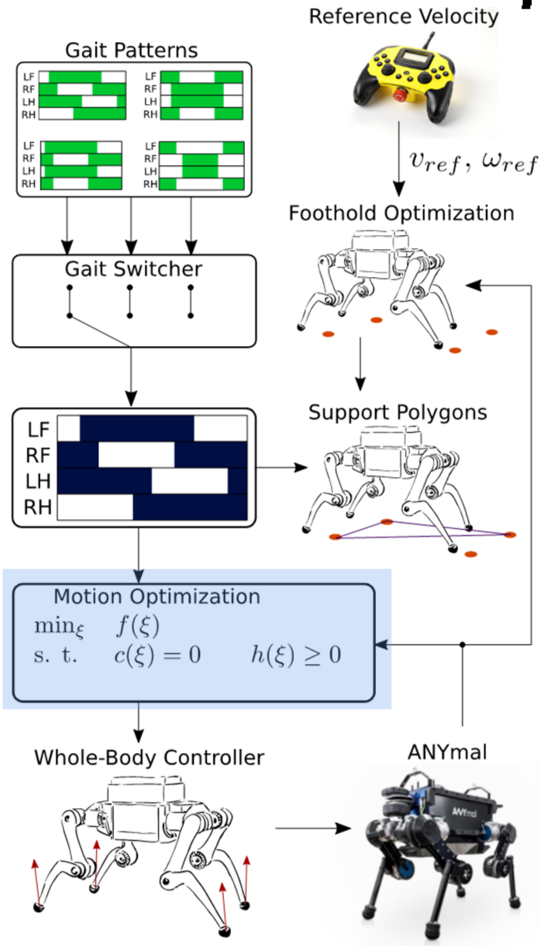
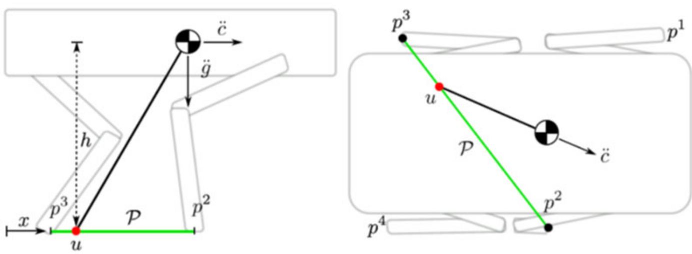


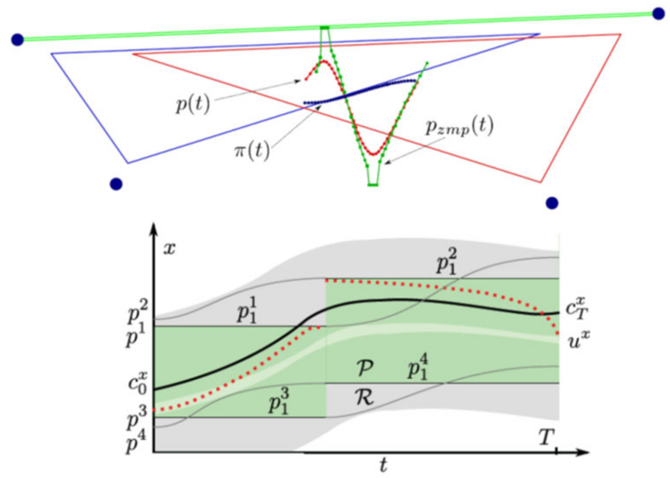
Torso Motion Optimization



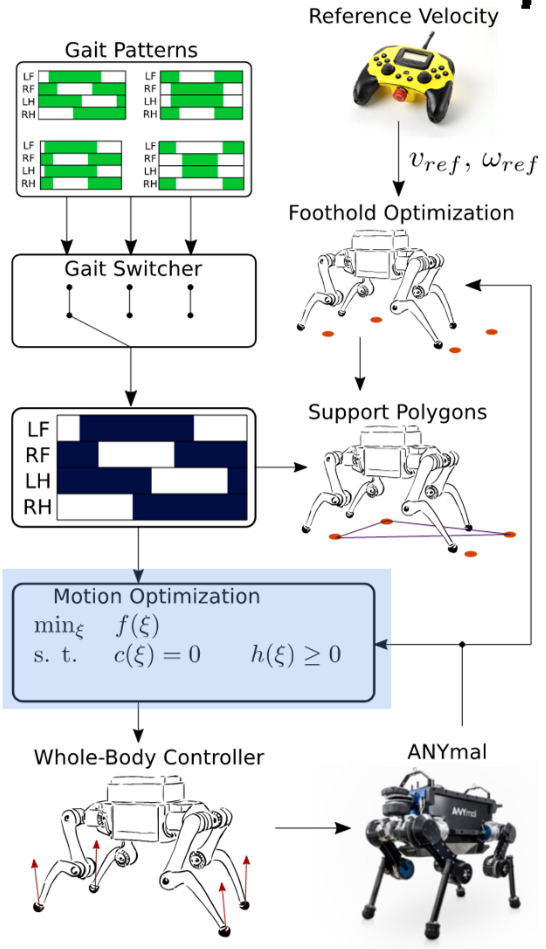
- COG trajectory = a sequence of quintic splines for x,y,z.
- Objective: velocity tracking, smoothness
- Constraints: Sampled Zero-Moment point (ZMP) within support polygon

$$x_{zmp} = x_{com} - \frac{z_{com}\ddot{x}_{com}}{g + \ddot{z}_{com}}$$





Torso Motion Optimization



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- Optimization duration: 2…40 ms (depending on gait)

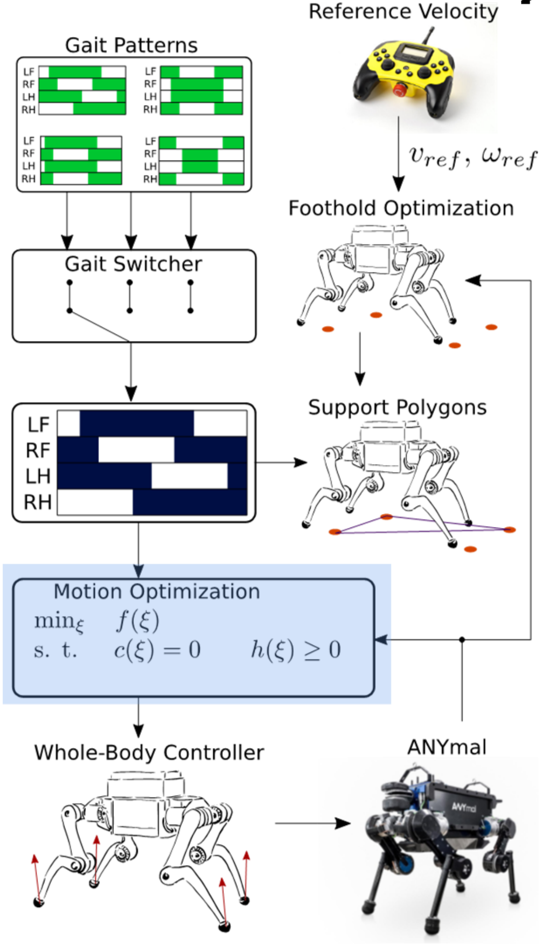
$$\min_{\boldsymbol{\xi}}. \quad \boldsymbol{f}(\boldsymbol{\xi}) \qquad \text{s. t.} \qquad \boldsymbol{c}(\boldsymbol{\xi}) = \mathbf{0}, \quad \boldsymbol{h}(\boldsymbol{\xi}) \leq \mathbf{0}$$

Cost function
Minimize acceleration
Deviation from previous solution
Terminal conditions
First samples of ZMP

Equality Constraints
Spline junctions
Initial conditions

Inequality Constraints
ZMP in support polygons
Terminal conditions

Torso Motion Optimization



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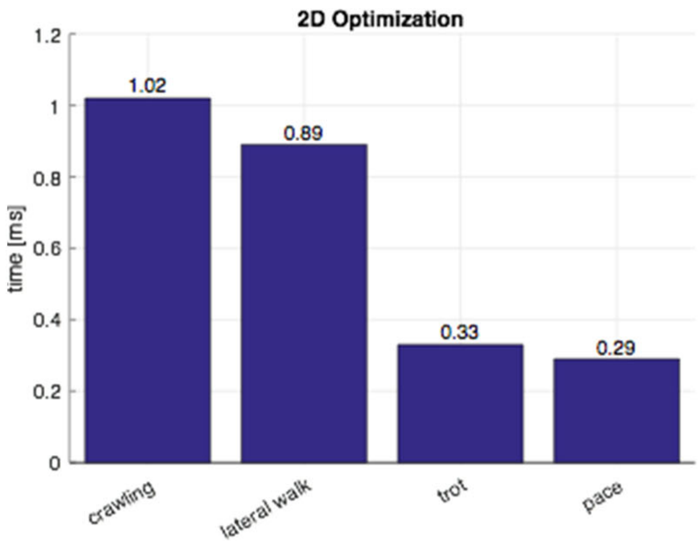
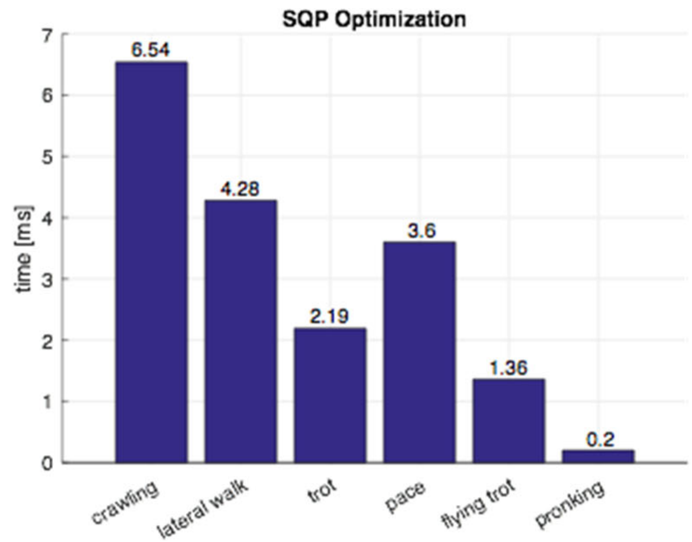
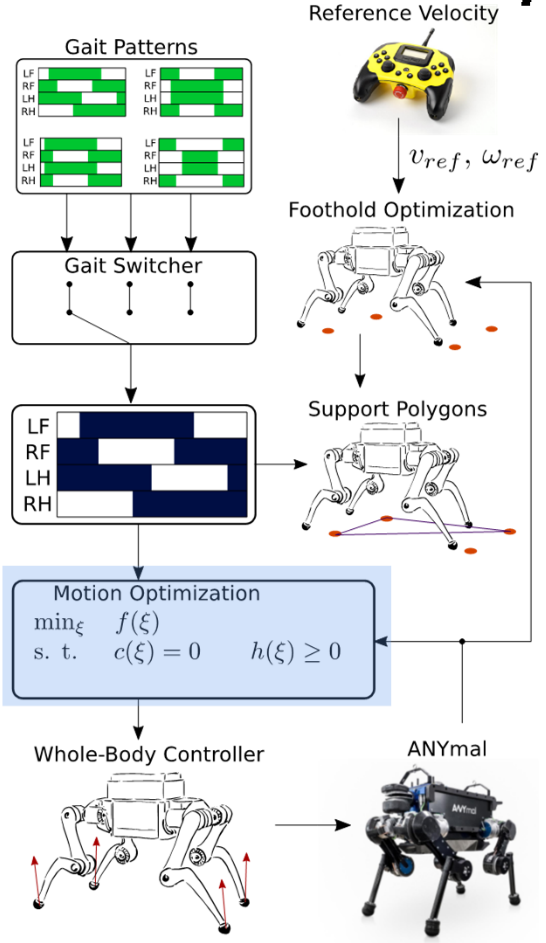




Torso Motion Optimization



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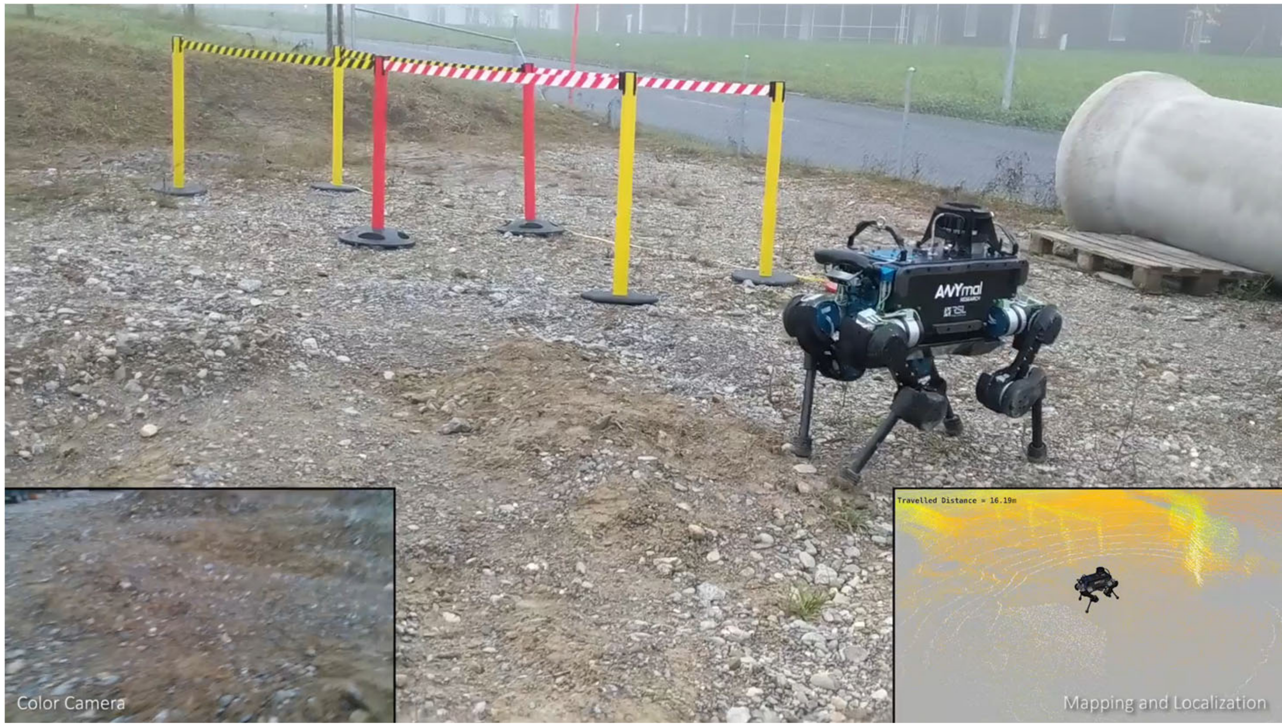
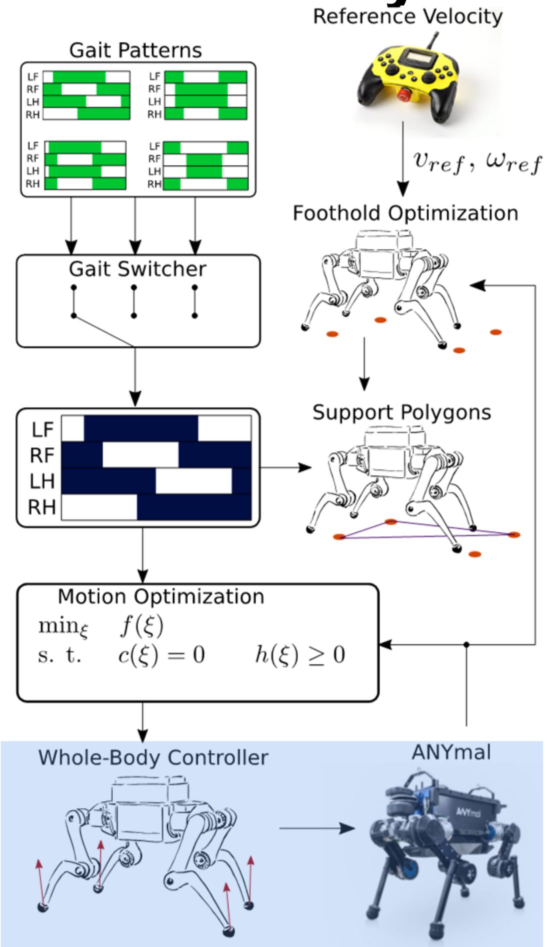
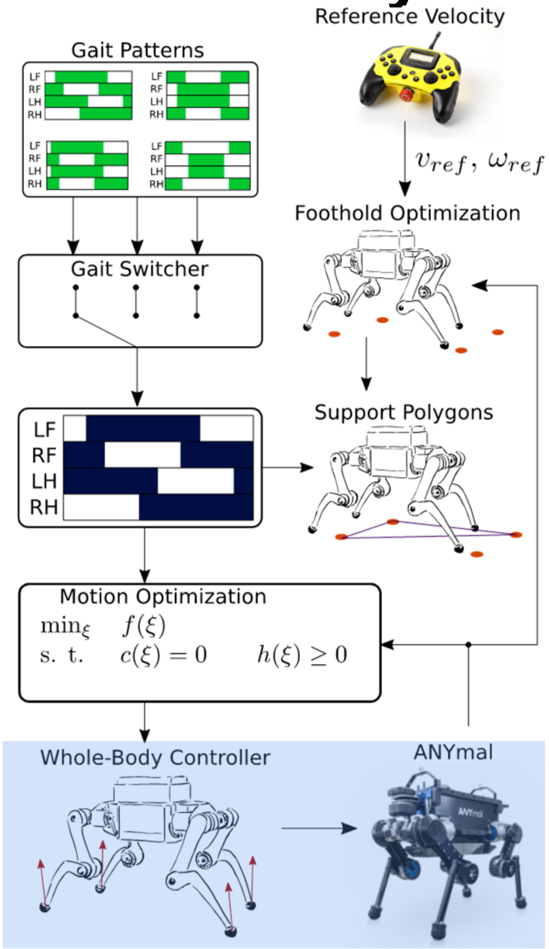


Whole Body Control (WBC)



- Solves a cascade of prioritized tasks
  - Equation of motion
  - No slippage condition
  - Limits on torques
  - Motion tracking
  - …

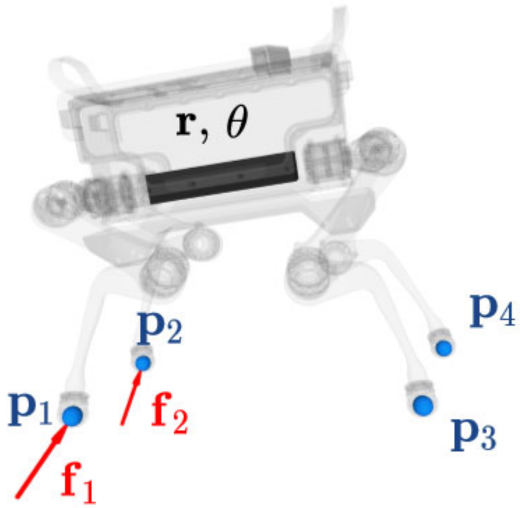
Whole Body Control (WBC)



- Probabilistic contact detection
- Slippage estimation
- In case of slippage => Impedance stabilization and friction cone adaptation

Nonlinear MPC including foothold position and timinig

$$
\begin{aligned}
\text{find} \quad & \mathbf{r}(t) \in \mathbb{R}^3 \quad \text{(CoM)} \\
& \theta(t) \in \mathbb{R}^3 \quad \text{(Base orientation)} \\
& \text{for every foot } i \in \{1, \ldots, n_{ee}\}: \\
& \quad \mathbf{p}_i(t) \in \mathbb{R}^3 \quad \text{(Foot position)} \\
& \quad \mathbf{f}_i(t) \in \mathbb{R}^3 \quad \text{(Foot force)}
\end{aligned}
$$



Nonlinear MPC including foothold position and timinig

- Foot alternates between swing and stance => continuous phase duration ΔT_i

Given:
- height map $h(x, y) \in \mathbb{R}$
- normals $\mathbf{n}(x, y) \in \mathbb{R}^3$
- tangents $\mathbf{t}(x, y) \in \mathbb{R}^3$

$t \in \mathcal{C}$

Foot can only stand *on* terrain

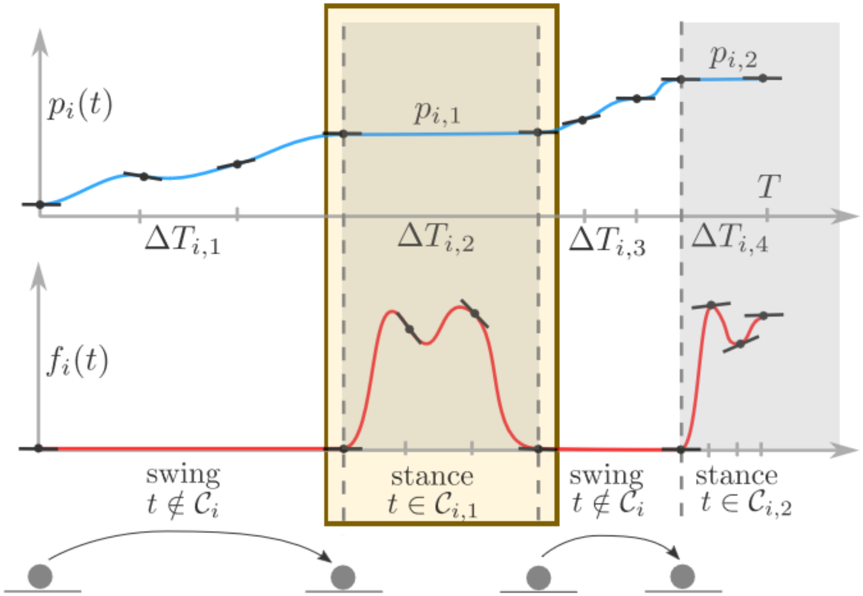
$$p^z_{i,s} = h(p^x_{i,s}, p^y_{i,s})$$

Forces can only push

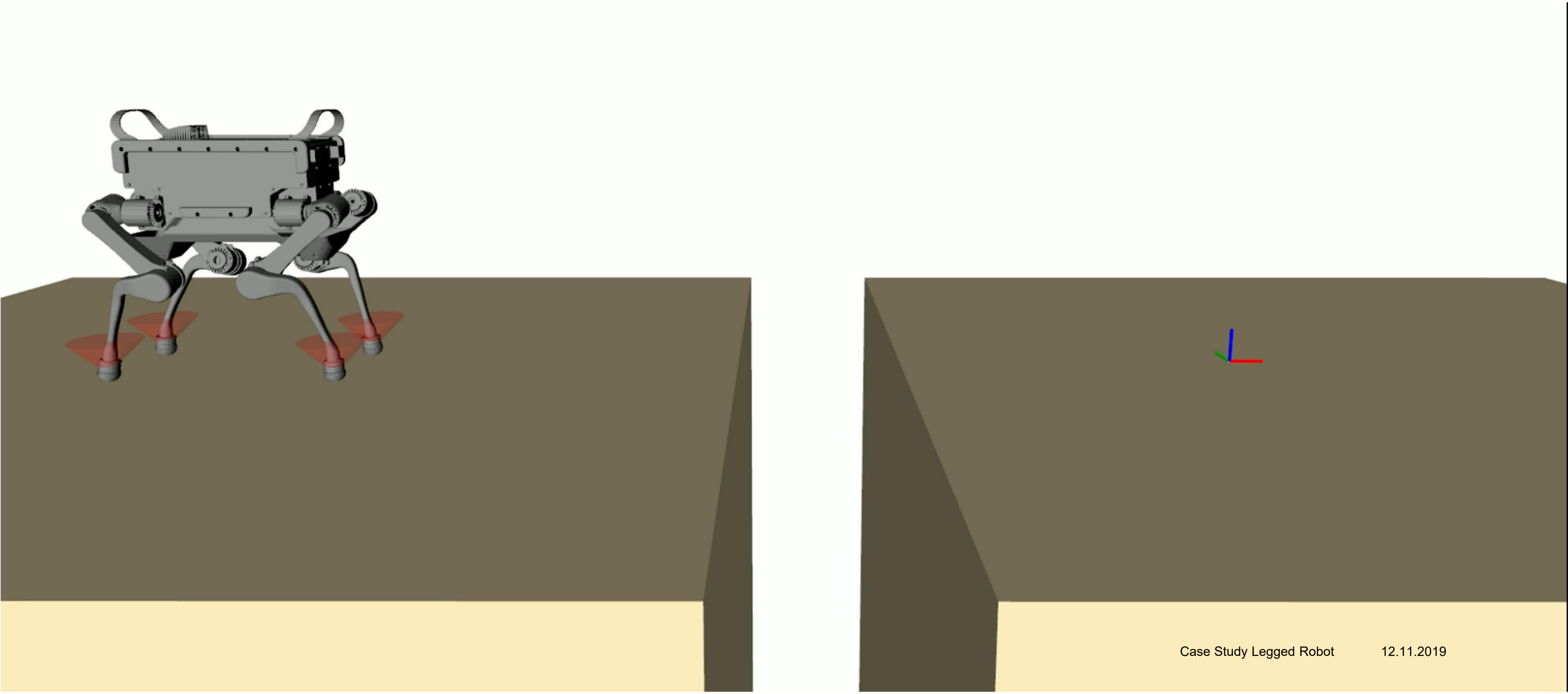
$$\mathbf{f}_i(t) \cdot \mathbf{n}(p^x_{i,s}, p^y_{i,s}) \geq 0$$

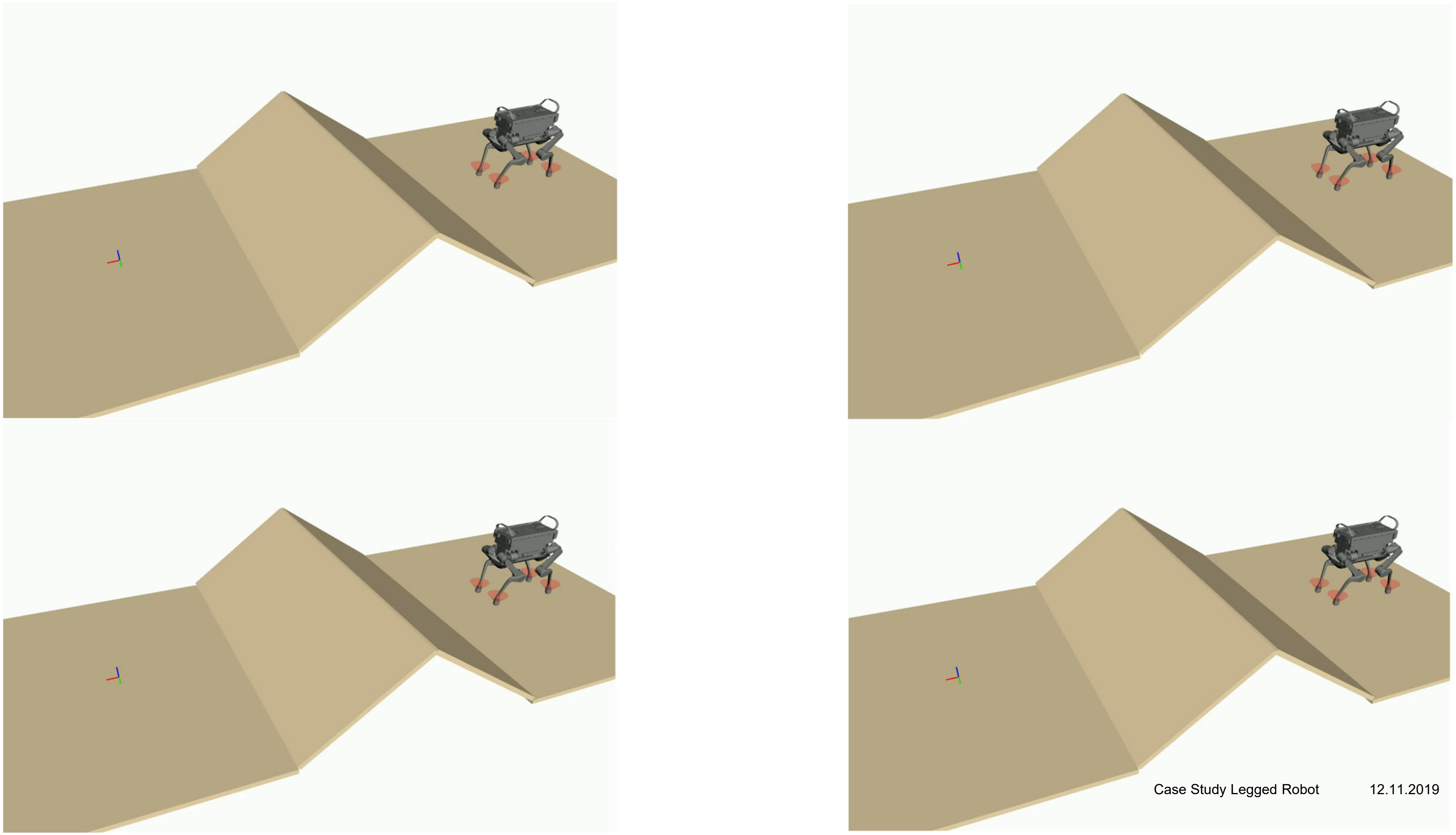
Forces inside friction pyramid

$$|\mathbf{f}_i(t) \cdot \mathbf{t}(p^x_{i,s}, p^y_{i,s})| < \mu \mathbf{f}_i(t) \cdot \mathbf{n}(p^x_{i,s}, p^y_{i,s})$$



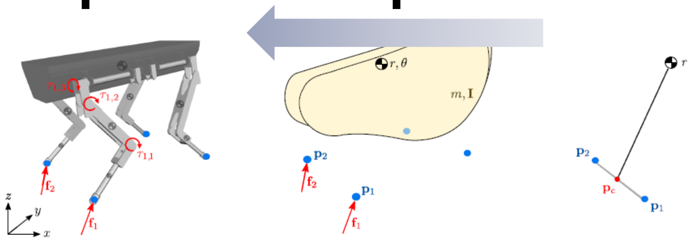
Locomotion – a nonlinear optimization problem





Locomotion – a nonlinear optimization problem

Constrained DDP-based Algorithm (SLQ)



- The real world is not ideal

Control policy
$\pi(t, \mathbf{x}) = \mathbf{u}_{ff}(t) + \mathbf{K}(t)\mathbf{x}$

Forward **rollout** the system

Linear-Quadratic (LQ) approx. of **dynamics** and **cost**

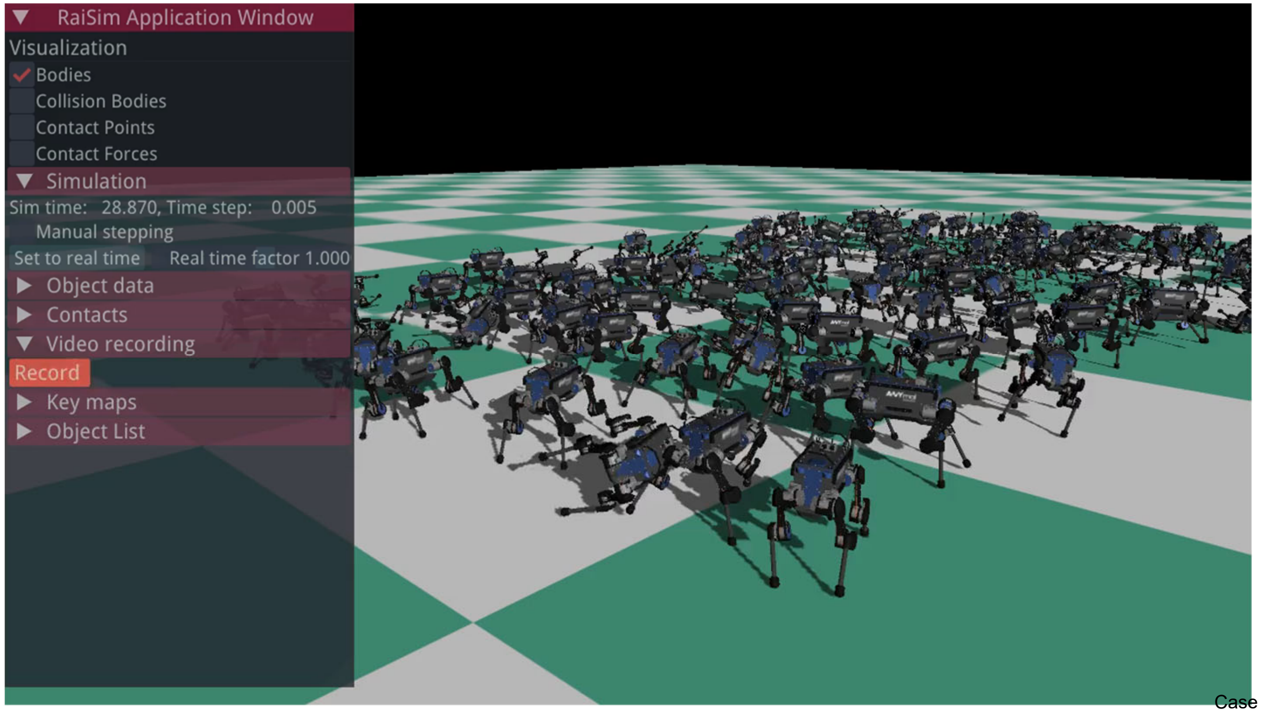
Linear approx. of **constraints**
Updating **LQ** model.

- **State-input equality** constraints: **Lagrangian method**
- **State-only equality** constraints: **Penalty method**
- **Inequality** constraints: **Relaxed barrier function**

Solve Riccati-like equations using constrained LQ model

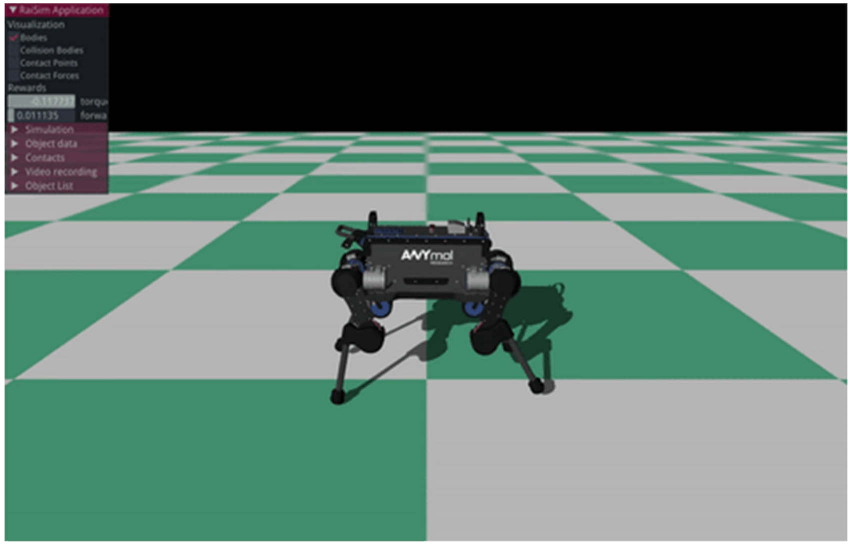
Reinforcement learning for locomotion control

- Learn from massive data generated with a fast and accurate simulator
  - Efficient solution of hard contact dynamics using a bisection method *[Hwangbo, ICRA 2018]*
  - Fast implementation of MBD

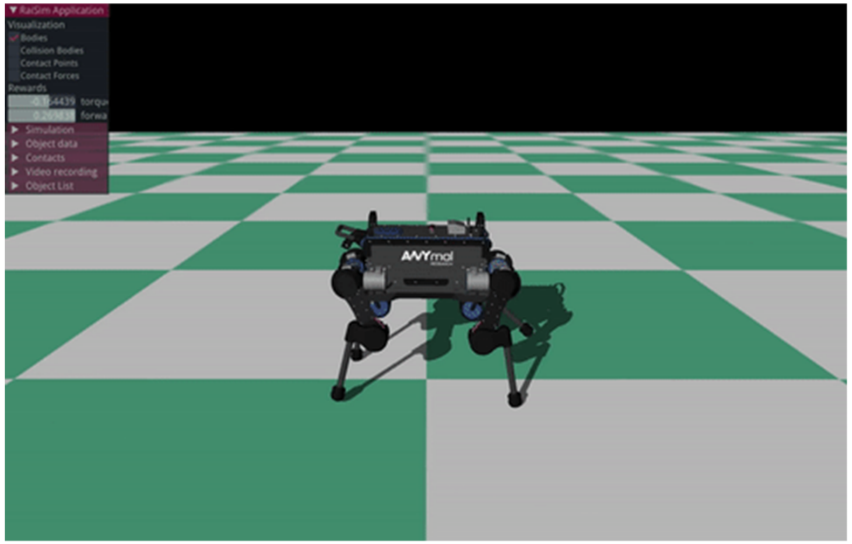


Training example

- ANYmal
  - 18 DOF, 12 actuated joints
  - Trained on a single CPU and a single GPU (8700K, RTX 2080)

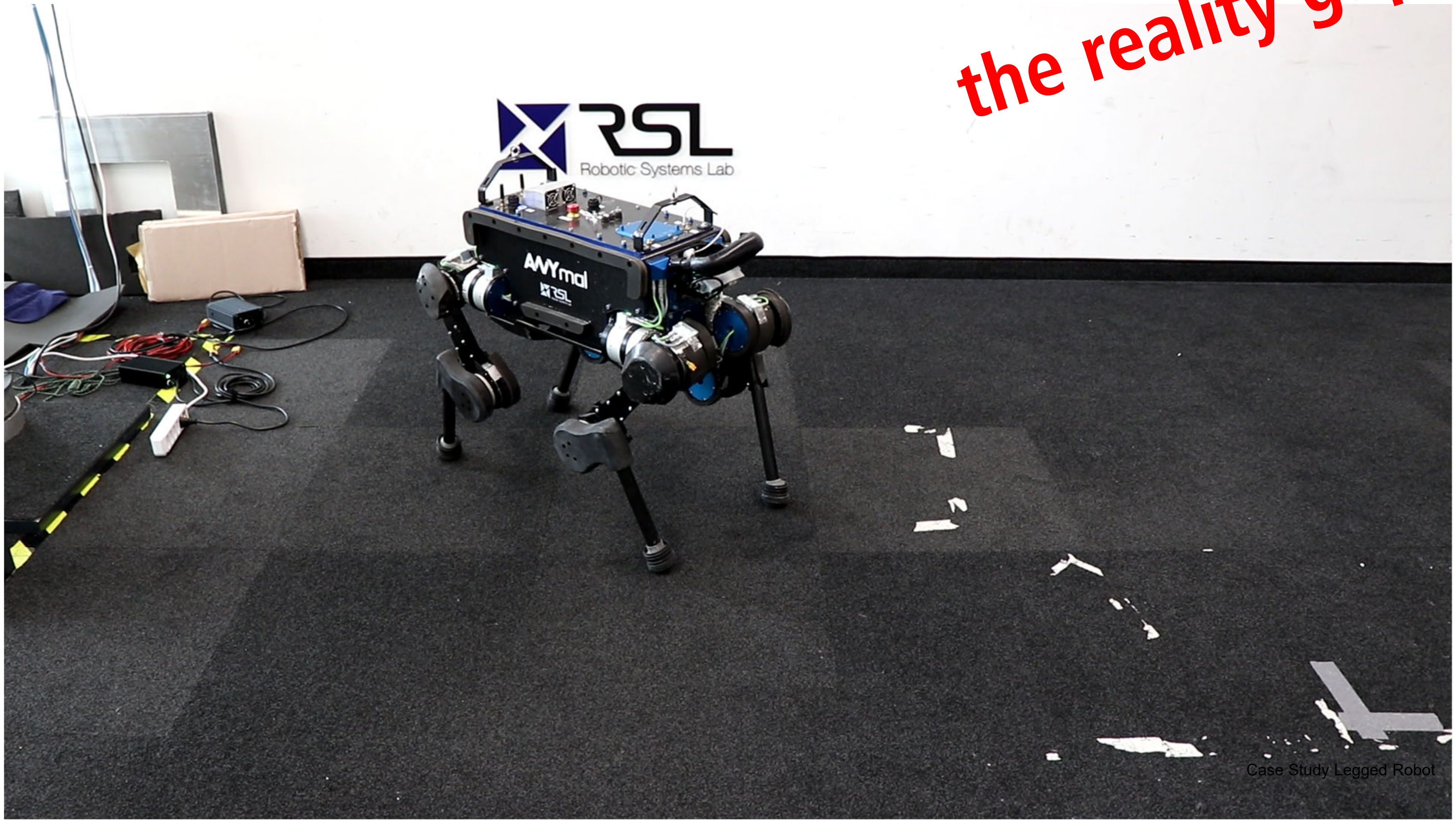


Initial policy



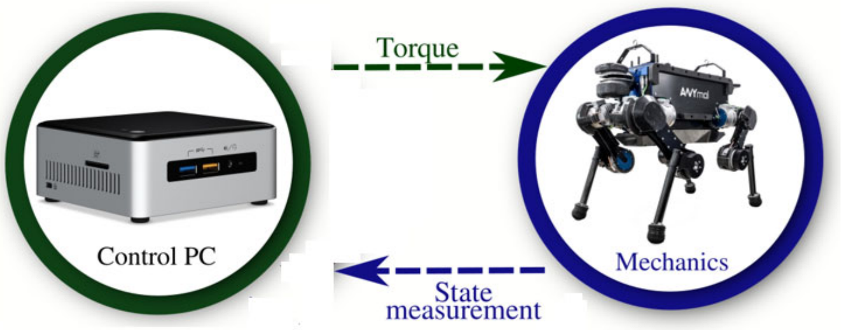
After 112 seconds of training (PPO)
(150 iterations, 24M time steps)

Deployment of learned policy on the robot

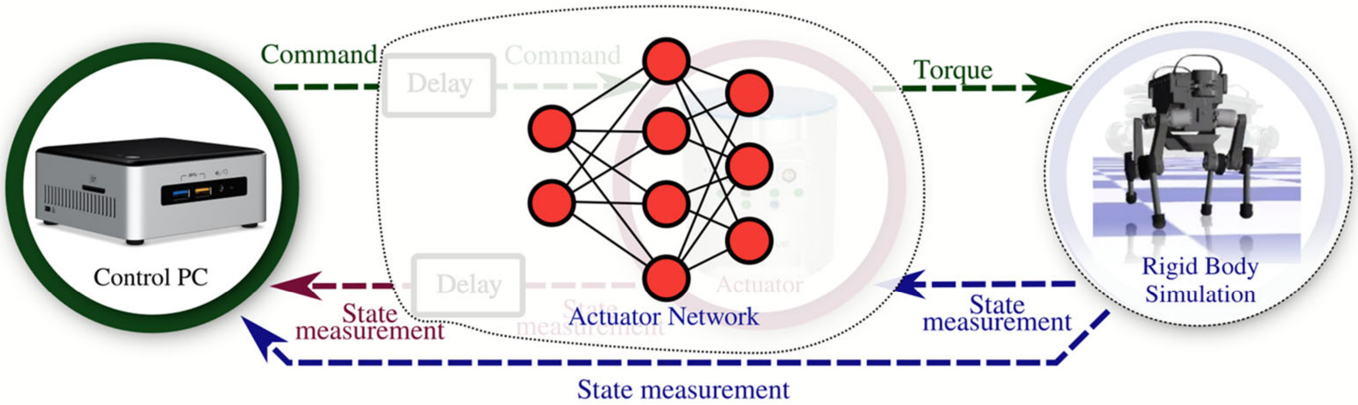


the reality gap

Sim-to-real: The reality gap



Sim-to-real: The reality gap



Difficult to model.
Easy to learn

Easy to model.
Difficult to learn

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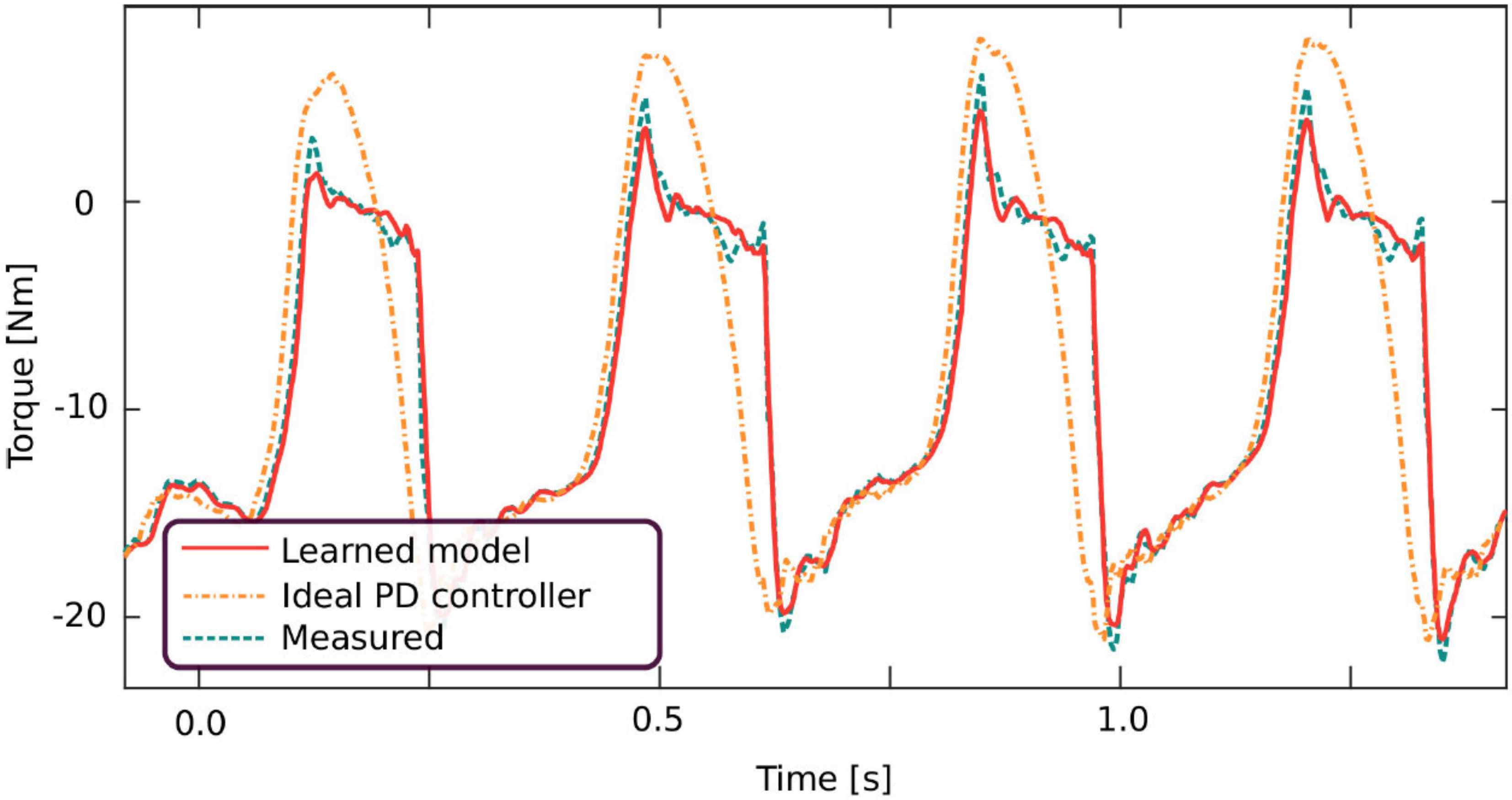
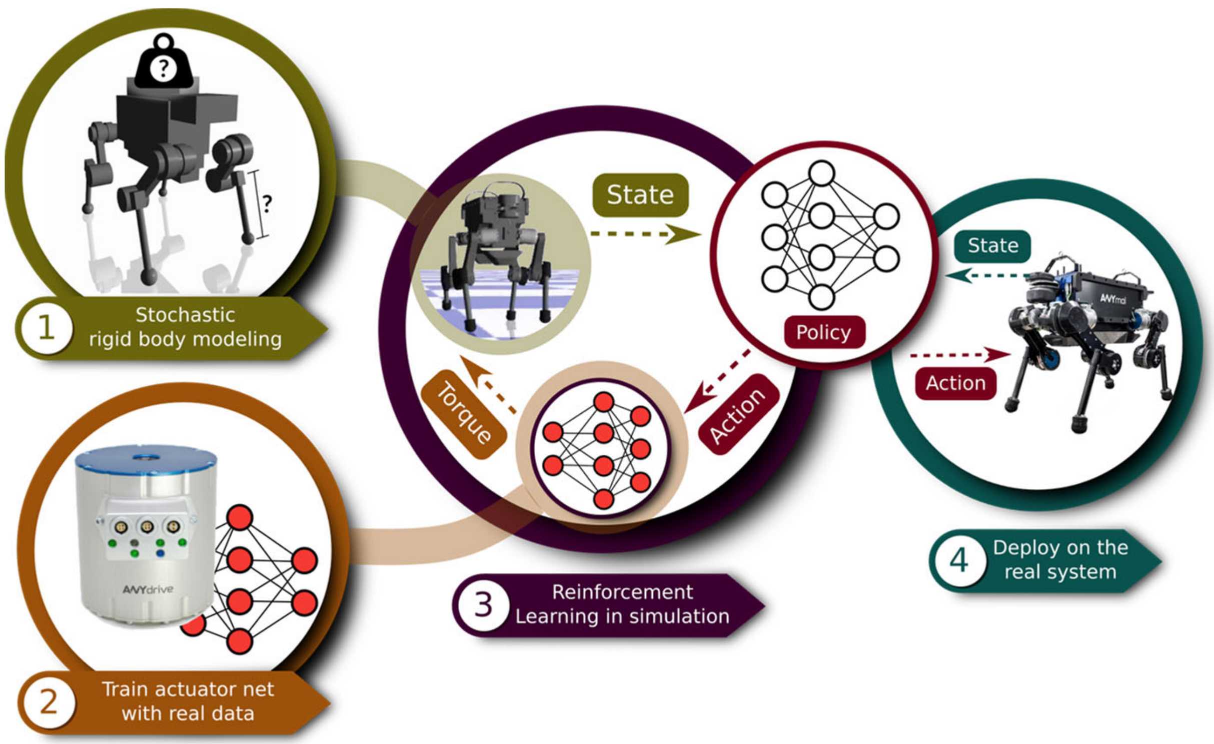
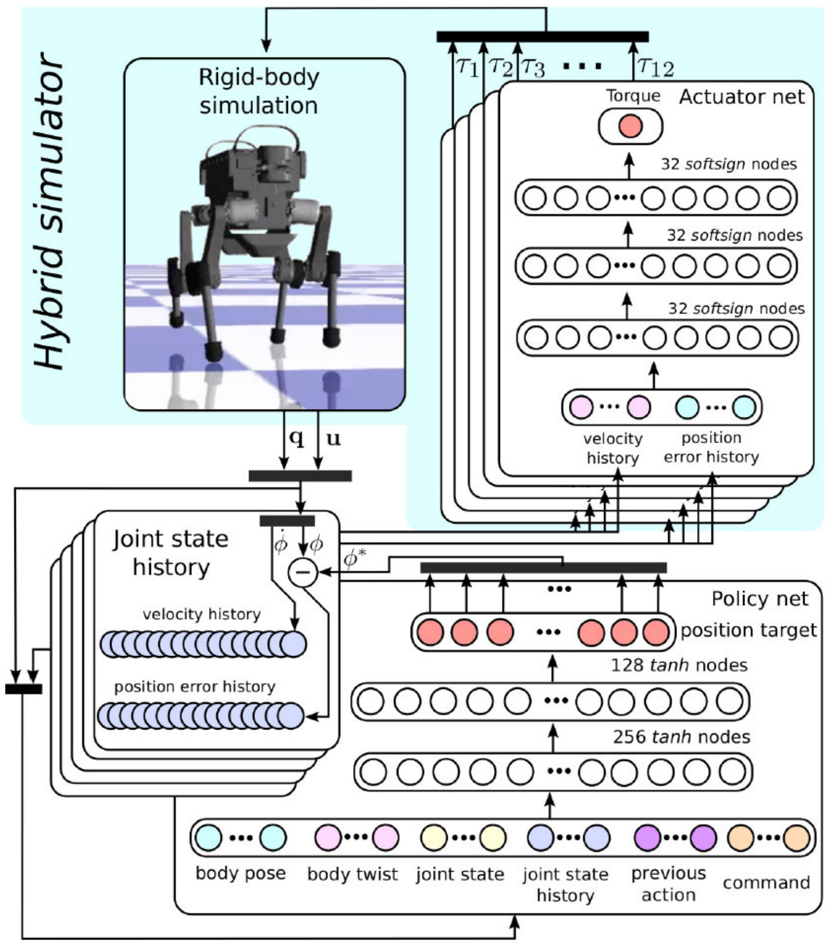
Modeling unknown dynamics

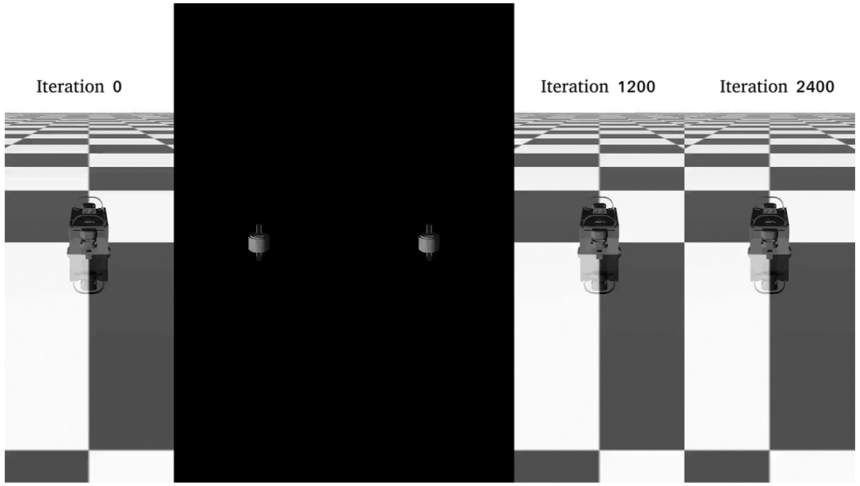


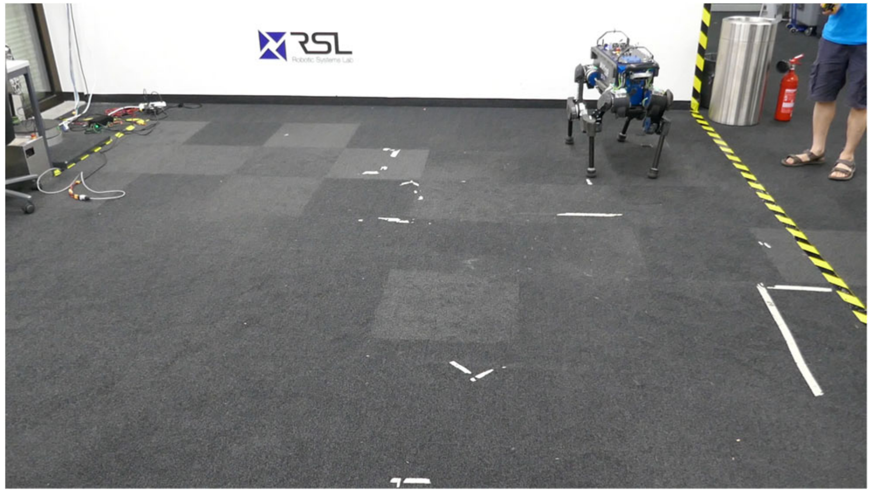
Simulation-based RL for legged robots





Release of our software framework



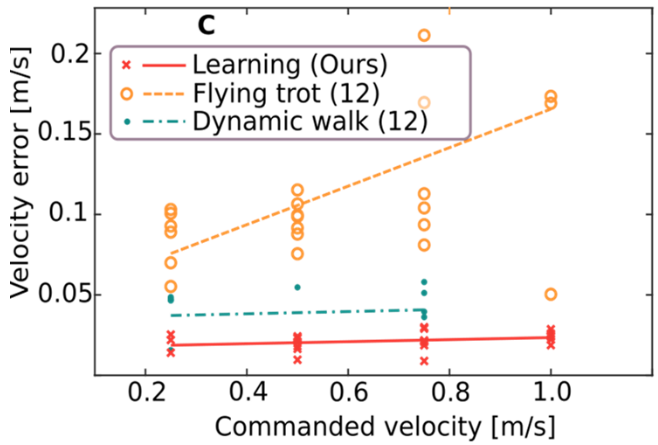


- Released the software to reproduce the work
  - **RaisimLib**: The physics engine (https://github.com/leggedrobotics/raisimLib), based on [2]
  - **RaisimOgre**: The visualizer (https://github.com/leggedrobotics/raisimOgre)
  - **RaisimGym**: Training examples (https://github.com/leggedrobotics/raisimGym)

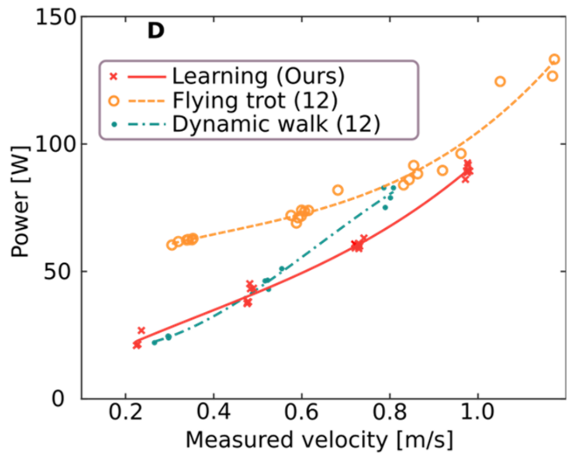
[1] Hwangbo, et al., Learning agile and dynamic motor skills for legged robots, 2019

[2] Hwangbo, Lee and Hutter, Per-contact iteration method for solving contact dynamics, 2018

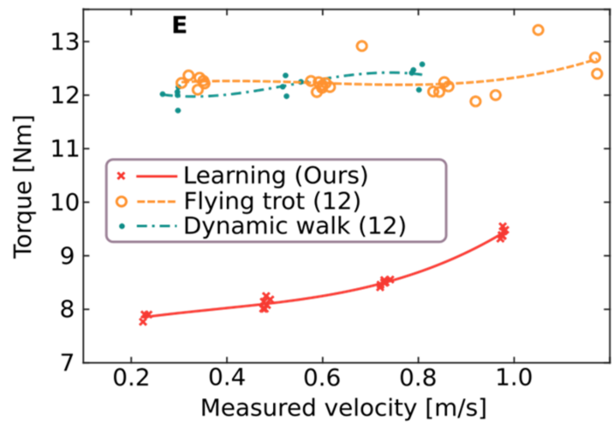
Advantages of a learned controller



- **More precise**



- **Uses less power**

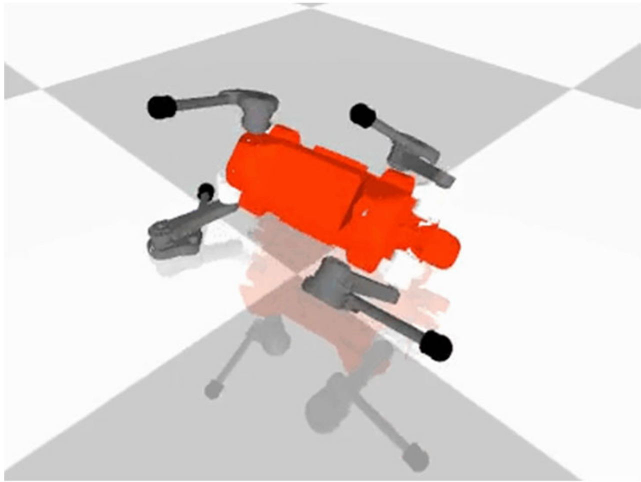


- **Uses less torque**

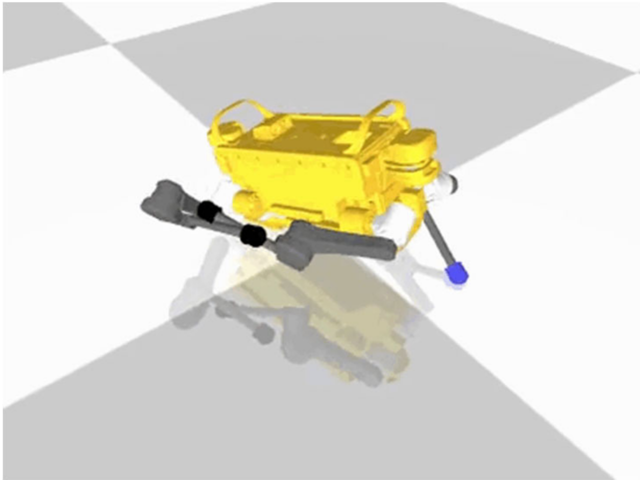
- Computationally efficient (uses about 0.1% of onboard computation resources)
- Automated (no tuning, no human designed control structure)
- More robust against external disturbances

Learning multiple behaviors

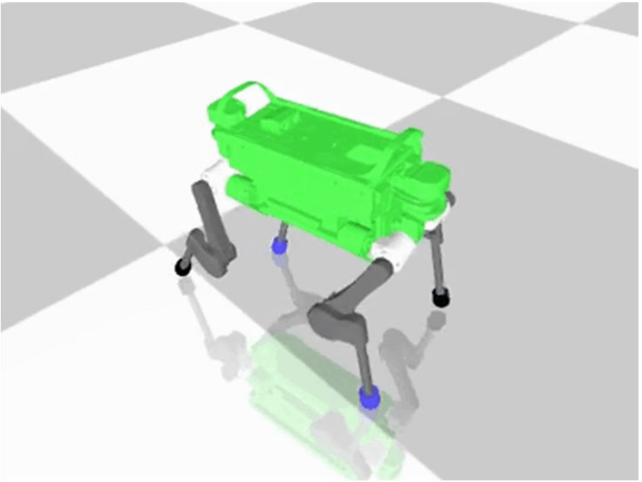
Self-righting



Standing up

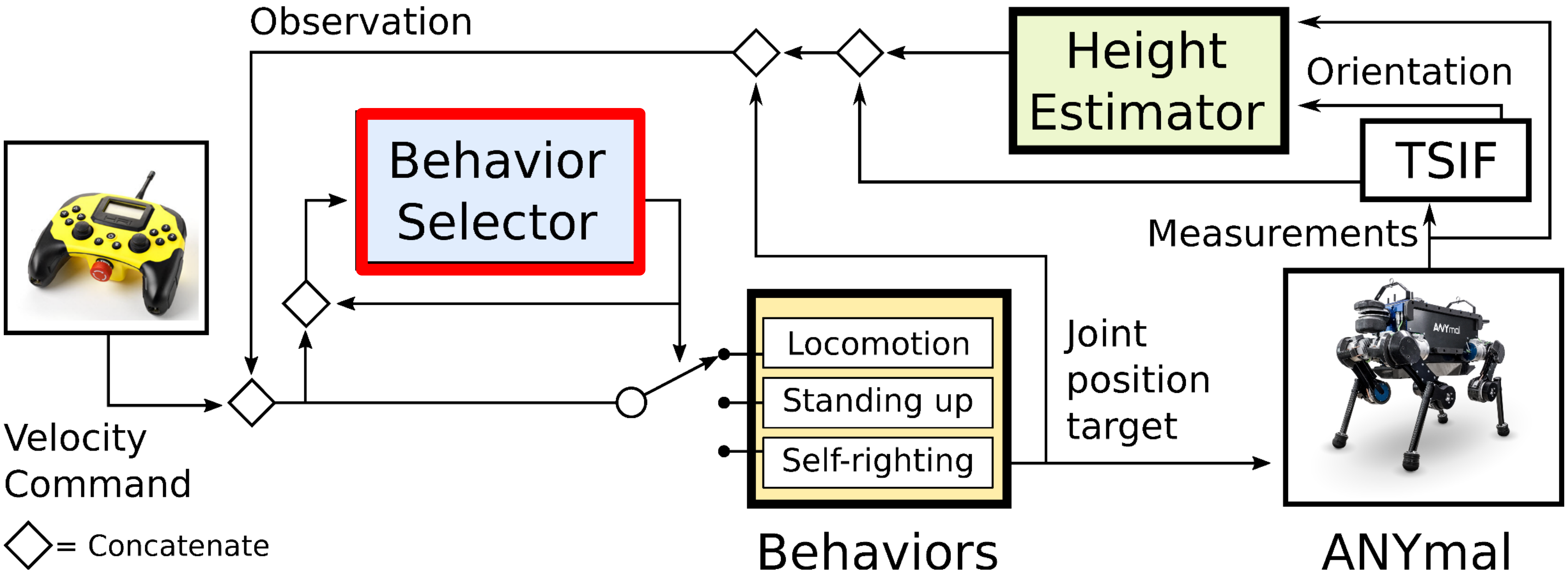


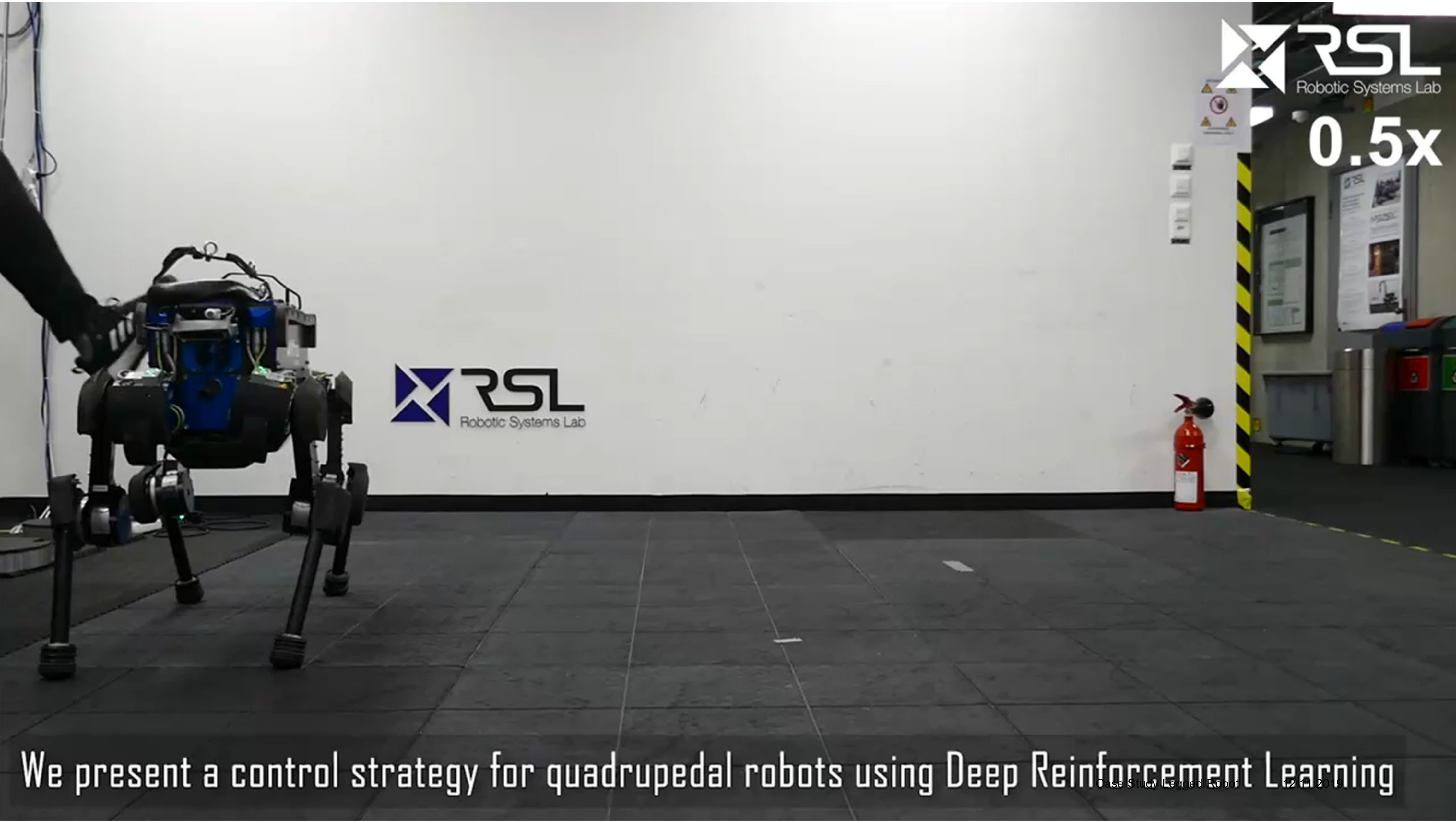
Locomotion



Hierarchical behaviour learning for complex maneuvers

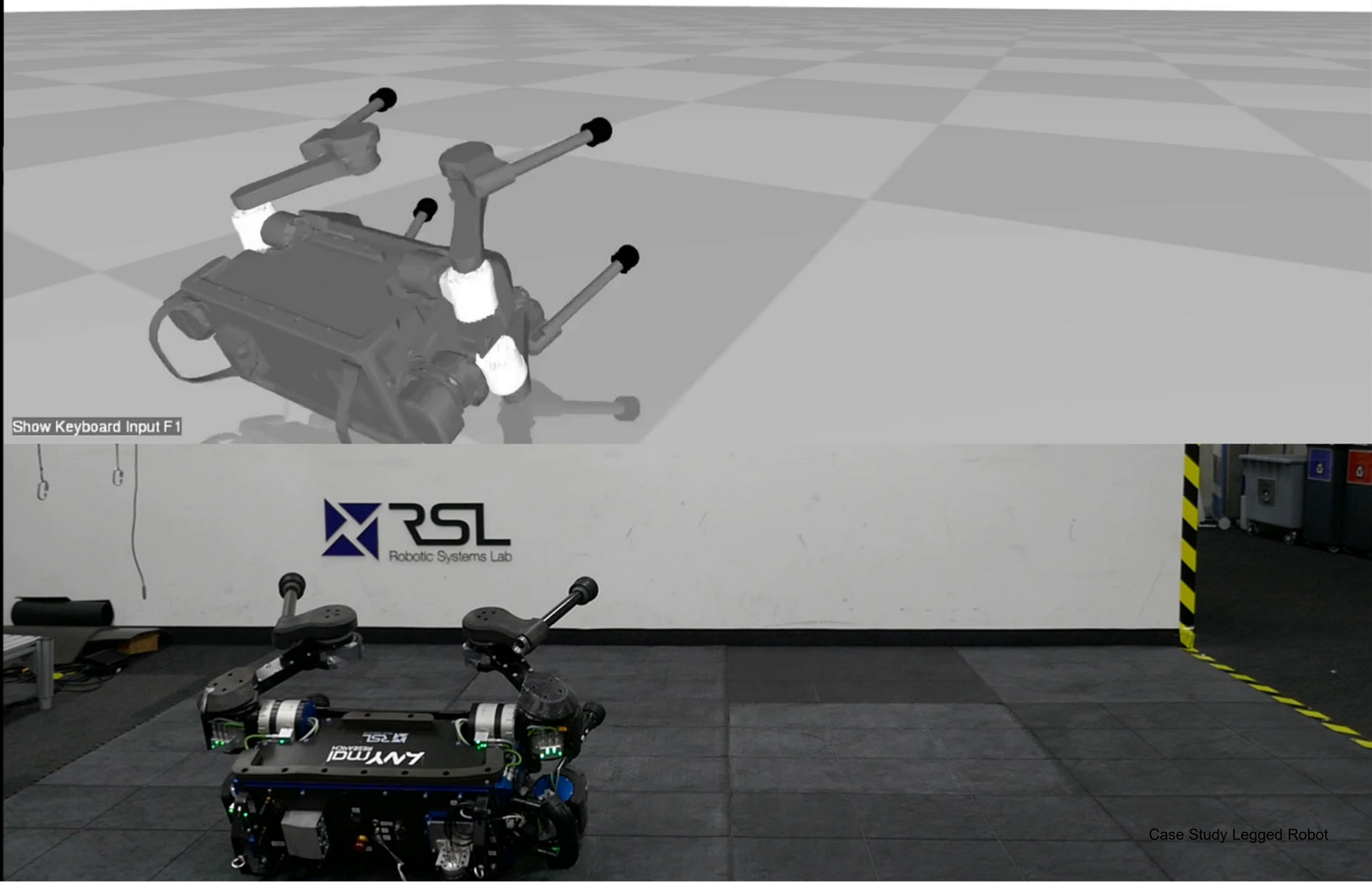
[Lee, arxiv 2019]




RSL
Robotic Systems Lab
0.5x
RSL
Robotic Systems Lab
We present a control strategy for quadrupedal robots using Deep Reinforcement Learning

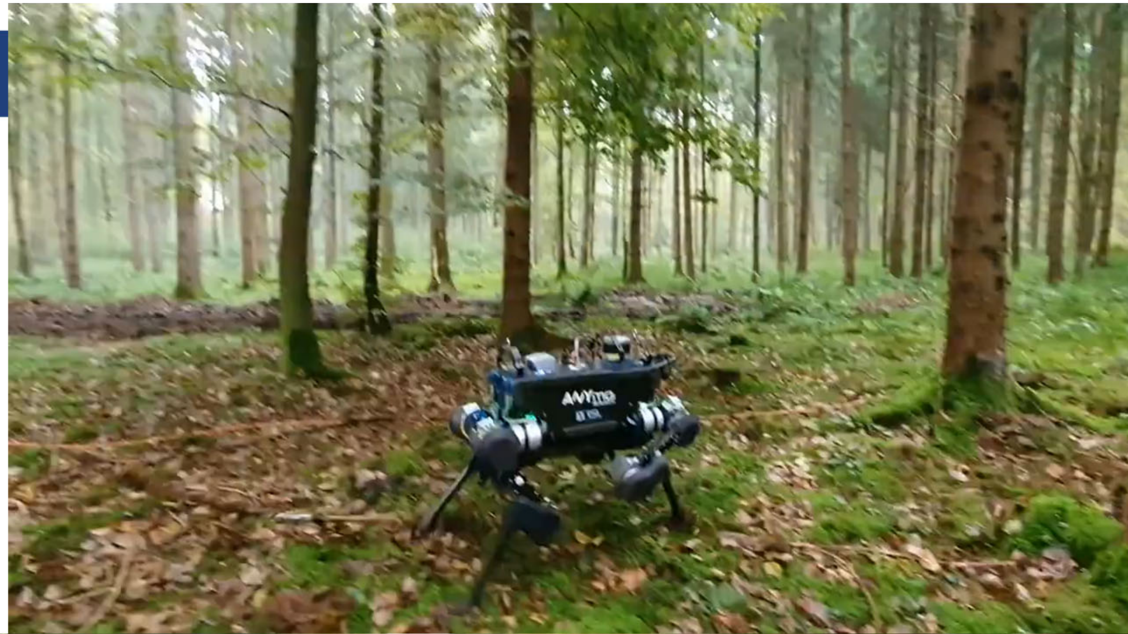

RSL
Robotic Systems Lab
ANYmal
even in various leg configurations

With the same initial states and base velocity commands



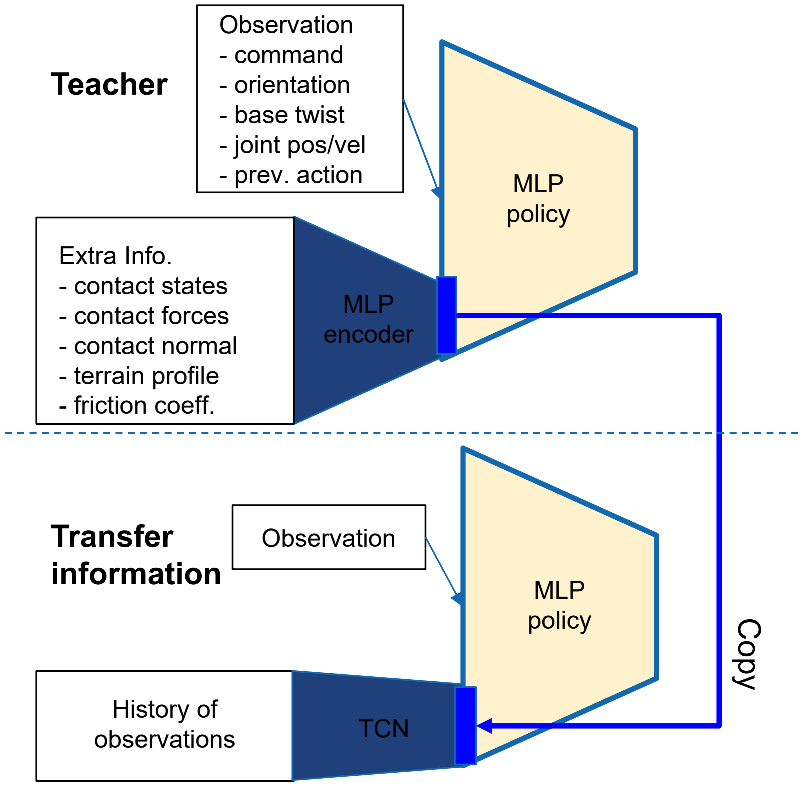
ANYmal in the Forest

- Deployment in the forest
  - Slippery and soft terrain
  - Branches and leaves



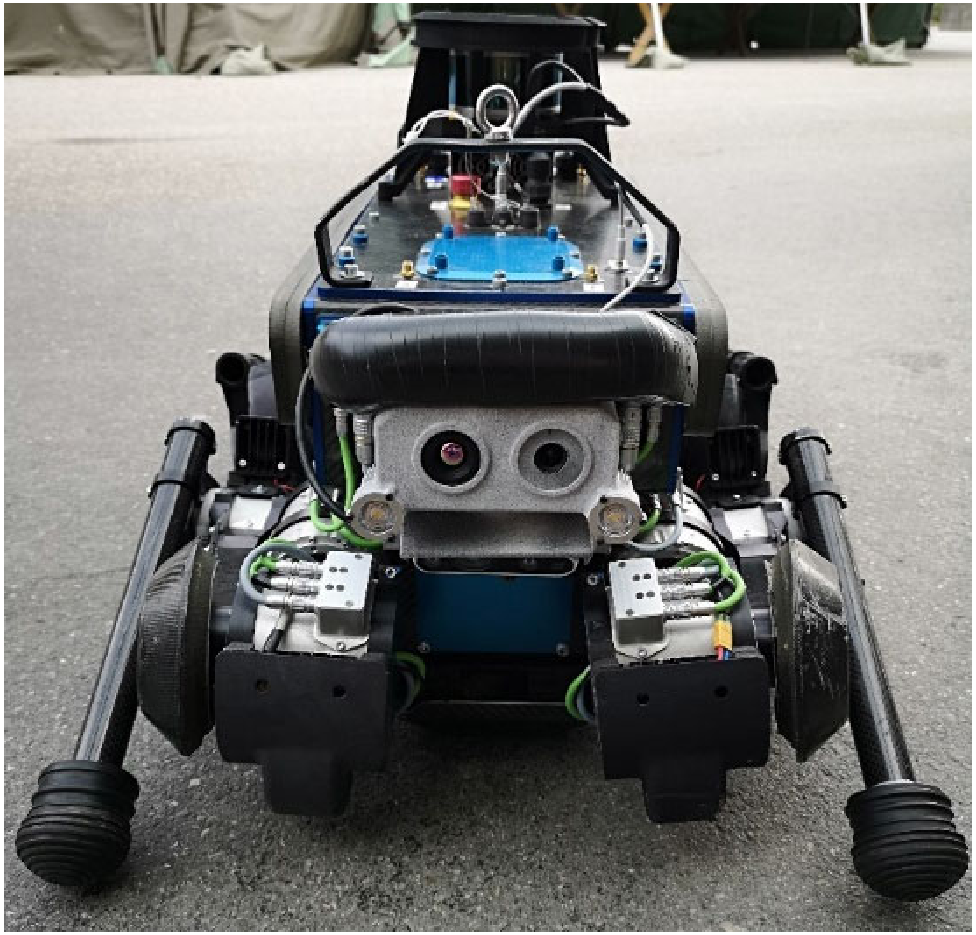
Training Scheme

- Learn locomotion using extra information in simulation
  - Embed the extra observations with an encoder
  - This feature map drives different foot clearance, contact-conditioned motions, terrain adapting behaviors, .. during the locomotion
- Replace the encoder with a TCN network
  - Supervise-learn the embedding with TCN
    - Squared loss for output & embedding
    - DAGGER-style data collection [1]
- RL the whole network (Fine-tuning)



[1] Ross, Stéphane, Geoffrey Gordon, and Drew Bagnell. "A reduction of imitation learning and structured prediction to no-regret online learning." *Proceedings of the fourteenth international conference on artificial intelligence and statistics*. 2011.

Environment perception



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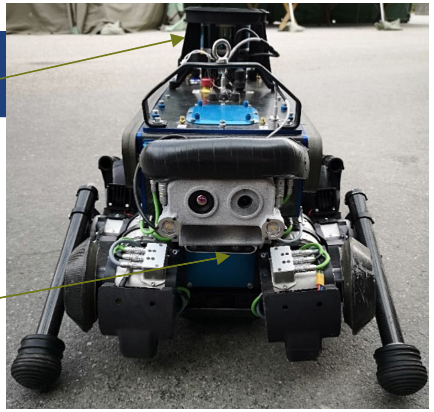
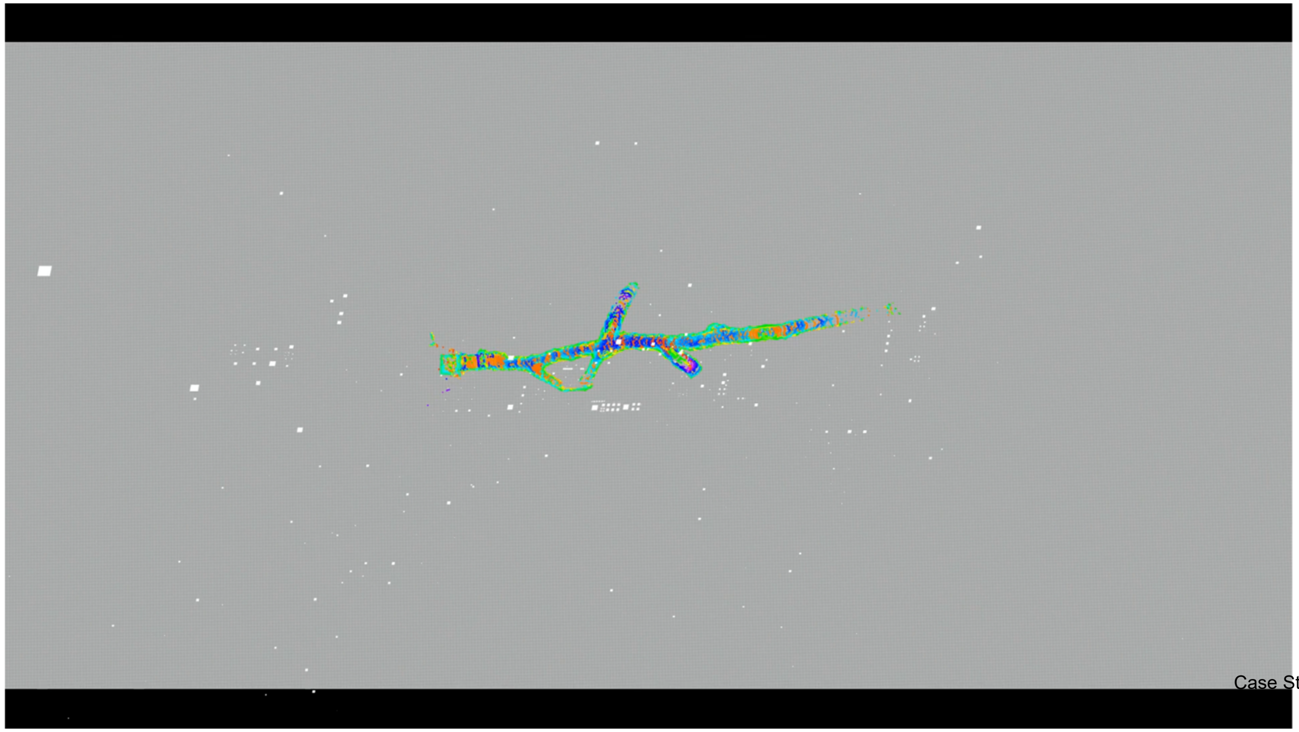
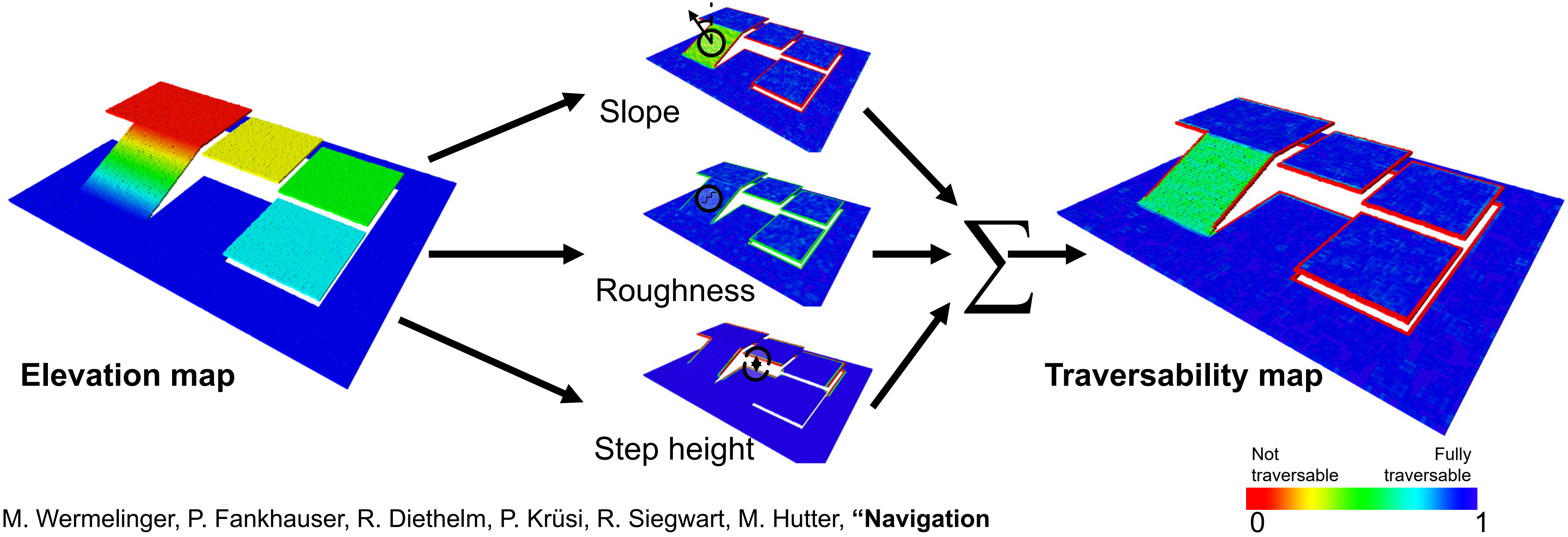
Environment perception



1. ICP-based mapping and localization using lidar
2. Robot-centric elevation mapping for foothold planning using active stereo camera

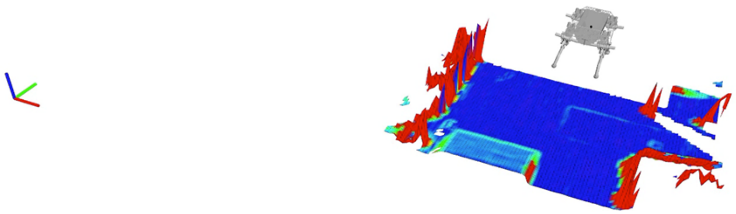


Navigation
Traversability estimation



M. Wermelinger, P. Fankhauser, R. Diethelm, P. Krüsi, R. Siegwart, M. Hutter, **"Navigation Planning for Legged Robots in Challenging Terrain,"** in IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2016.

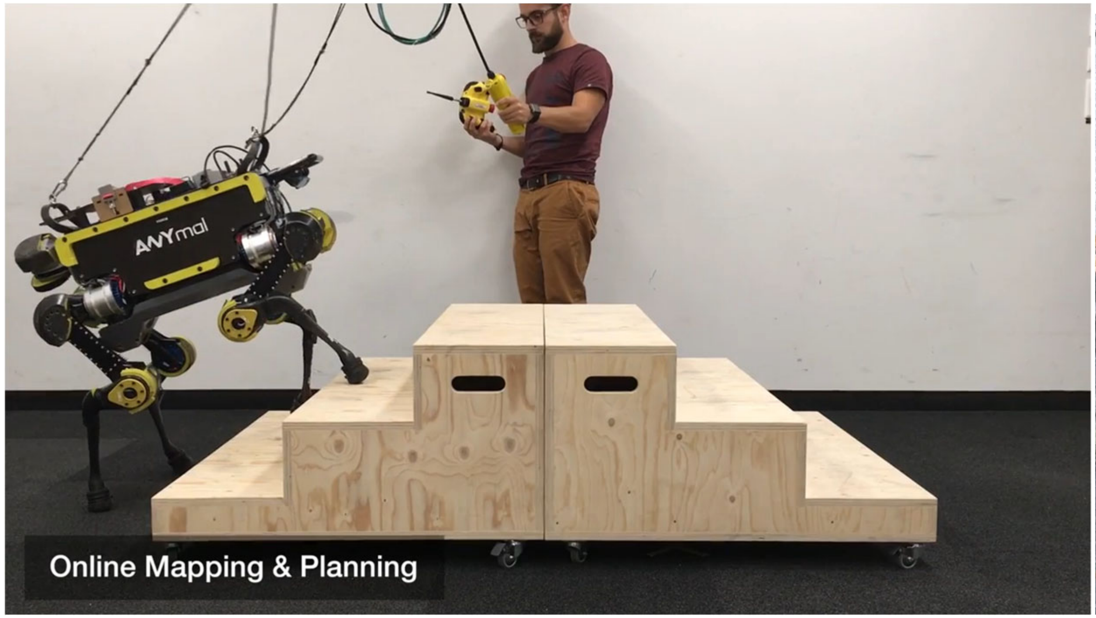
Navigation Planning

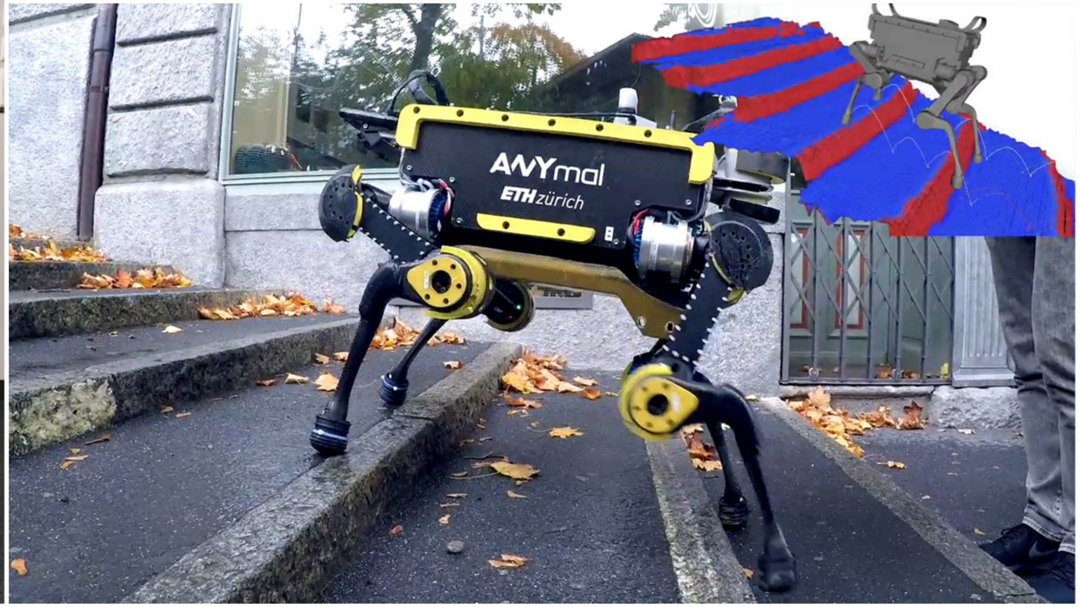


- Online navigation planning based on RRT* (OMPL)
- Works with and without initial map
- Continuous for changing environments

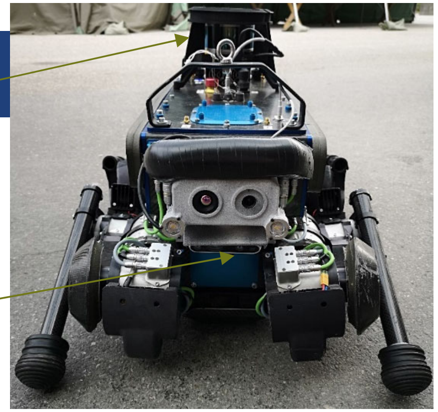
M. Wermelinger, P. Fankhauser, R. Diethelm, P. Krüsi, R. Siegwart, M. Hutter, **"Navigation Planning for Legged Robots in Challenging Terrain,"** in IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2016.

Terrain Mapping and Foothold Planning





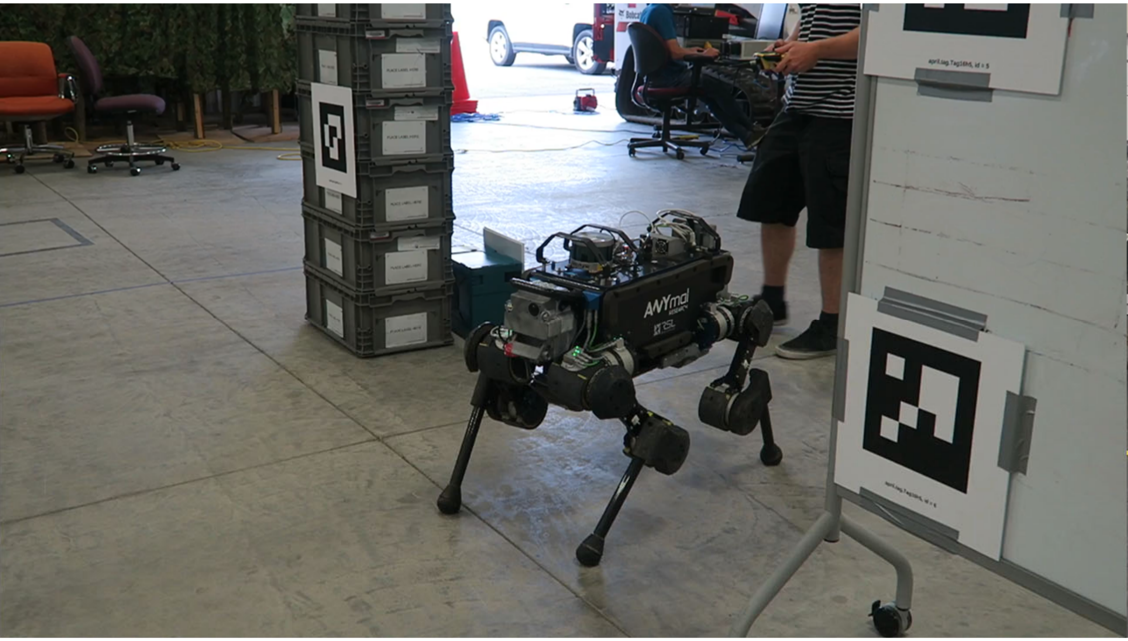
Velodyne Laser

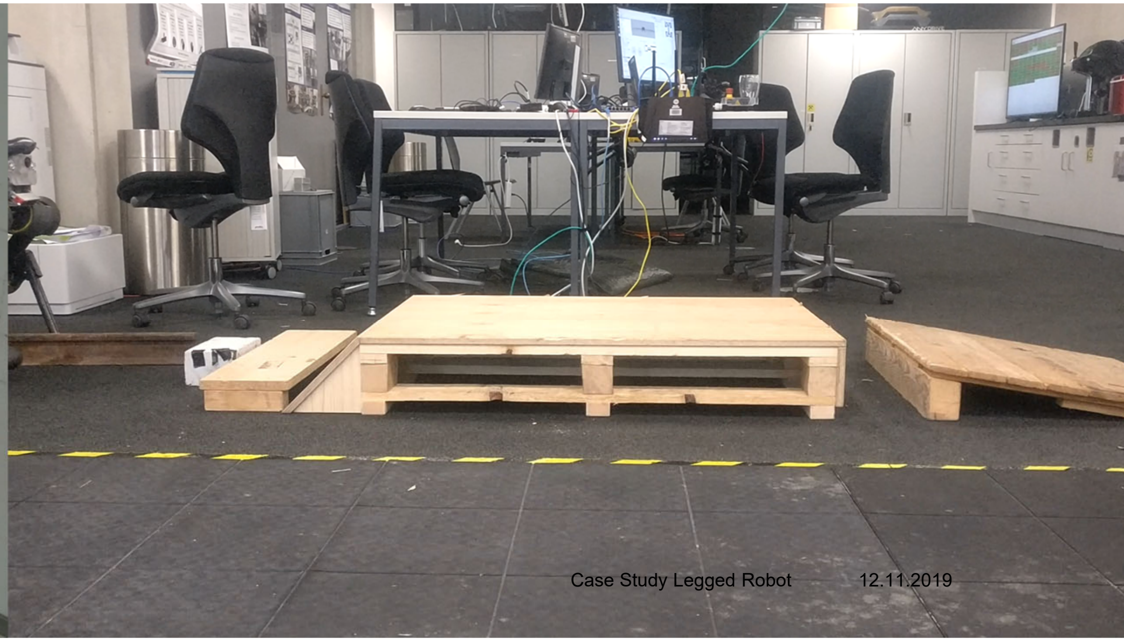


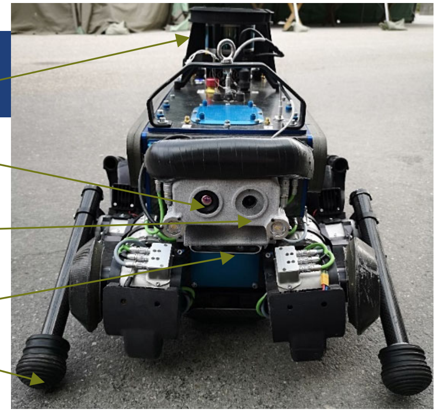
Stereo-Camera with IR-Projector

Environment perception

1. ICP-based mapping and localization using lidar
2. Robot-centric elevation mapping for foothold planning using active stereo camera







Environment perception

1. ICP-based mapping and localization using lidar
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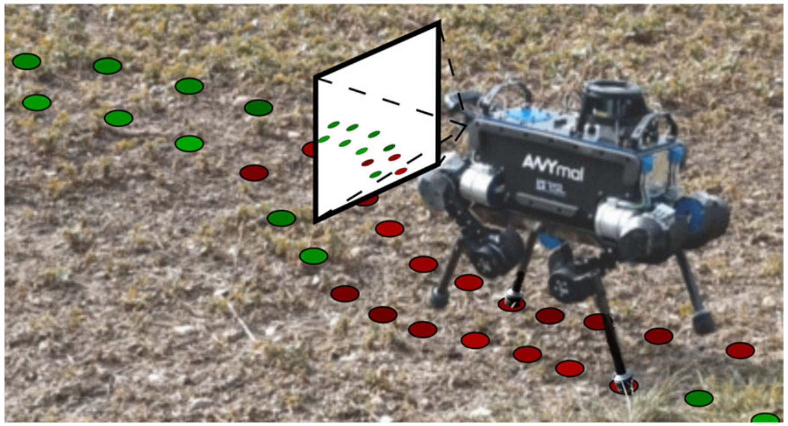
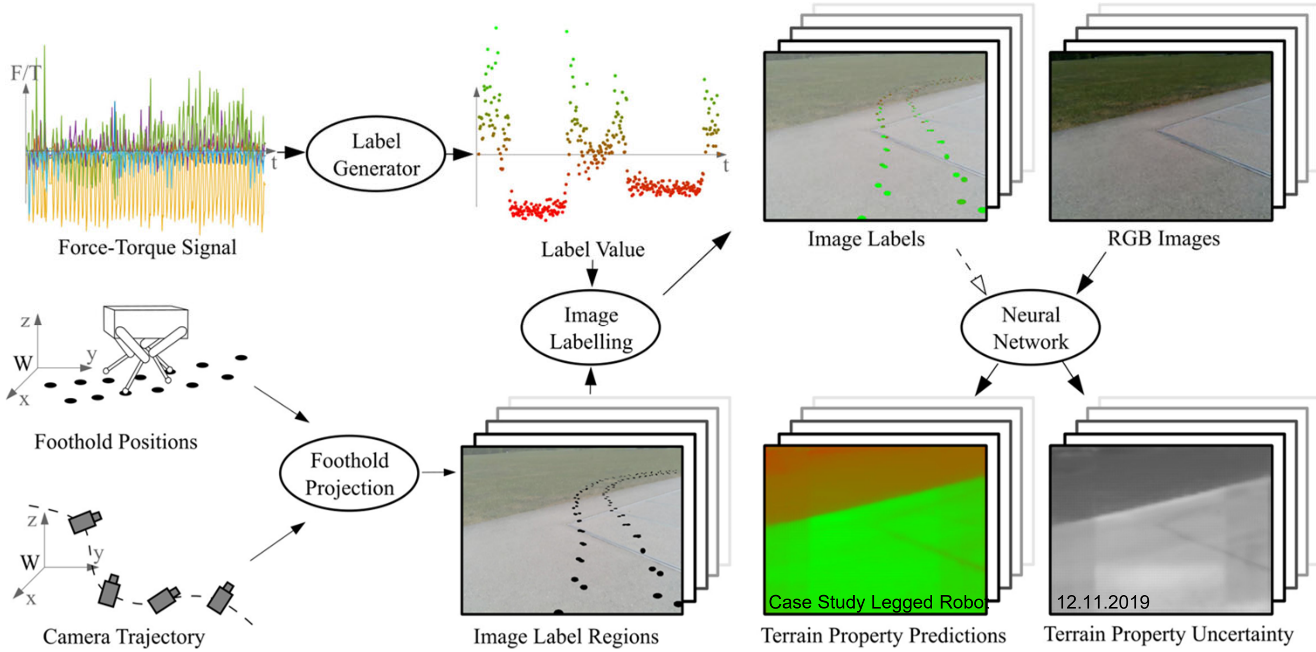
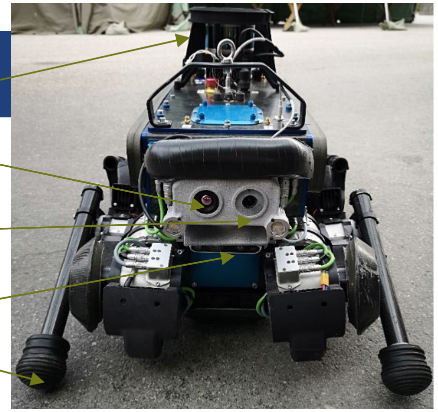
3. Multi-modal terrain quality estimation

[Wellhausen, RAL 2019]







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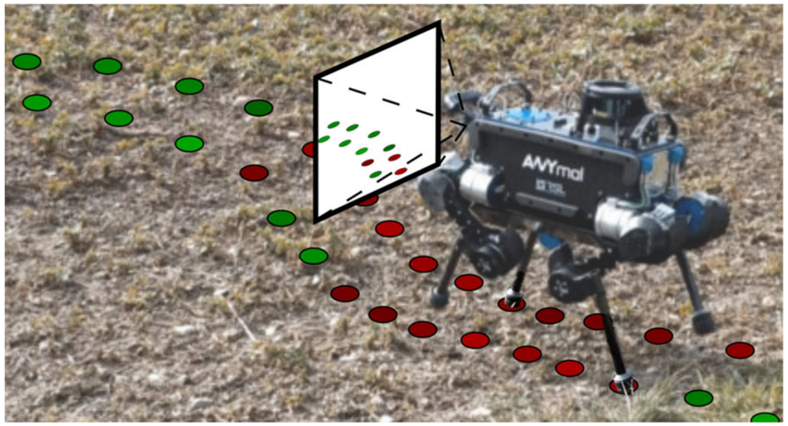
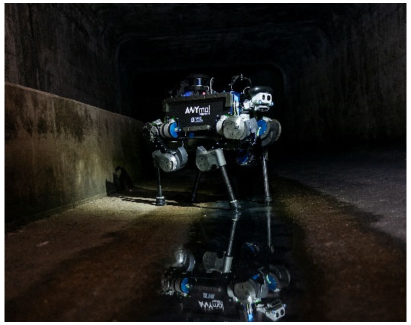
[Wellhausen, RAL 2019]



Real world applications

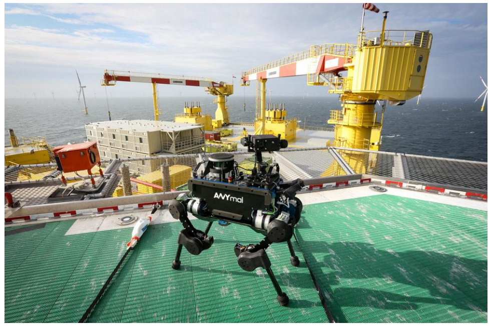
Search and rescue

Sewer and mine inspection



Underground exploration

Industrial inspection



Real world applications

Search and rescue

Sewer and mine inspection

Underground exploration

Industrial inspection

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Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

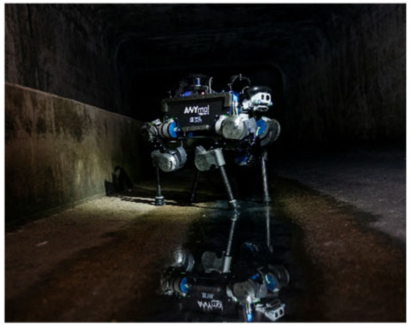
armasuisse
Wissenschaft + Technologie
Schweizer Drohnen- und Robotik-Zentrum
SDRZ VBS

Some more impressions

Real world applications

Search and rescue

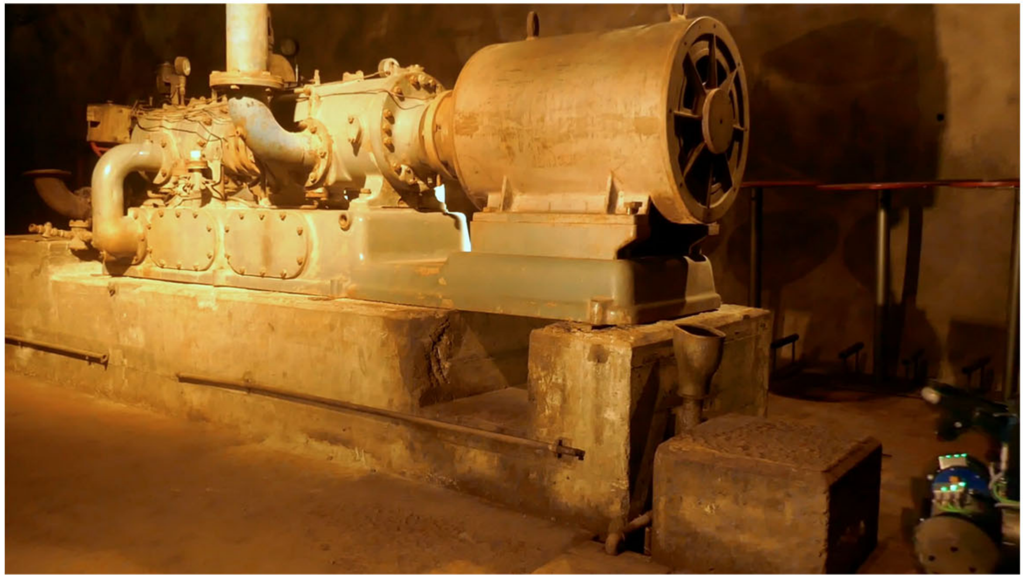
Sewer and mine inspection



Underground exploration

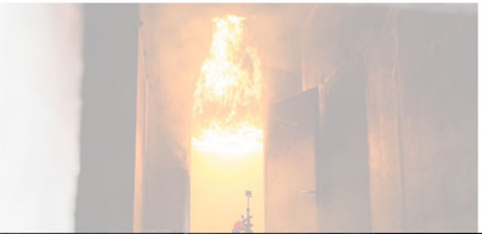
Industrial inspection

[Kolvenbach, FSR 2019]

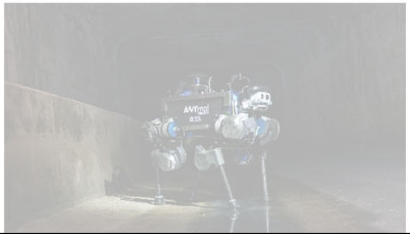


Real world applications

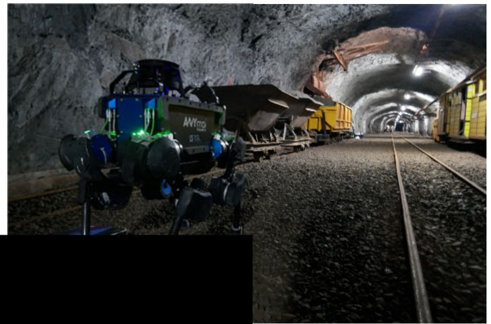
Search and rescue



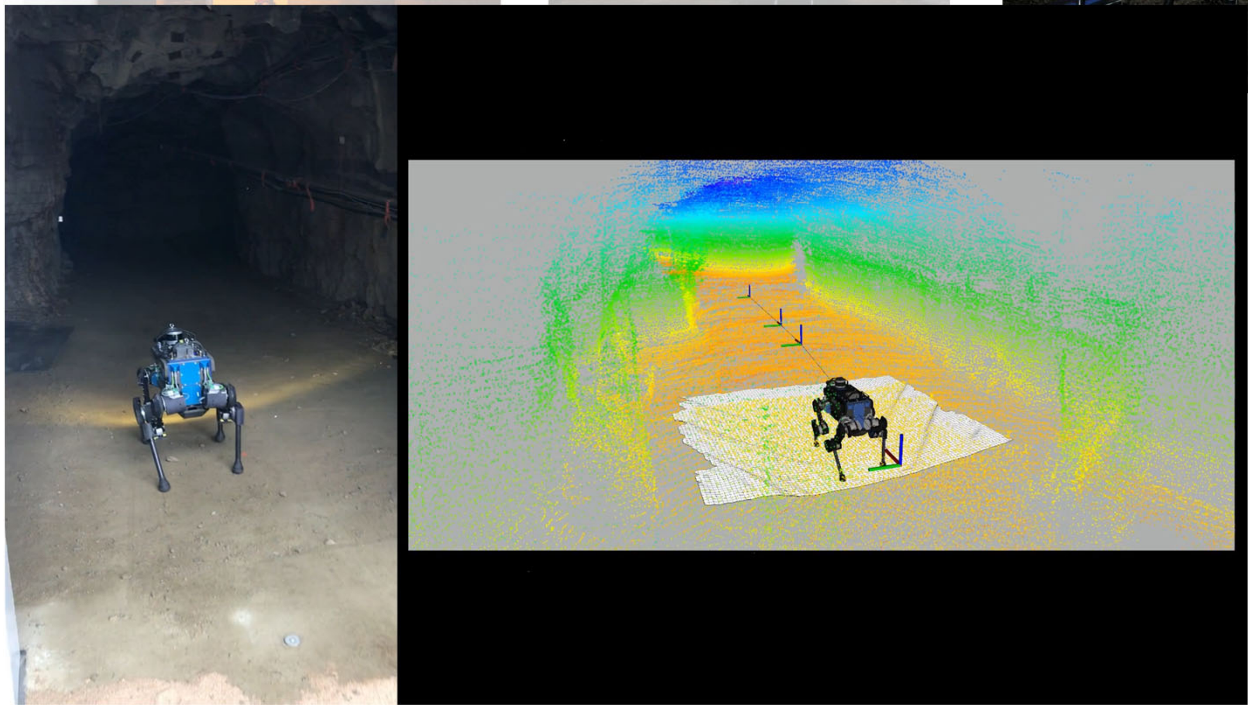
Sewer and mine inspection



Underground exploration



Industrial inspection



Real world applications

Search and rescue

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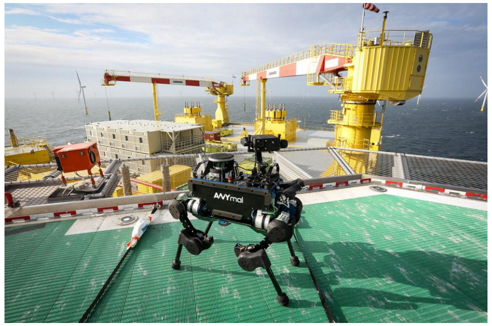
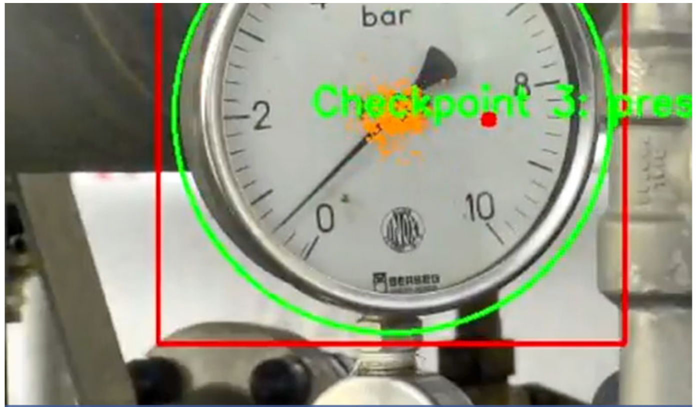


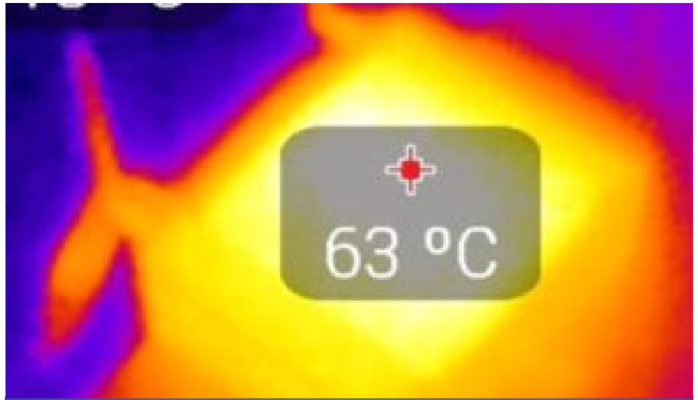
ANYbotics

- Commercialization of legged robots
- Growing team of > 35 people
- Various customers
  - Oil- and gas
  - Windparks
  - Transport
  - …

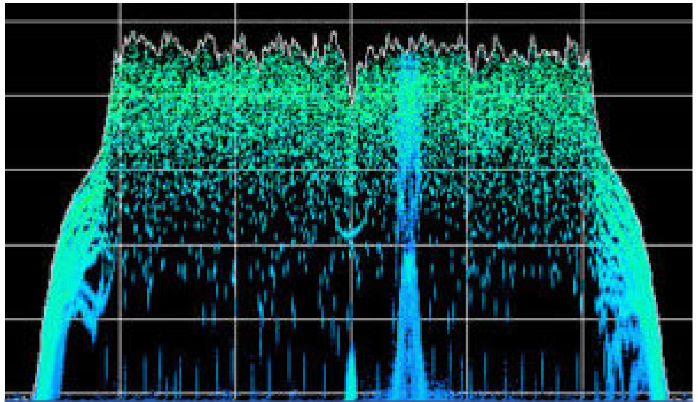
Inspection Tasks



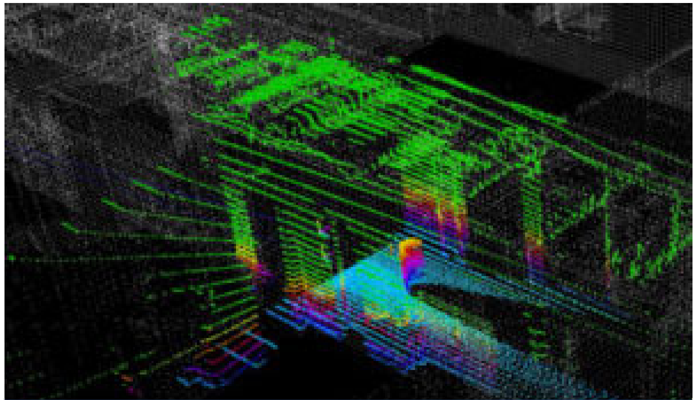
Visual Inspection



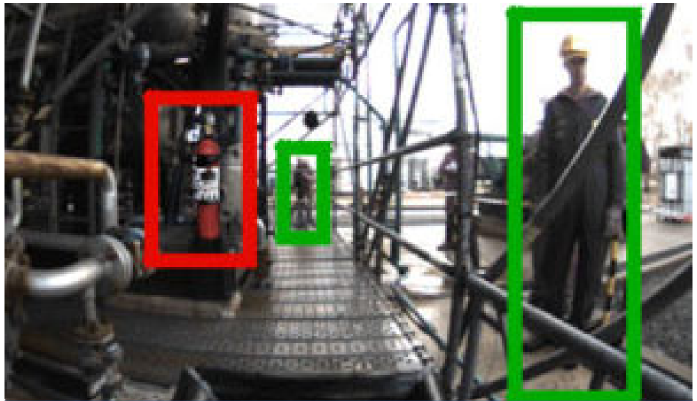
Thermal Inspection



Audio Inspection



3D Mapping



Object Detection

Leak Detection

ANYbotics

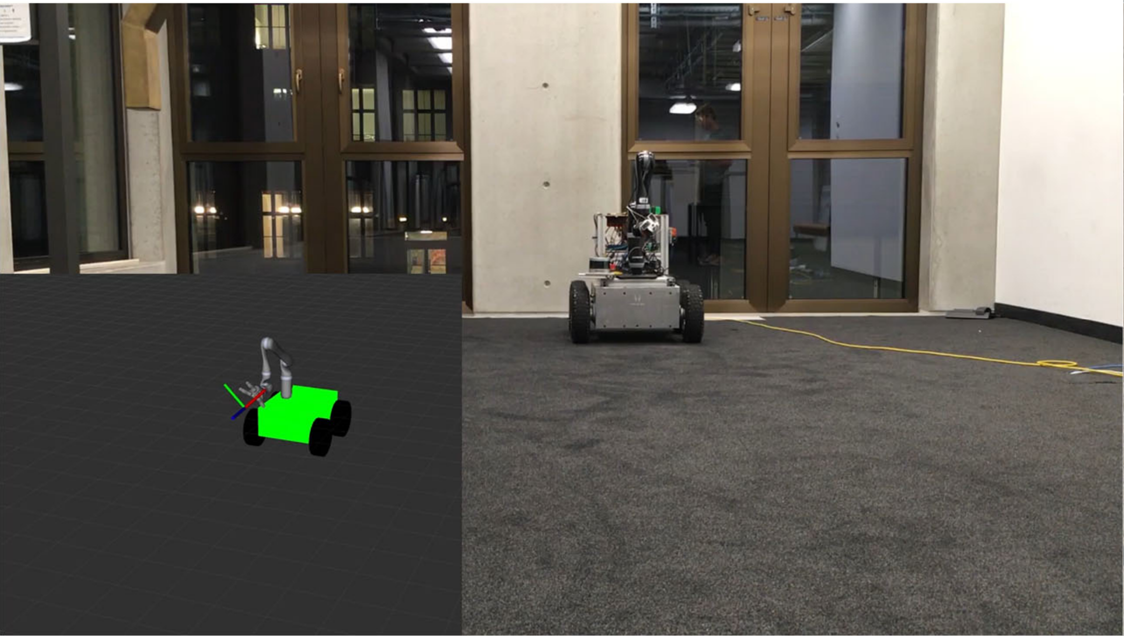
Why unmanned?

Open Lab Day

Friday Dez 13th

- Drinks, food and robotshows
- Find a Semester or Master Thesis

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Lecture «Robot Dynamics»:

Case Study on Menzi Muck

151-0851-00 V

lecture:	CAB G11	Tuesday 10:15 – 12:00, every week
exercise:	HG E1.2	Wednesday 8:15 – 10:00, according to schedule (about every 2nd week)

Marco Hutter, Roland Siegwart, and Thomas Stastny

From Legged Robots to Walking Excavators

Large Scale Legged Locomotion and Manipulation

youtube:
Menzi Muck Extreme

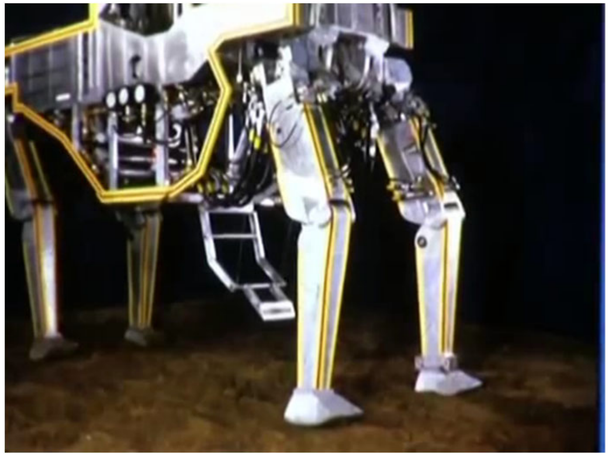


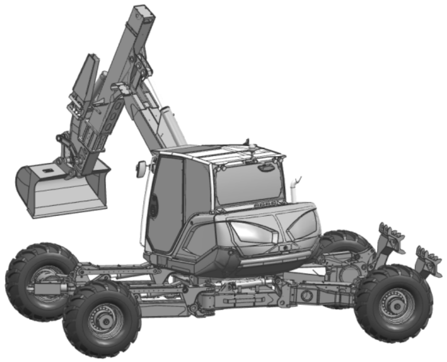


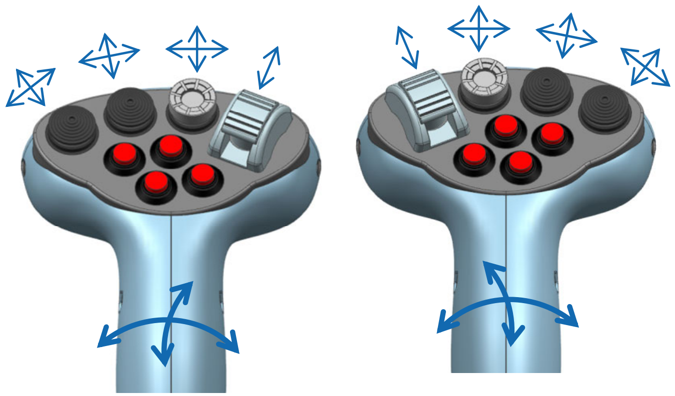

Walking Excavator Control
manual chassis balancing

- Control today:
  - 28DoF manual control, 80 functions
  - No active stabilization, zero automation

GE Truck, 1968

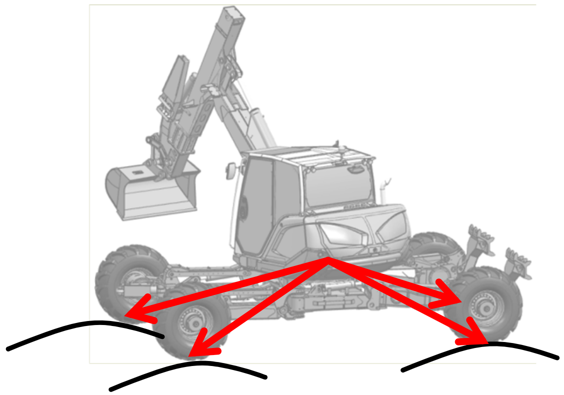


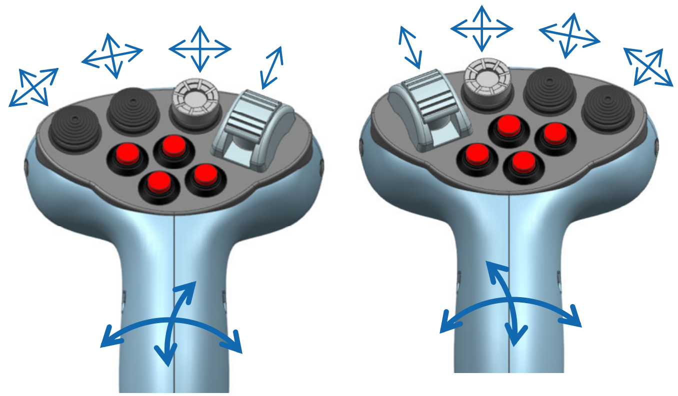




Walking Excavator Control
manual chassis balancing

- Control today:
  - 28DoF manual control, 80 functions
  - No active stabilization, zero automation
  - Simple hydraulic flow commands = position control





Walking Excavator Control
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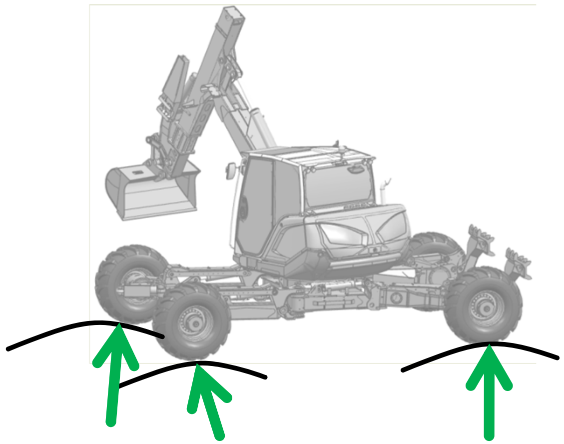
- Desired control:
  - Active regulation of the interaction forces



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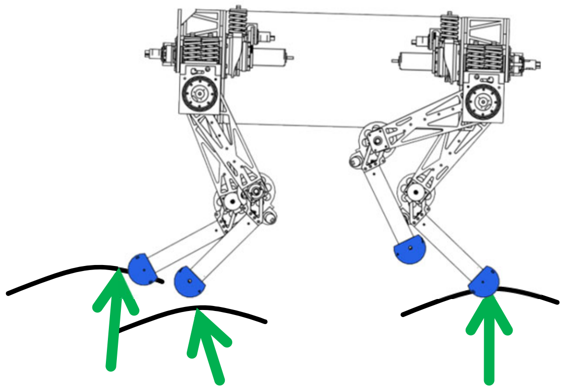
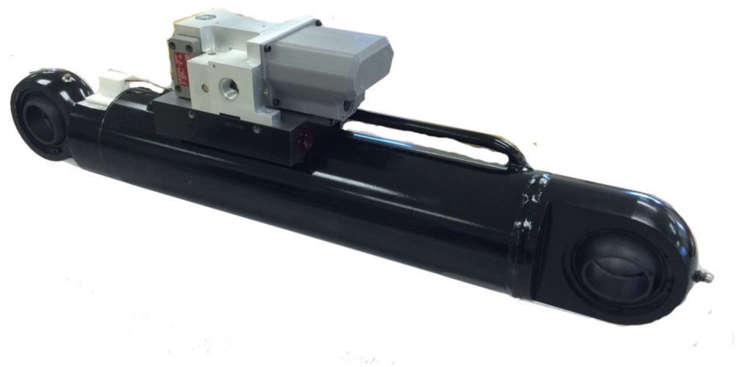


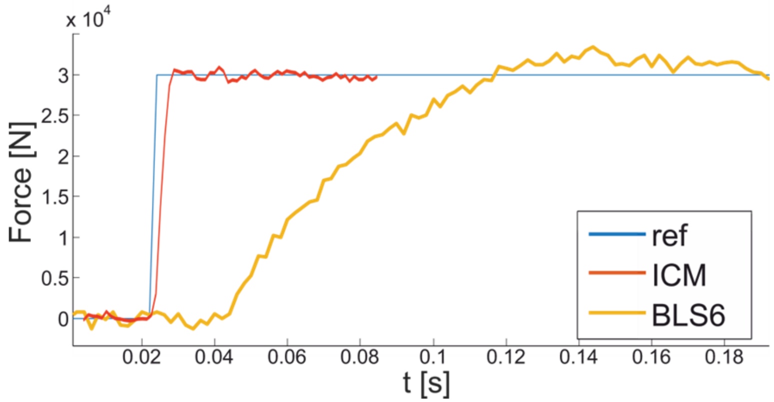
- Precise and fast force control of the hydraulic cylinder
- Optimal force distribution algorithm

- Guarantee safety for operator in all cases!

Intelligent Control Module
a modular hydraulic valve with integrated safety

- G761 servo valve
  - “Fastest valve of its kind”
  - 100Hz force control bandwidth
- Servo-actuated safety valves
  - Supply pressure surveillance
  - Pressure drop in supply leads to immediate lock of both chambers
- Redundant electronics and dual CAN bus
  - ARM and PIC processors
  - Signal comparison for safety
  - 10kHz loop rate
- Integrated position sensing
  - Magnetized piston rod w/ read head
  - Position control (<10um)





Whole-body Control for Walking Excavator
exploiting contact redundancy

- Contact force distribution as prioritized constrained optimization problem

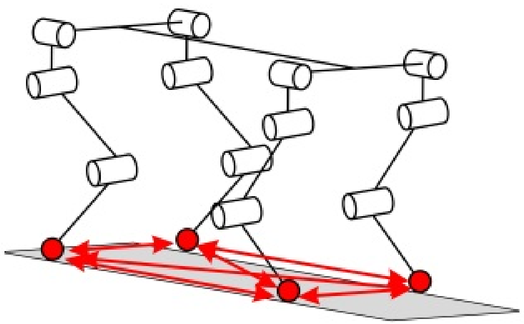
$$
\begin{aligned}
\min \quad & \mathbf{F}_c^T \mathbf{W}_F \mathbf{F}_c + \boldsymbol{\tau}^T \mathbf{W}_\tau \boldsymbol{\tau} \\
s.t. \quad & \mathbf{M}\ddot{\mathbf{q}} + \mathbf{b} + \mathbf{g} + \mathbf{J}_c^T \mathbf{F}_c = \mathbf{S}^T \boldsymbol{\tau} \\
& \ddot{\mathbf{x}}_{base} = \mathbf{J}_{base}\ddot{\mathbf{q}} + \dot{\mathbf{J}}_{base}\dot{\mathbf{q}} \\
& \mathbf{F}_c^{\min} < \mathbf{F}_c < \mathbf{F}_c^{\max} \\
& \boldsymbol{\tau}^{\min} < \boldsymbol{\tau} < \boldsymbol{\tau}^{\max}
\end{aligned}
$$

⟵ Weighted optimization between effort and contact force

⟵ Equation of motion

⟵ Desired base motion

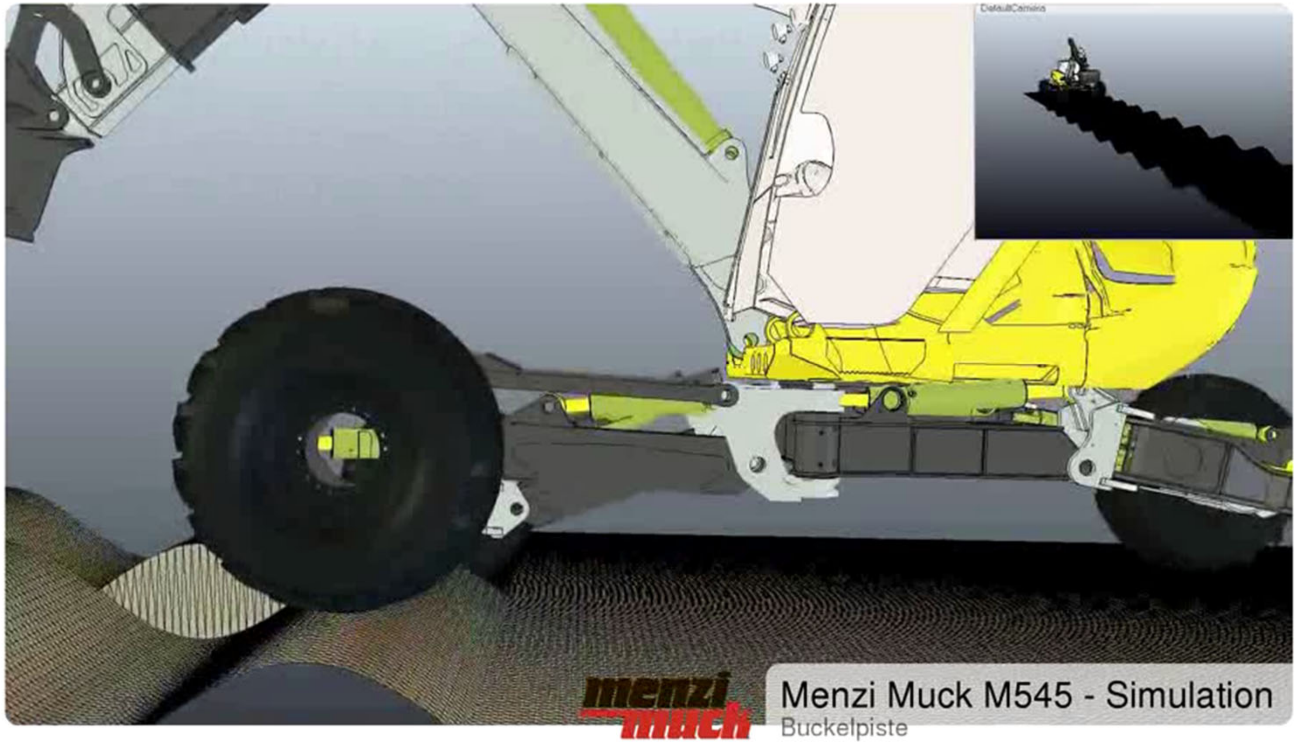
⟵ Friction and normal force if normal direction is known



Quasi-static approximation possible

$$\mathbf{g} + \mathbf{J}_c^T \mathbf{F}_c = \mathbf{S}^T \boldsymbol{\tau}$$

Moving on Uneven Ground
simulations



Simplification in control for nominal pose

Virtual model for height, roll, and pitch

- The most important control directions are height, roll, and pitch
- Apply a virtual force depending on how the base position and orientation should change

$$
\begin{aligned}
{}_B F_v &= PID^p \left({}_B z^{des} - {}_B z_b \right) \\
{}_B \mathbf{T}_v &= PID^r \left({}_B \varphi^{des} - {}_B \varphi \right)
\end{aligned}
$$

- Only look at the vertical forces!
- These virtual forces must come from contact forces

$$
\underbrace{\begin{bmatrix} 1 & \dots & 1 \\ {}_B y_{BC_1} & \dots & {}_B y_{BC_4} \\ -{}_B x_{BC_1} & \dots & -{}_B x_{BC_4} \end{bmatrix}}_{\mathbf{A}} \underbrace{\begin{pmatrix} F_{(Cz)_1} \\ F_{(Cz)_2} \\ F_{(Cz)_3} \\ F_{(Cz)_4} \end{pmatrix}}_{\mathbf{x}} = \underbrace{\sum_{i=1}^{n} m_i g \begin{pmatrix} 1 \\ {}_B y_{BS_i} \\ -{}_B x_{BS_i} \end{pmatrix} + \begin{pmatrix} {}_B F_v \\ {}_B \mathbf{T}_v \end{pmatrix} + \begin{pmatrix} m_{UM} g \\ 0 \\ 0 \end{pmatrix}}_{\mathbf{b}}
$$

- Find the optimal solution

$$
\begin{aligned}
\min \quad & \mathbf{x}^T \mathbf{W} \mathbf{x} \\
s.t. \quad & F_{(Cz)_i} > F_{c,min} && \text{(Prio 1)} \\
& F_{(Cz)_i} < F_{c,max} && \text{(Prio 1)} \\
& \mathbf{A}\mathbf{x} - \mathbf{b} = \mathbf{0} && \text{(Prio 2)}
\end{aligned}
$$

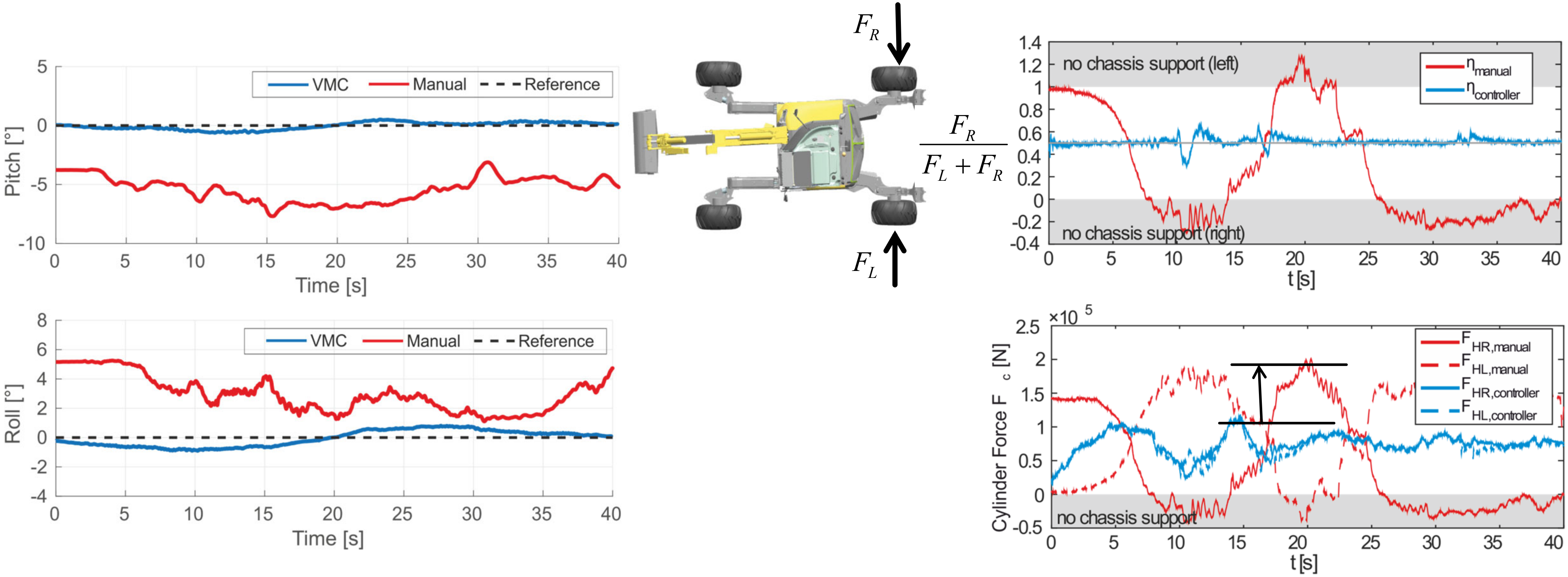
ETH zürich

Automatic Chassis Balancing

manual operation

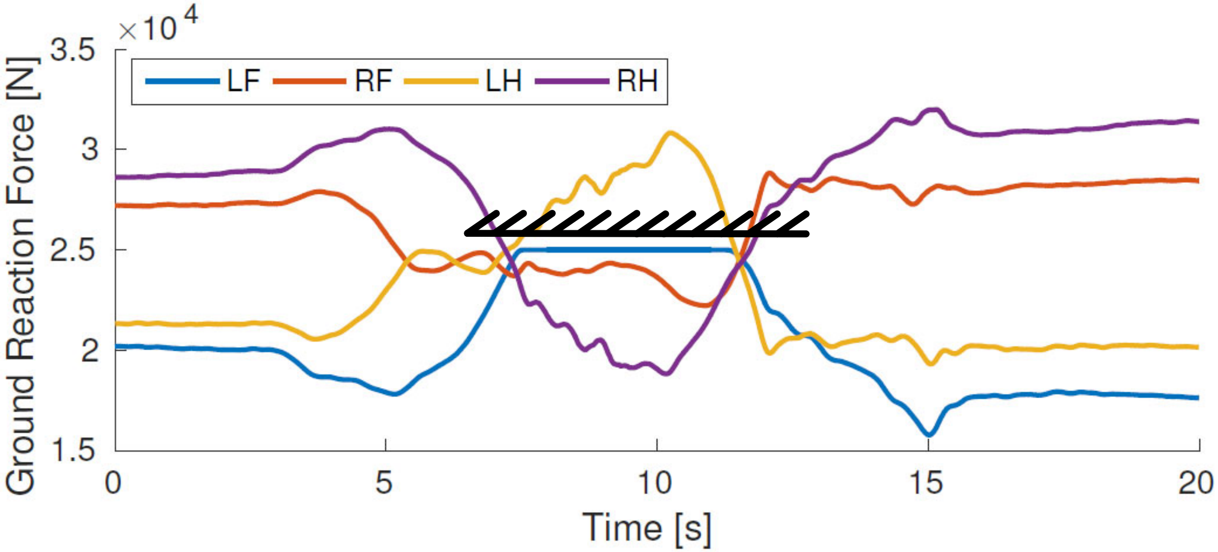
automated chassis

Automatic Chassis Balancing

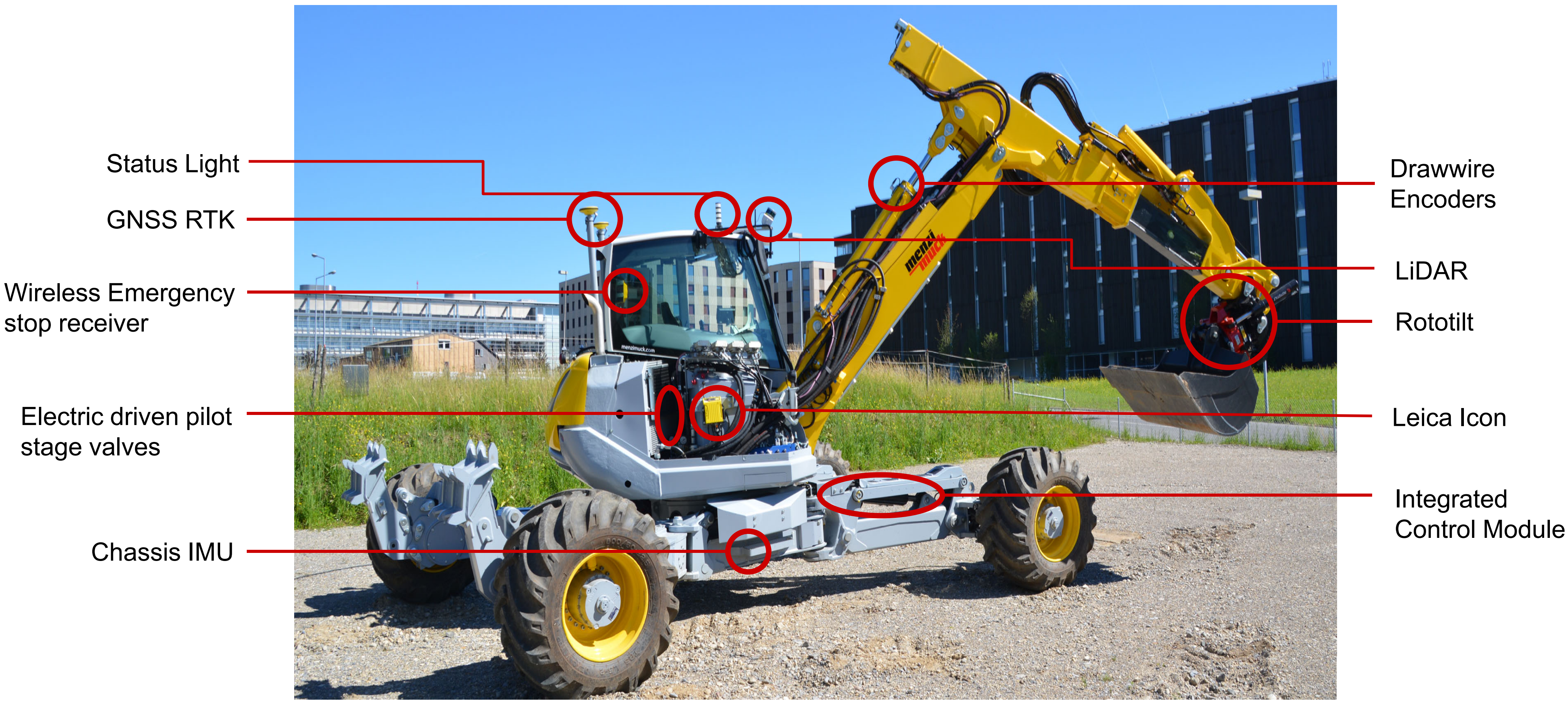


Working with Limited Contact Force
experiment

- Situation: Work on ground where one leg has limited force
  e.g. While doing work around a house and standing on a manhole cover



Fully automated and teleoperable Menzi Muck M545

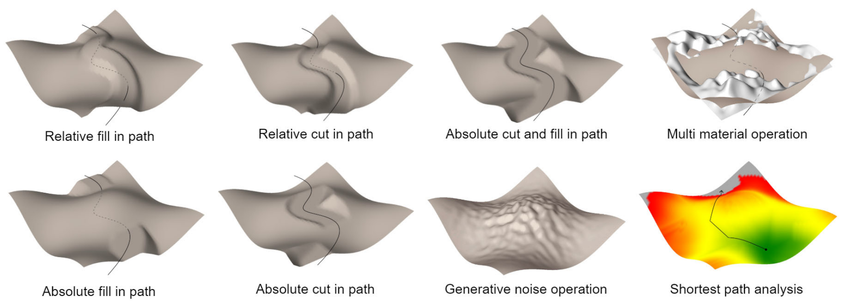


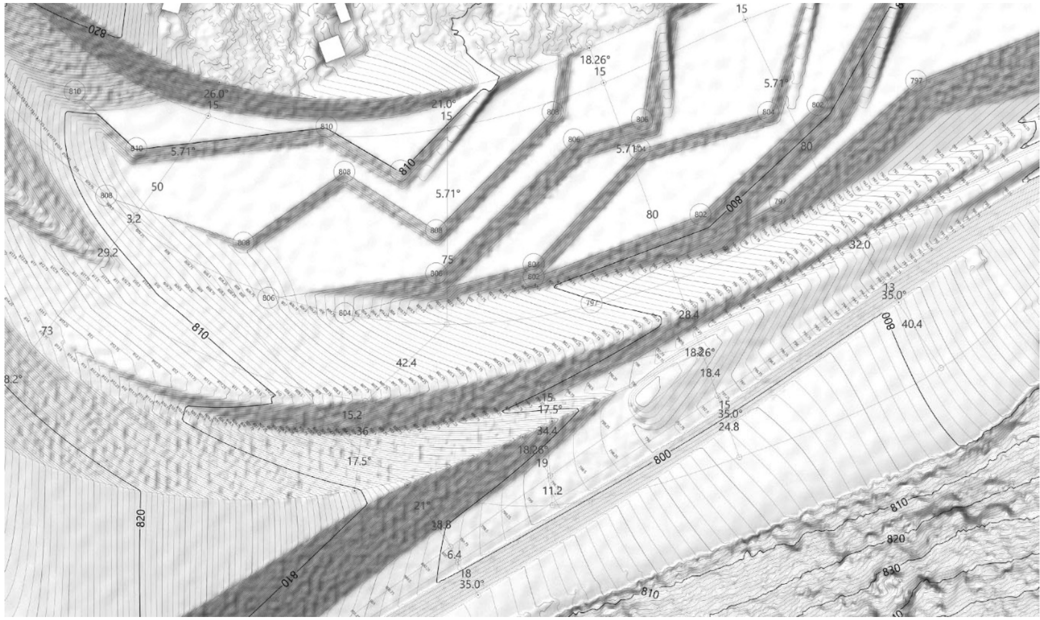
Machine Automation

- Precise end-effector control using whole-body-dynamics
- Machine learning for high-precision control
- Automated terrain adaptation
- Safety guarantee, reduced machine load, less terrain damage

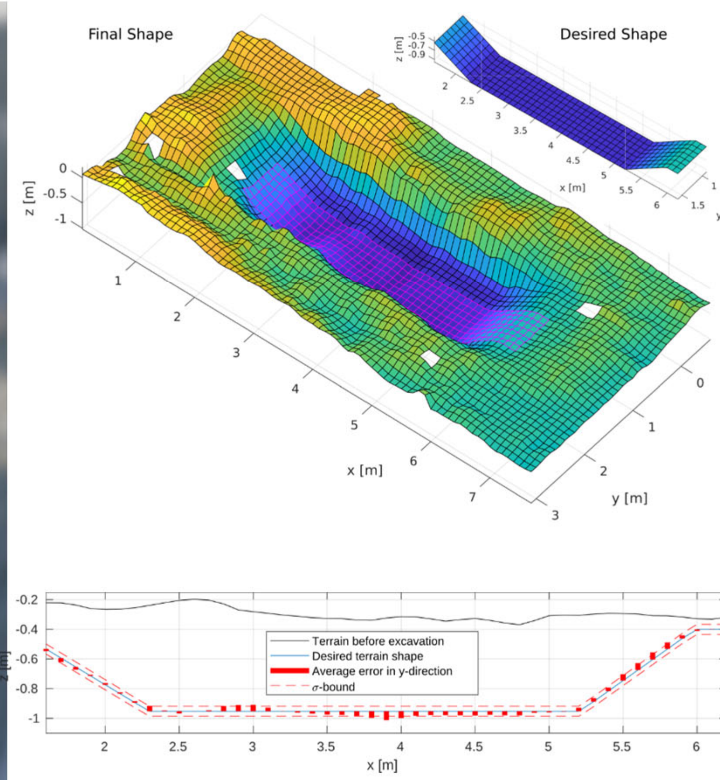
Robotic Landscaping

- New computational terrain modelling





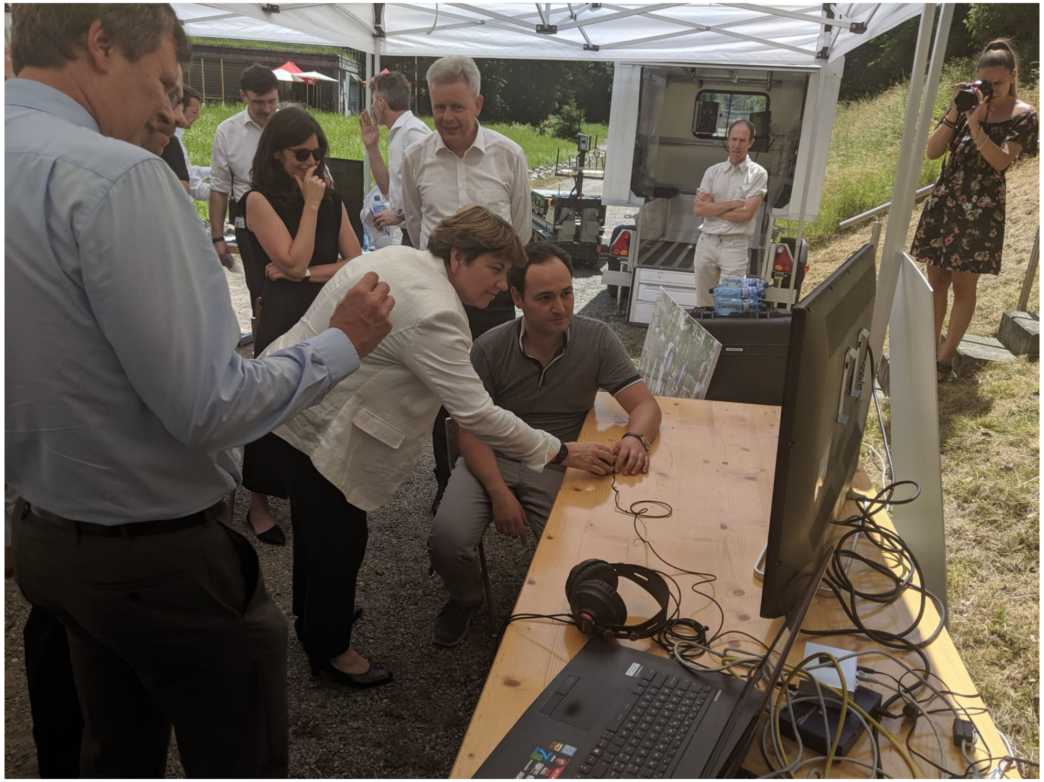
Robotic Landscaping



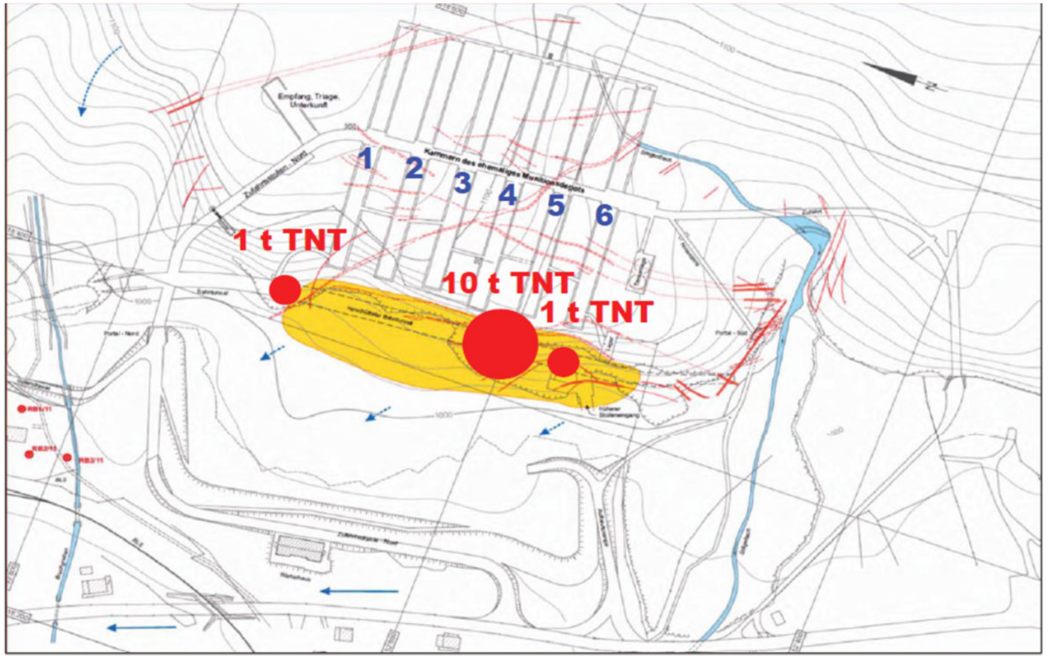
Teleoperation

Mitholz Excavator

Teleoperated excavator for ammunition deposit



Example Mitholz
- 3000 tons air bombs



Autonomous Construction from found Objects