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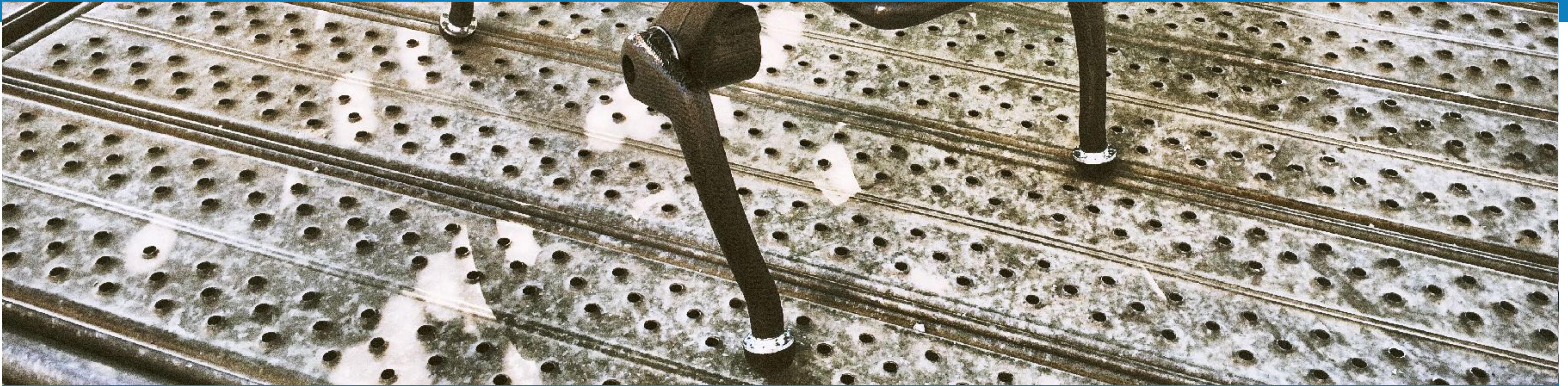
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# ANYmal at the ARGOS Challenge

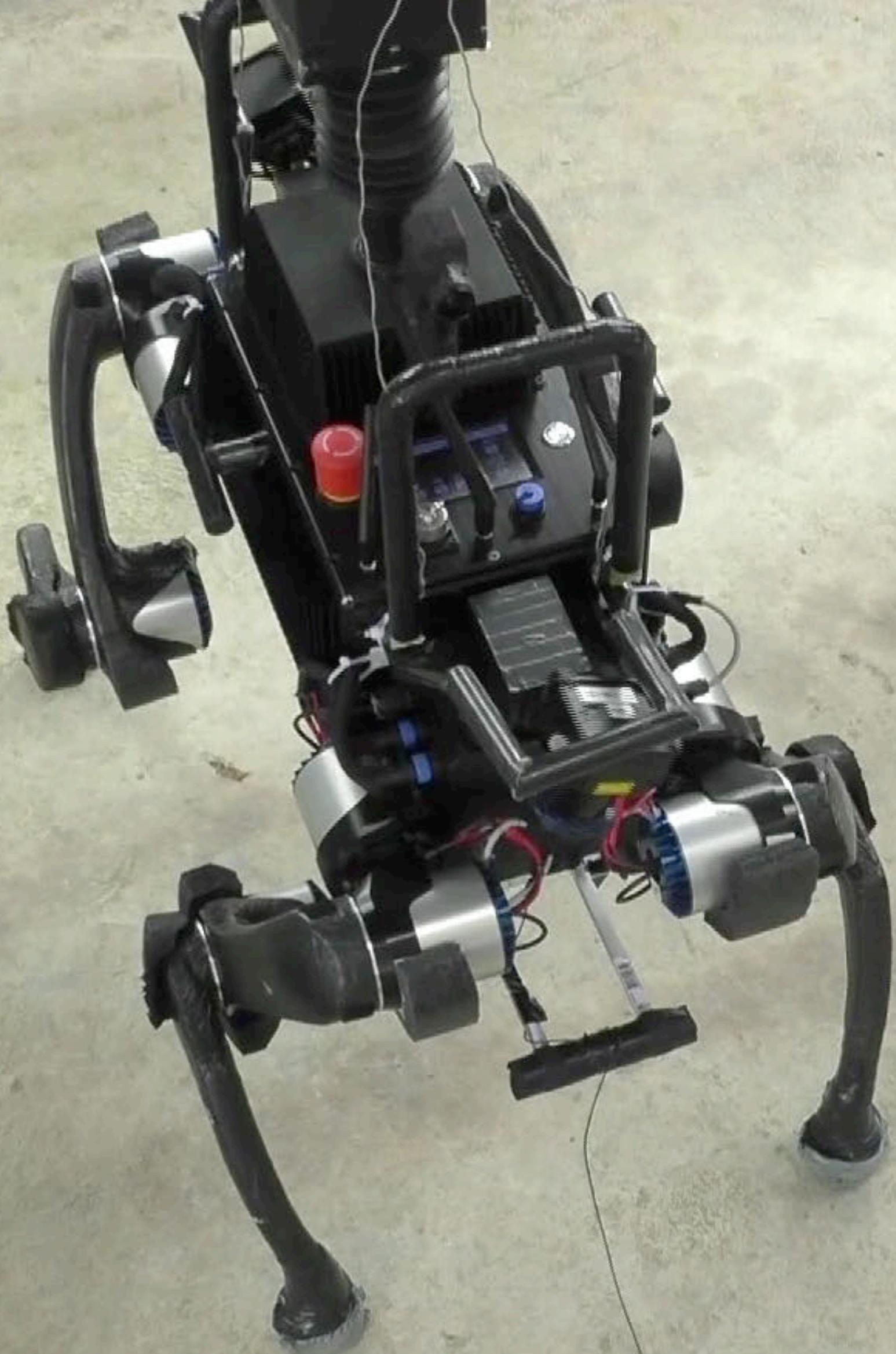
**Tools and Experiences from the Autonomous  
Inspection of Oil & Gas Sites with a Legged Robot**

**Péter Fankhauser**

Remo Diethelm, Samuel Bachmann, Christian Gehring, Martin Wermelinger, Dario Bellicoso,  
Vassilios Tsounis, Andreas Lauber, Michael Bloesch, Philipp Leemann, Gabriel Hottiger,  
Dominik Jud, Ralf Kaestner, Linus Isler, Mark Hoepflinger, Roland Siegwart, Marco Hutter

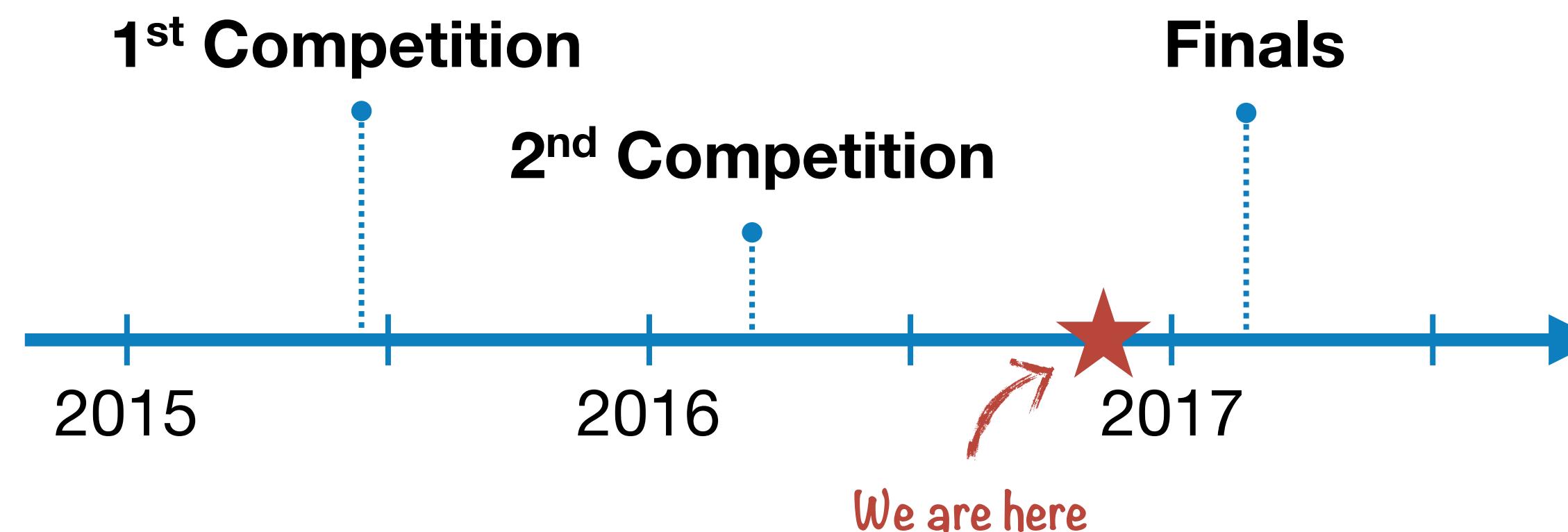


ANYmal for the  
Oil & Gas Industry



# ARGOS Challenge

“Creating the first autonomous robot for gas and oil sites”



## WELCOME TO THE ARGOS CHALLENGE WEBSITE

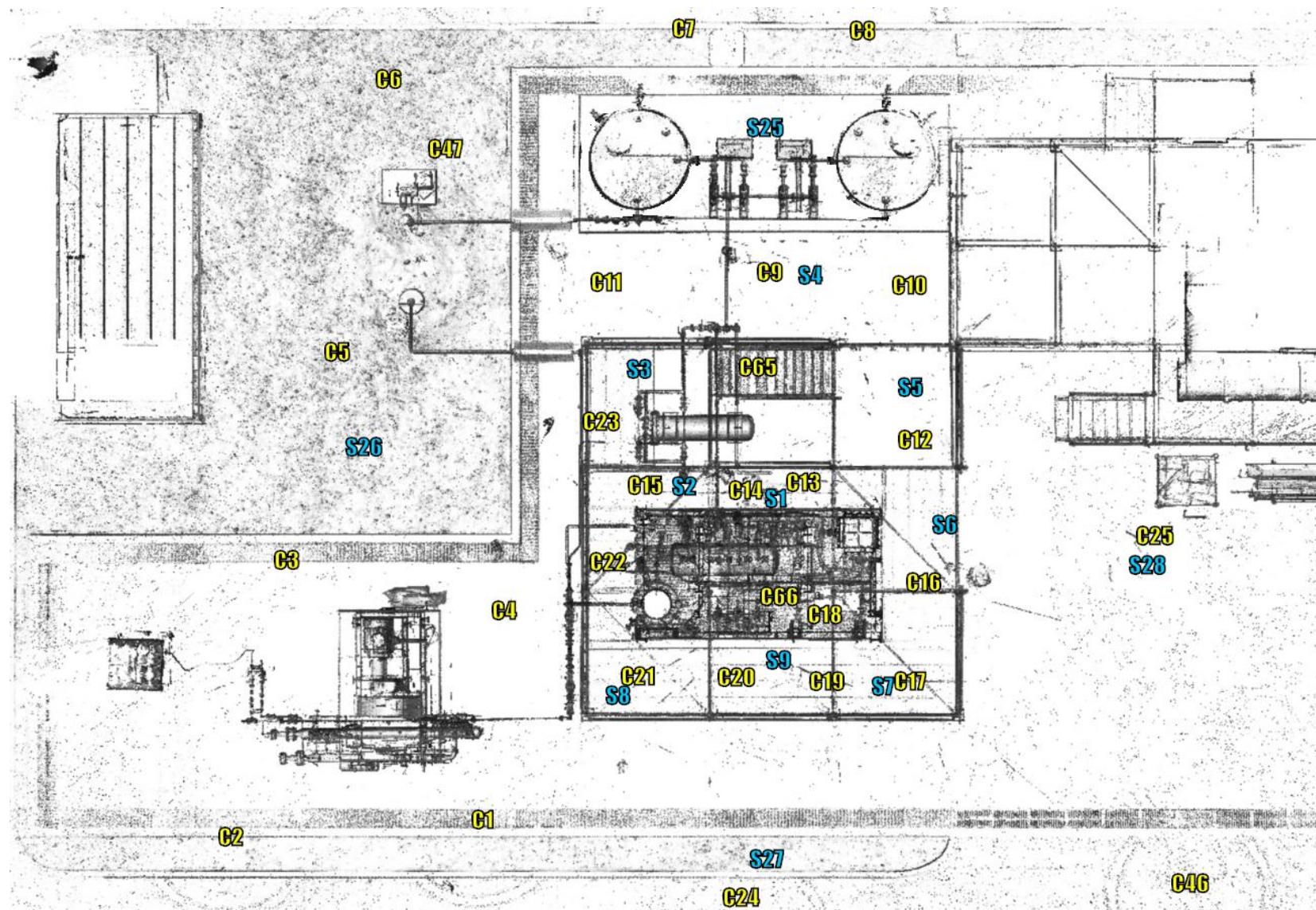
Today's exploration and production activities are increasingly confronted with extreme and harsh conditions: extreme cold, acid effluents, isolated sites, onshore and offshore alike, etc. In order to meet these new challenges and improve the safety of operators, Total has launched the ARGOS (Autonomous Robot for Gas and Oil Sites) Challenge in December 2013, in partnership with the French National Research Agency (ANR). Five teams from Austria and Germany, Spain and Portugal, France, Japan and Switzerland, were selected to design and build in less than three years the first autonomous surface robots adapted to oil & gas sites. The prototypes will match their skills and capabilities in three competitions scheduled between June 2015 and March 2017. The winner of the ARGOS Challenge will be announced in spring 2017.

2016 PRESS RELEASE - [Total Energy Ventures invests in Smart Grids with Autogrid](#)  
2016 Press release: Paris, September 15, 2016 – Total Energy Ventures (TEV), the venture capital arm of Total investing in start-ups, has acquired an interest in Autogrid, a company that develops digital...

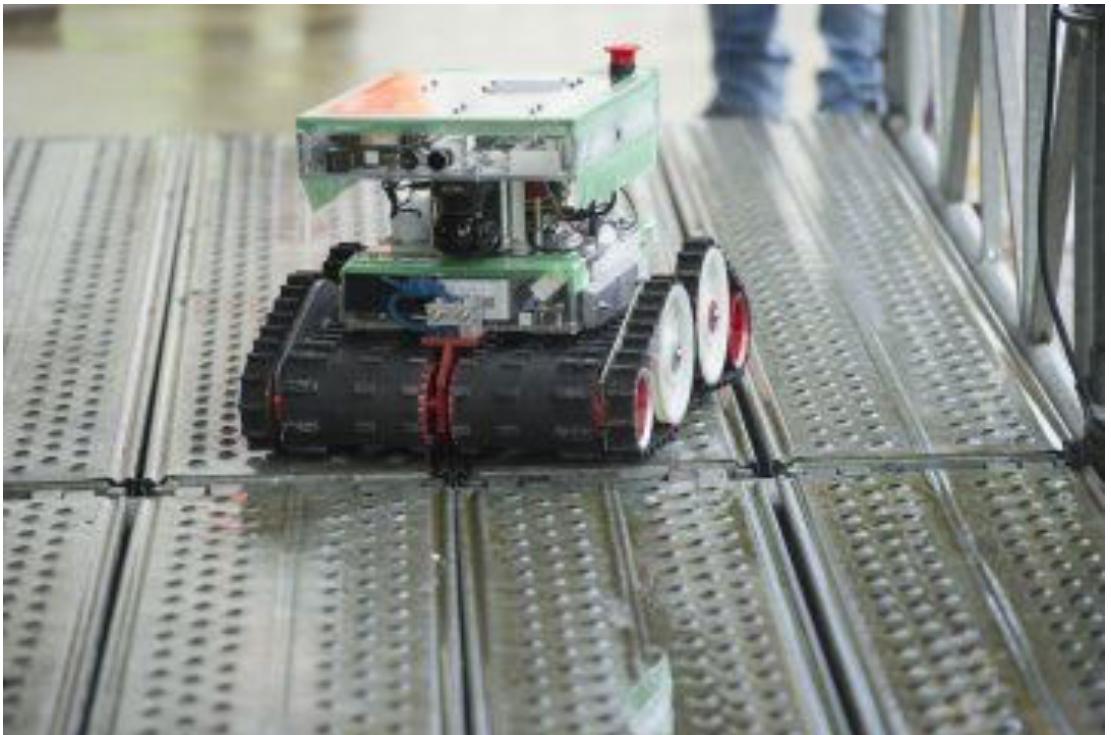
<http://www.argos-challenge.com>

# ARGOS Challenge

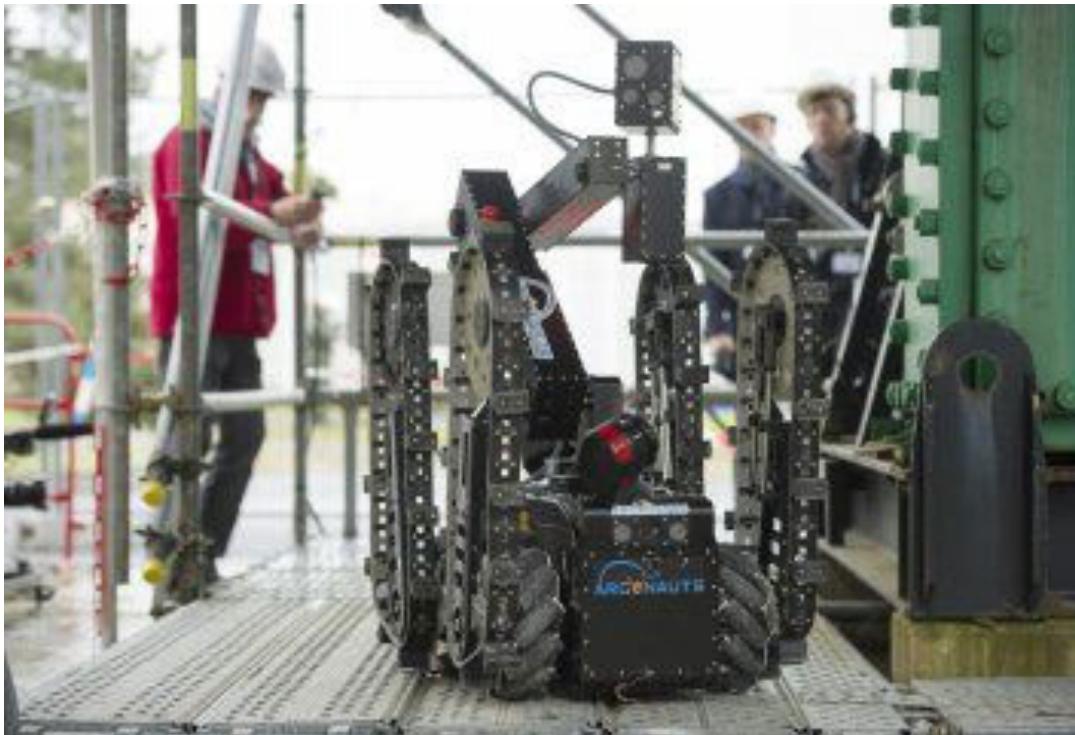
## Autonomous Inspection of Oil and Gas Sites



# ARGOS Challenge 5 International Teams



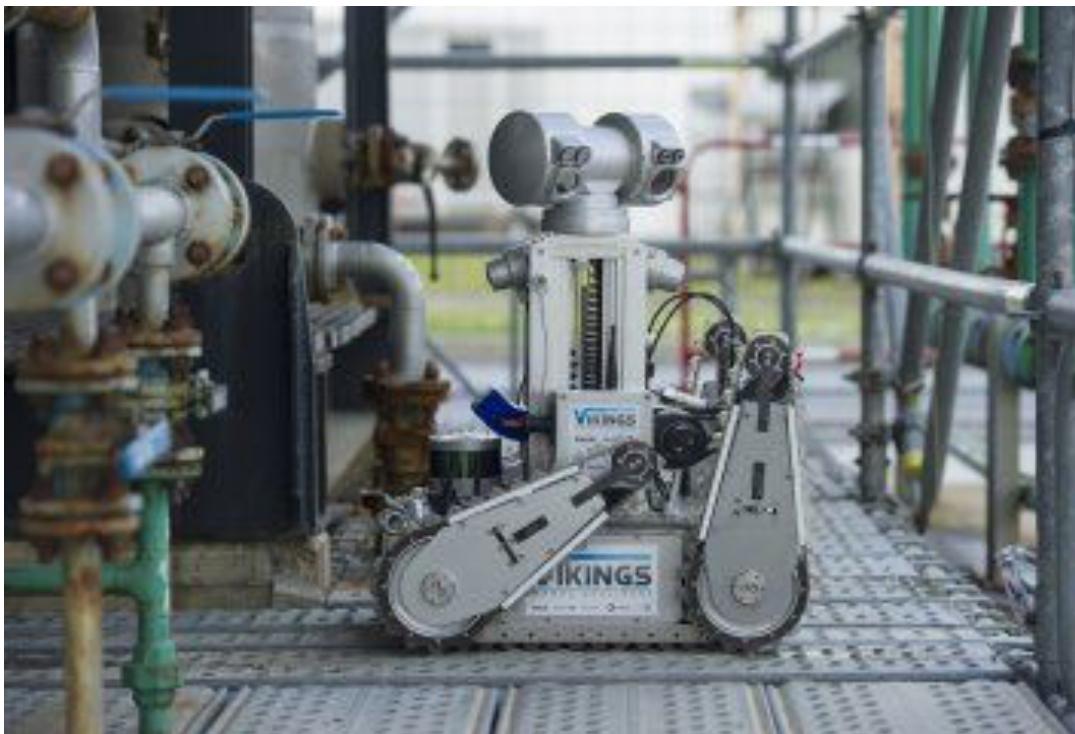
**AIR-K**  
Japan



**ARGONAUTS**  
Austria & Germany



**FOXIRIS**  
Spain & Portugal



**VIKINGS**  
France

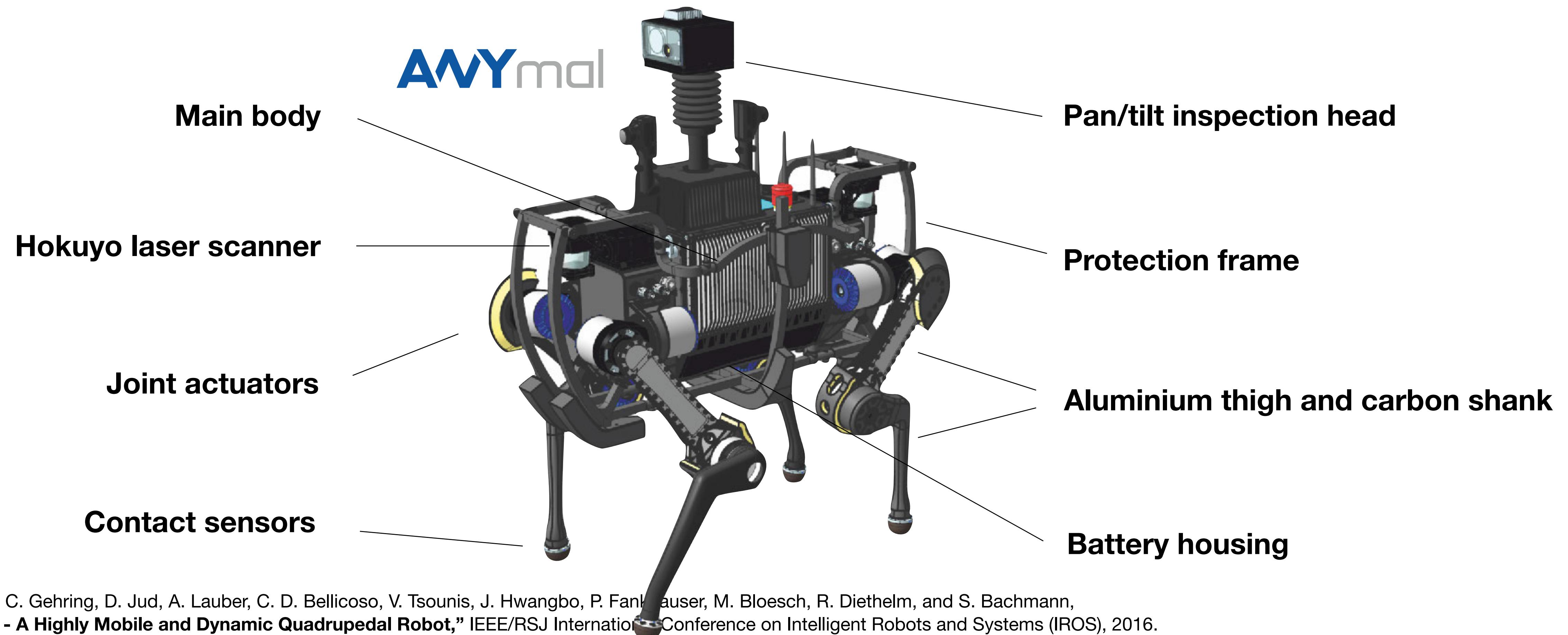


**LIO**  
Switzerland

# ARGOS Challenge Team LIO



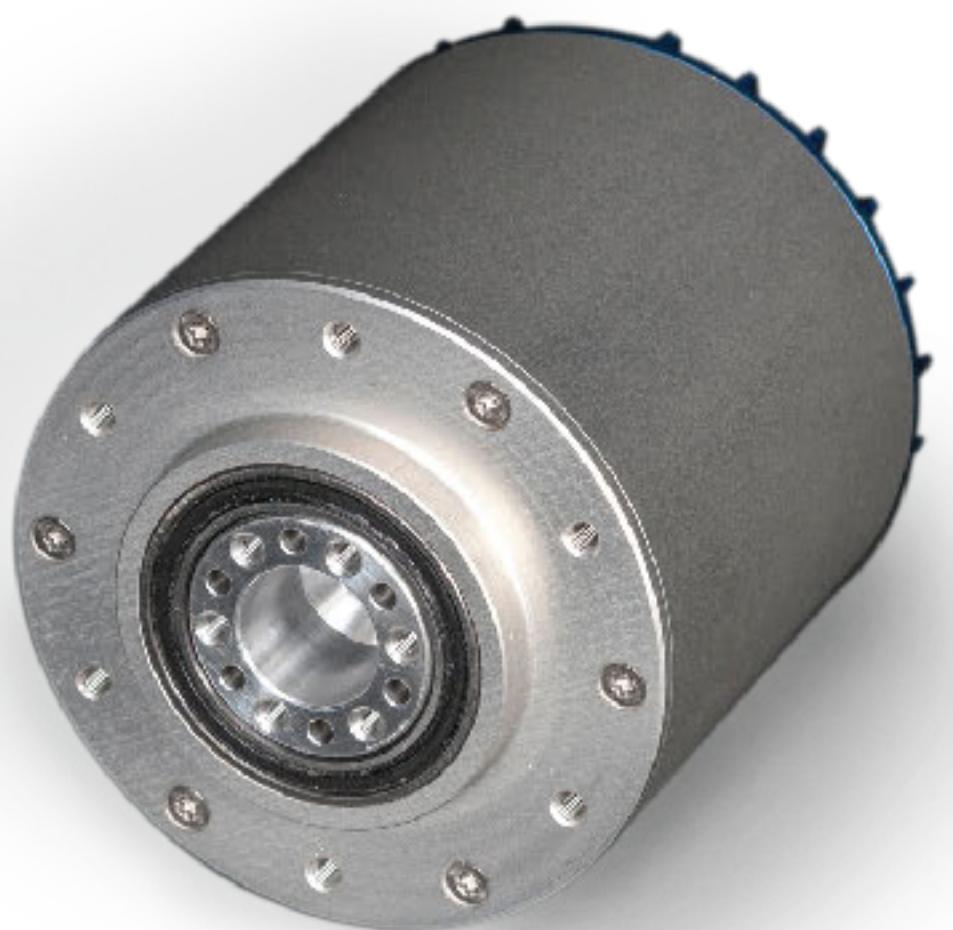
# ANYmal – A High-Performance & Versatile Quadrupedal Robot



M. Hutter, C. Gehring, D. Jud, A. Lauber, C. D. Bellicoso, V. Tsounis, J. Hwangbo, P. Fankhauser, M. Bloesch, R. Diethelm, and S. Bachmann,  
“ANYmal - A Highly Mobile and Dynamic Quadrupedal Robot,” IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2016.

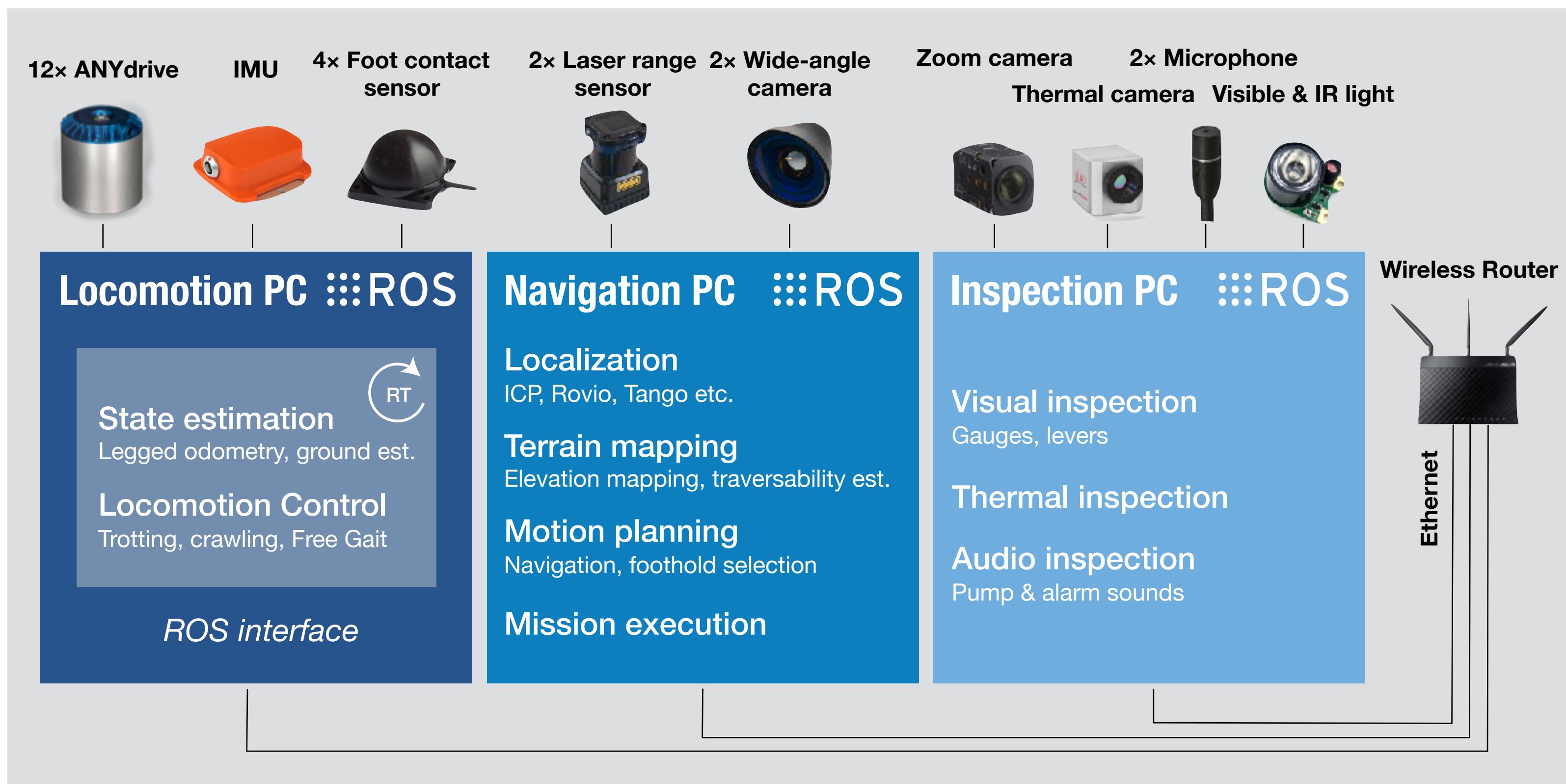
# ANYdrive – A Integrated, Robust, Torque-Controllable Robot Joint

- Fully integrated
- Accurate position & torque control
- Absolute position sensing
- Programmable controller
- Impact robust
- Hollow-shaft
- Water-proof



**ANY**drive

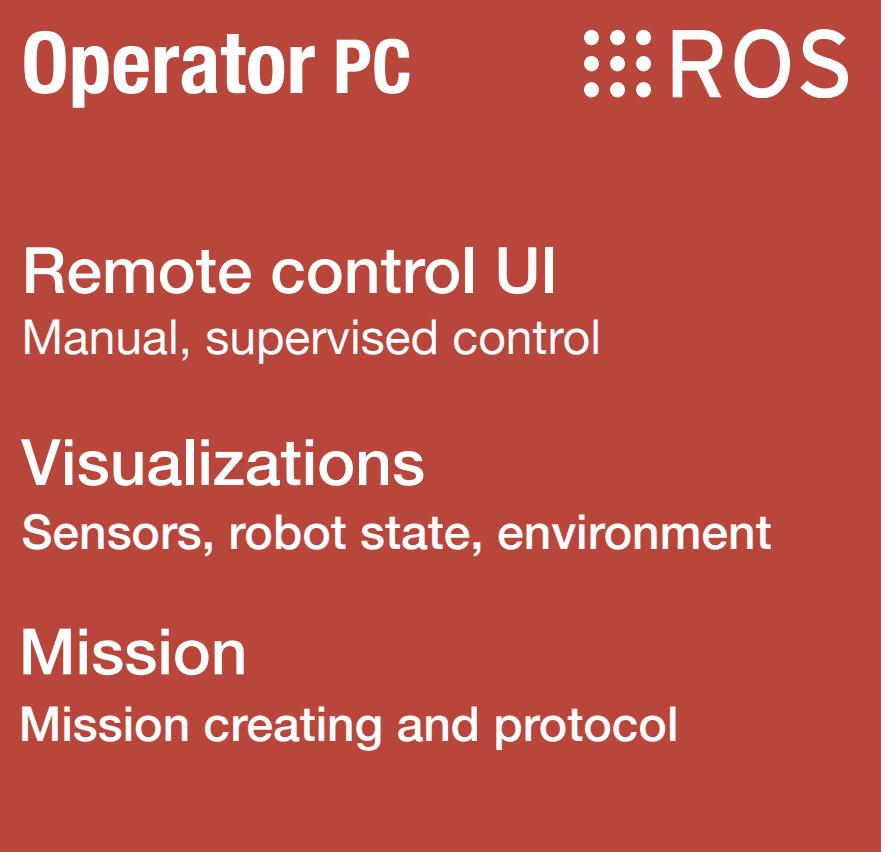
# System Overview



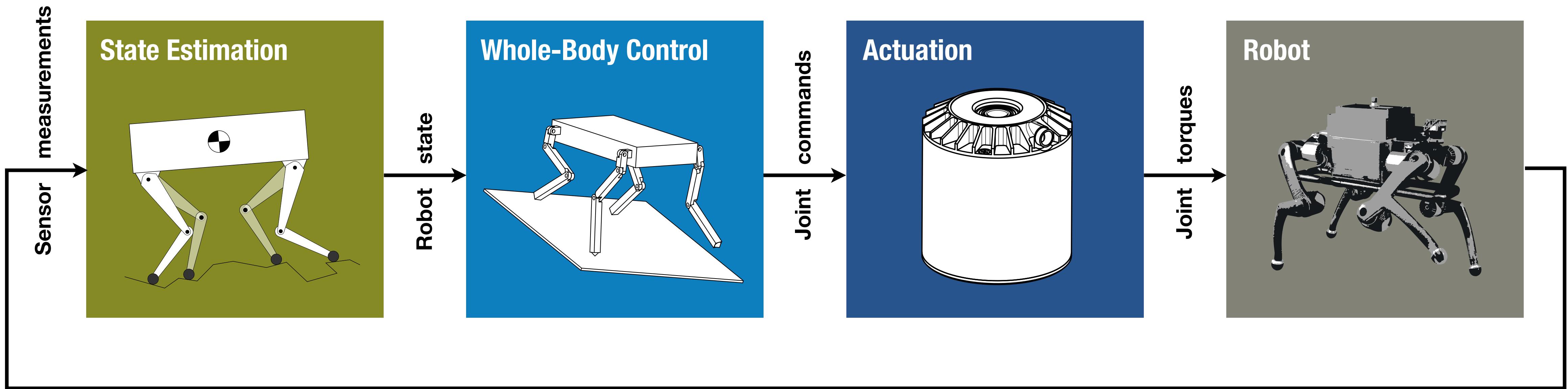
Industrial  
Wireless



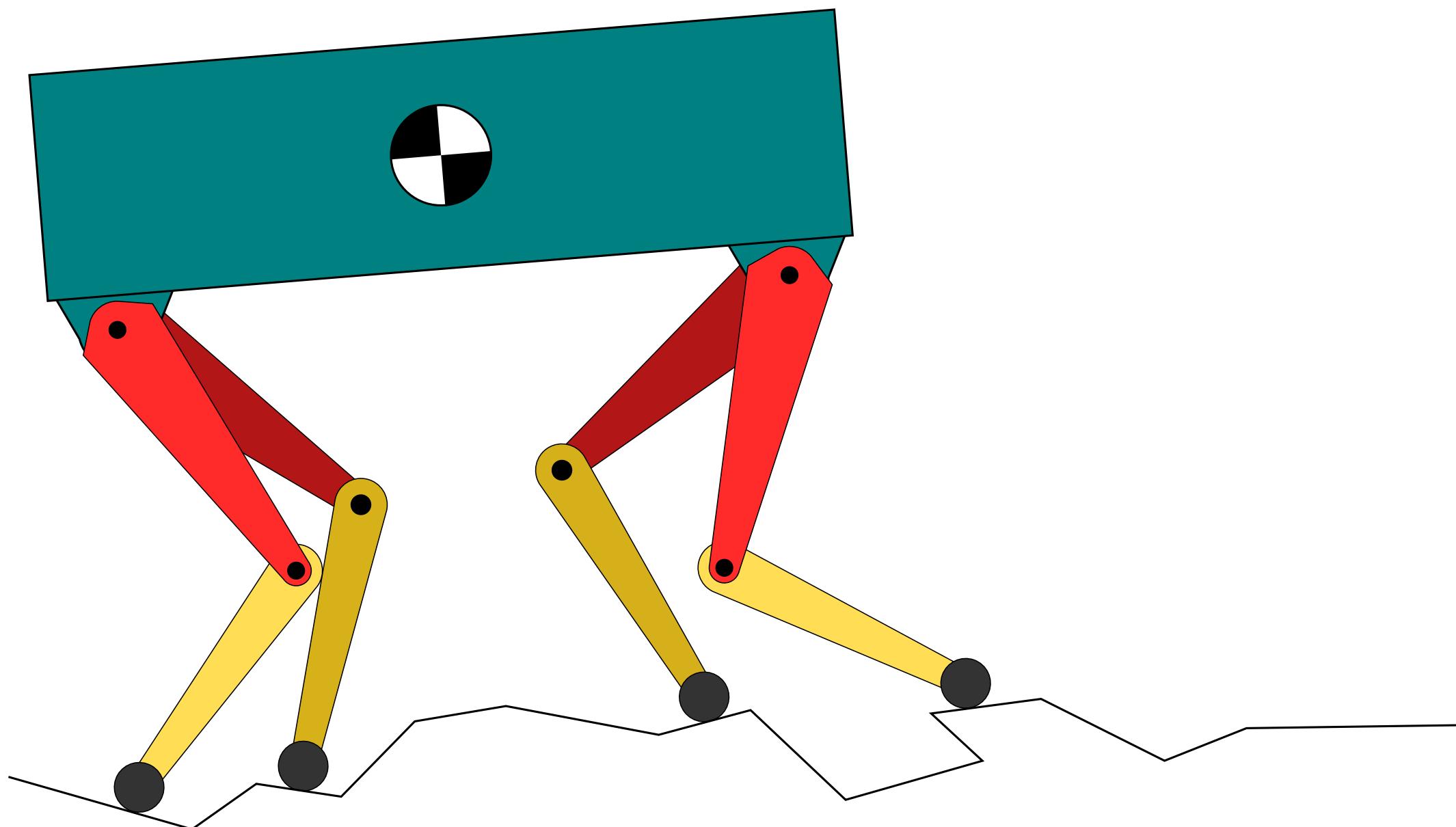
Radio



# Locomotion



# Locomotion State Estimation

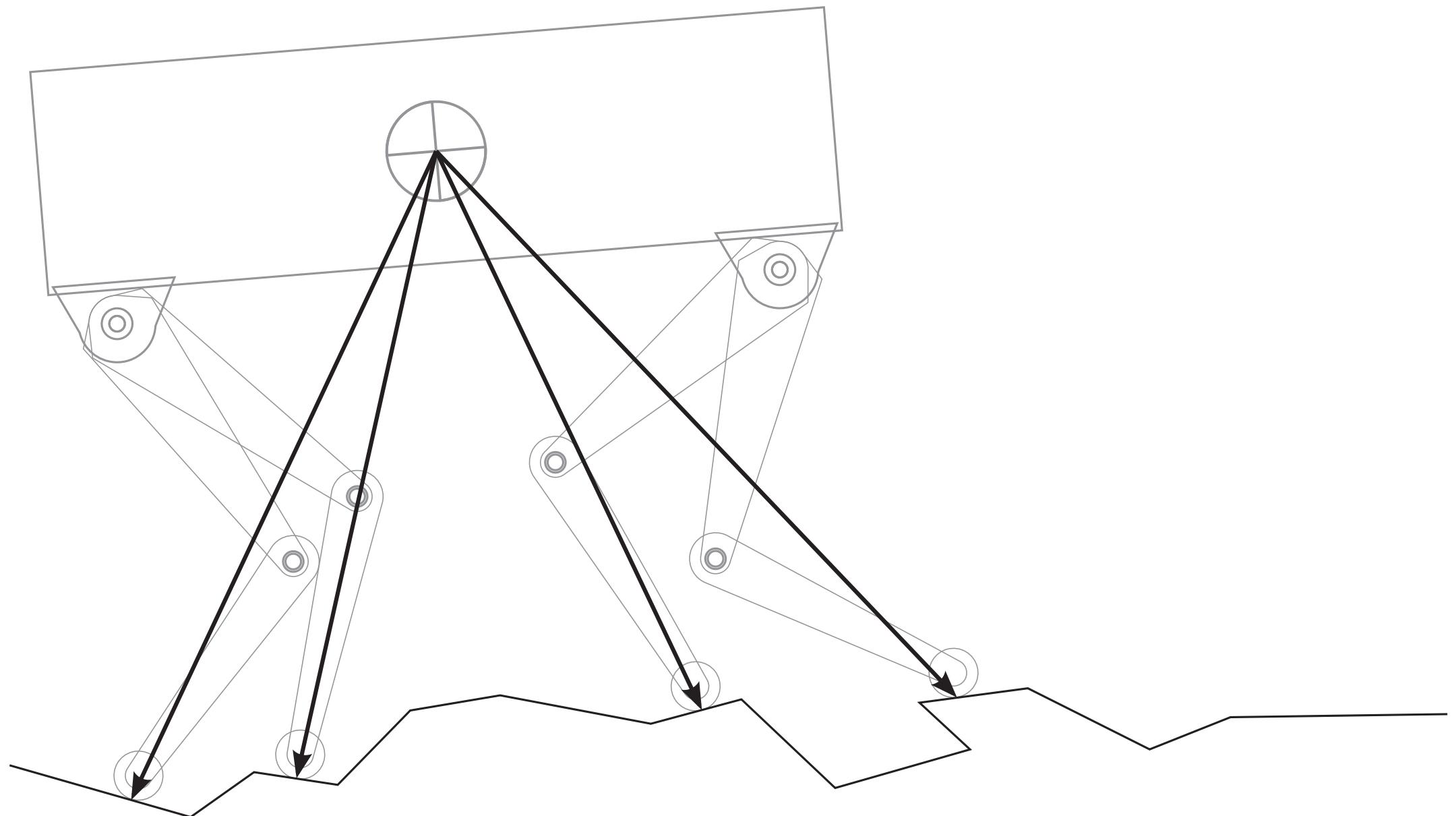


## Extended Kalman Filter

- No assumption on terrain

M. Bloesch, C. Gehring, P. Fankhauser, M. Hutter, M. A. Hoepflinger and R. Siegwart, “**State Estimation for Legged Robots on Unstable and Slippery Terrain**”, in International Conference on Intelligent Robots and Systems (IROS), 2013.

# Locomotion State Estimation

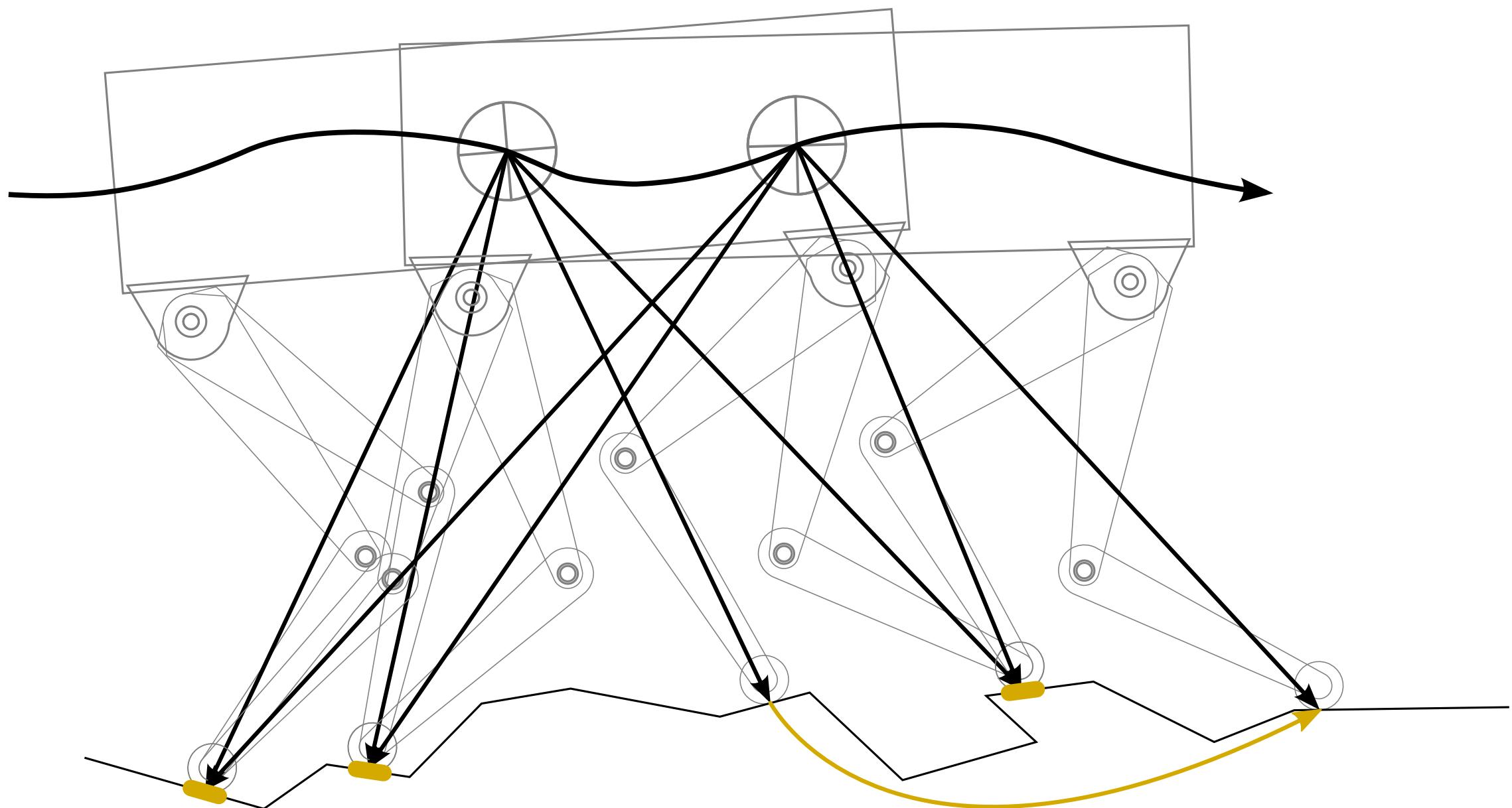


## Extended Kalman Filter

- No assumption on terrain
- Kinematic measurements (encoders) for legs in contact

M. Bloesch, C. Gehring, P. Fankhauser, M. Hutter, M. A. Hoepflinger and R. Siegwart, “**State Estimation for Legged Robots on Unstable and Slippery Terrain**”, in International Conference on Intelligent Robots and Systems (IROS), 2013.

# Locomotion State Estimation



**Kinematic measurements**

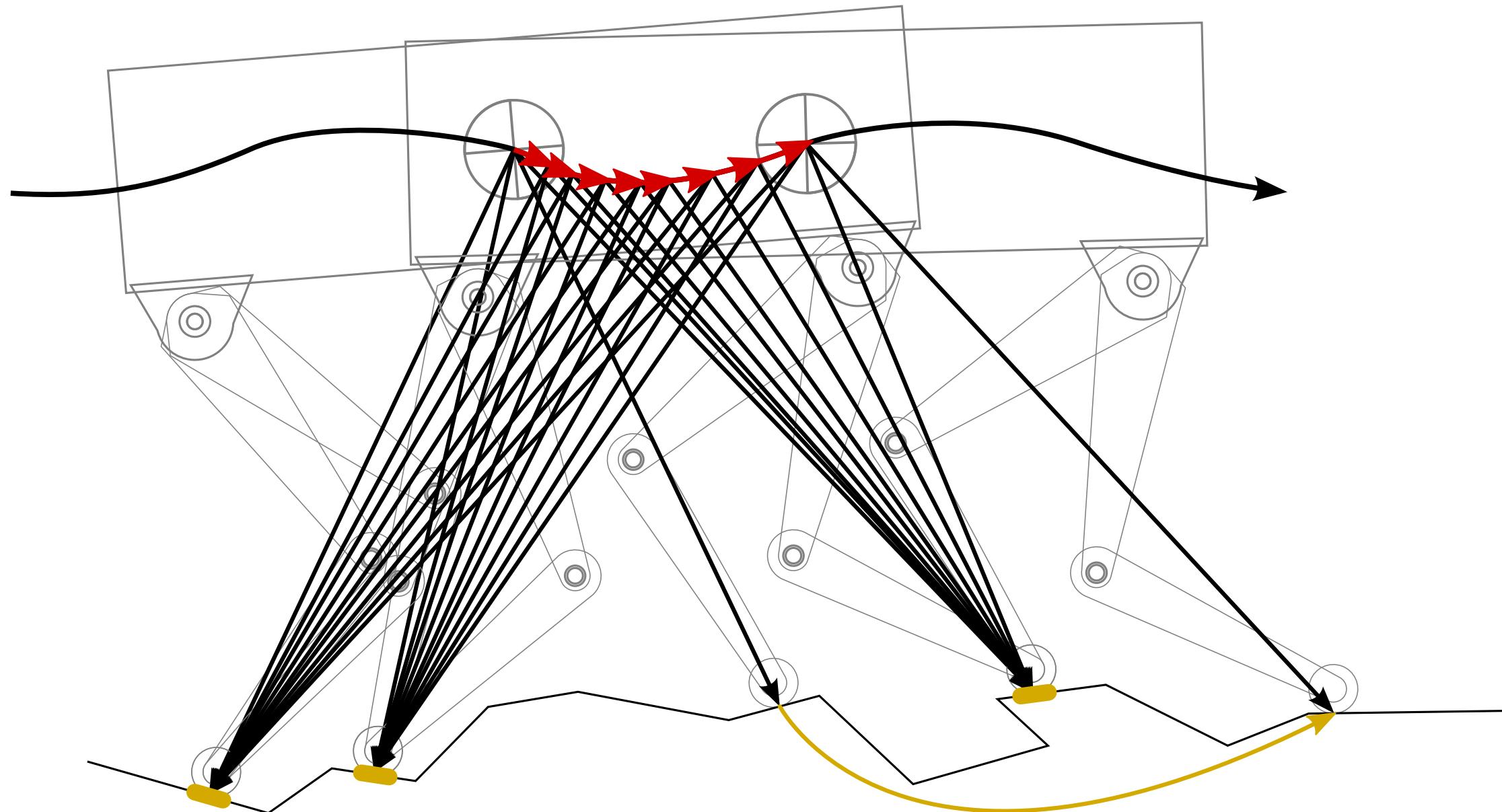
M. Bloesch, C. Gehring, P. Fankhauser, M. Hutter, M. A. Hoepflinger and R. Siegwart, “State Estimation for Legged Robots on Unstable and Slippery Terrain”, in International Conference on Intelligent Robots and Systems (IROS), 2013.

## Extended Kalman Filter

- No assumption on terrain
- Kinematic measurements (encoders) for legs in contact

# Locomotion State Estimation

## Inertial measurements



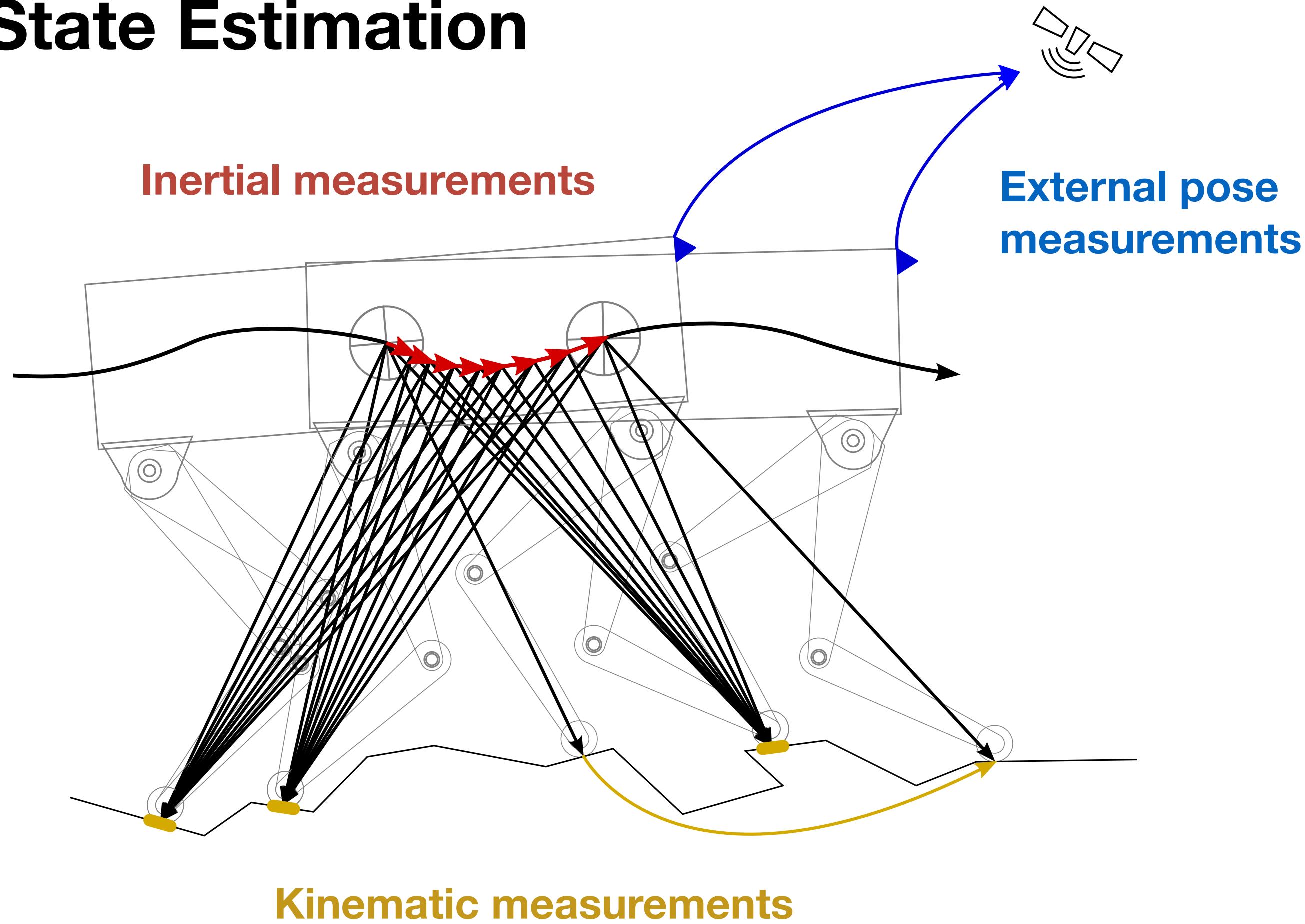
## Kinematic measurements

M. Bloesch, C. Gehring, P. Fankhauser, M. Hutter, M. A. Hoepflinger and R. Siegwart, “State Estimation for Legged Robots on Unstable and Slippery Terrain”, in International Conference on Intelligent Robots and Systems (IROS), 2013.

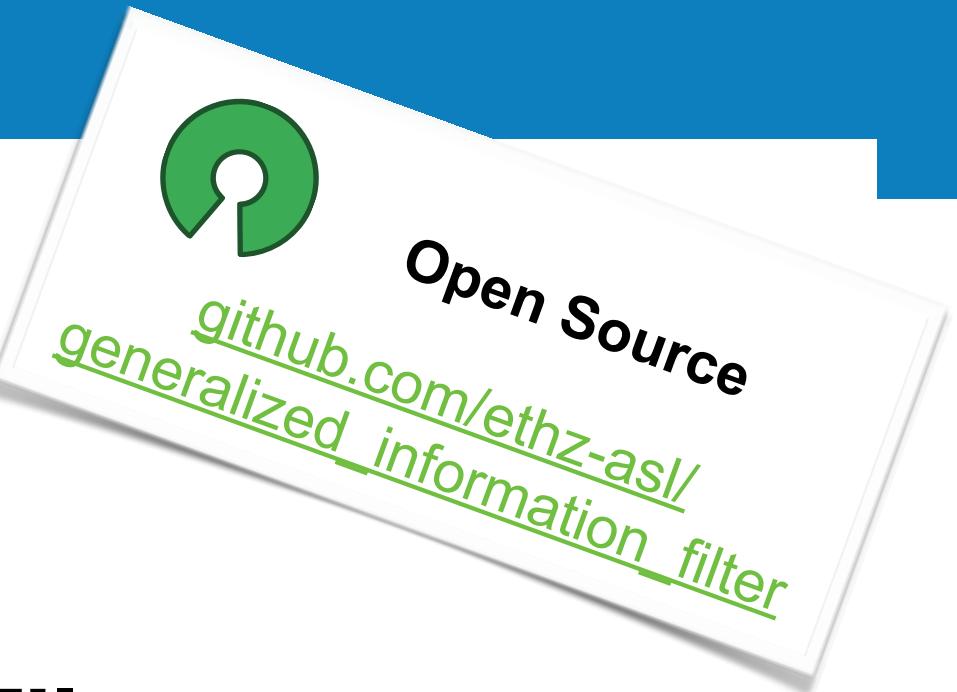
## Extended Kalman Filter

- No assumption on terrain
- Kinematic measurements (encoders) for legs in contact
- Fused with inertial measurements (IMU)
- Error < 5% over distance

# Locomotion State Estimation



M. Bloesch, C. Gehring, P. Fankhauser, M. Hutter, M. A. Hoepflinger and R. Siegwart, “State Estimation for Legged Robots on Unstable and Slippery Terrain”, in International Conference on Intelligent Robots and Systems (IROS), 2013.



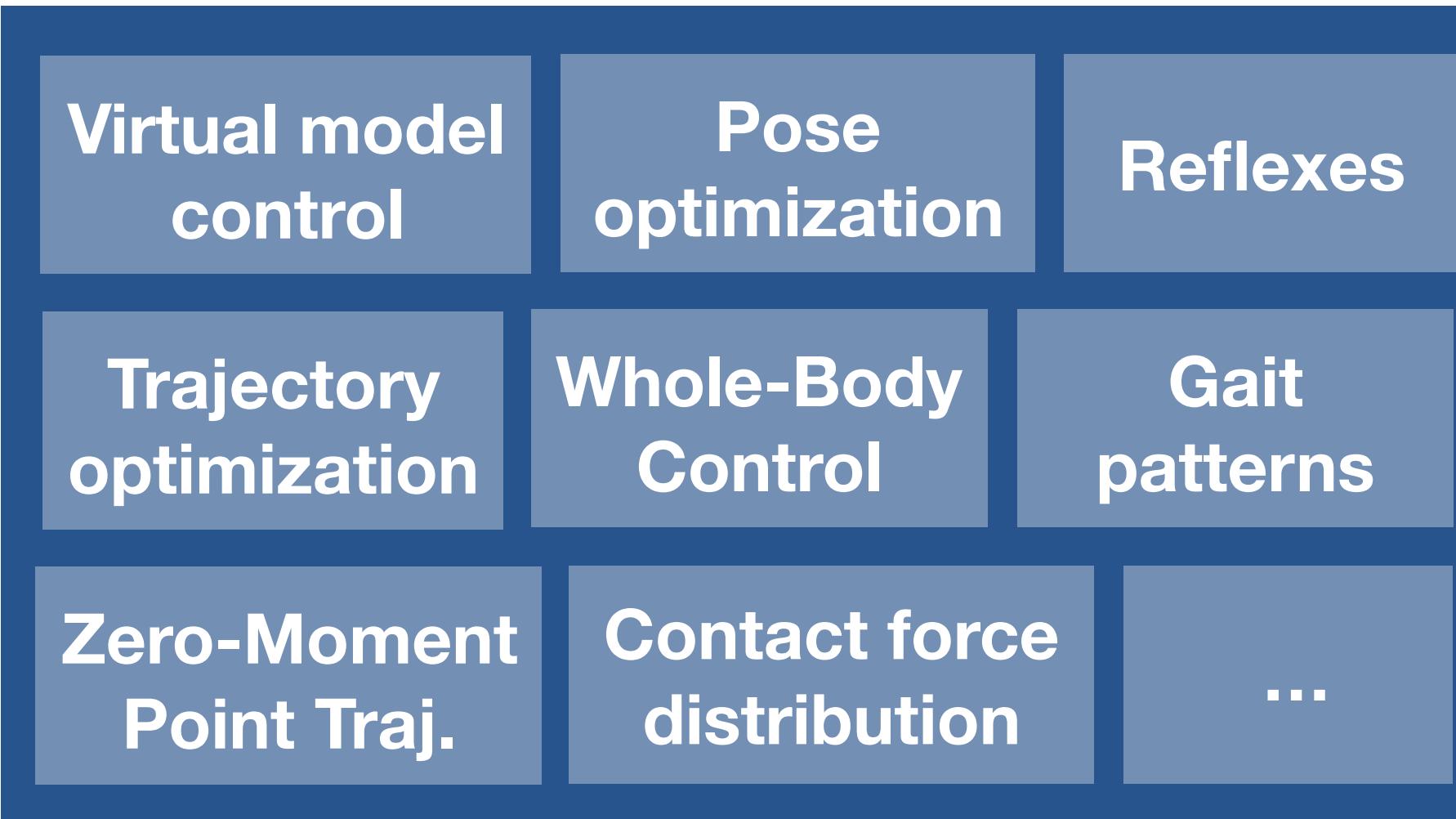
## Extended Kalman Filter

- No assumption on terrain
- Kinematic measurements (encoders) for legs in contact
- Fused with inertial measurements (IMU)
- Error < 5% over distance
- Optionally combined with external pose (GPS, laser, vision, etc.)

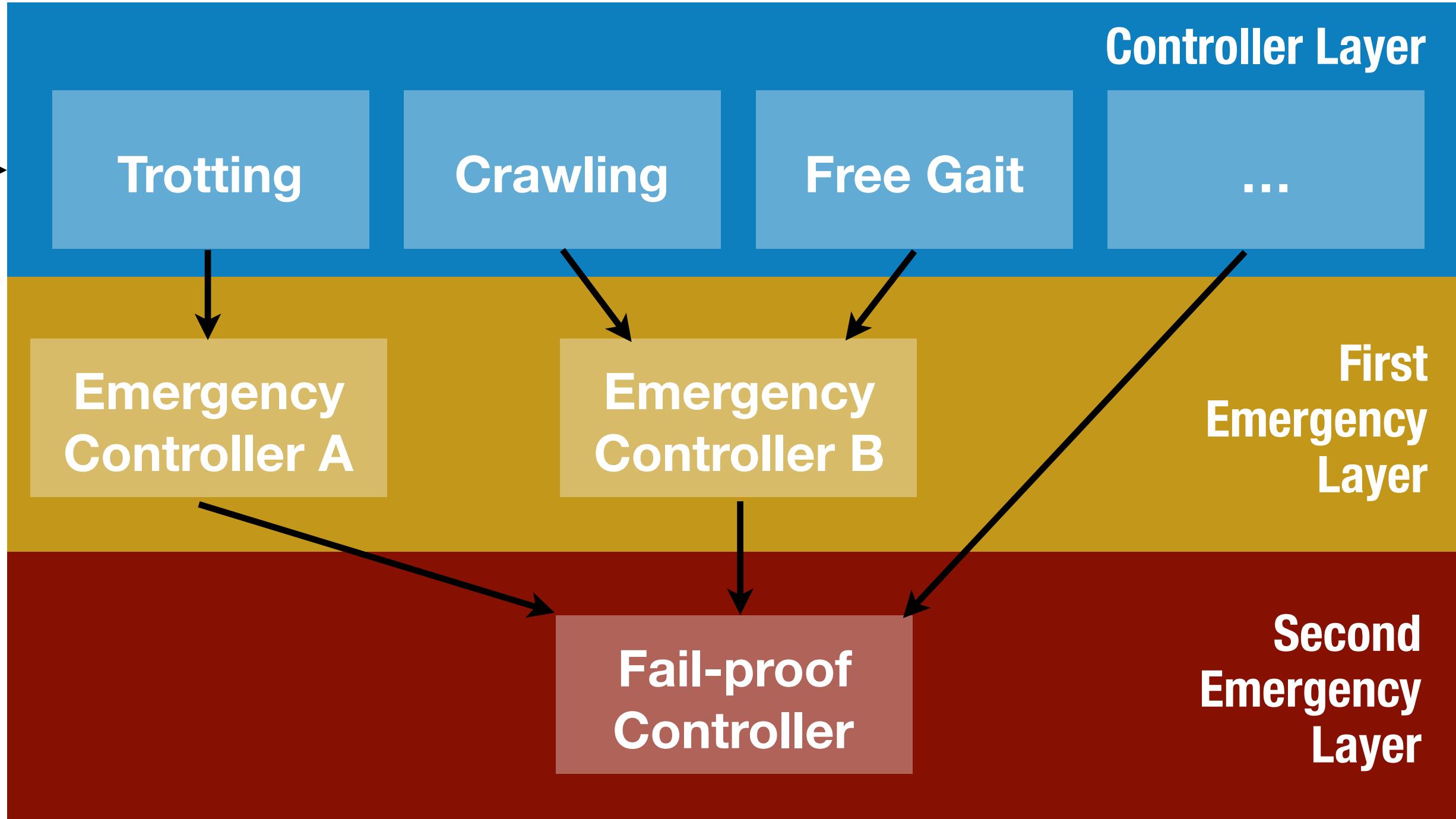
# Locomotion Whole-Body Control



## Locomotion Controller Modules (Loco)



## Robot Controller Manager (Rocoma)



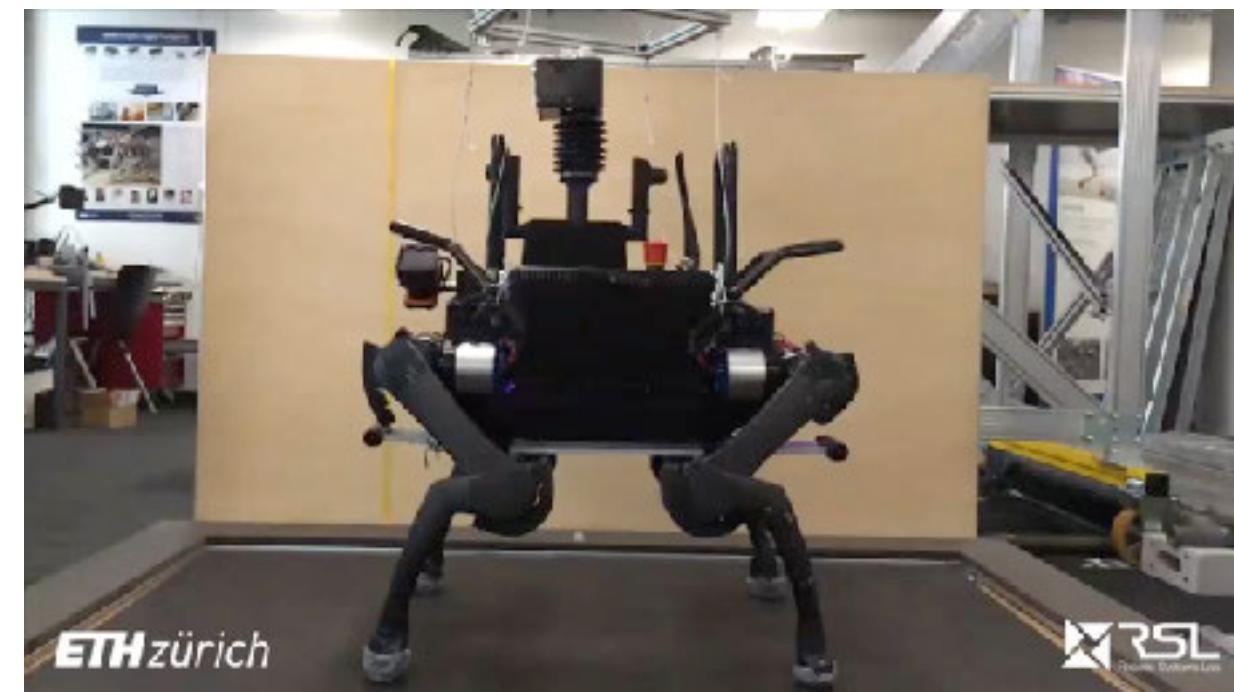
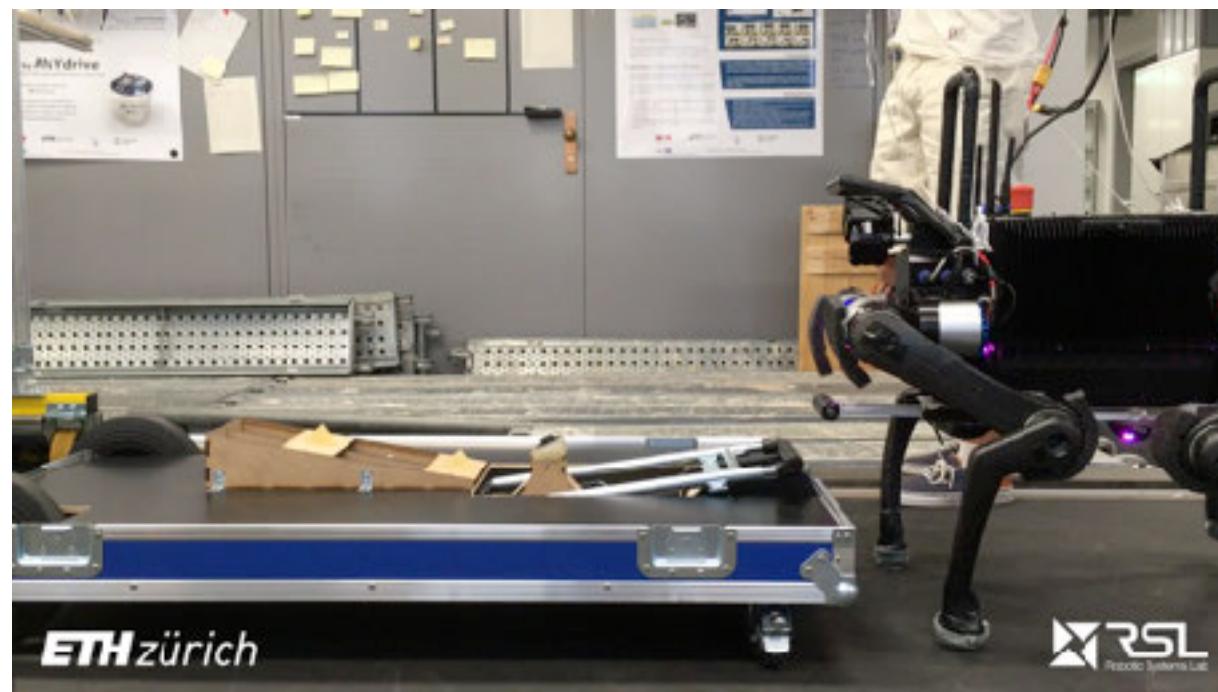
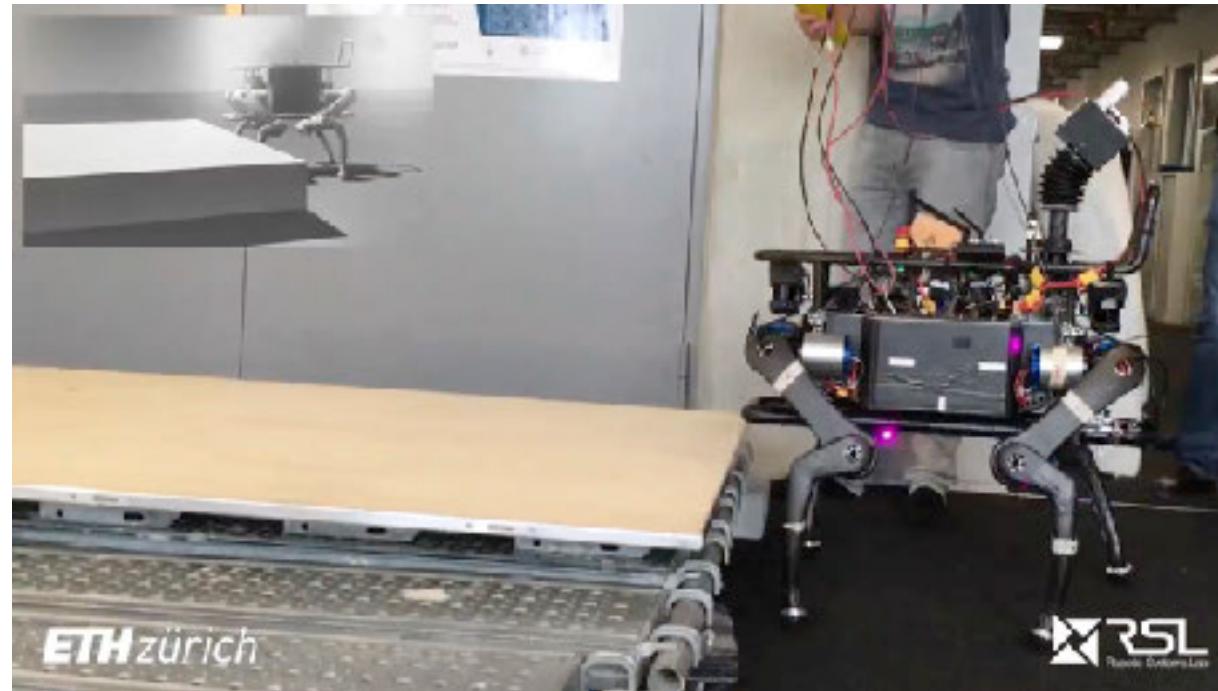
C. Gehring, S. Coros, M. Hutter, D. Bellicoso, H. Heijnen, R. Diethelm, M. Bloesch, P. Fankhauser, J. Hwangbo, M. A. Hoepflinger, and R. Siegwart, “**Practice Makes Perfect: An Optimization-Based Approach to Controlling Agile Motions for a Quadruped Robot.**”, in IEEE Robotics & Automation Magazine, 2016.

C. Dario Bellicoso, C. Gehring, J. Hwangbo, P. Fankhauser, M. Hutter, “**Emerging Terrain Adaptation from Hierarchical Whole Body Control,**” in IEEE Internal Conference on Humanoid Robots (Humanoids), 2016.



# Locomotion

## Free Gait – An Architecture for the Versatile Control of Legged Robots



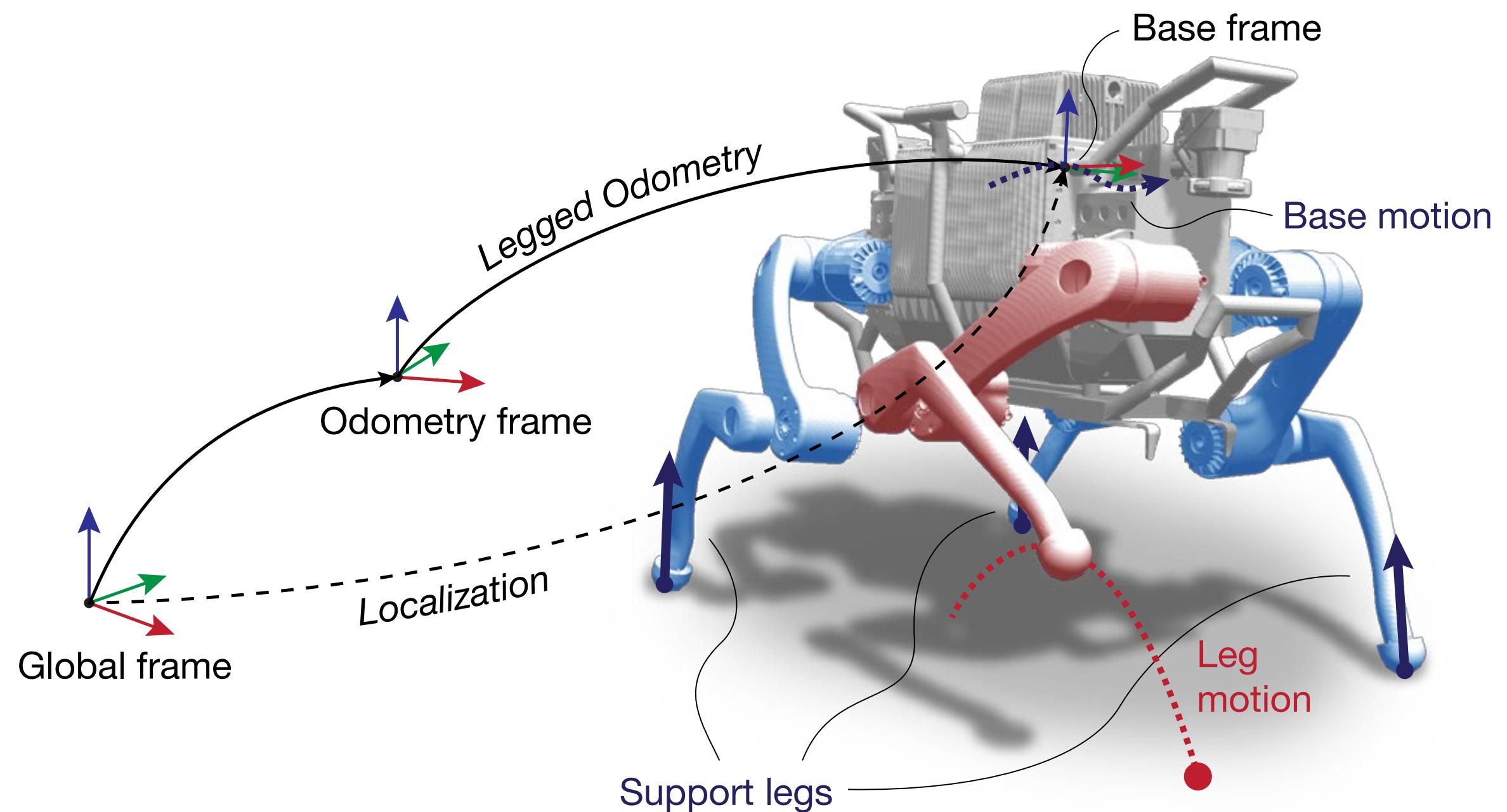
- Abstraction Layer for Whole-Body Motions (Free Gait API)

P. Fankhauser, D. Bellicoso, C. Gehring, R. Dubé, A. Gawel, and M. Hutter, “**Free Gait – An Architecture for the Versatile Control of Legged Robots**,” in IEEE-RAS International Conference on Humanoid Robots (Humanoids), 2016.



## Locomotion

## Free Gait – An Architecture for the Versatile Control of Legged Robots



- Abstraction Layer for Whole-Body Motions (Free Gait API)
- Robust motion execution in task space

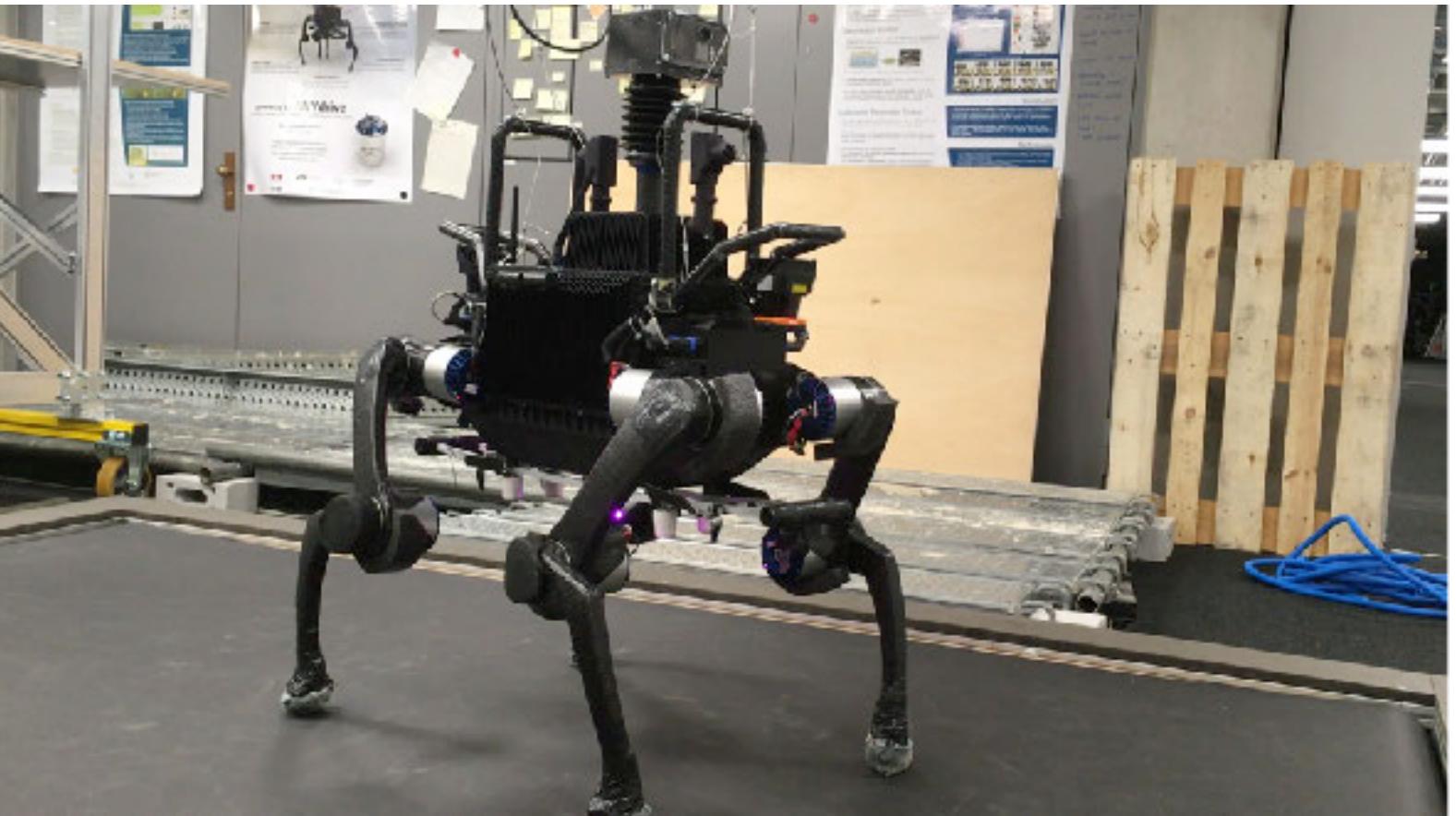
P. Fankhauser, D. Bellicoso, C. Gehring, R. Dubé, A. Gawel, and M. Hutter, “Free Gait – An Architecture for the Versatile Control of Legged Robots,” in IEEE-RAS International Conference on Humanoid Robots (Humanoids), 2016.



# Locomotion

## Free Gait – An Architecture for the Versatile Control of Legged Robots

```
steps:
  - step:
    - base_auto:
    - step:
      - end_effector_target:
        name: RF_LEG
        ignore_contact: true
        target_position:
          frame: footprint
          position: [0.39, -0.24, 0.20]
  - step:
    - base_auto:
      height: 0.38
      ignore_timing_of_leg_motion: true
    - end_effector_target: &foot
      name: RF_LEG
      ignore_contact: true
      ignore_for_pose_adaptation: true
      target_position:
        frame: footprint
        position: [0.39, -0.24, 0.20]
  - step:
    - base_auto:
      height: 0.45
      ignore_timing_of_leg_motion: true
    - end_effector_target: *foot
  - step:
    - footstep:
      name: RF_LEG
      profile_type: straight
      target:
        frame: footprint
        position: [0.32, -0.24, 0.0]
  - step:
    - base_auto:
```



- Abstraction Layer for Whole-Body Motions (Free Gait API)
- Robust motion execution in task space
- Implemented as ROS Action (with frameworks for YAML, Python, C++)

P. Fankhauser, D. Bellicoso, C. Gehring, R. Dubé, A. Gawel, and M. Hutter, “**Free Gait – An Architecture for the Versatile Control of Legged Robots**,” in IEEE-RAS International Conference on Humanoid Robots (Humanoids), 2016.

# Locomotion Kindr – Kinematics and Dynamics for Robotics



- C++ library for the consistent handling of 3d position and rotations
- Support for *rotation matrices*, *quaternions*, *angle-axis*, *rotation vectors*, *Euler angles*, etc.
- Support for all common operations and includes time-derivates
- ROS interface available
- Based on Eigen, 1000+ unit tests

**Kindr Library – Kinematics and Dynamics for Robotics**  
Christian Gehring, C. Dario Bellicoso, Michael Bloesch, Hannes Sommer, Peter Fankhauser, Marco Hutter, Roland Siegwart

Nomenclature	
(Hyper-)complex number	$Q$ normal capital letter
Column vector	$\mathbf{a}$ bold small letter
Matrix	$M$ bold capital letter
Identity matrix	$I_{n \times m}$ $n \times m$ -matrix
Coordinate system (CS)	$e_x^A, e_y^A, e_z^A$ Cartesian right-hand system $A$ with basis (unit) vectors $\mathbf{e}$
Inertial frame	$e_x^B, e_y^B, e_z^B$ global / inertial / world coordinate system (never moves)
Body-fixed frame	$e_x^B, e_y^B, e_z^B$ local / body-fixed coordinate system (moves with body)
Rotation	$\Phi \in SO(3)$ generic rotation (for all parameterizations)
Machine precision	$\epsilon$

Operators	
Cross product/skew/unskew	$\mathbf{a} \times \mathbf{b} = \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} \times \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} = (\mathbf{a})^\wedge \mathbf{b} = \hat{\mathbf{a}} \mathbf{b} = \begin{bmatrix} 0 & -a_3 & a_2 \\ a_3 & 0 & -a_1 \\ -a_2 & a_1 & 0 \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix}$
$\mathbf{a} = \hat{\mathbf{a}}^T \mathbf{a}$ , $\hat{\mathbf{a}} = -\hat{\mathbf{a}}^T$ , $\mathbf{a} \times \mathbf{b} = -\mathbf{b} \times \mathbf{a}$	
Euclidean norm	$\ \mathbf{a}\  = \sqrt{\mathbf{a}^T \mathbf{a}} = \sqrt{a_1^2 + \dots + a_n^2}$
Exponential map for matrix	$\exp : \mathbb{R}^{3 \times 3} \rightarrow \mathbb{R}^{3 \times 3}, \mathbf{A} \mapsto e^{\mathbf{A}}, \quad \mathbf{A} \in \mathbb{R}^{3 \times 3}$
Logarithmic map for matrix	$\log : \mathbb{R}^{3 \times 3} \rightarrow \mathbb{R}^{3 \times 3}, \mathbf{A} \mapsto \log \mathbf{A}, \quad \mathbf{A} \in \mathbb{R}^{3 \times 3}$

Position & Orientation	
Vector	$\mathbf{r}_{OP}$ from point $O$ to point $P$
Position vector	$B\mathbf{r}_{OP} \in \mathbb{R}^3$ from point $O$ to point $P$ expr. in frame $B$
Homogeneous pos. vector	$B\mathbf{r}_{OP} = [B\mathbf{r}_{OP}^T \ 1]^T$ from point $O$ to point $P$ expr. in frame $B$

Orientation/Rotation	
1) Active Rotation:	$\Phi^A : I\mathbf{r}_{OP} \mapsto I\mathbf{r}_{OQ}$ (rotates the vector $\mathbf{r}_{OP}$ )
2) Passive Rotation:	$\Phi^P : I\mathbf{r}_{OP} \mapsto B\mathbf{r}_{OP}$ (rotates the frame $(e_x^P, e_y^P, e_z^P)$ )
3) Elementary Rotations	$I\mathbf{r}_{OP} = C_{IB} B\mathbf{r}_{OP}$
	around z-axis: $C_{IB} = \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$
	around y-axis: $C_{IB} = \begin{bmatrix} \cos \theta & 0 & \sin \theta \\ 0 & 1 & 0 \\ -\sin \theta & 0 & \cos \theta \end{bmatrix}$
	around x-axis: $C_{IB} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \theta & -\sin \theta \\ 0 & \sin \theta & \cos \theta \end{bmatrix}$
4) Inversion:	$\Phi^{A^{-1}}(\mathbf{r}) = \Phi^P(\mathbf{r})$
5) Concatenation:	$\Phi_2^P(\Phi_1^P(\mathbf{r})) = (\Phi_2^P \otimes \Phi_1^P)(\mathbf{r}) = (\Phi_1^{P^{-1}} \otimes \Phi_2^{P^{-1}})^{-1}(\mathbf{r})$
6) Exponential map:	$\exp : \mathbb{R}^3 \rightarrow SO(3), \mathbf{v} \mapsto \exp(\tilde{\mathbf{v}}), \quad \mathbf{v} \in \mathbb{R}^3$
7) Logarithmic map:	$\log : SO(3) \rightarrow \mathbb{R}^3, \Phi \mapsto \log(\tilde{\Phi}), \quad \Phi \in SO(3)$
8) Box plus:	$\Phi_2 = \Phi_1 \boxplus \mathbf{v} = \exp(\mathbf{v}) \otimes \Phi_1, \quad \Phi_1, \Phi_2 \in SO(3), \mathbf{v} \in \mathbb{R}^3$
9) Box minus:	$\mathbf{v} = \Phi_1 \boxminus \Phi_2 = \log(\Phi_1 \otimes \Phi_2^{-1}), \quad \Phi_1, \Phi_2 \in SO(3), \mathbf{v} \in \mathbb{R}^3$
10) Discrete integration:	$\Phi_{IB}^{k+1} = \Phi_{IB}^k \boxplus (\nu \omega_{IB}^k \Delta t), \quad \Phi_{IB}^{k+1} = \Phi_{IB}^k \boxplus (-\mu \omega_{IB}^k \Delta t)$
11) Discrete differential:	$\nu \omega_{IB}^k = (\Phi_{IB}^{k+1} \boxminus \Phi_{IB}^k) / \Delta t, \quad \mu \omega_{IB}^k = (\Phi_{IB}^{k+1} \boxminus \Phi_{IB}^k) / \Delta t$
12) (Spherical) linear interpolation $t \in [0, 1]$ :	$= (\Phi_1 \otimes \Phi_0^{-1})^t \otimes \Phi_0$

Rotation Parameterizations	
Rotation Matrix	$C_{IB} \in SO(3)$ The rotation matrix (Direction Cosine Matrix)
$I\mathbf{r}_{OP} = C_{IB} B\mathbf{r}_{OP}$	is a coordinate transformation matrix, which transforms vectors from frame $B$ to frame $I$ .
$C_{IB} = C_{IB}^q$	$q = q_0 + q_1 i + q_2 j + q_3 k \in \mathbb{H}, \quad q_i \in \mathbb{R}, \quad \ Q\  = 1$
Quaternion	$\mathbf{q}_{IB} = [q_0 \ q_1 \ q_2 \ q_3]^T$ Hamiltonian unit quaternion (hypercomplex number)
Angle-axis	$(\theta, \mathbf{n})_{IB}$ Rotation with unit rotation axis $\mathbf{n}$ and angle $\theta \in [0, \pi]$ .
Rotation Vector	$\phi_{IB}$ Rotation with rotation axis $\mathbf{n} = \frac{\phi}{\ \phi\ }$ and angle $\theta = \ \phi\ $ .
Euler Angles ZYX	$[z, y, x]_{IB}$ Tait-Bryan angles (Flight conv.); $z = y' - x''$ , i.e. yaw-pitch-roll. Singularities are at $y = \pm \frac{\pi}{2}$ .
Euler Angles YPR	$[x, y, z]_{IB}$ Cardan angles: $x = y' - z'', y = -z' + x'', z = -x' + y''$ . Singularities are at $y = \pm \frac{\pi}{2}$ .
Euler Angles XYZ	$[x, y, z]_{IB}$
Euler Angles RPY	$[x, y, z]_{IB}$

**Rotation Quaternion**  
A rotation quaternion is a Hamiltonian unit quaternion:  
 $Q = q_0 + q_1 i + q_2 j + q_3 k \in \mathbb{H}, \quad q_i \in \mathbb{R}, \quad i^2 = j^2 = k^2 = ijk = -1, \quad \|Q\| = \sqrt{q_0^2 + q_1^2 + q_2^2 + q_3^2} = 1$

Tuple:  $Q = (q_0, q_1, q_2, q_3) = (q_0, \tilde{\mathbf{q}})$  with  $\tilde{\mathbf{q}} := (q_1, q_2, q_3)^T$

4 x 1-vector:  $\mathbf{q} = [q_0 \ q_1 \ q_2 \ q_3]^T$

Conjugate:  $\mathbf{q}^* = (q_0, -\tilde{\mathbf{q}})$

Inverse:  $Q^{-1} = Q^* = (q_0, -\tilde{\mathbf{q}})$

Quaternion multiplication:  
 $Q \cdot P = (q_0 p_0 - \tilde{\mathbf{q}}^T \mathbf{p}, q_0 \tilde{\mathbf{q}} + \tilde{\mathbf{q}} \times \mathbf{p}) \Leftrightarrow$

$\mathbf{q} \otimes \mathbf{p} = \mathbf{Q}(\mathbf{q}) \mathbf{p} = \begin{pmatrix} q_0 & -\tilde{\mathbf{q}}^T \\ \tilde{\mathbf{q}} & q_0 \mathbb{I}_{3 \times 3} + \tilde{\mathbf{q}} \mathbf{I} \end{pmatrix} \begin{pmatrix} p_0 \\ p_1 \\ p_2 \\ p_3 \end{pmatrix} = \begin{pmatrix} q_0 & -q_1 & -q_2 & -q_3 \\ q_1 & q_0 & -q_3 & q_2 \\ q_2 & q_3 & q_0 & -q_1 \\ q_3 & -q_2 & q_1 & q_0 \end{pmatrix} \begin{pmatrix} p_0 \\ p_1 \\ p_2 \\ p_3 \end{pmatrix}$

$= \mathbf{Q}(\mathbf{p}) \mathbf{q} = \begin{pmatrix} p_0 & -\tilde{\mathbf{p}}^T \\ \tilde{\mathbf{p}} & p_0 \mathbb{I}_{3 \times 3} - \tilde{\mathbf{p}} \mathbf{I} \end{pmatrix} \begin{pmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{pmatrix} = \begin{pmatrix} p_0 & -p_1 & -p_2 & -p_3 \\ p_1 & p_0 & p_3 & -p_2 \\ p_2 & -p_3 & p_0 & p_1 \\ p_3 & p_2 & -p_1 & p_0 \end{pmatrix} \begin{pmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{pmatrix}$

Note that  $Q_{IB}$  and  $-Q_{IB}$  represent the same rotation, but not the same unit quaternion.

**Rotation Quaternion  $\Leftrightarrow$  Rotation Vector**  
 $Q_{IB} = \begin{cases} \left[ \begin{array}{c} \cos(\frac{1}{2}\|\phi\|) \\ \frac{\phi^T}{\|\phi\|} \sin(\frac{1}{2}\|\phi\|) \end{array} \right]^T & \text{if } \|\phi\| \geq \epsilon \\ \left[ \begin{array}{c} 1 \\ \frac{1}{2}\phi^T \end{array} \right]^T & \text{otherwise} \end{cases} \Leftrightarrow \phi_{IB} = \begin{cases} 2 \arctan2(\|\tilde{\mathbf{q}}\|, q_0) \frac{\tilde{\mathbf{q}}}{\|\tilde{\mathbf{q}}\|} & \text{if } \|\tilde{\mathbf{q}}\| \geq \epsilon \\ 2 \operatorname{sign}(q_0) \tilde{\mathbf{q}} & \text{otherwise} \end{cases}$

**Rotation Quat ernion  $\Leftrightarrow$  Angle-Axis**  
 $q_{IB} = \begin{bmatrix} \cos \frac{\theta}{2} \\ \mathbf{n} \sin \frac{\theta}{2} \end{bmatrix} \Leftrightarrow (\theta, \mathbf{n})_{IB} = \begin{cases} (2 \arccos(q_0), \frac{\mathbf{q}}{\|\mathbf{q}\|}) & \text{if } \|\mathbf{q}\| \geq \epsilon \\ (0, [1 \ 0 \ 0]^T) & \text{otherwise} \end{cases}$

**Rotation Quat ernion  $\Leftrightarrow$  Rotation Matrix**  
 $C_{IB} = \mathbb{I}_{3 \times 3} + 2q_0 \tilde{\mathbf{q}} + 2\tilde{\mathbf{q}}^2 = (2q_0^2 - 1)\mathbb{I}_{3 \times 3} + 2q_0 \tilde{\mathbf{q}} + 2\tilde{\mathbf{q}}^2$

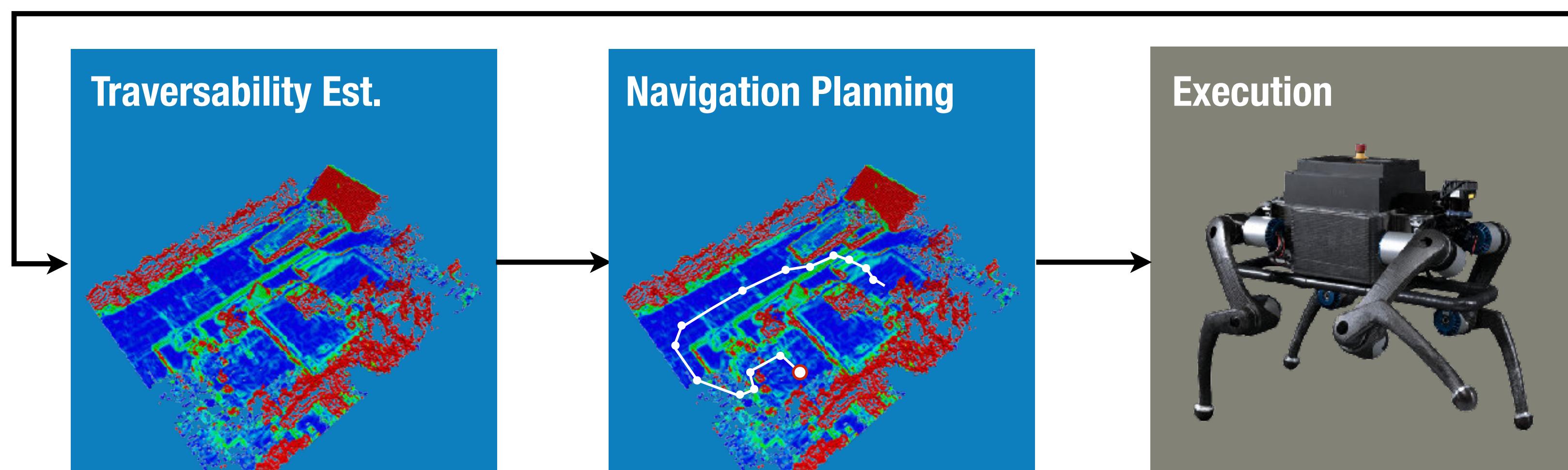
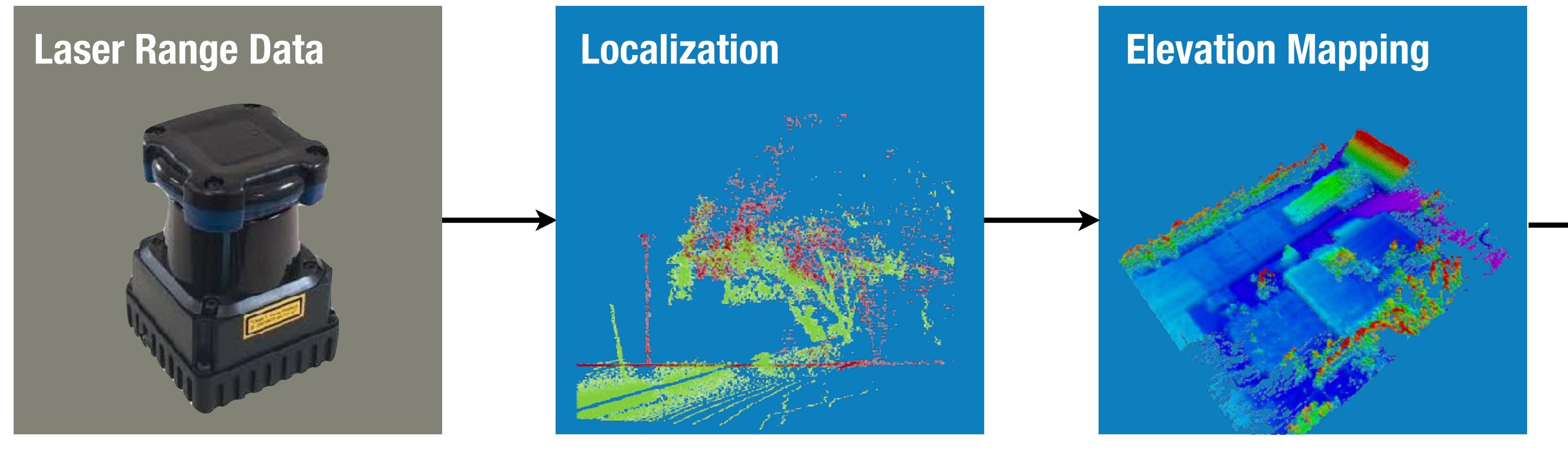
 $= \begin{bmatrix} q_0^2 + q_1^2 - q_2^2 - q_3^2 & 2q_1q_2 - 2q_0q_3 & 2q_2q_3 - 2q_0q_1 \\ 2q_0q_3 + 2q_2q_1 & q_0^2 - q_1^2 + q_2^2 - q_3^2 & 2q_2q_3 - 2q_0q_1 \\ 2q_1q_3 - 2q_0q_2 & 2q_0q_1 + 2q_2q_3 & q_0^2 - q_1^2 - q_2^2 + q_3^2 \end{bmatrix}$ 

$C_{IB}^{-1} = C_{IB} = \mathbb{I}_{3 \times 3} - 2q_0 \tilde{\mathbf{q}} + 2\tilde{\mathbf{q}}^2$

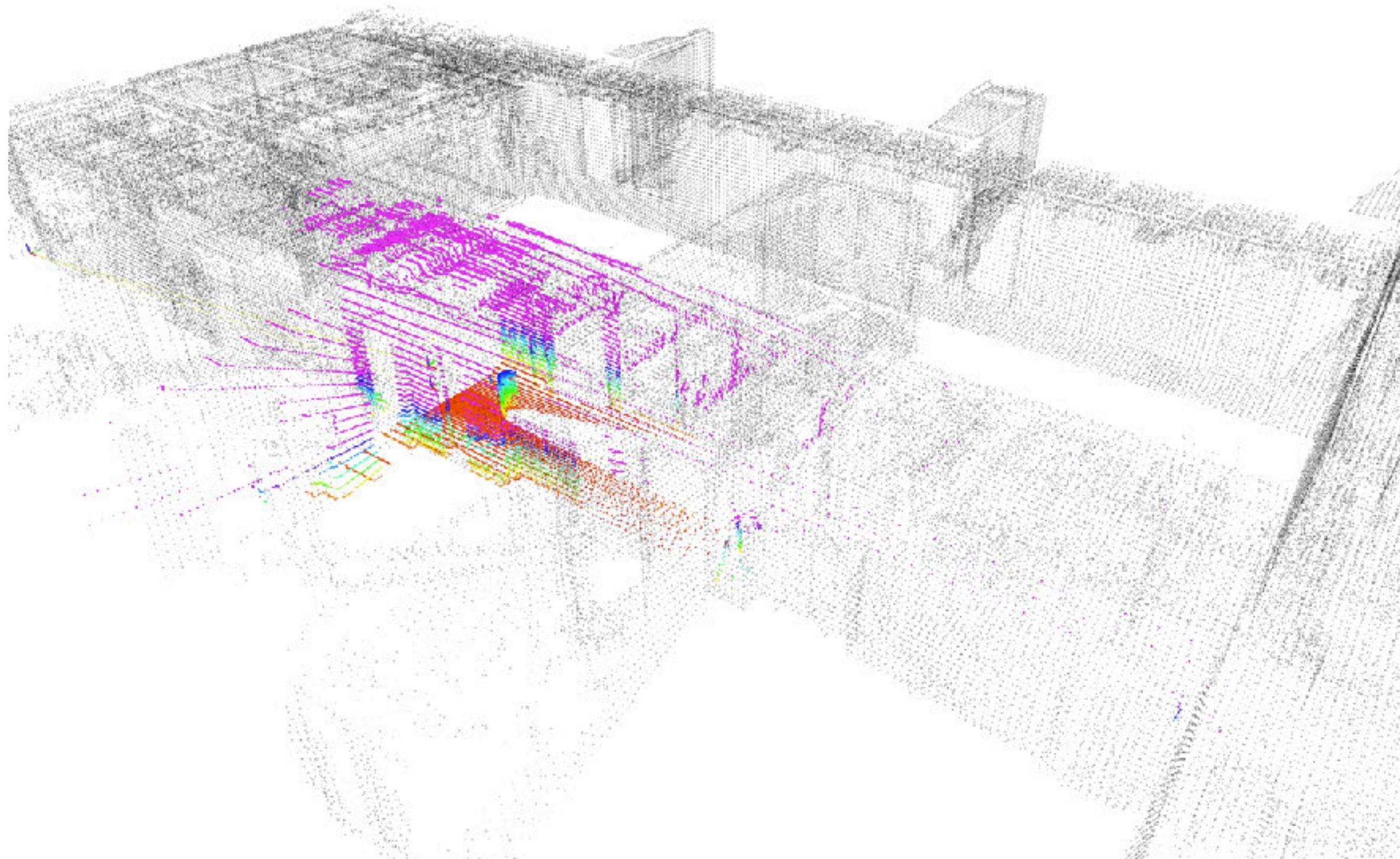
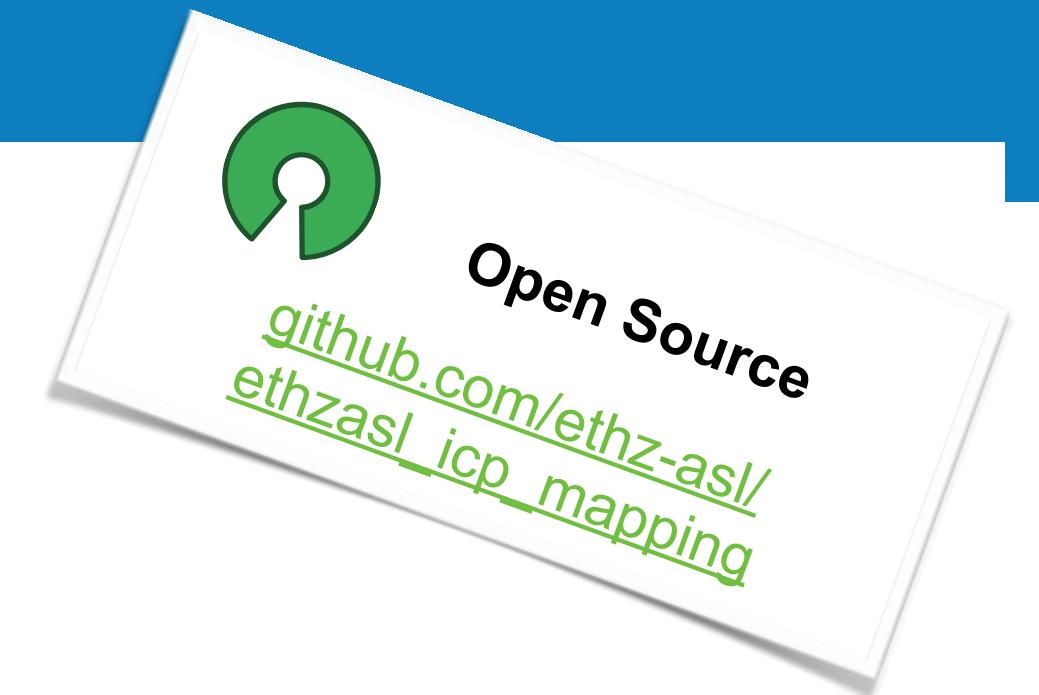
 $= \begin{bmatrix} q_0^2 + q_1^2 - q_2^2 - q_3^2 & 2q_0q_3 + 2q_1q_2 & 2q_1q_3 - 2q_0q_2 \\ 2q_1q_2 - 2q_0q_3 & q_0^2 - q_1^2 + q_2^2 - q_3^2 & 2q_0q_1 + 2q_2q_3 \\ 2q_0q_1 - 2q_2q_3 & 2q_2q_3 - 2q_0q_1 & q_0^2 - q_1^2 - q_2^2 + q_3^2 \end{bmatrix}$ 

M. Bloesch, H. Sommer, T. Laidlow, M. Burri, G. Nuetzi, P. Fankhauser, D. Bellicoso, C. Gehring, S. Leutenegger, M. Hutter, R. Siegwart, “A Primer on the Differential Calculus of 3D Orientations,” in arXiv:1606.05285, 2016.

# Navigation



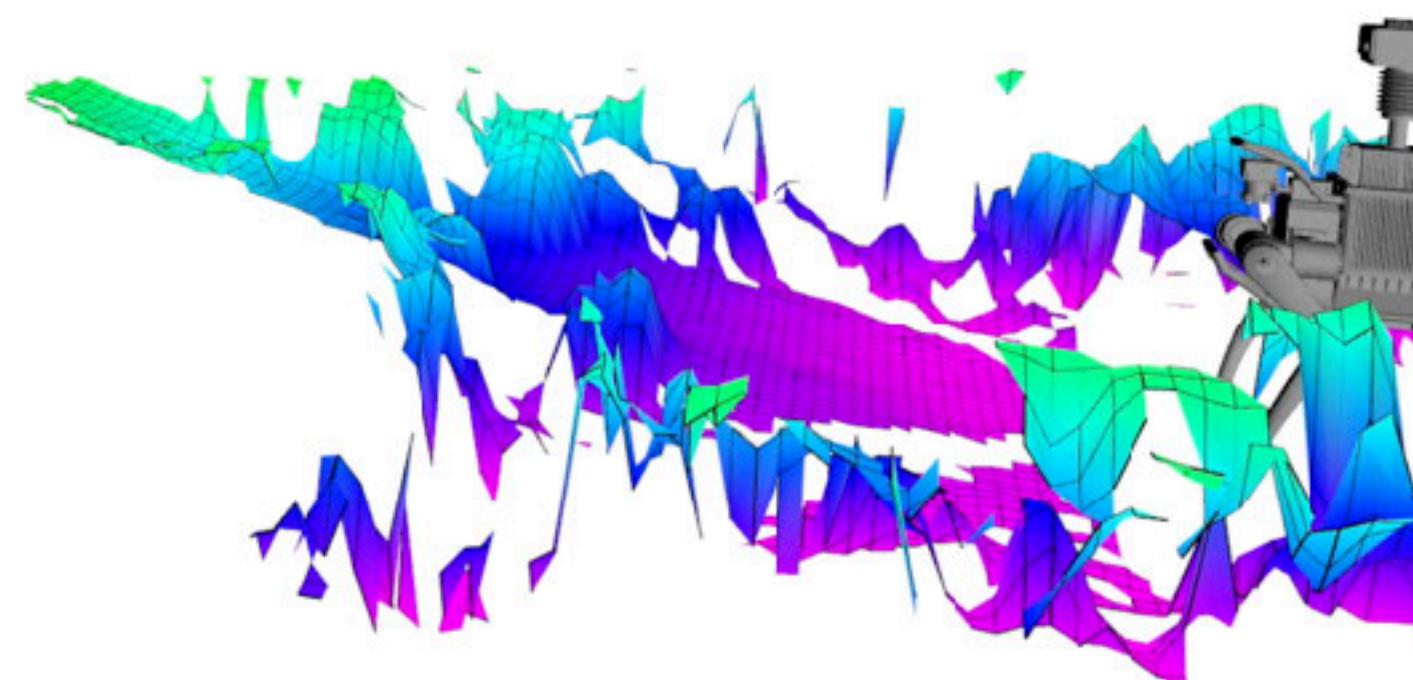
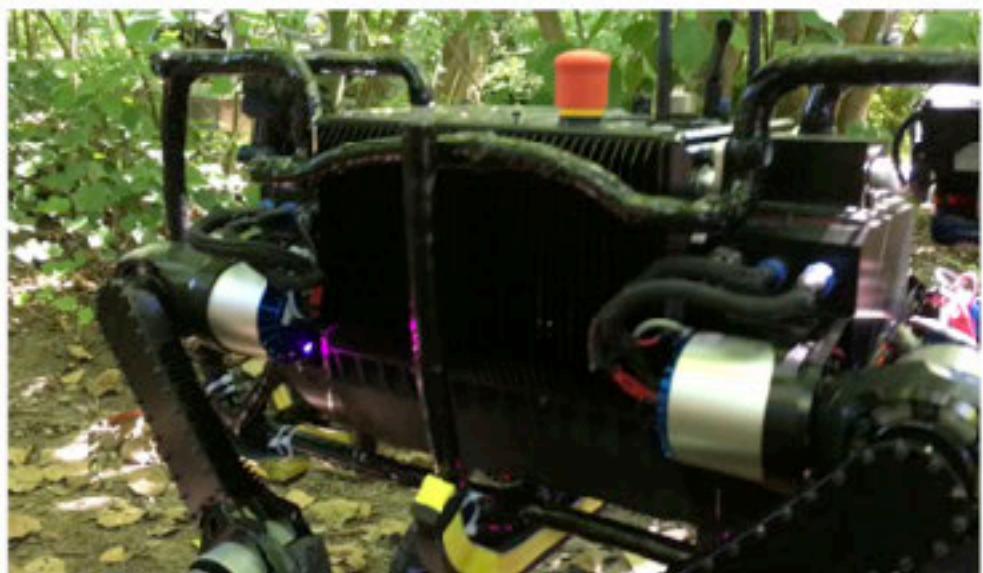
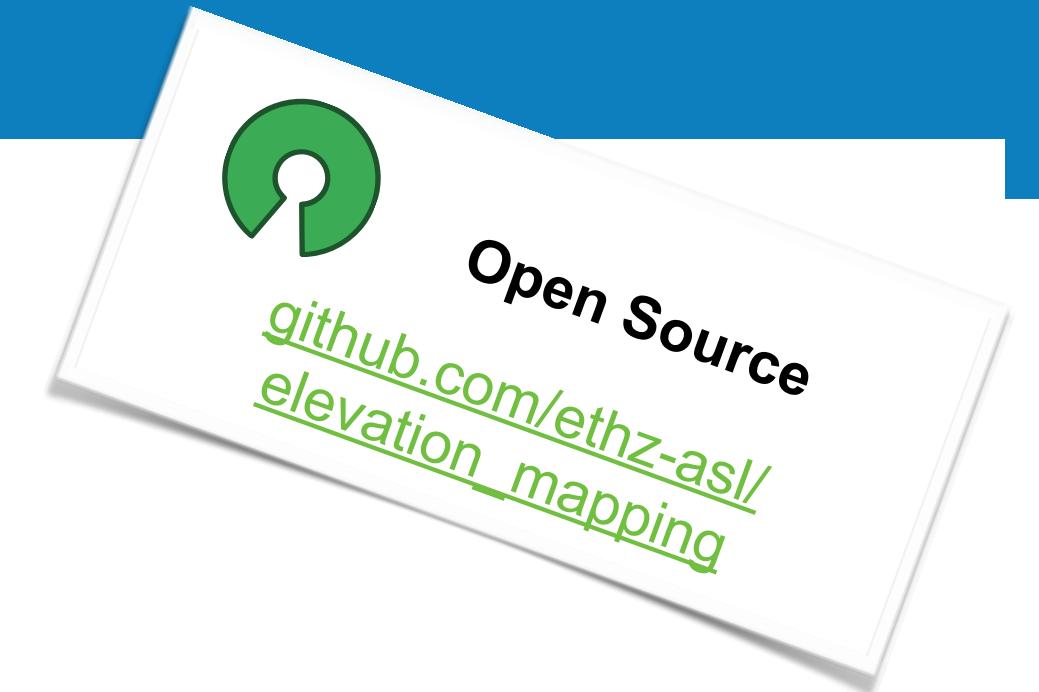
# Navigation Laser-Based Localization (Iterative Closest Point (ICP))



- Point cloud registration for localization in reference map
- Full rotation of LiDAR is aggregated for point cloud
- Use of existing maps or online mapping

Pomerleau, F., Colas, F., Siegwart, R., Magnenat, S., “Comparing ICP variants on real-world data sets”, in Autonomous Robots, 2013.

# Navigation Elevation Mapping – Dense Terrain Mapping

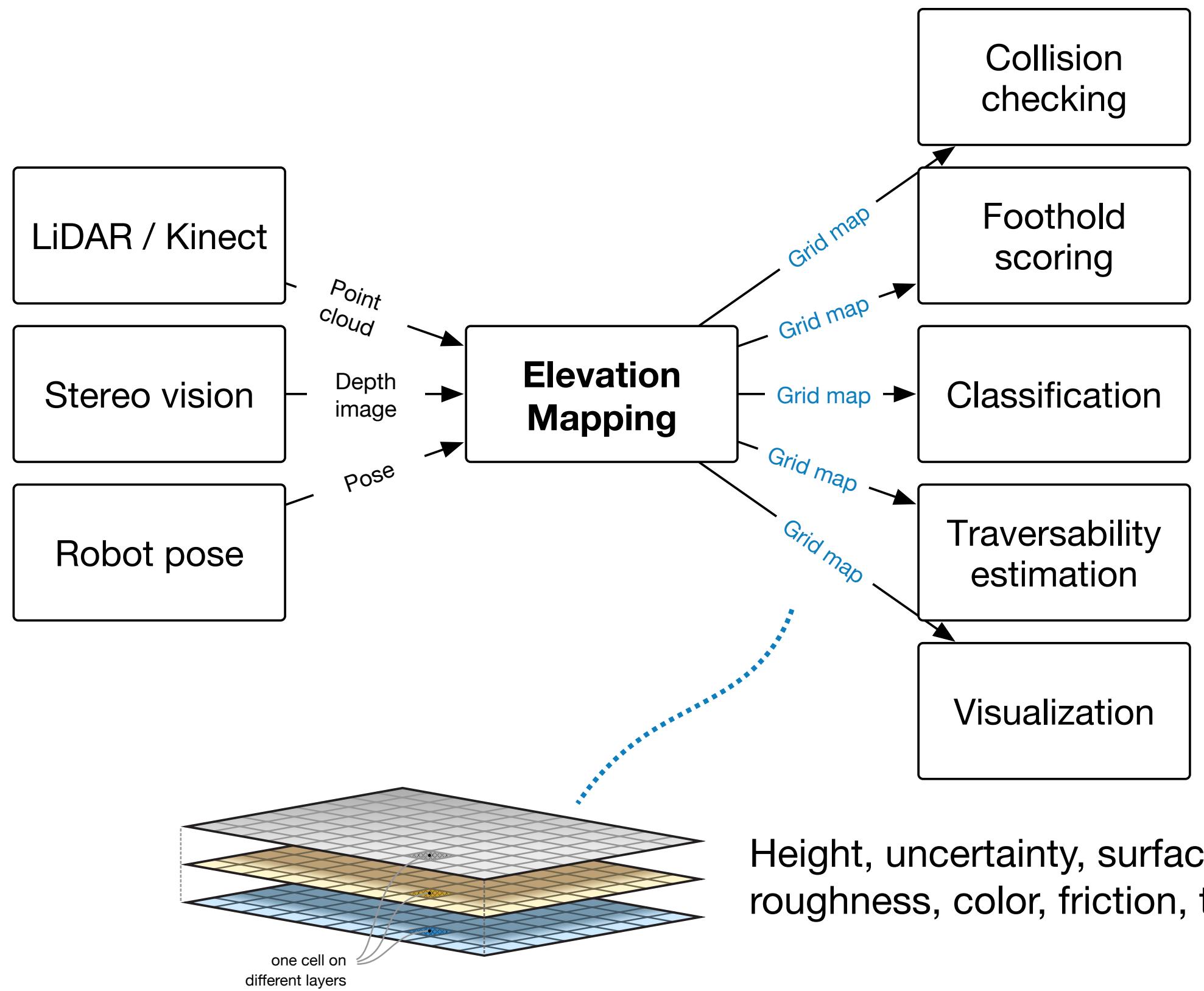
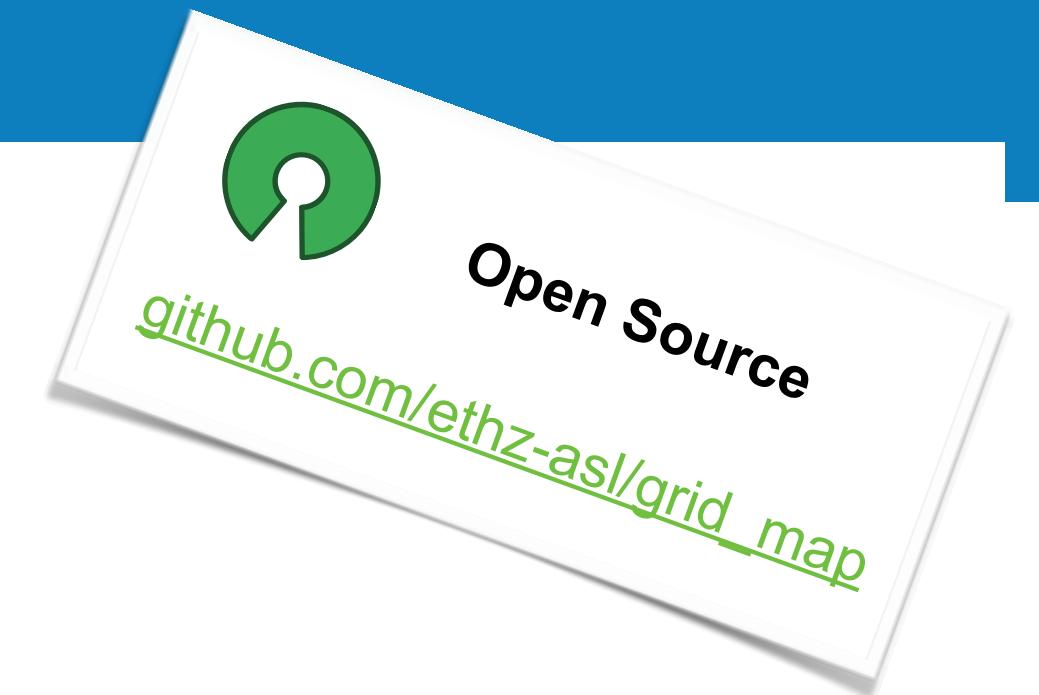


- Probabilistic fusion of range measurements and pose estimation
- Explicitly handles drift of state estimation (robot-centric)
- Input data from laser, Kinect, stereo cameras, Velodyne etc.

P. Fankhauser, M. Bloesch, C. Gehring, M. Hutter, R. Siegwart “**Robot-Centric Elevation Mapping with Uncertainty Estimates**,” in International Conference on Climbing and Walking Robots (CLAWAR), 2014.

# Navigation

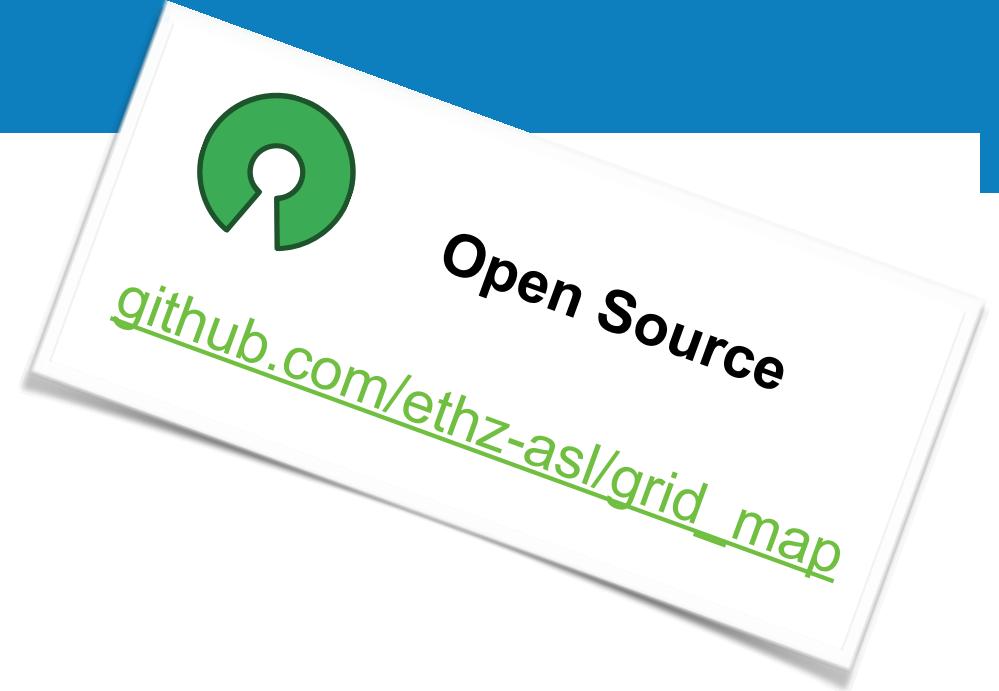
## Grid Map – Universal Multi-Layer Grid Map Library



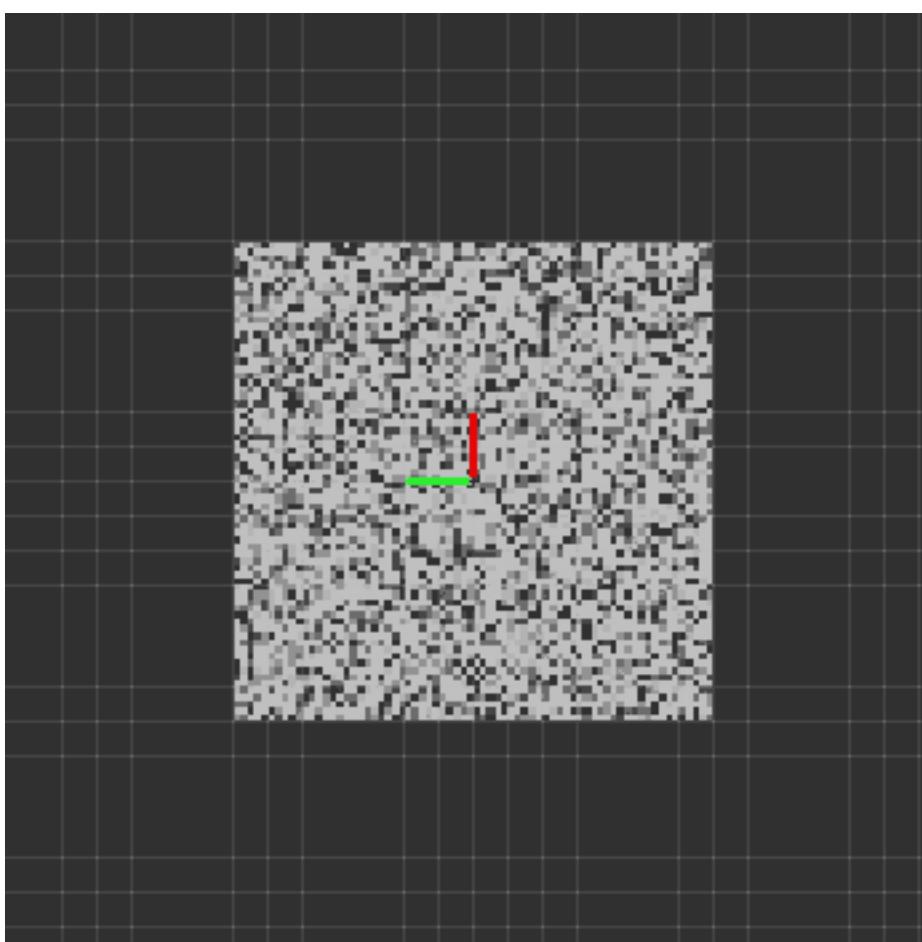
P. Fankhauser and M. Hutter, “A Universal Grid Map Library: Implementation and Use Case for Rough Terrain Navigation,”  
in Robot Operating System (ROS) - The Complete Reference, Springer, 2015.

# Navigation

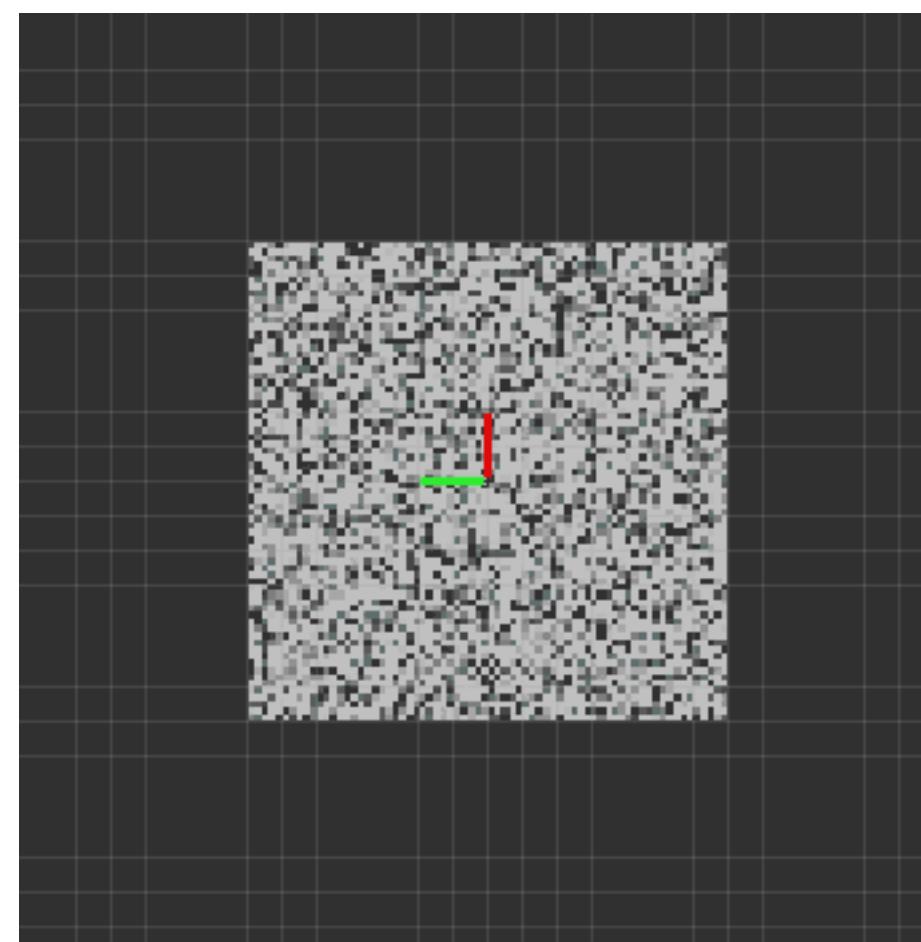
## Grid Map – Universal Multi-Layer Grid Map Library



- 2D circular buffer data structure
  - Efficient map repositioning



`setPosition(...)`

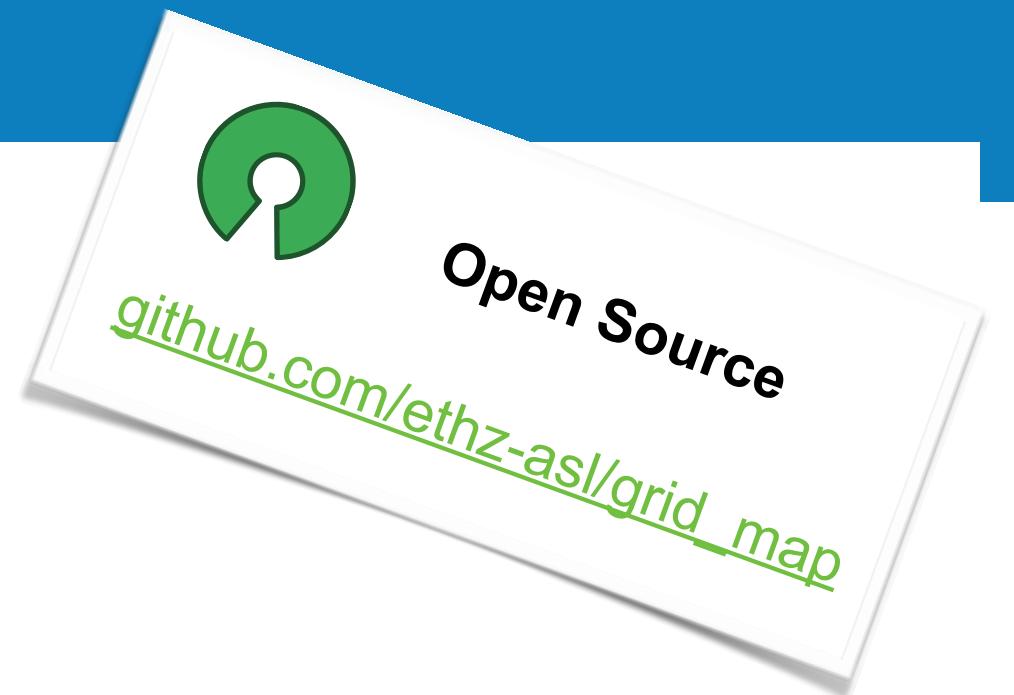


`move(...)`

P. Fankhauser and M. Hutter, “A Universal Grid Map Library: Implementation and Use Case for Rough Terrain Navigation,”  
in Robot Operating System (ROS) - The Complete Reference, Springer, 2015.

# Navigation

## Grid Map – Universal Multi-Layer Grid Map Library



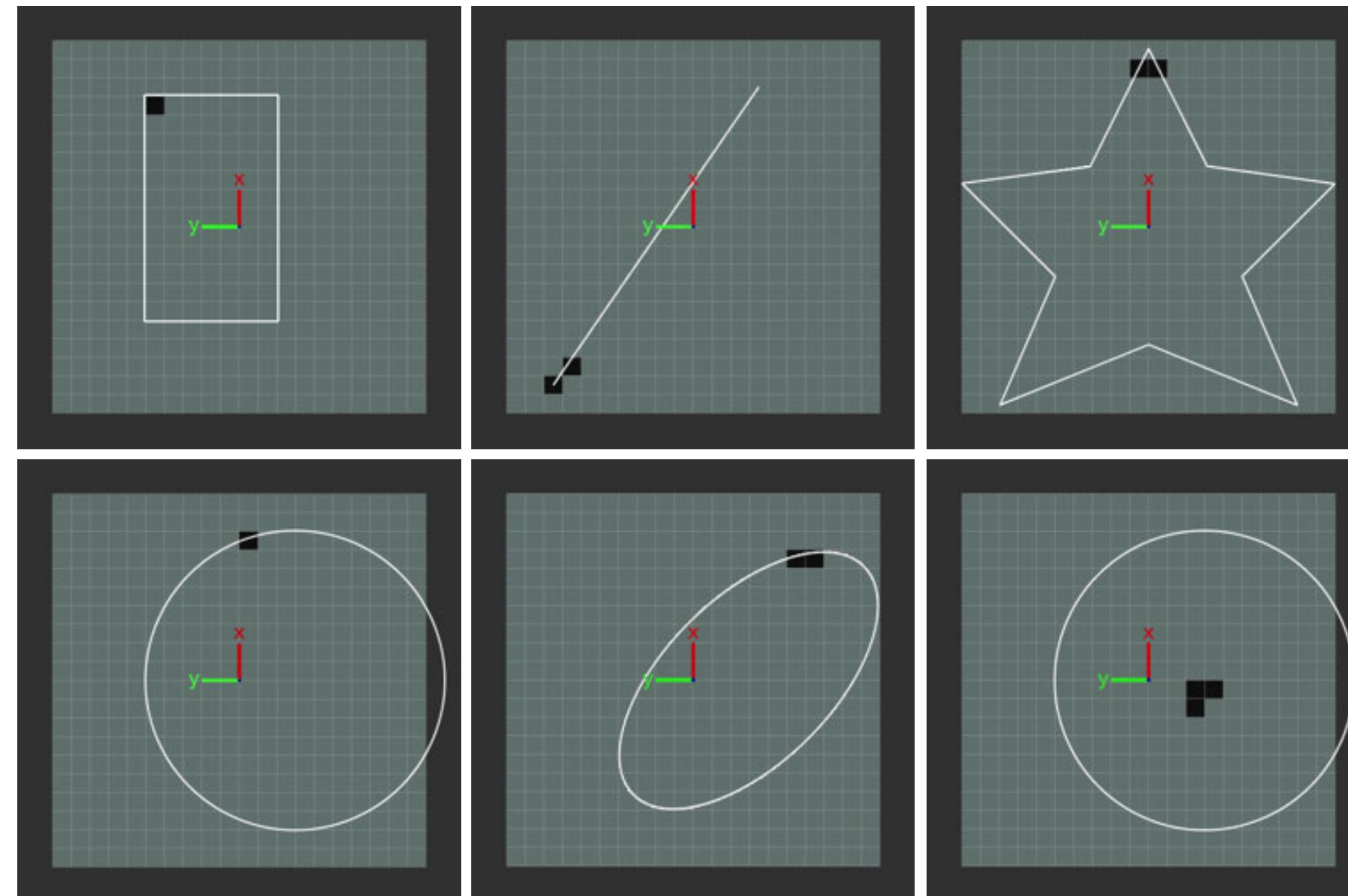
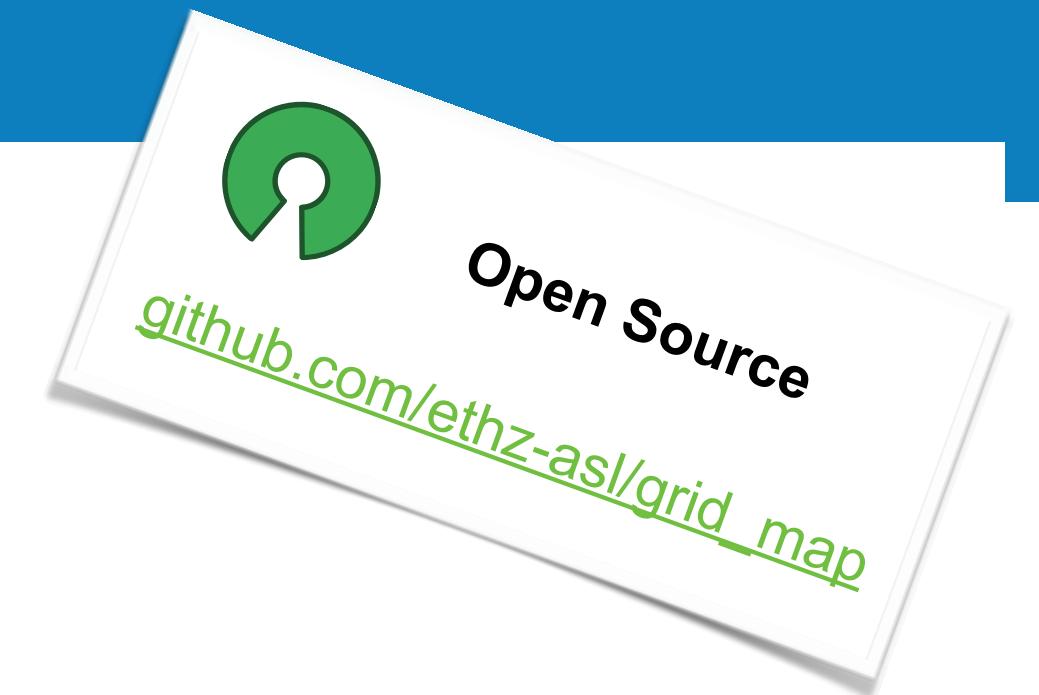
- 2D circular buffer data structure
  - Efficient map repositioning
- Based on Eigen (C++)
  - Versatile and efficient data manipulation

```
double rmse =  
    sqrt(map["error"].array().pow(2).sum() / nCells);
```

P. Fankhauser and M. Hutter, “A Universal Grid Map Library: Implementation and Use Case for Rough Terrain Navigation,”  
in Robot Operating System (ROS) - The Complete Reference, Springer, 2015.

# Navigation

## Grid Map – Universal Multi-Layer Grid Map Library

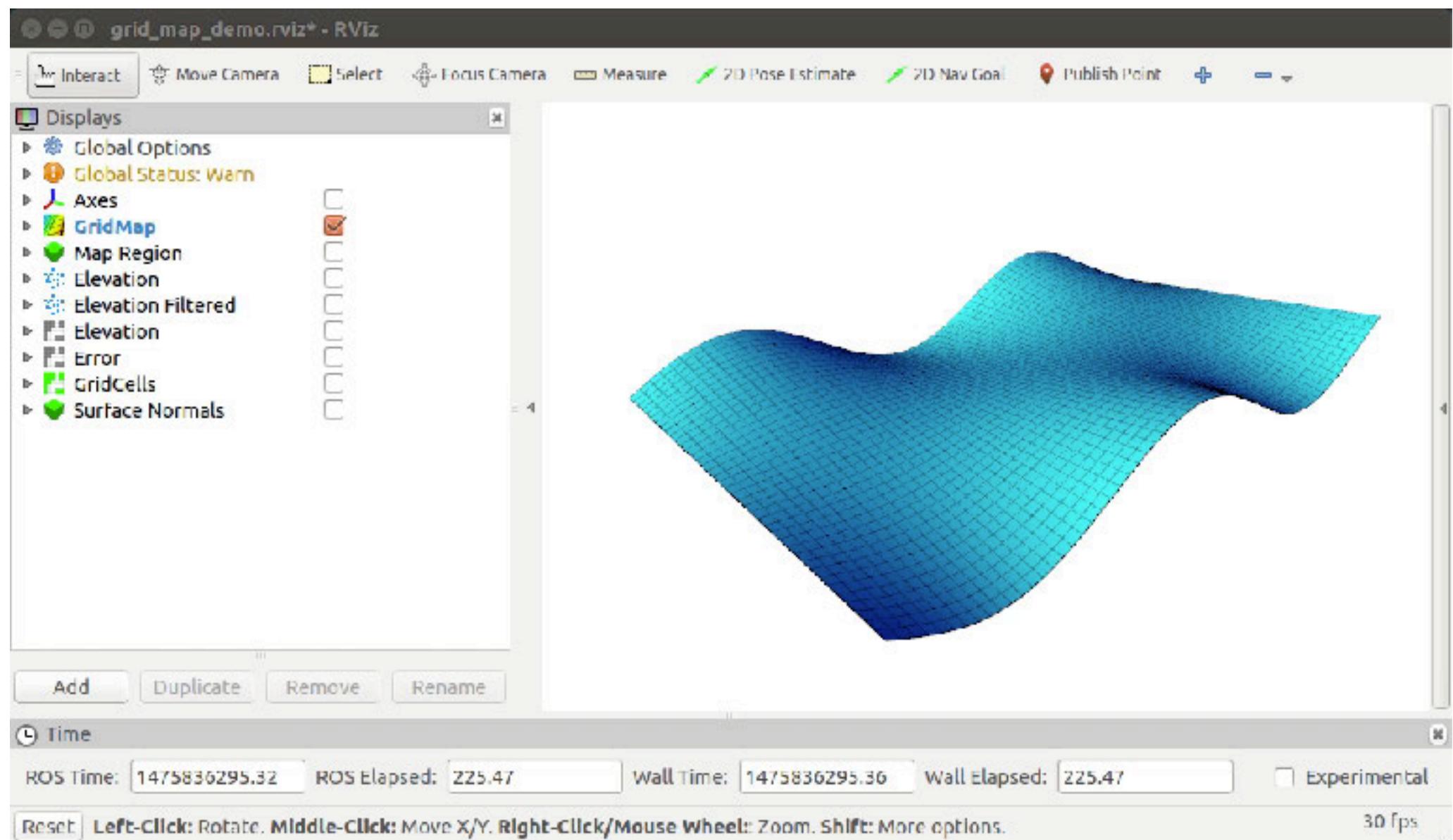
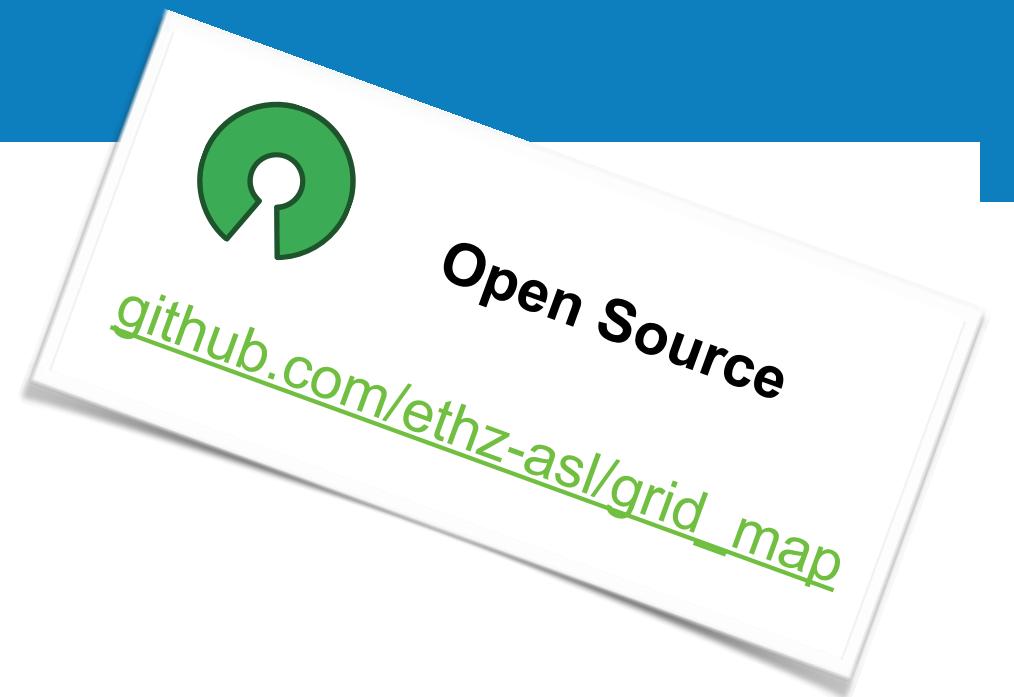


- 2D circular buffer data structure
  - Efficient map repositioning
- Based on Eigen (C++)
  - Versatile and efficient data manipulation
- Convenience functions
  - Iterators, math tools, etc.

P. Fankhauser and M. Hutter, “A Universal Grid Map Library: Implementation and Use Case for Rough Terrain Navigation,”  
in Robot Operating System (ROS) - The Complete Reference, Springer, 2015.

# Navigation

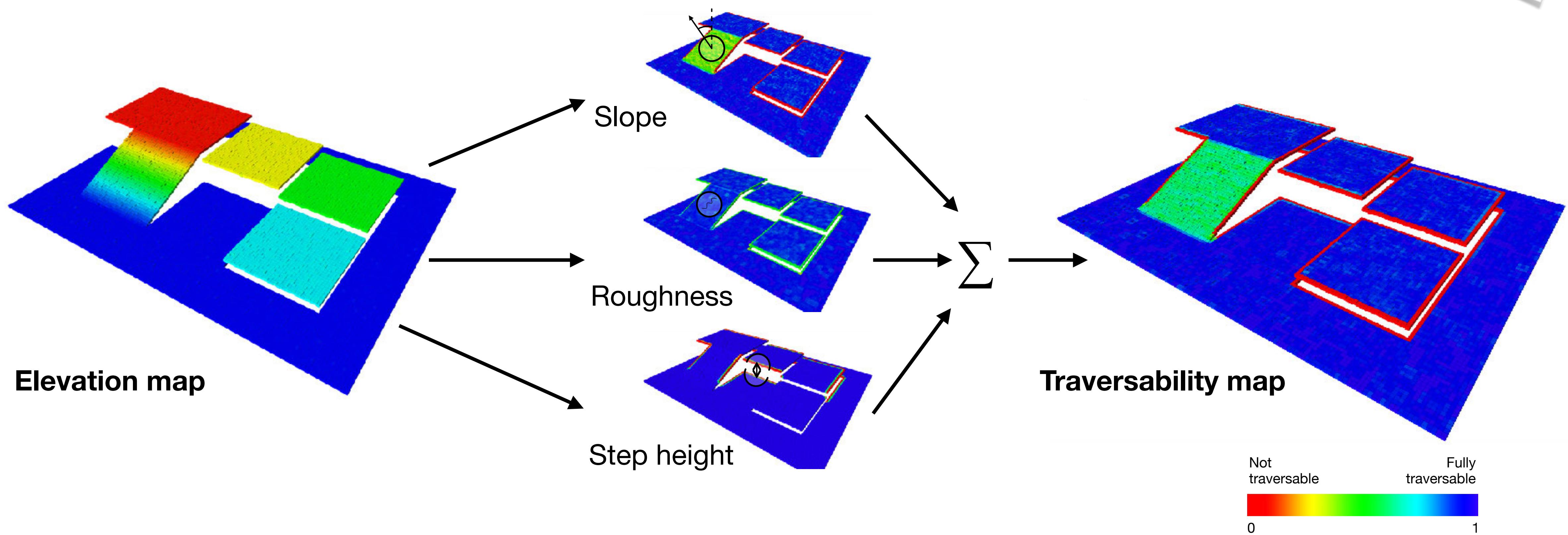
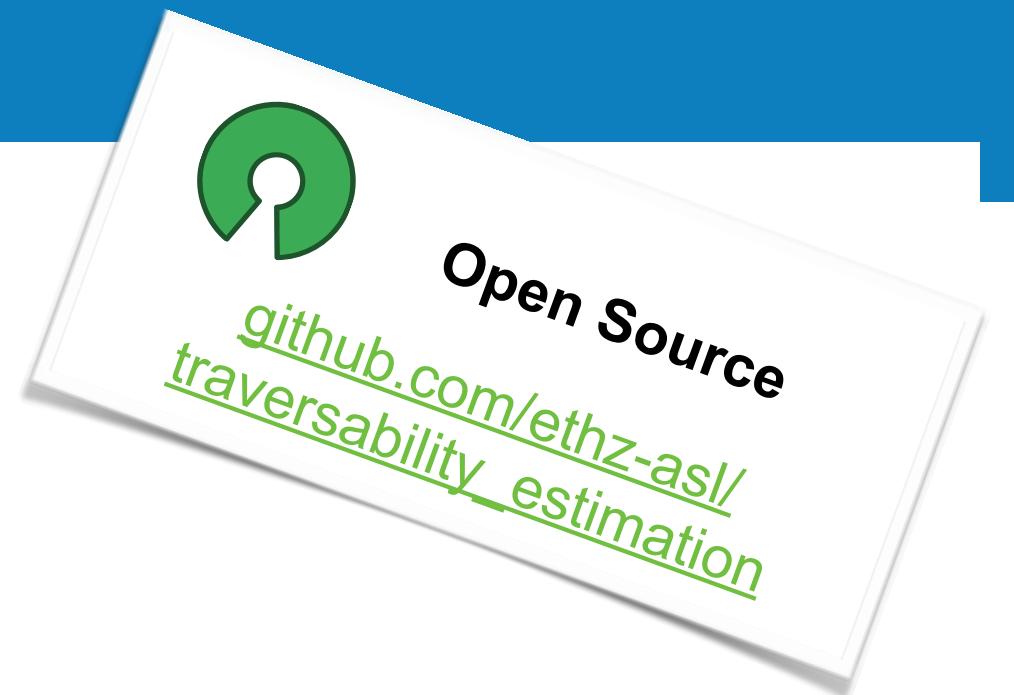
## Grid Map – Universal Multi-Layer Grid Map Library



- 2D circular buffer data structure
  - Efficient map repositioning
- Based on Eigen (C++)
  - Versatile and efficient data manipulation
- Convenience functions
  - Iterators, math tools, etc.
- ROS & OpenCV interfaces
  - Conversion from/to images, point clouds, occupancy grids, grid cells

P. Fankhauser and M. Hutter, “A Universal Grid Map Library: Implementation and Use Case for Rough Terrain Navigation,”  
in Robot Operating System (ROS) - The Complete Reference, Springer, 2015.

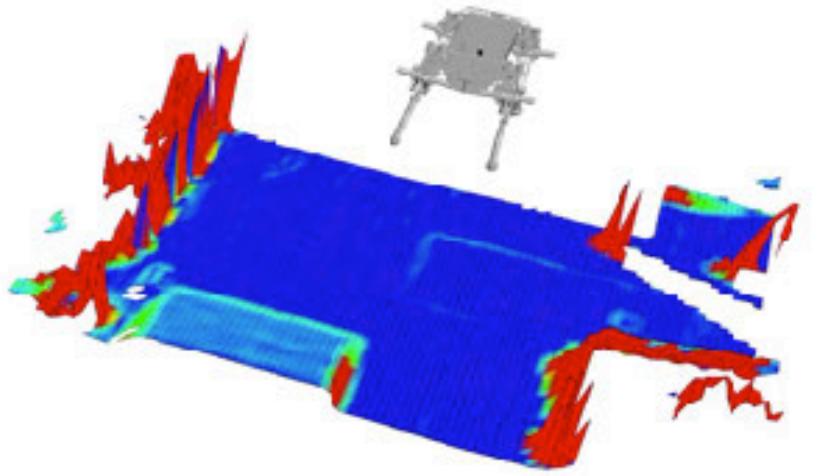
# Navigation Traversability Estimation



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

## Navigation Planning

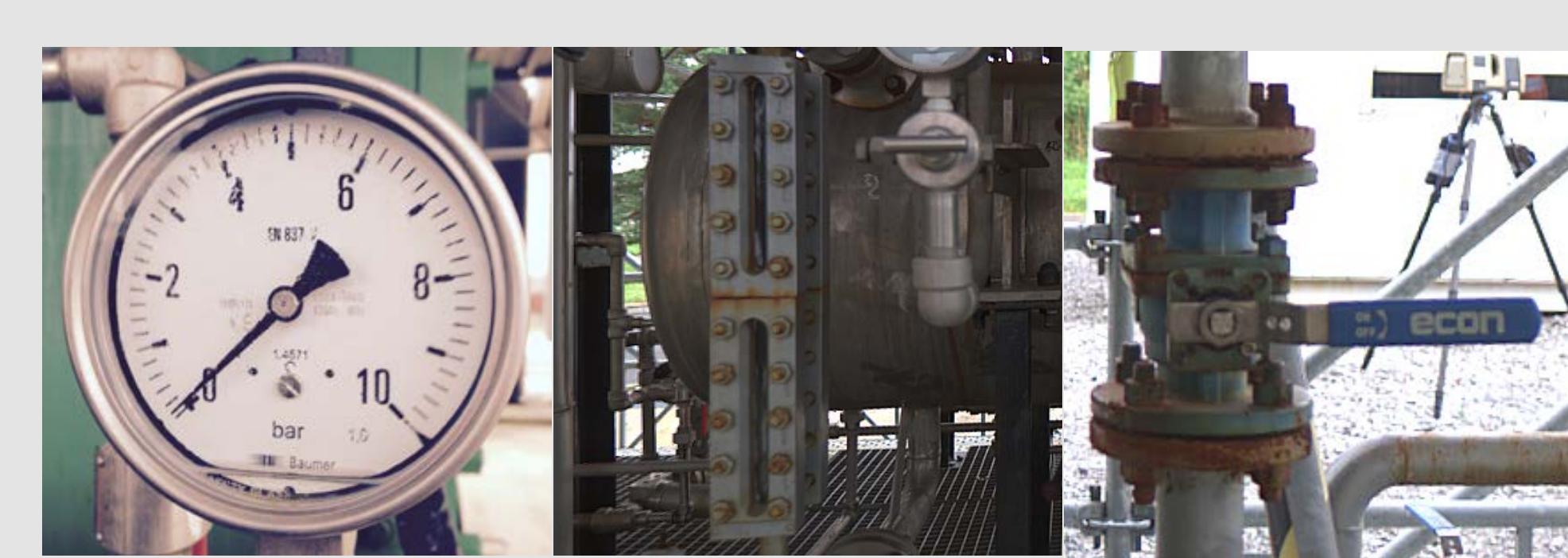


- Online navigation planning based on RRT\* (OMPL)
- Works with and without initial map
- Continuous for changing environments

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.

# Inspection

## Visual inspection



**Pressure & Level gauges      Valves**

## Thermal Inspection



**Thermal points**

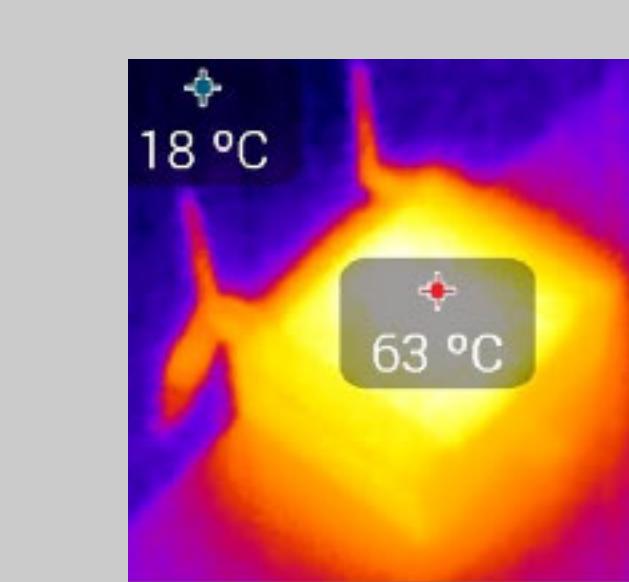
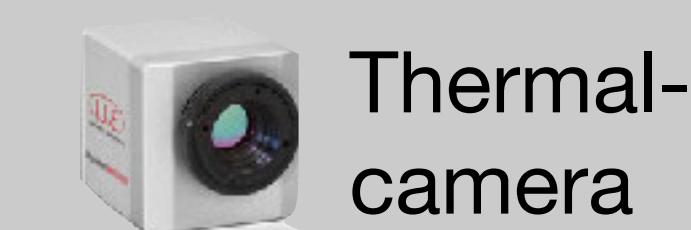
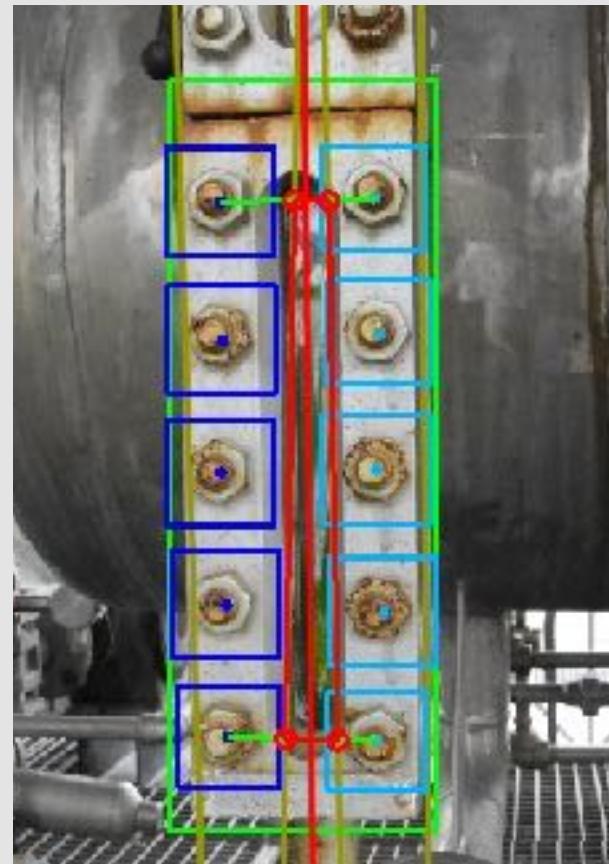
## Auditive Inspection



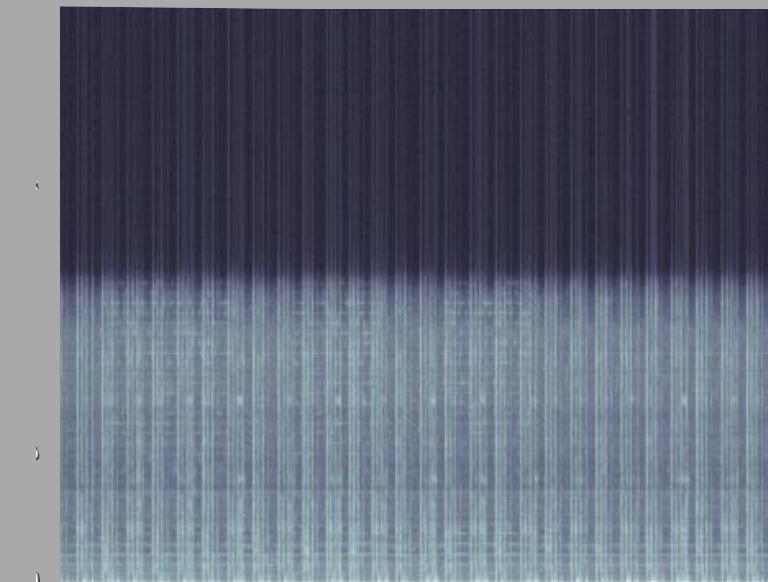
**Pumps                    Gas leaks                    Platform alarm**



**Zoom-camera**



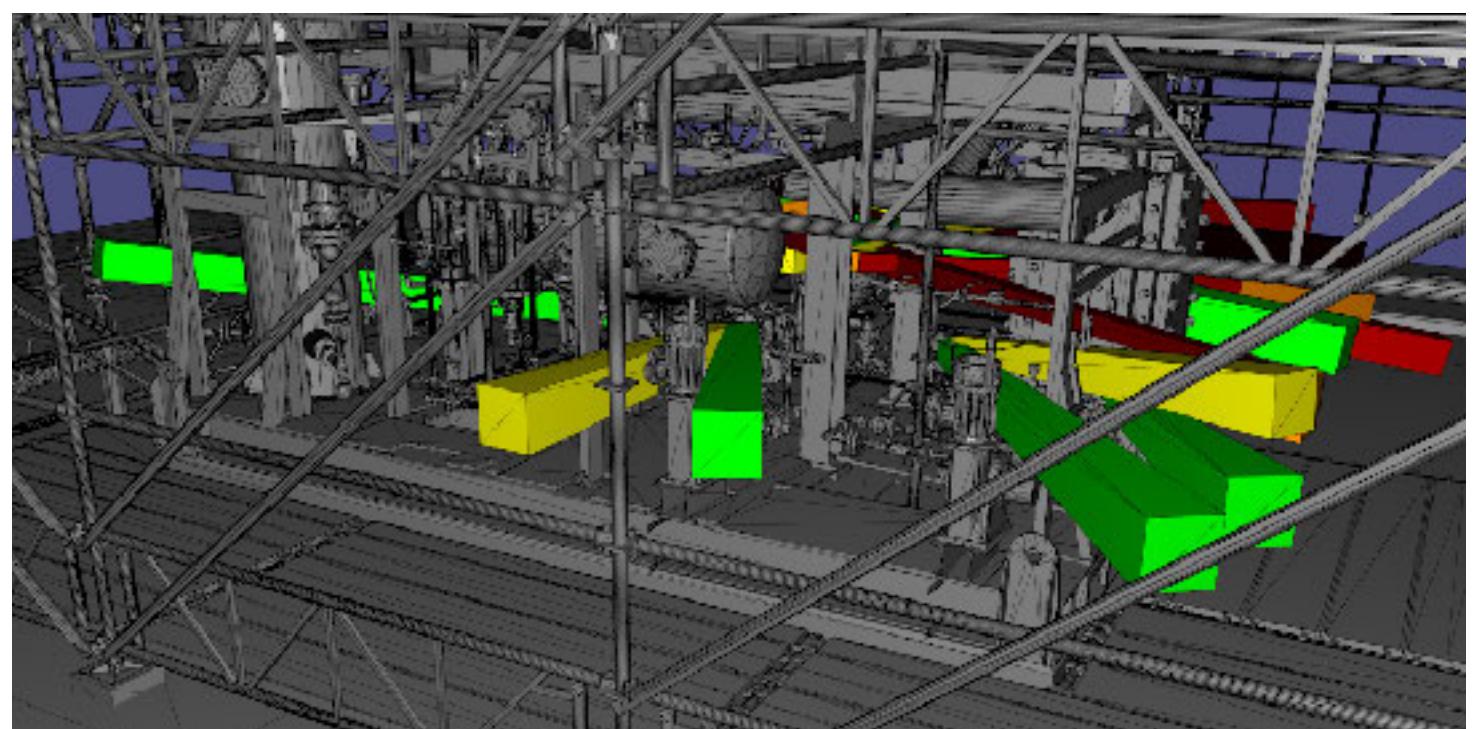
**Microphones (audible and ultra-sonic)**



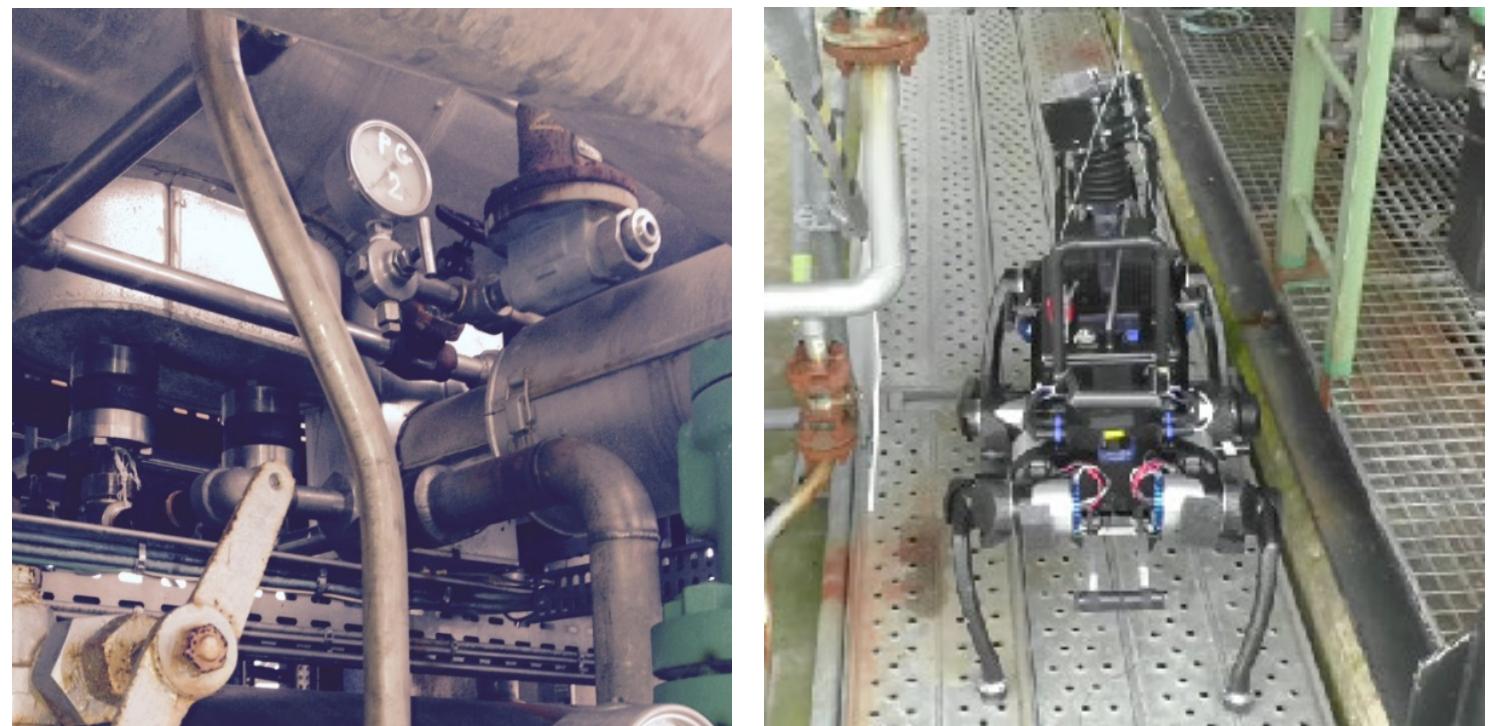
# Inspection

## Visual Inspection of Pressure Gauges

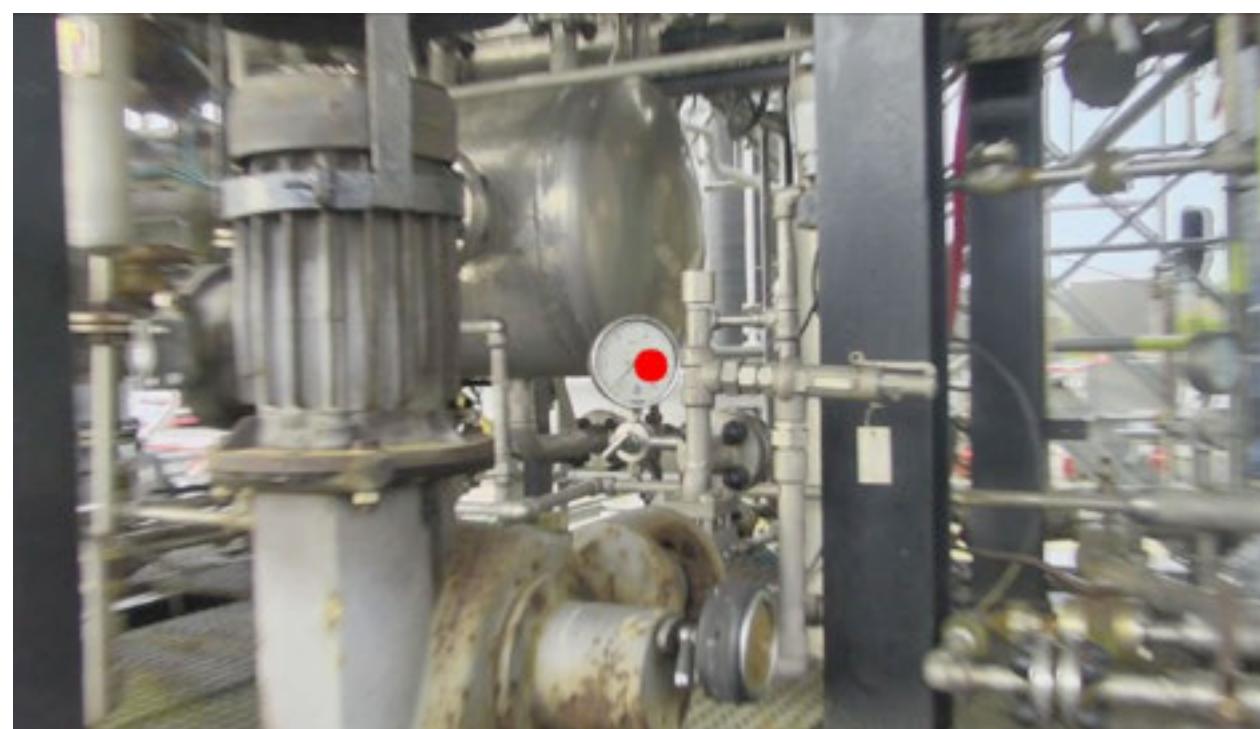
**A** Automatic view point generation



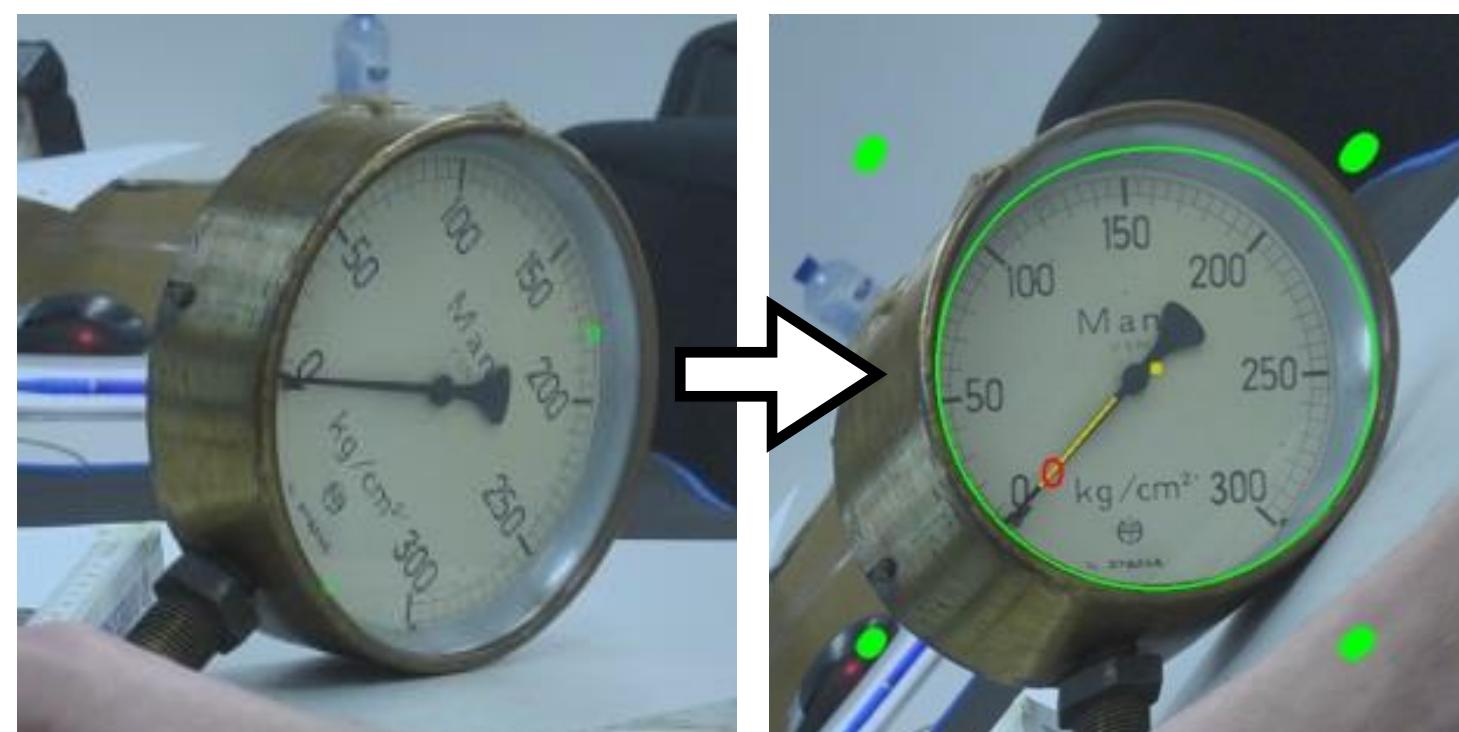
**B** Whole-body camera positioning



**C** Visual servoing



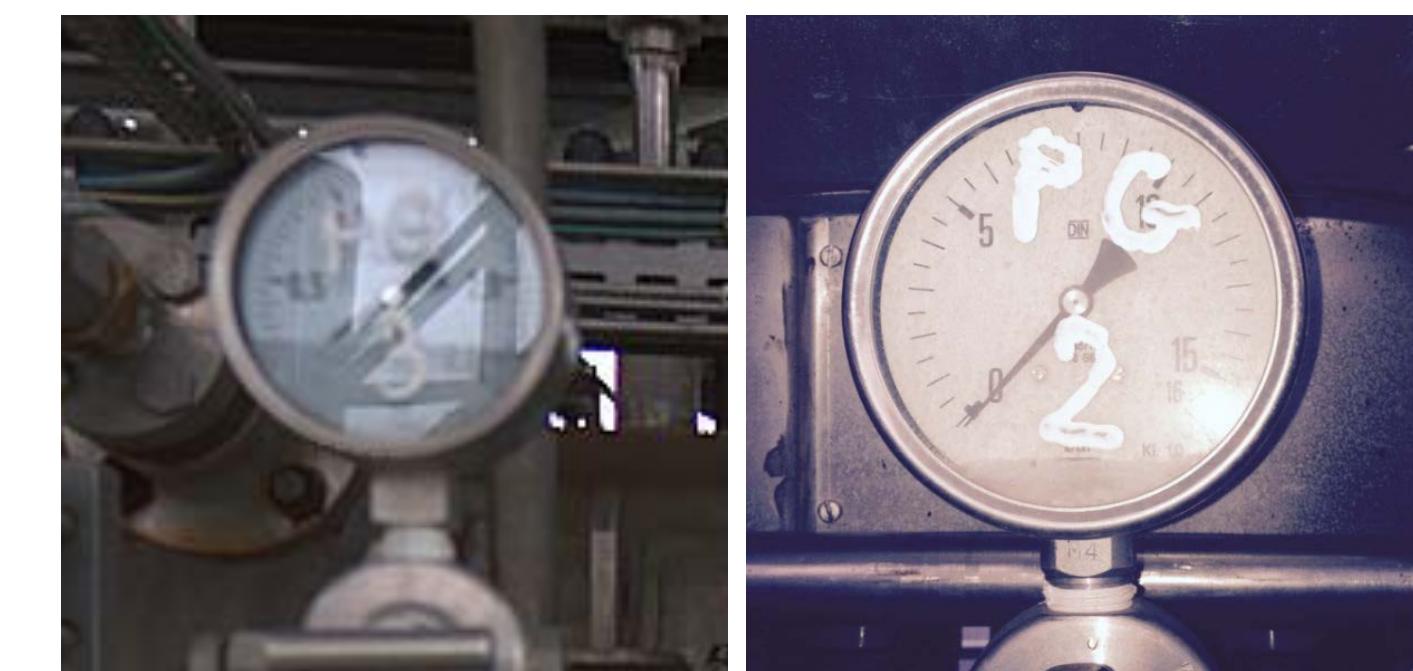
**D** Image de-warping



**E** Indicator reading



→ Reading ok

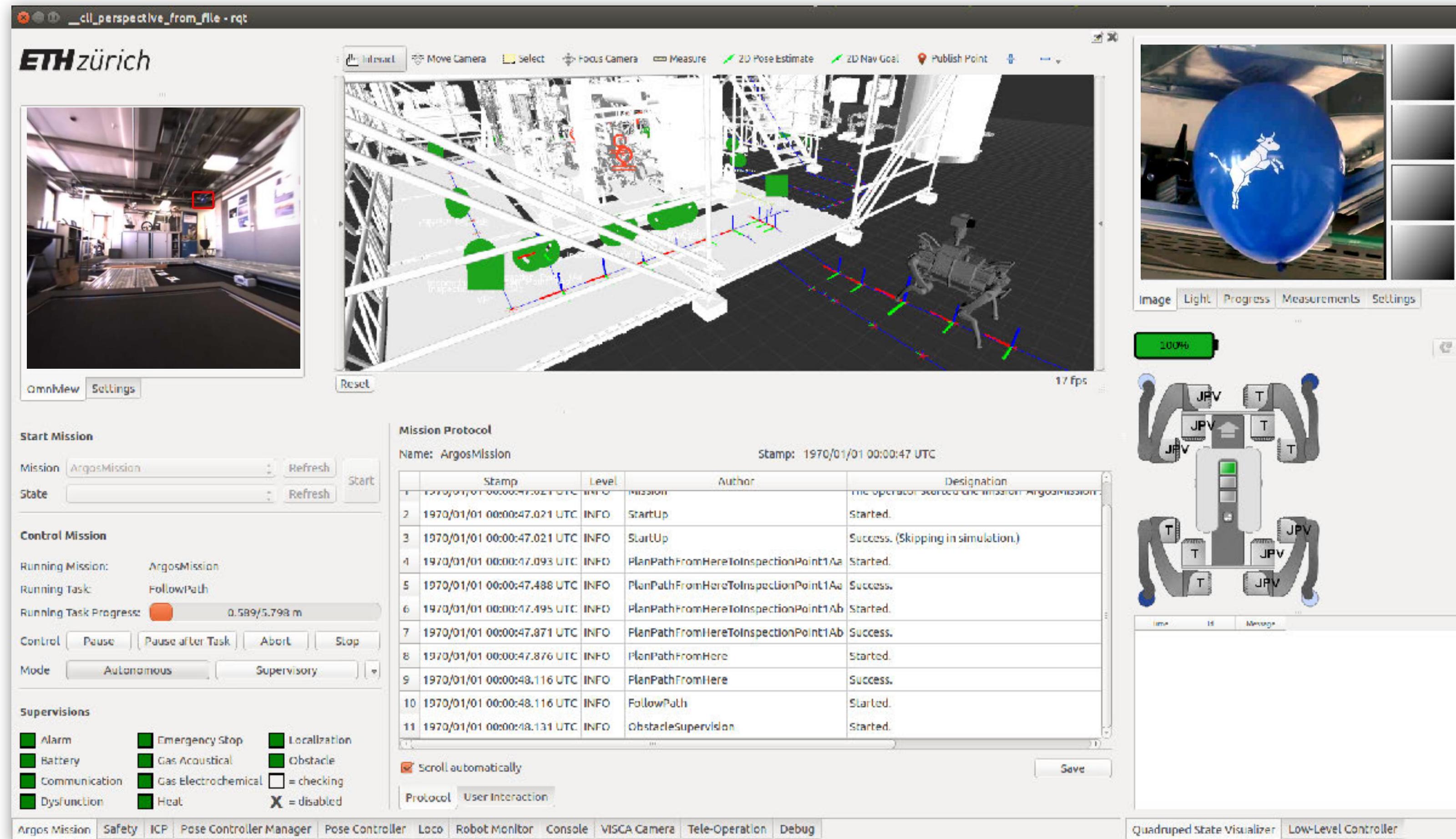


→ Reading unsuccessful, try alternative position or report as unknown

S. Bachmann, "Visual Inspection of Manometers and Valve Levers", Master's Thesis, ETH Zurich, 2015.

# User Interface

Interface for remote control, semi-, and full autonomous operation.



# User Interface

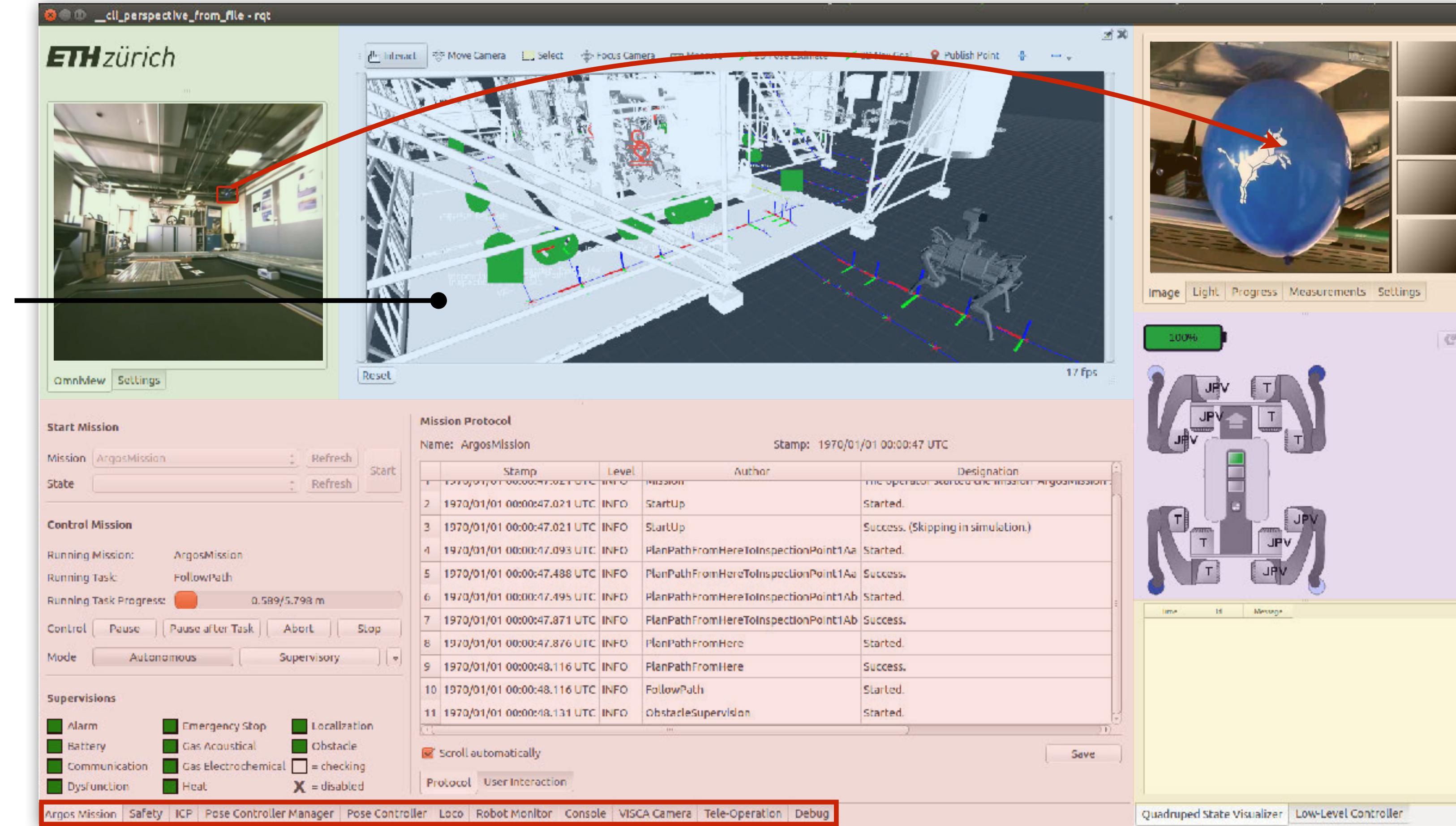
Interface for remote control, semi-, and full autonomous operation.

Situational  
camera

3D view (RViz)

Mission control  
& protocol

Other modules

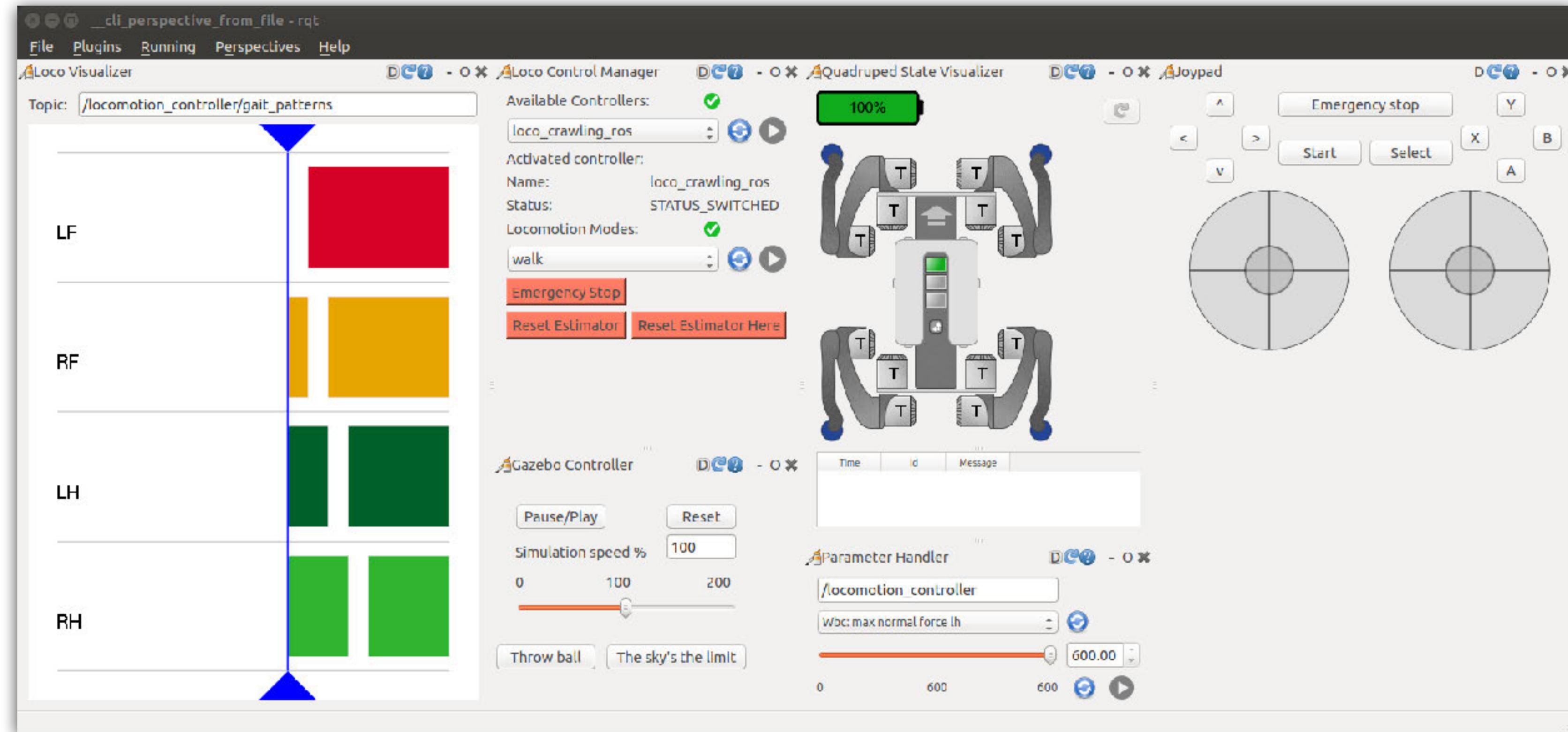


Inspection  
cameras

Robot actuators  
& sensors

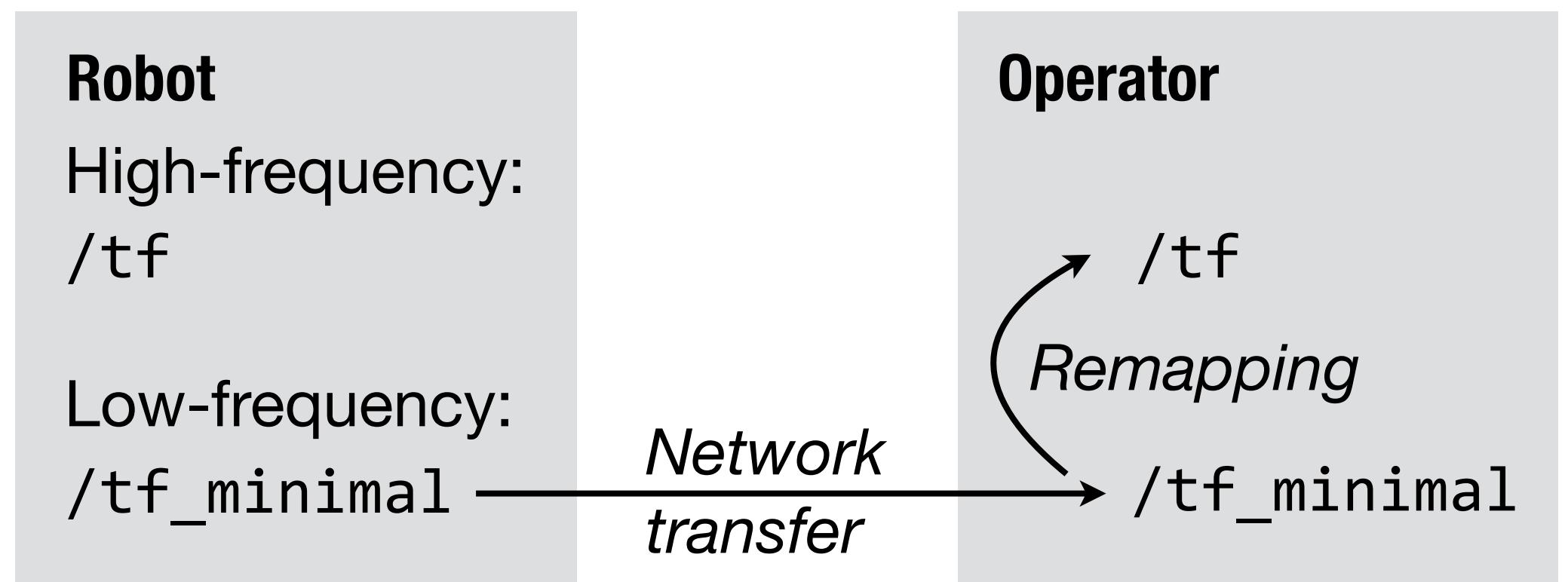
Error protocol

# User Interface

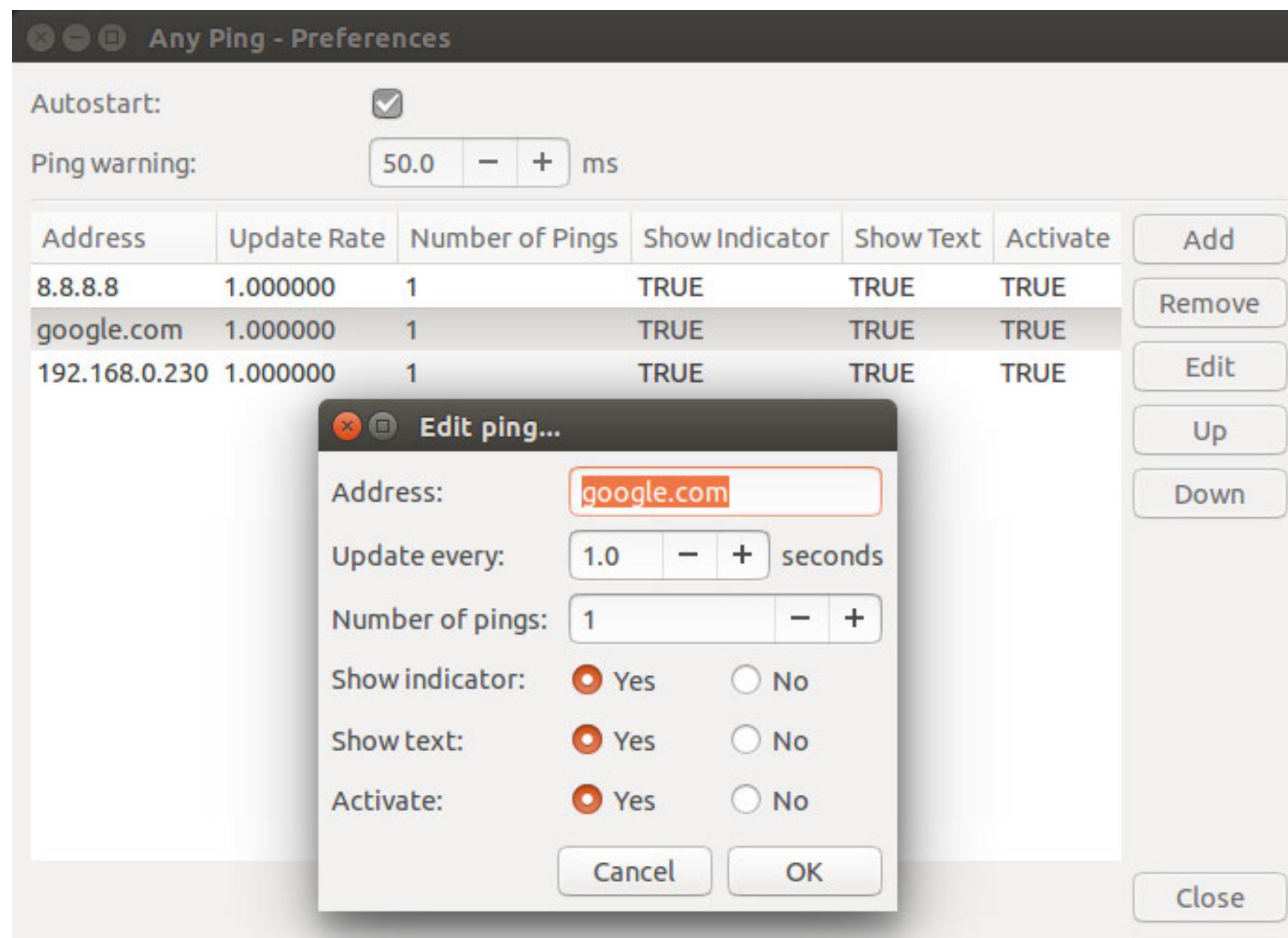


# User Interface Bandwidth Considerations

- Only critical data is transmitted by default (robot state and position)
- Other data is transmitted on demand (video, maps, etc.)
- Separation of onboard TF and operator TF
- Connection status node monitors WiFi status and triggers recovery behavior

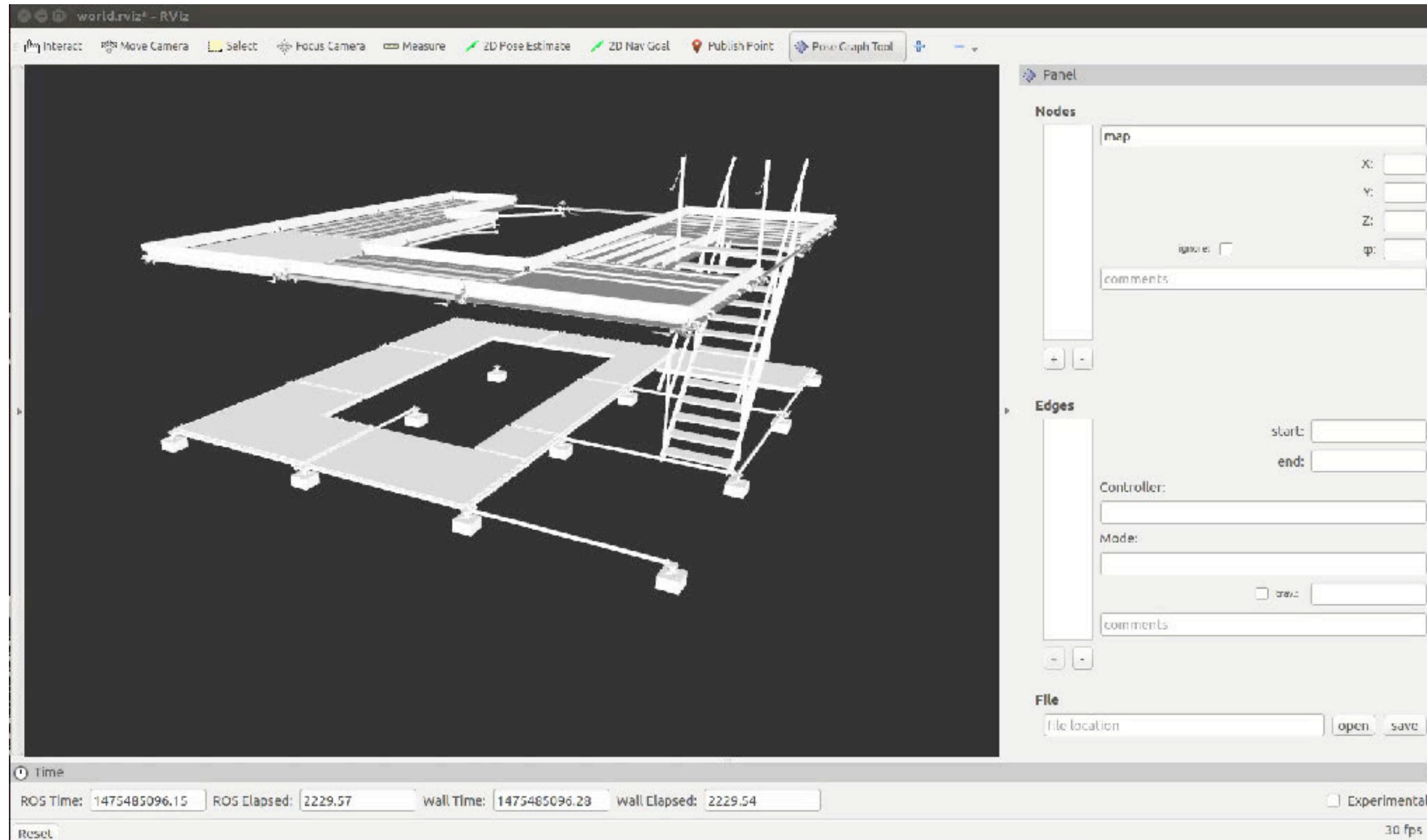


# User Interface ANYping Indicator



- Indicates PC network availability in Ubuntu menu bar

# User Interface Pose Graph

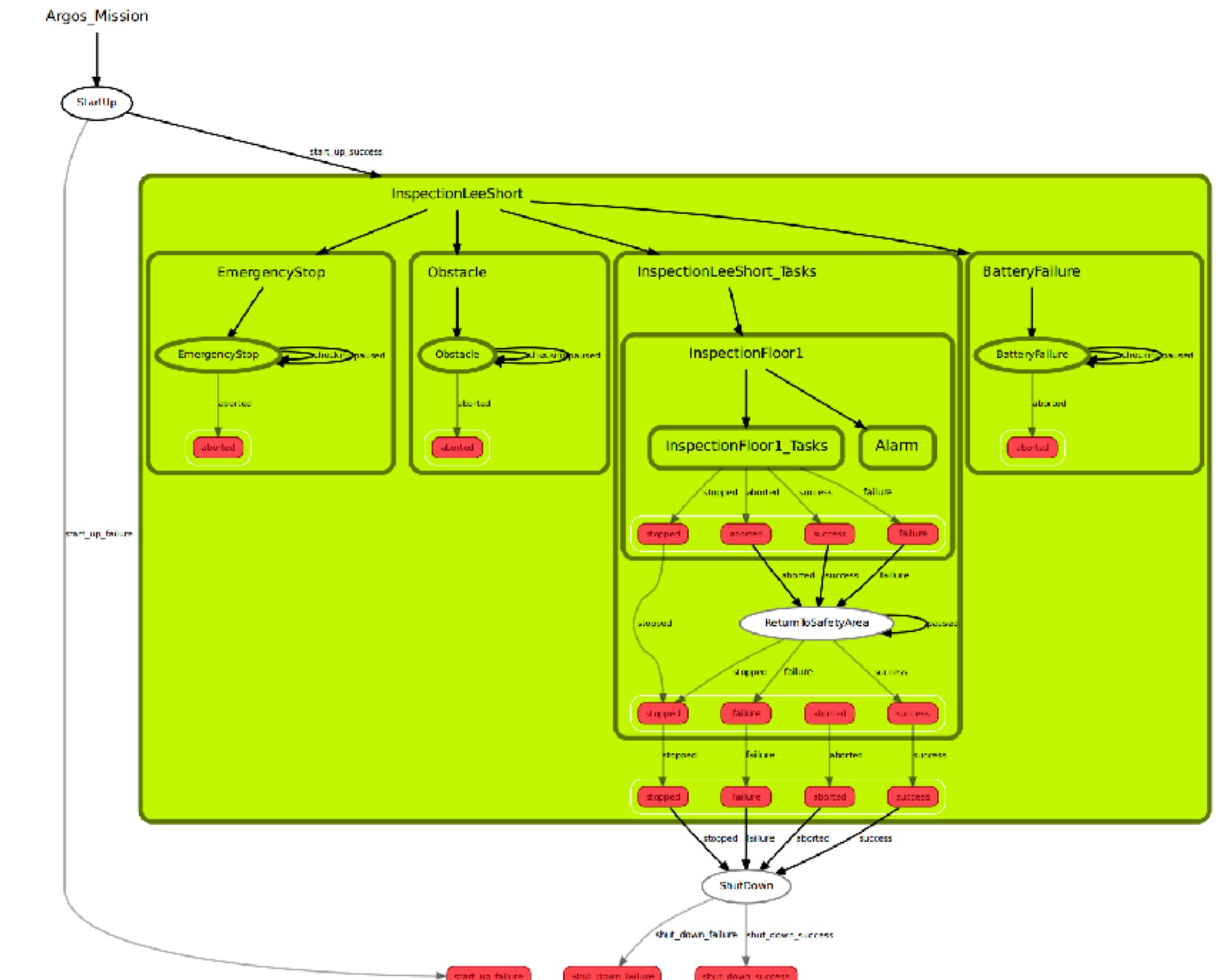


- Pose graph for inspection, special maneuvers (e.g. stairs), docking station etc.
- Visualization and interactive editing of pose graph
- Continuous updating and (re-)planning on pose graph during mission

# User Interface

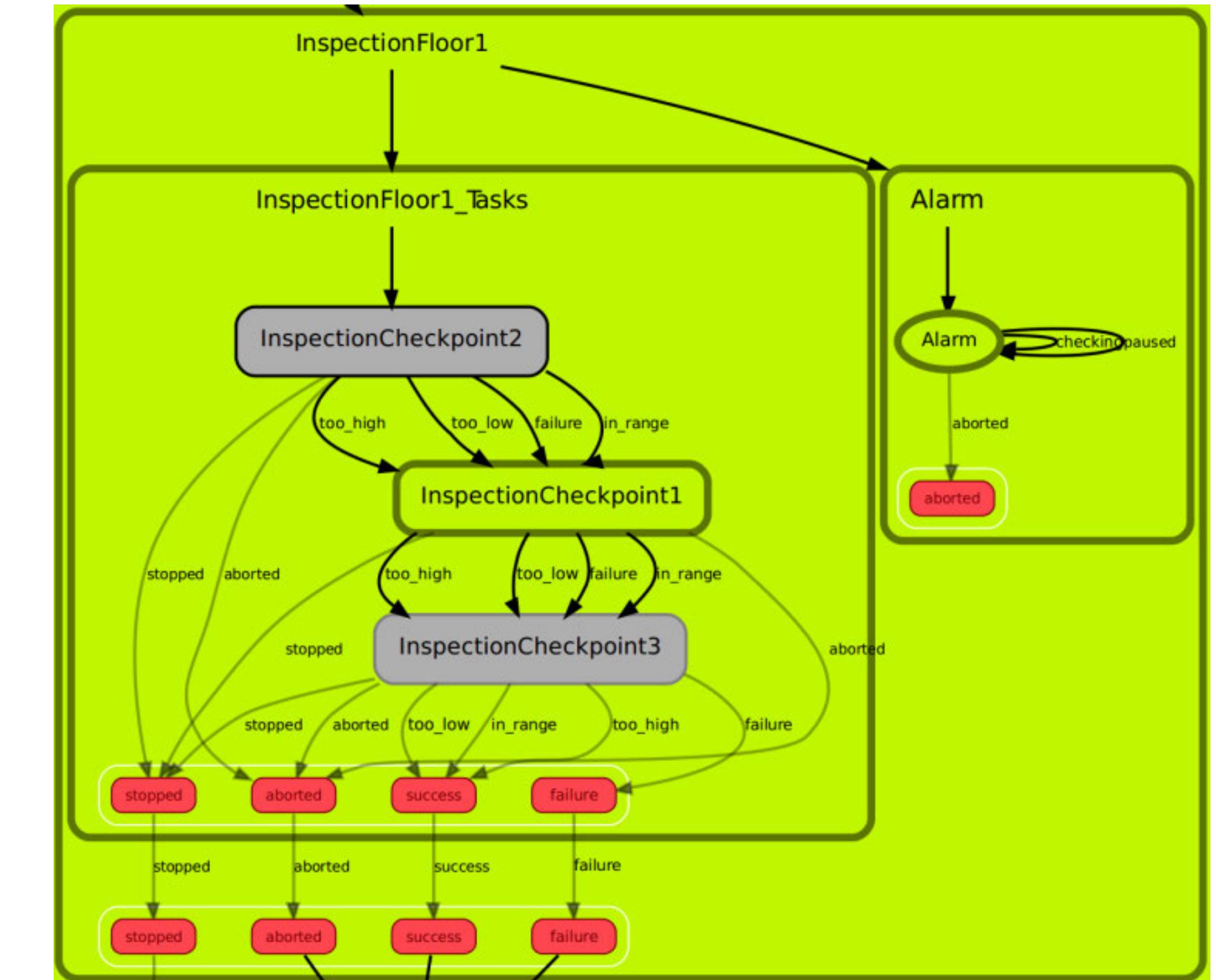
## Mission Creation

- Task-level state machine (C++ library, similar to SMACH)
- State machine defined in YAML format
- Common building blocks to facilitate construction



# User Interface Mission Creation

- Task-level state machine (C++ library, similar to SMACH)
- State machine defined in YAML format
- Common building blocks to facilitate construction
- Typical missions programmed in 5–20 minutes



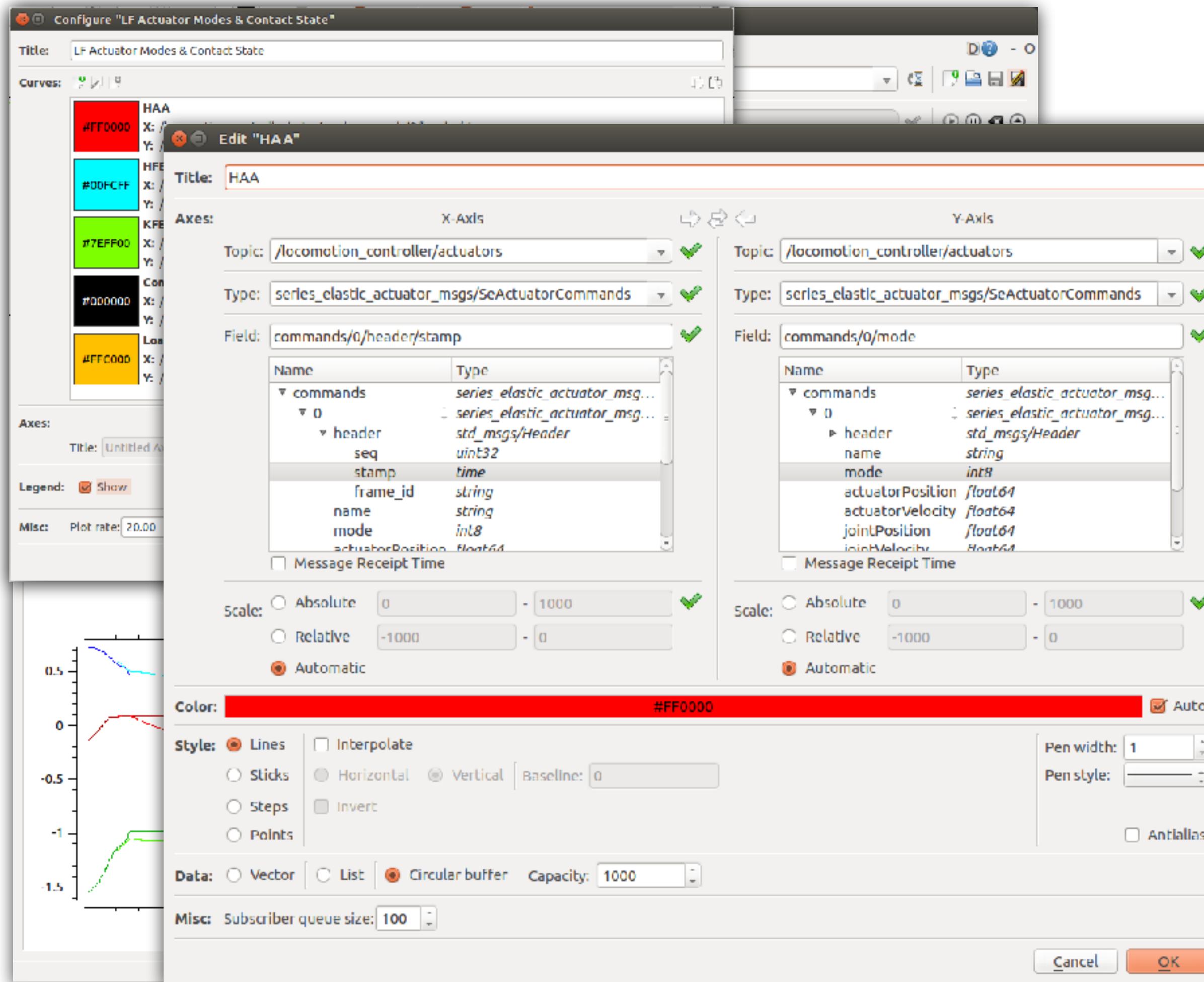
# RQT Multiplot Plugin & Variant Topic Tools



- C++ library (alternative to rqt\_plot)
- Multiple plots in one window
- Edit, save, and load configurations
- Live plotting or load rosbags



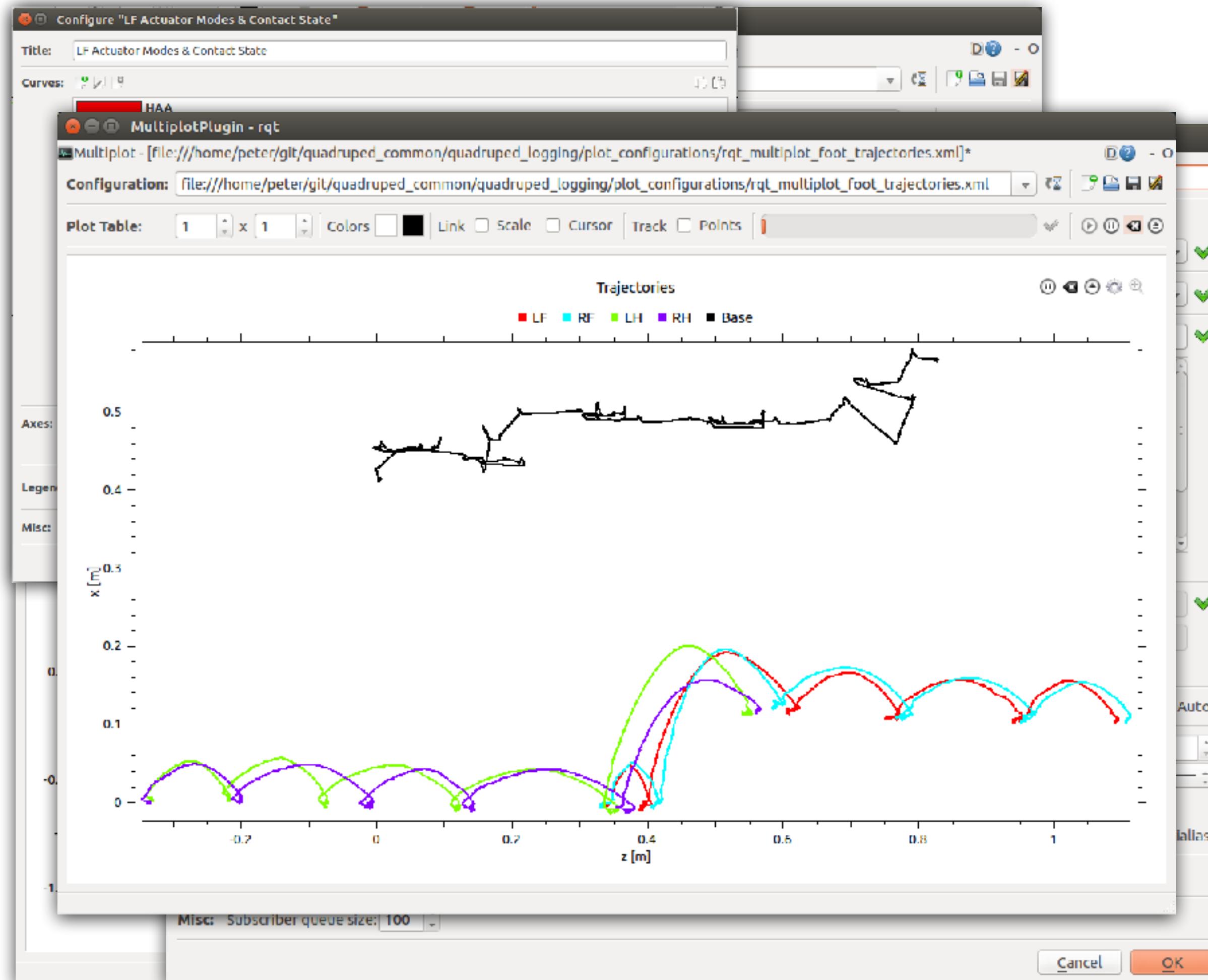
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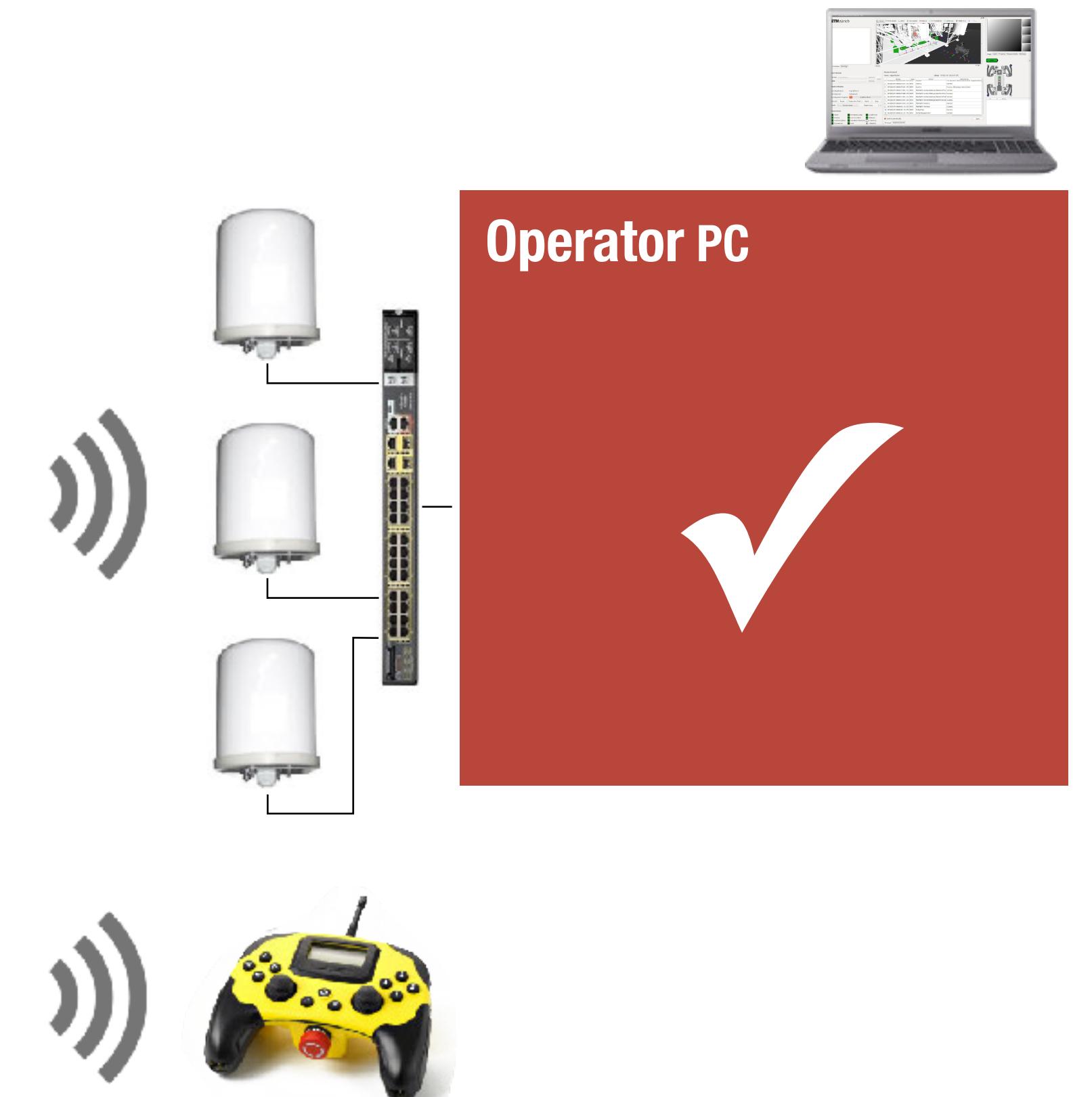
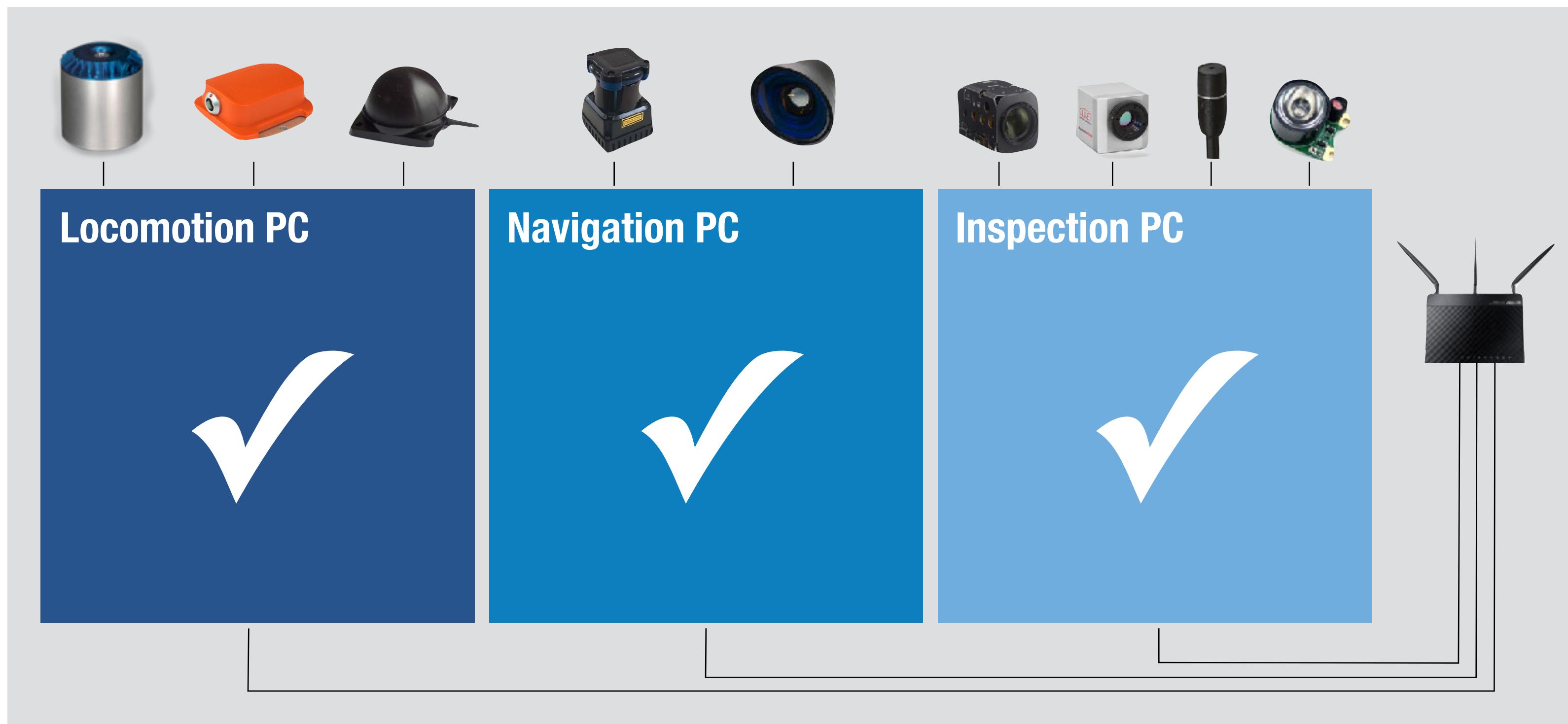


# RQT Multiplot Plugin & Variant Topic Tools



- C++ library (alternative to rqt\_plot)
- Multiple plots in one window
- Edit, save, and load configurations
- Live plotting or load rosbags
- Easy to setup configurations
- x- and y-axis freely configurable





# Software Tools – How We (Try) To Keep Things Smooth

- All developers and robots same setup  
→ Ubuntu 14.04 LTS, ROS Indigo



# Software Tools – How We (Try) To Keep Things Smooth

- All developers and robots same setup
  - Ubuntu 14.04 LTS, ROS Indigo
- Software version control with Git
  - Bitbucket & GitHub



**GitHub**

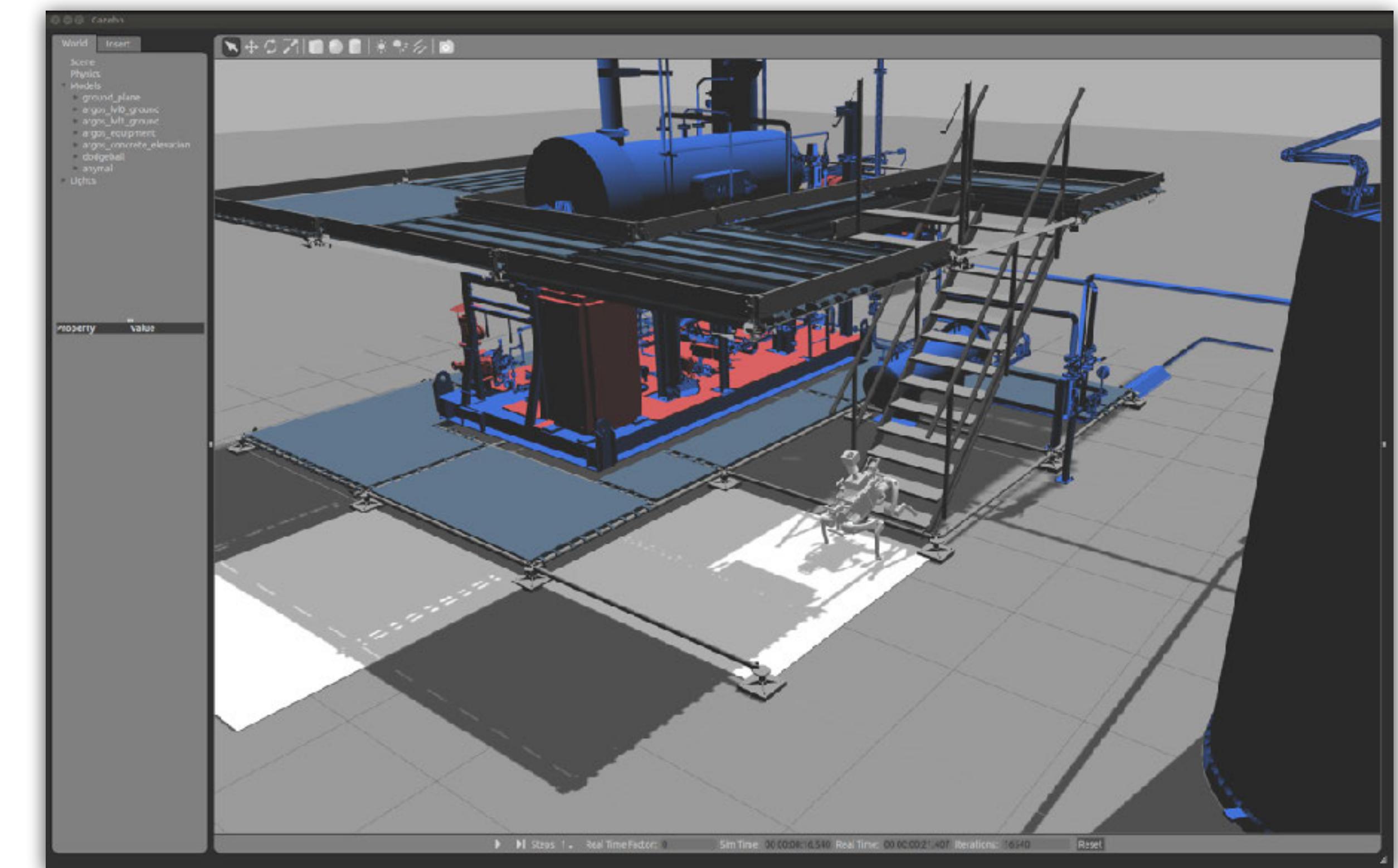
# Software Tools – How We (Try) To Keep Things Smooth

- All developers and robots same setup
  - Ubuntu 14.04 LTS, ROS Indigo
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- Conventions for package structure, format, naming, and code style
  - [github.com/ethz-asl/ros\\_best\\_practices/wiki](https://github.com/ethz-asl/ros_best_practices/wiki)

The screenshot shows a GitHub wiki page titled "ROS Best Practices". The page is edited by Péter Fankhauser on May 13, 2015, with 22 revisions. The content is a loose collection of best practices, conventions, and tricks for using the Robot Operating System (ROS). It builds upon the official ROS documentation and other resources and is meant as a summary and overview. The page includes sections for "Official ROS documentation" (linking to REP documents), "Other References" (linking to various ROS-related papers and guides), and a "TODO" section (linking to a Stack Exchange question about ROS best practices). The GitHub interface shows standard navigation like "Code", "Issues", "Pull requests", "Projects", "Wiki" (which is active), "Graphs", and "Settings". There are also buttons for "Edit" and "New Page". On the right side, there's a sidebar with "Pages" (Home) and options to "Clone this wiki locally" or "Clone in Desktop".

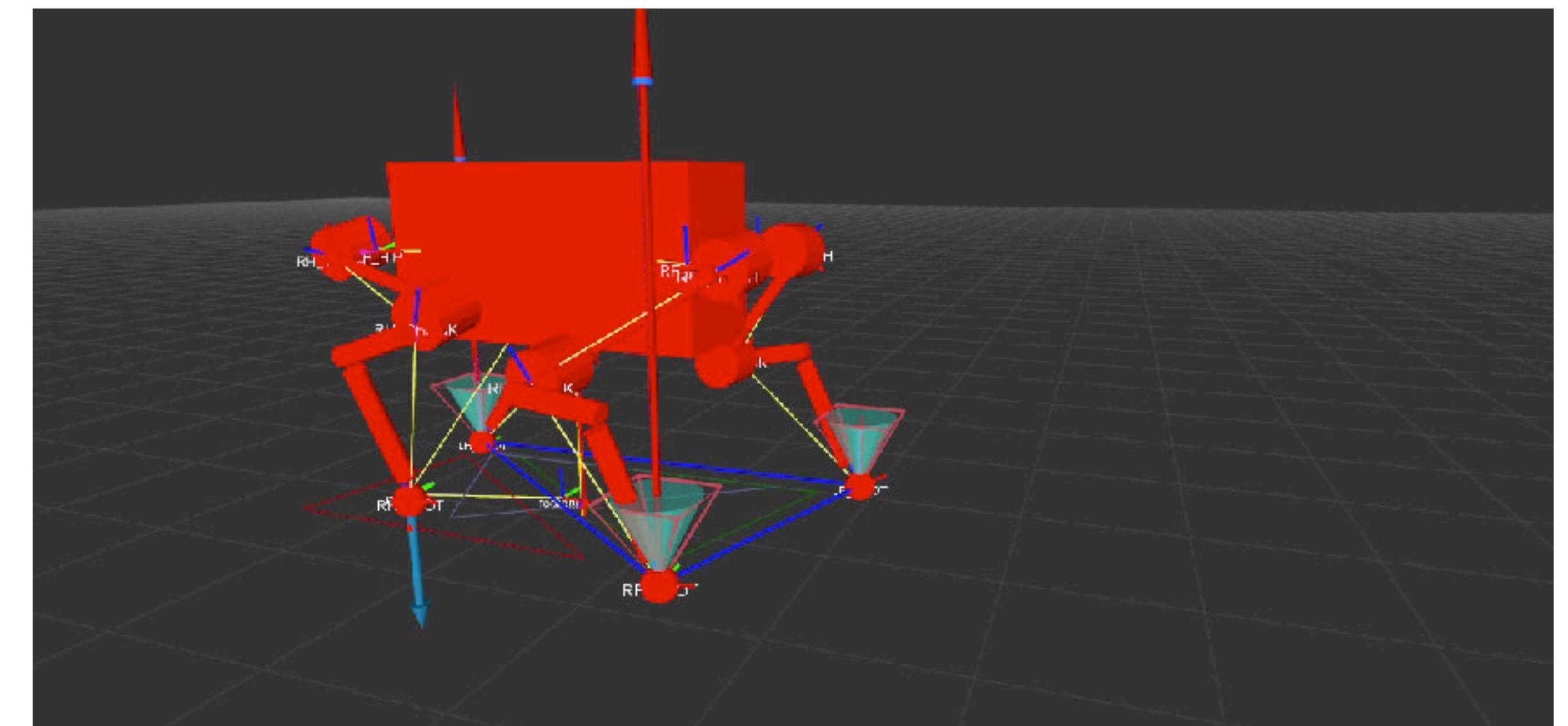
# Software Tools – How We (Try) To Keep Things Smooth

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- Extensive use of simulation
  - [Gazebo](#)



# Software Tools – How We (Try) To Keep Things Smooth

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- Extensive use of simulation
  - [Gazebo](#)
- Visualizing as much as possible



# Software Tools – How We (Try) To Keep Things Smooth

- Lots of tests on hardware
  - Weekly “shakeouts” for defined tasks
  - Lots of demos



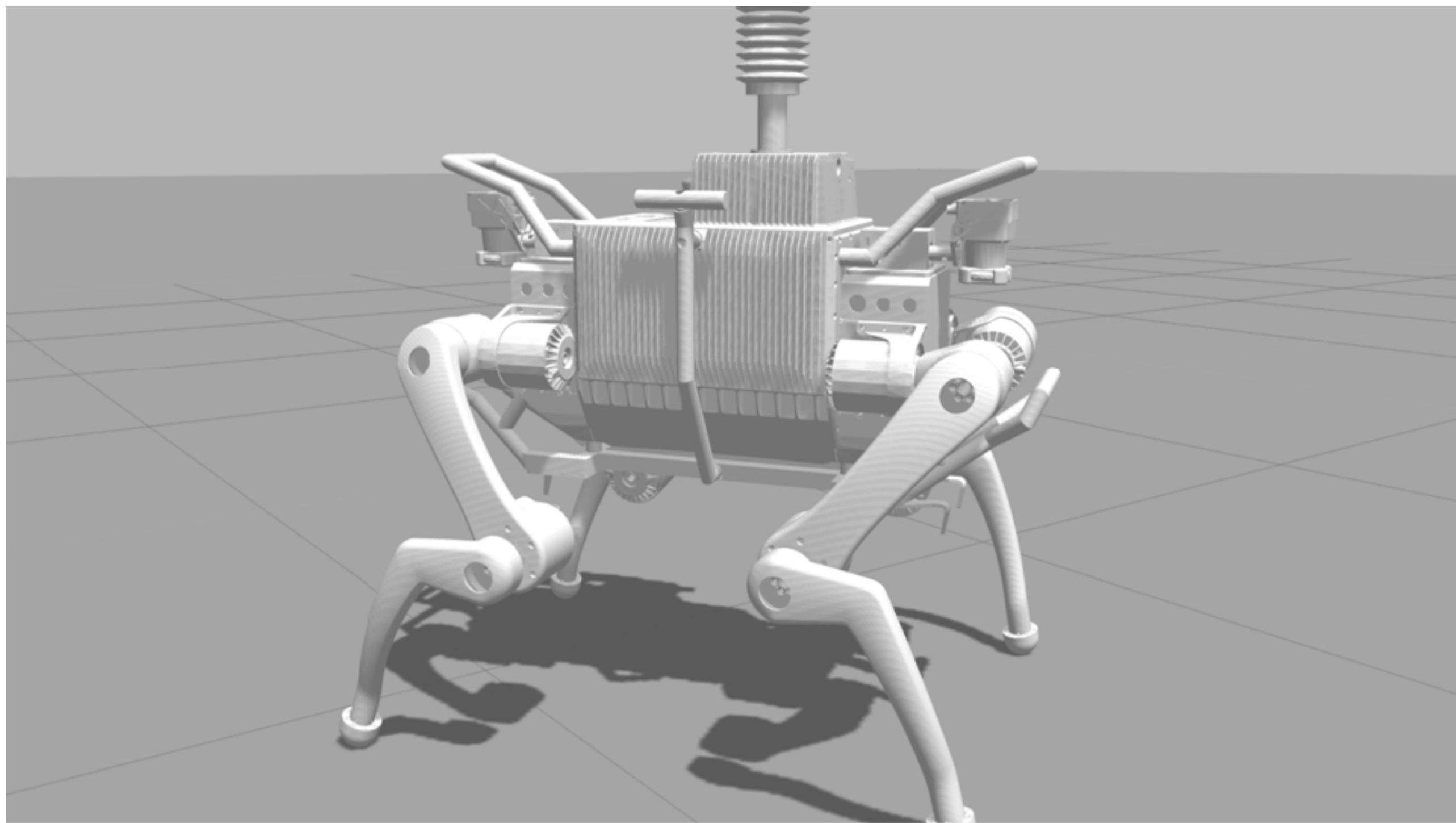
# Software Tools - How We (Try) To Keep Things Smooth

- Lots of tests on hardware
    - ➡ Weekly “shakeouts” for defined tasks
    - ➡ Lots of demos
  - Continuous Integration
    - ➡ Jenkins
    - ➡ Unit tests (after each change)
    - ➡ ROS integration tests (at night)



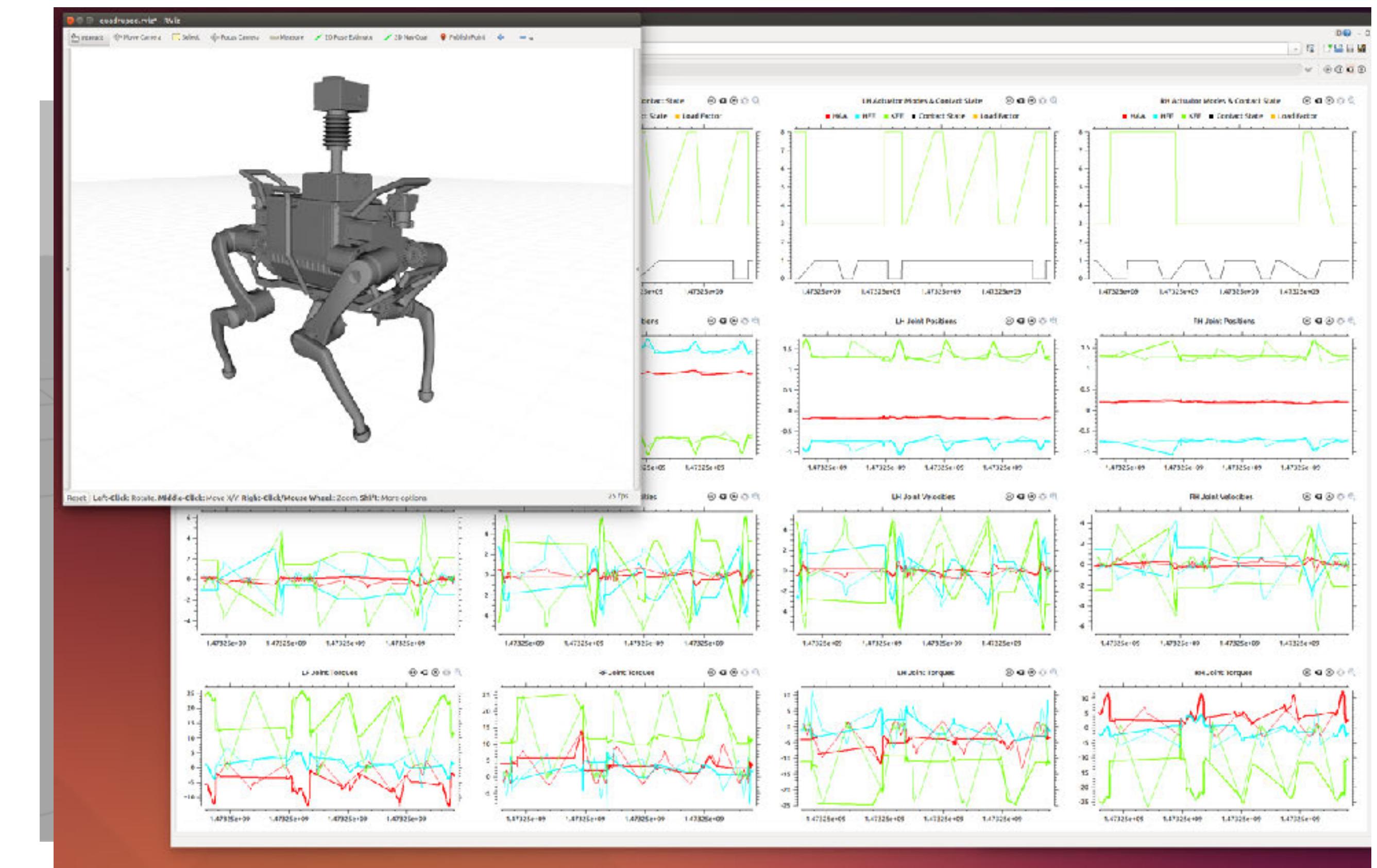
# Software Tools – How We (Try) To Keep Things Smooth

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# Software Tools – How We (Try) To Keep Things Smooth

- Lots of tests on hardware
  - Weekly “shakeouts” for defined tasks
  - Lots of demos
- Continuous Integration
  - Jenkins
  - Unit tests (after each change)
  - ROS integration tests (at night)
- Logging (rosbag)
  - All important information is always logged
  - Review logs with RViz and RQT Multiplot



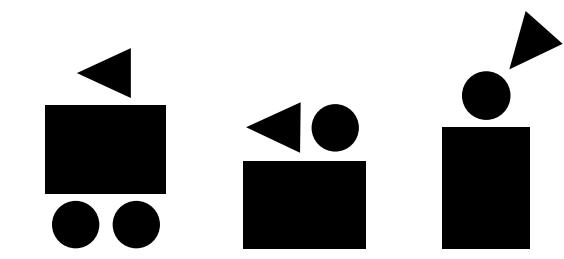
# Conclusion

- Introduced 10 open-source packages, 250+ internal packages
- Coordination of a big team is hard
- Good naming is important
- ROS as “glue”
- WiFi is often problematic
- Reliability is crucial

# Thank You



[www.rsl.ethz.ch](http://www.rsl.ethz.ch)



**Autonomous Systems Lab**

[www.asl.ethz.ch](http://www.asl.ethz.ch)

## Open-Source Software

[github.com/ethz-asl](https://github.com/ethz-asl)

[github.com/leggedrobotics](https://github.com/leggedrobotics)

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Dario Bellicoso

Michael Bloesch

Remo Diethelm

Christian Gehring

Mark Hoepflinger

Gabriel Hottiger

Marco Hutter

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Dominic Jud

Ralf Kaestner

Bruno Kaufmann

Philipp Krüsi

Andreas Lauber

Philipp Leemann

Konrad Meyer

Roland Siegwart

Vassilios Tsounis

Martin Wermelinger