ETH zürich

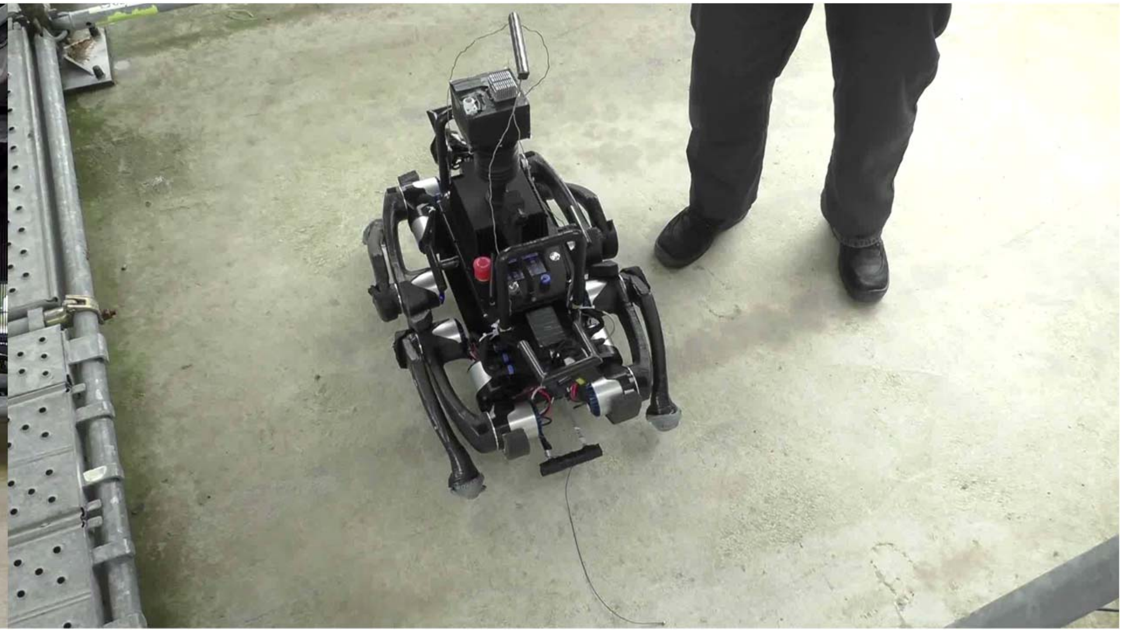
ANYmal – Dynamic Legged Locomotion in Realistic Terrains

Marco Hutter + Legged Robotics Folks at ETH and ANYbotics

ETH Zurich

RSL Robotic Systems Lab

ANYmal applications – Industrial inspection



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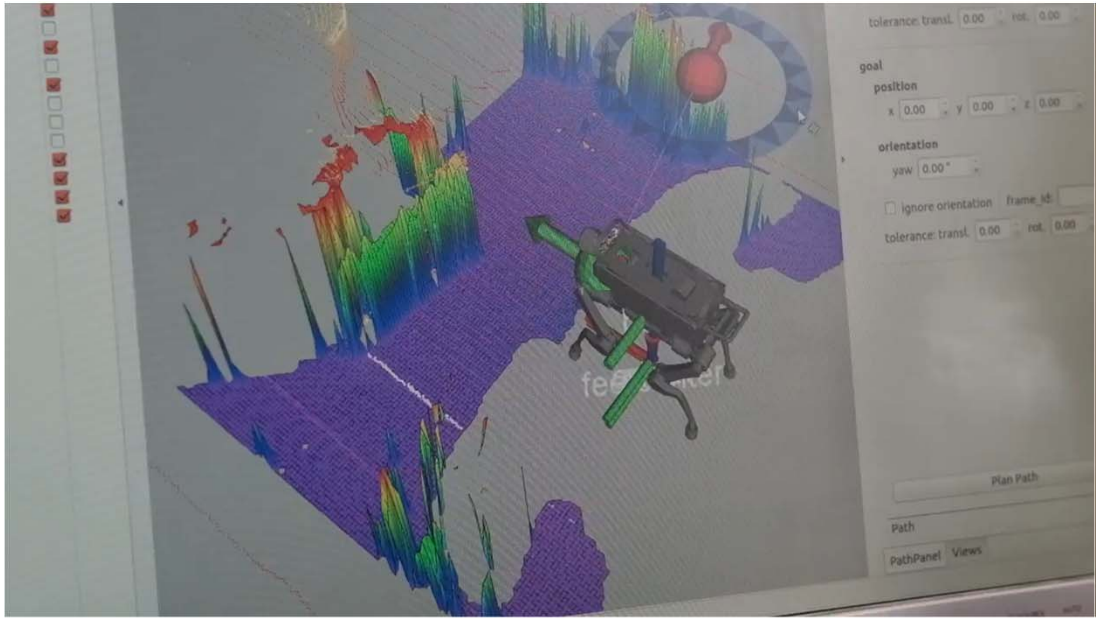
ANYmal applications – Search and Rescue



ANYmal applications – forestry and many others

Locomotion control so far

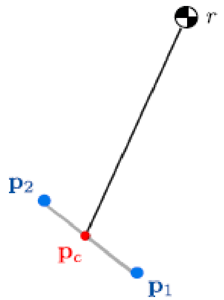
- Relatively flat ground with no obstacles
- ➢ stable, reactive trot

- Obstacles/rough terrain
- ➢ walking with foothold planning

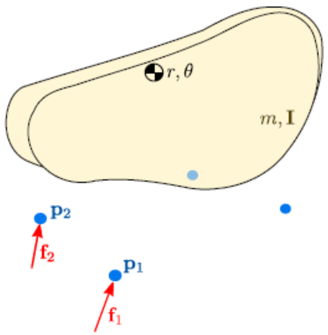
Motion generation trough (real-time) trajectory optimization

- Generate a optimal/feasible motion to cross a terrain
  - Motion of base
  - Foothold location
  - Footfall timing

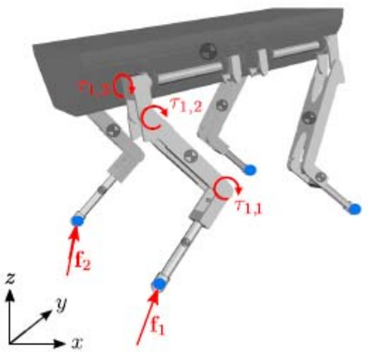
Motion generation trough (real-time) trajectory optimization



Bellicoso et al: ***Dynamic Locomotion through Online Nonlinear Motion Optimization for Quadrupedal Robots***

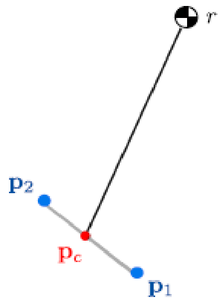


Winkler et al: **Gait and Trajectory Optimization for Legged Systems through Phase-Based End-Effector Parameterization**



Neunert et al: ***Whole-Body Nonlinear Model Predictive Control through Contacts for Quadrupeds***

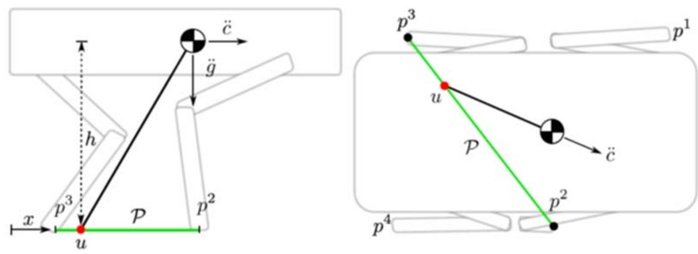
Reduced complexity models for real-time TO



Bellicoso et al: ***Dynamic Locomotion through Online Nonlinear Motion Optimization for Quadrupedal Robots***

Simpify the model for realtime optimization

Trajectory optimization using ZMP-model

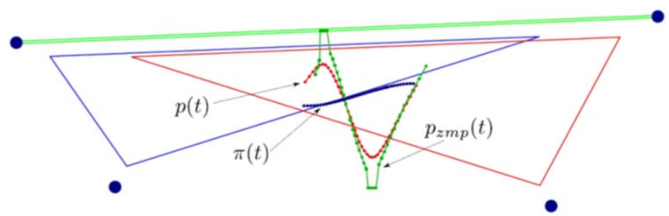


- Trajectory optimization based on ZMP
  - Legs are comparably lightweight
  - Body keeps orientation
  - (mostly) Body is moving horizontally

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

Linearizes the problem!

- Optimize for polynomial spline paramters of the CoG trajectory
  - Min integral over acceleration^2 + regularization
    s.t. - target goal is reached in time
    - ZMP is within support area

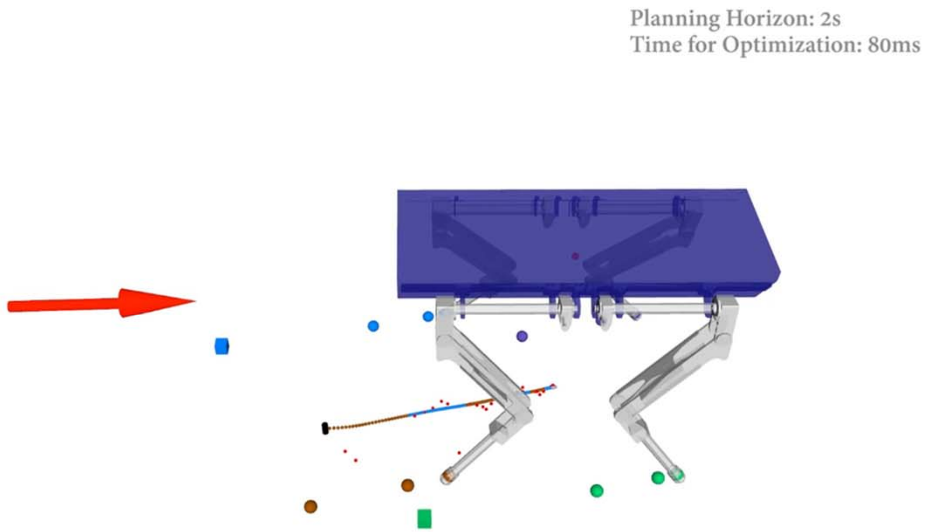


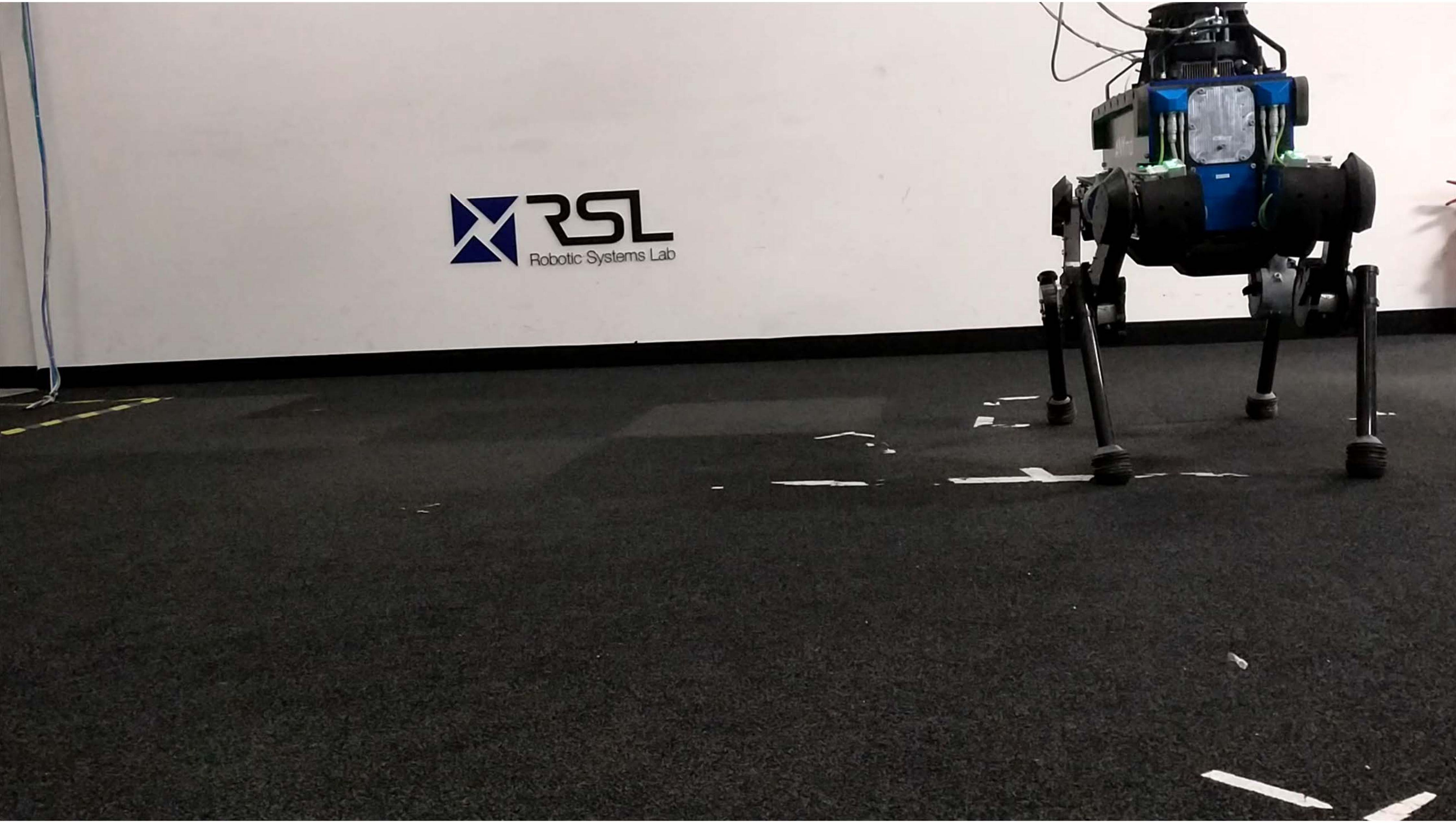
- Optimize for foothold locations separately
  - Min offset to nominal footholds
    s.t. – reachability is fulfilled

linear system:	*QP (e.g. QuadProg++)*	*<1ms*
Non-linear system:	*SQP (e.g. IPOPT,SNOPT)*	*<10ms-100ms*

Bellicoso et al, 2017

Winkler 2017, Bellicoso 2018


Planning Horizon: 2s
Time for Optimization: 80ms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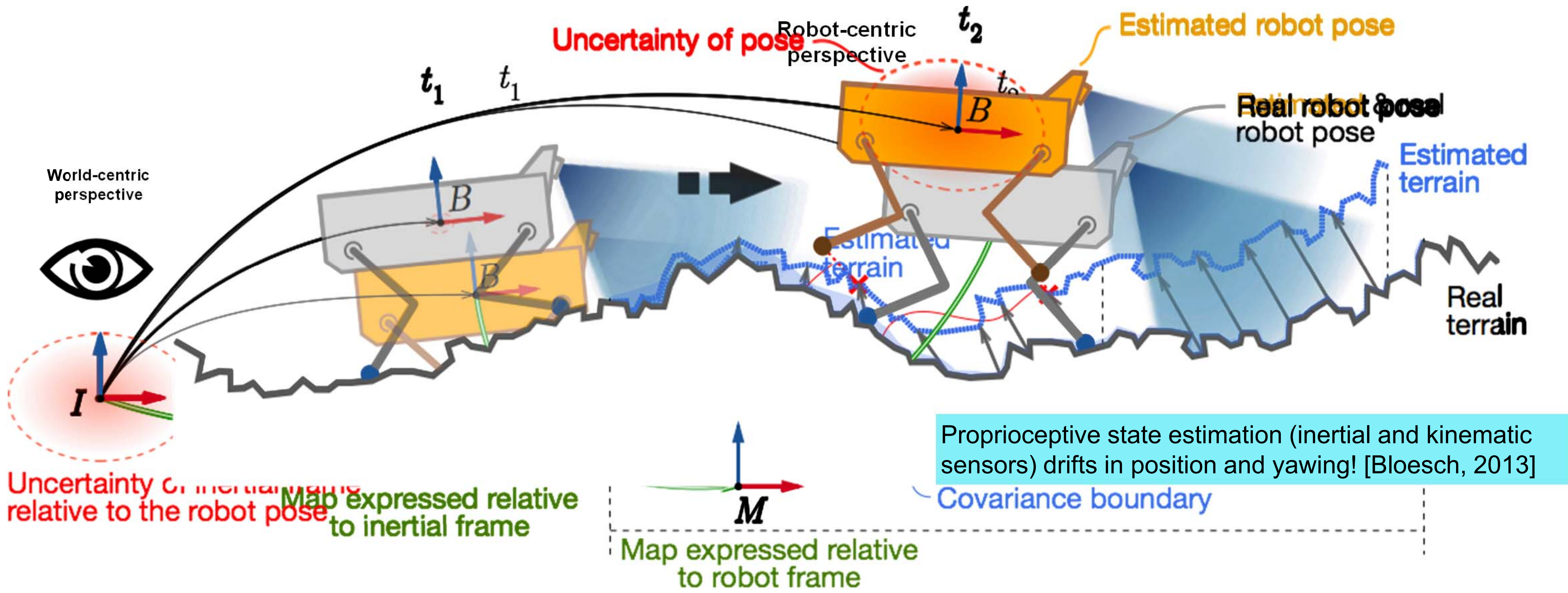
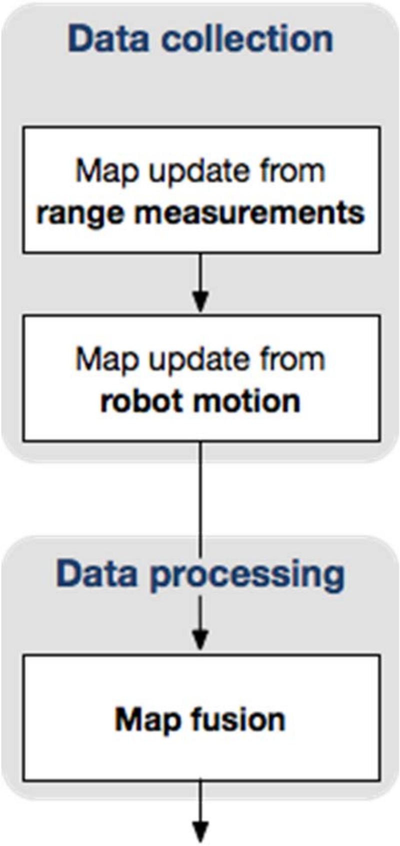
Let’s combine this with perception…

Robot-Centric Terrain Mapping Approach

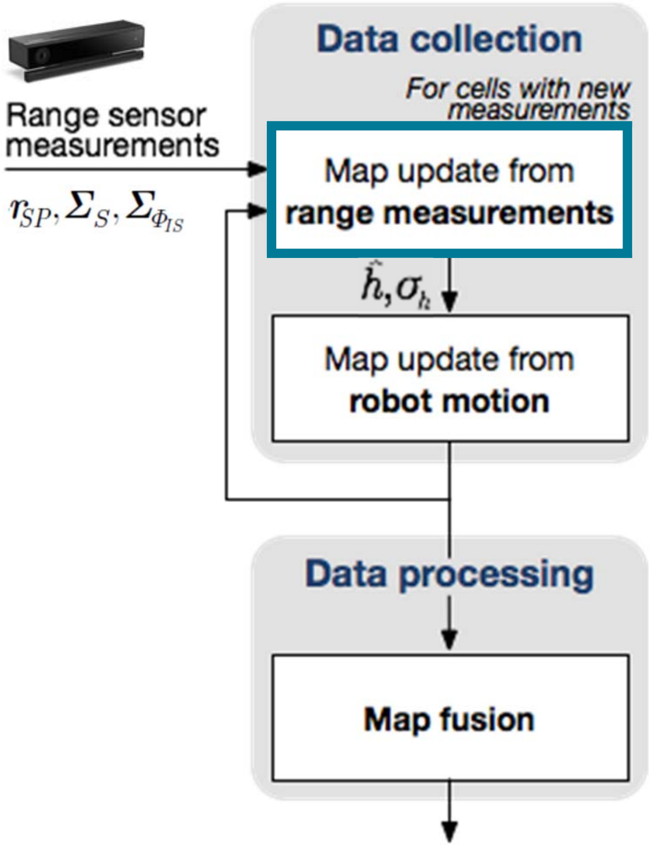


Proprioceptive state estimation (inertial and kinematic sensors) drifts in position and yawing! [Bloesch, 2013]

Mapping Method



Mapping Method: Update from Range Measurements



For cells with new range measurements:

- Height measurement in map frame *M*

$$p = \mathbf{P}\left(\Phi_{SM}^{-1}\left({}_S\mathbf{r}_{SP}\right) - {}_M\mathbf{r}_{SM}\right)$$

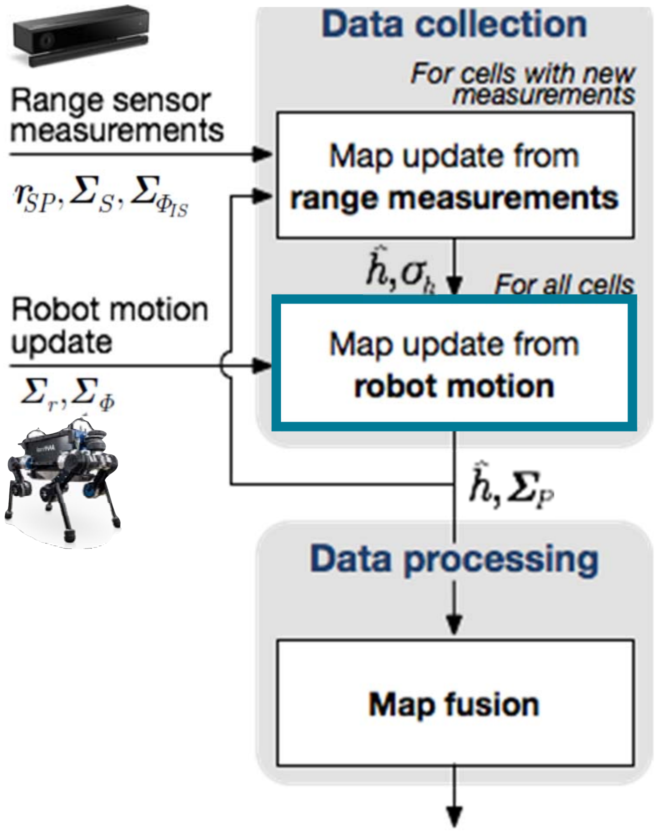
- Error propagation for height measurement variance

$$\sigma_p^2 = \mathbf{J}_S \mathbf{\Sigma}_S \mathbf{J}_S^{\mathsf{T}} + \mathbf{J}_\Phi \mathbf{\Sigma}_{\Phi_{IS}} \mathbf{J}_\Phi^{\mathsf{T}}$$

- If data exists in cell, fuse with Kalman filter

New height for cell $\hat{h}^+ = \dfrac{\sigma_p^2\,\hat{h}^- + \hat{\sigma}_h^{2-}\,\tilde{p}}{\sigma_p^2 + \hat{\sigma}_h^{2-}}$, New variance for cell $\sigma_h^{2+} = \dfrac{\hat{\sigma}_h^{2-}\,\sigma_p^2}{\hat{\sigma}_h^{2-} + \sigma_p^2}$

Mapping Method: Update from Robot Motion



For all cells in map:

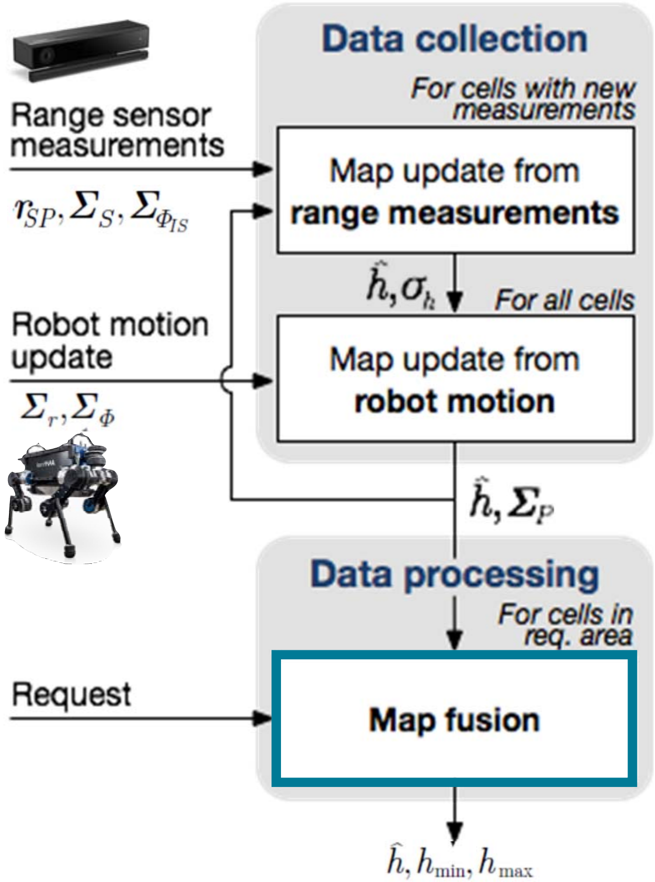
- Transform to covariance matrix

$$\Sigma_{P_i} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \sigma_{h_i}^2 \end{bmatrix} \in \mathbb{R}^{3\times 3}$$

- Update robot pose uncertainty from time *k* to *k*+1

$$\underbrace{\Sigma_{P_i,k+1}}_{\text{New cell covariance}} = \underbrace{\Sigma_{P_i,k}}_{\text{Previous cell covariance}} + \underbrace{J_r \Sigma_r J_r^\top + J_\Phi \Sigma_\Phi J_\Phi^\top}_{\text{Robot pose covariance from } k \text{ to } k+1}$$

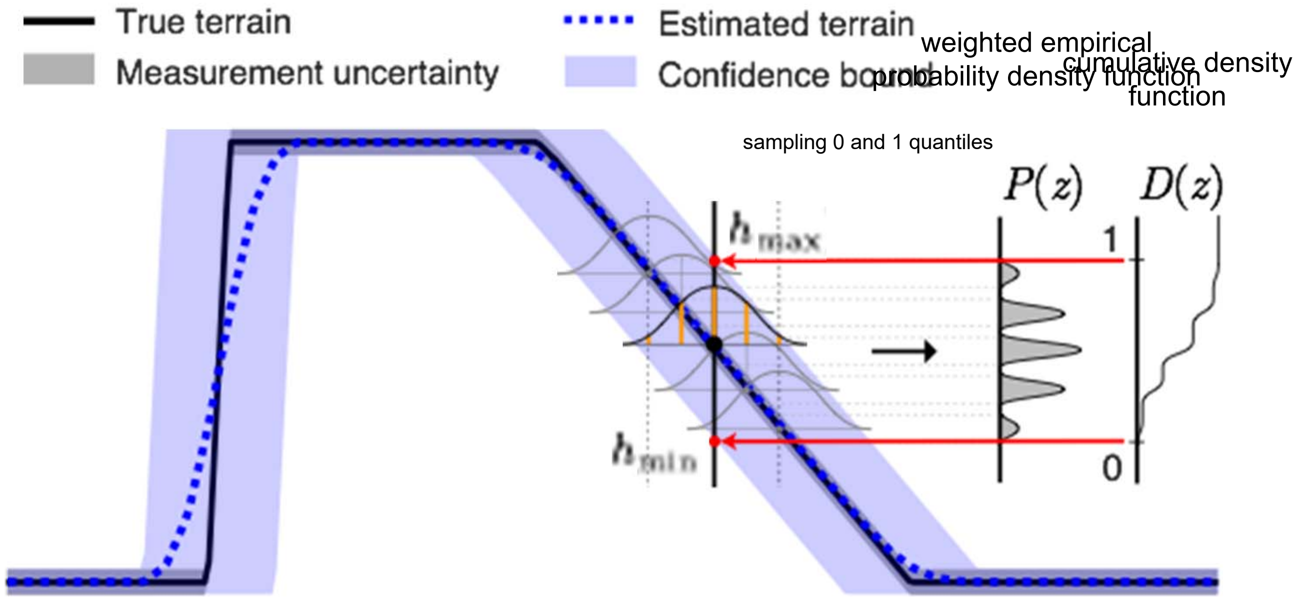
Mapping Method: Map Fusion



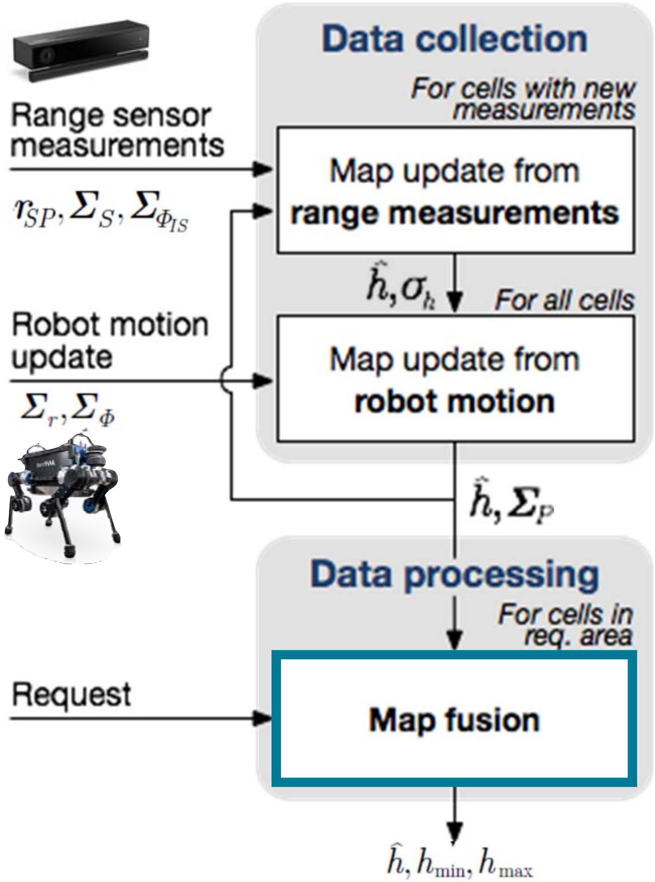
For the cells in a requested area:

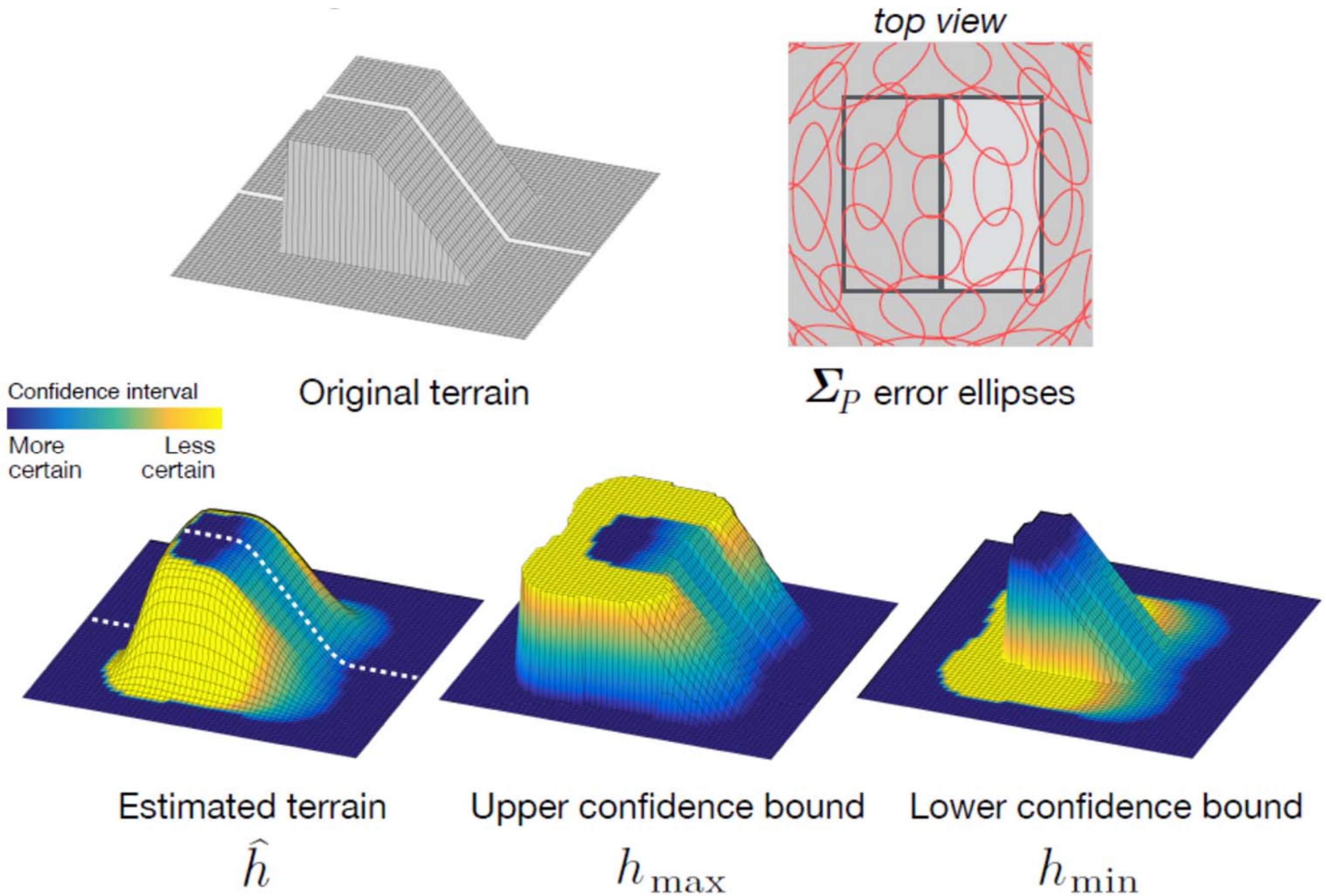
- Compute terrain height estimate from neighboring cells

$$\hat{h}_i,\ \Sigma_{P_i} \in \mathbb{R}^{3\times3} \xrightarrow{\text{map fusion}} (\hat{h}, h_{\min}, h_{\max})$$
$\forall i \in$ confidence area — s.t. real height $h \in [h_{\min}, h_{\max}]$



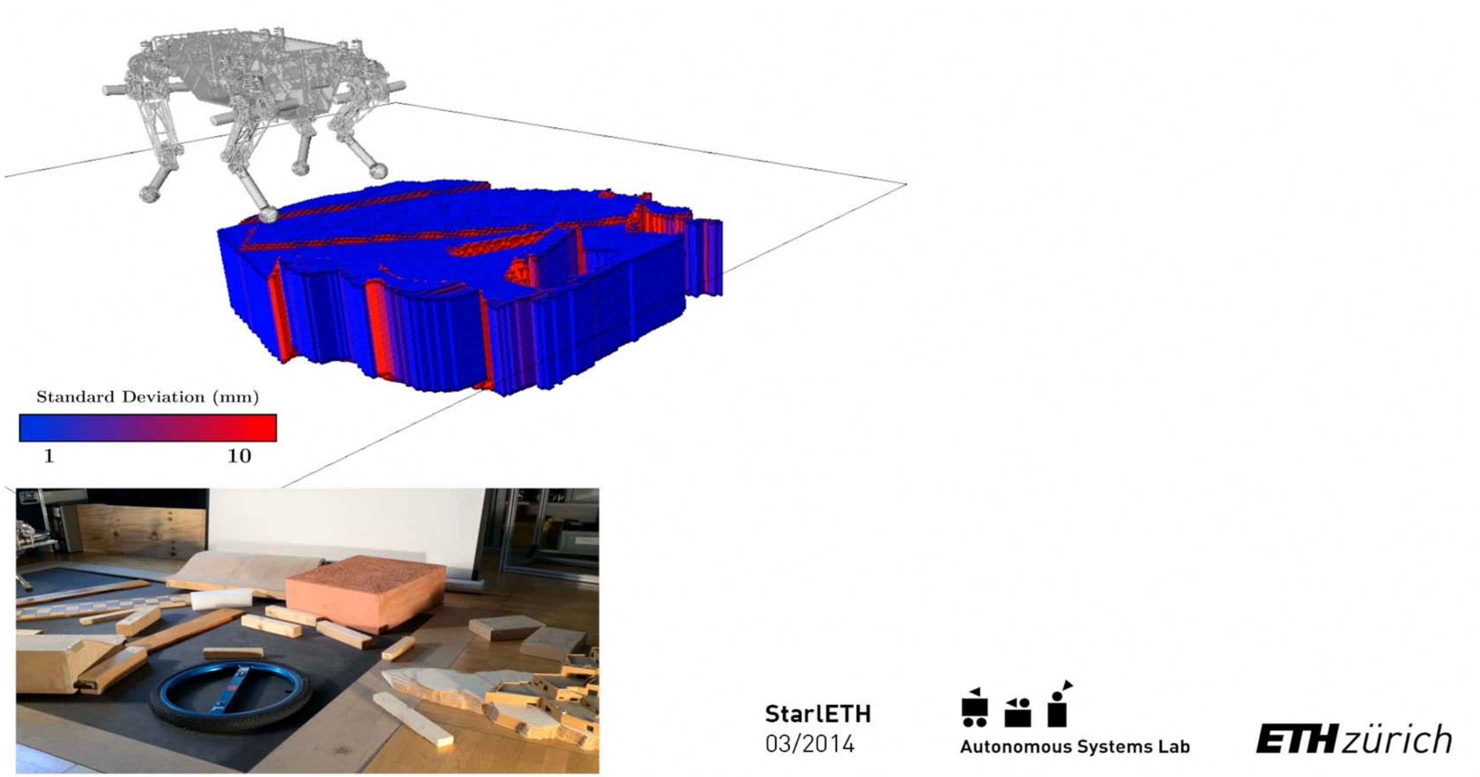
Mapping Method: Map Fusion Example



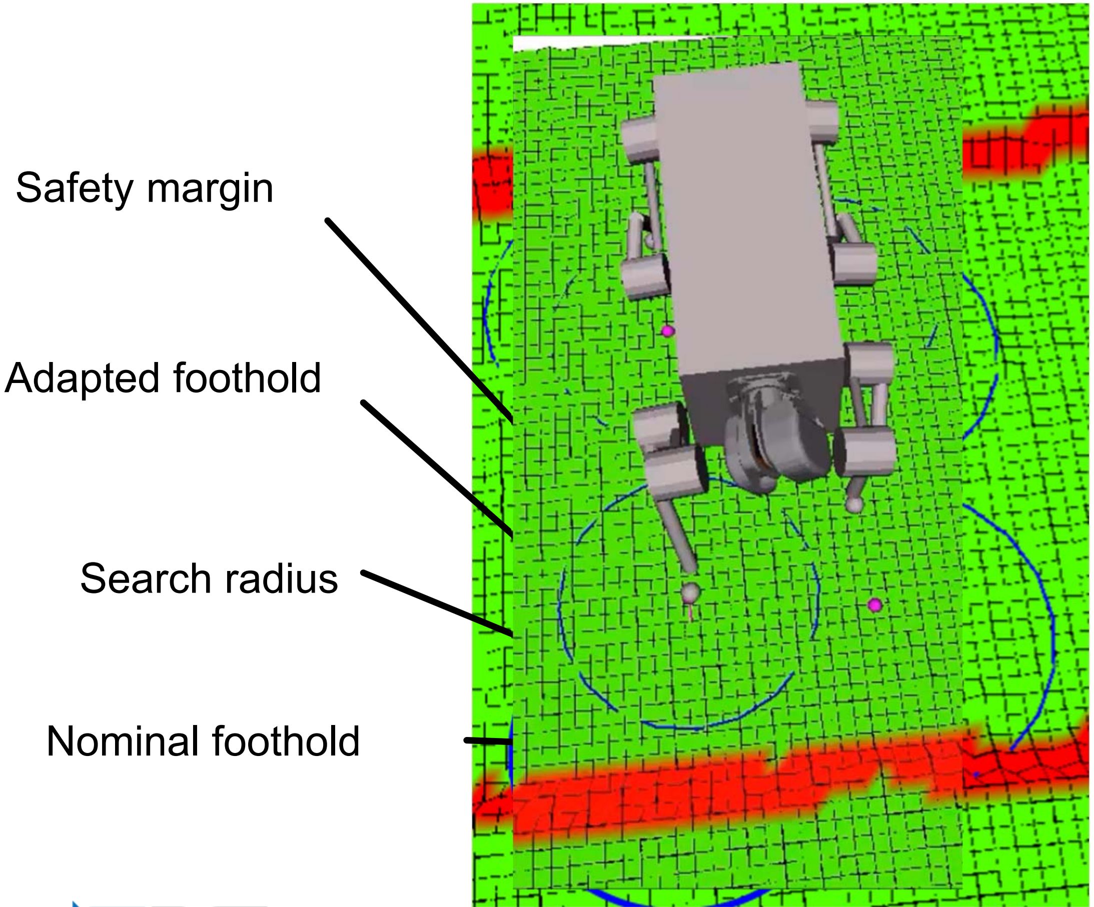


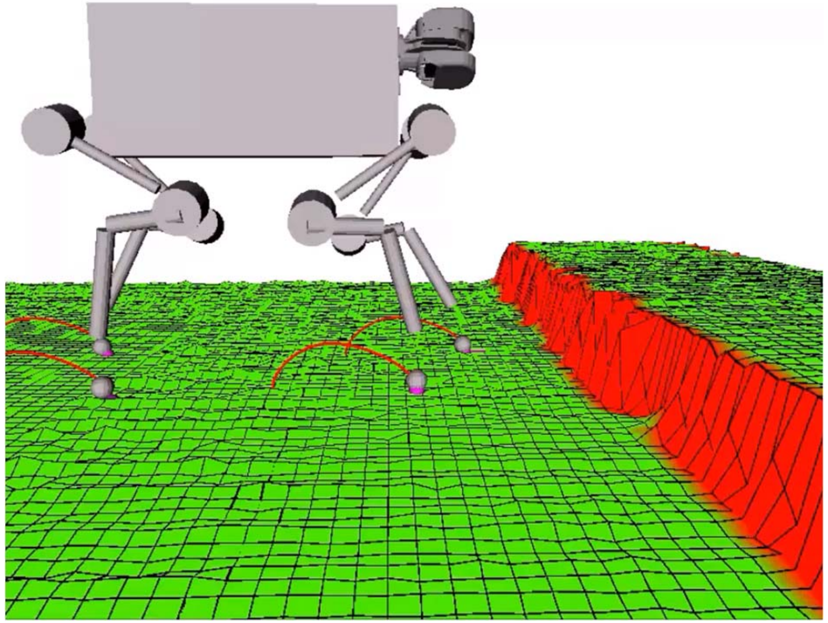
Terrain Mapping Results I

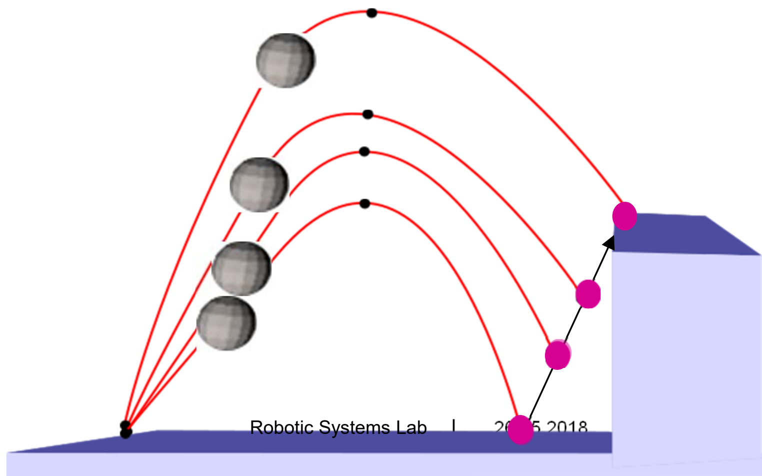
Indoor, structured-light sensor, static gait



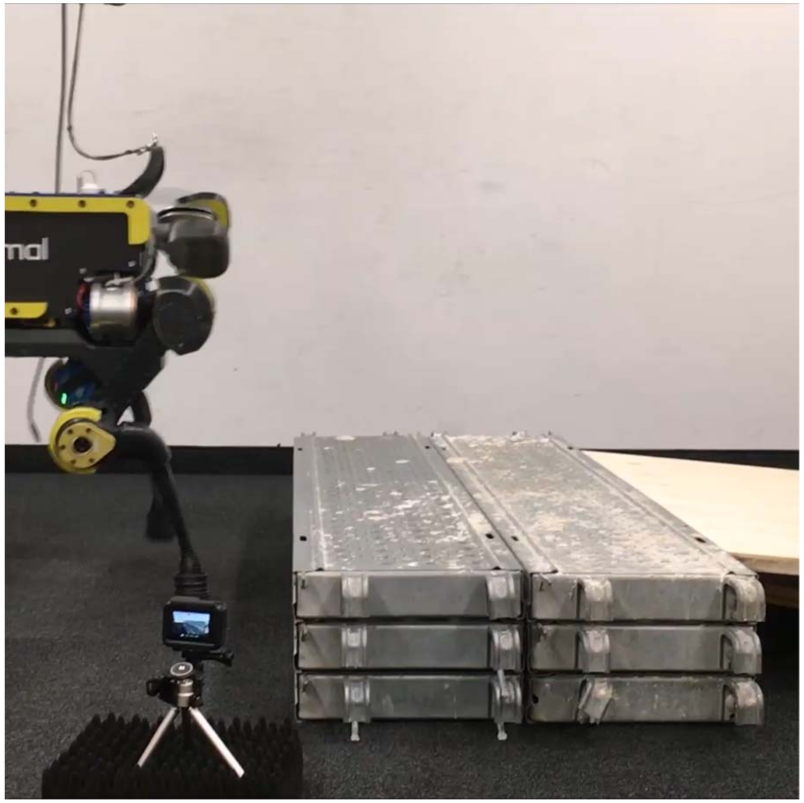
Map-based foothold adaptation



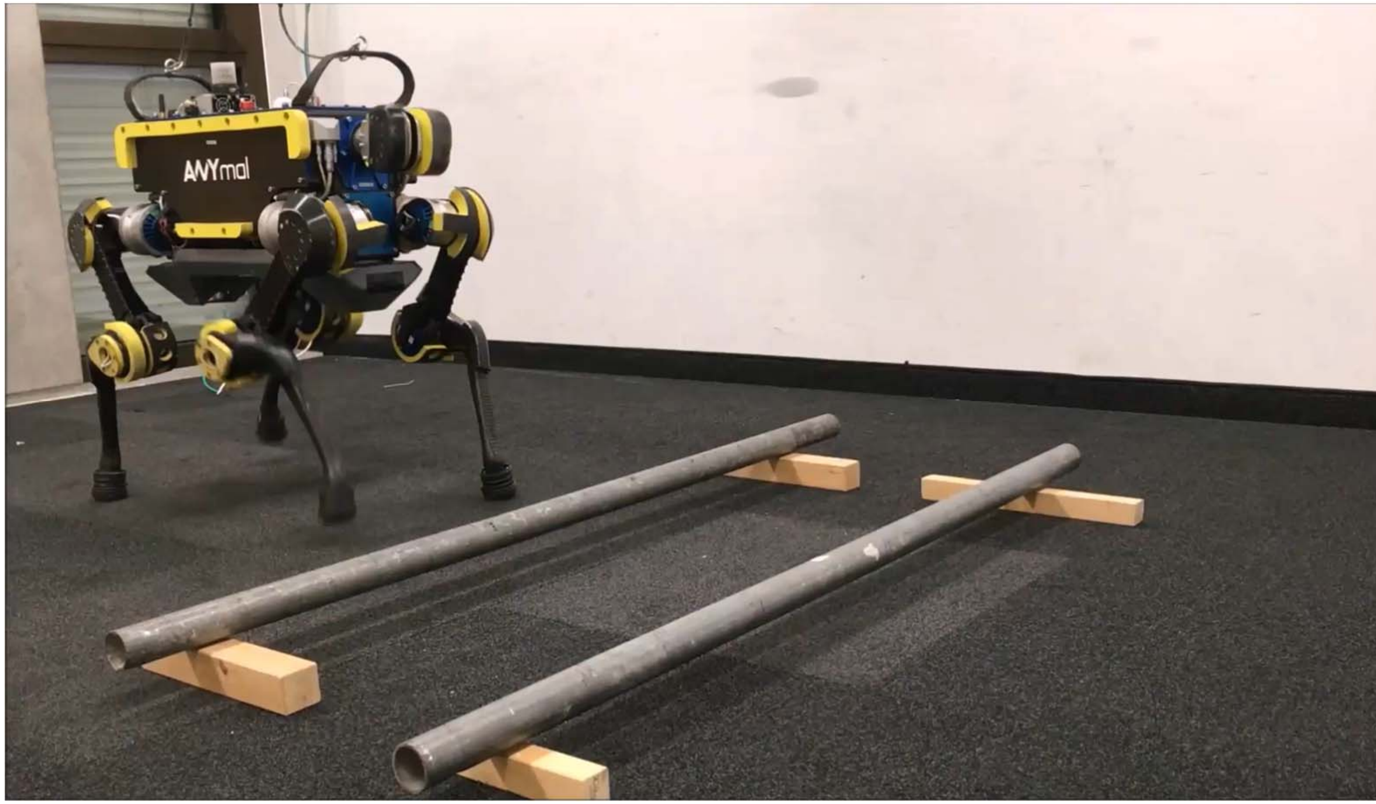




Trotting with online terrain mapping



Step height: 21 cm



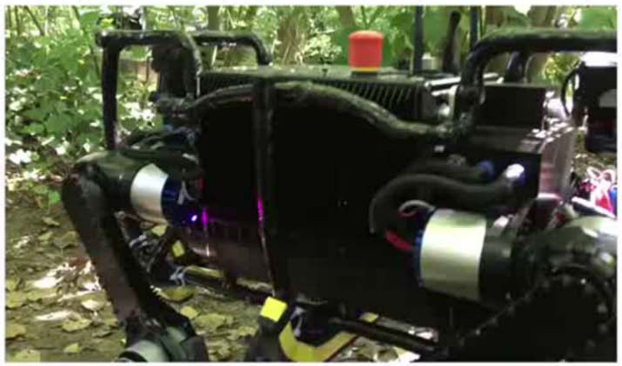
Step height: 10 cm

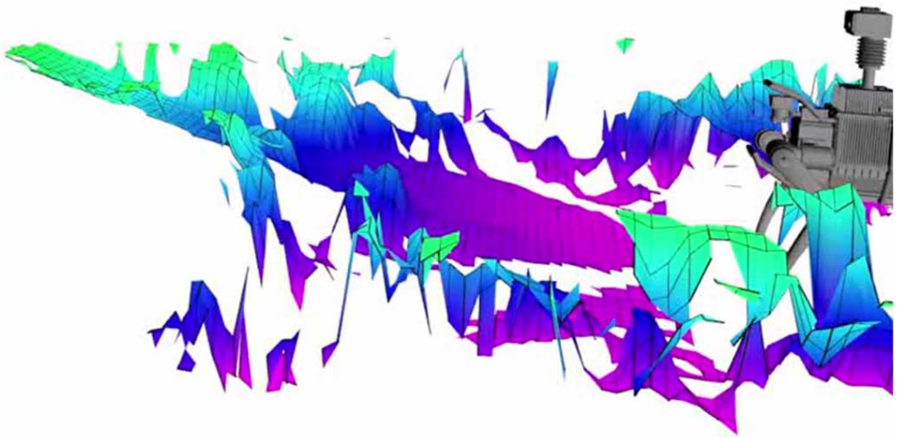
From semi-structured to fully unstructured environments

- Semi-structured
  - Industrial sites, household, etc.

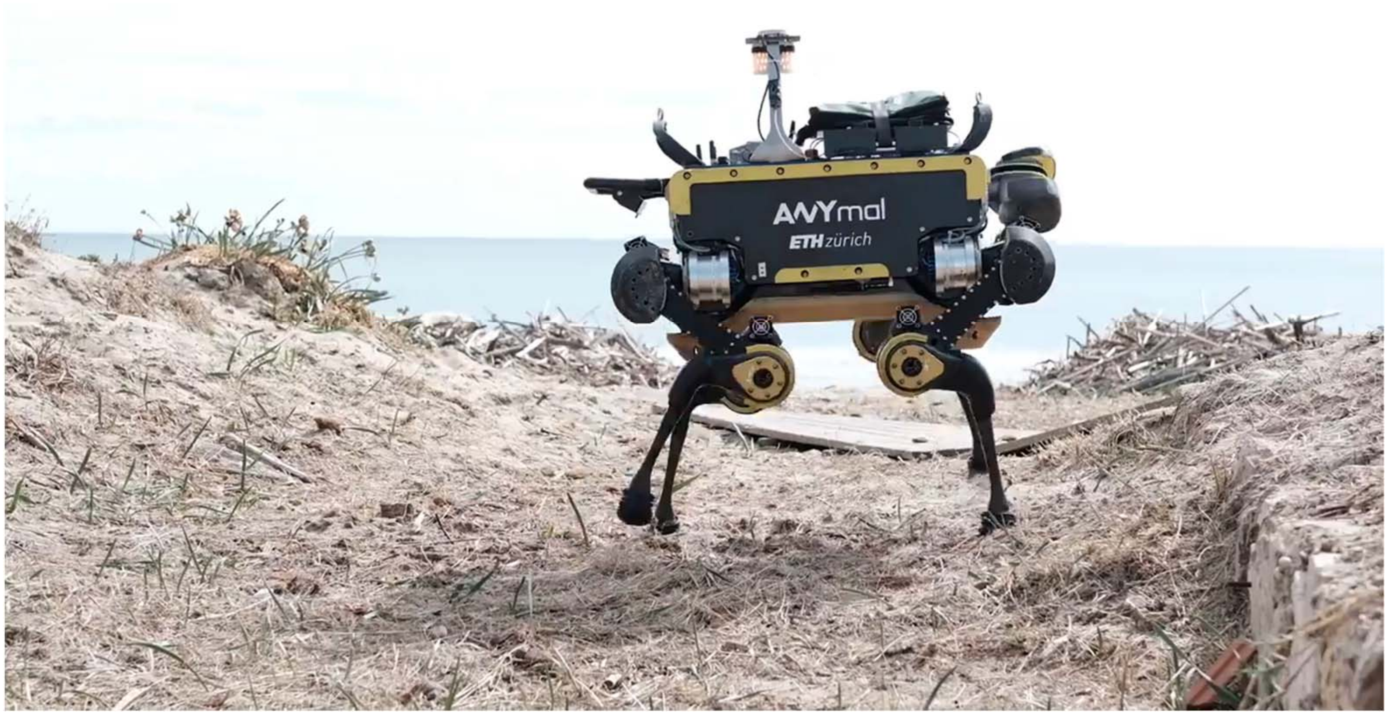
- Fully unstructured

From semi-structured to fully unstructured environments





ANYmal @ ERL Challenge



Dynamic Legged Locomotion in Realistic Terrains

Sand dunes are tricky

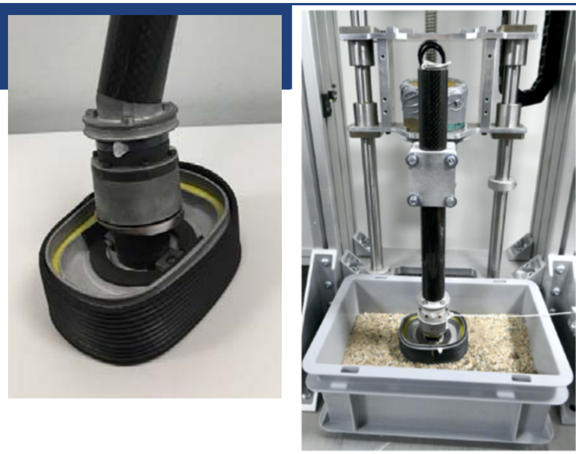
Dynamic Legged Locomotion in Realistic Terrains

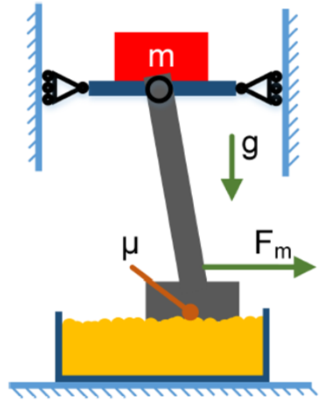
Sand (dunes) are tricky

Running trot on sand

Walking trot on sand

Evaluation of «Realistic» Terrain



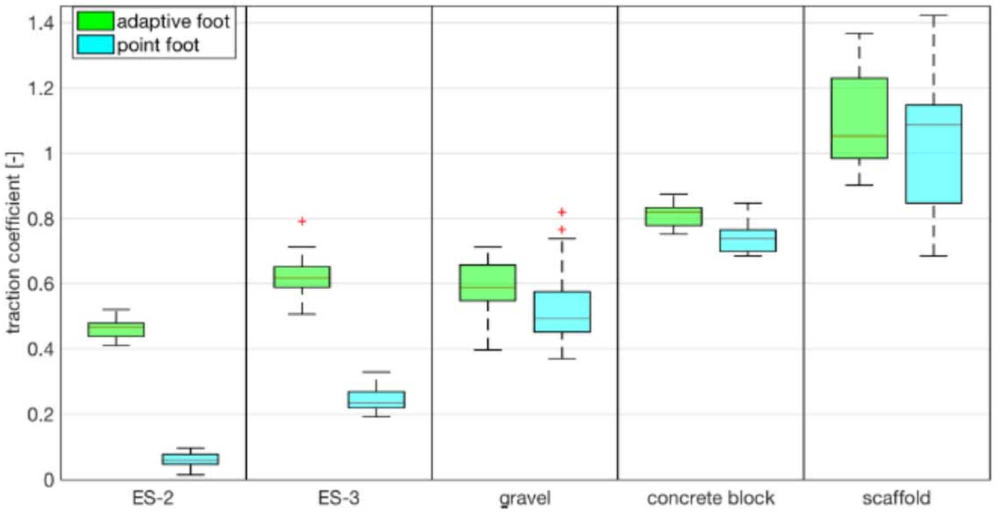


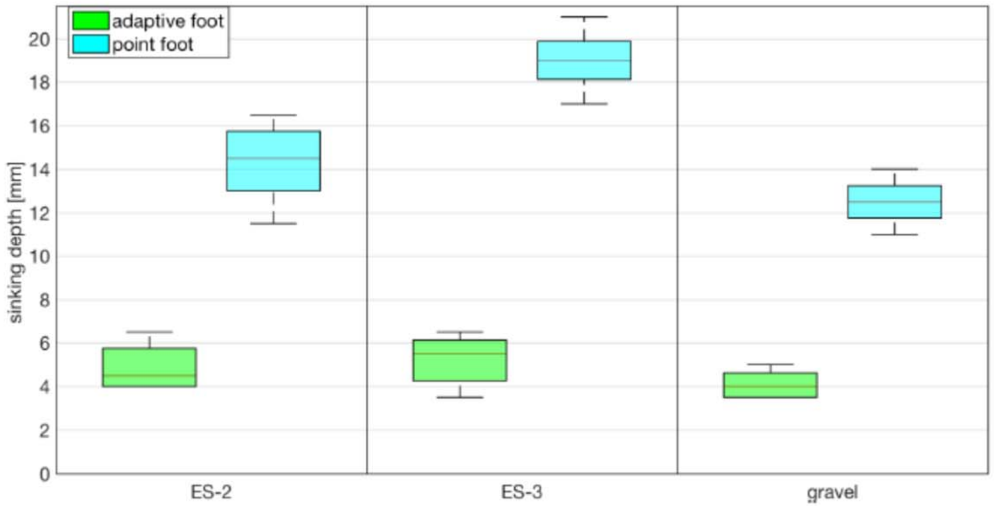
(a) Test bench setup

(b) Schematic test bench setup

traction

sinking depth





ARCHE (http://arche.website)

Advanced Robot Companions for Hazardous Environments

- Annual robot rescue week organized in Wangen a/A
- Robotic capabilities to support humans with disaster prevention & post-disaster recovery

Possible Scenarios
Colapsed buildings of various floors / Tunnels





Possible Scenarios

Heat / Fire house / heavy smoke / simulated flood


C.14


ANYmal

Hardware Experiments with ANYmal on Site

https://www.srf.ch/sendungen/einstein/einstein-bei-den-robotern#

Hardware Experiments with ANYmal on Site

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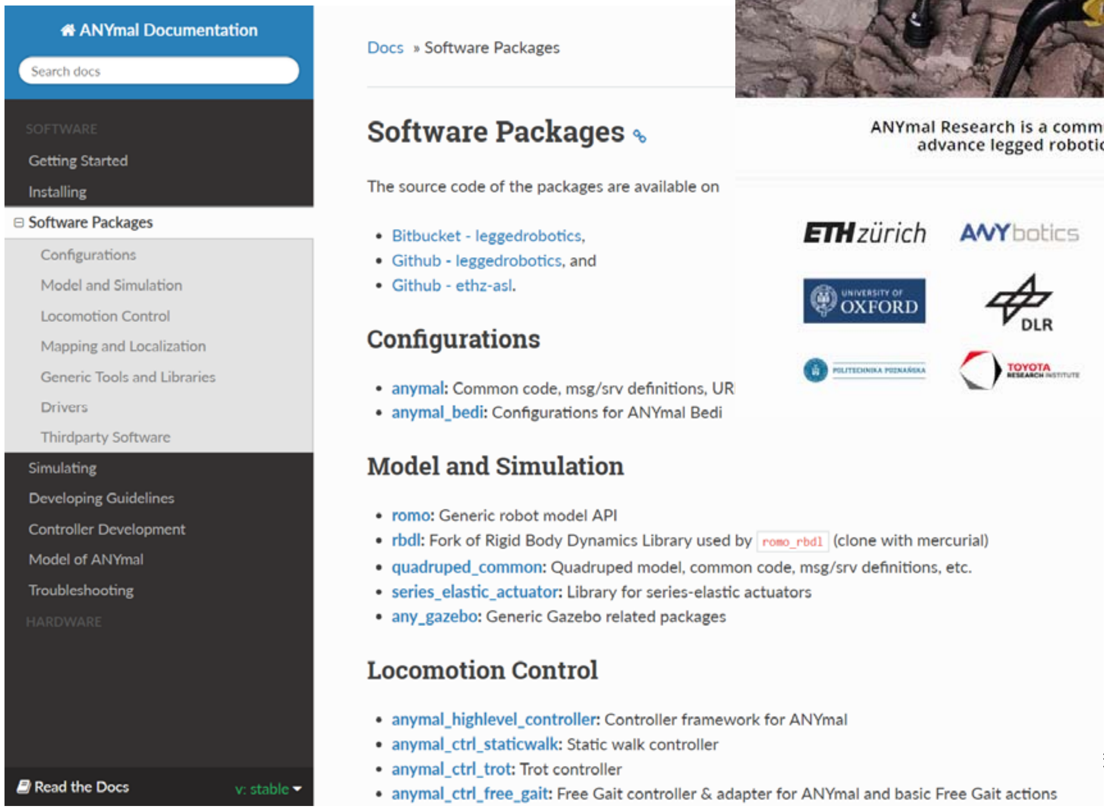
ANYmal Research
An attempt for collaboration on legged locomotion

- Affordable and simple hardware
  - Exchangeable joint modules
  - Exchangeable payload
- Open source software framework
  - Simulation
  - Locomotion control
  - State estimation
  - Localization/mapping/navigation
  - …
- Comprehensive documentation

[www.anymal-research.org]



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