Legged Robots @ ETH

EPFL, 2024

Marco Hutter
ETH Zurich and ANYbotics AG

29.10.2024


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

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

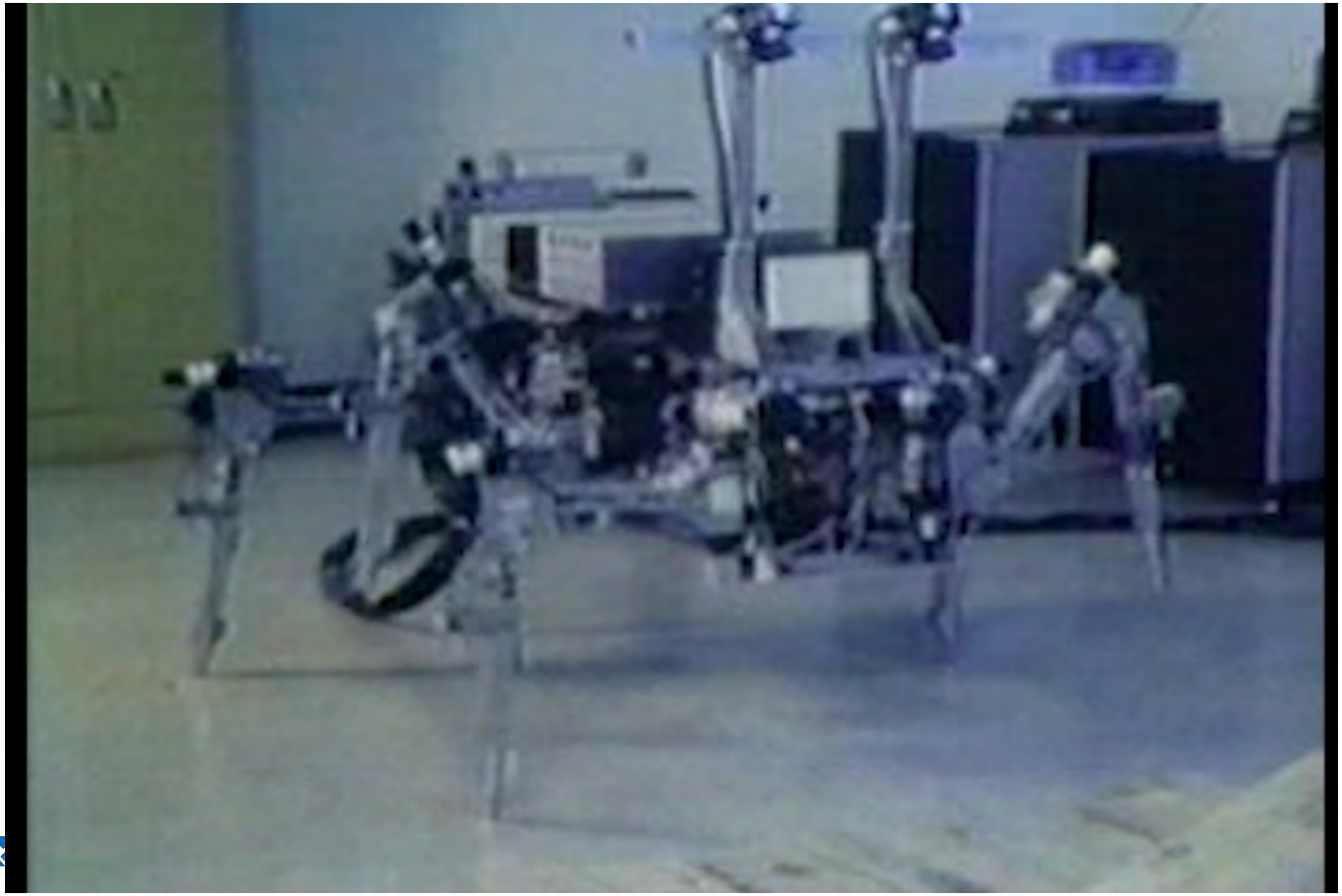
1. Quadrupeds
2. Control
3. Navigation
4. Applications
5. (if time) Future stuff

ETH zürich

Robotic Systems Lab

Part 1: RSL Quadrupeds

OSU walker, early 80ies



Raibert, Leg Lab, late 80ies


Boston Dynamics

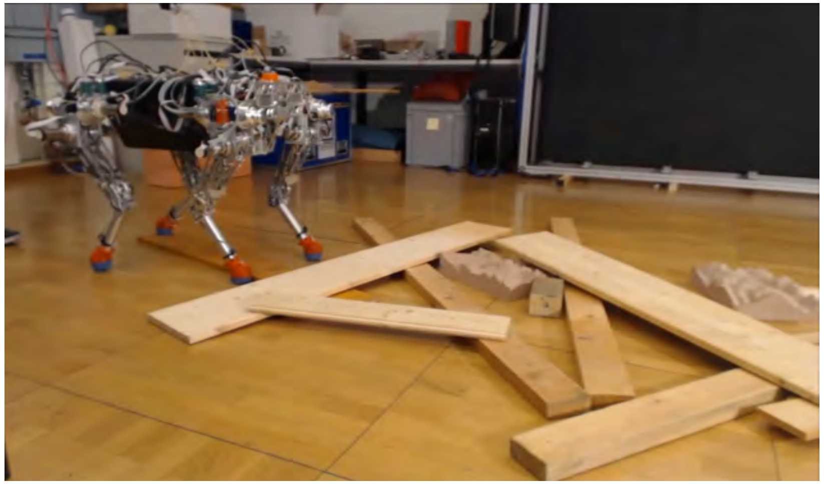
Legged (Quadruped) robots have become a commodity

From research prototypes to comercial products in 1 decade

2012

ETH Zurich - Robotic Systems Lab

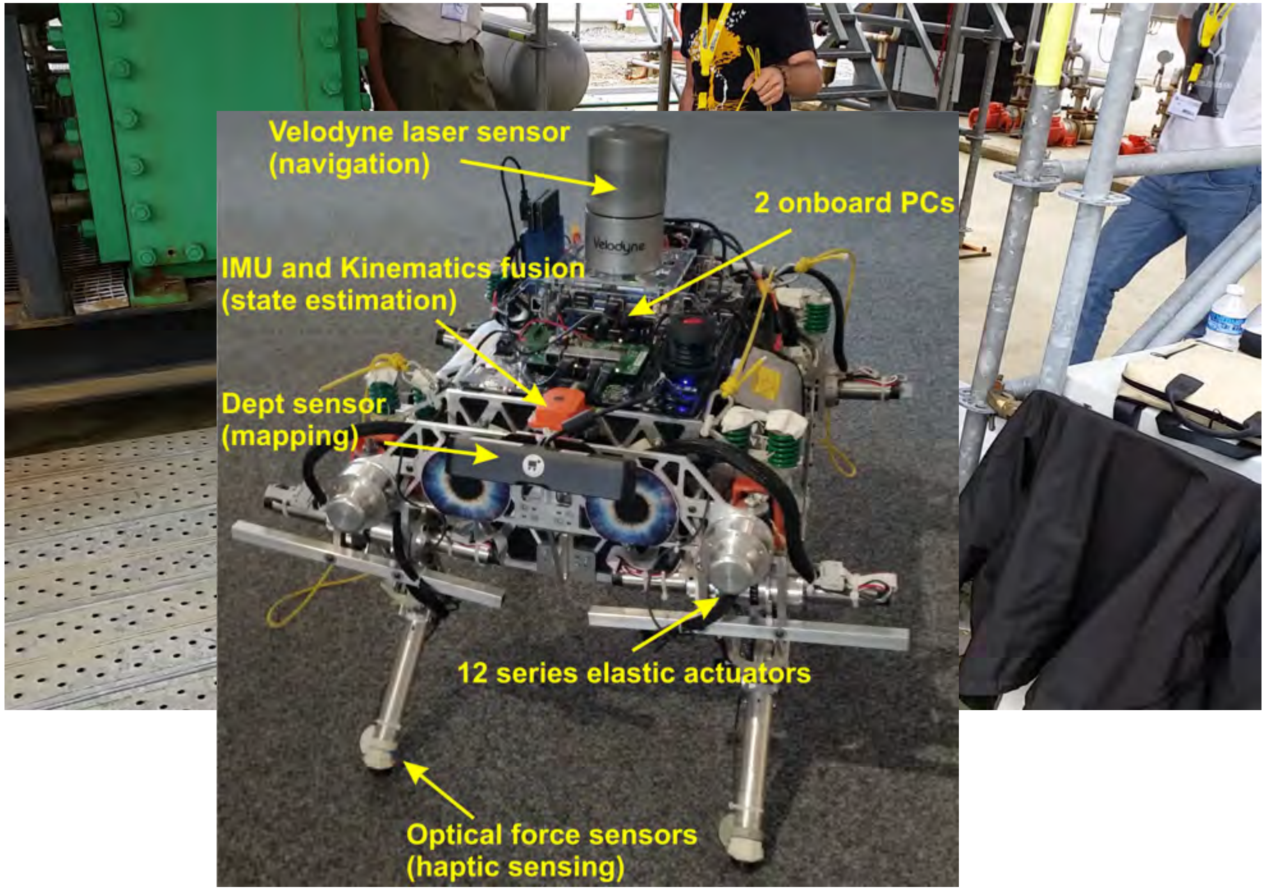
Research on autonomous robots



ARGOS – first field application of legged robots towards industrial inspection

- ARGOS competition 2013-2017

- 4 teams with classic tracked vehicles
- 1 team with a legged robot



From research prototypes to comercial products in 1 decade

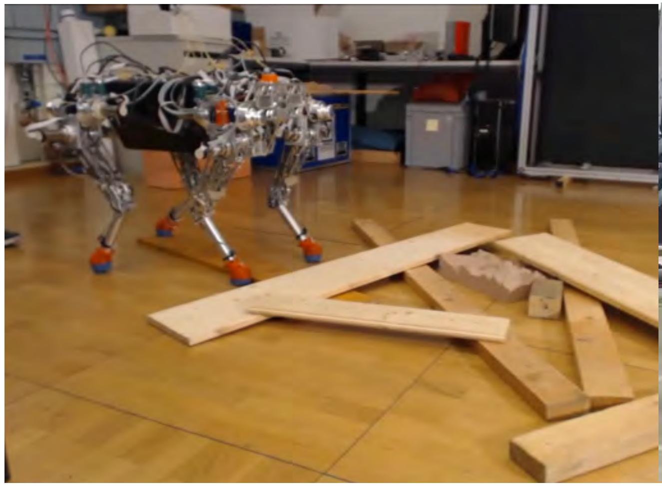
2012 2014 2016 2018 2019 2021 2022

ETH Zurich - Robotic Systems Lab

Research on autonomous robots

ANYbotics

founded 2016, >150 employees



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From research prototypes to comercial products in 1 decade

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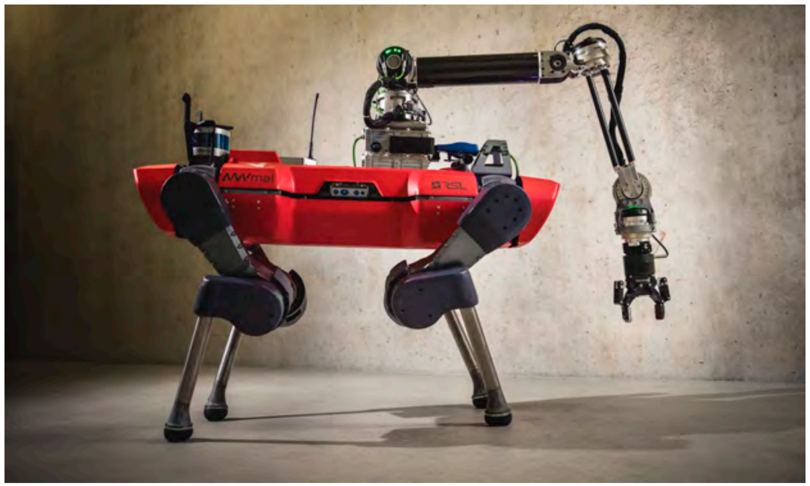


ETH zürich RSL Robotic Systems Lab

HARDWARE DEVELOPMENT //

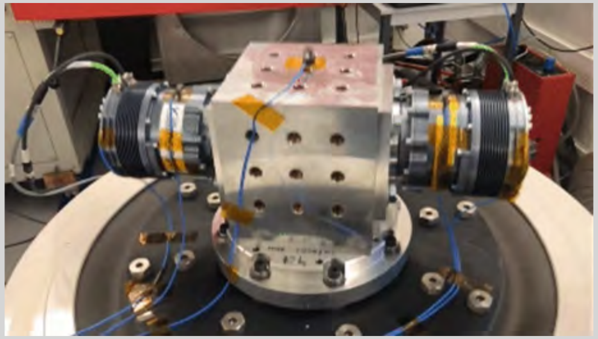
Specifications

- 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

HARDWARE DEVELOPMENT //

Design for reliability



Reliability

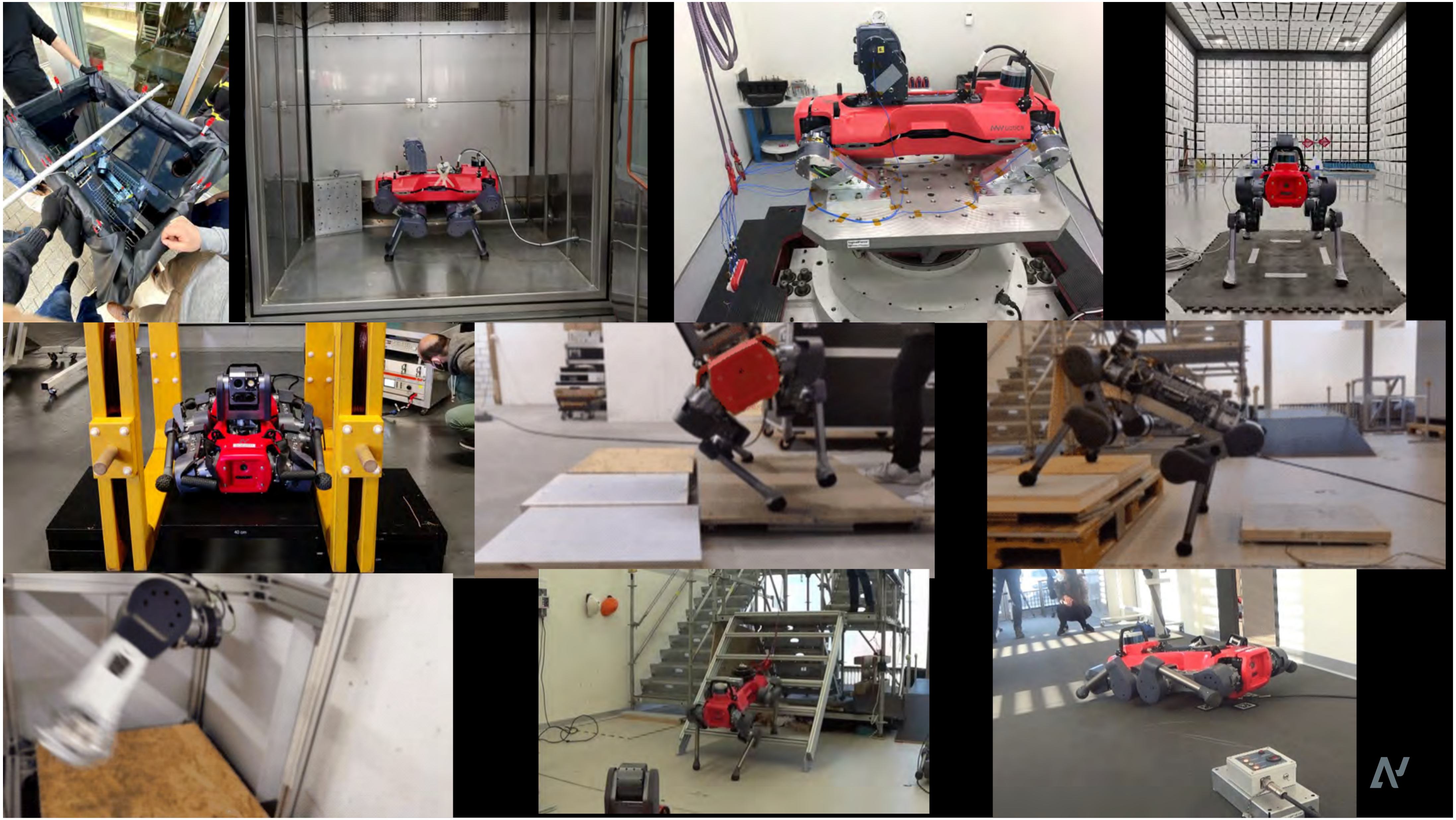
Large operating temperature ranges, thermal cycling, humidity exposure/cycling, vibration/shock, component lifetimes

Electromagnetic & radio compliance

Emissions, immunity, electrostatic discharge, radios

Environment

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




SRF news
Archiv

Part 2: Control

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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



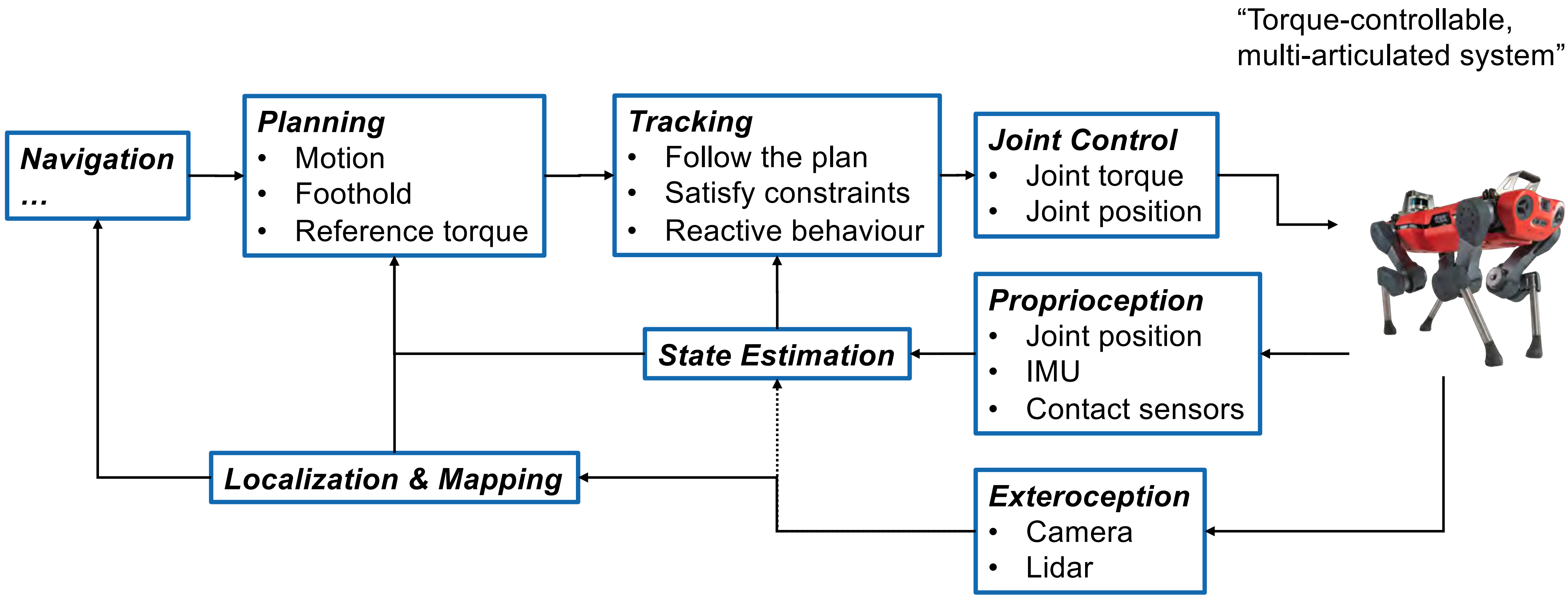



"Torque-controllable, multi-articulated system"

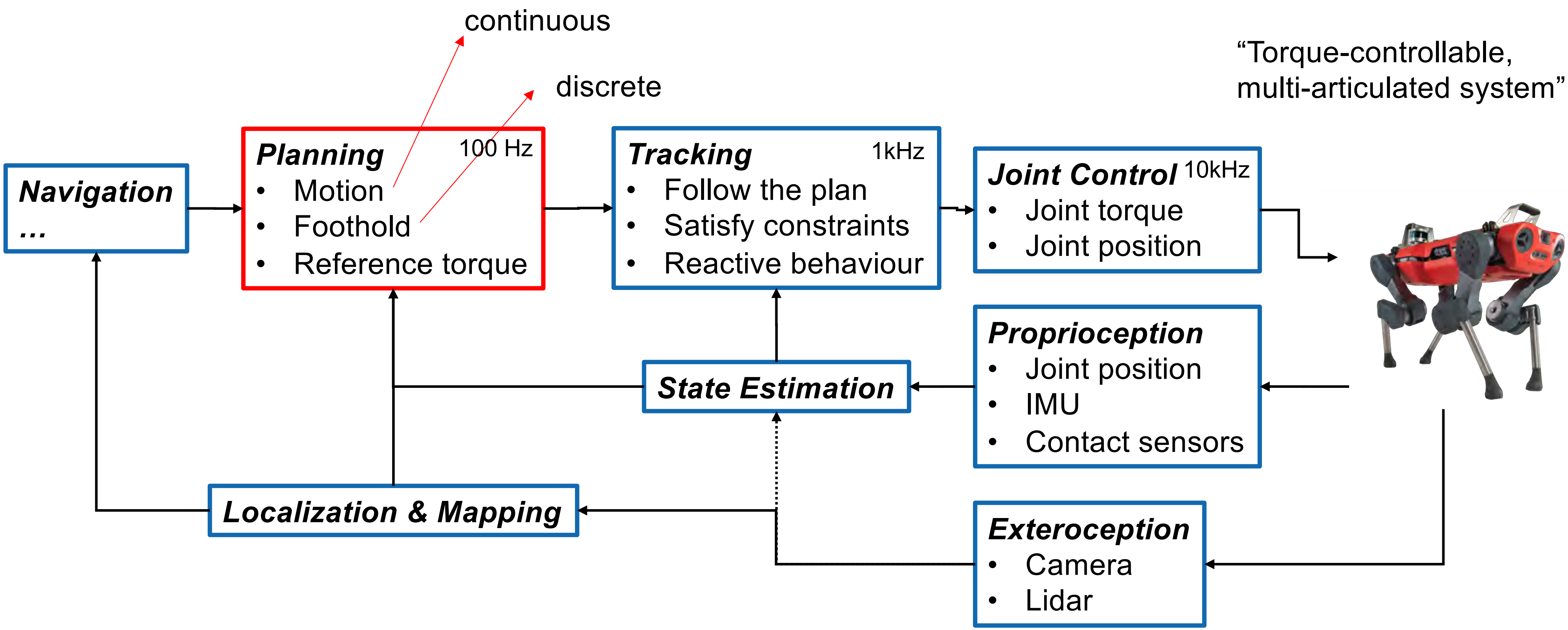
3. Hydra ure and/or load cell)



Control, Planning and Autonomy for Legged Robots



Control, Planning and Autonomy for Legged Robots



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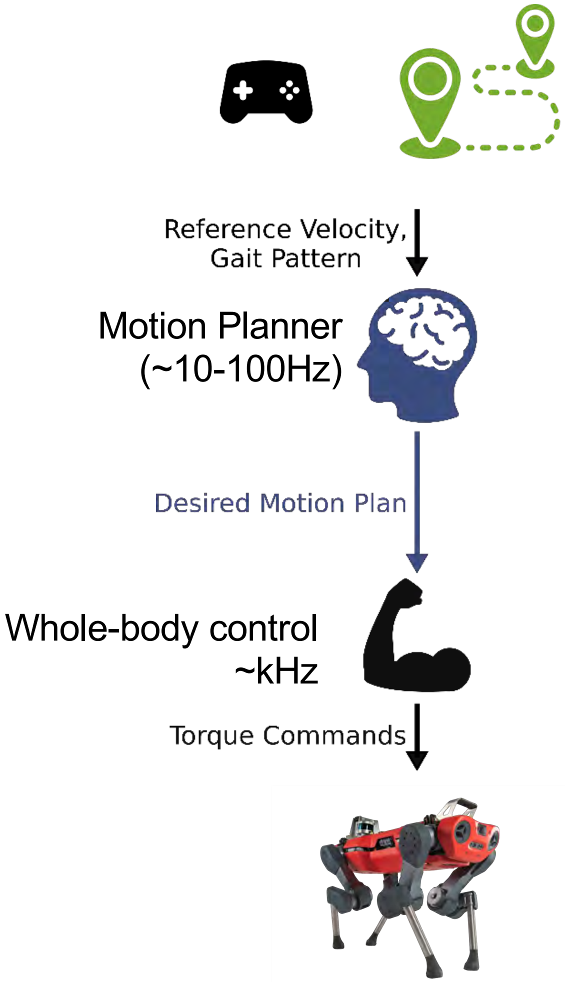

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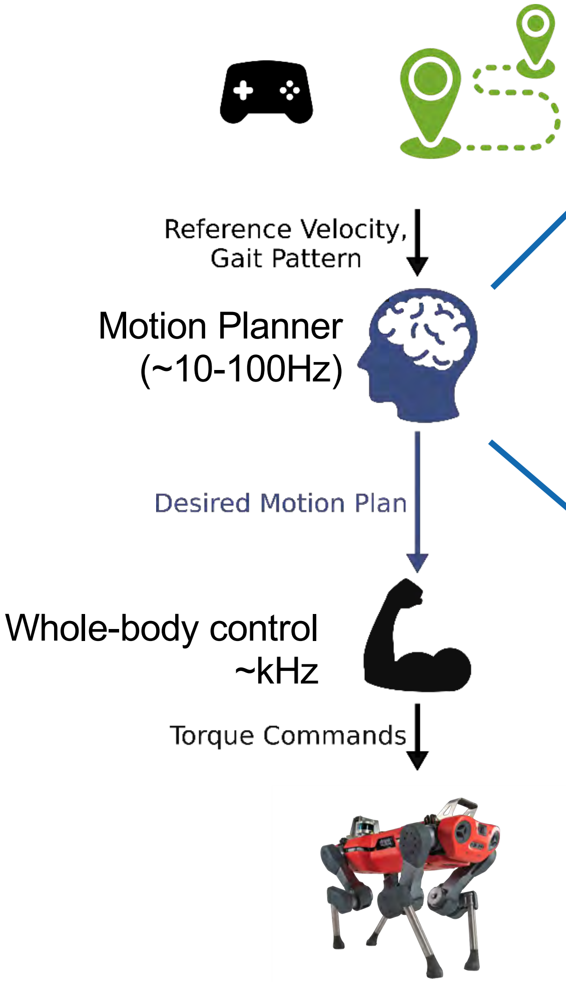

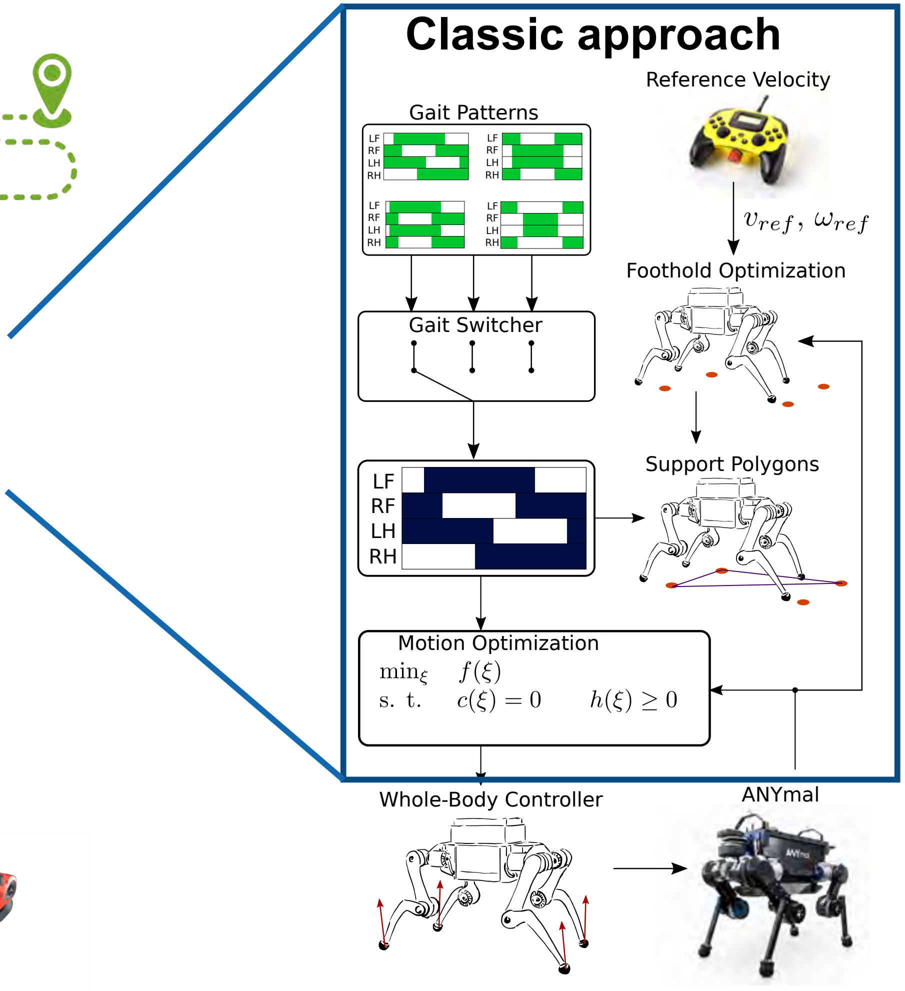

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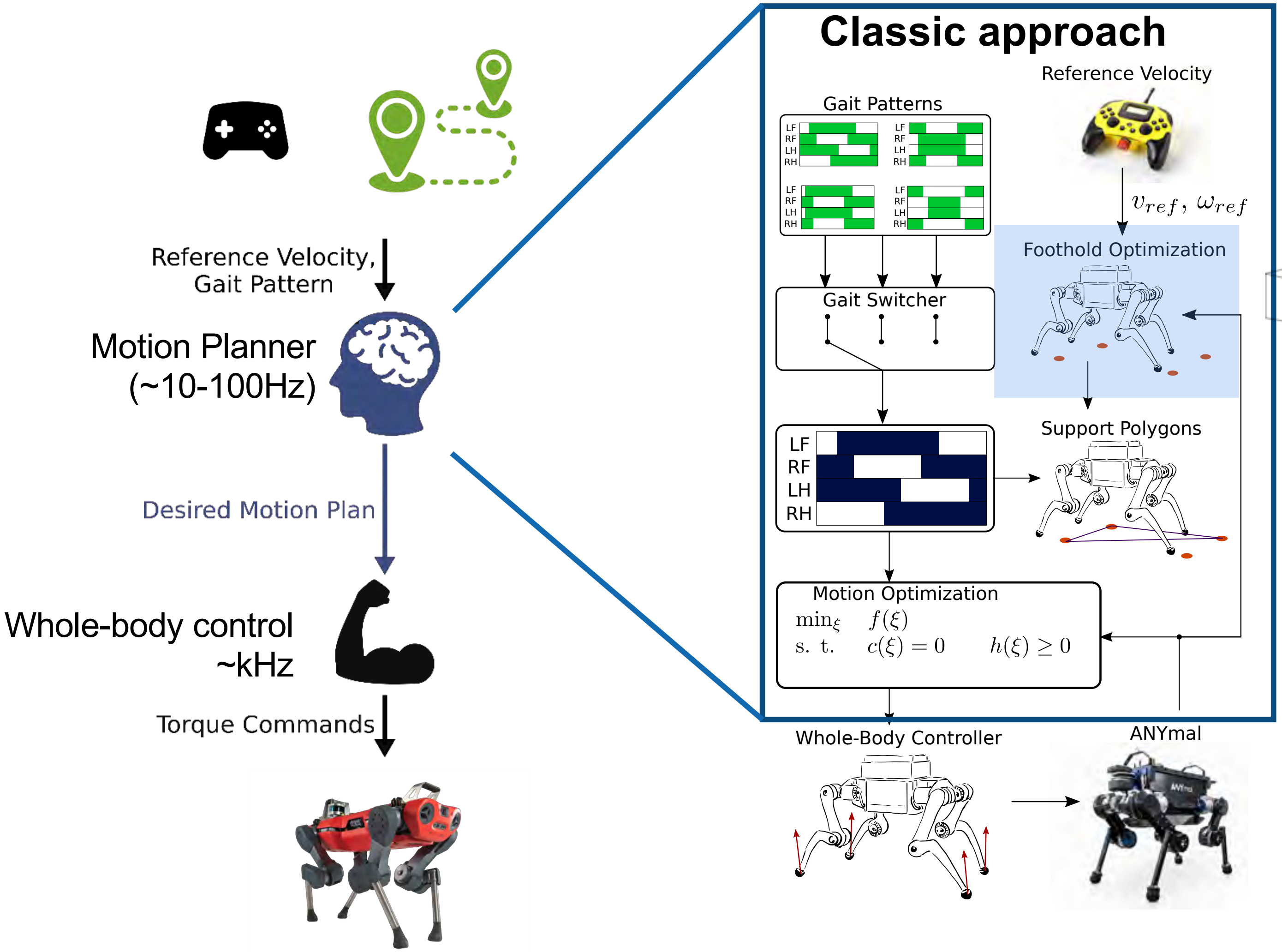
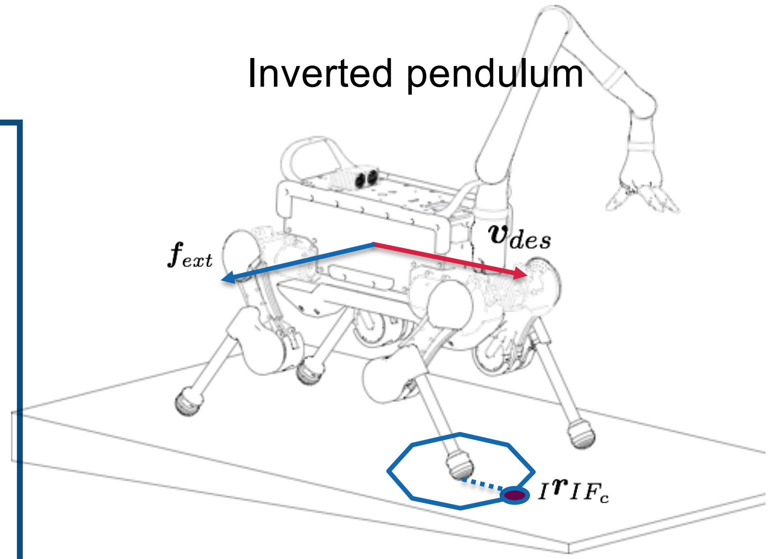
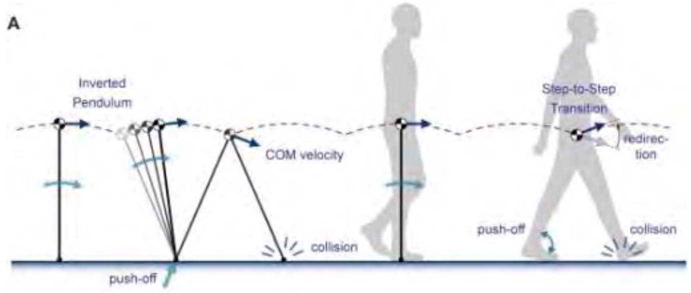


Inverted pendulum





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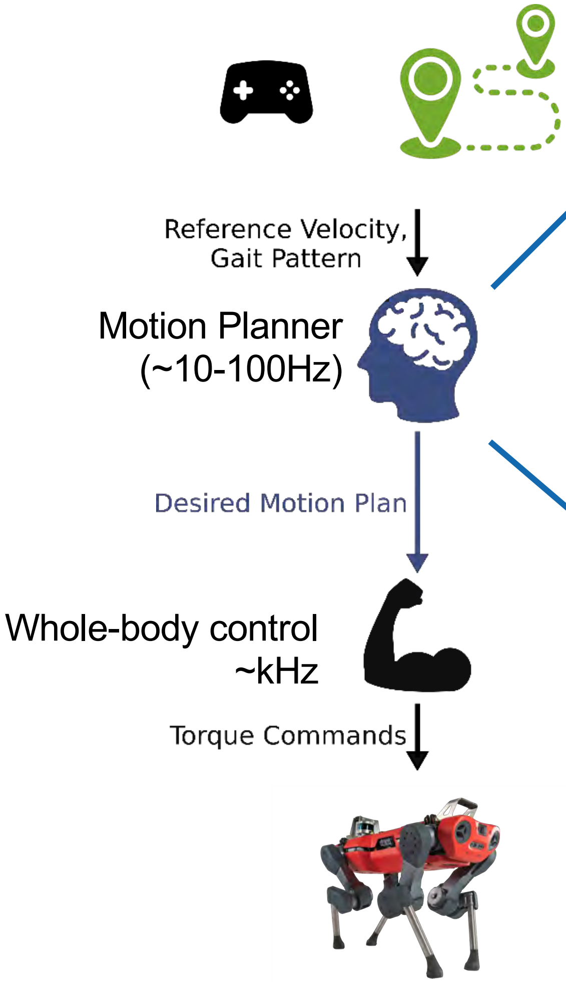
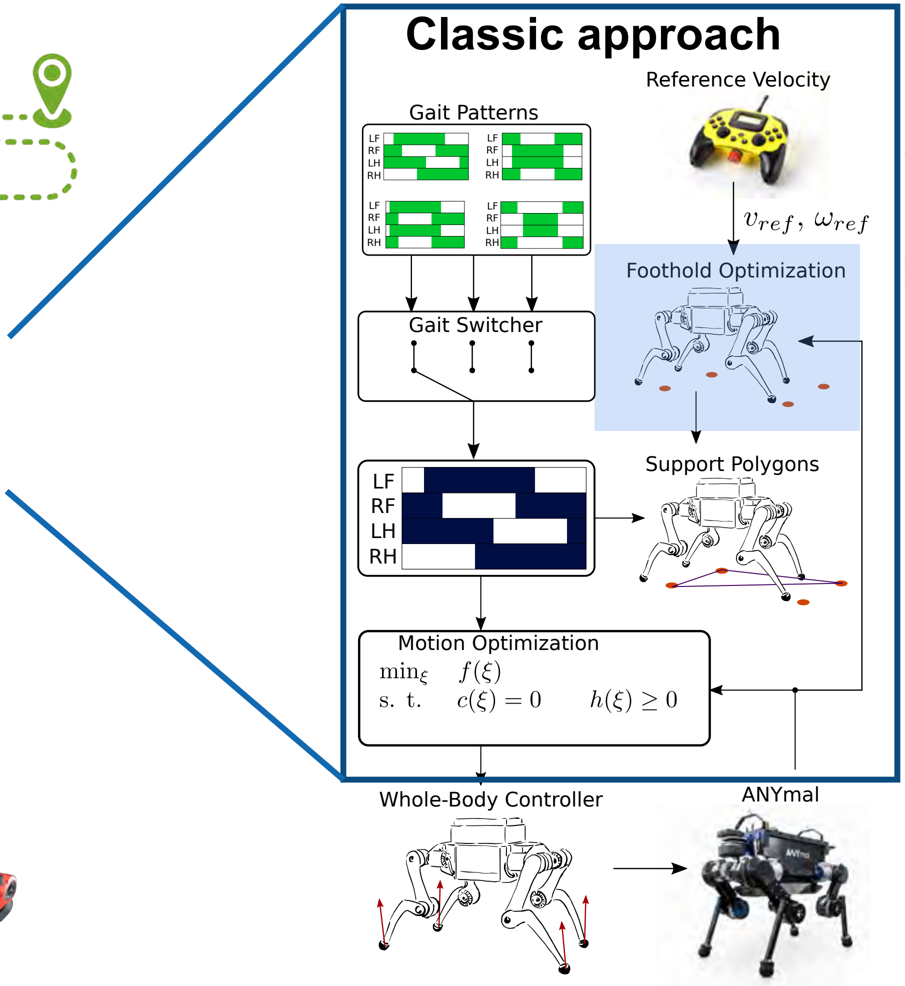
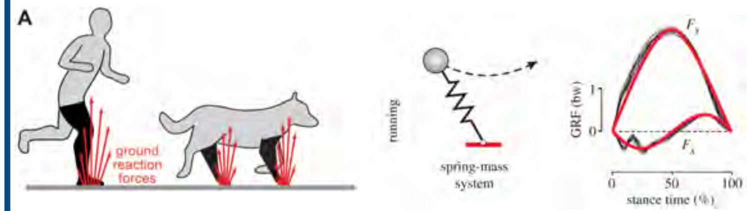


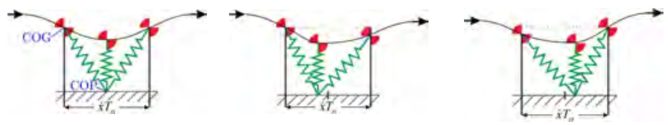


- Biomechanical studies suggest SLIP models to describe complex running behaviors



[Dickinson, Farley, Full 2000] *[Geyer 2006]*

- Simple step-length rule to adjust the velocity

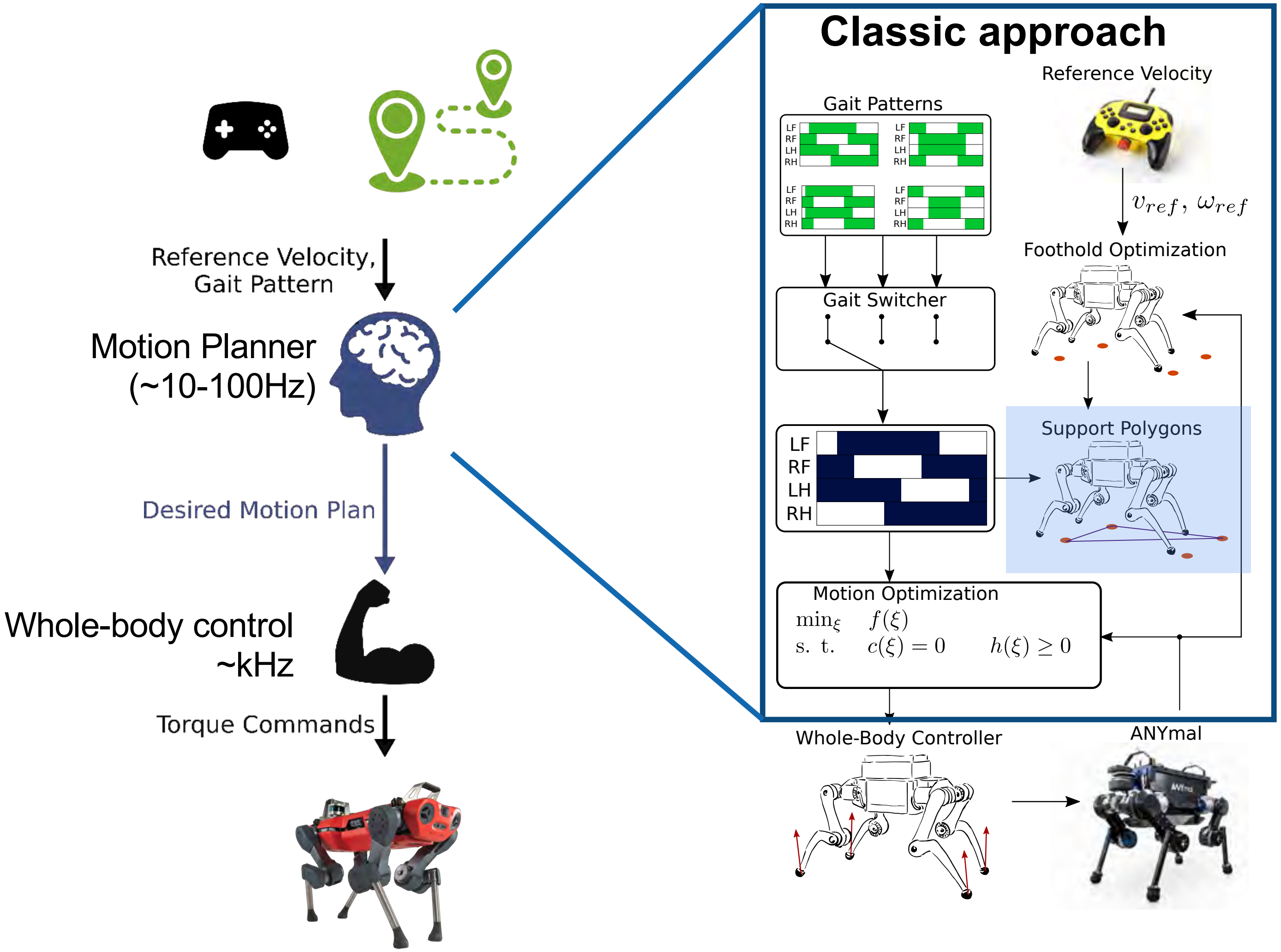


Constant speed Accelerate Decelerate

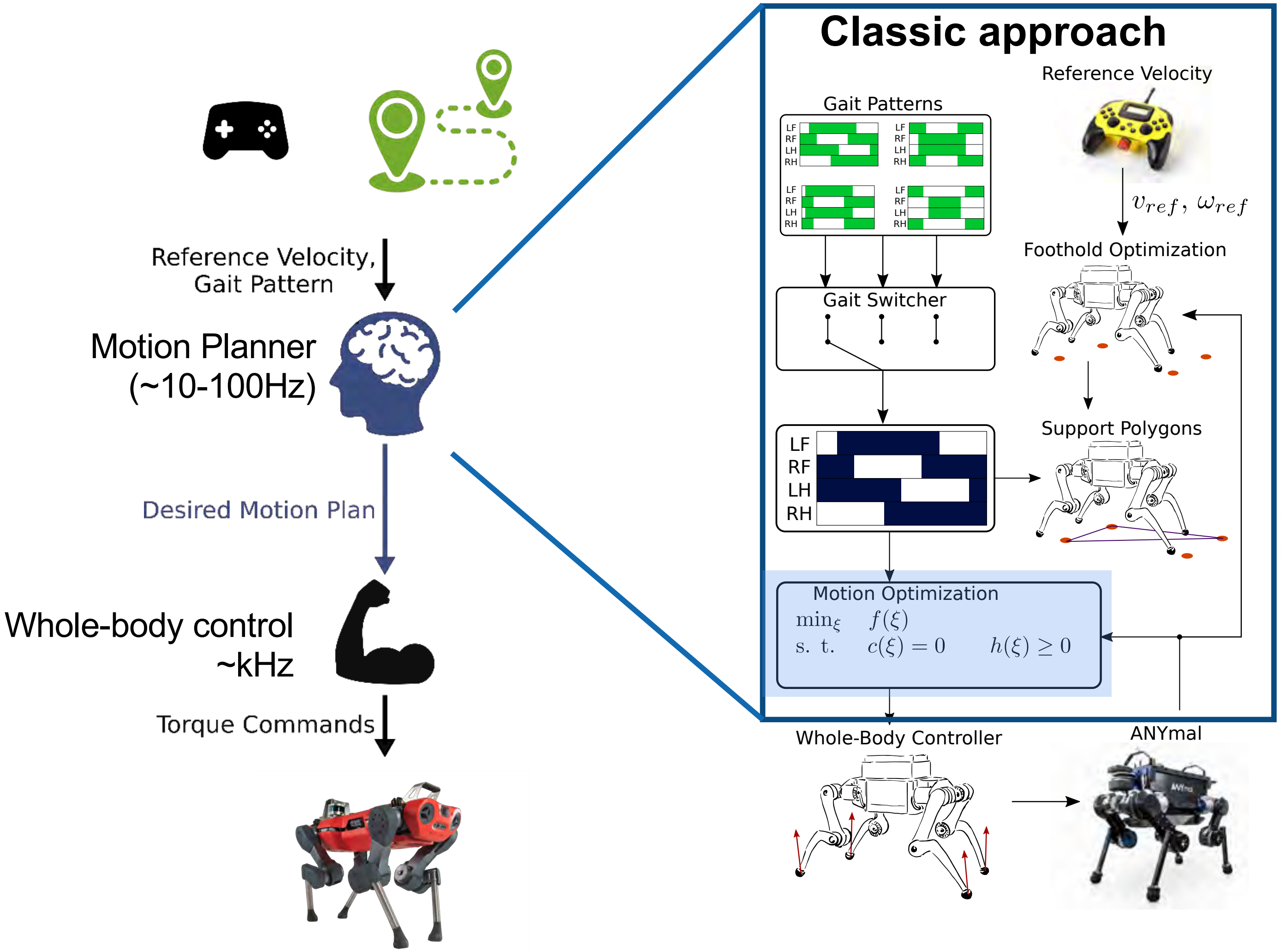
$$\mathbf{r}_F = \frac{1}{2}\dot{\mathbf{r}}_{HC,des}T_{st} + k_R^{FB}\left(\dot{\mathbf{r}}_{HC,des} - \dot{\mathbf{r}}_{HC}\right)\sqrt{h_{HC}}$$

[Raibert 1986]

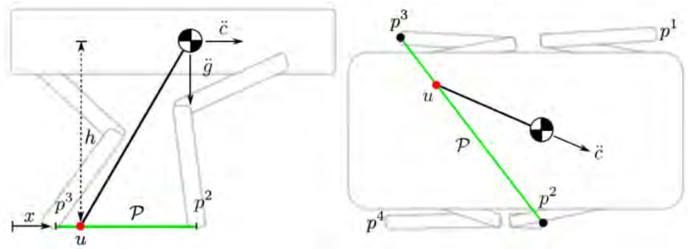
Control, Planning and Autonomy for Legged Robots



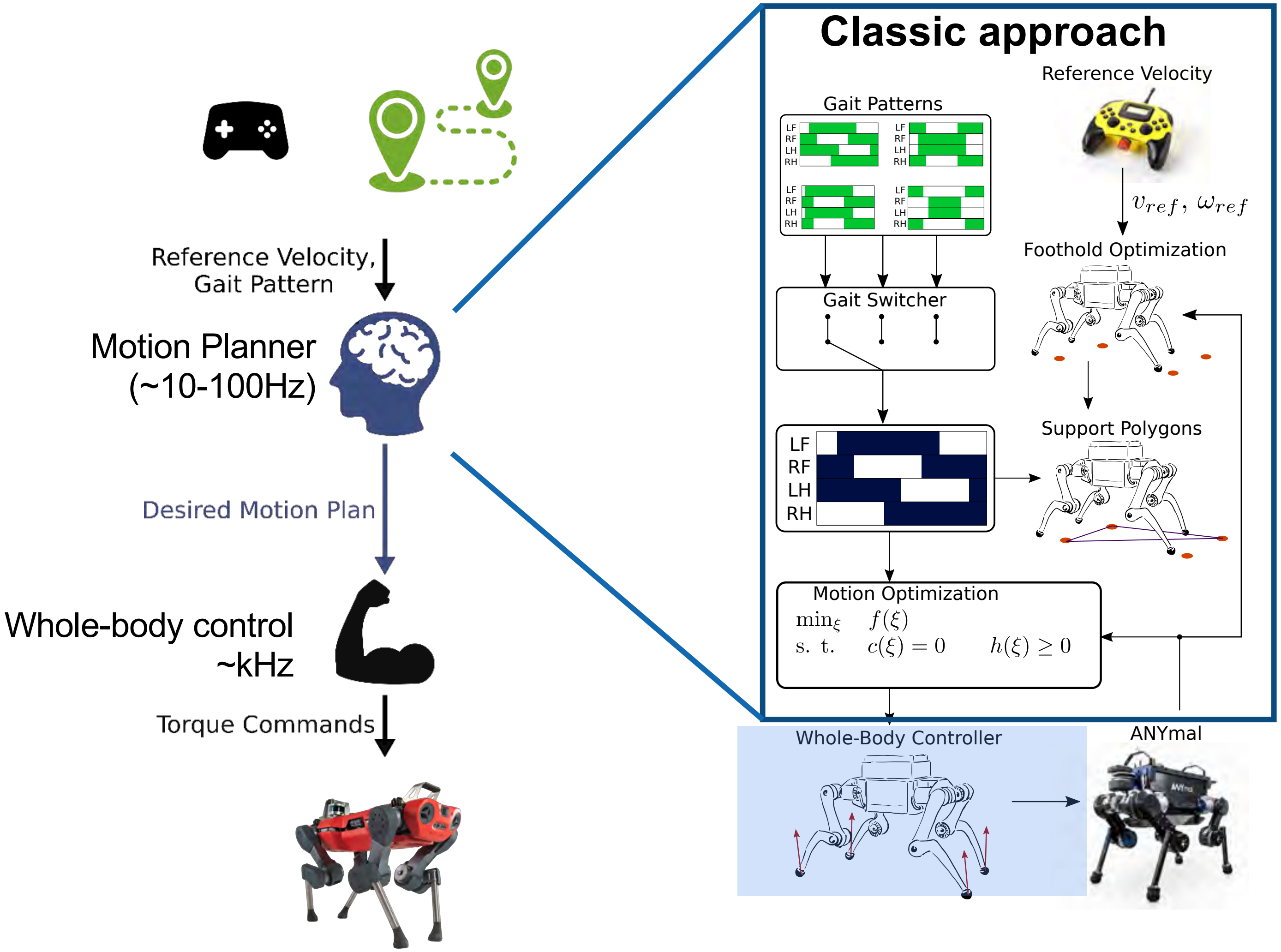
Control, Planning and Autonomy for Legged Robots



ZMP models



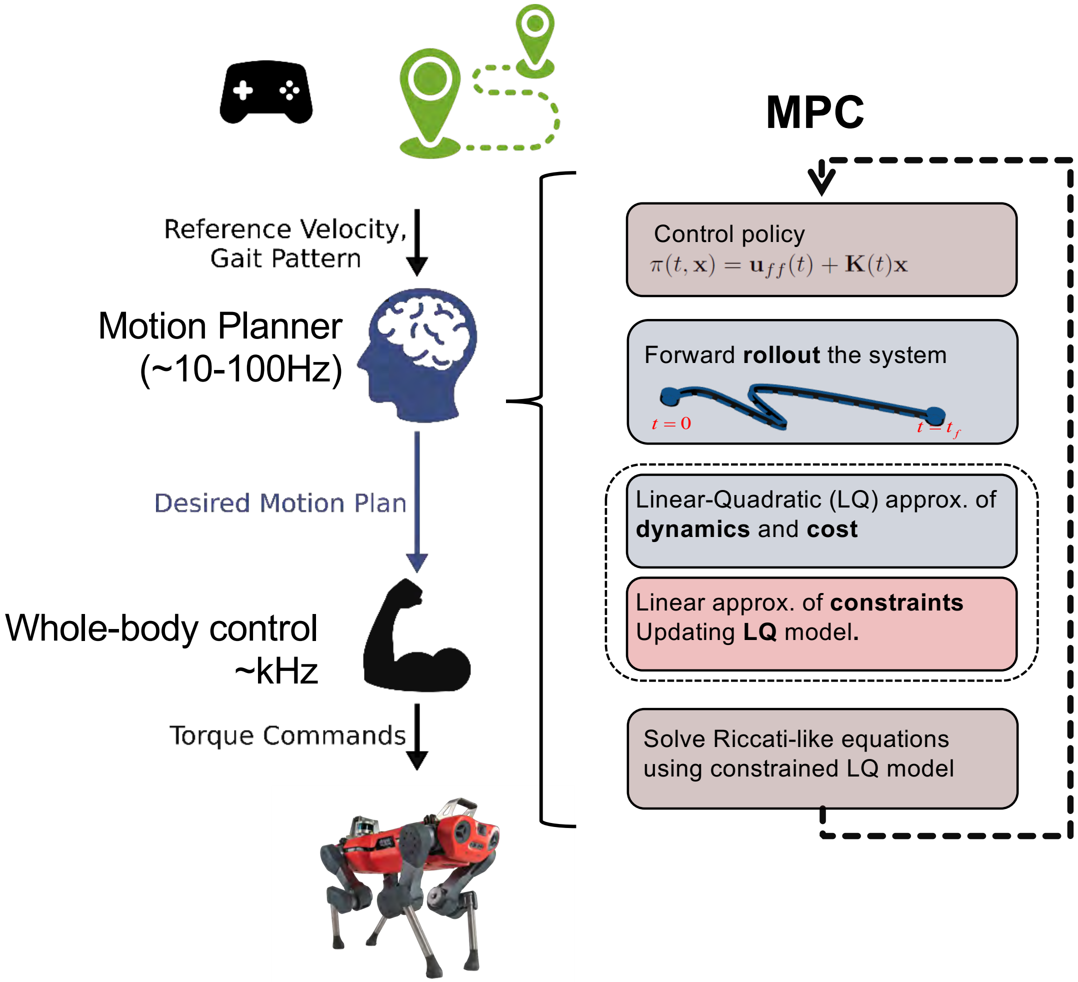
Control, Planning and Autonomy for Legged Robots

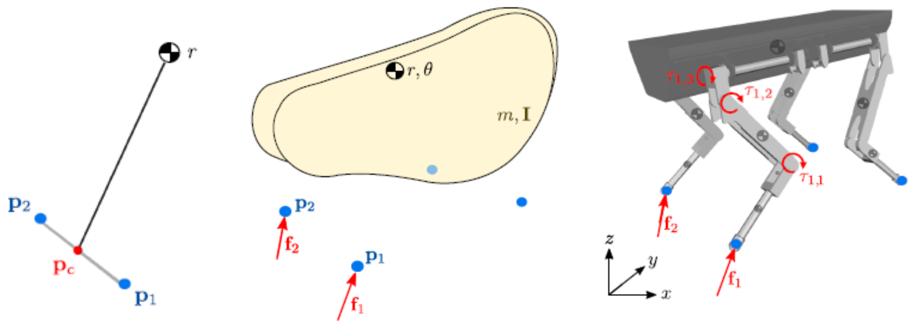


- Solves a cascade of prioritized tasks
  - Equation of motion
  - No slippage condition
  - Limits on torques
  - Motion tracking
  - …

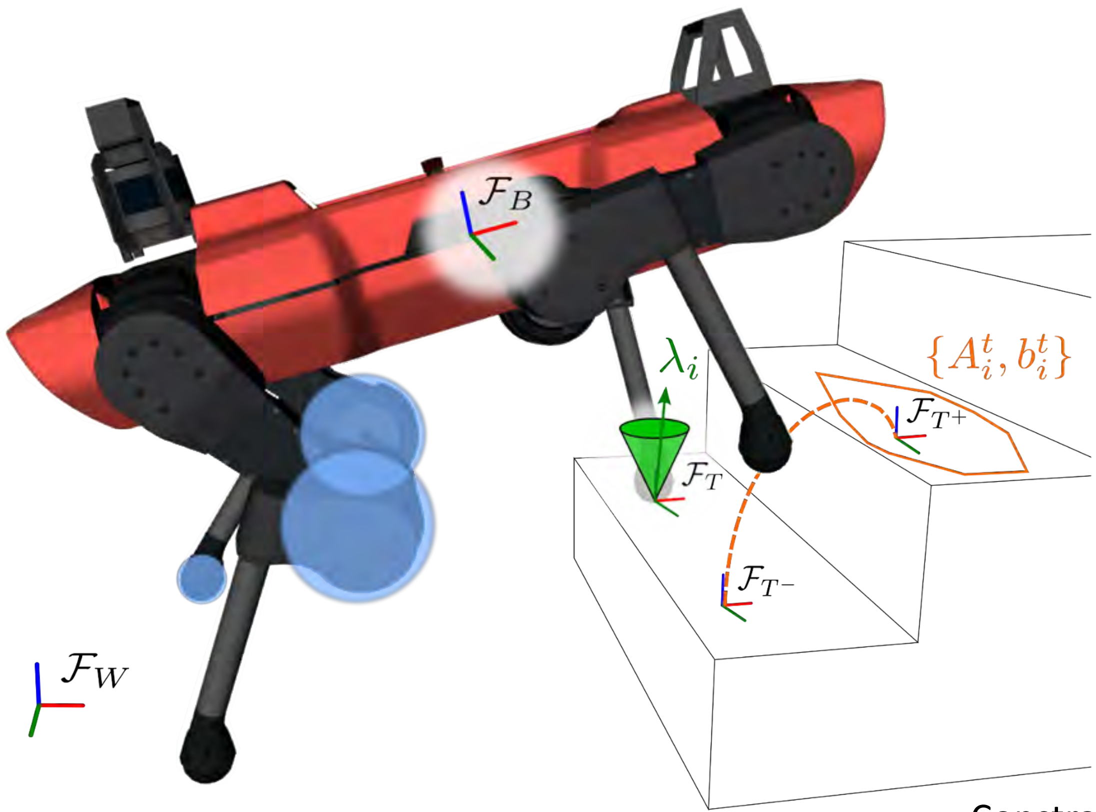

Travelled Distance = 38.98m
ANYmal
Color Camera
Mapping and Localization

Control, Planning and Autonomy for Legged Robots





Locomotion as optimization problem



Finite-Time Optimal Control Problem

$$
\begin{cases}
\min\limits_{\boldsymbol{u}(.)} \quad \Phi(\boldsymbol{x}(T)) + \int_0^T L(\boldsymbol{x}(t), \boldsymbol{u}(t), t)dt \\
\text{s.t.} \quad \dot{\boldsymbol{x}}(t) = \boldsymbol{f}(\boldsymbol{x}(t), \boldsymbol{u}(t), t) \\
\qquad \boldsymbol{g}_1(\boldsymbol{x}(t), \boldsymbol{u}(t), t) = 0 \\
\qquad \boldsymbol{g}_2(\boldsymbol{x}(t), t) = 0 \\
\qquad \boldsymbol{h}(\boldsymbol{x}(t), \boldsymbol{u}(t), t) \geq 0 \\
\qquad \boldsymbol{x}(0) = \boldsymbol{x}_0,
\end{cases}
$$

Constrained DDP-based Algorithm (SLQ) *[Farshidian 2017 IFAC]*
[https://bitbucket.org/leggedrobotics/ocs2]

Locomotion as optimization problem

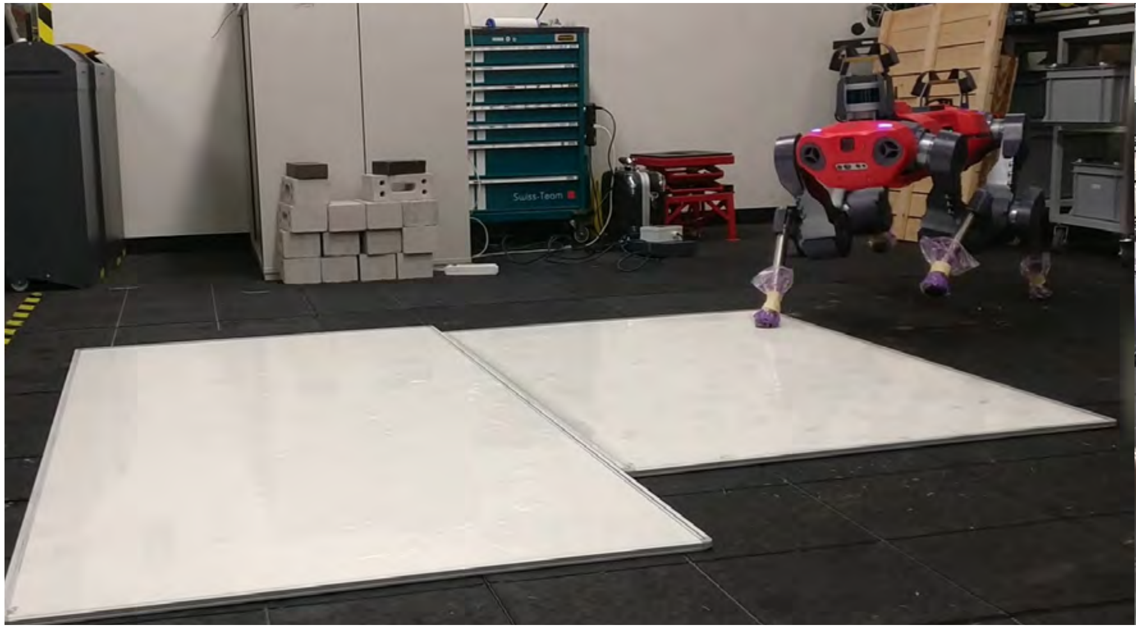
Source: youtube, video by Boston Dynamics, Talk by Scott Kuindersma

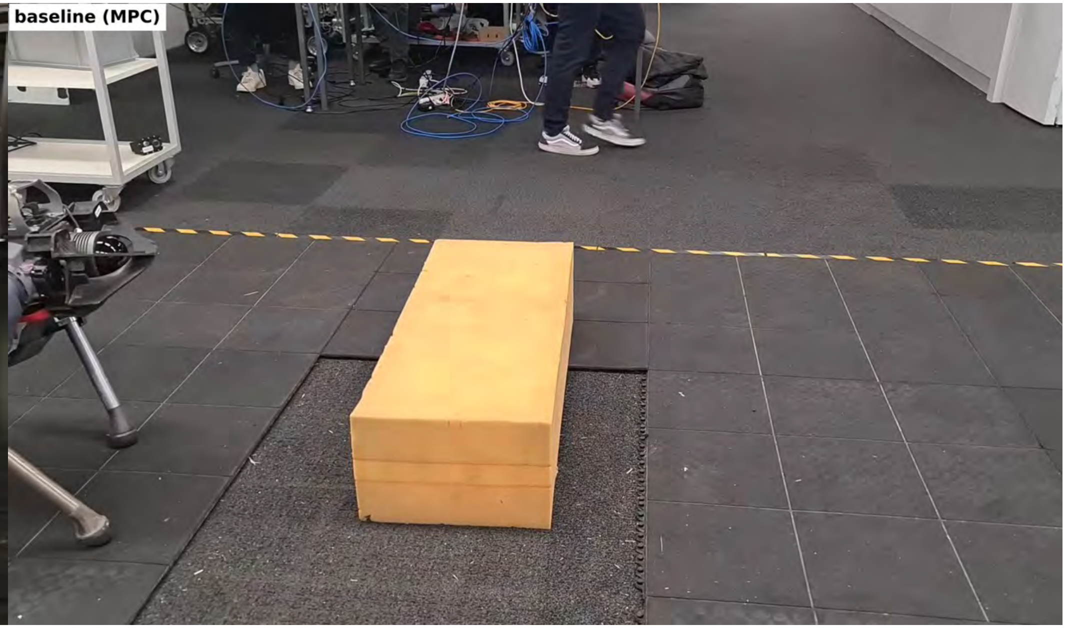
Legged robots work well on structured ground
… but they often have issues over compliant, slippery or moving terrain

- **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 reactio…
  - Slip detection and …
  - …ait and frequency adaptation
  - Regain contacts…

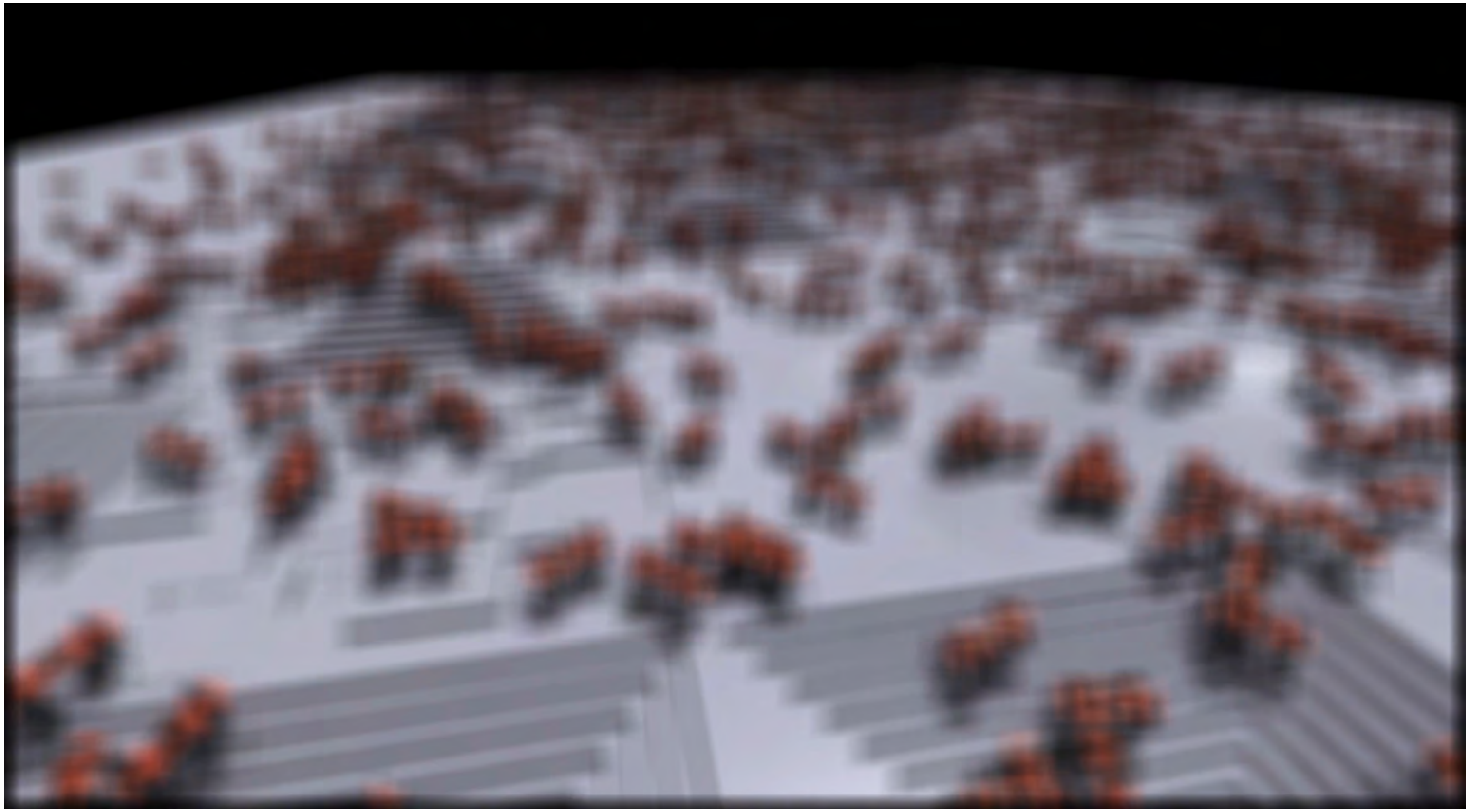
Could we not make the robot to learn all of this

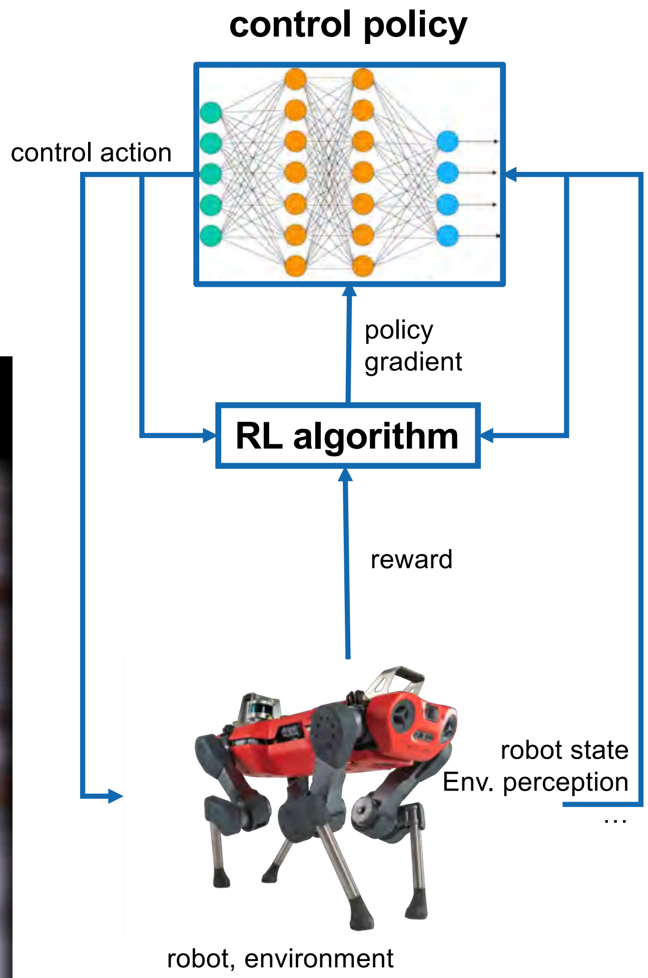




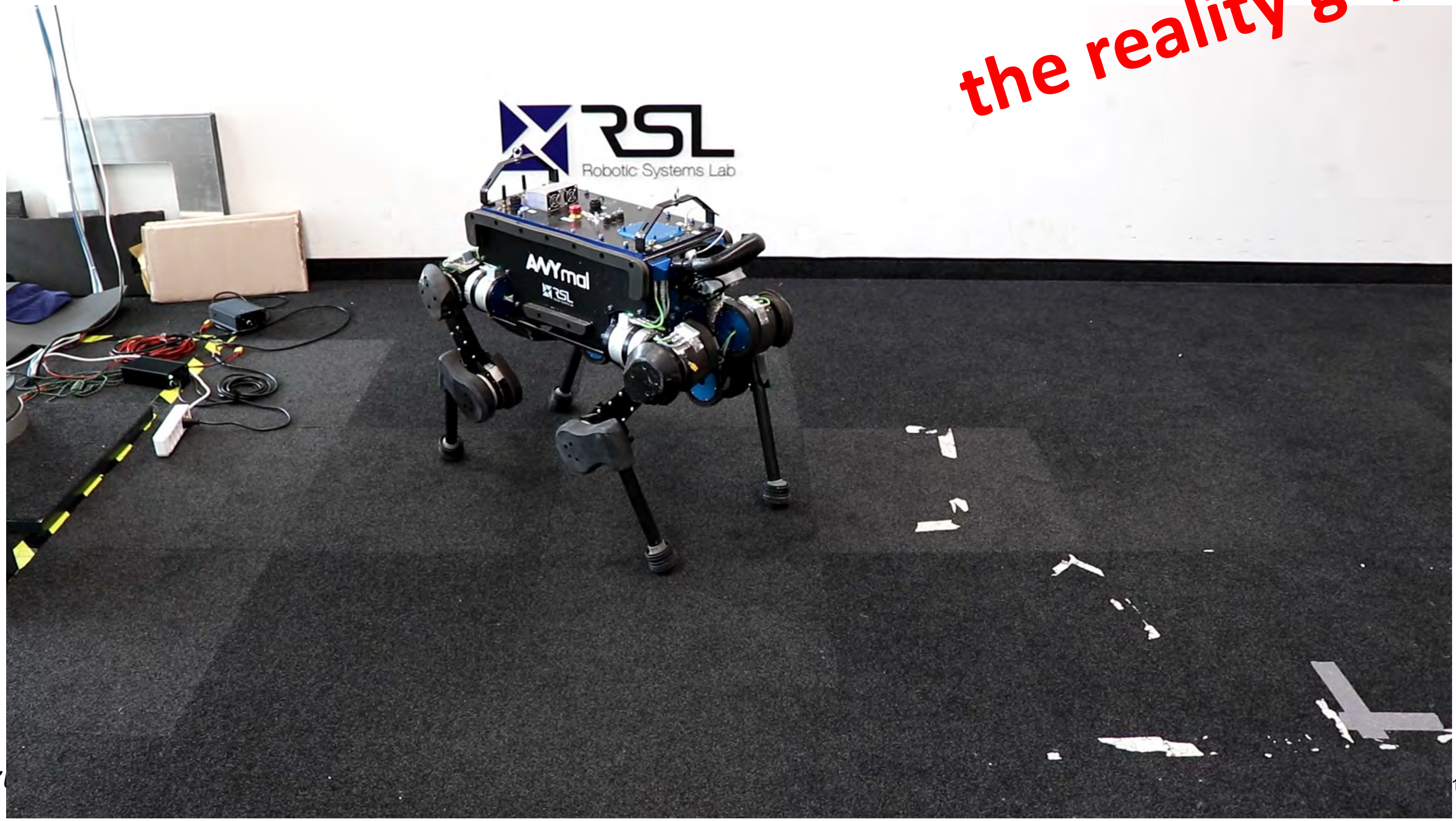
Reinforcement learning for locomotion control

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



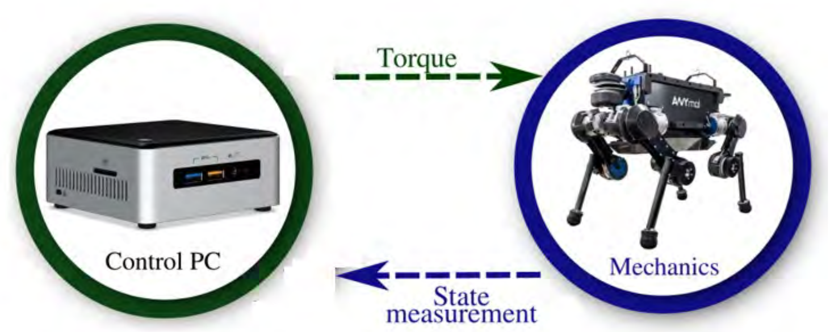


Deployment of learned policy on the robot

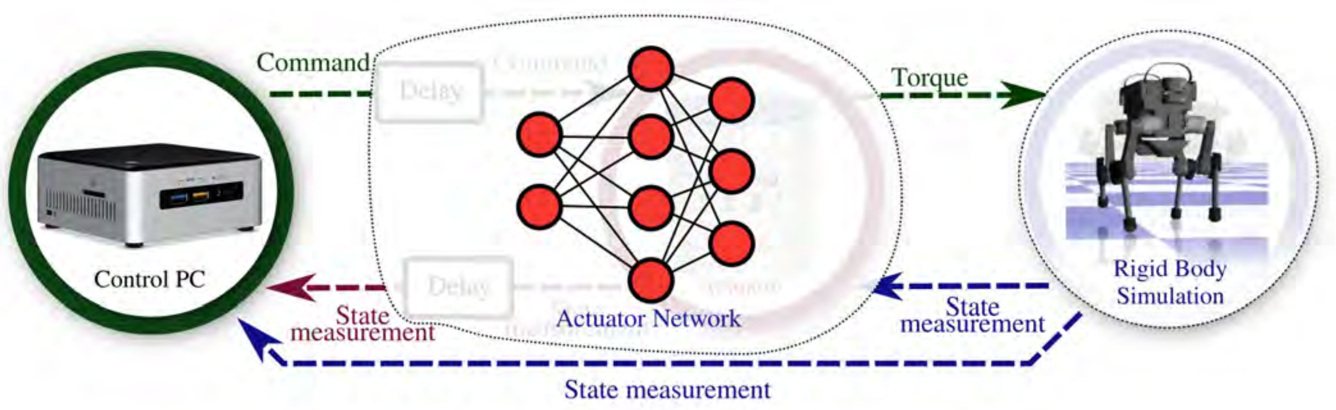


the reality gap

Sim-to-real: The reality gap



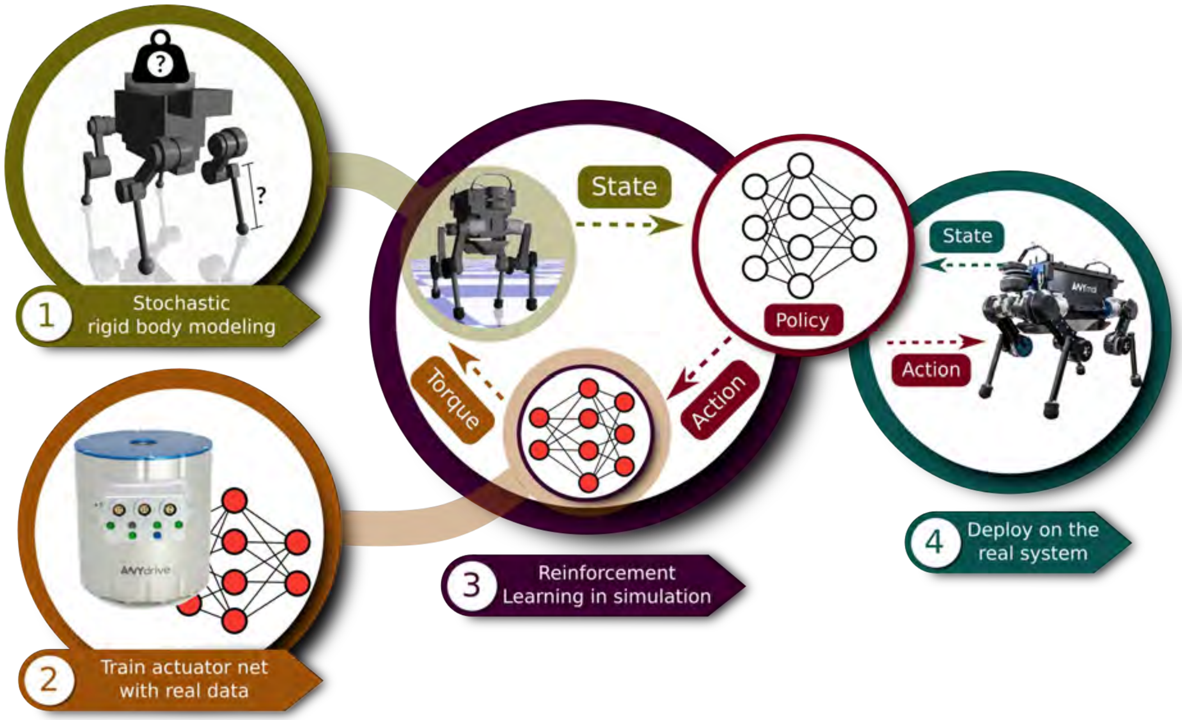
Sim-to-real: The reality gap

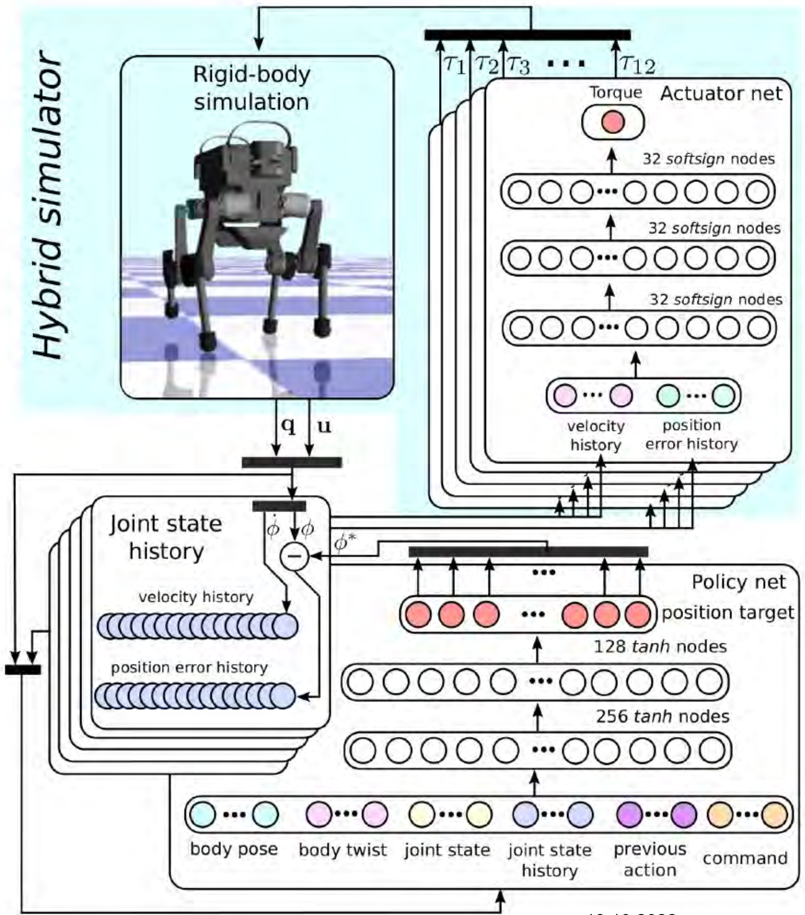


Difficult to model.
Easy to learn

Easy to model.
Difficult to learn

Simulation-based RL for legged robots

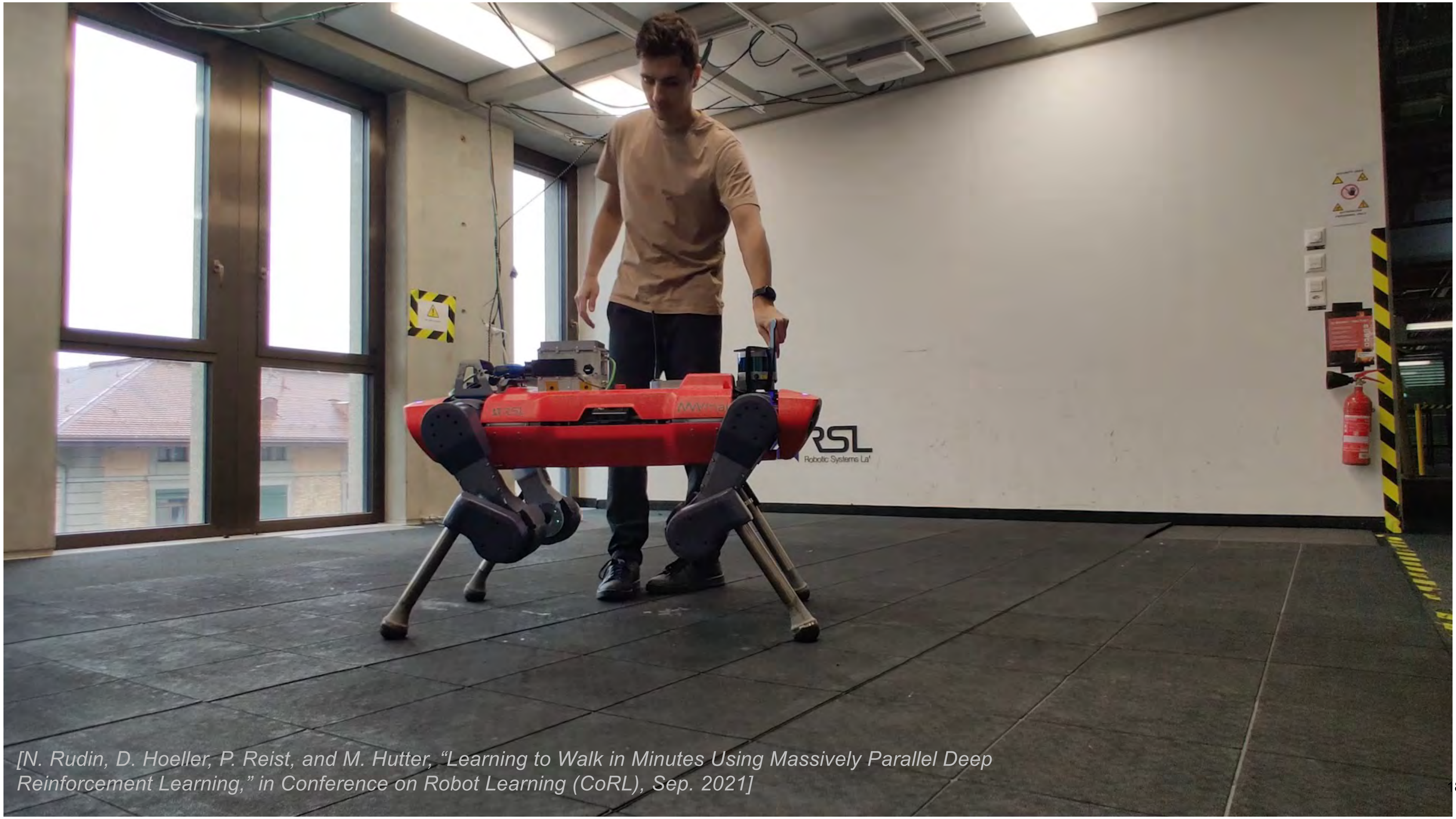




ANYmal is (one of) the first RL-controlled robot product

Every sequence:

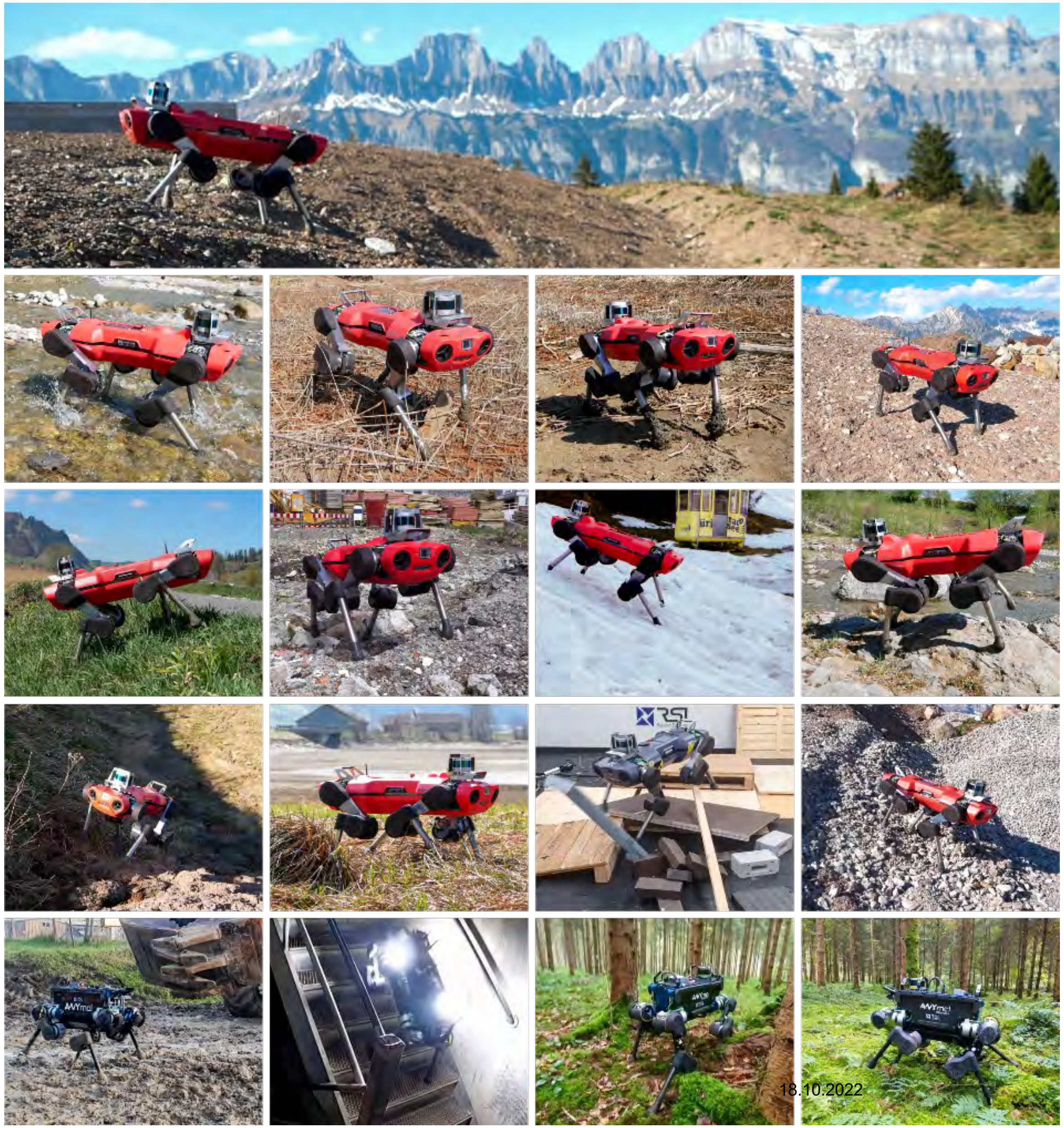
- 15 policy iterations
- ~1.5M steps
- ~8.3 hours of simulated time



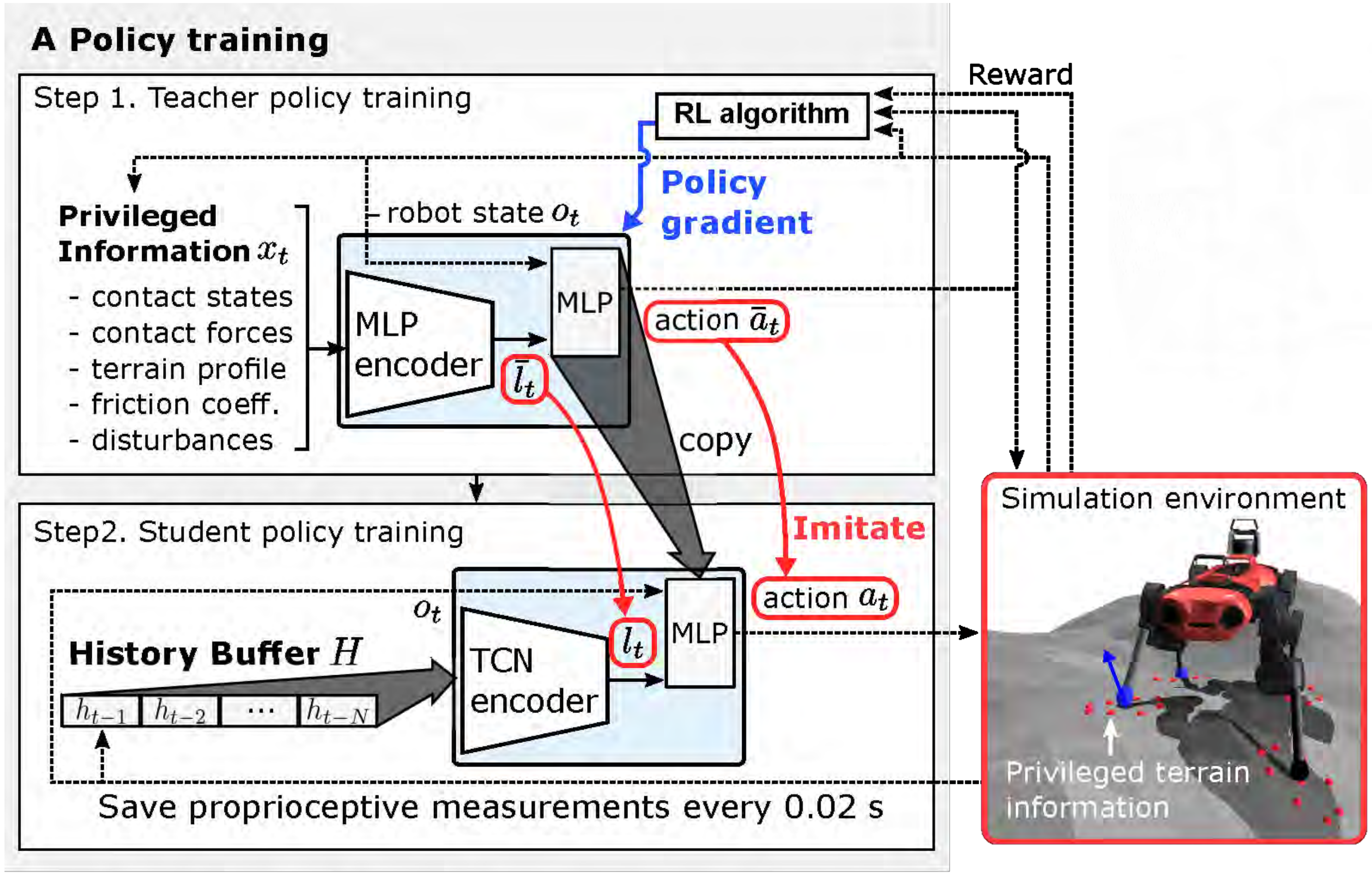
[N. Rudin, D. Hoeller, P. Reist, and M. Hutter, “Learning to Walk in Minutes Using Massively Parallel Deep Reinforcement Learning,” in Conference on Robot Learning (CoRL), Sep. 2021]

Real World Deployment

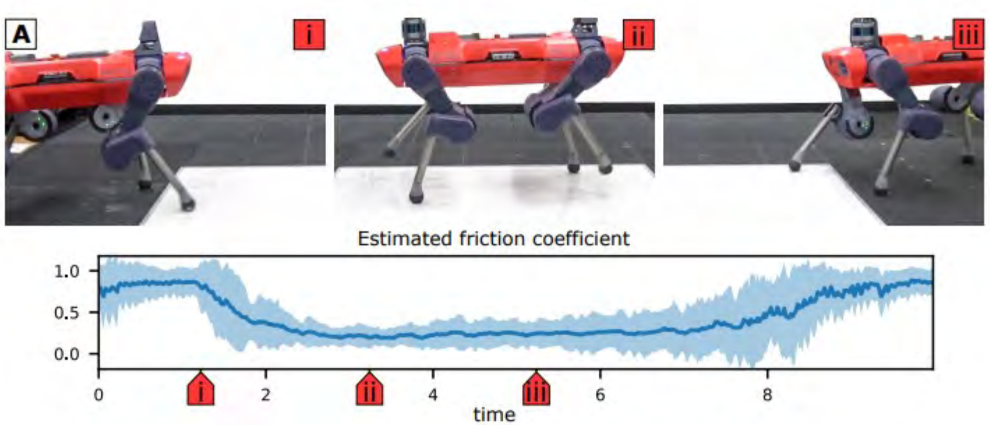
- Large variations in terrain in reality
  - Impossible to model in simulation
  - Hard to sense from perception
- What's important for locomotion



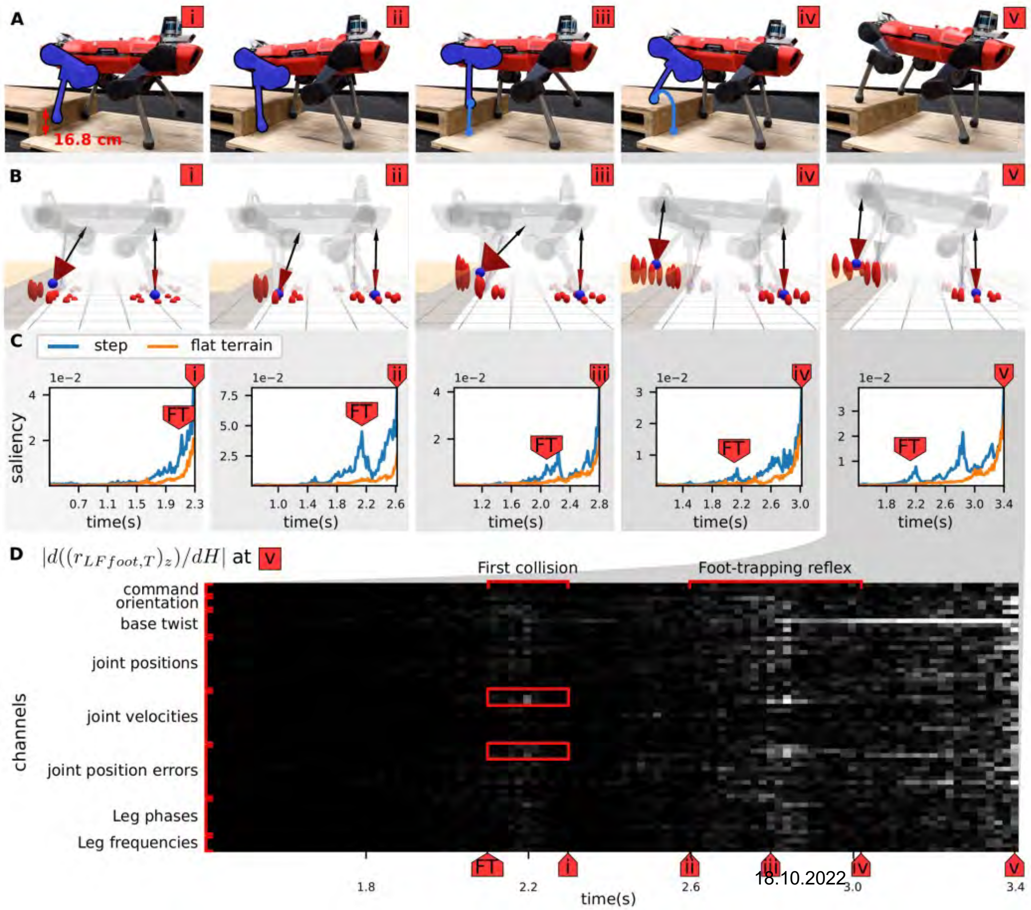
Method: privileged training



Friction estimation



Foot trapping reflex



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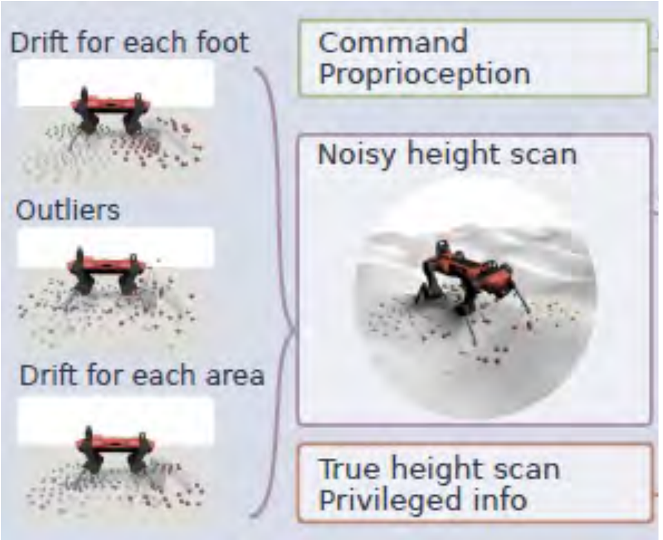
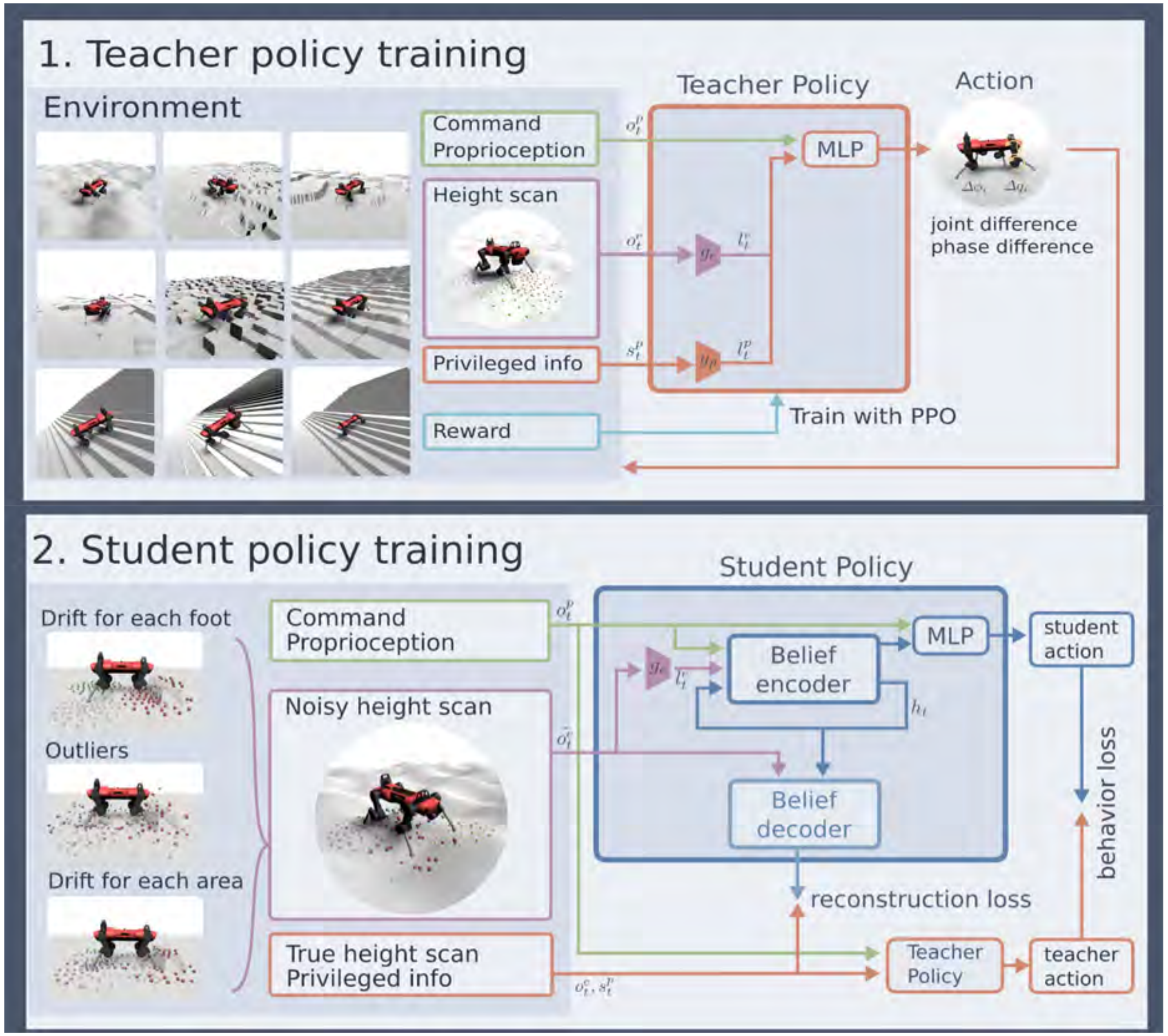
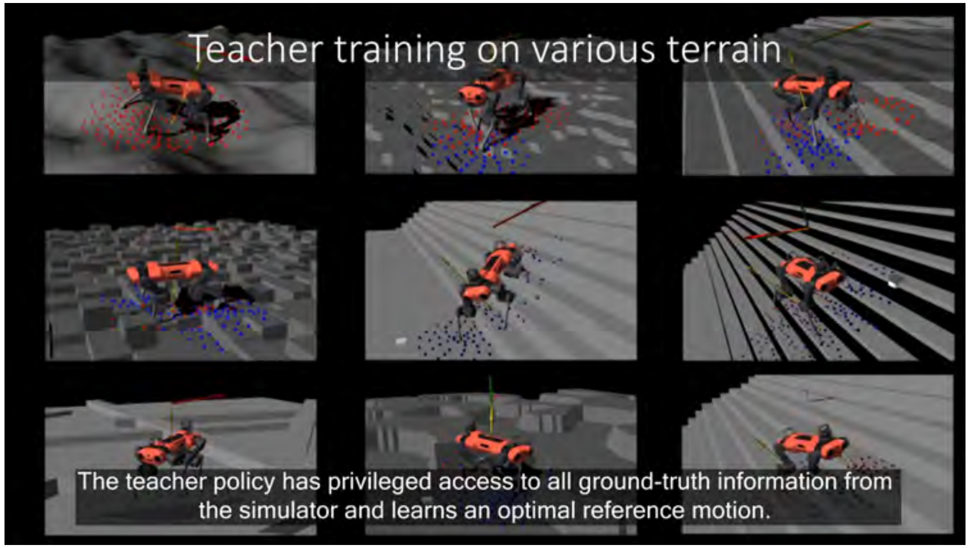
Learning-based locomotion including perception



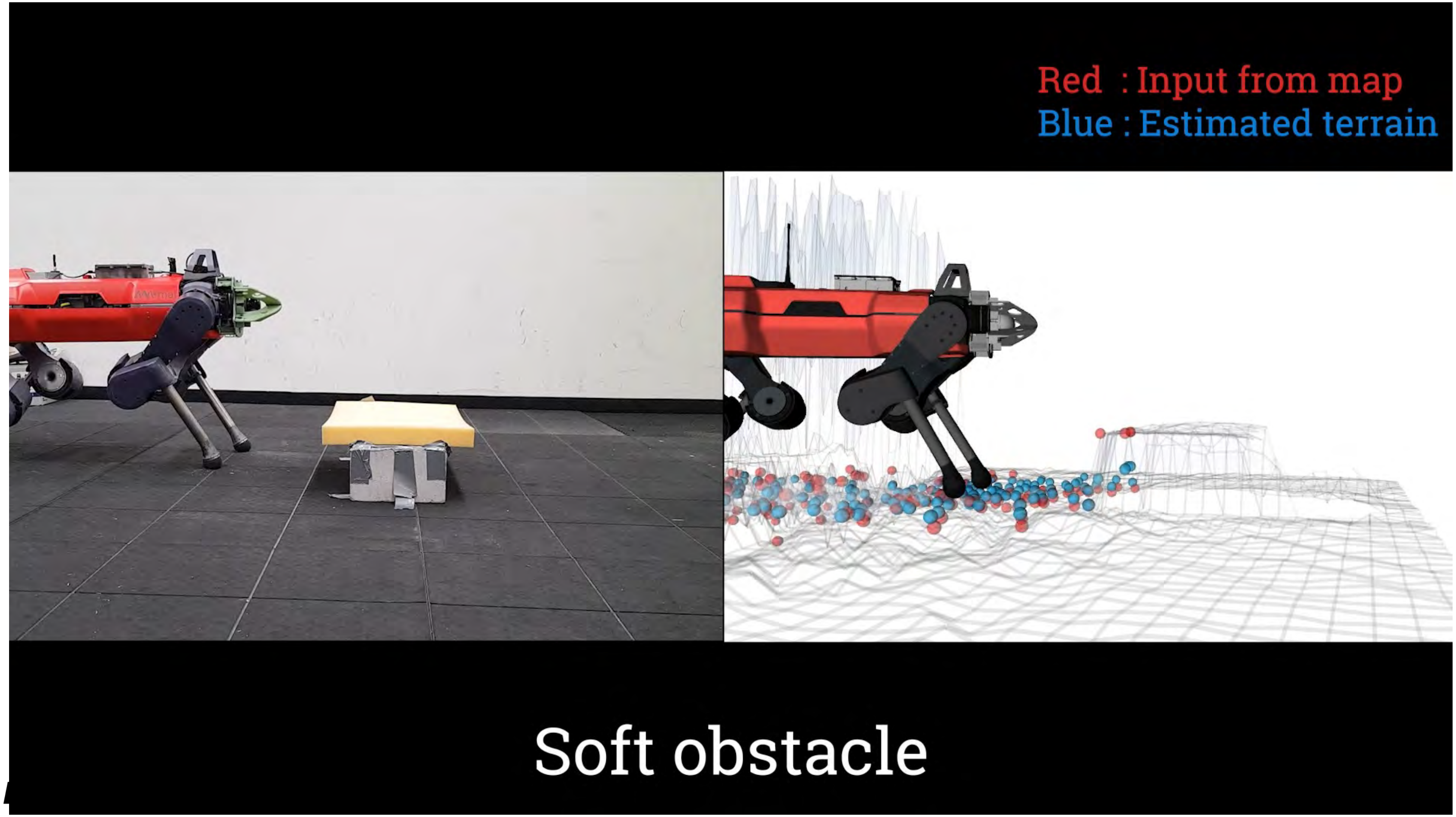
Teacher-Student training

[T. Miki, J. Lee, J. Hwangbo, L. Wellhausen, V. Koltun, and M. Hutter, “Learning robust perceptive locomotion for quadrupedal robots in the wild,” Science Robotics, 2022.]





What is recognized in the belief state?

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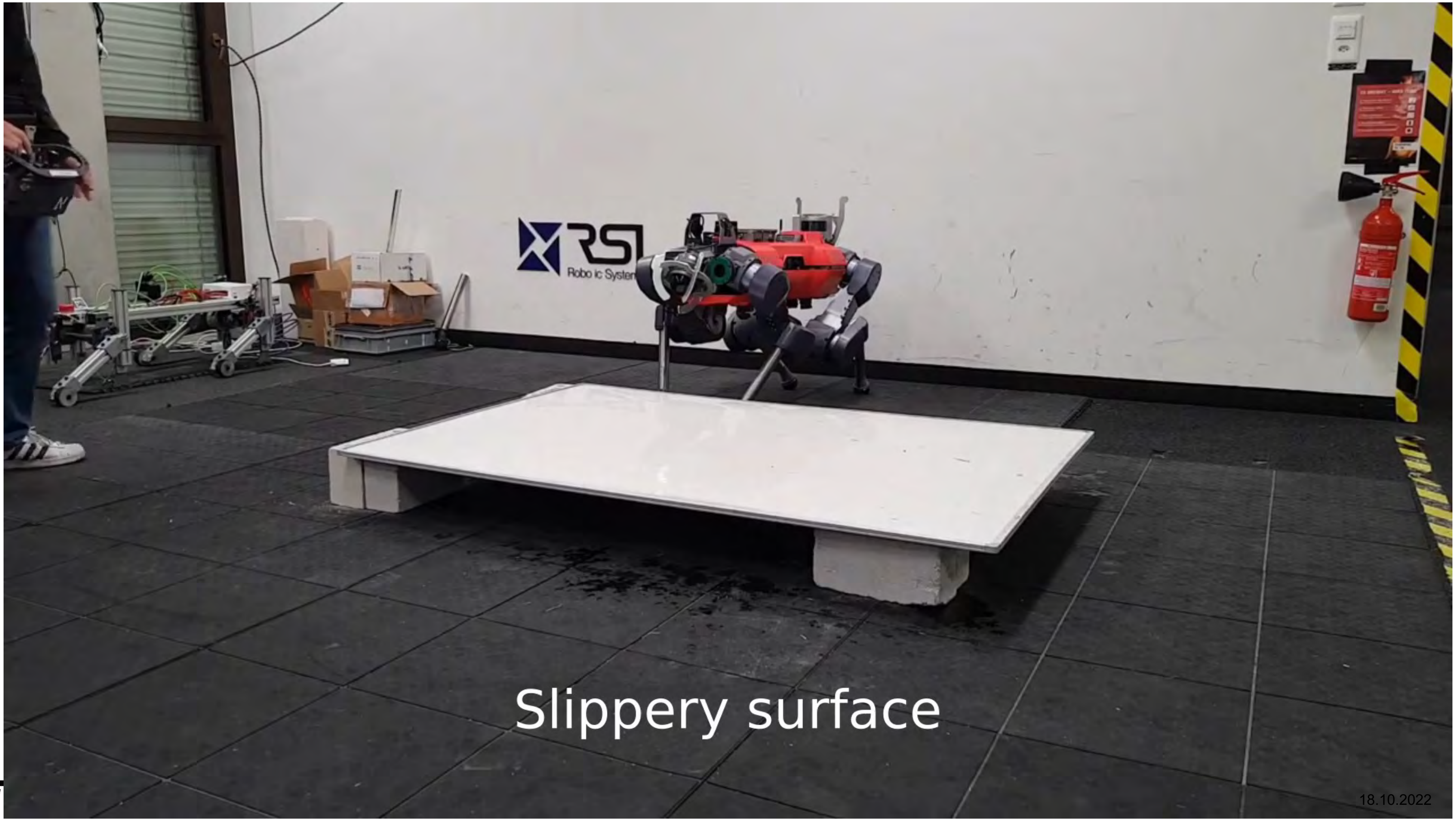
Robustness



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RSL Robotic Systems Lab

Part 3: Navigation

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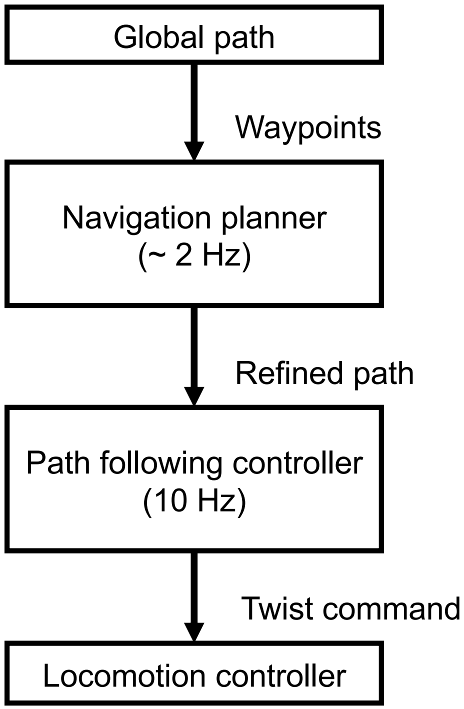
Conventional approach

Planning assumes static environment



Conventional approach

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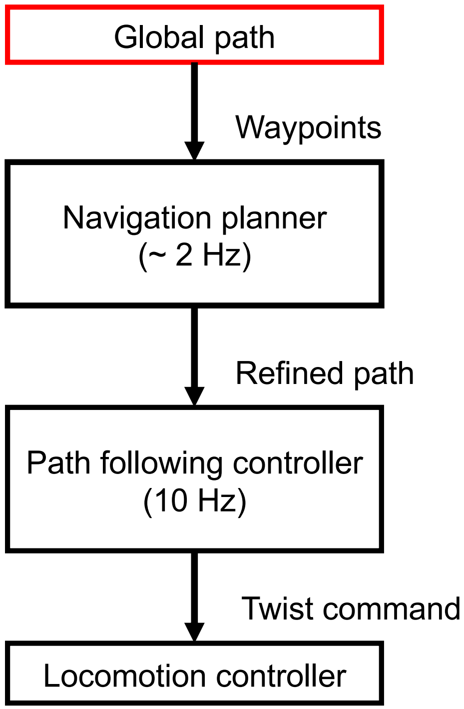

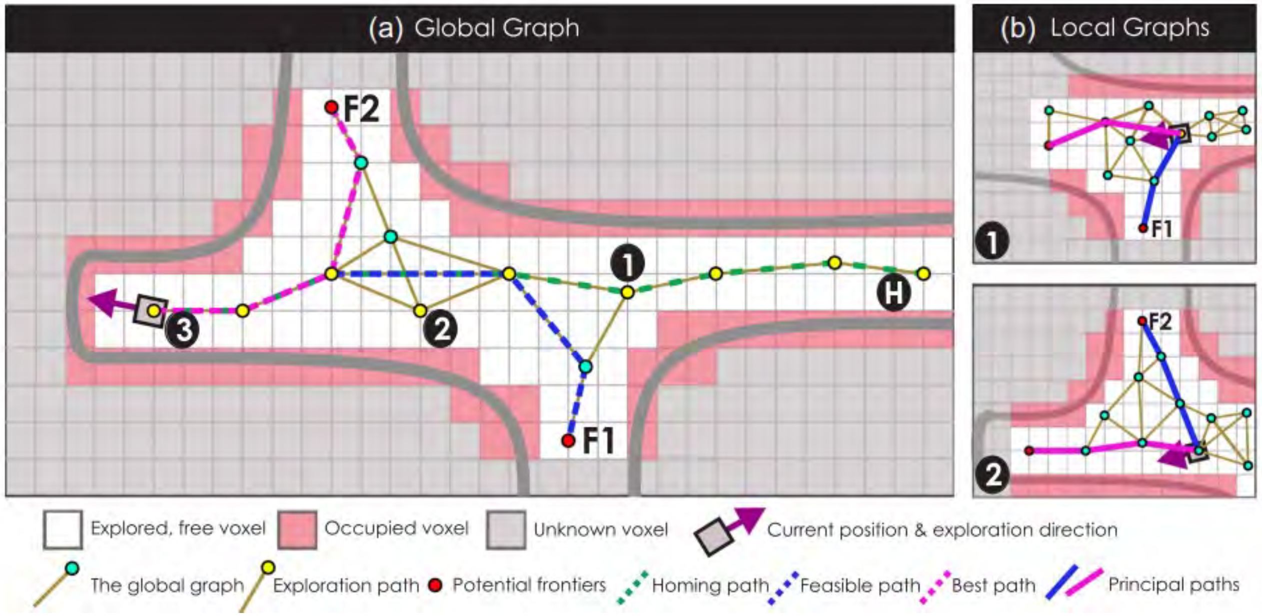

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Conventional approach

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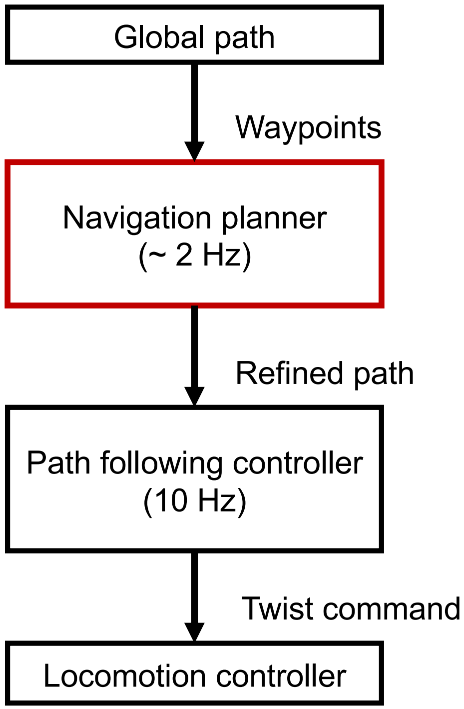
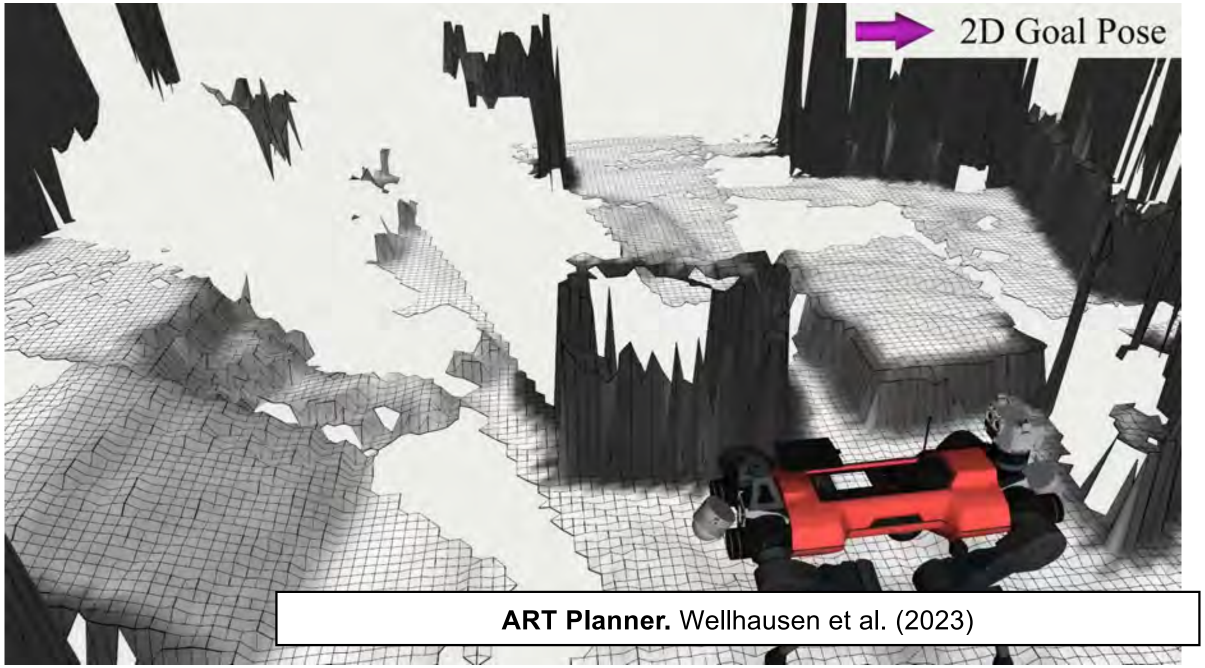
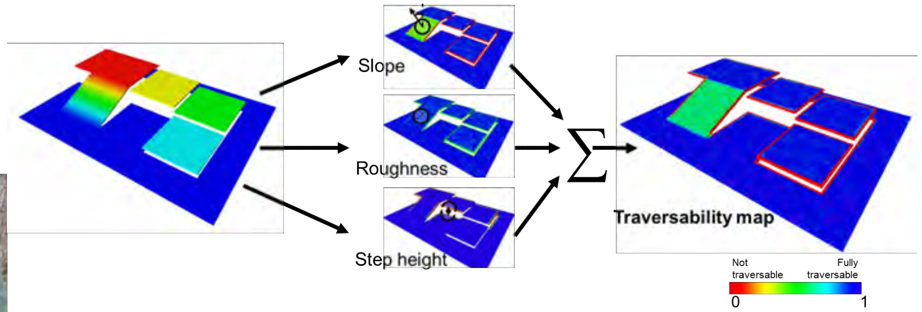
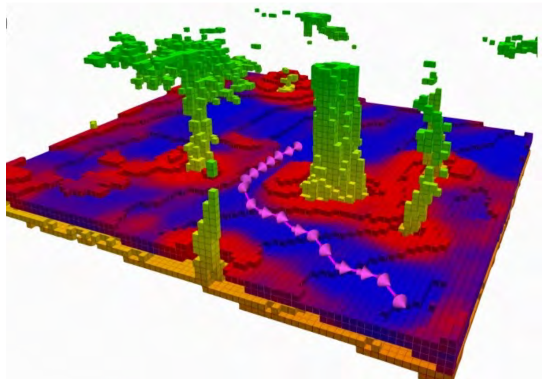


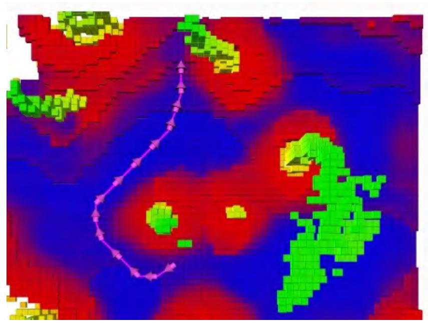


ART Planner. Wellhausen et al. (2023)

Traversability estimation and navigation

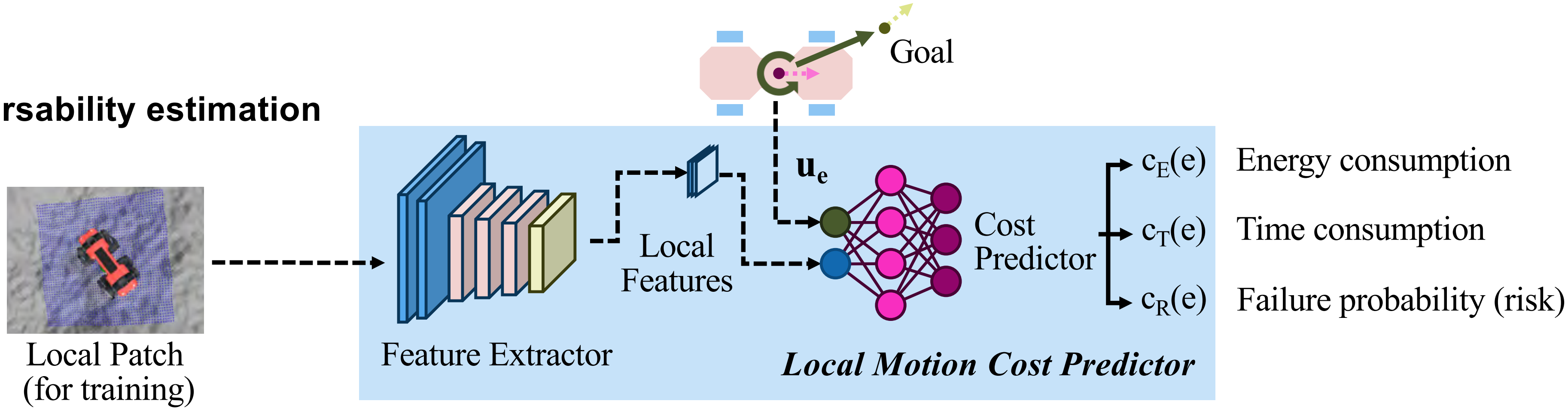


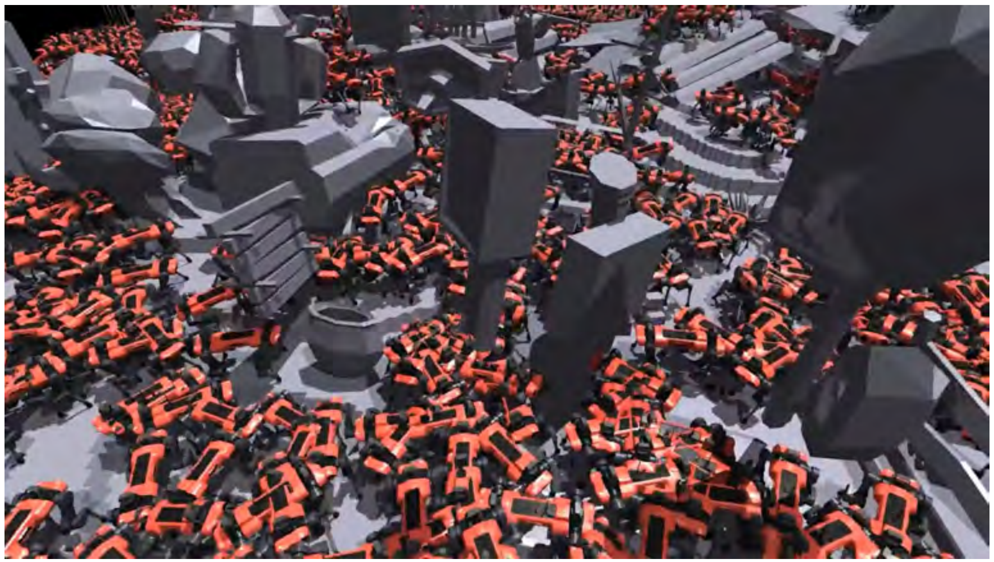




Finding the right local path

- **Traversability estimation**





Finding the right local path

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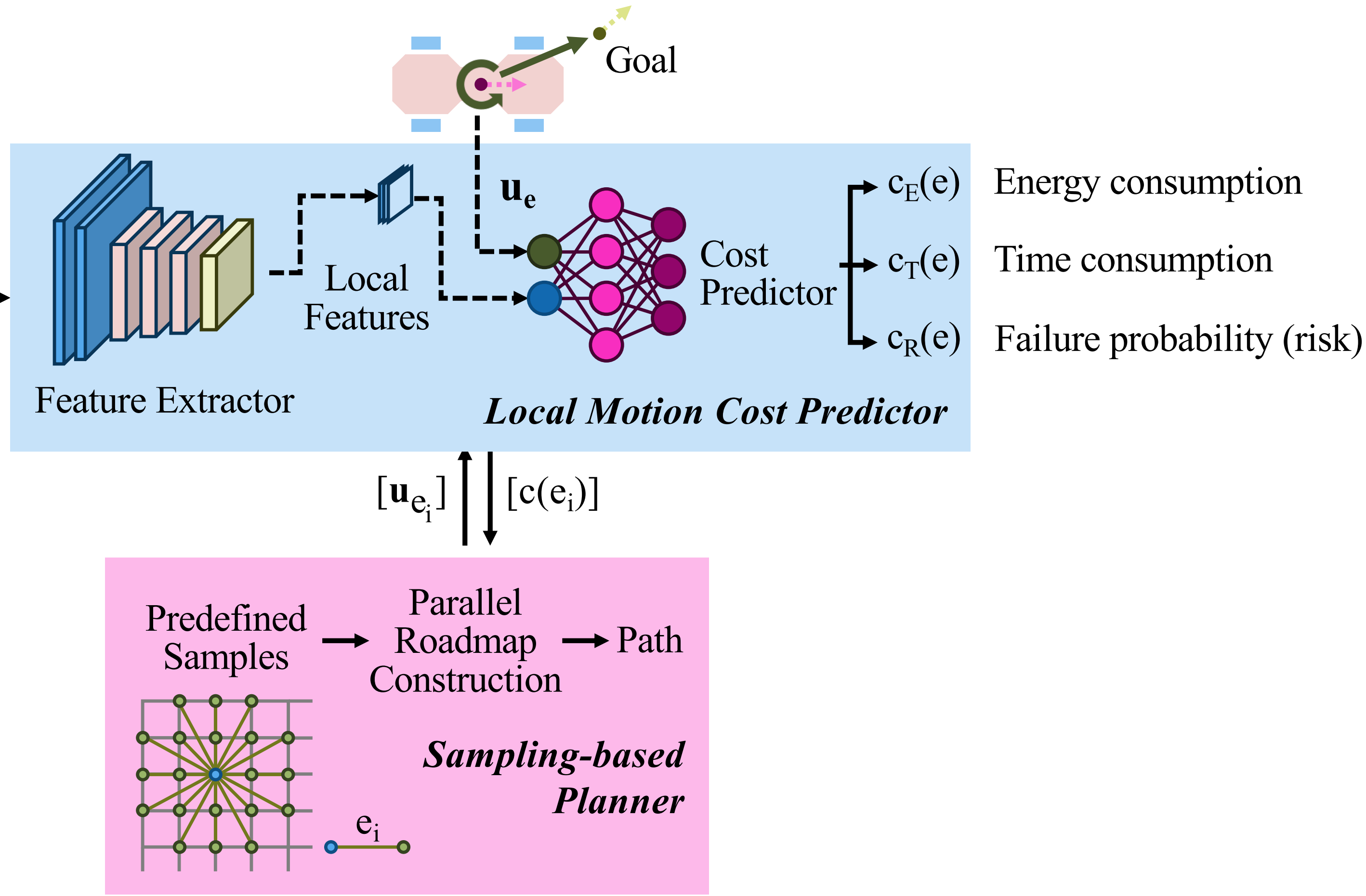
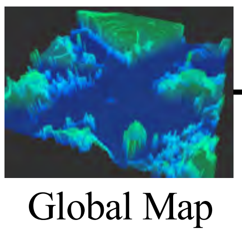
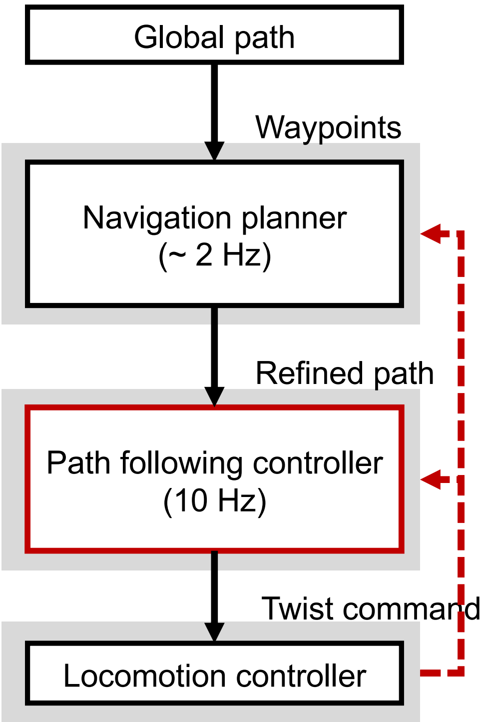


- **Find the best path**

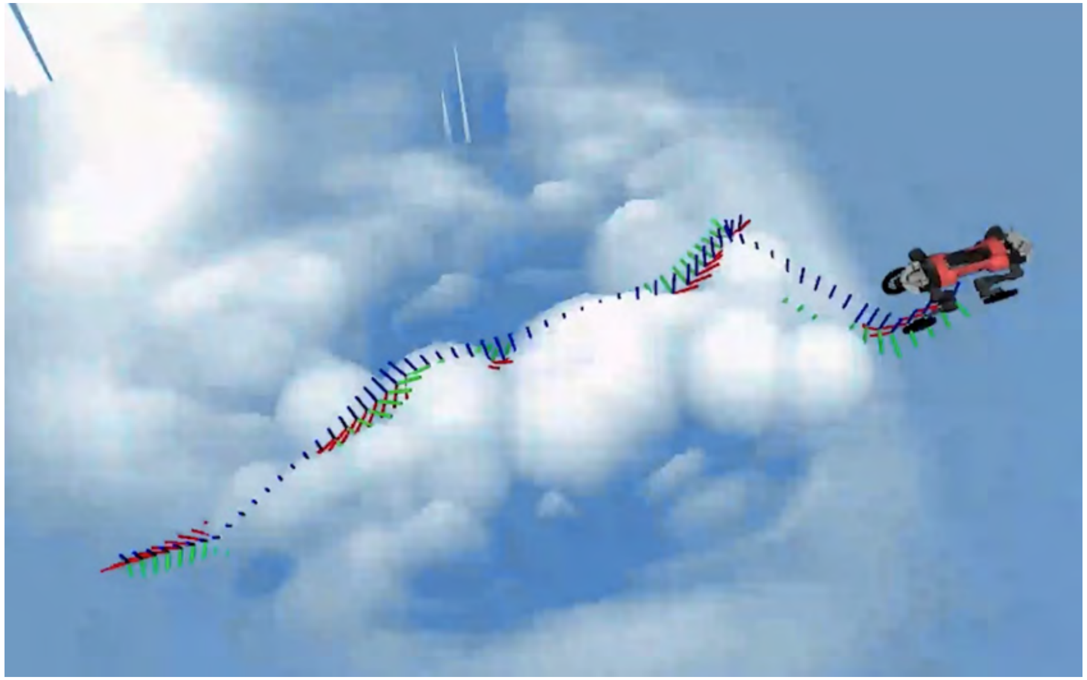


Conventional approach

Dynamics-unaware control and delayed response



Information loss



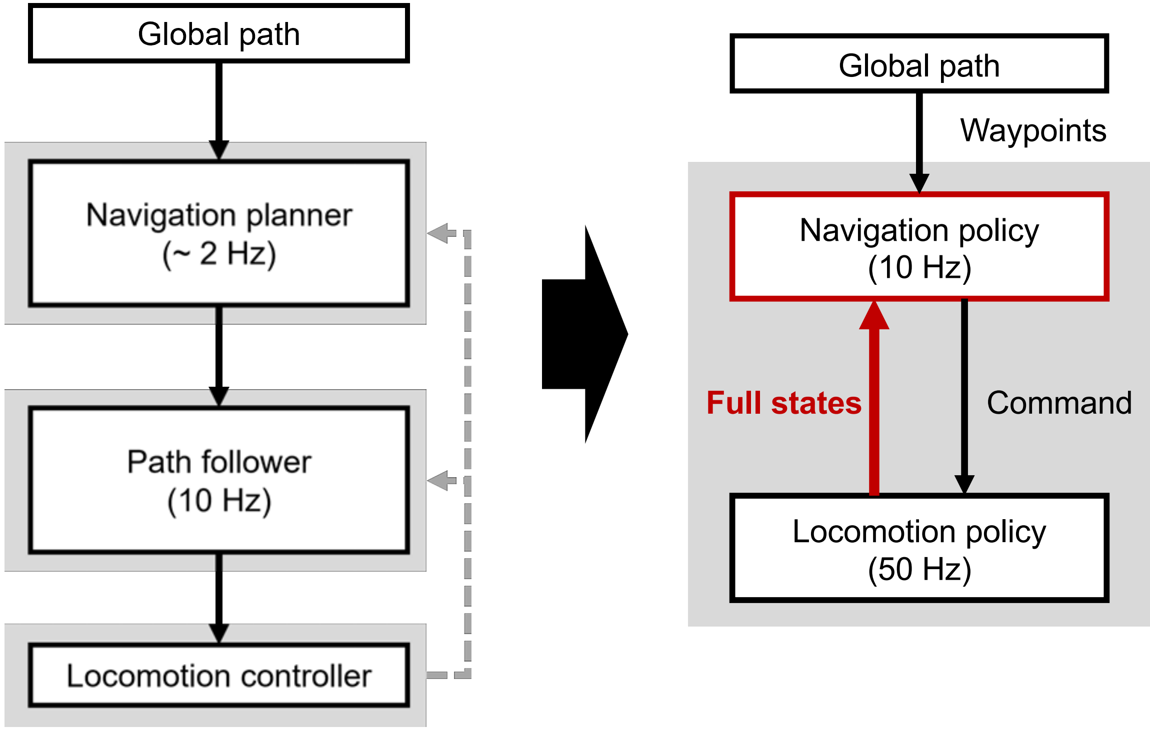
+ communication delay
+ computation delay
+ abstraction
…

Method (1/4): Revise the system design

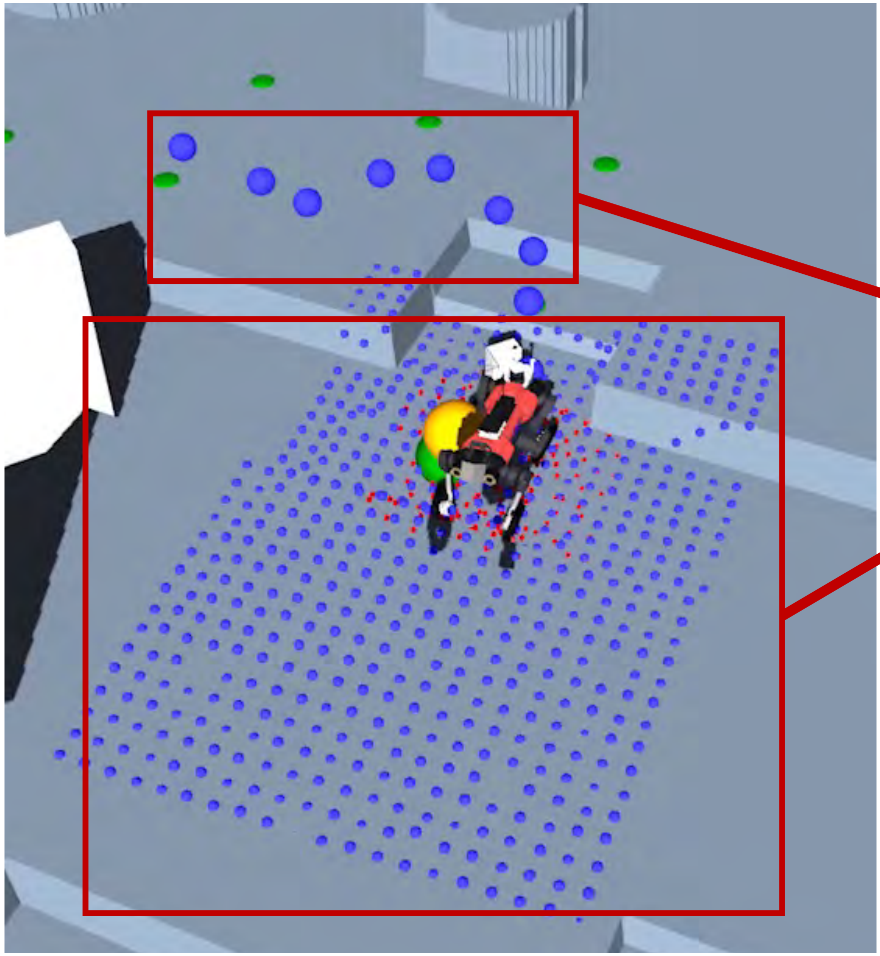
Learning Robust Autonomous Navigation and Locomotion for Wheeled-Legged Robots

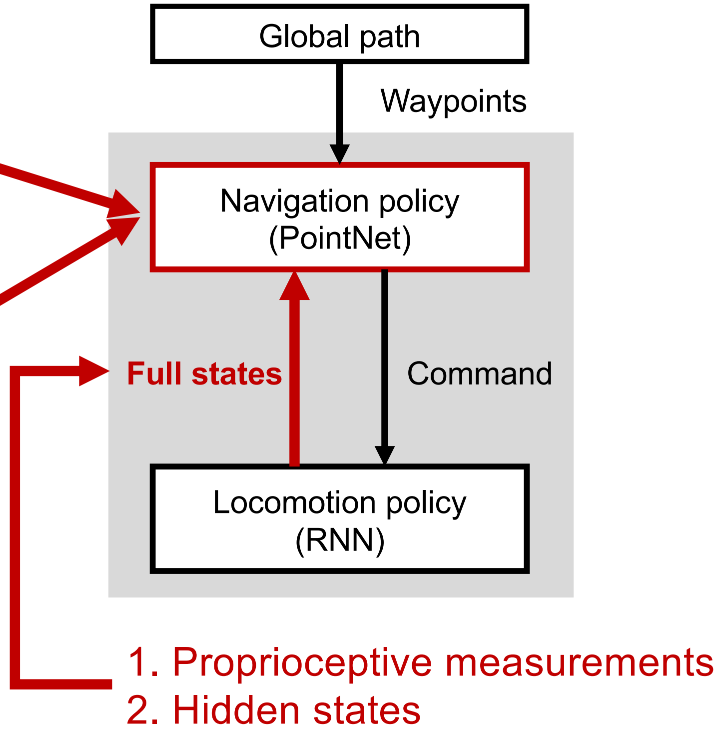
Joonho Lee[1*], Marko Bjelonic[2], Alexander Reske[2], Lorenz Wellhausen[2], Takahiro Miki[1], Marco Hutter[1]

Everything into a single module



Method (2/4): Revise the system design



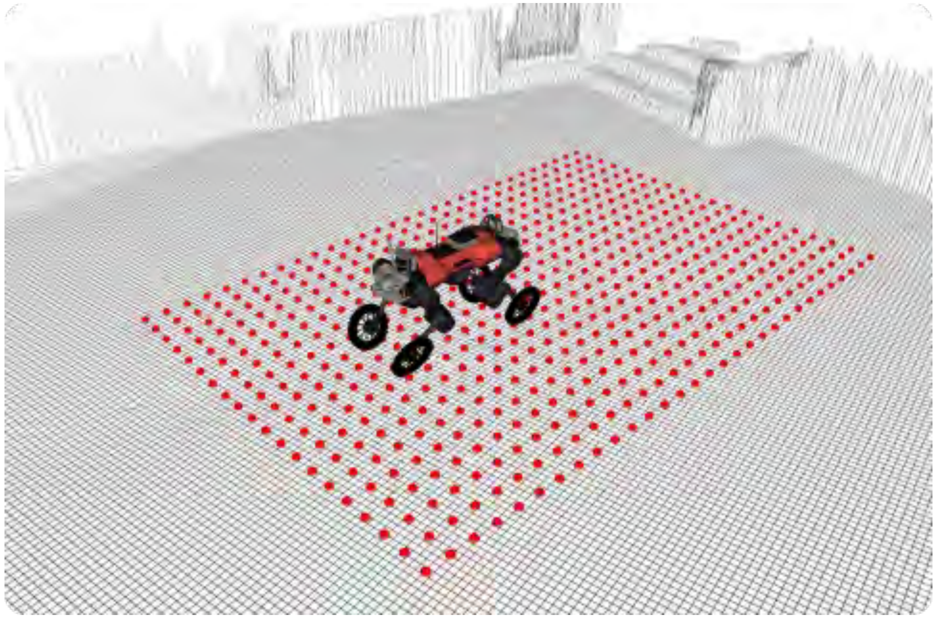


Fast and dynamics-aware control

The resulting navigation controller is very reliable

Exploration behavior

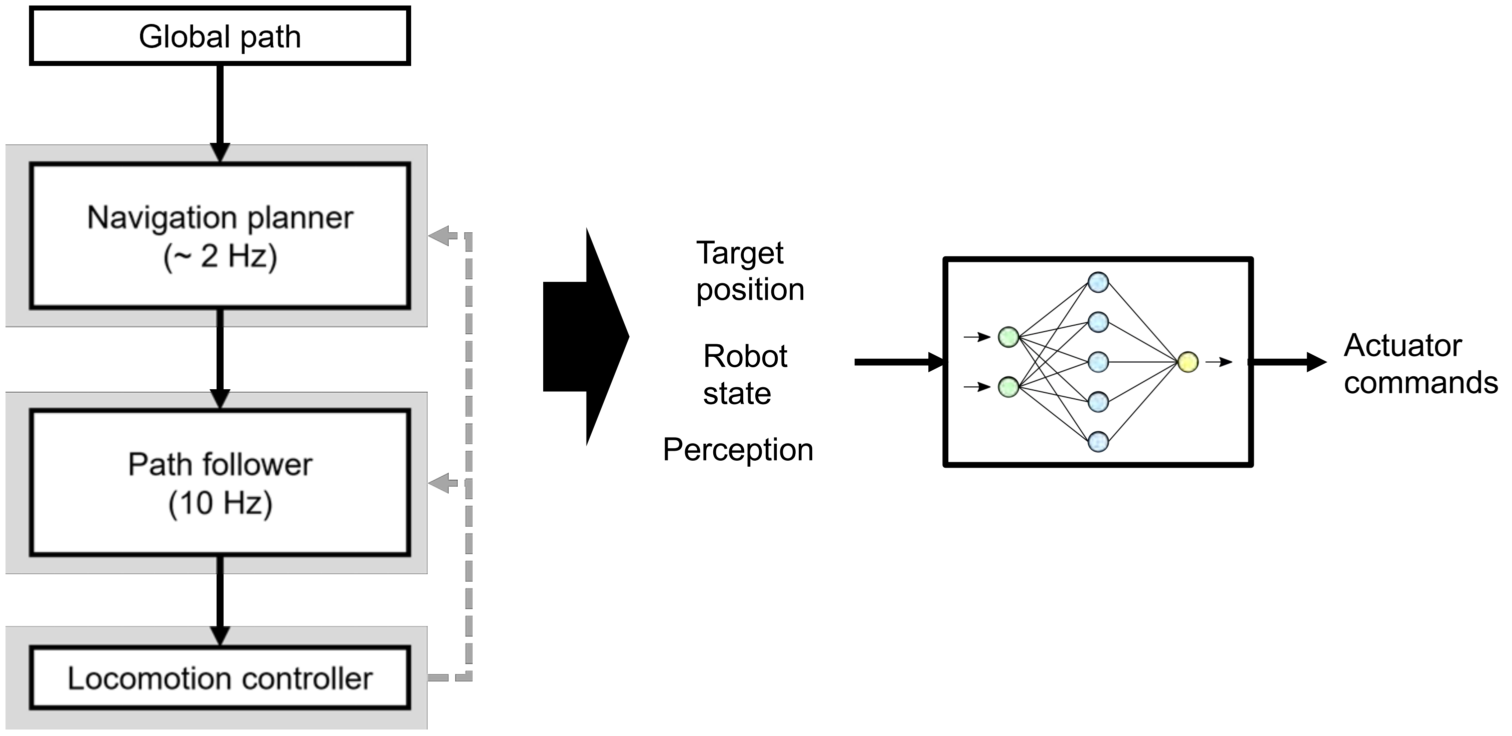
Limited field of view → Overcomes with exploration



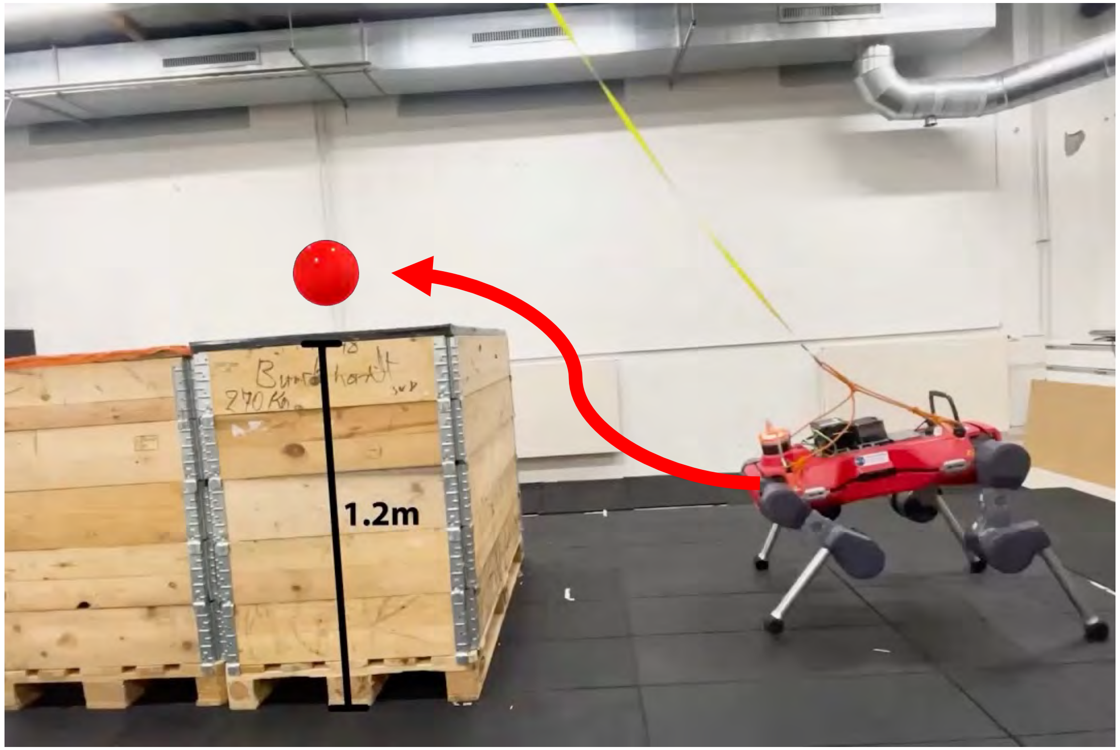
ETH zürich RSL Robotic Systems Lab

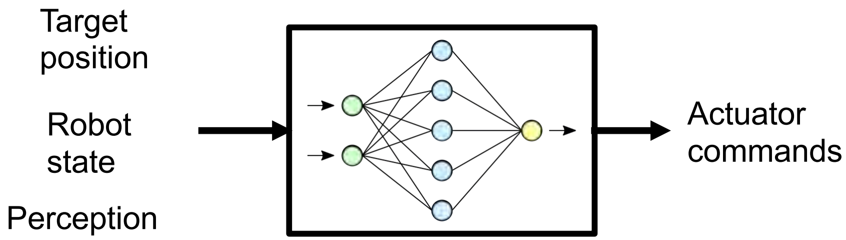
Method (1/4): Revise the system design

Everything into a single module



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

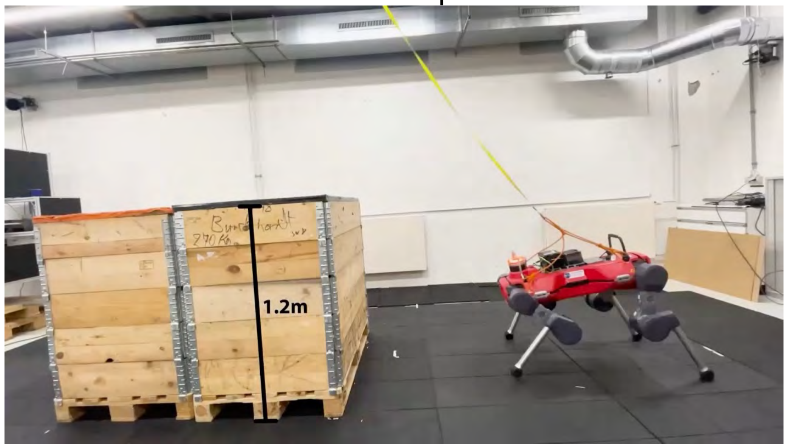




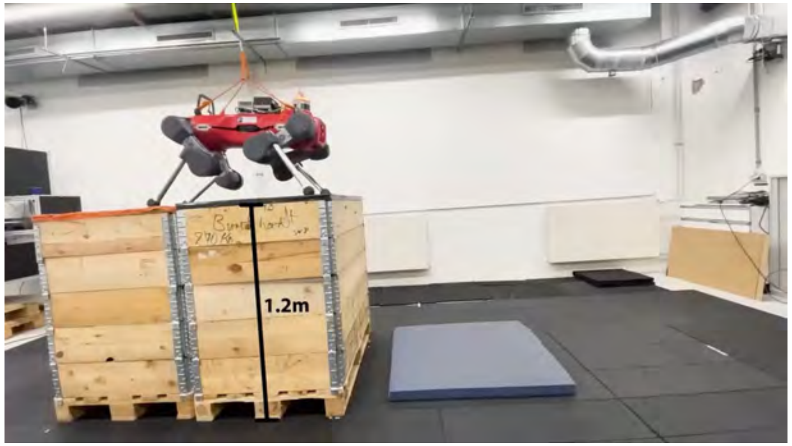
[D. Hoeller, N. Rudin, E. Sako, M. Hutter,
***ANYmal parkour: Learning agile navigation for quadrupedal robots*.**
*Sci. Robot.***9**,eadi7566(2024).]

Locomotion Module

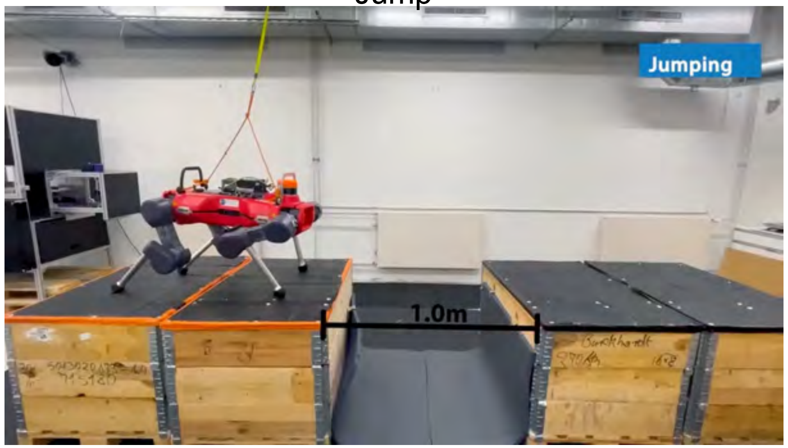
Climb up



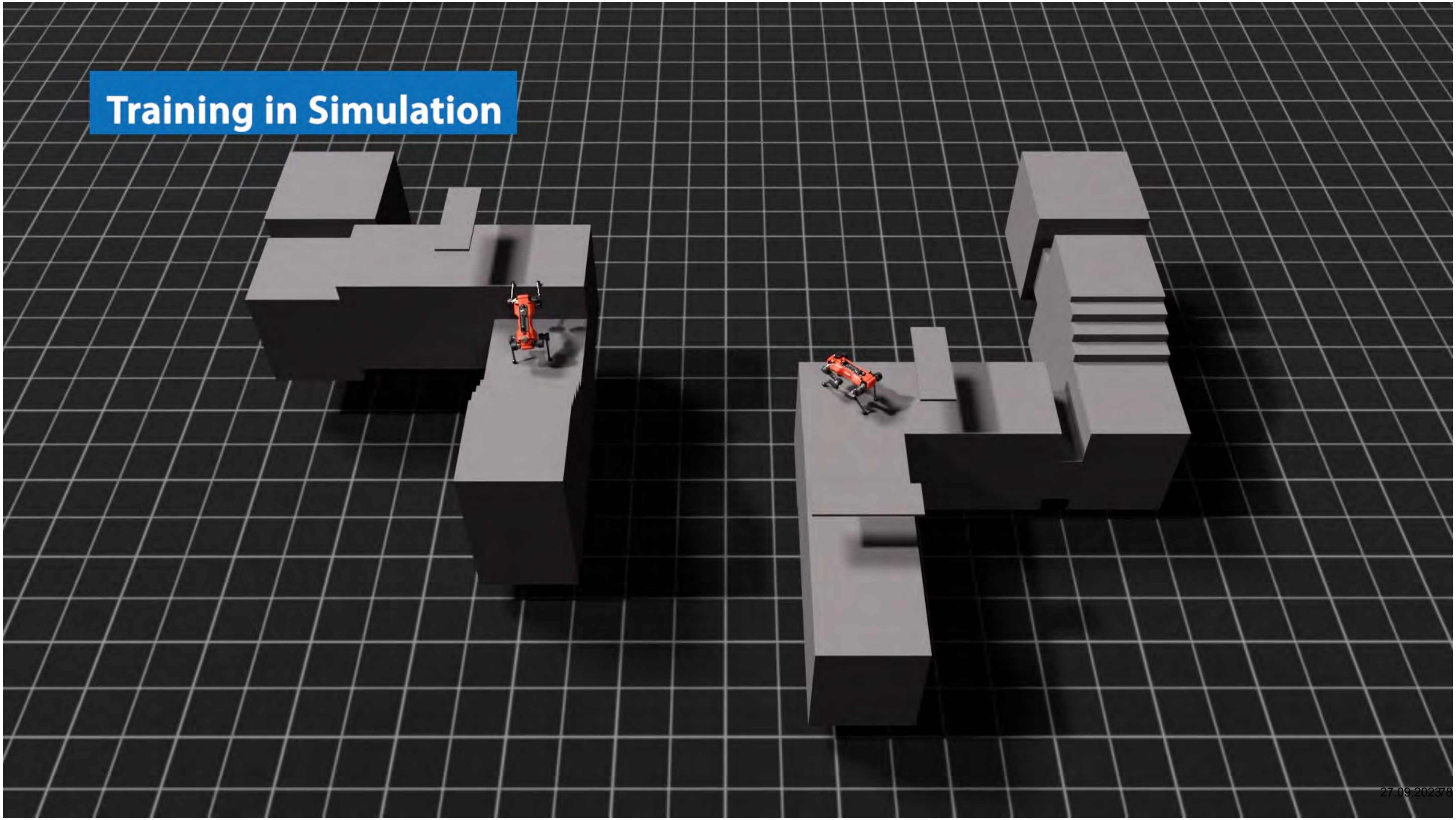
Climb down



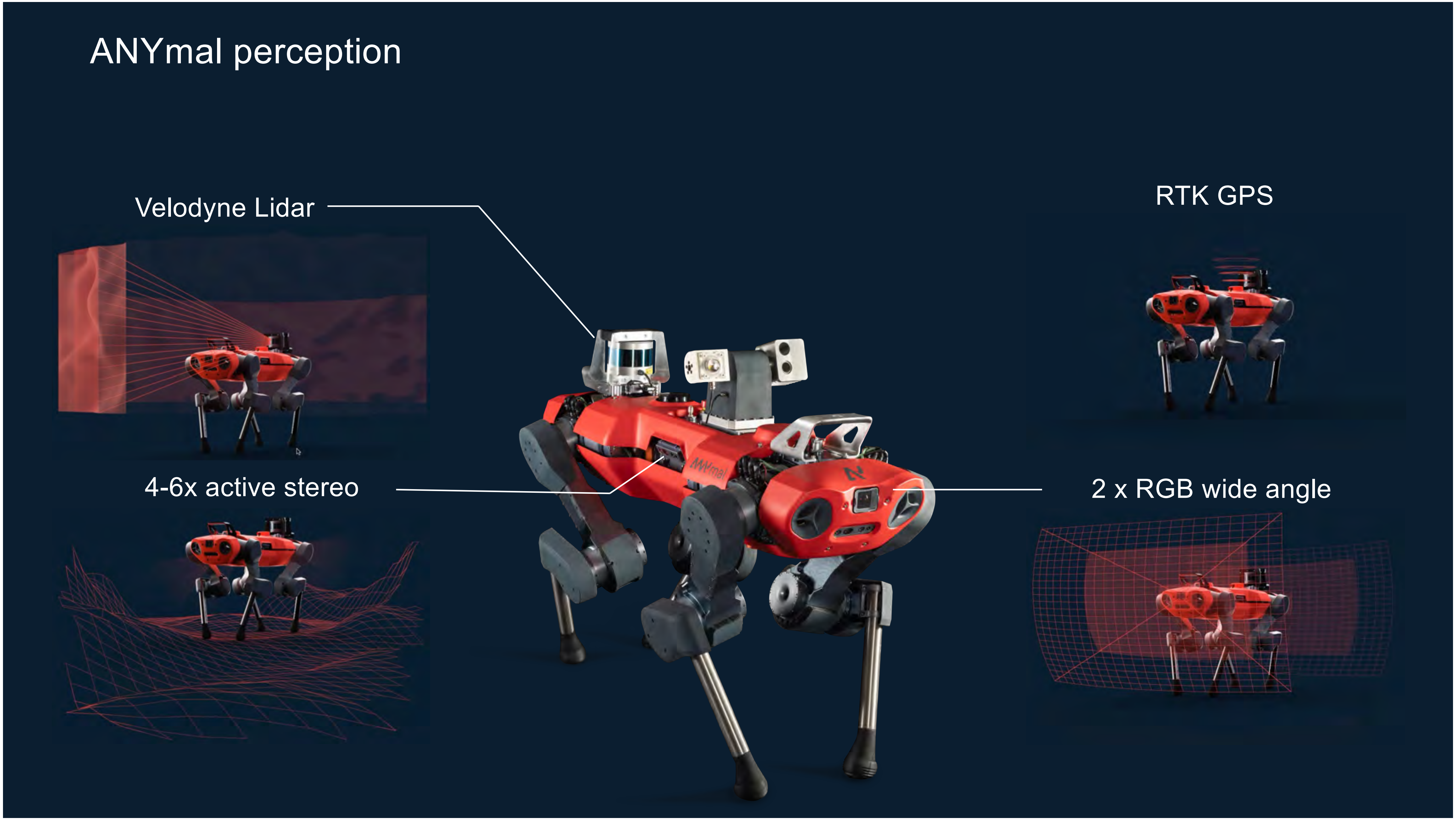
Jump



Crouch


Training in Simulation

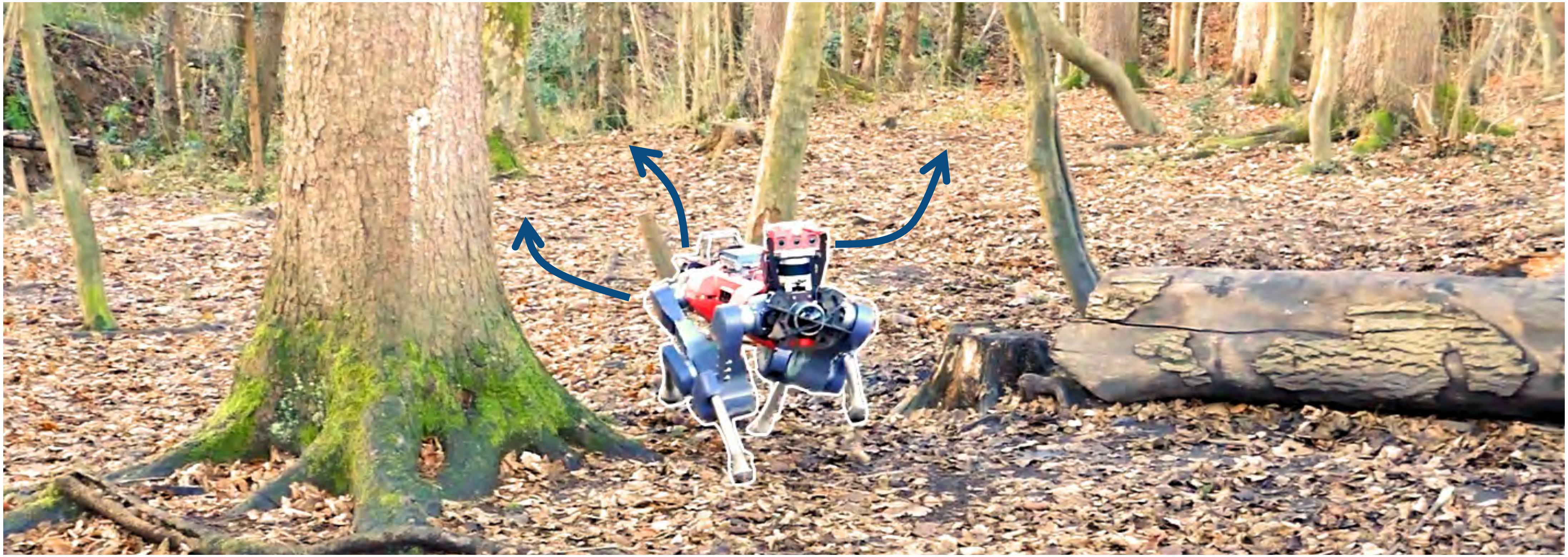
- Onboard sensing only
- No handcrafting
- No a priori knowledge of the environment


ANYmal perception
Velodyne Lidar
RTK GPS
4-6x active stereo
2 x RGB wide angle

[redacted]

Traversability estimation and navigation

- Depends on the Hardware (Robot) and Software (Motion Control)
- Depends on the Terrain (Geometrical Obstacles, Semantics, Slipping)



Traversability estimation and navigation

- Depends on the Hardware (Robot) and Software (Motion Control)
- Depends on the Terrain (Geometrical Obstacles, Semantics, Slipping)

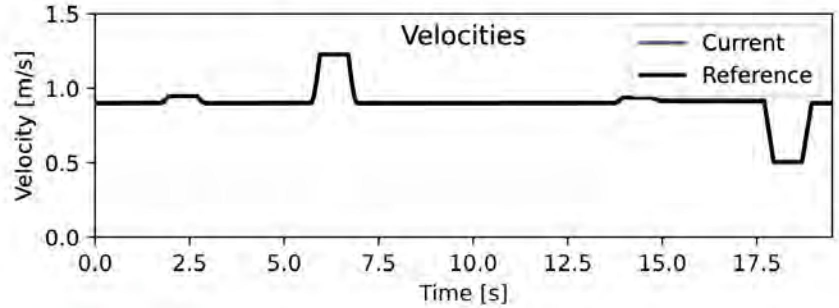
Visual Traversability Estimation

Problem:

- Simulating realistic images and physics is hard
- Real-world data with labels is expensive

Solution:

- Self-supervised learning
- Adaptation during deployment from few data
- Supervision by velocity-tracking error



[Frey, J., Khattak, S., Patel, M., Atha, D., Nubert, J., Padgett, C., Hutter, M., & Spieler, P. (2024). *RoadRunner - Learning Traversability Estimation for Autonomous Off-road Driving*.]
[Mattamala, M., Frey, J., Libera, P., Chebrolu, N., Martius, G., Cadena, C., Hutter, M., & Fallon, M. (2024). *Wild Visual Navigation: Fast Traversability Learning via Pre-Trained Models and Online Self-Supervision*.]

Visual Traversability Estimation

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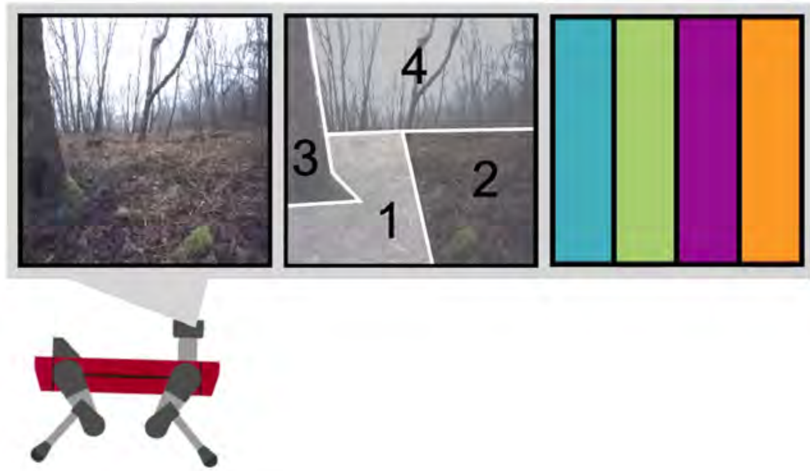


use high-dimensional features from pre-trained self-supervised models,

- implicitly encode semantic information
- massively simplifies the learning task

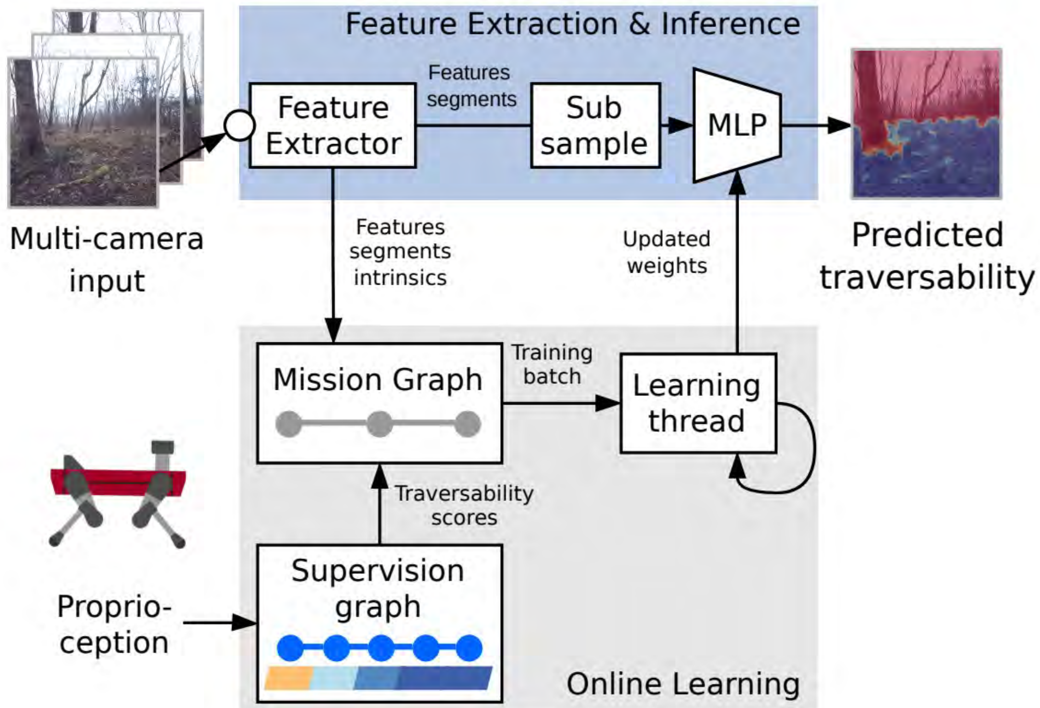
Visual Traversability Estimation

Problem:

- Simulating realistic images and physics is hard
- Real-world data with labels is expensive

Solution:

- Self-supervised learning
- Adaptation during deployment from few data
- Supervision by velocity-tracking error
- Online training



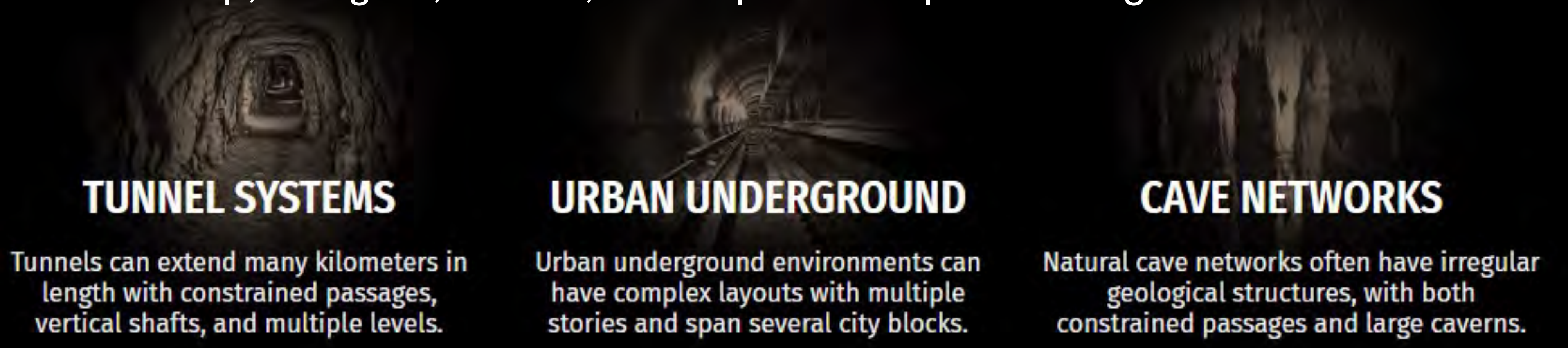
Visual Traversability Estimation V1

Part 4: Applications

DARPA SubT Challenge (2019-2021)

Mobile robots for challenging environments

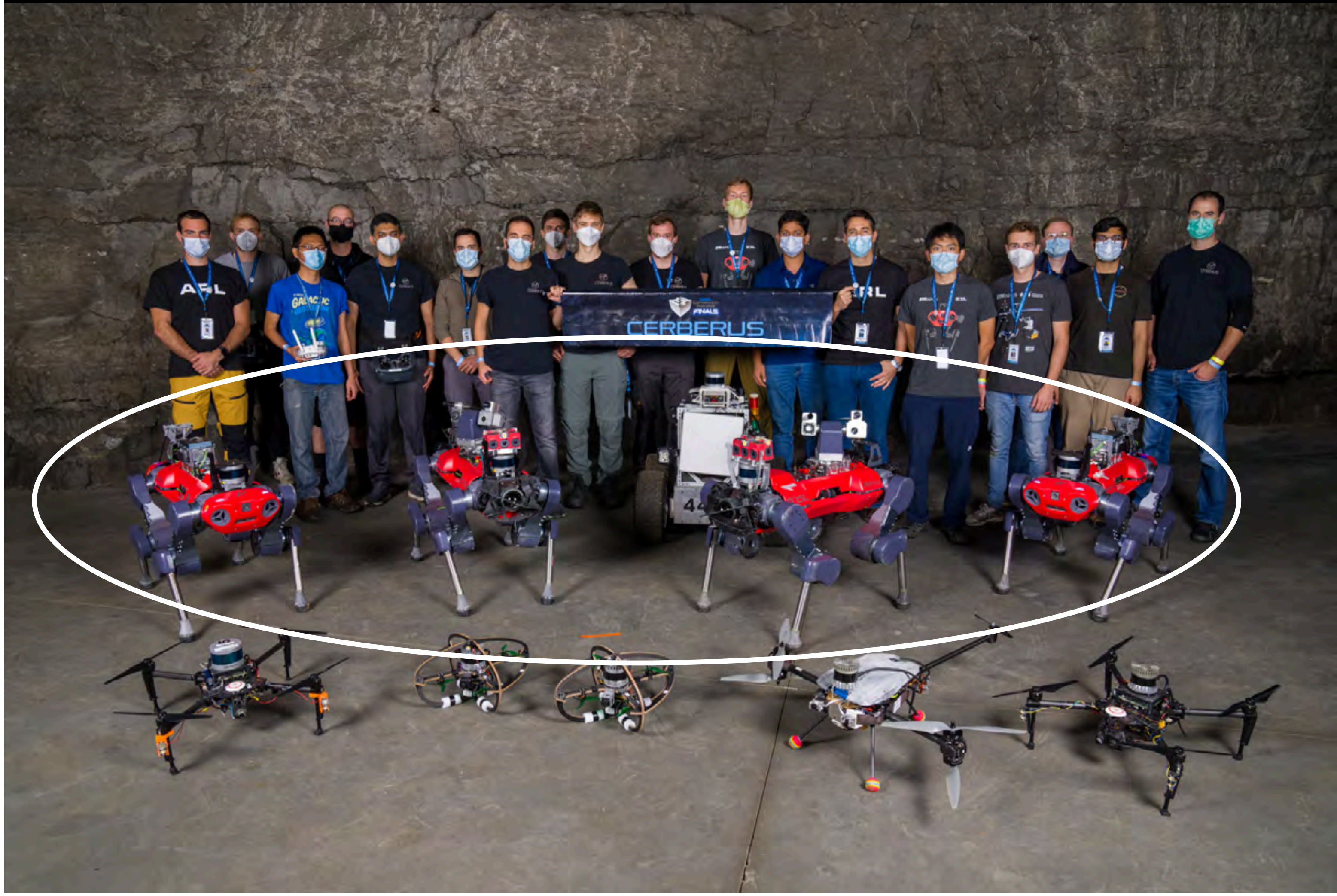
Goal: map, navigate, search, and explore complex underground environments



Challenges:

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

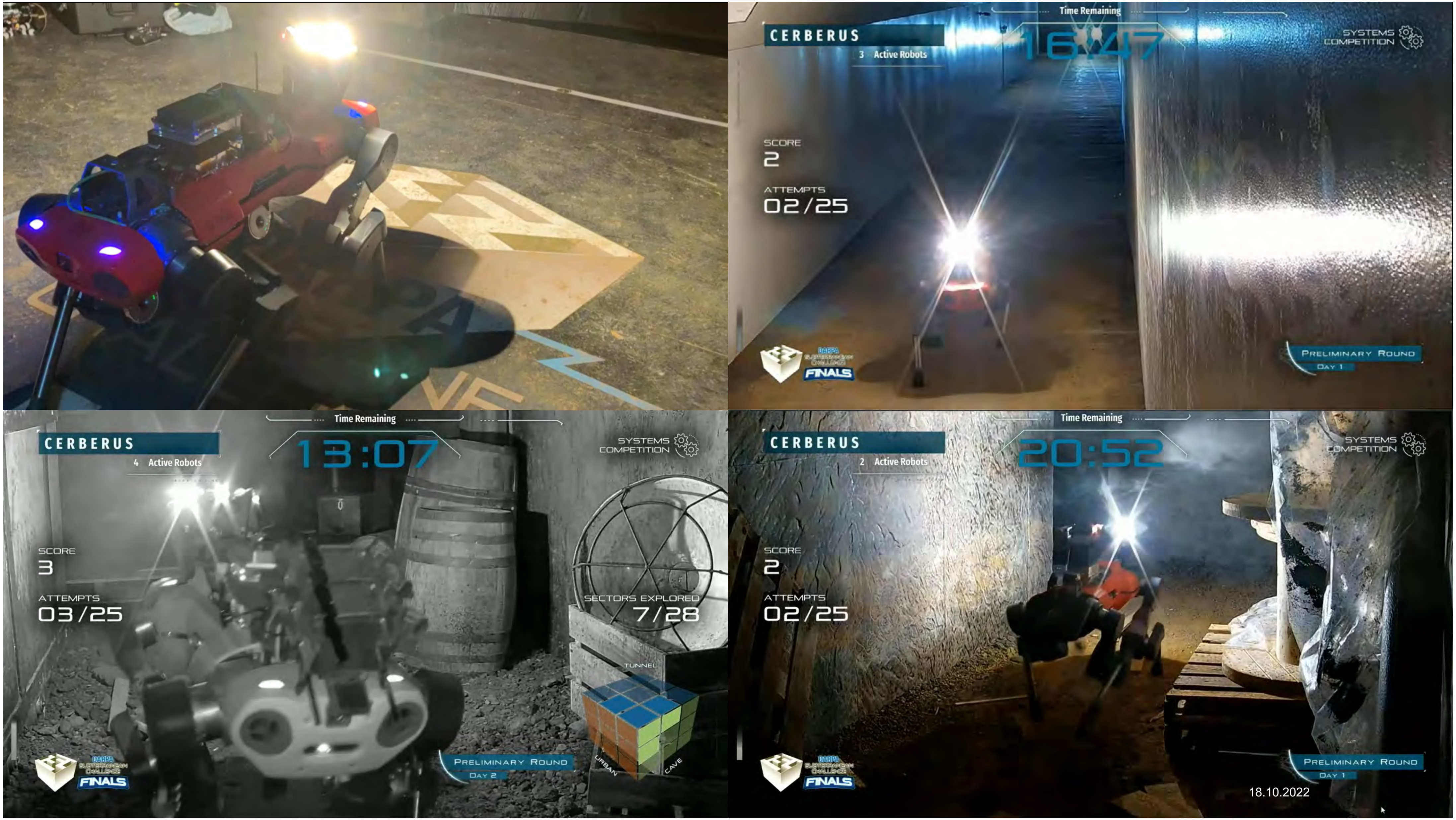
DARPA SubT Challenge – Mobile robots for challenging environments

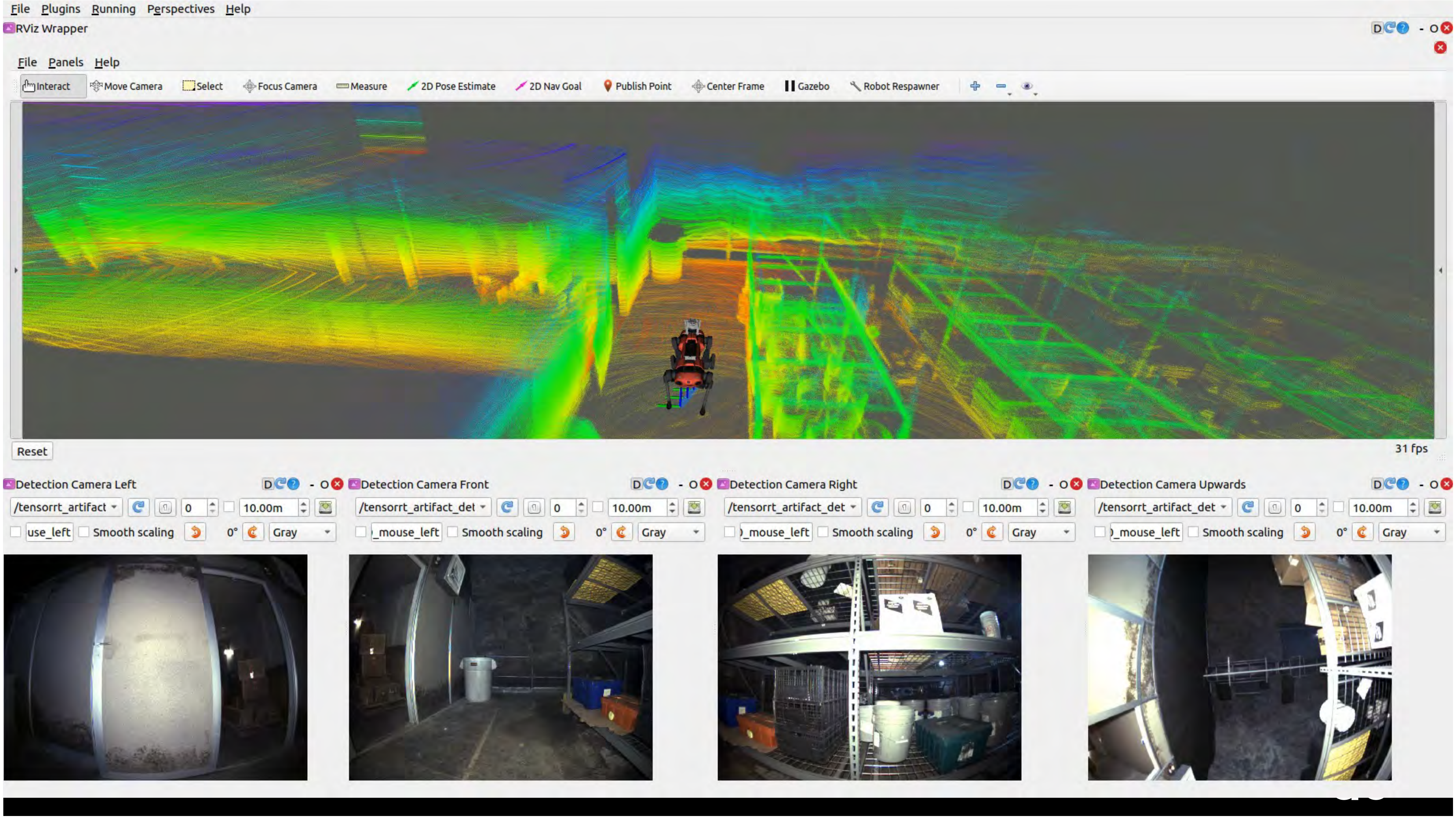


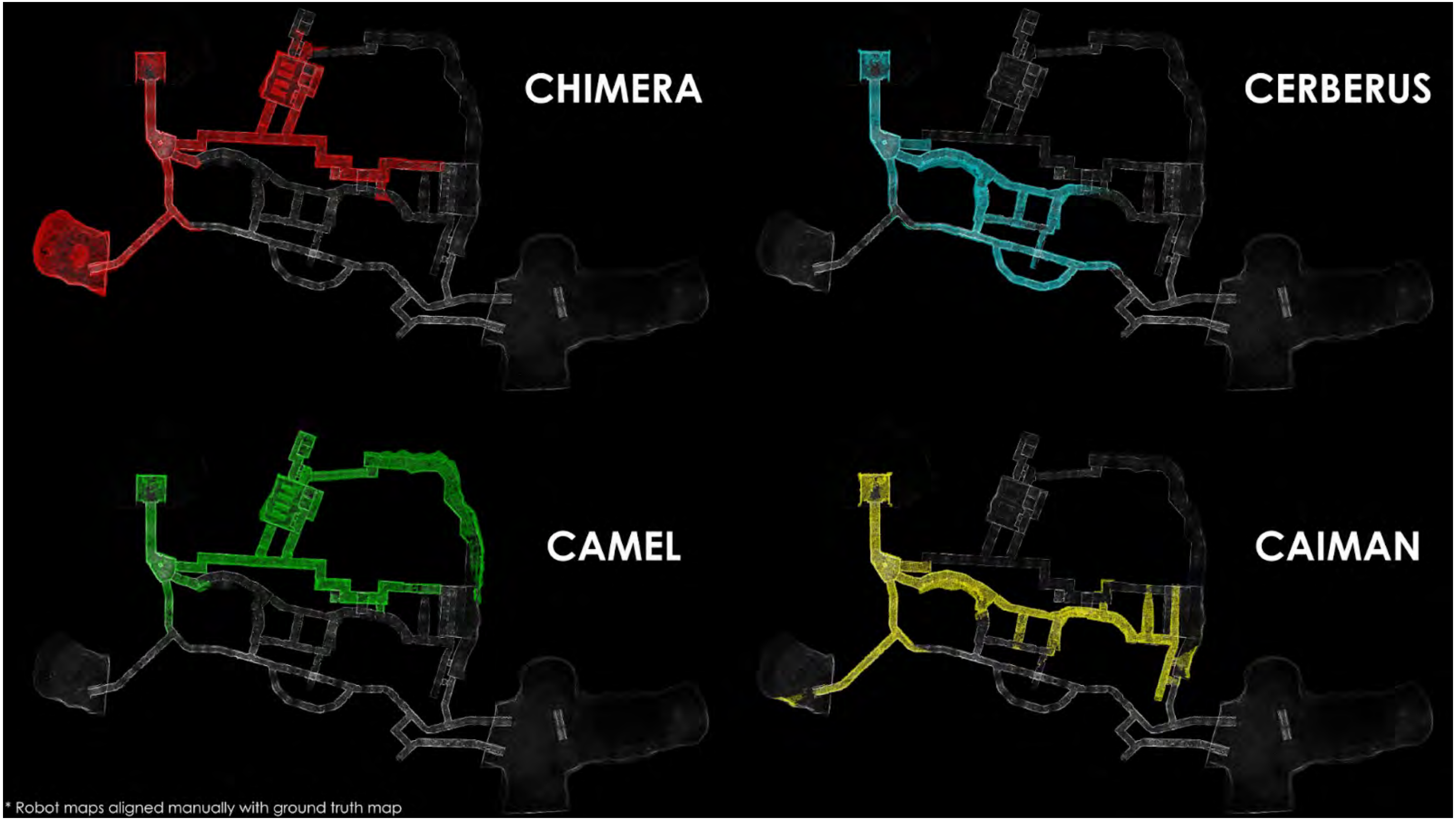
Team CERBERUS

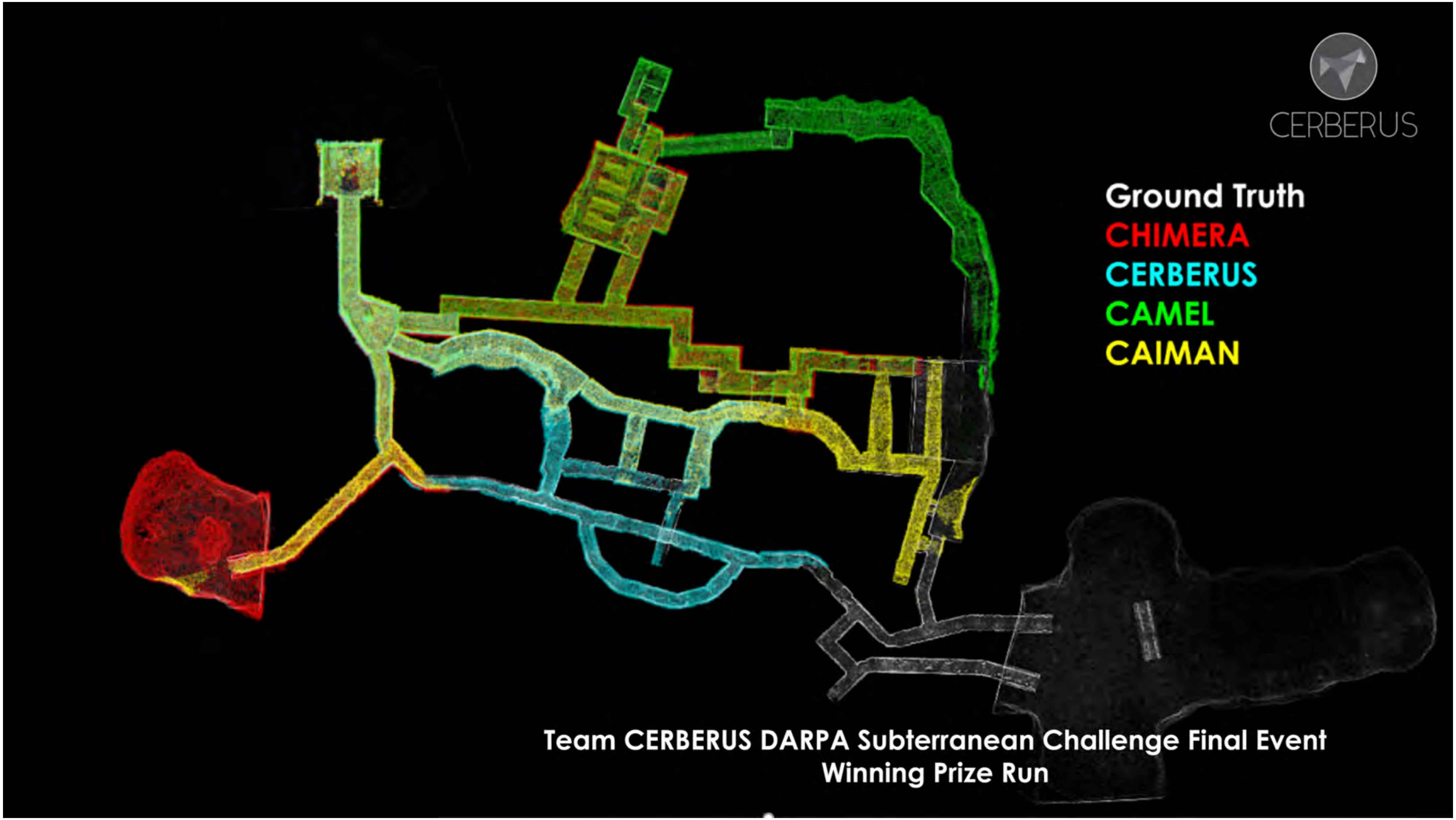
At Finals:
ARL – UNR/NTNU
RSL – ETHZ
ASL – ETHZ

Other Contributors:
Oxford, Flyability, Berkeley, SNC


Time Remaining
CERBERUS
3 Active Robots
16:47
SYSTEMS COMPETITION
SCORE
2
ATTEMPTS
02/25
FINALS
PRELIMINARY ROUND
DAY 1
Time Remaining
CERBERUS
4 Active Robots
13:07
SYSTEMS COMPETITION
SCORE
3
ATTEMPTS
03/25
SECTORS EXPLORED
7/28
TUNNEL
URBAN
CAVE
FINALS
PRELIMINARY ROUND
DAY 2
Time Remaining
CERBERUS
2 Active Robots
20:52
SYSTEMS COMPETITION
SCORE
2
ATTEMPTS
02/25
FINALS
PRELIMINARY ROUND
DAY 1
18.10.2022


File Plugins Running Perspectives Help
RViz Wrapper
File Panels Help
Interact
Move Camera
Select
Focus Camera
Measure
2D Pose Estimate
2D Nav Goal
Publish Point
Center Frame
Gazebo
Robot Respawner
Reset
31 fps
Detection Camera Left
Detection Camera Front
Detection Camera Right
Detection Camera Upwards
/tensorrt_artifact
/tensorrt_artifact_det
10.00m
use_left
_mouse_left
Smooth scaling
0°
Gray


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

AUTOMATED MANUFACTURING

Enabled by 3 million
industrial robots in operation

SMART WAREHOUSING

Enabled by 600'000
warehouse robots in operation

AUTONOMOUS INDUSTRY

Enabled by
autonomous mobile robots


ANYbotics

Industrial plant inspection

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

Thank you!

More information:
- leggedrobotics.com
- youtube.com/leggedrobotics
- bitbucket.org/leggedrobotics
- github.com/leggedrobotics

Start to collaborate
- anymal-research.org

National Centre of Competence in Research Digital Fabrication
armasuisse W+T Wissenschaft + Technologie FoProg. 5/6
NVIDIA
European Commission | Horizon 2020 European Union funding for Research & Innovation
DARPA
intel
MOOG
menzi muck
Leica Geosystems
ECHORD++
FNSNF Fonds National Suisse Schweizerischer Nationalfonds Fondo Nazionale Svizzero Swiss National Science Foundation
KTI/CTI
society in science The Branco Weiss Fellowship
erc European Research Council
FESTO
TOTAL
ANYBOTICS
Wyss Zurich Translational Center
robotics Swiss National Centre of Competence in Research

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?

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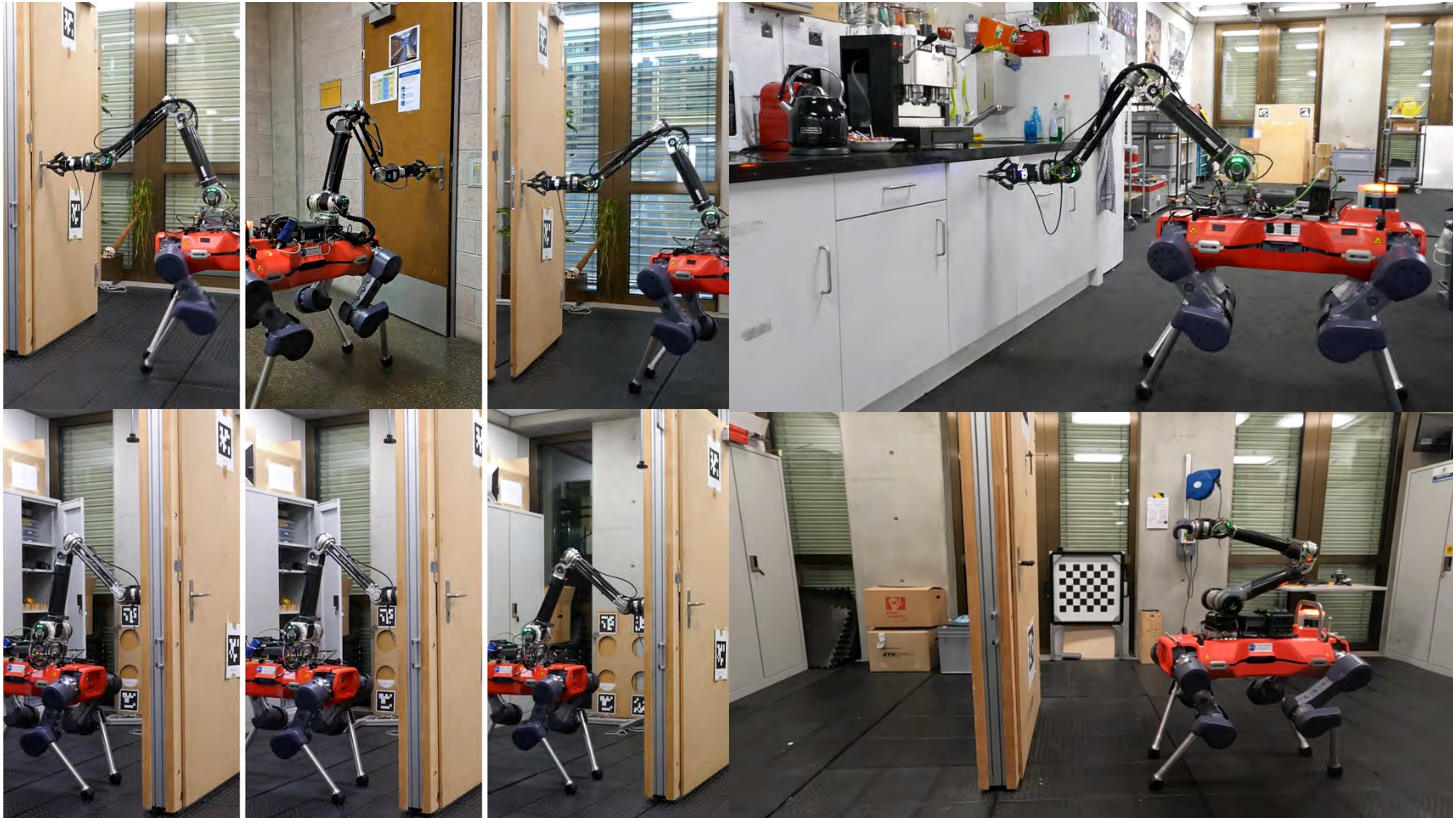
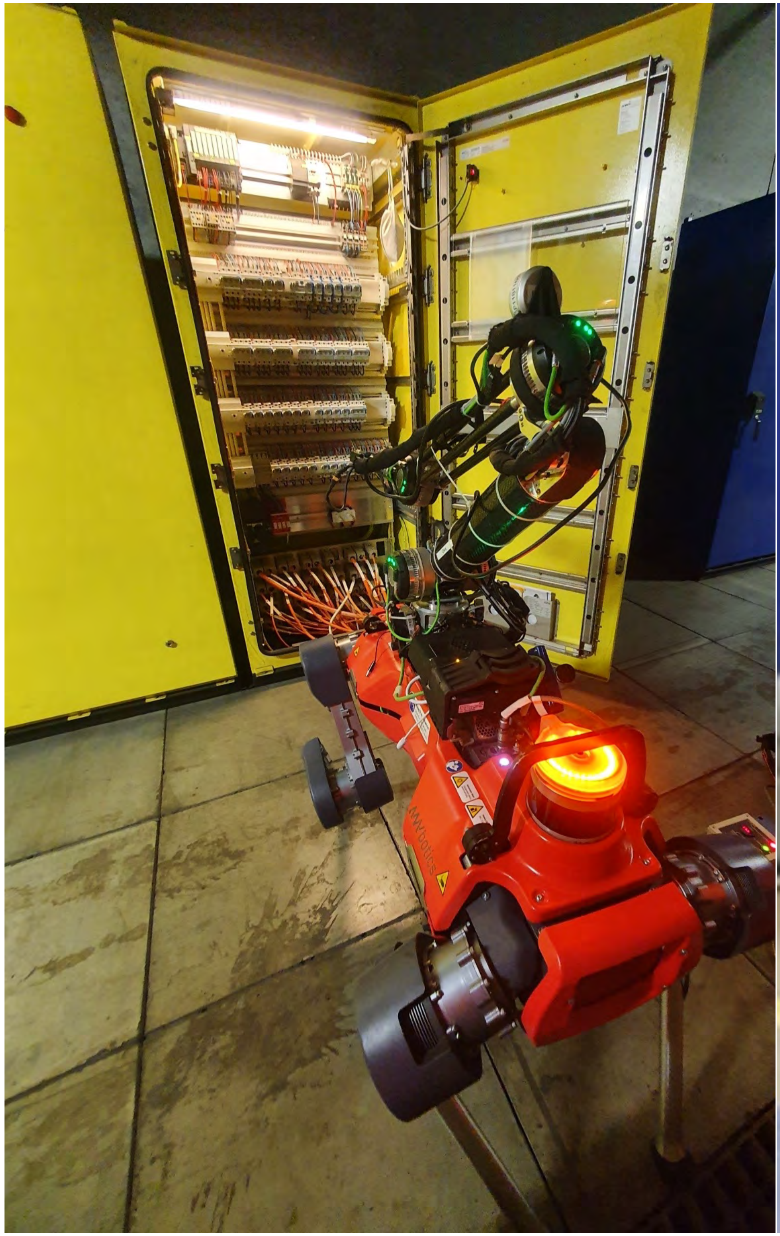
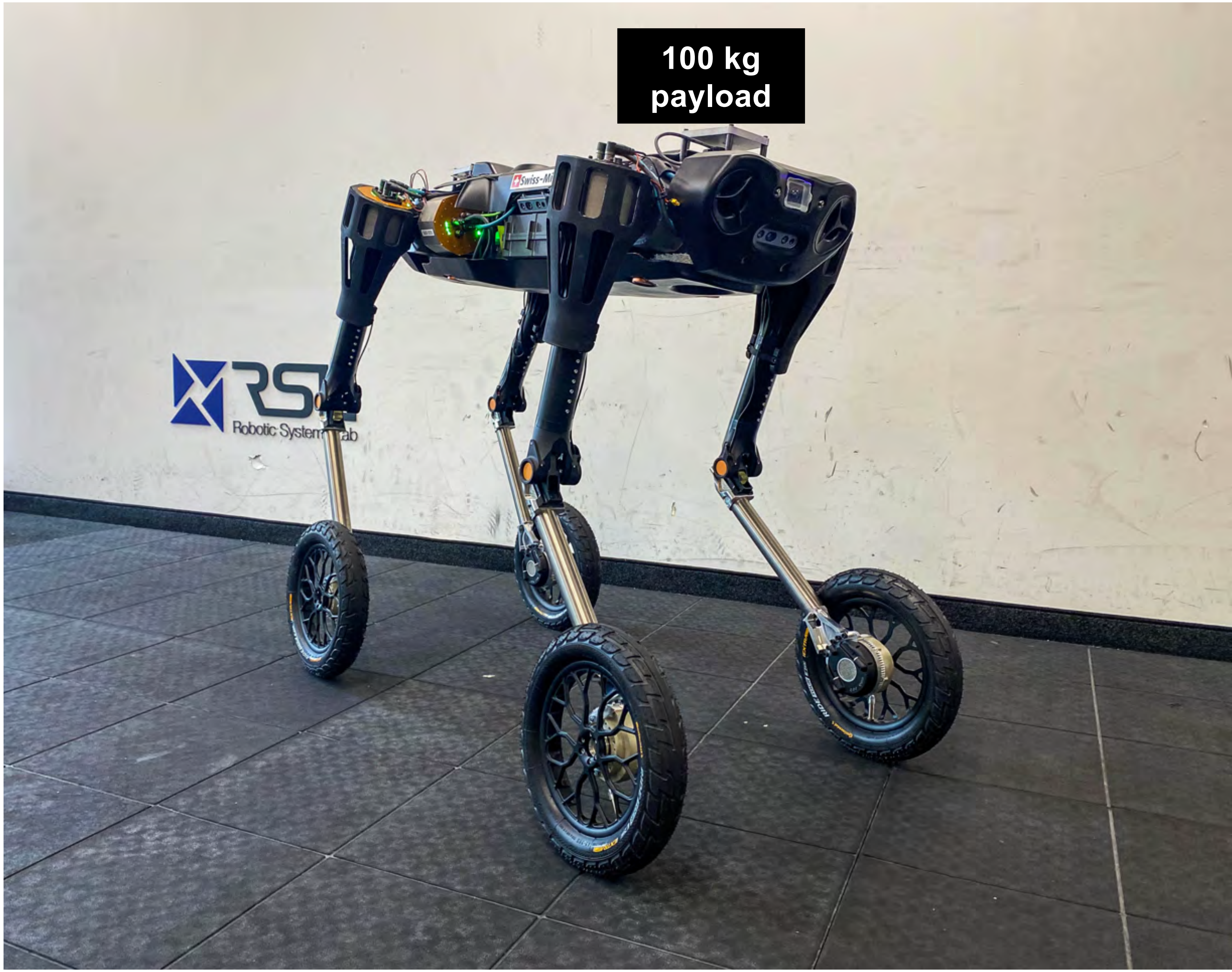
Part 5: Future stuff






maxon
maxon


Fast


100 kg
payload

Important Events

- 1.11.2024 Swiss Robotics Day (www.swissroboticsday.ch)
- 6.12.2024 RSL open lab evening (Friday evening, robots & party) www.rsl.ethz.ch