

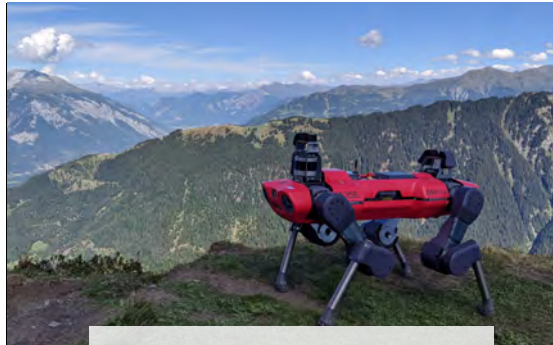
Legged Robots @ ETH

EPFL, 2025

Marco Hutter
ETH Zurich, ANYbotics, RAI
07.10.2025



Mobile Robots that can go ANYwhere
to take over the dull, dirty and dangerous jobs



natural environment



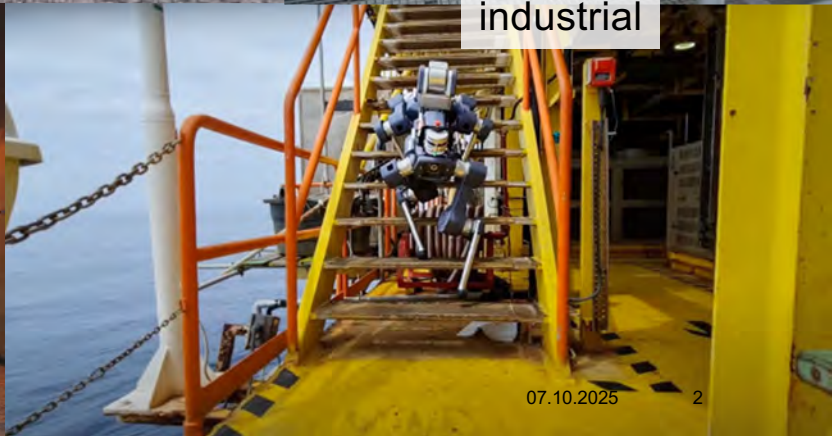
space



industrial



search and rescue



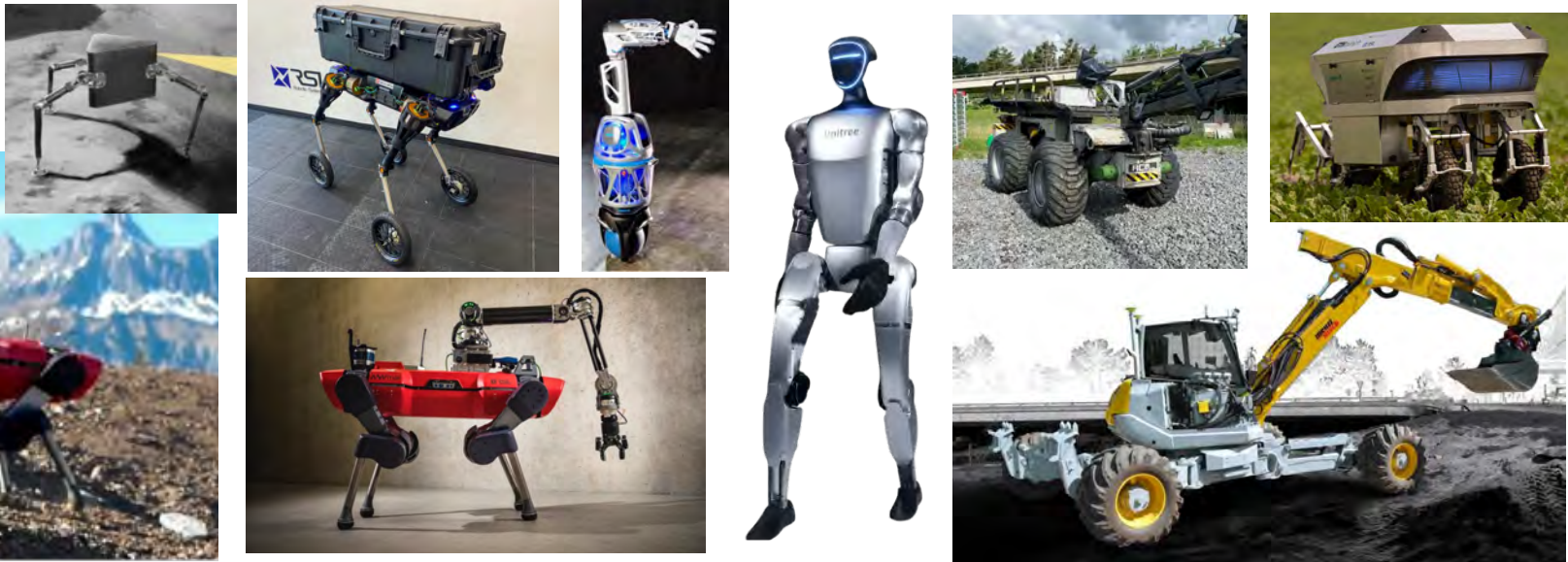
Research areas at RSL

Facts & Figures

- 6 PostDocs
- 25 PhD students
- 25 engineering/staff

- Focus: Locomotion and mobile manipulation with uncertain/unstructured environments
 - **Design** of actuators and robots
 - Model-based **planning and control** for hybrid systems
 - **Reinforcement learning** with sim-to-real transfer
 - Multi-modal **perception** and classification for traversability estimation and **navigation**

- Different platforms

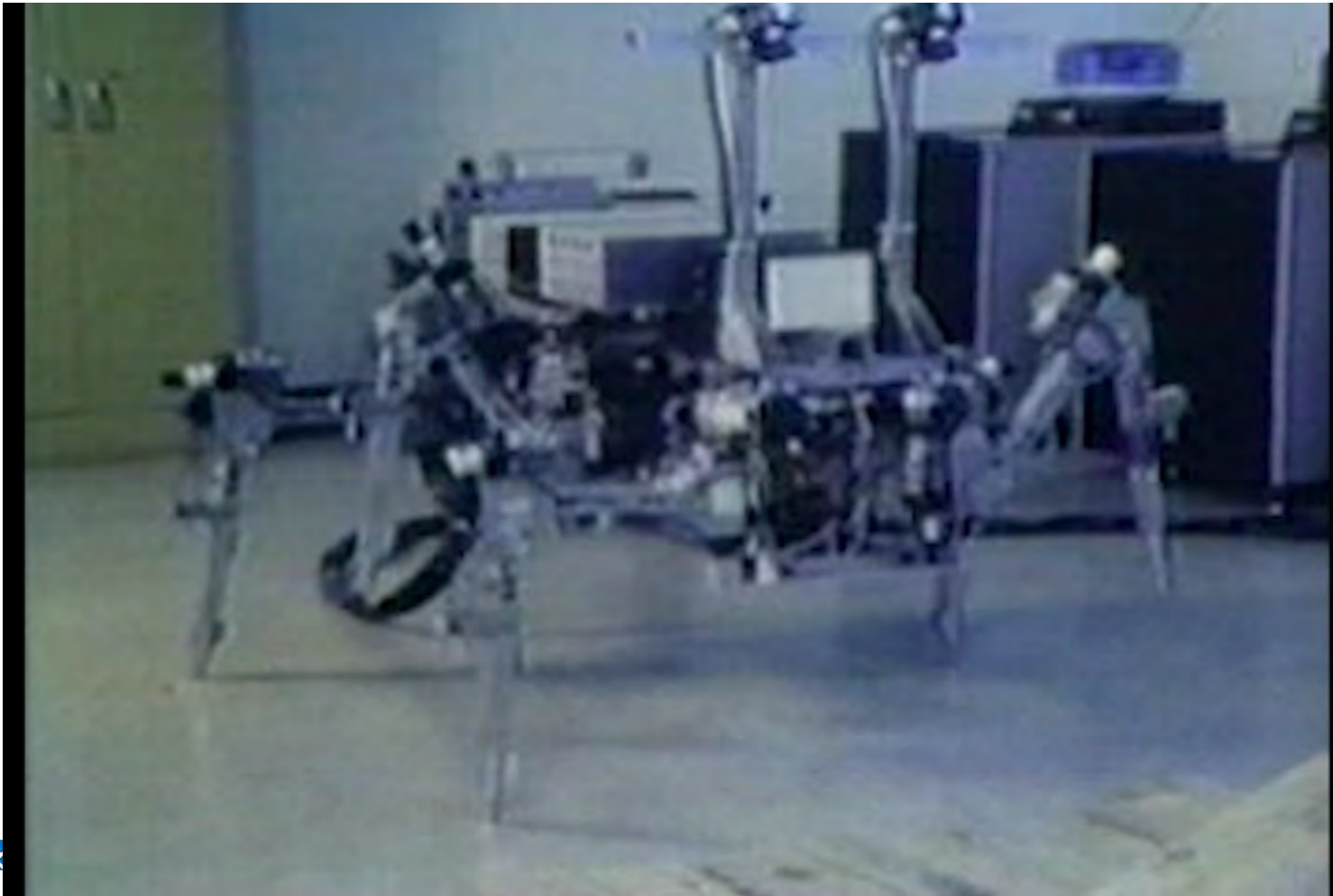


Lecture today in 5 parts

1. Quadrupeds
2. Control
3. Navigation
4. Applications

Part 1: RSL Quadrupeds

OSU walker, early 80ies



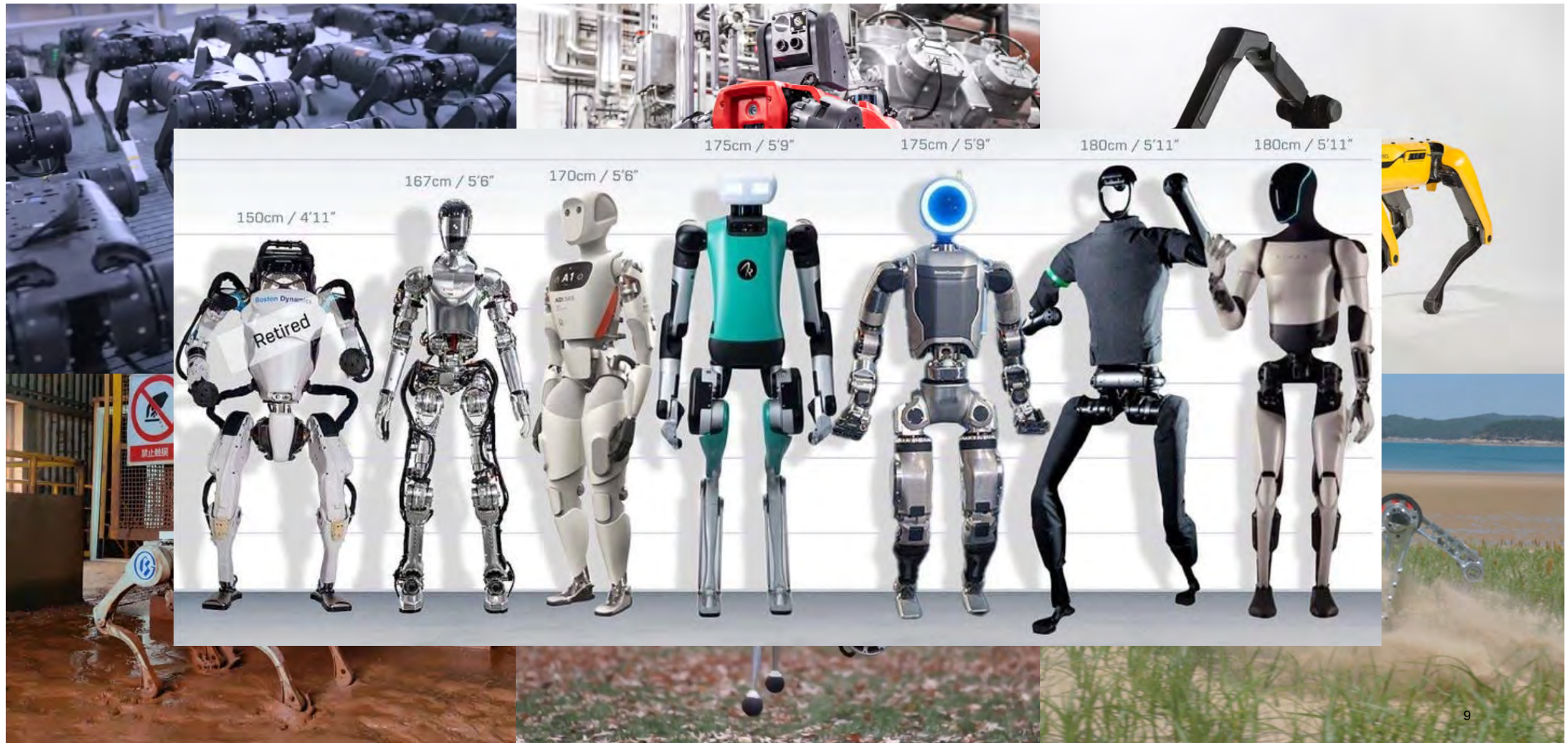
Raibert, Leg Lab, late 80ies





Boston Dynamics

Legged (Quadruped) robots have become a commodity



3 key factors making mobile robots ubiquitous and capable

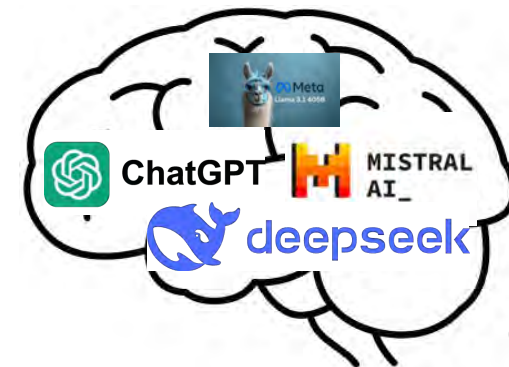
1. **Actuation:** Affordable, compact, powerful drives



2. **Control:** Reinforcement and imitation learning



3. **Autonomy:** Foundation models (LLM/VLM) for common sense



From research prototypes to commercial products in 1 decade

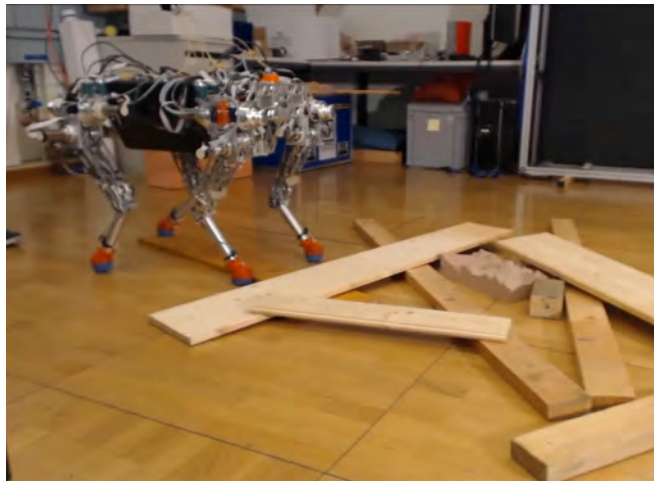


ETH Zurich - Robotic Systems Lab

Research on autonomous robots

ANYbotics

founded 2016, >200 employees



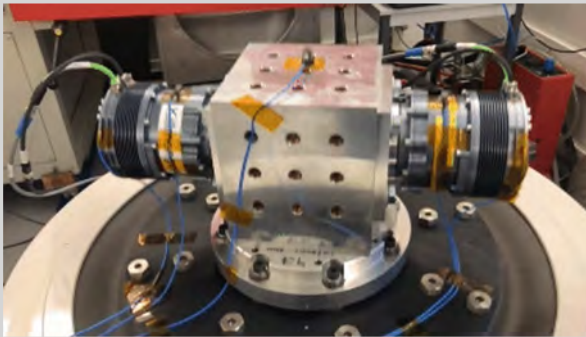
Specifications

- Integrated, torque controllable and impact robust joint units
- Simple 3-link kinematic leg structure
- Mainbody with 2-3 PCs
- Perception sensors for autonomy
 - Velodyne lidar
 - 6 RGB-D
 - 2 wide-angle RGB
- Inspection Payload
 - Zoom camera
 - Thermal camera
 - Light
 - Microphone



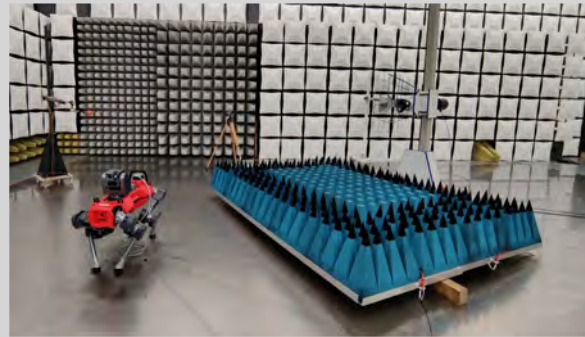
ANYmal D

Design for reliability



Reliability

Large operating temperature ranges, thermal cycling, humidity exposure/cycling, vibration/shock, component lifetimes



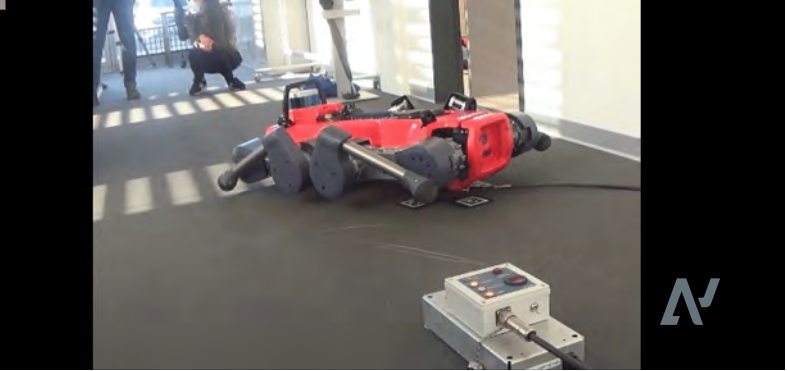
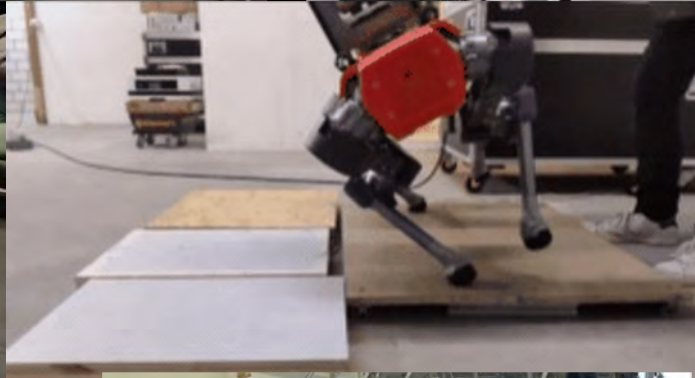
Electromagnetic & radio compliance

Emissions, immunity, electrostatic discharge, radios



Environment

Water/dust ingress, UV radiation, corrosion, humidity/condensation

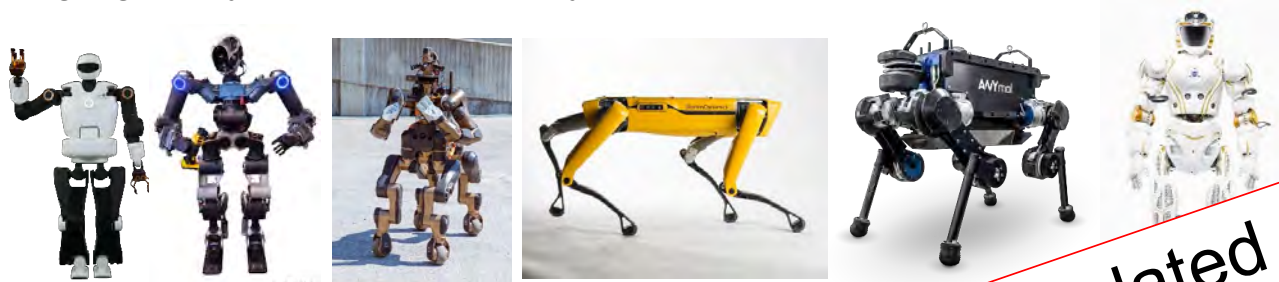




Part 2: Control

State of the Art Legged Robots – and their actuation

1. High-gear system with elasticity or torque sensor



2. Low gear system with current control only

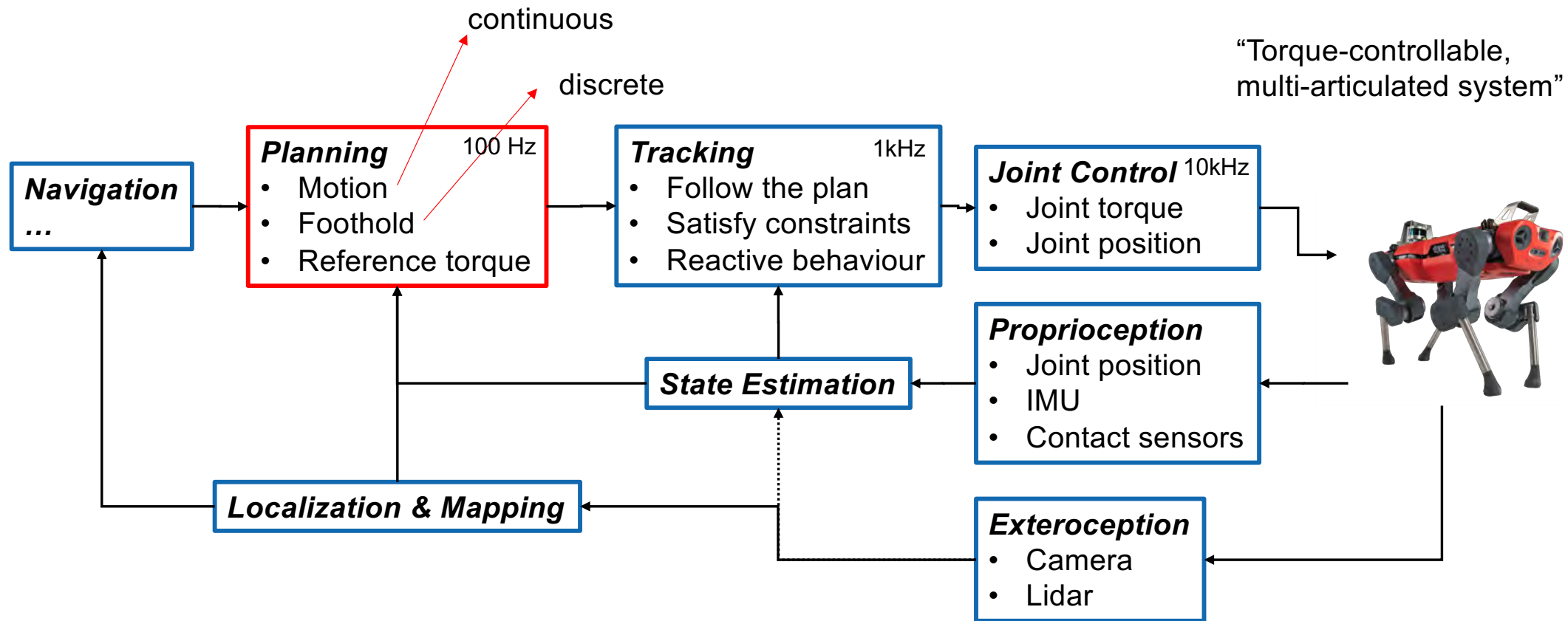


3. Hydraulic (pressure and/or load cell)

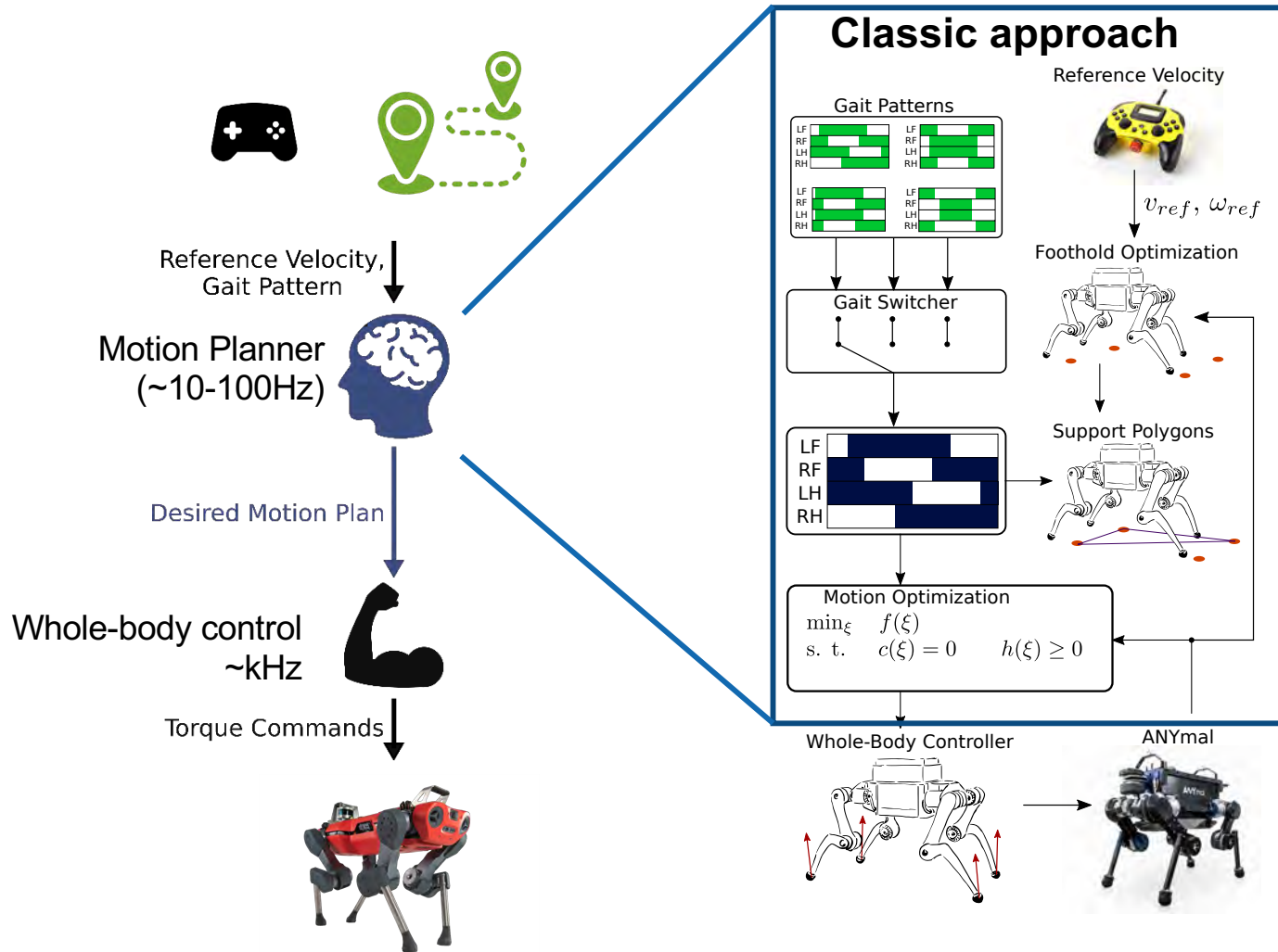


Torque-controllable, multi-articulated system”

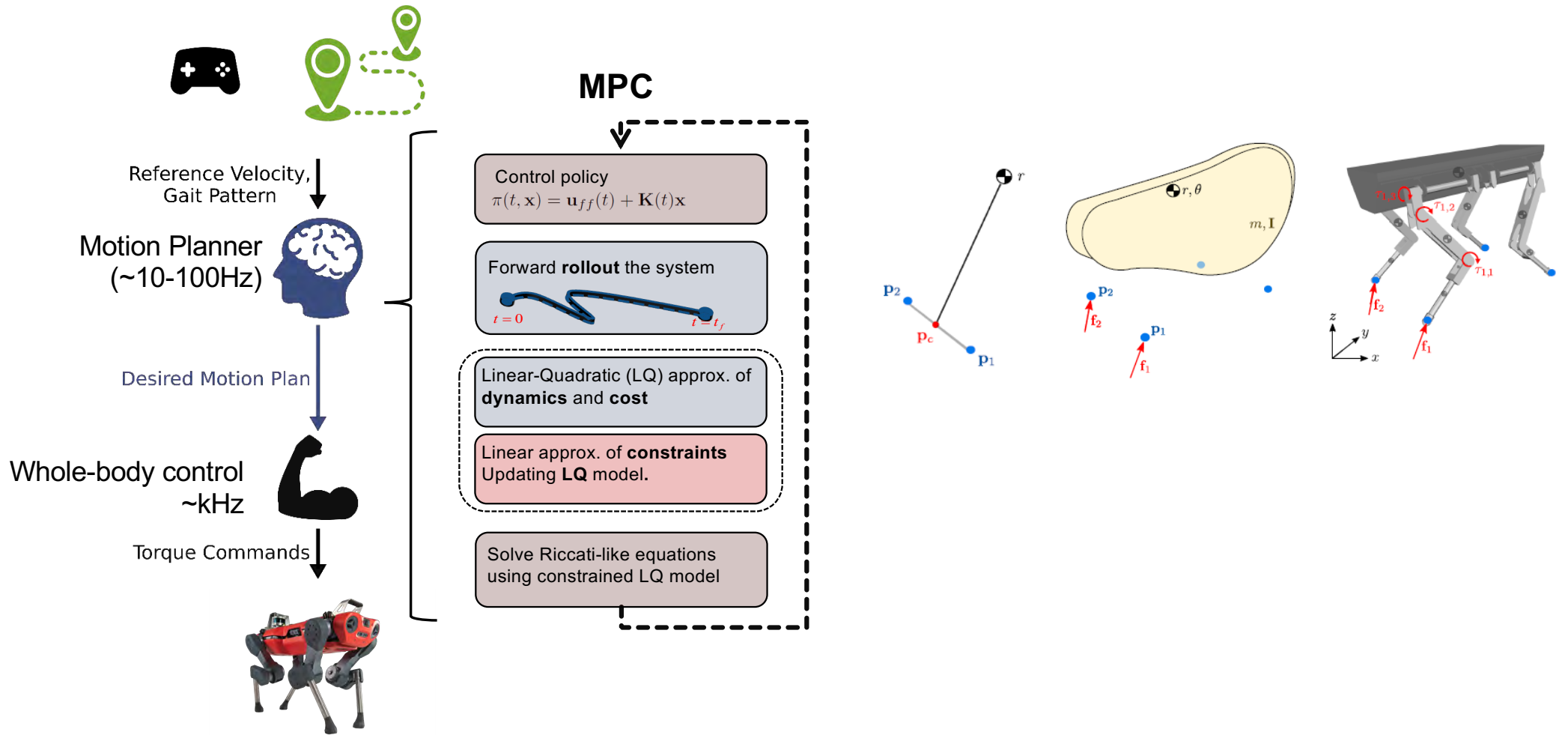
Control, Planning and Autonomy for Legged Robots



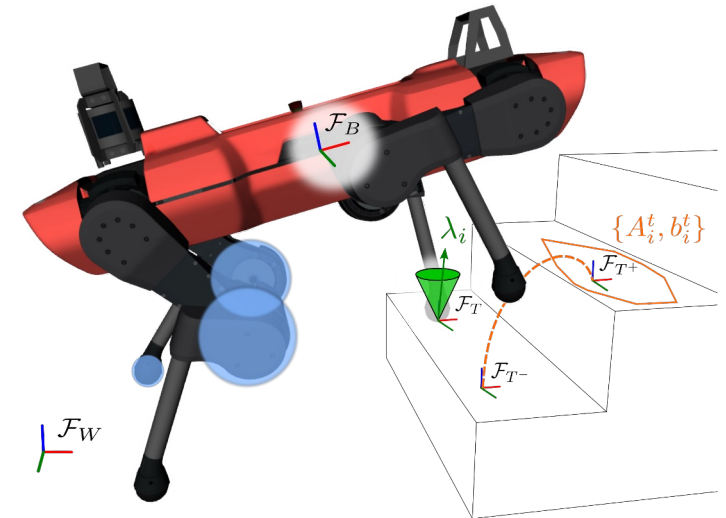
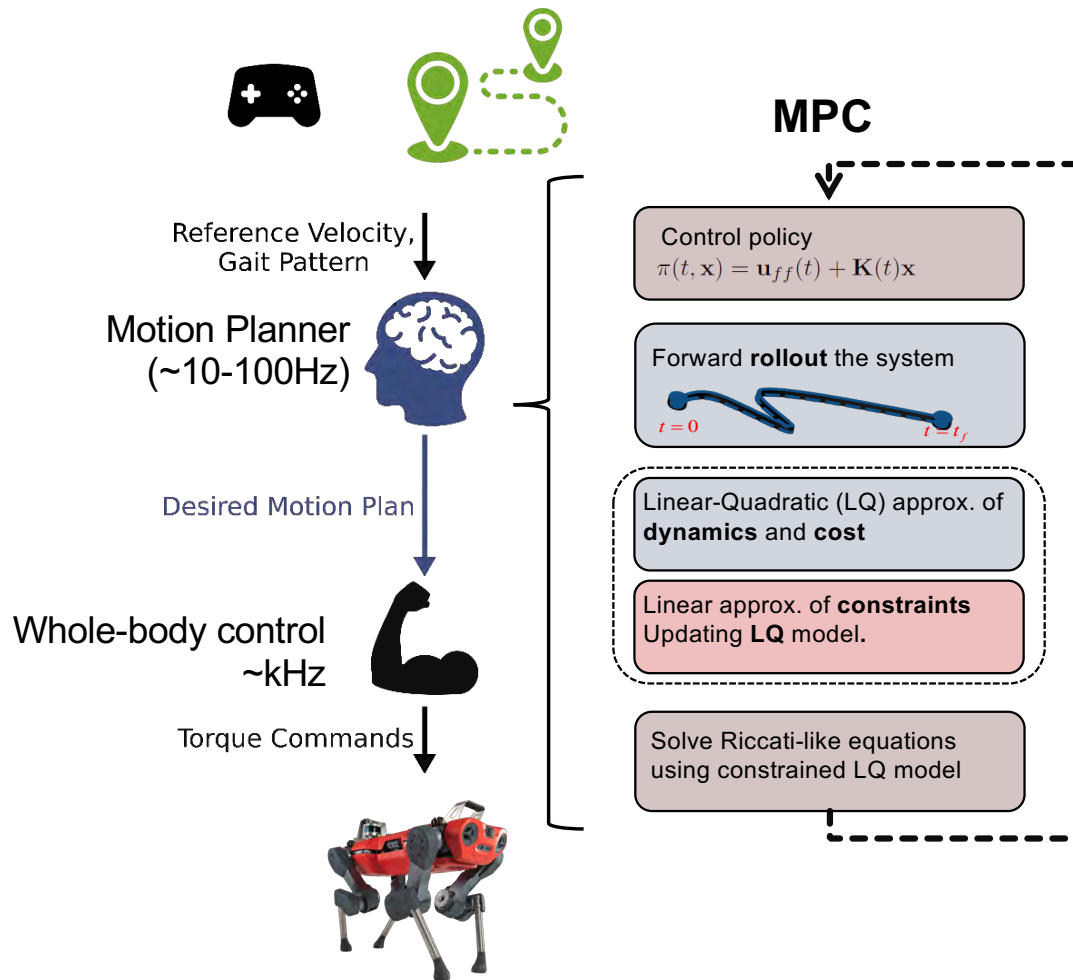
Control, Planning and Autonomy for Legged Robots



Control, Planning and Autonomy for Legged Robots



Control, Planning and Autonomy for Legged Robots



Finite-Time Optimal Control Problem

$$\left\{ \begin{array}{l} \min_{\mathbf{u}(\cdot)} \Phi(\mathbf{x}(T)) + \int_0^T L(\mathbf{x}(t), \mathbf{u}(t), t) dt \\ \text{s.t. } \dot{\mathbf{x}}(t) = \mathbf{f}(\mathbf{x}(t), \mathbf{u}(t), t) \\ \mathbf{g}_1(\mathbf{x}(t), \mathbf{u}(t), t) = 0 \\ \mathbf{g}_2(\mathbf{x}(t), t) = 0 \\ \mathbf{h}(\mathbf{x}(t), \mathbf{u}(t), t) \geq 0 \\ \mathbf{x}(0) = \mathbf{x}_0, \end{array} \right.$$

Constrained DDP-based Algorithm (SLQ) [Farshidian 2017 IFAC]

<https://bitbucket.org/leggedrobotics/ocs2>

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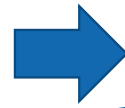
Locomotion as optimization problem

Source: youtube, video by Boston Dynamics, Talk by Scott Kuindersma



Legged robots work well on structured ground
... but they often have issues over compliant, slippery or moving terrain

- **Corner cases of model-based controllers**
- Underlying assumptions:
 - Contact only occurs at the feet
 - The terrain is static (and planar)



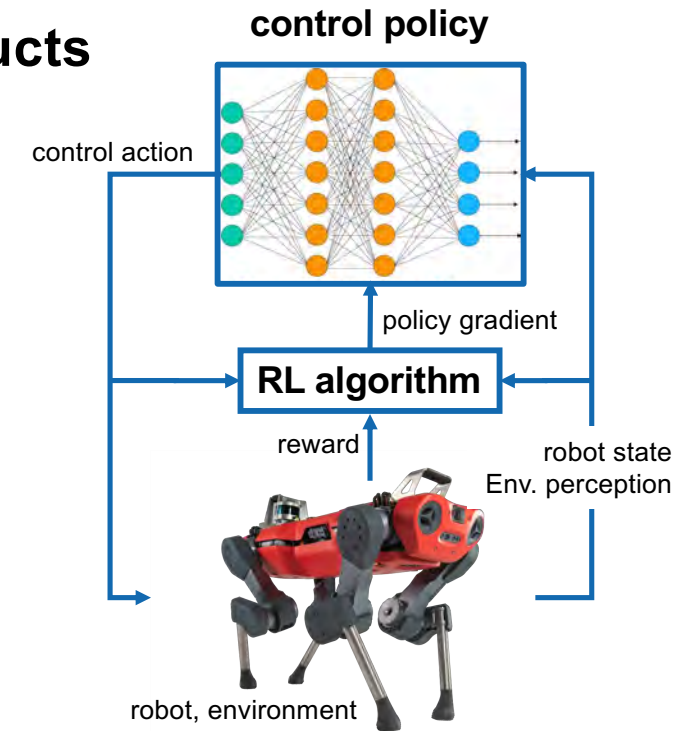
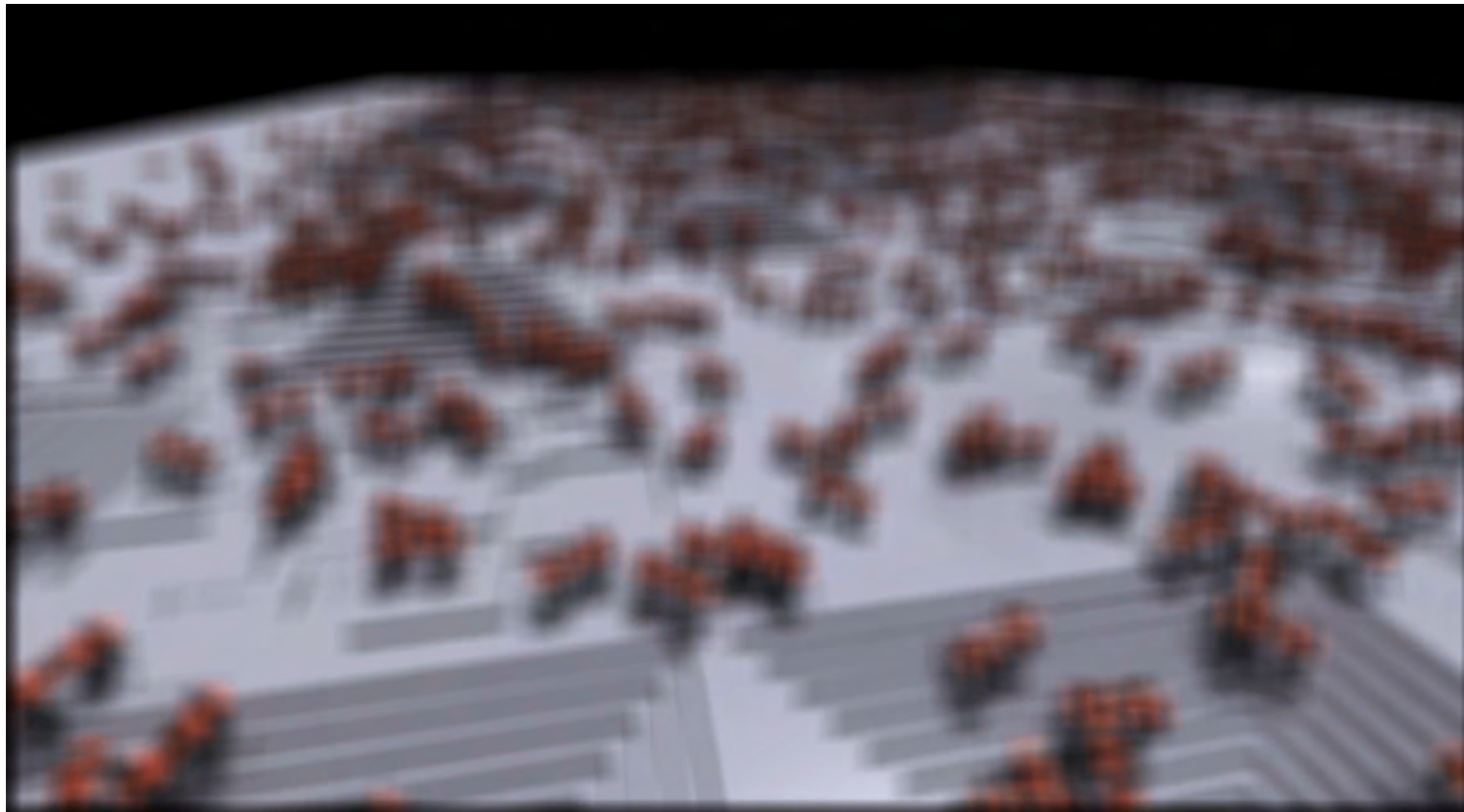
- Lots of handcrafted heuristics to compensate
 - Online disturbance observer and reaction
 - Slip detection and
 - Gait and frequency adaptation
 - Regain contacts...

Could we not make the robot to learn all of this



ANYmal is (one of) the first RL-controlled robot products

- Learn from massive data generated with a fast and accurate simulator



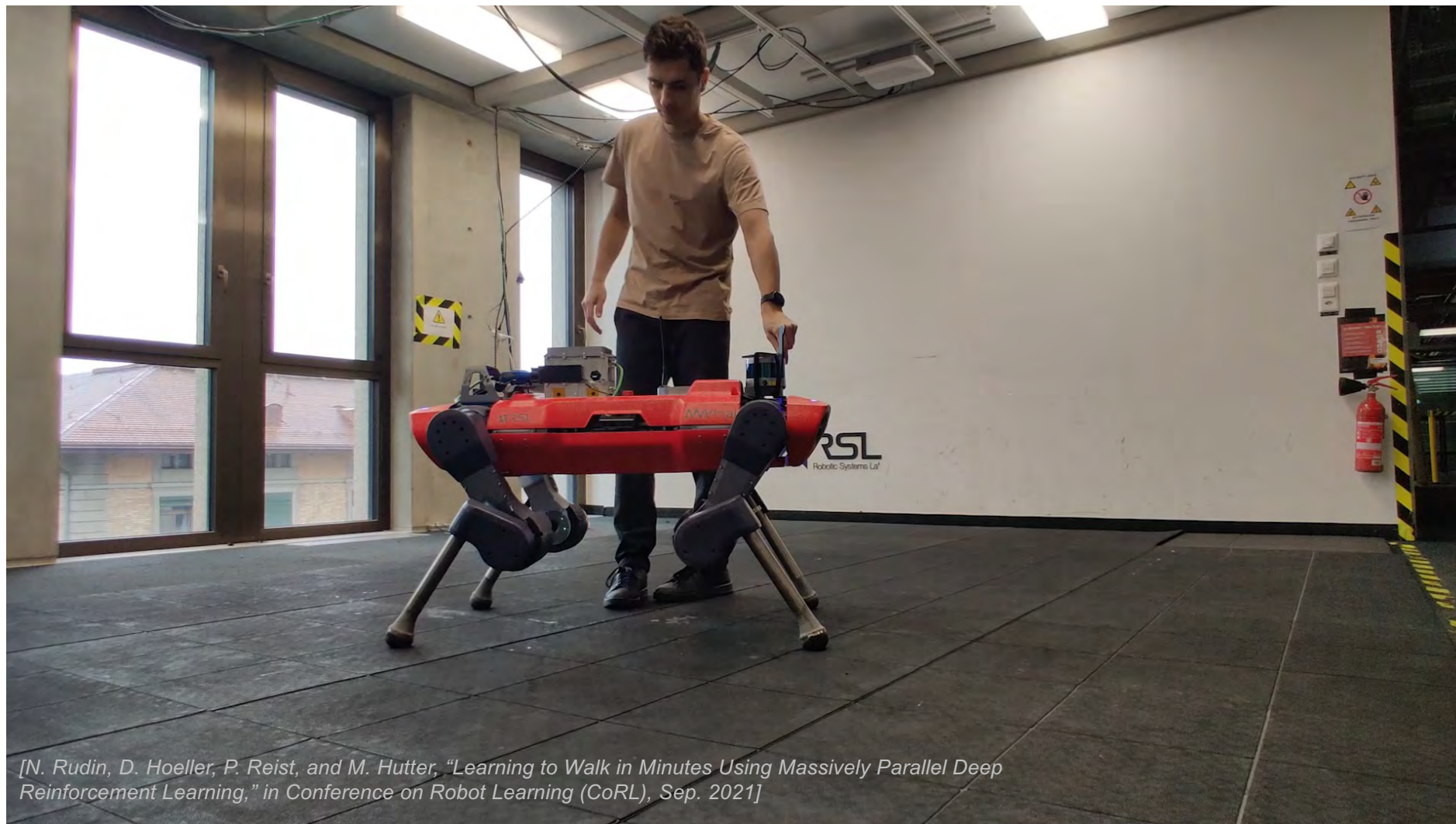
What makes this work in real:

- **Randomization**
- **Actuator modeling**
- **Privileged training**
- **Direct perception observation**
- ...

ANYmal is (one of) the first RL-controlled robot product

Every sequence:

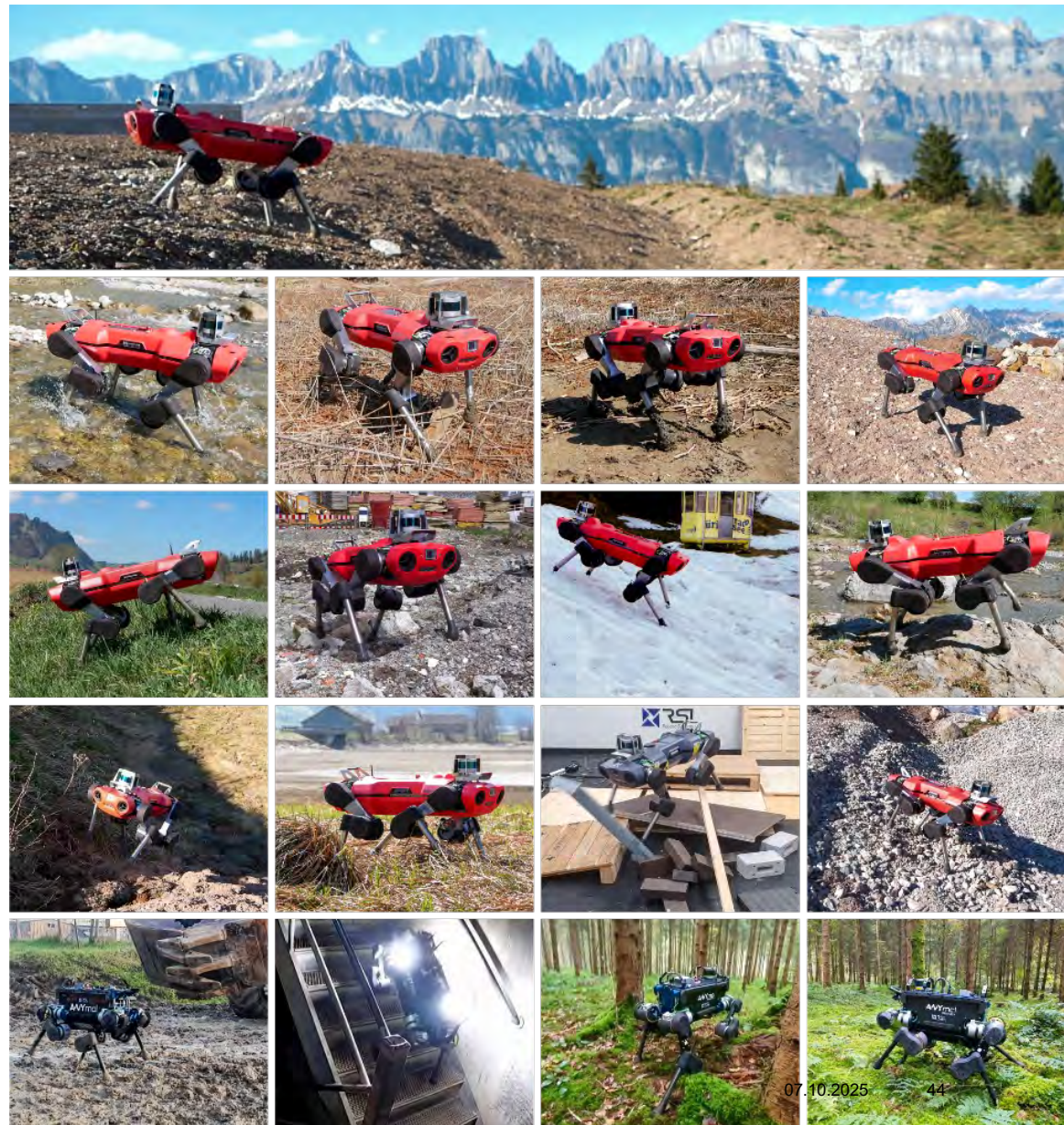
- 15 policy iterations
- ~1.5M steps
- ~8.3 hours of simulated time



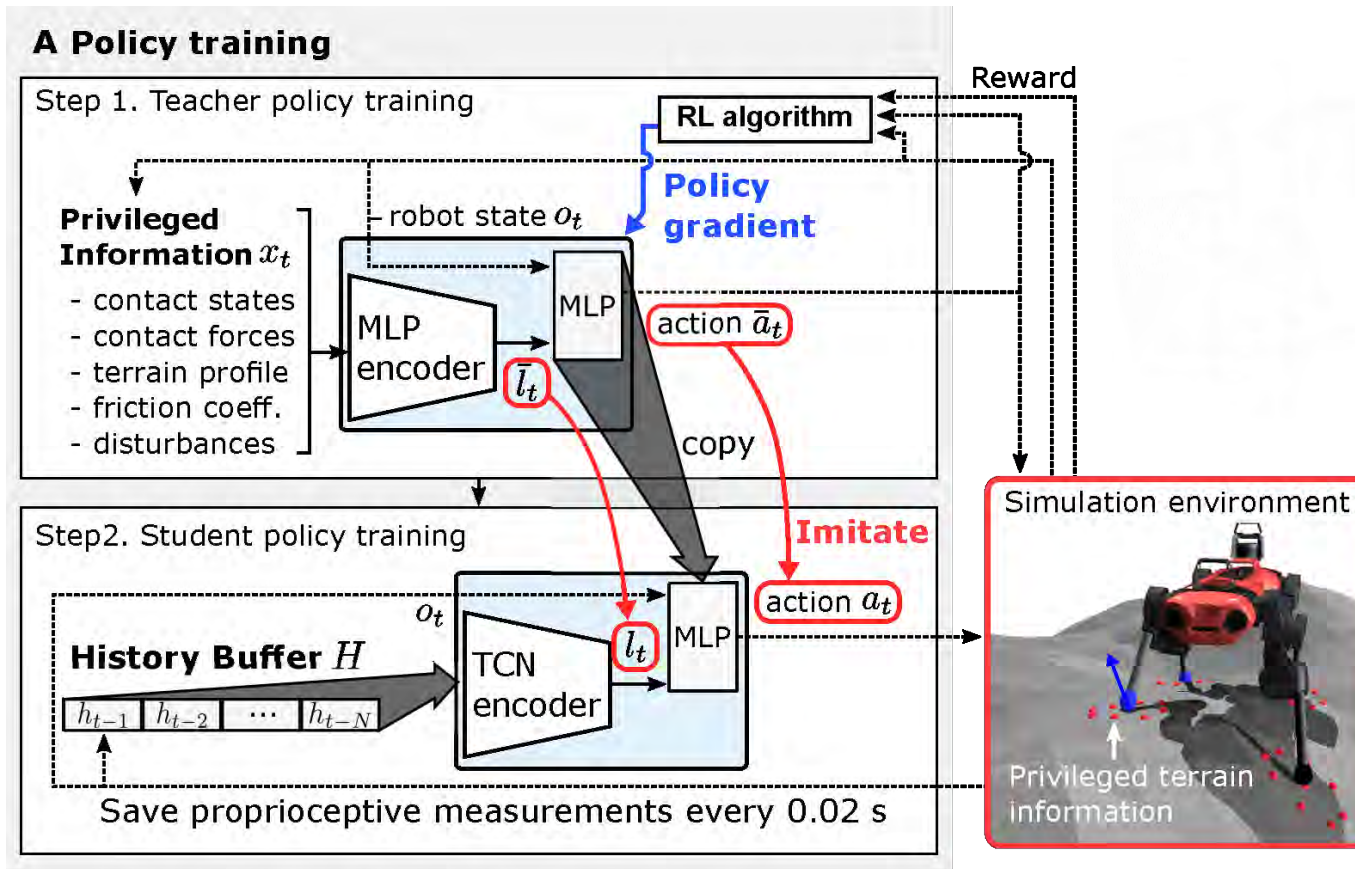
[N. Rudin, D. Hoeller, P. Reist, and M. Hutter, "Learning to Walk in Minutes Using Massively Parallel Deep Reinforcement Learning," in Conference on Robot Learning (CoRL), Sep. 2021]

Real World Deployment

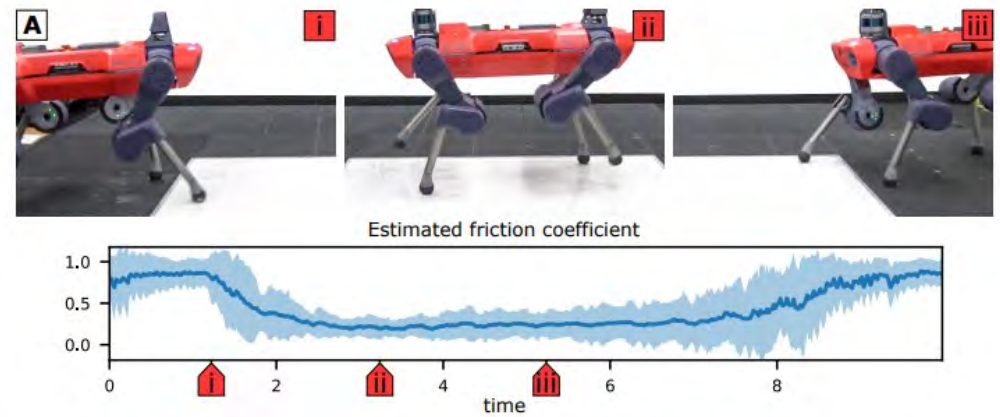
- Large variations in terrain in reality
 - Impossible to model in simulation
 - Hard to sense from perception
- What's important for locomotion



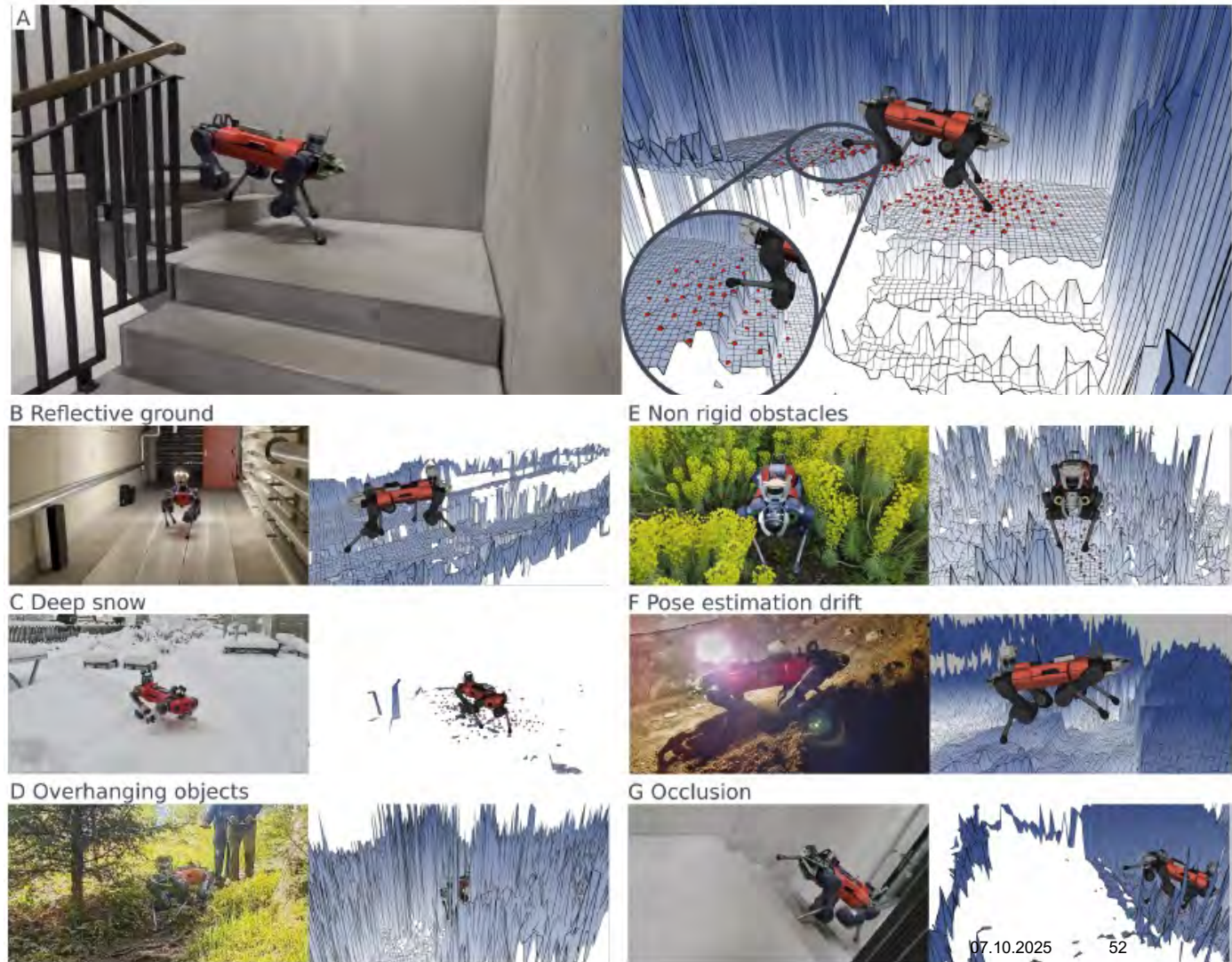
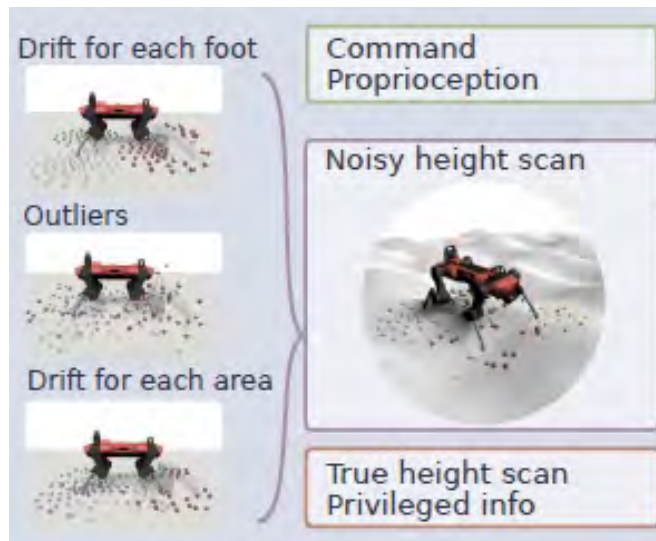
Method: privileged training



Friction estimation



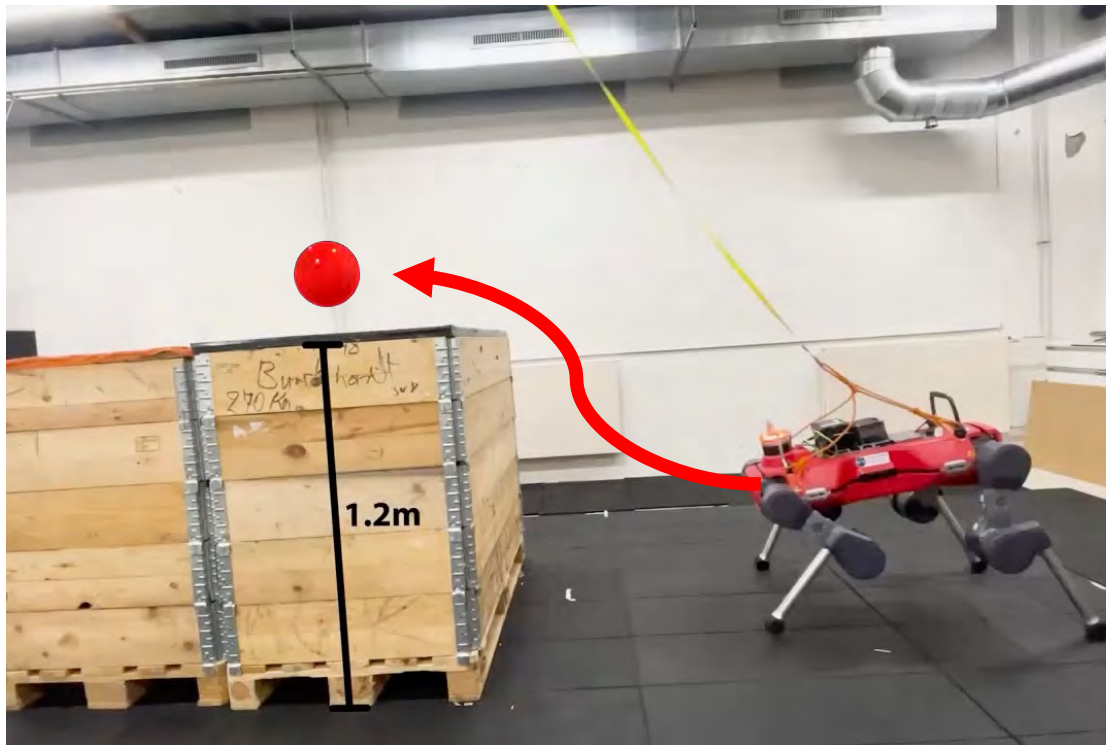
Learning-based locomotion including perception



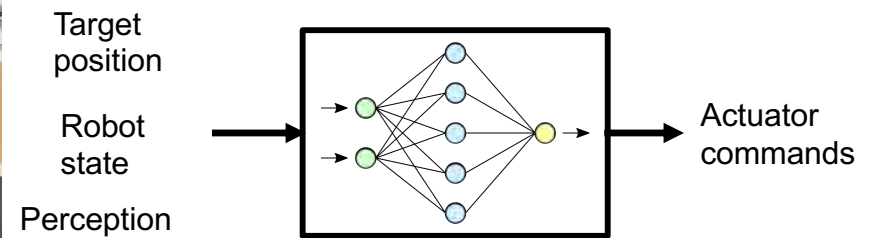




Avoid human guidance - Let the robot figure out how to move

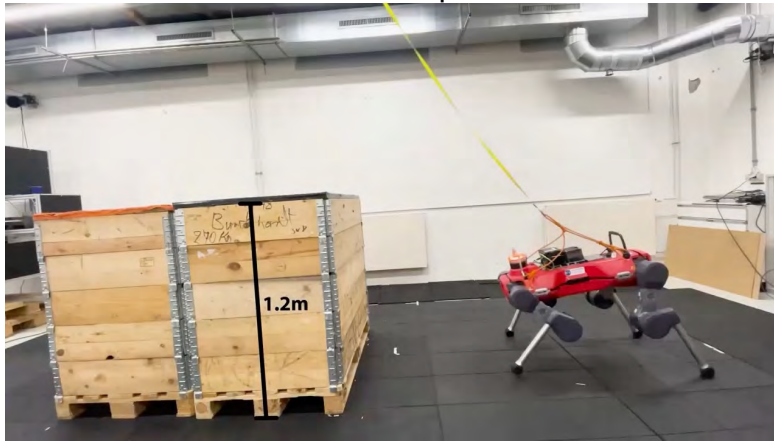


[D. Hoeller, N. Rudin, E. Sako, M. Hutter,
ANYmal parkour: Learning agile navigation for quadrupedal robots.
*Sci. Robot.*9,eadi7566(2024).]

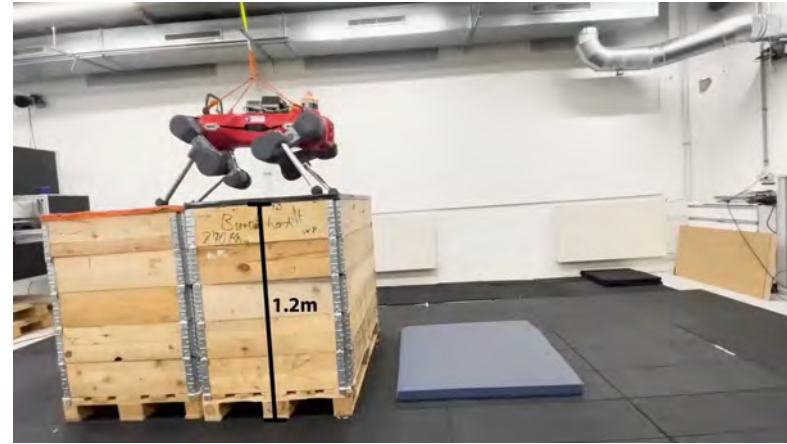


Locomotion Module

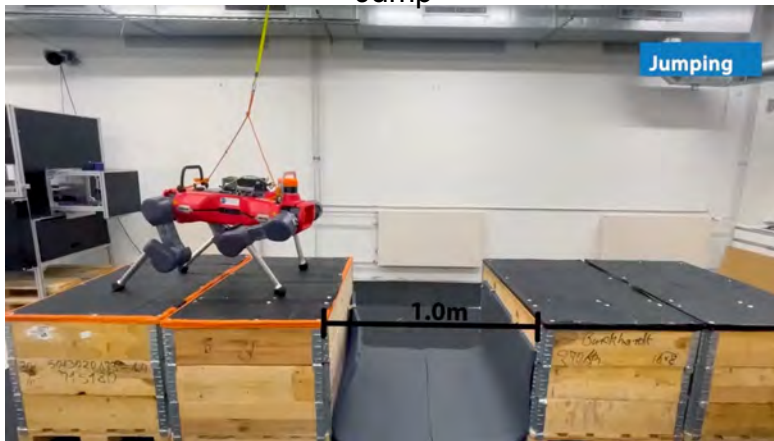
Climb up



Climb down



Jump

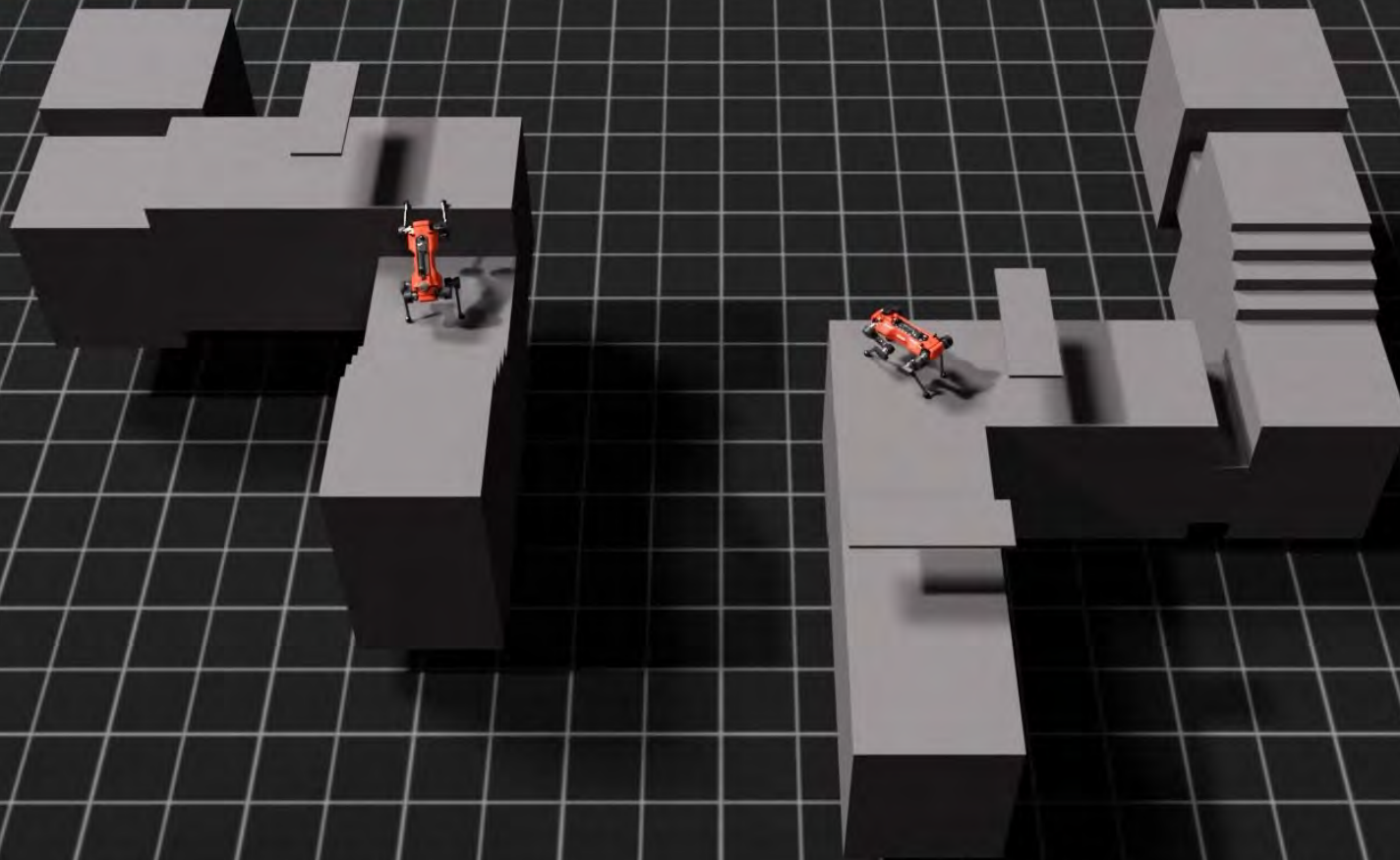


Crouch





Training in Simulation



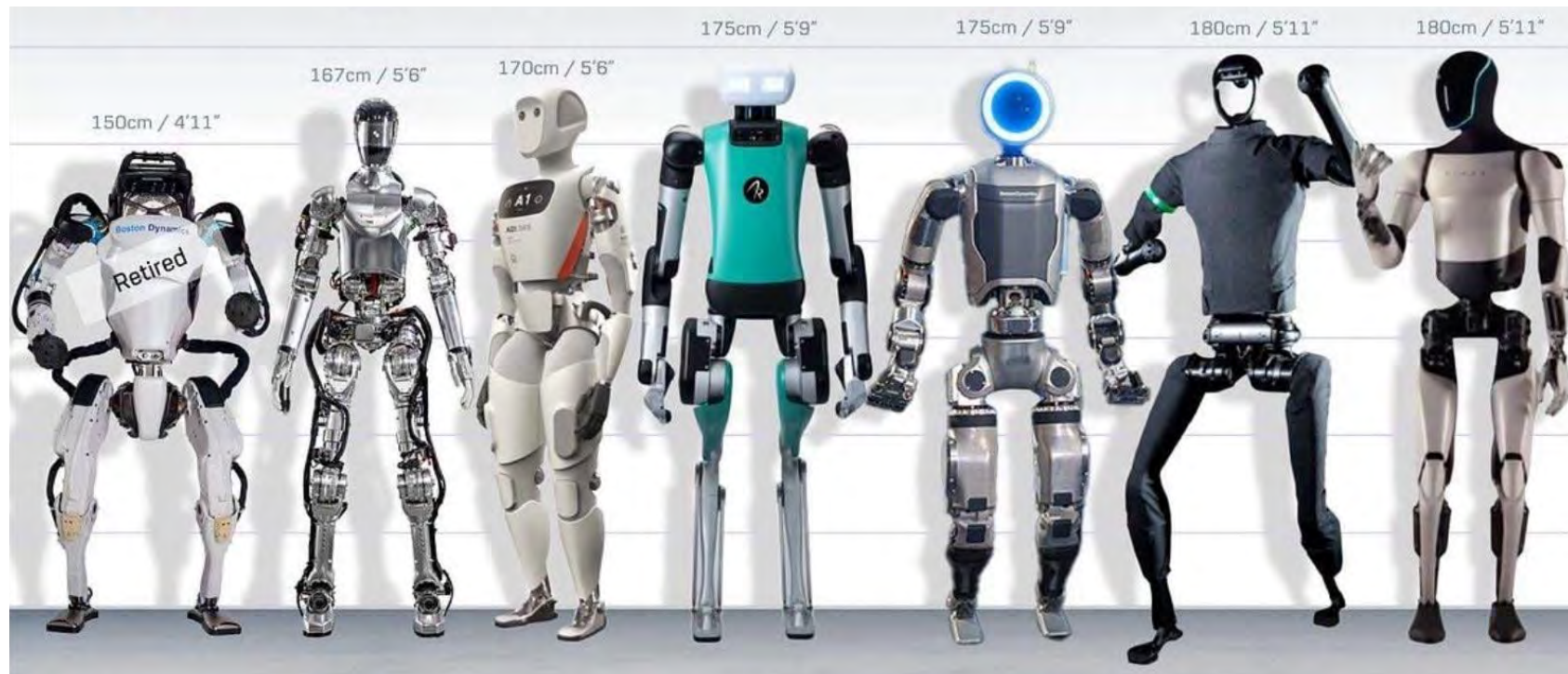




- Onboard sensing only
- No handcrafting
- No a priori knowledge of the environment











Part 3: Navigation



ANYmal perception

Velodyne Lidar



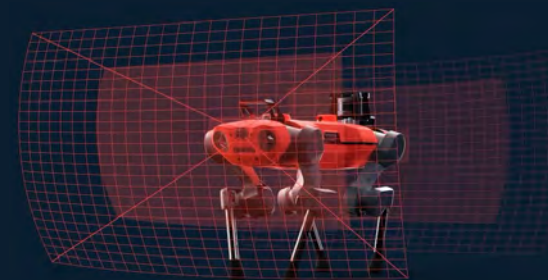
RTK GPS



4-6x active stereo

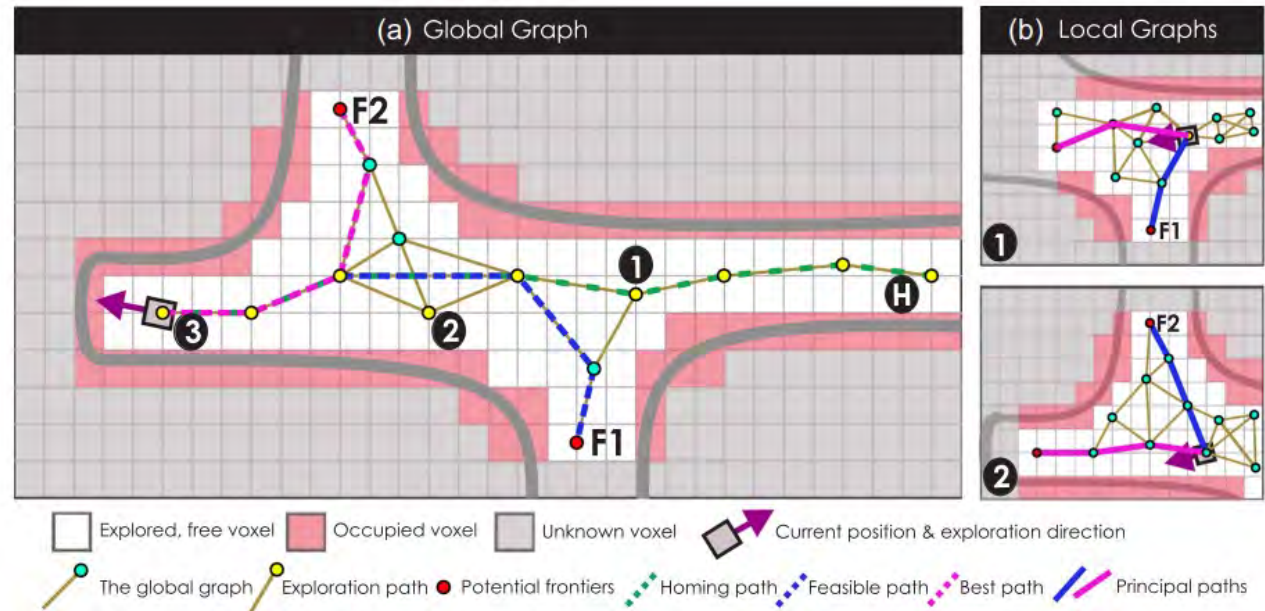
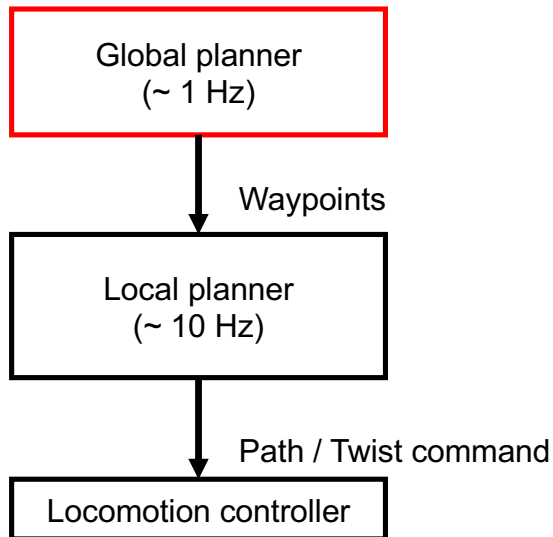


2 x RGB wide angle



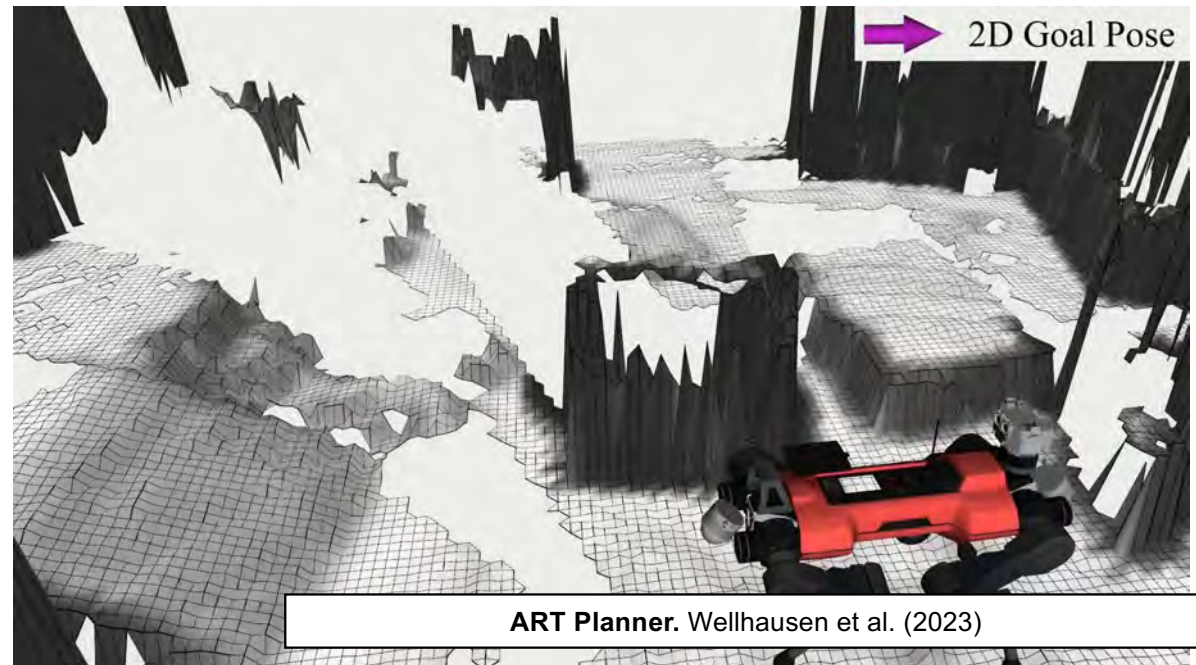
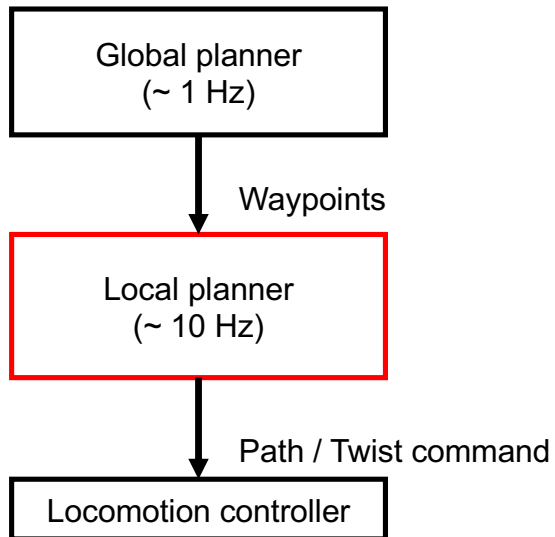
Conventional approach

Planning assumes static environment

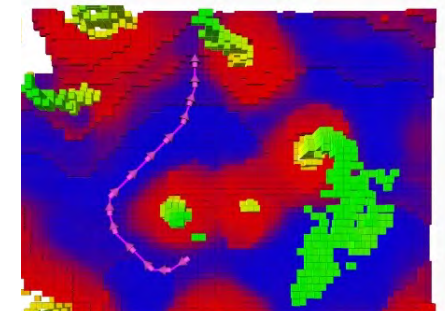
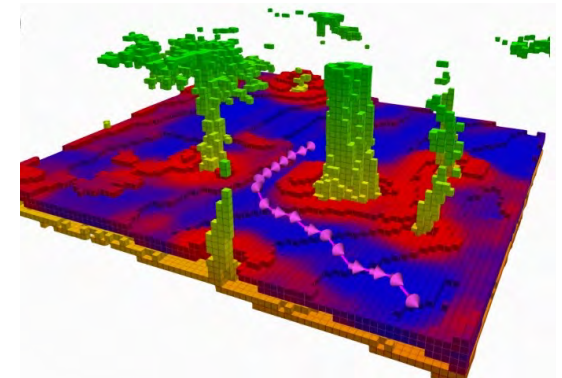
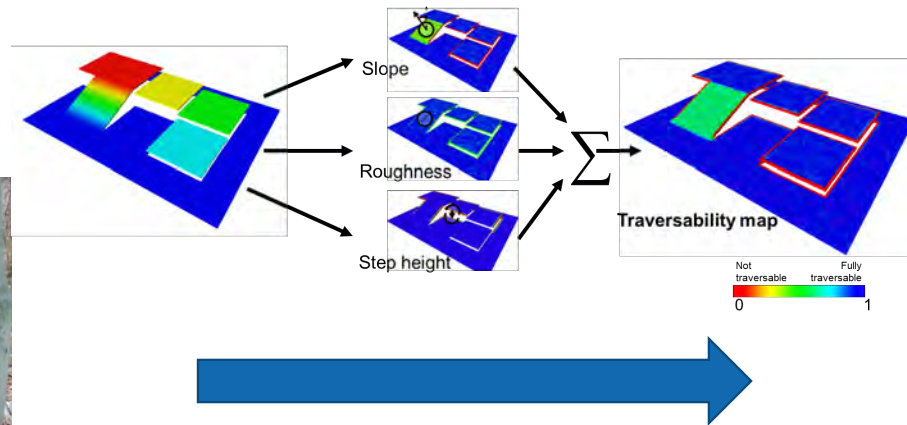


Conventional approach

Planning assumes static environment

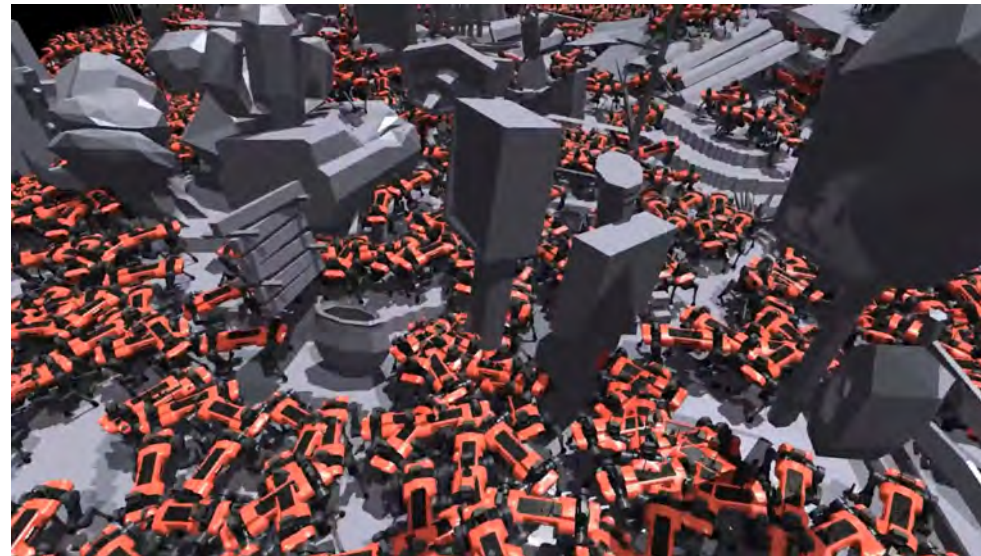
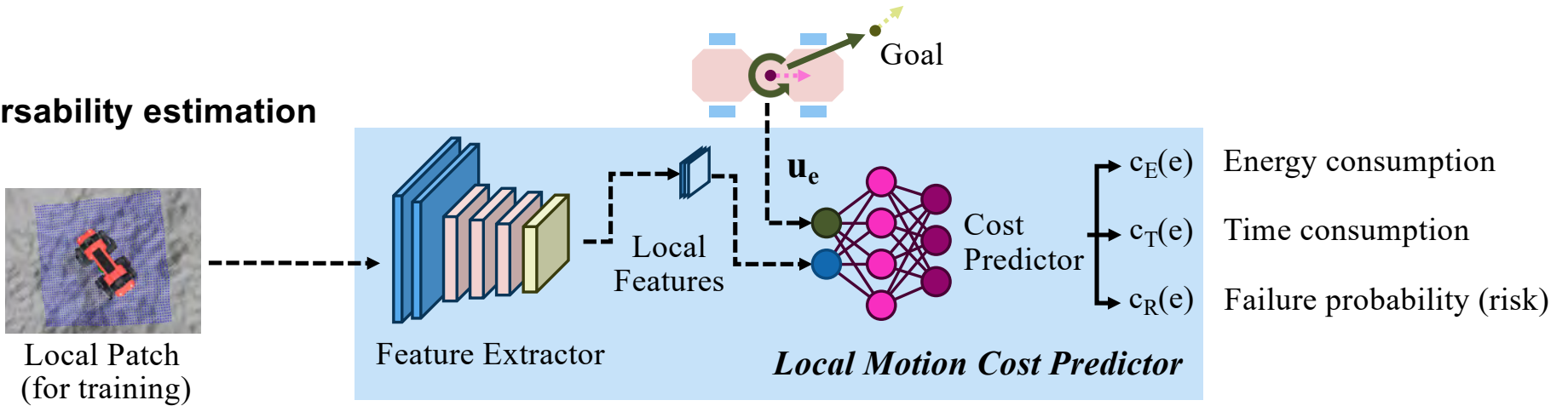


Traversability estimation and navigation

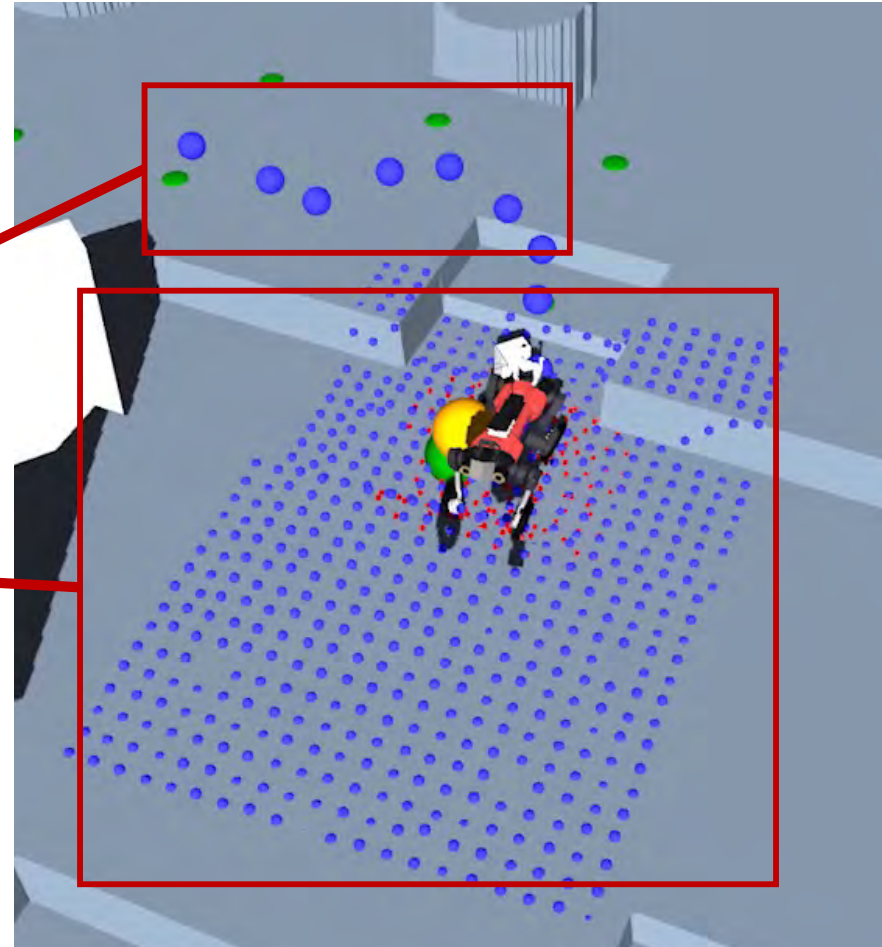
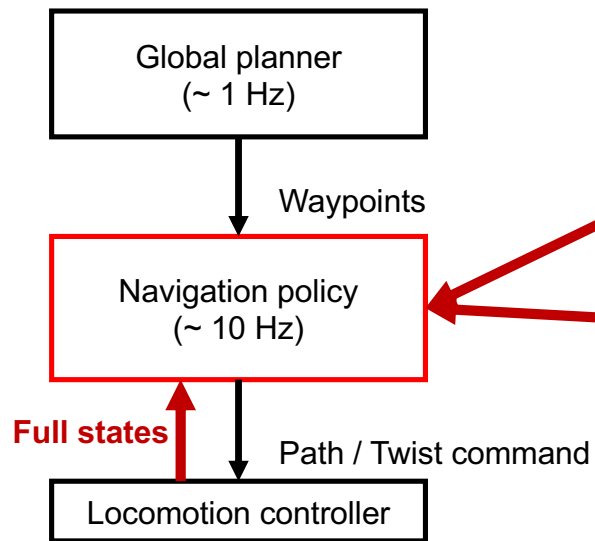


Finding the right local path

- Traversability estimation



Learned Navigation Policy

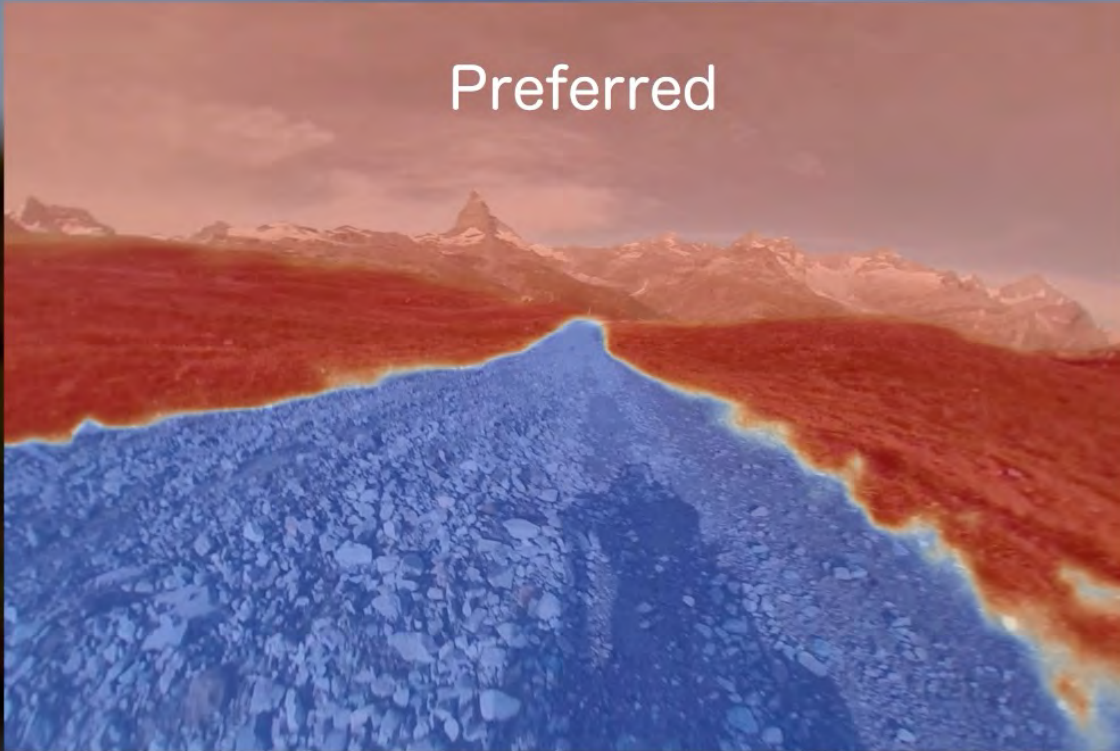


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onboard image

Preferred



The robot should continue to follow the gravel path.

Label	Risk	Preferred
gravel_path	0.2	1.0
grass	0.4	0.0
people	1.0	0.0
...		

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Part 4: Applications

DARPA SubT Challenge (2019-2021)

Mobile robots for challenging environments

Goal: map, navigate, search, and explore complex underground environments



TUNNEL SYSTEMS

Tunnels can extend many kilometers in length with constrained passages, vertical shafts, and multiple levels.



URBAN UNDERGROUND

Urban underground environments can have complex layouts with multiple stories and span several city blocks.



CAVE NETWORKS

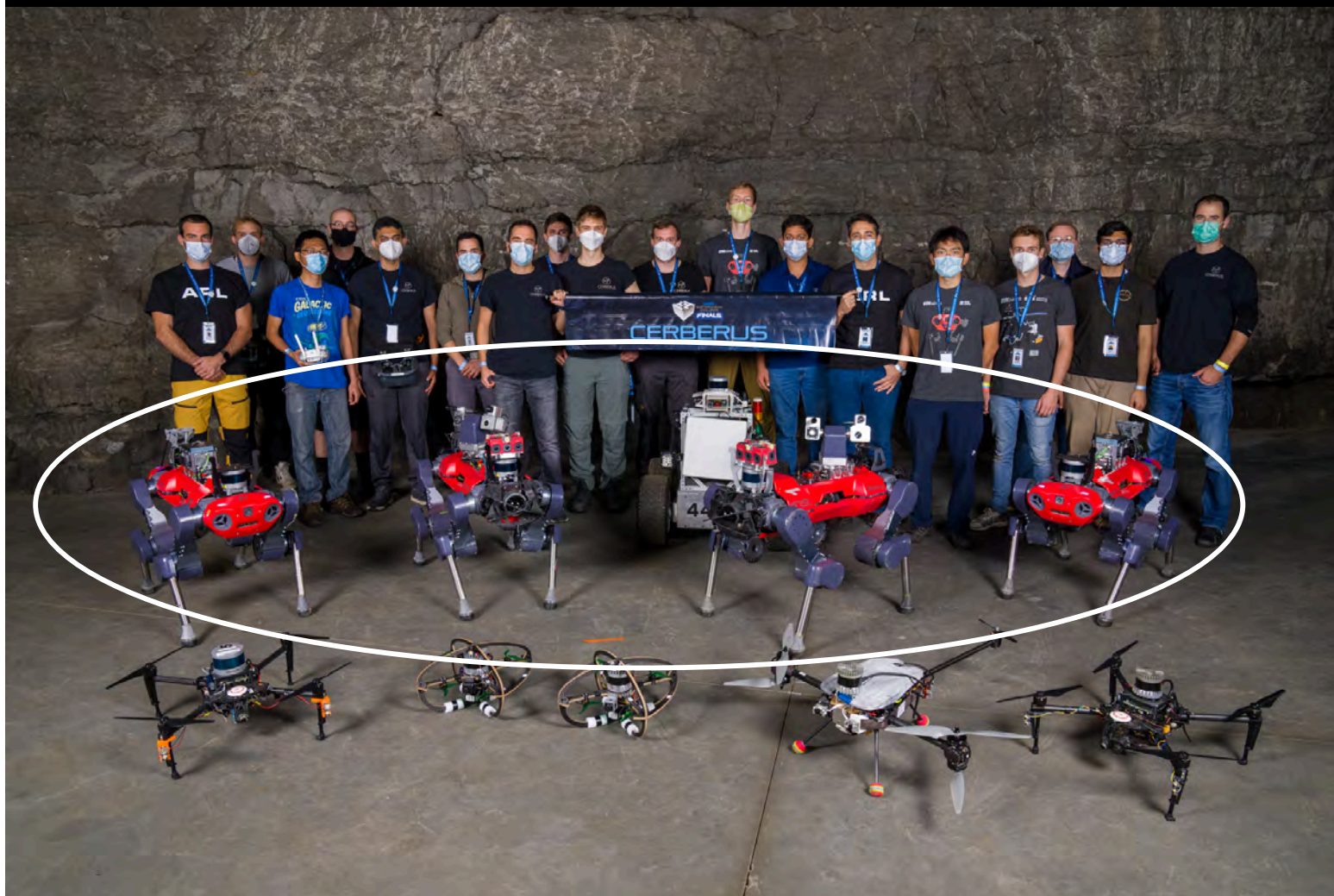
Natural cave networks often have irregular geological structures, with both constrained passages and large caverns.

Challenges:

- unstructured & unknown environment of different scale,
- rough and hardly traversable terrain,
- degraded perception,
- missing communication, ...



DARPA SubT Challenge – Mobile robots for challenging environments



Team CERBERUS

At Finals:

ARL – UNR/NTNU

RSL – ETHZ

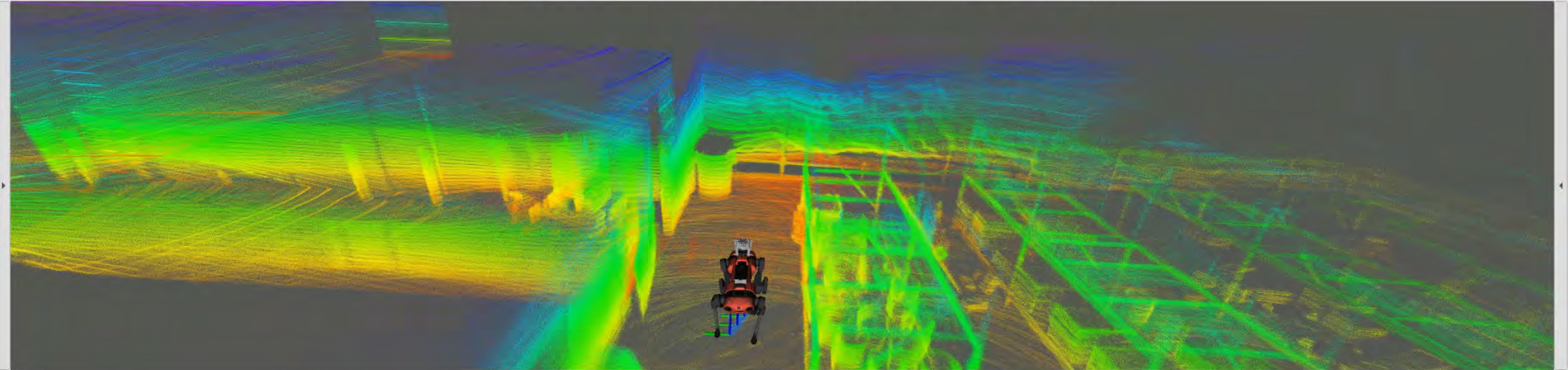
ASL – ETHZ

Other Contributors:

Oxford, Flyability, Berkeley, SNC







Reset

31 fps

Detection Camera Left

Detection Camera Front

Detection Camera Right

Detection Camera Upwards

Detection Camera Upwards

/tensorsrt_artifact [0] 10.00m [Gray] [Smooth scaling] [0°]

/tensorsrt_artifact_det [0] 10.00m [Gray] [Smooth scaling] [0°]

/tensorsrt_artifact_det [0] 10.00m [Gray] [Smooth scaling] [0°]

/tensorsrt_artifact_det [0] 10.00m [Gray] [Smooth scaling] [0°]



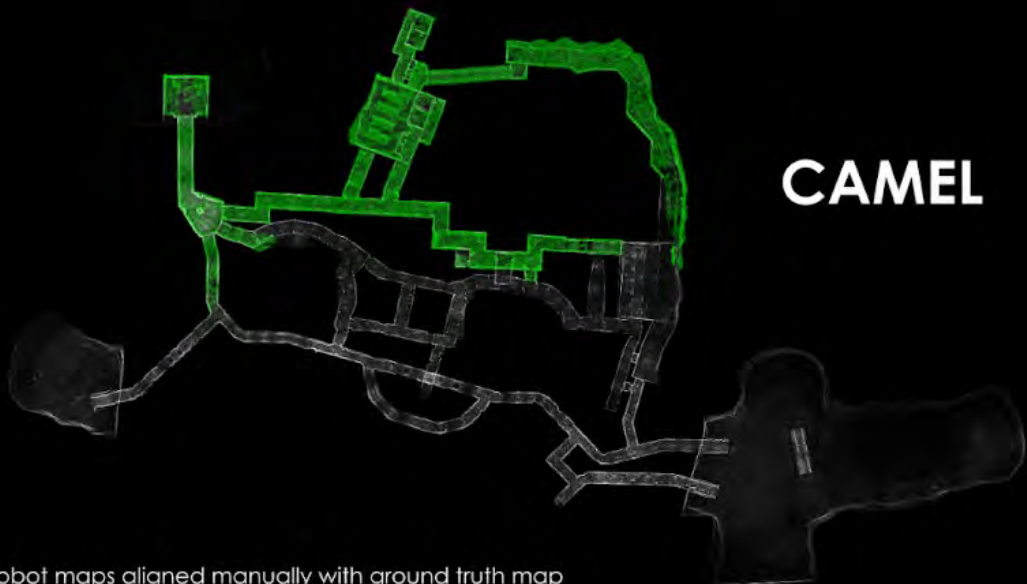
CHIMERA



CERBERUS



CAMEL



CAIMAN



* Robot maps aligned manually with ground truth map



CERBERUS

Ground Truth

CHIMERA

CERBERUS

CAMEL

CAIMAN



Team CERBERUS DARPA Subterranean Challenge Final Event
Winning Prize Run

We are on the verge of the next robotic revolution

AUTONOMOUS INDUSTRY

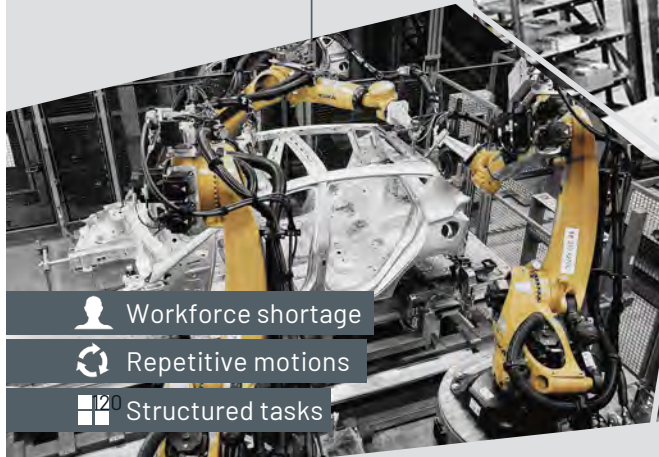
Enabled by autonomous mobile robots

SMART WAREHOUSING

Enabled by 600'000 warehouse robots in operation

AUTOMATED MANUFACTURING

Enabled by 3 million industrial robots in operation



- Workforce shortage
- Repetitive motions
- Structured tasks



- Workforce shortage
- Repetitive tasks
- Structured environment



- Workforce shortage
- Repetitive work
- Structured problem
- Dangerous environment



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AMVbotics

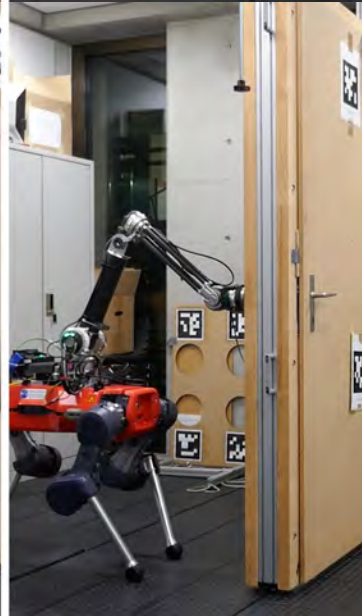
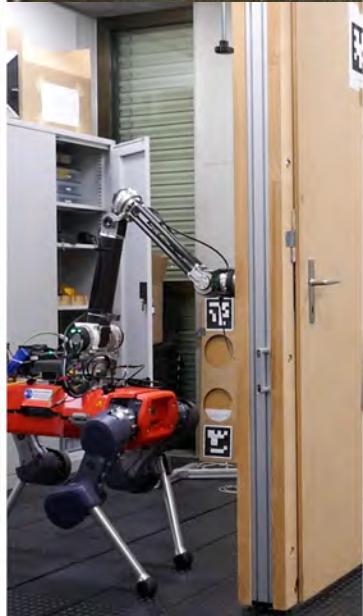
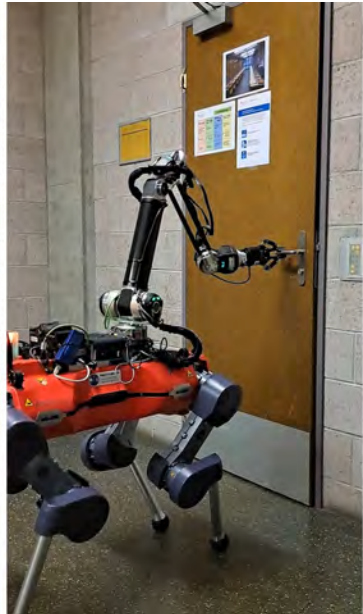
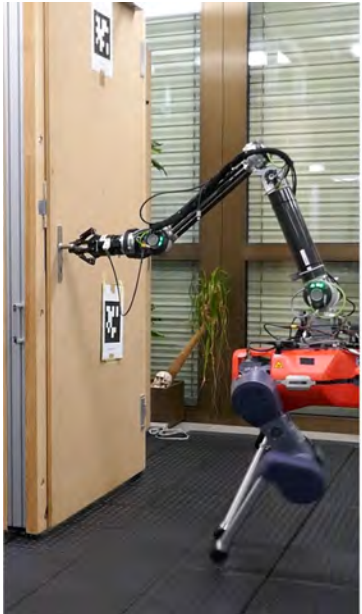


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Industrial plant inspection



- ✓ Periodic condition monitoring and hazard detection of equipment
- ✓ Remote sensing from control room





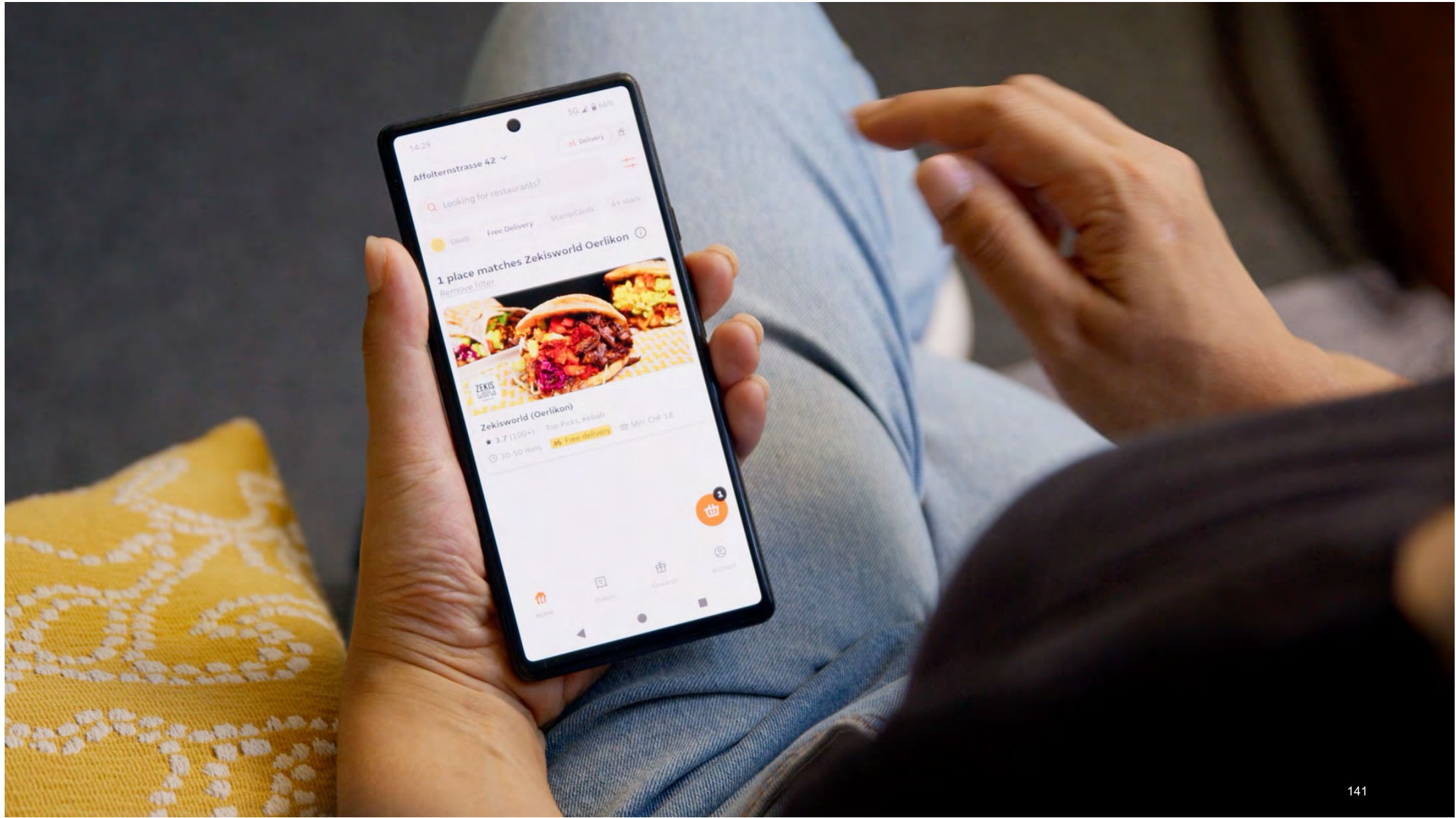


versatility + mobility



efficiency





ETH zürich



**Lunar
Leaper**



Lunar Leaper 1 Exploring Lava Tubes on the Moon



Thank you

Robotic Systems Lab
www.rsl.ethz.ch
[@leggedrobotics](https://twitter.com/leggedrobotics)

ETH startups:
ANYbotics
RIVR
Gravis Robotics
Duatic
Flexion

and the **RAI Institute**



Possible exam questions

- Sketch a typical framework required to enable a legged robot to autonomously navigate unknown environments. List the most important building blocks.
- What type of sensors are often used on legged robots and what are they used for?
- Provide different abstraction levels for legged robots. What is this useful for?
- Motion planning for legged systems is a hybrid problem. What is a hybrid problem? What are possible approaches to solve it?
- What is the reality gap and how could one overcome it?
- Reinforcement learning allows training a locomotion policy for legged robots. What are typical observations (i.e. input signals to the neural network) and actions (i.e. output signals of the neural network) for a robot that walks blindly (i.e. without lidar or camera sensors)?
- How can a robot identify, if a terrain is traversable?
- What are possible fields of application of legged robots?