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

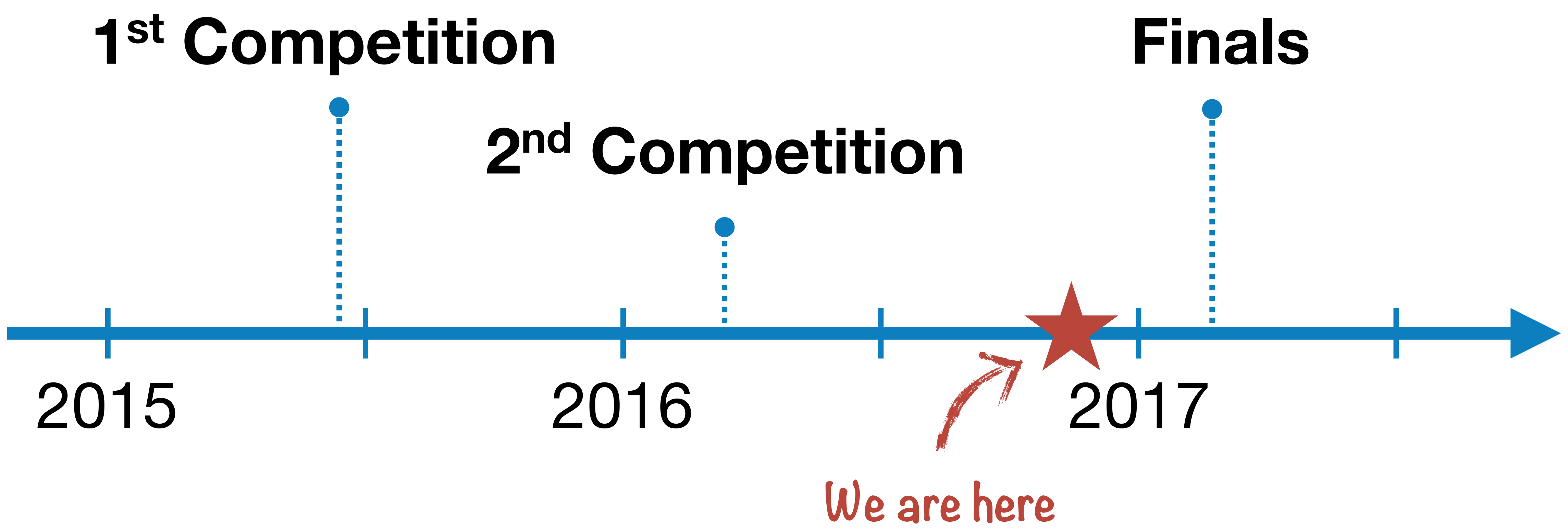
ARGOS Challenge

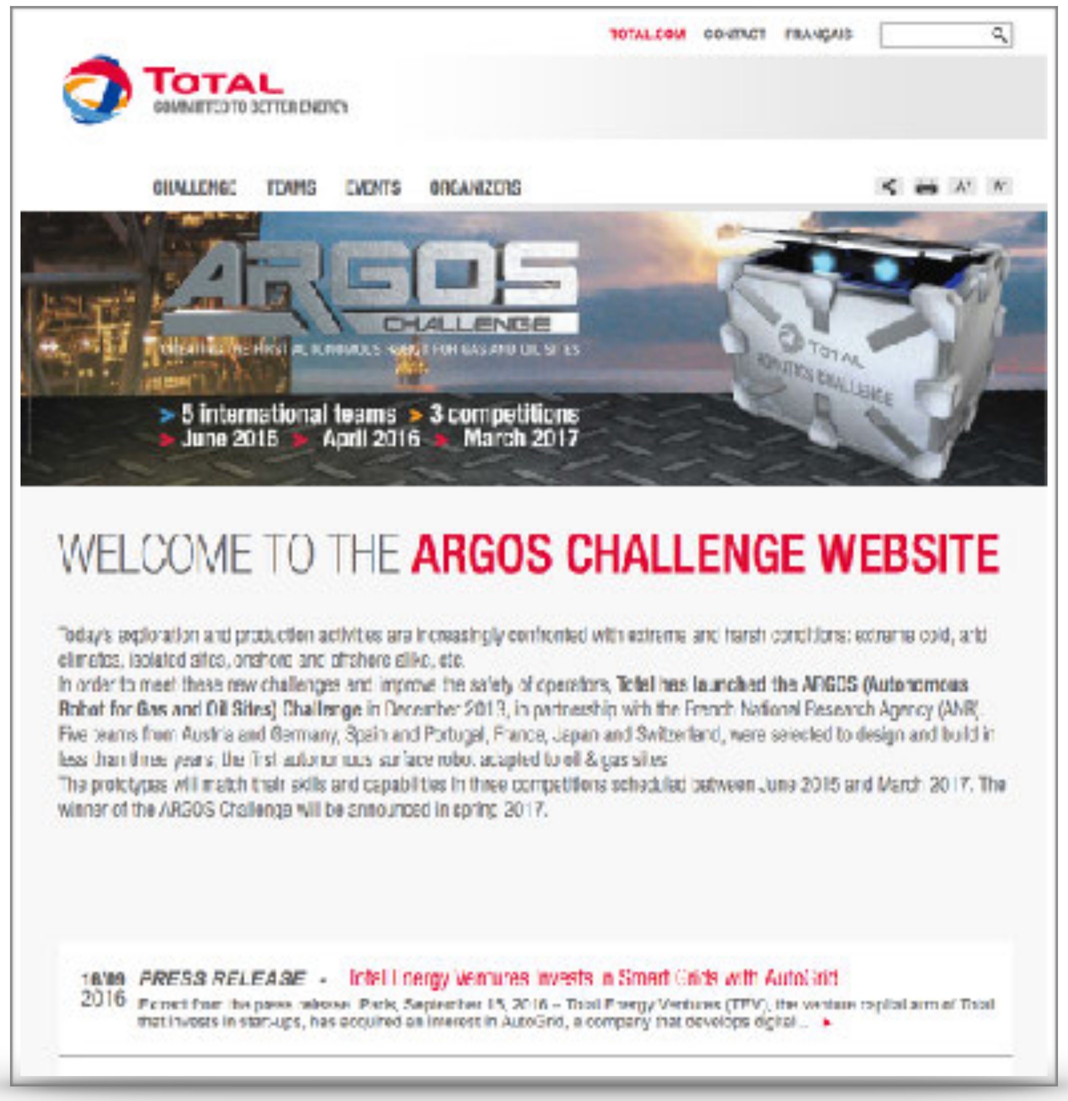
"Creating the first autonomous robot for gas and oil sites"

ARGOS CHALLENGE
LOOKING FOR THE FIRST AUTONOMOUS ROBOT FOR GAS AND OIL SITES

TOTAL COMMITTED TO BETTER ENERGY

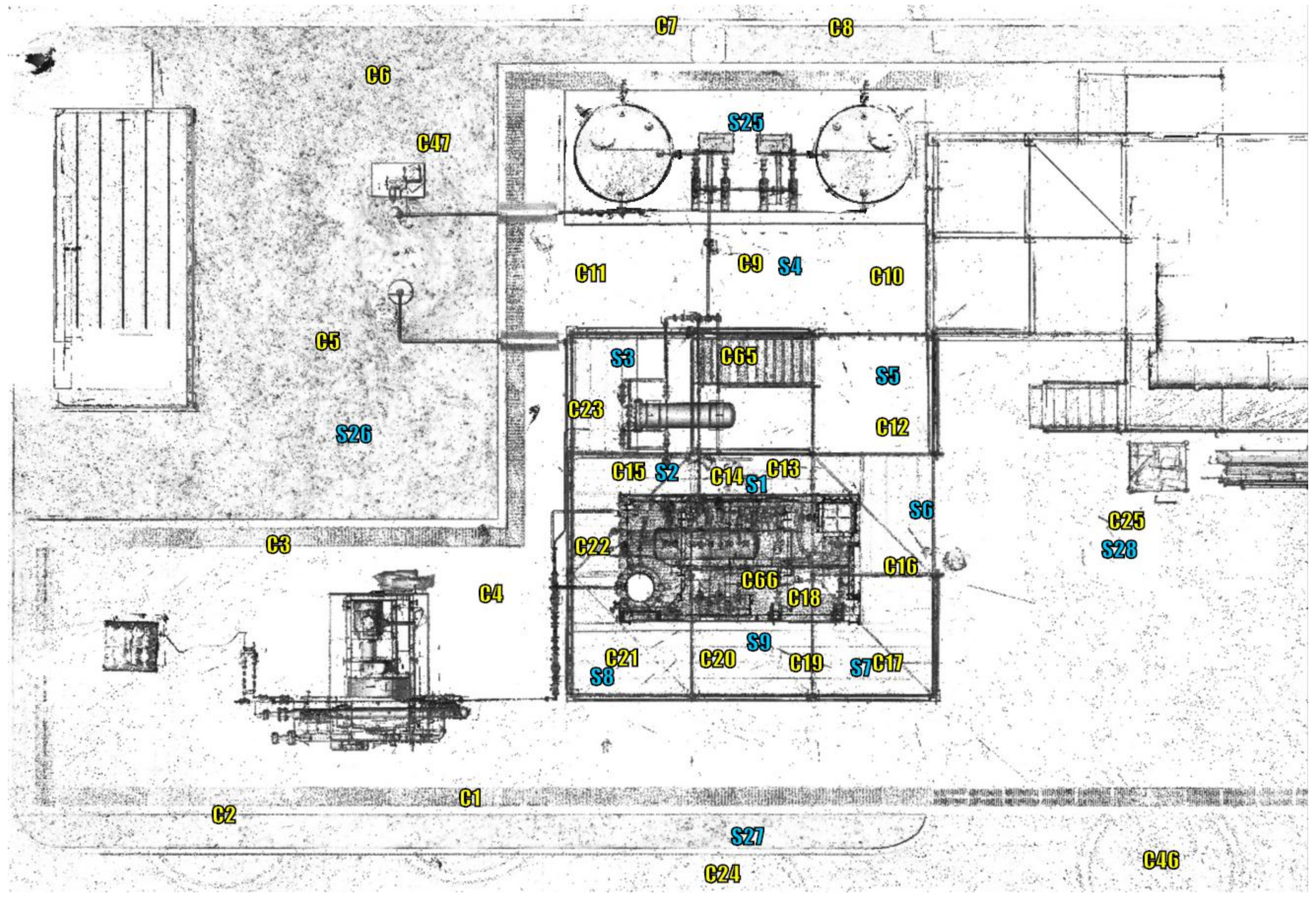
Agence Nationale de la Recherche ANR

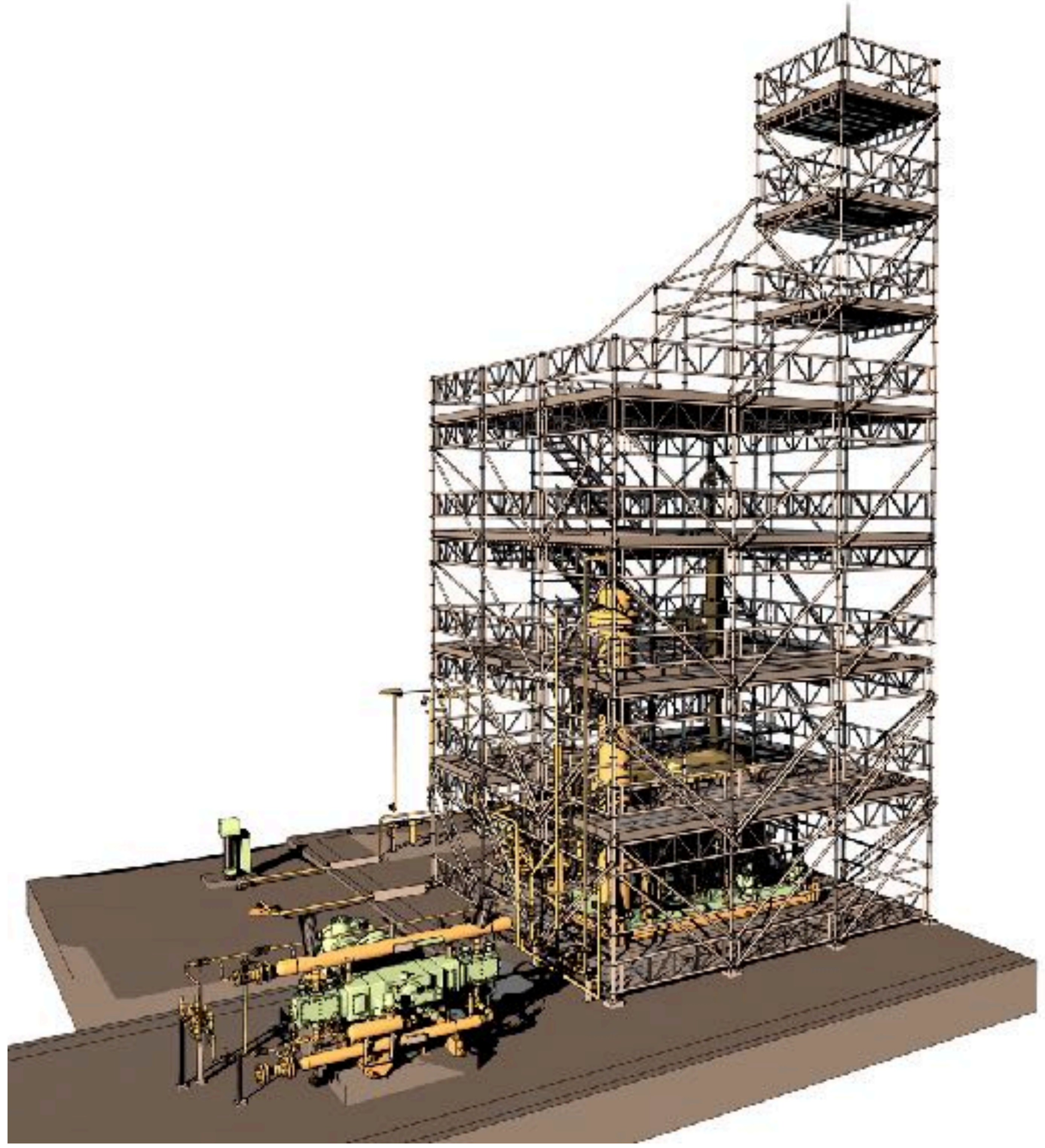


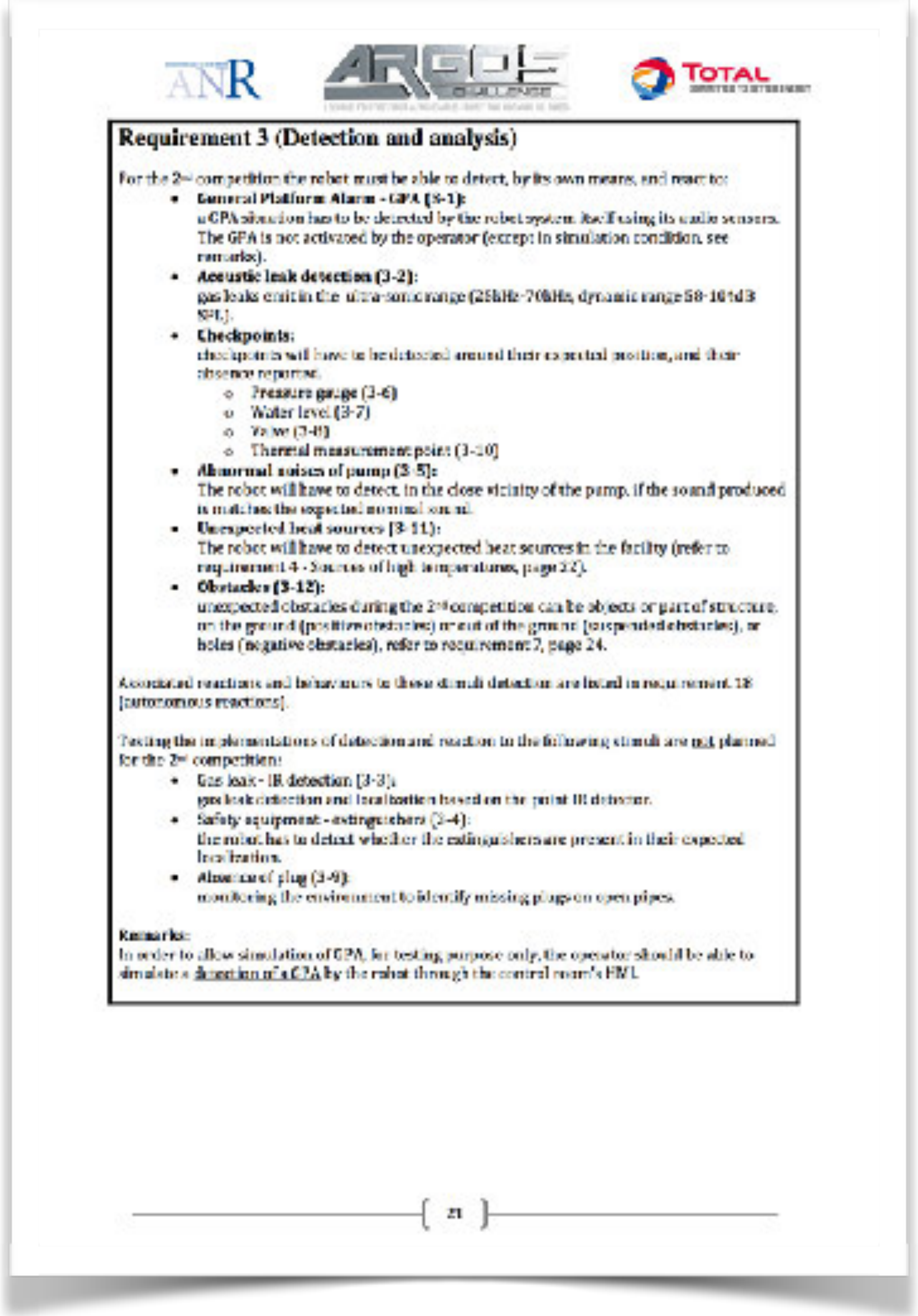


http://www.argos-challenge.com

ARGOS Challenge
Autonomous Inspection of Oil and Gas Sites






Requirement 3 (Detection and analysis)

For the 2nd competition the robot must be able to detect, by its own means, and react to:

- **General Platform Alarm - GPA (3-1):** a GPA situation has to be detected by the robot system itself using its audio sensors. The GPA is not activated by the operator (except in simulation condition, see remarks).
- **Acoustic leak detection (3-2):** gas leaks emit in the ultra-sonic range (25kHz-70kHz, dynamic range 58-101dB SPL).
- **Checkpoints:** checkpoints will have to be detected around their expected position, and their absence reported.
  - Pressure gauge (3-6)
  - Water level (3-7)
  - Valve (3-8)
  - Thermal measurement point (3-10)
- **Abnormal noises of pump (3-5):** The robot will have to detect, in the close vicinity of the pump, if the sound produced is matching the expected normal sound.
- **Unexpected heat sources (3-11):** The robot will have to detect unexpected heat sources in the facility (refer to requirement 4 - Sources of high temperatures, page 22).
- **Obstacles (3-12):** unexpected obstacles during the 2nd competition can be objects or part of structure, on the ground (positive obstacles) or out of the ground (suspended obstacles), or holes (negative obstacles), refer to requirement 7, page 24.

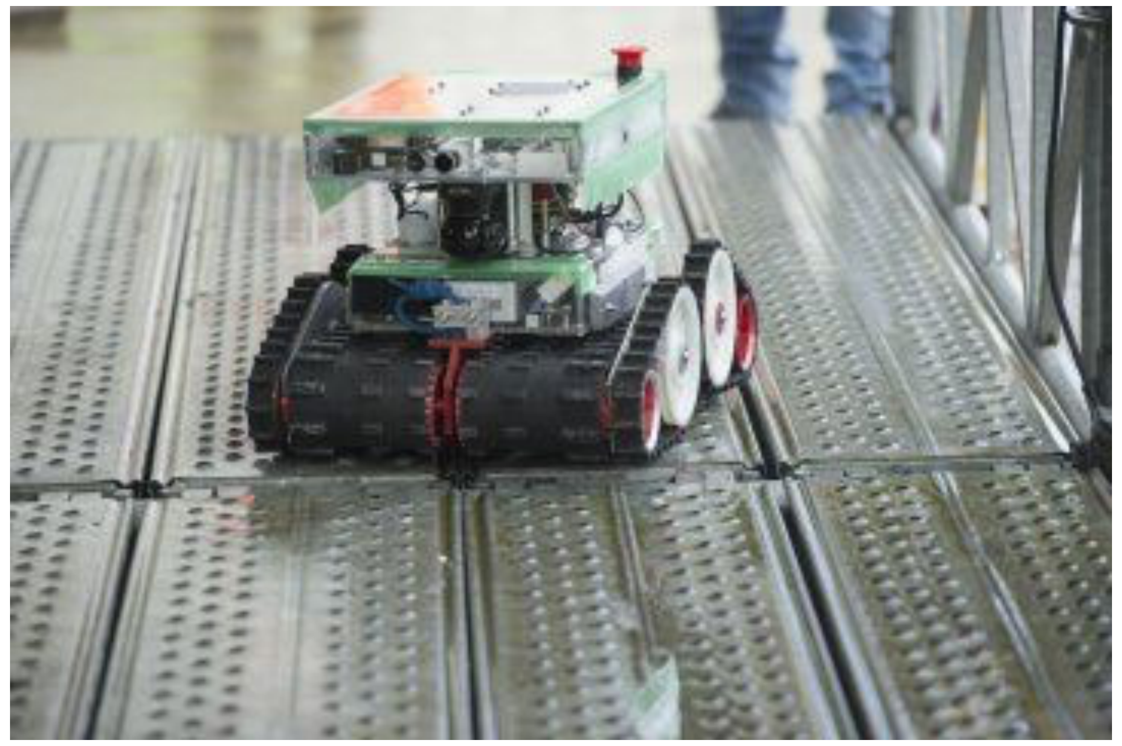
Associated reactions and behaviours to these stimuli detection are listed in requirement 18 [autonomous reactions].

Testing the implementations of detection and reaction to the following stimuli are not planned for the 2nd competition:

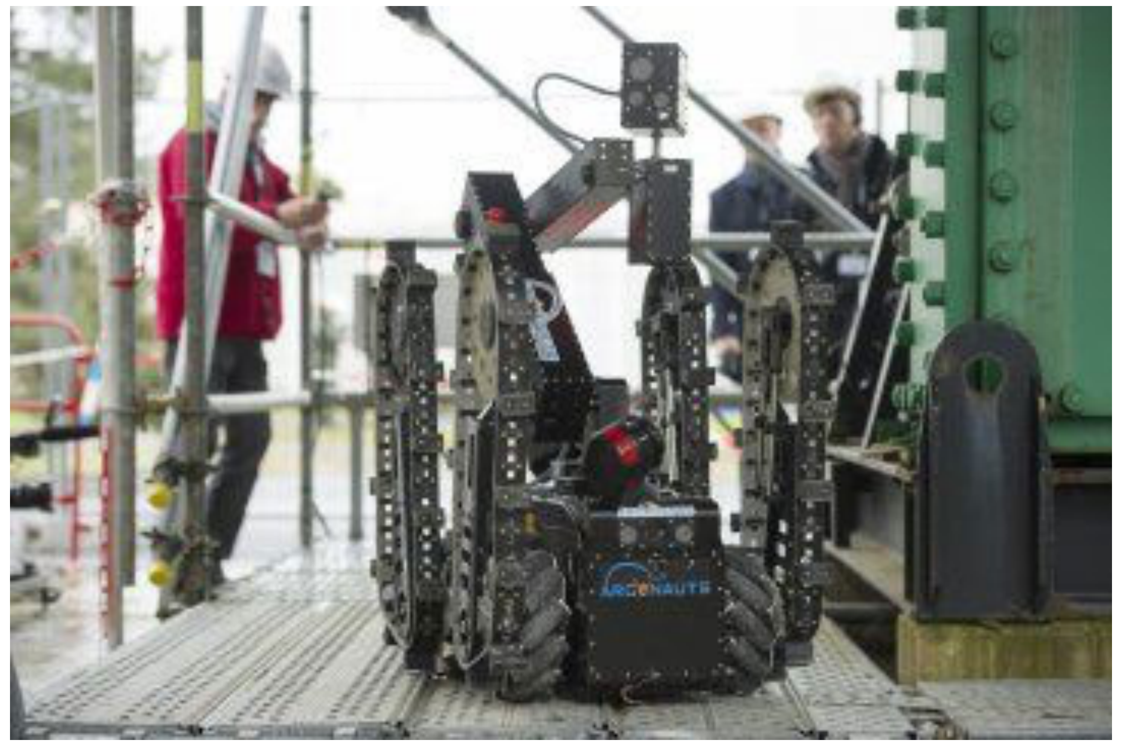
- Gas leak - IR detection (3-3): gas leak detection and localization based on the point IR detector.
- Safety equipment - extinguishers (3-4): the robot has to detect whether the extinguishers are present in their expected localization.
- Absence of plug (3-9): monitoring the environment to identify missing plugs on open pipes.

Remarks:
In order to allow simulation of GPA, for testing purpose only, the operator should be able to simulate a detection of a GPA by the robot through the control room's HMI.

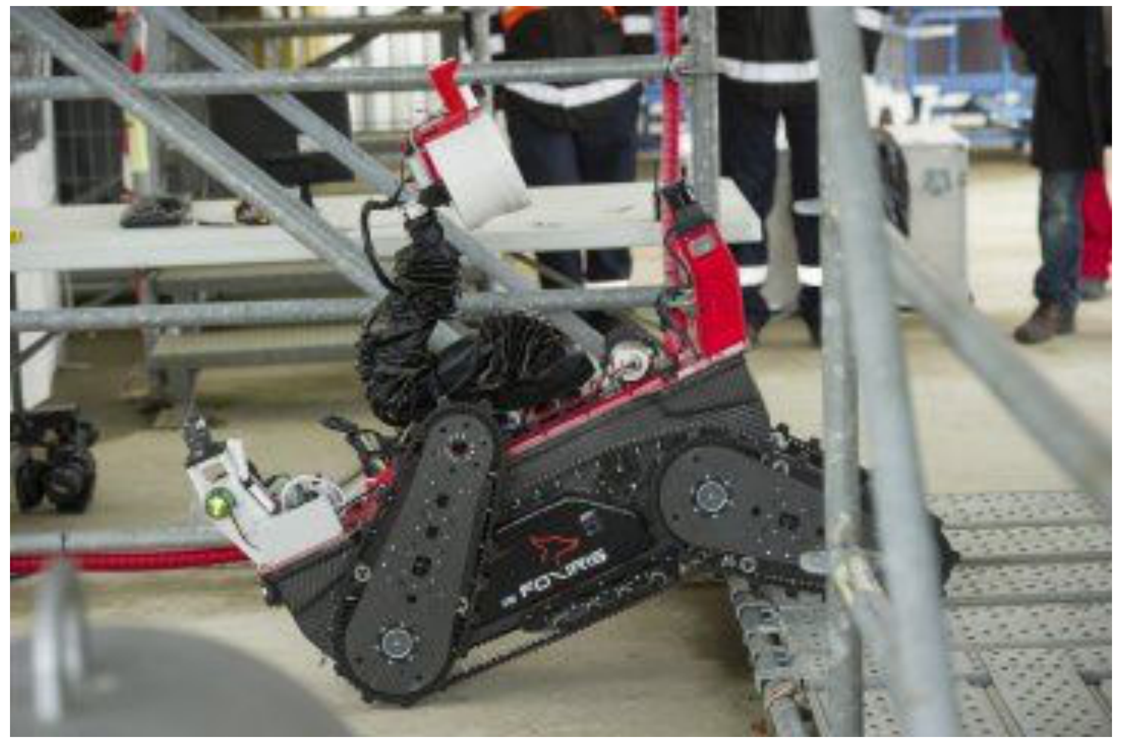
ARGOS Challenge
5 International Teams



AIR-K
Japan



ARGONAUTS
Austria & Germany



FOXIRIS
Spain & Portugal

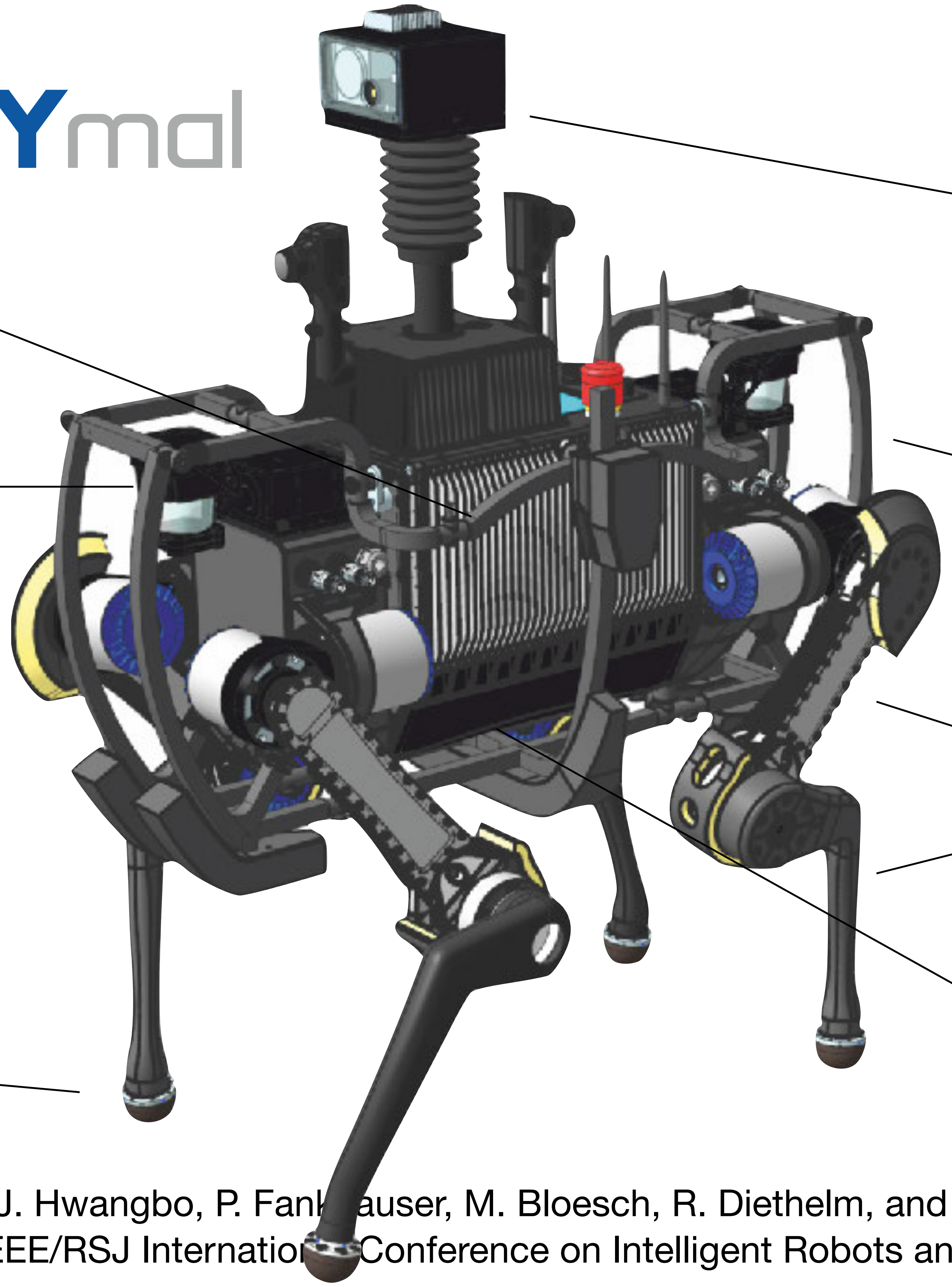
VIKINGS
France

LIO
Switzerland

ARGOS Challenge
Team LIO

ANYmal – A High-Performance & Versatile Quadrupedal Robot

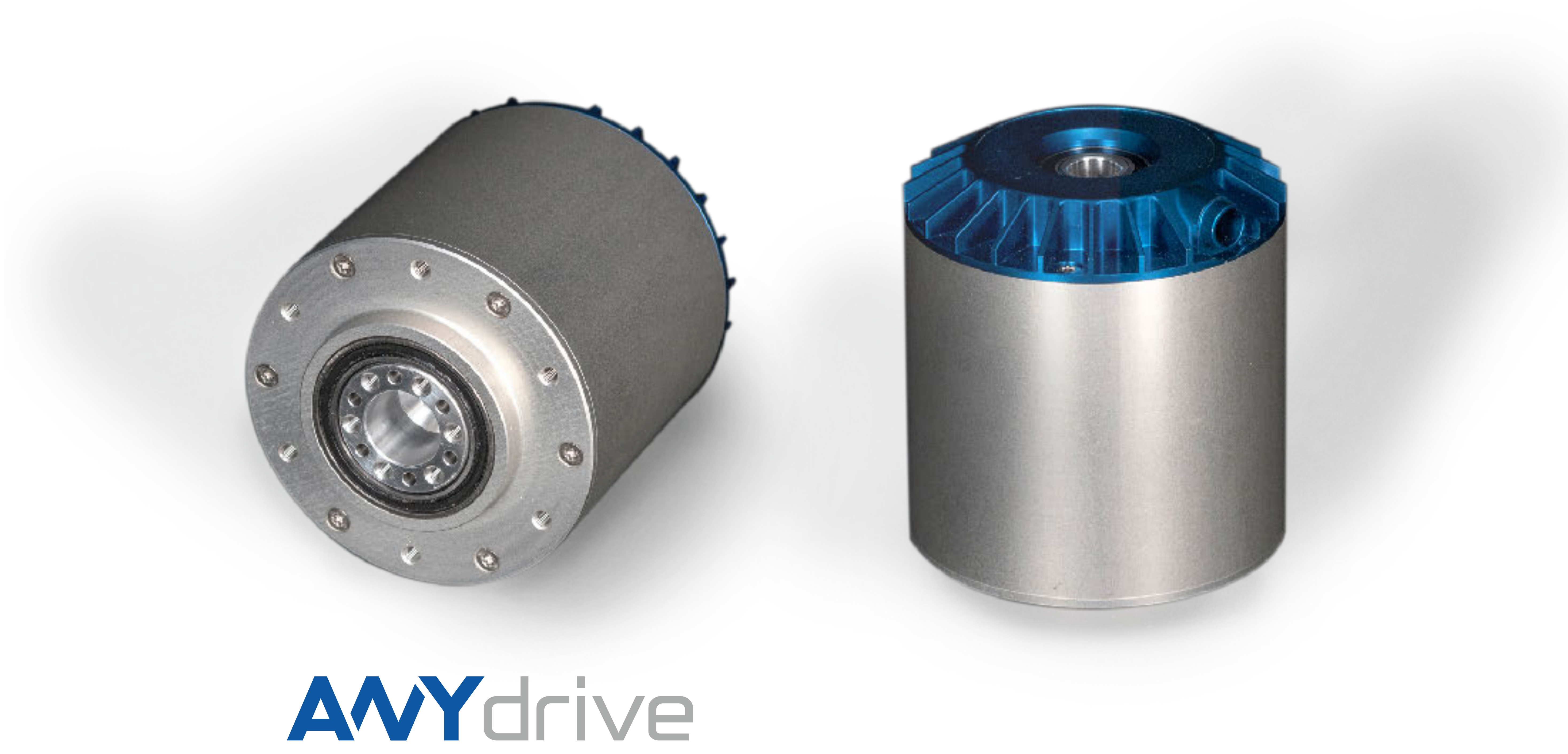
ANYmal



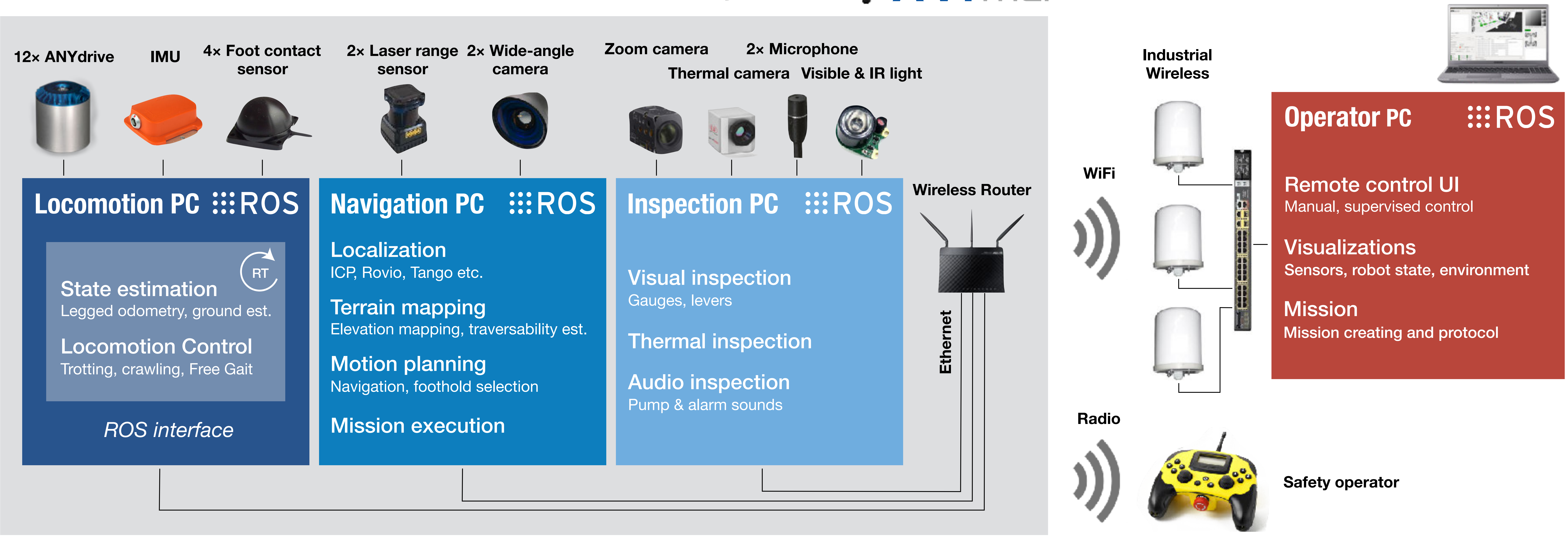
M. Hutter, C. Gehring, D. Jud, A. Lauber, C. D. Bellicoso, V. Tsounis, J. Hwangbo, P. Fankhauser, M. Bloesch, R. Diethelm, and S. Bachmann, **"ANYmal - A Highly Mobile and Dynamic Quadrupedal Robot,"** IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2016.

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

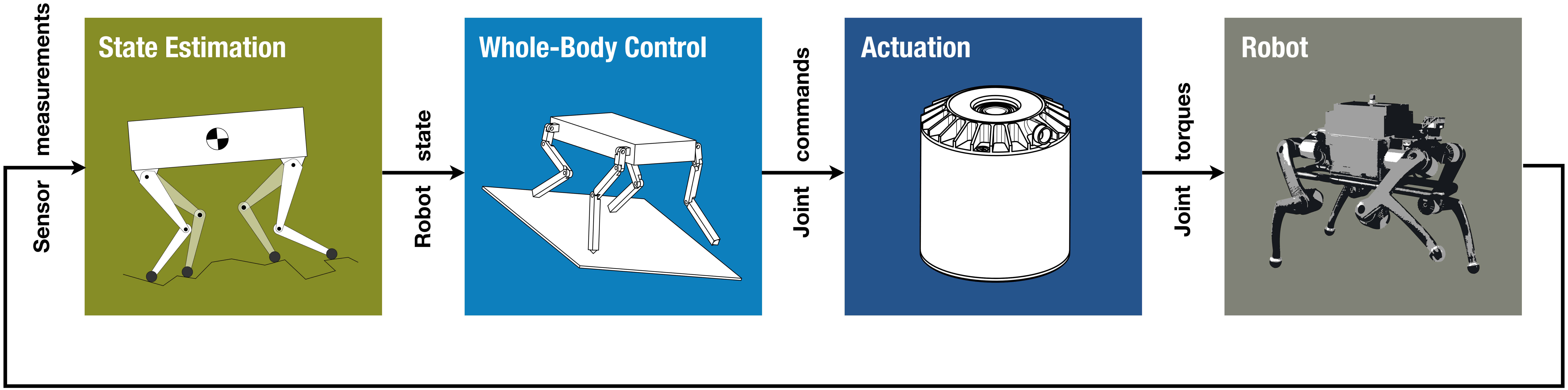
- Fully integrated
- Accurate position & torque control
- Absolute position sensing
- Programmable controller
- Impact robust
- Hollow-shaft
- Water-proof



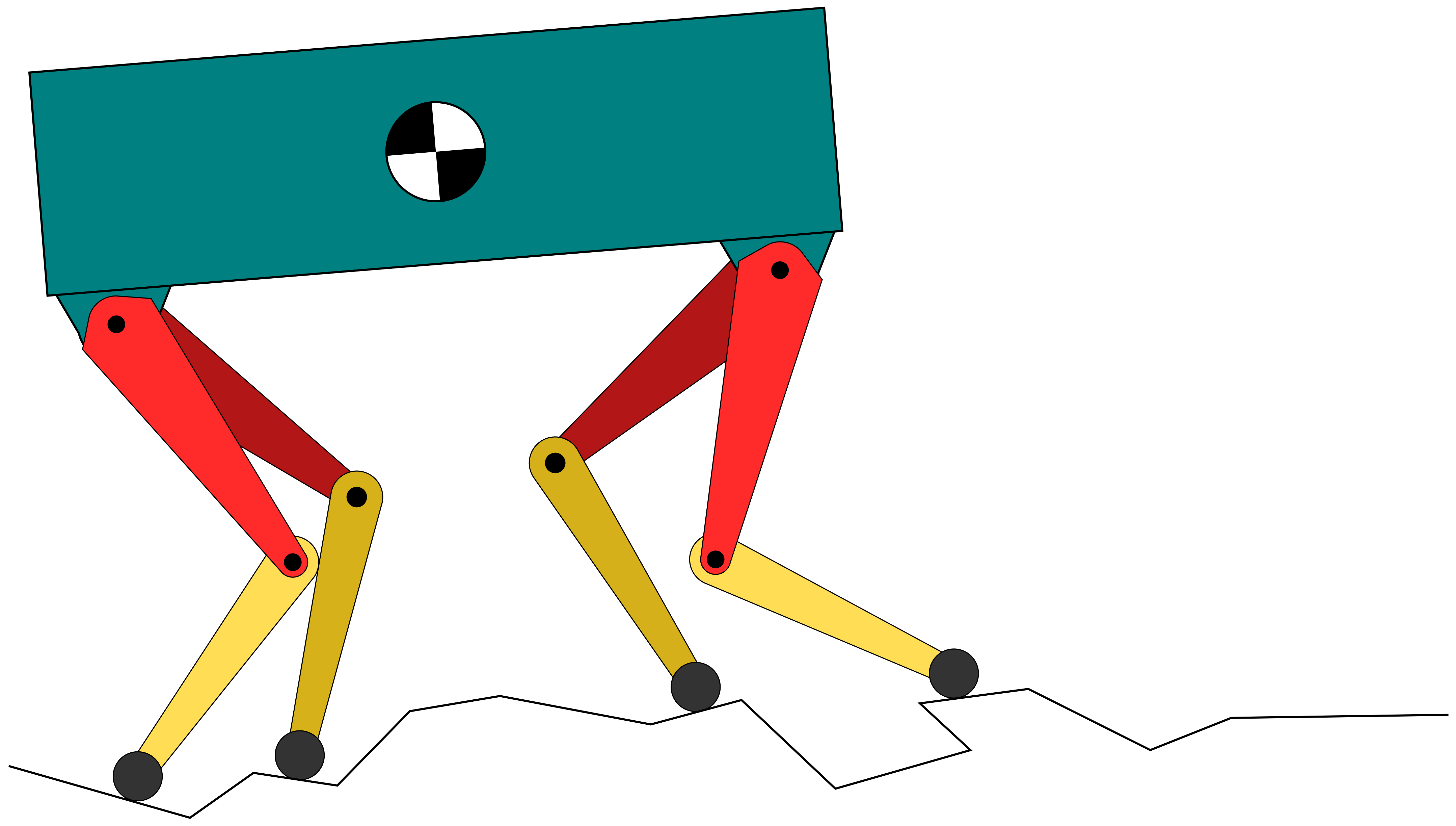
System Overview



Locomotion


Sensor measurements
State Estimation
Robot state
Whole-Body Control
Joint commands
Actuation
Joint torques
Robot

Locomotion
State Estimation

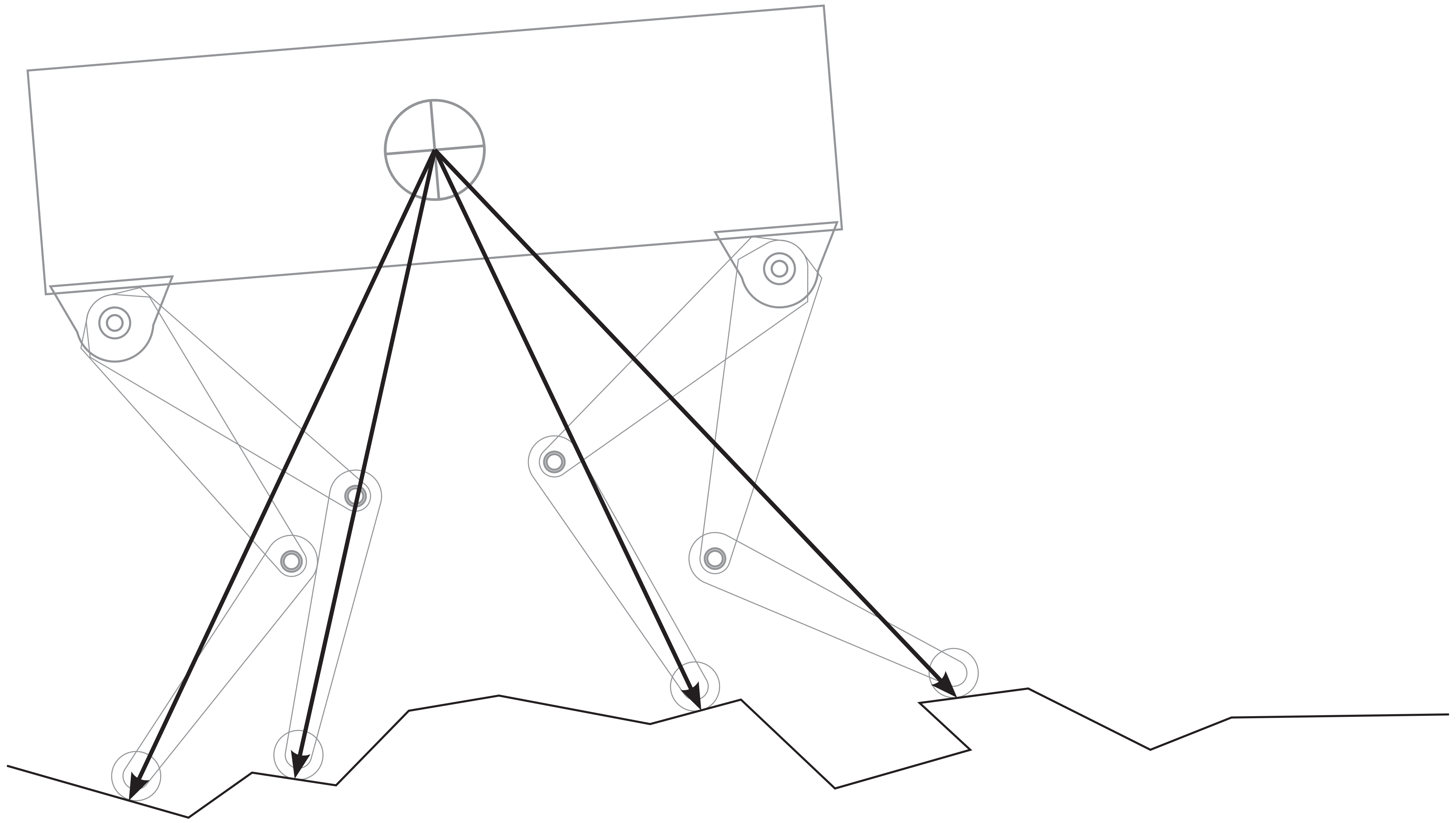


Extended Kalman Filter

- 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

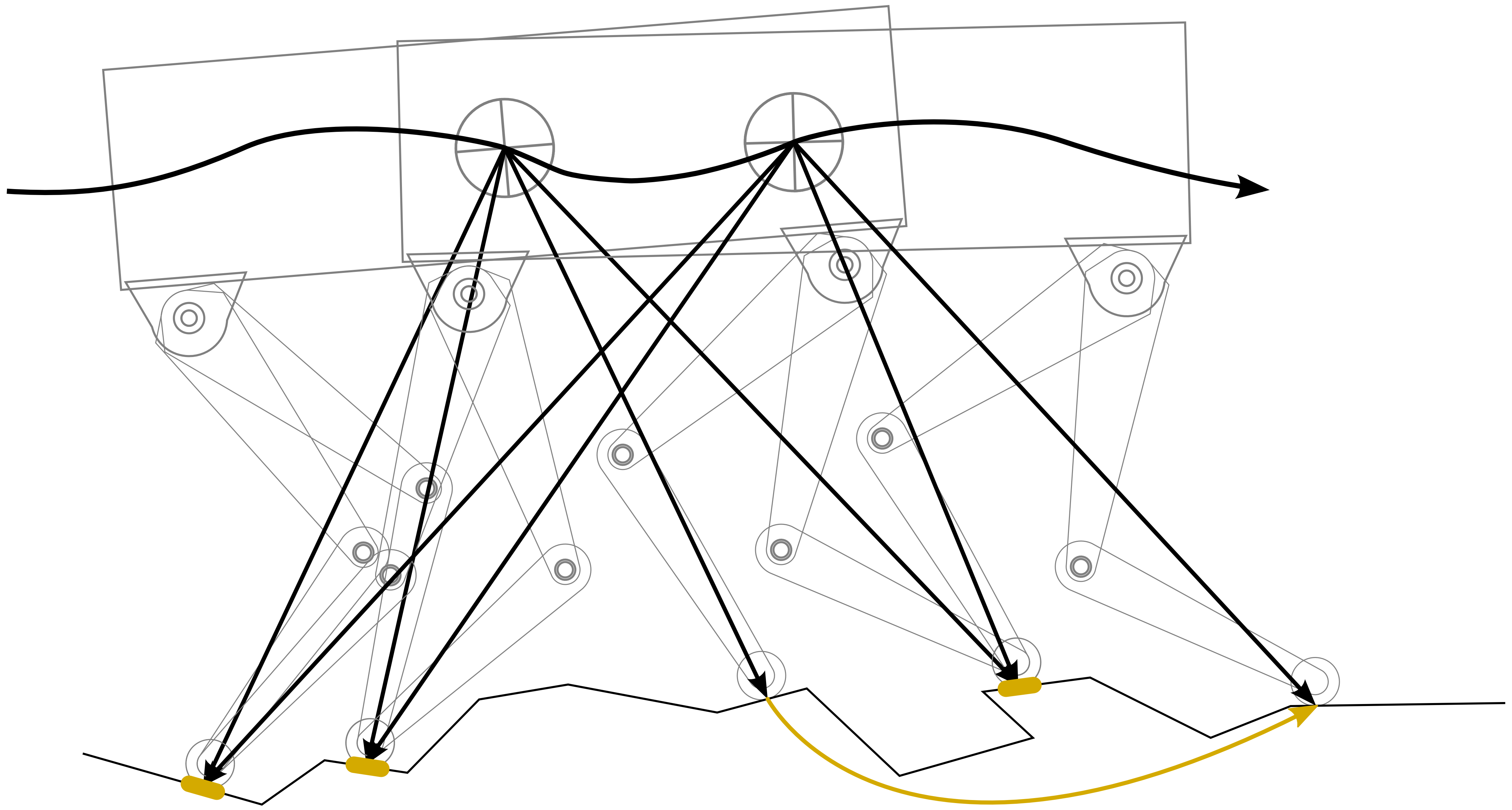


Extended Kalman Filter

- 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



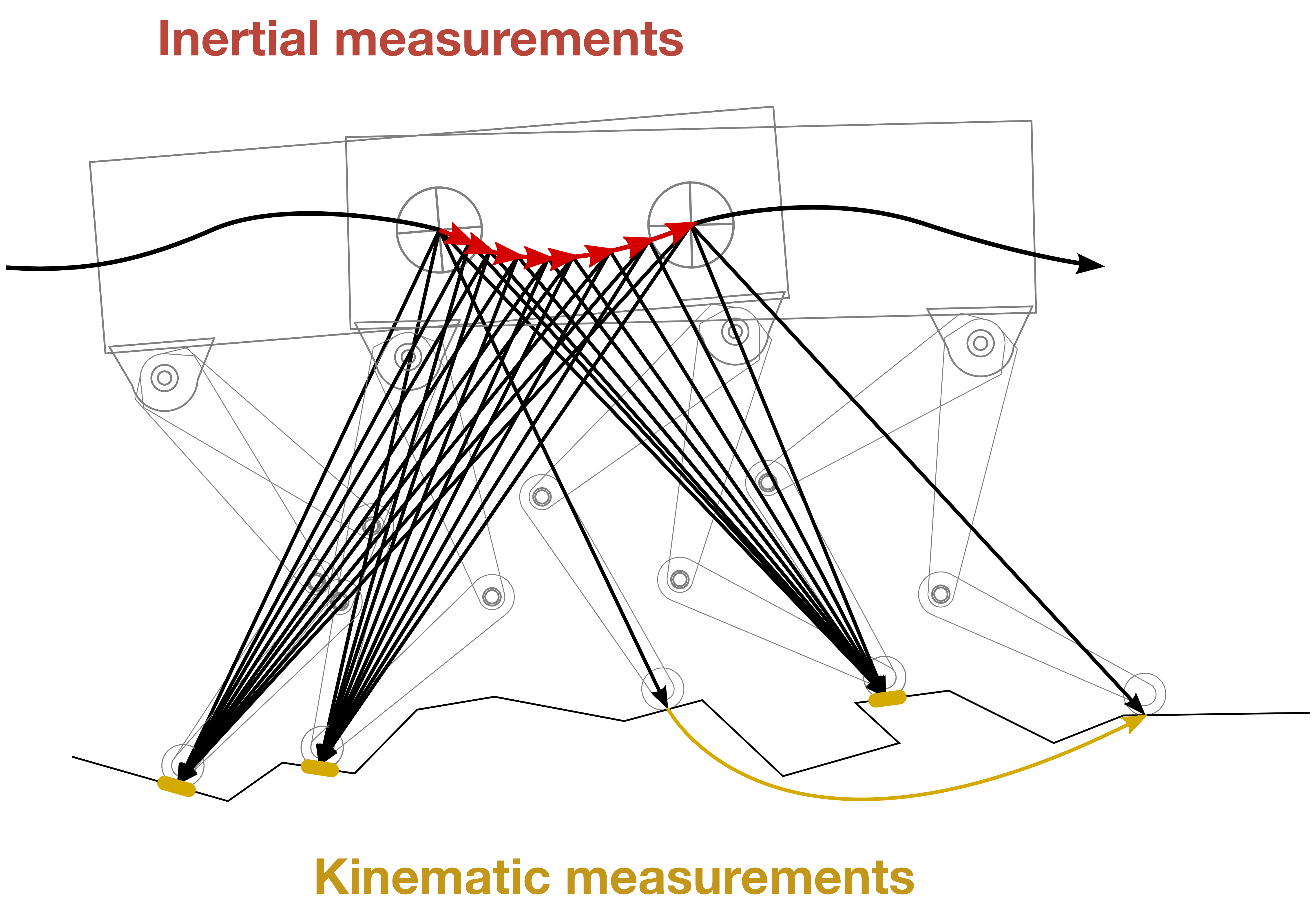
Kinematic measurements

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

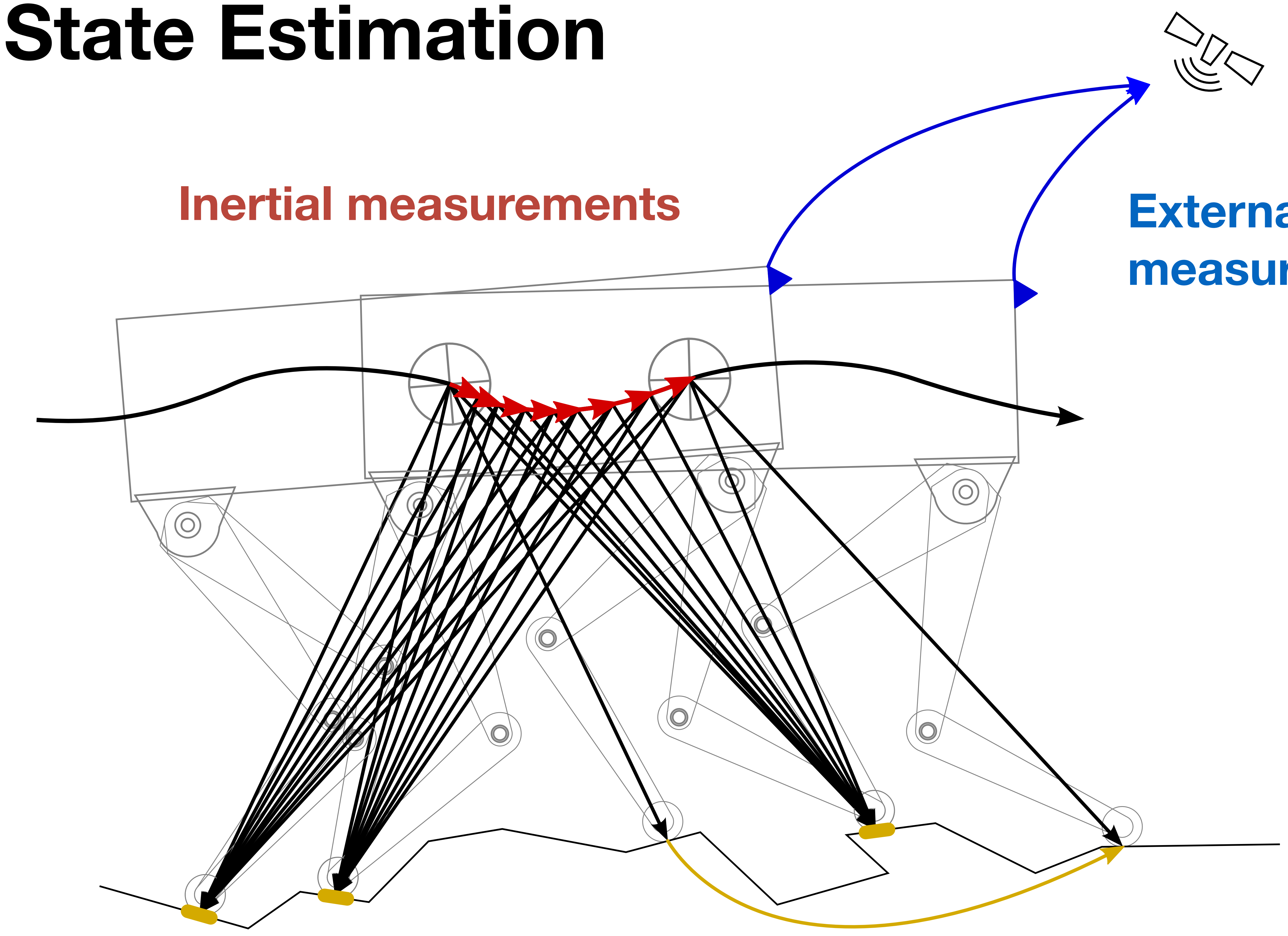


Extended Kalman Filter

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

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

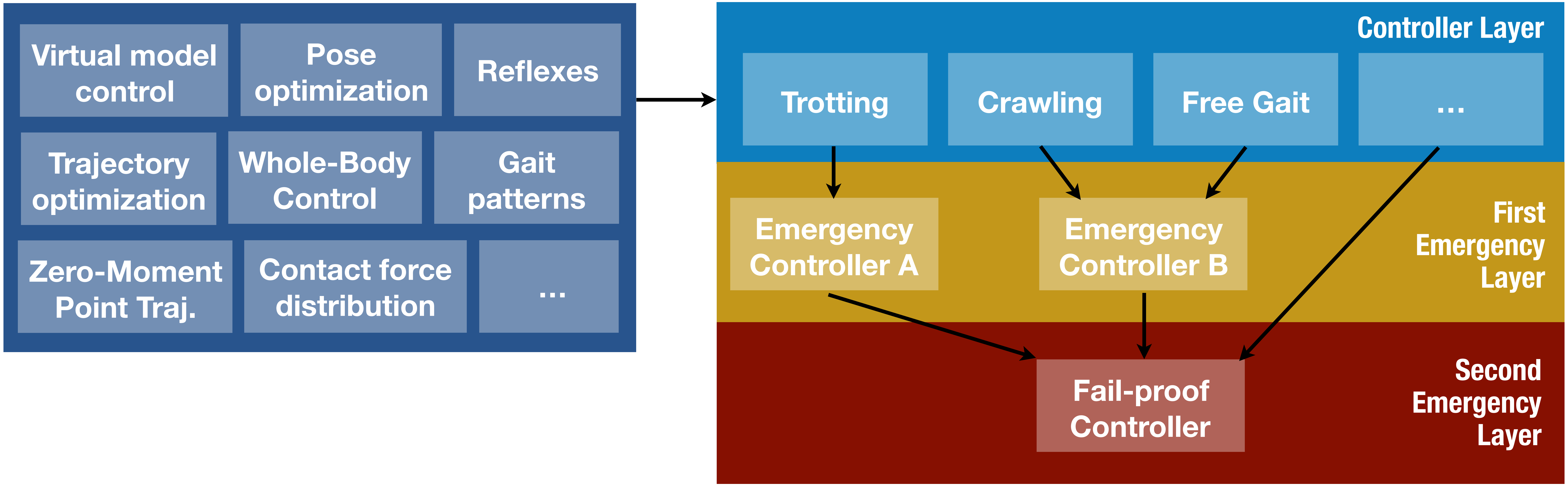
- No assumption on terrain
- Kinematic measurements (encoders) for legs in contact
- Fused with inertial measurements (IMU)
- Error < 5% over distance
- Optionally combined with external pose (GPS, laser, vision, etc.)

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
Whole-Body Control

Open Source (coming soon)

Locomotion Controller Modules (Loco) | **Robot Controller Manager (Rocoma)**

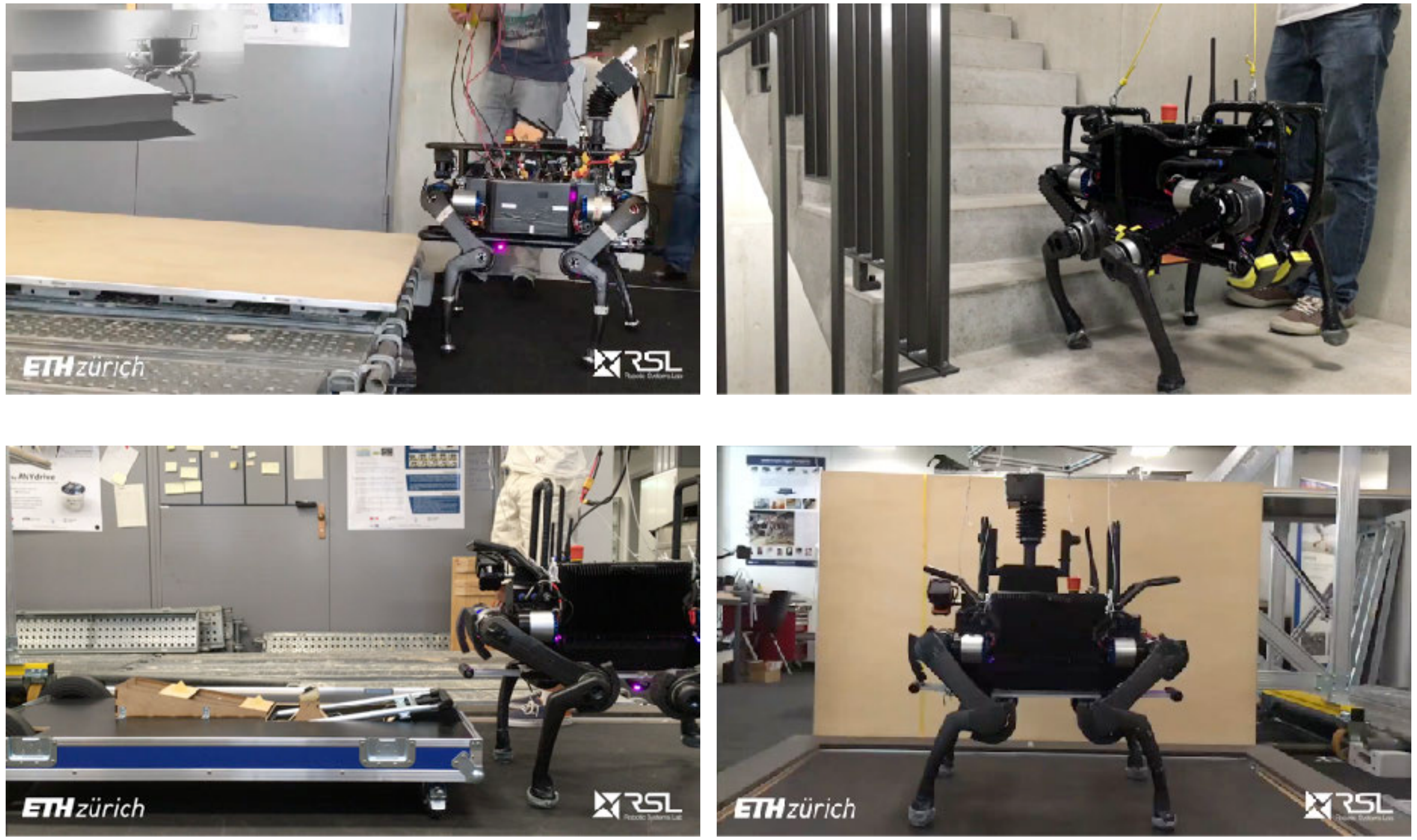


C. Gehring, S. Coros, M. Hutter, D. Bellicoso, H. Heijnen, R. Diethelm, M. Bloesch, P. Fankhauser, J. Hwangbo, M. A. Hoepflinger, and R. Siegwart, "**Practice Makes Perfect: An Optimization-Based Approach to Controlling Agile Motions for a Quadruped Robot.**", in IEEE Robotics & Automation Magazine,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

Open Source
github.com/leggedrobotics/free_gait (in progress)

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



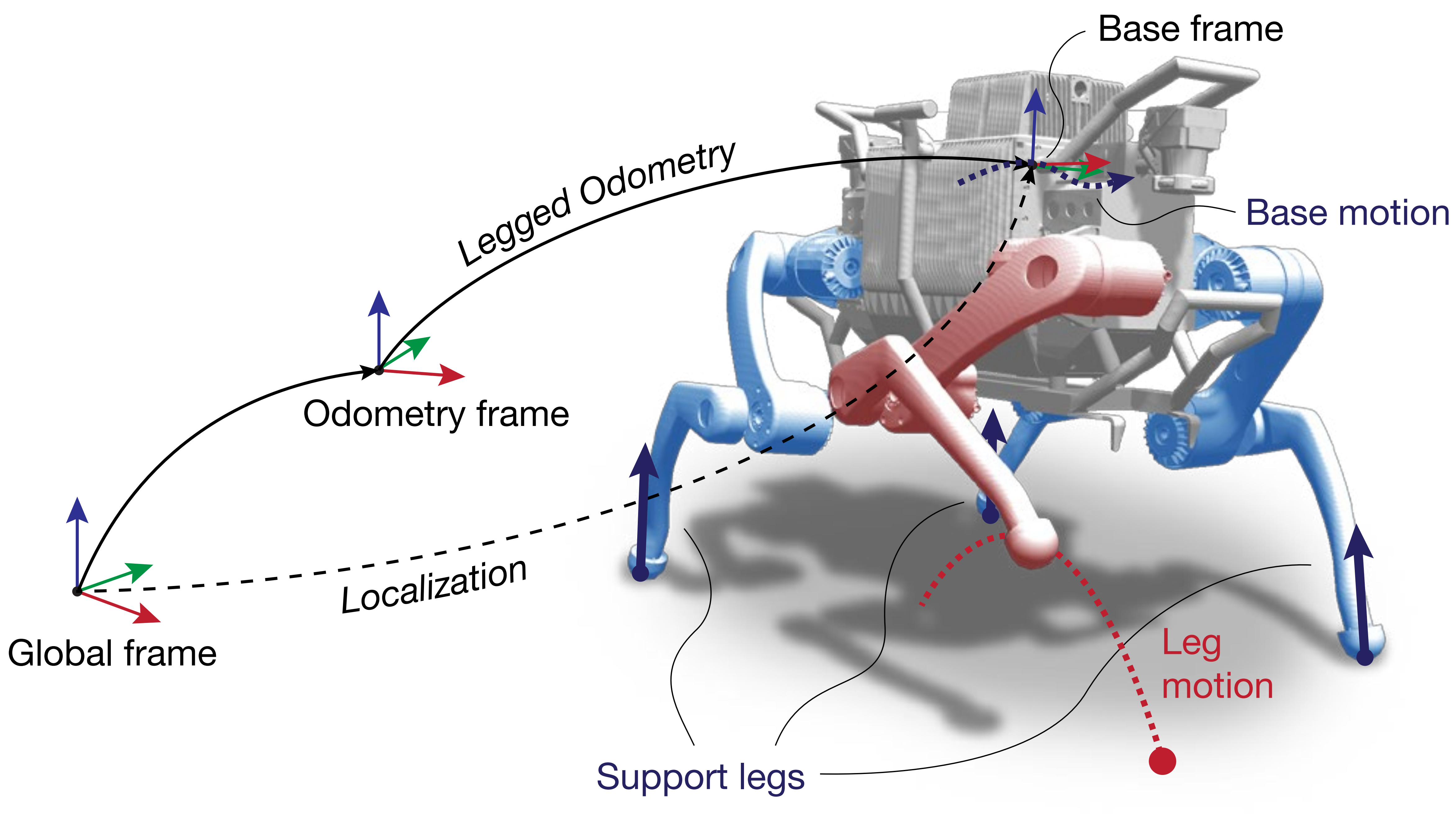
- Abstraction Layer for Whole-Body Motions (Free Gait API)

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.

Open Source
github.com/leggedrobotics/free_gait (in progress)

Locomotion

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



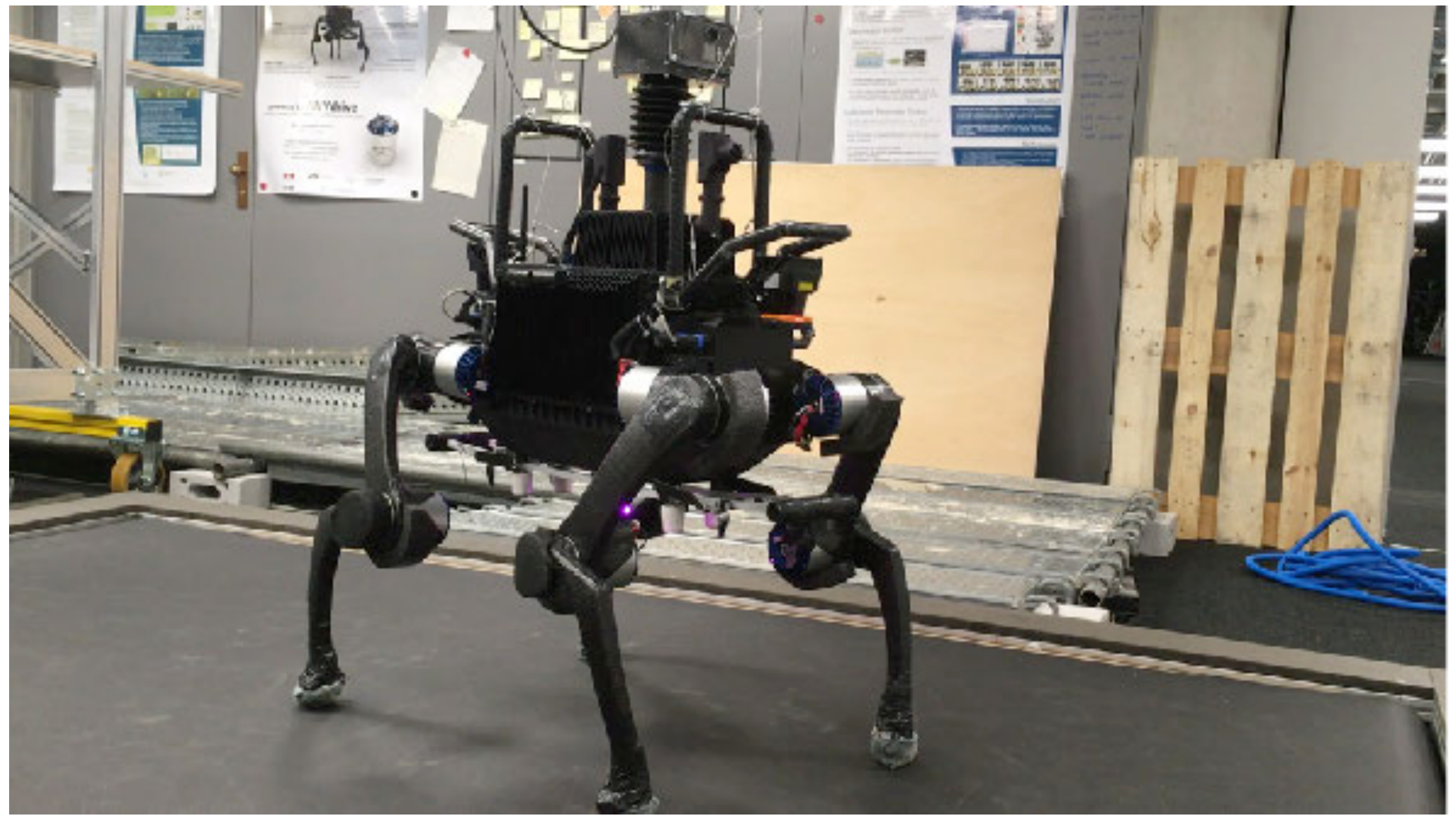
- Abstraction Layer for Whole-Body Motions (Free Gait API)
- Robust motion execution in task space

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.

Open Source
github.com/leggedrobotics/free_gait (in progress)

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

```yaml
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:
```



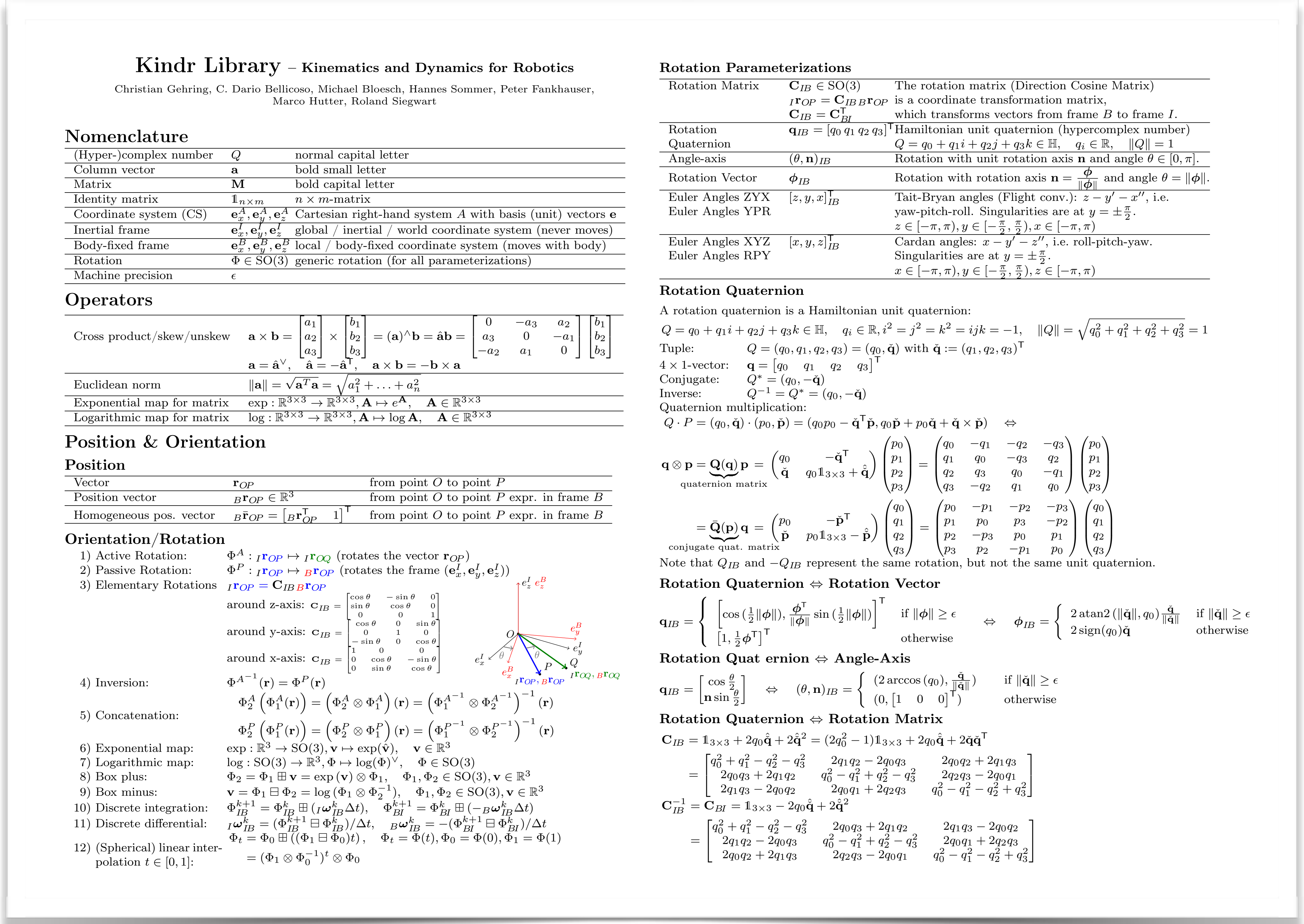
- Abstraction Layer for Whole-Body Motions (Free Gait API)
- Robust motion execution in task space
- Implemented as ROS Action (with frameworks for YAML, Python, C++)

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

Open Source
github.com/ethz-asl/kindr

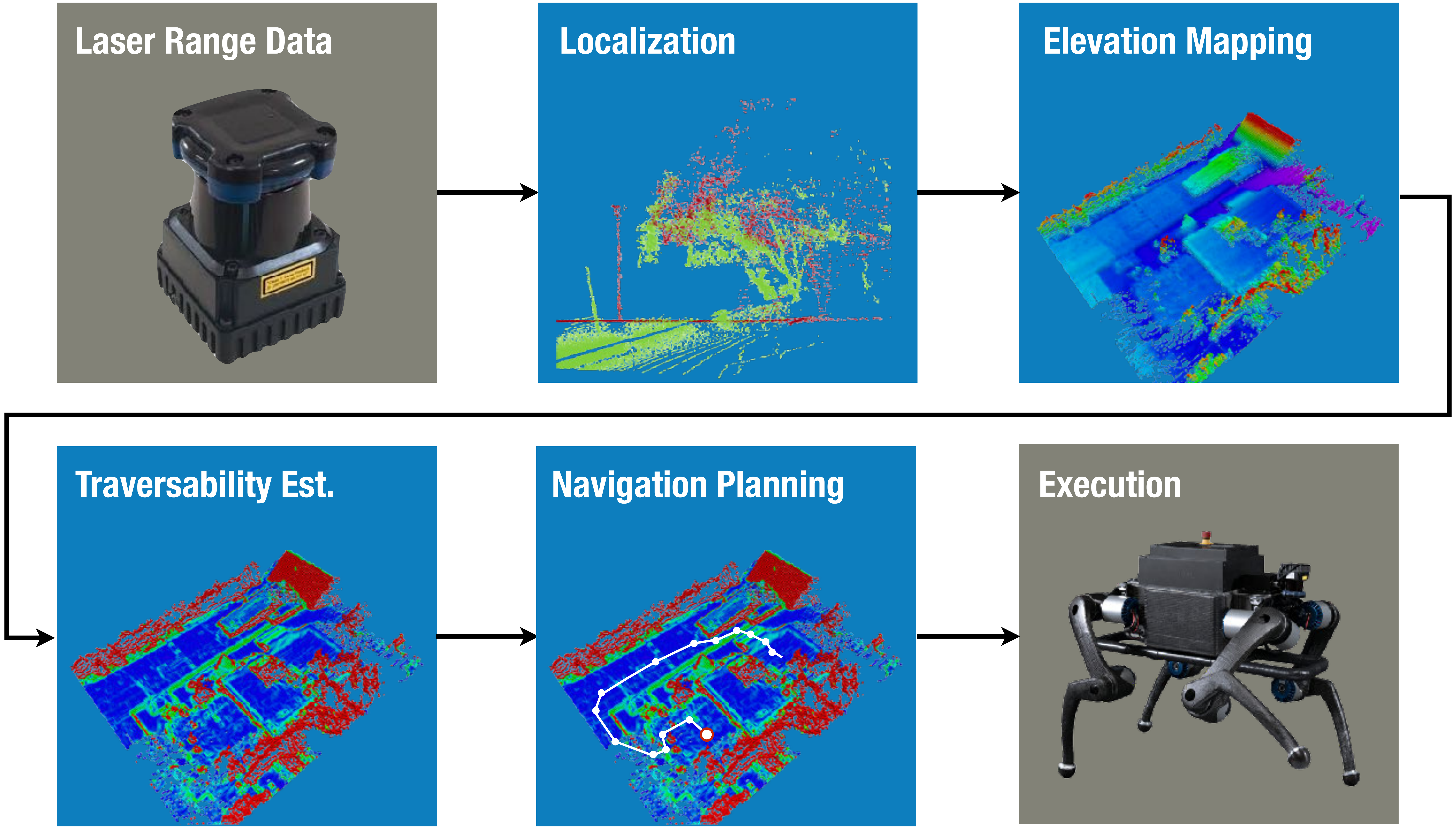
- C++ library for the consistent handling of 3d position and **rotations**
- Support for *rotation matrices*, *quaternions*, *angle-axis*, *rotation vectors*, *Euler angles*, etc.
- Support for all common operations and includes time-derivates
- ROS interface available
- Based on Eigen, 1000+ unit tests



Cheat-sheet (incl. derivations)

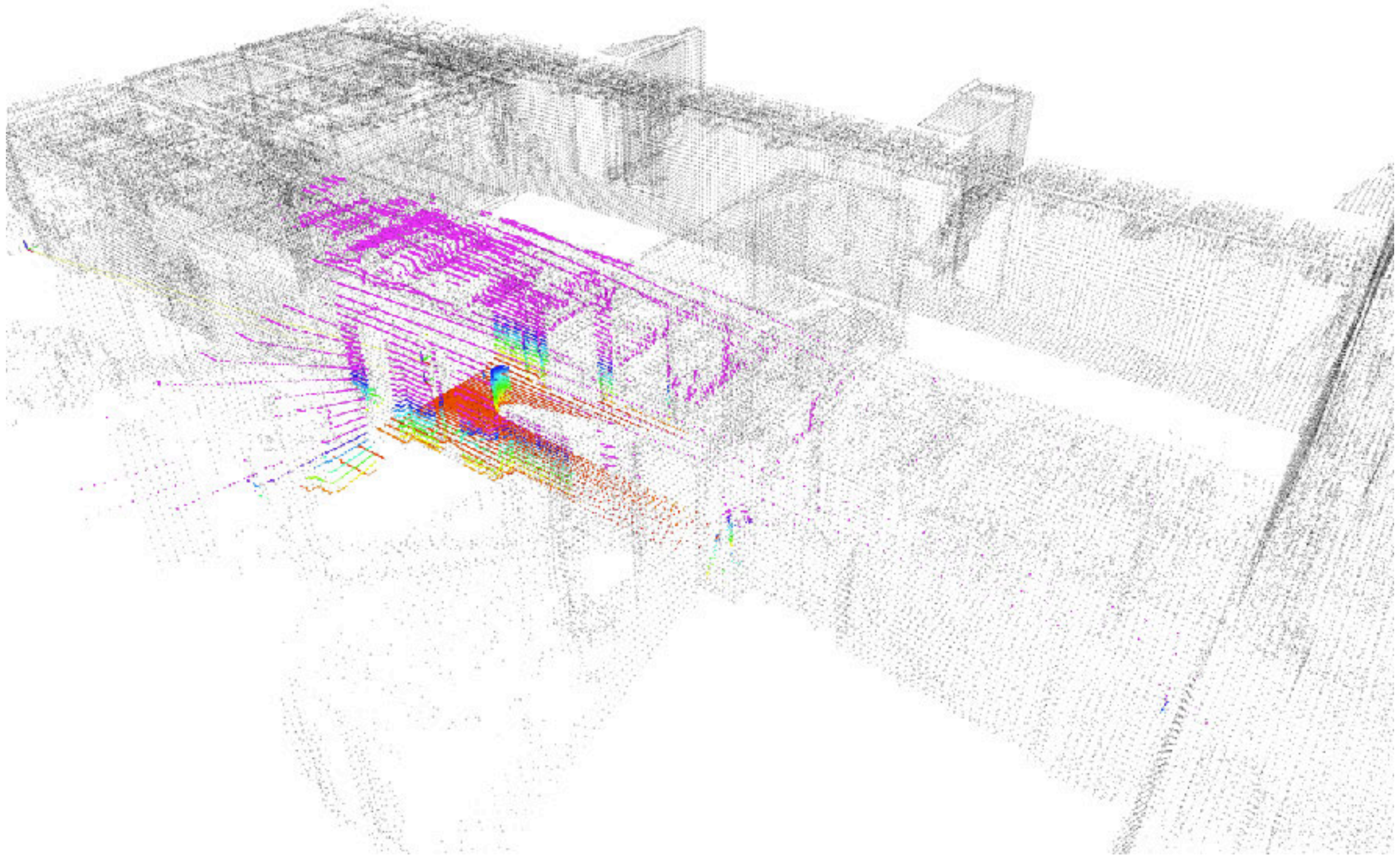
M. Bloesch, H. Sommer, T. Laidlow, M. Burri, G. Nuetzi, P. Fankhauser, D. Bellicoso, C. Gehring, S. Leutenegger, M. Hutter, R. Siegwart, **“A Primer on the Differential Calculus of 3D Orientations,”** in arXiv:1606.05285, 2016.

Navigation


Laser Range Data
Localization
Elevation Mapping
Traversability Est.
Navigation Planning
Execution

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

Open Source
github.com/ethz-asl/ethzasl_icp_mapping



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

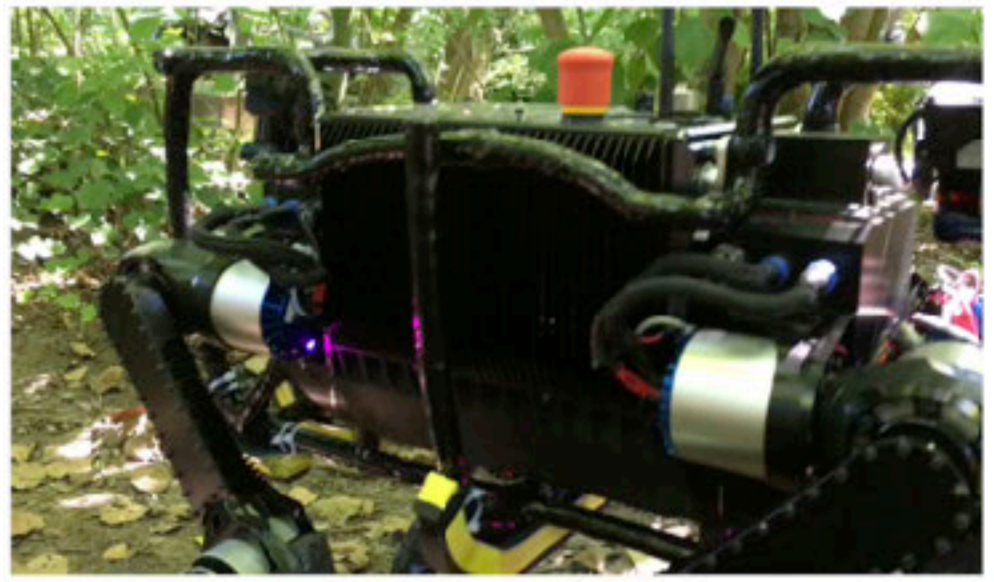
Pomerleau, F., Colas, F., Siegwart, R., Magnenat, S., "**Comparing ICP variants on real-world data sets**", in Autonomous Robots, 2013.

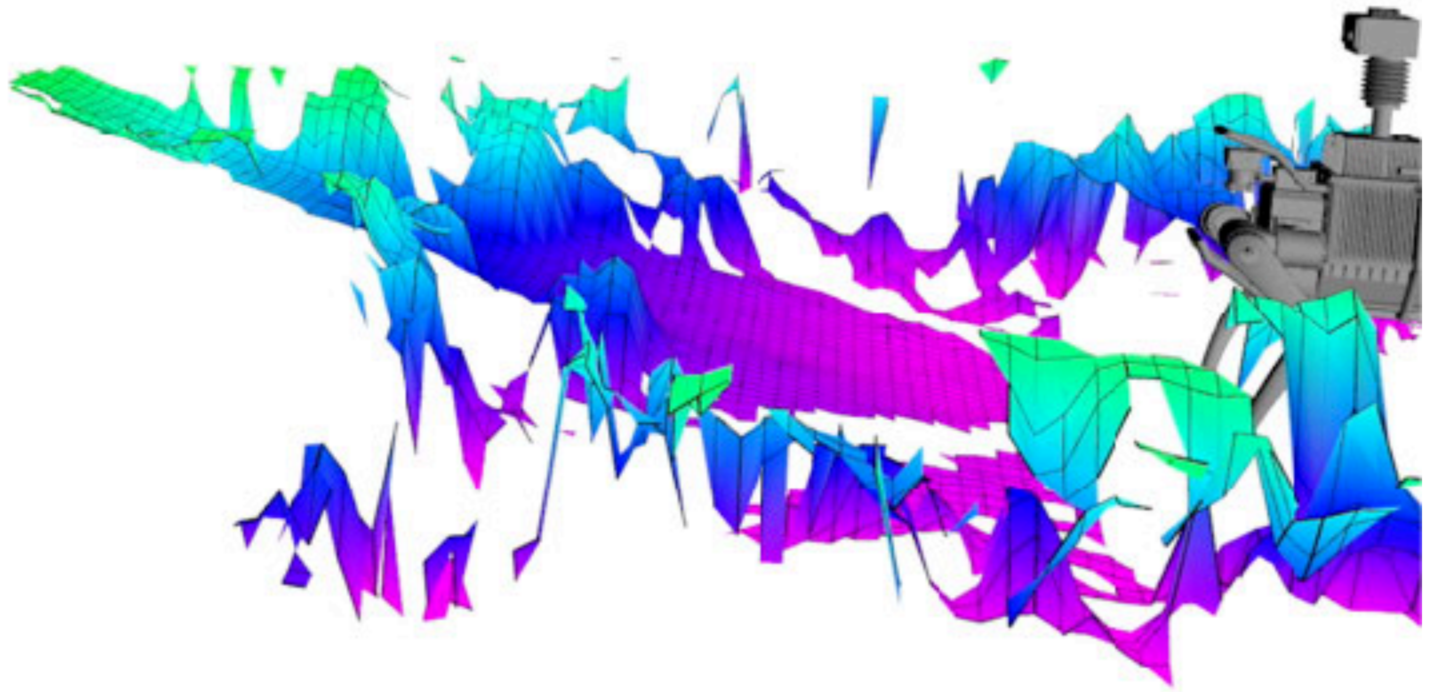
Navigation

Elevation Mapping – Dense Terrain Mapping

Open Source
github.com/ethz-asl/elevation_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.

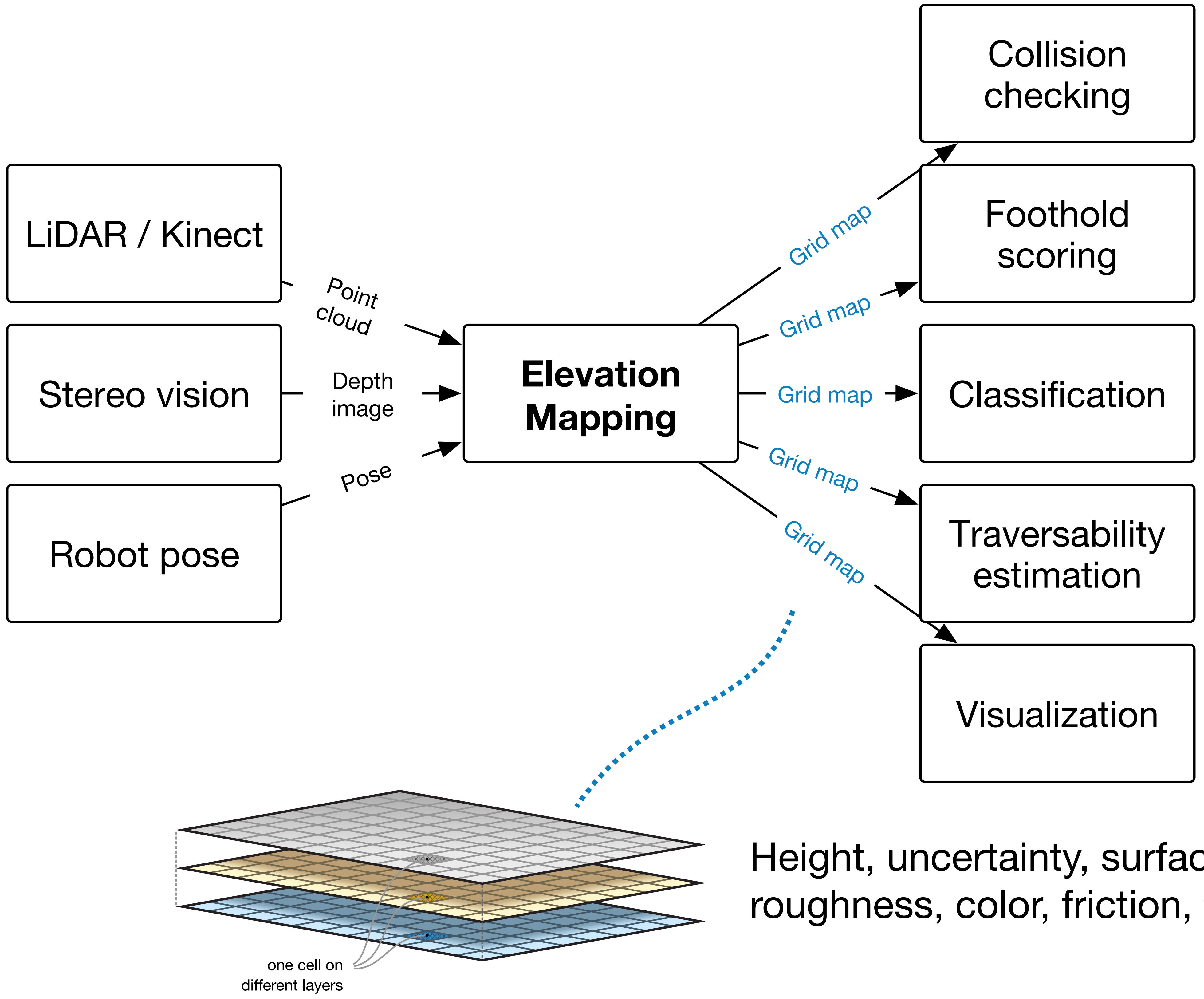




P. Fankhauser, M. Bloesch, C. Gehring, M. Hutter, R. Siegwart **"Robot-Centric Elevation Mapping with Uncertainty Estimates,"** in International Conference on Climbing and Walking Robots (CLAWAR), 2014.

Navigation
Grid Map – Universal Multi-Layer Grid Map Library

Open Source
github.com/ethz-asl/grid_map



Height, uncertainty, surface normal, roughness, color, friction, traversability …

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.

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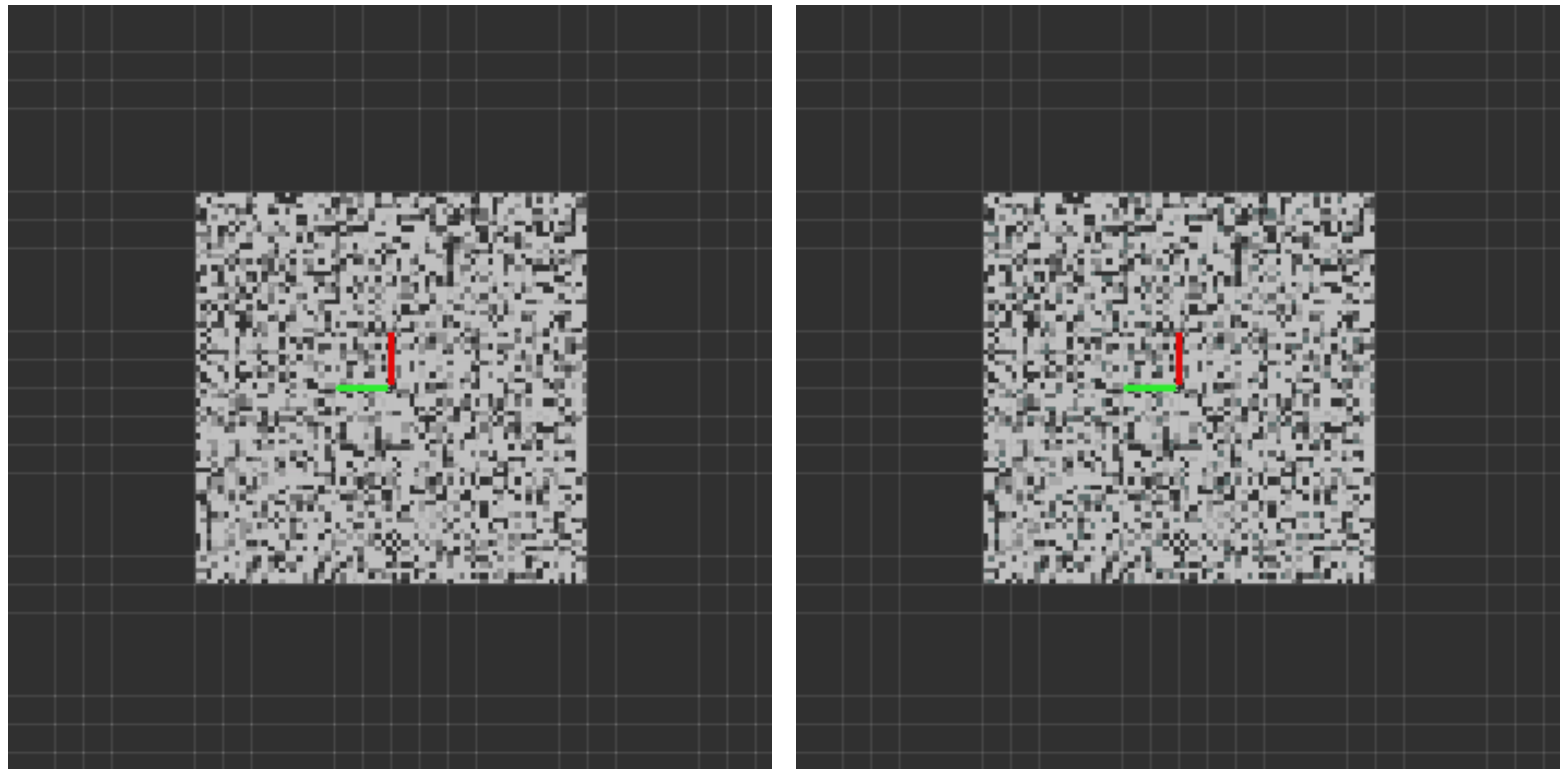

`setPosition(…)`   `move(…)`

- 2D circular buffer data structure
  - ➡ Efficient map repositioning

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

Open Source
github.com/ethz-asl/grid_map

- 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

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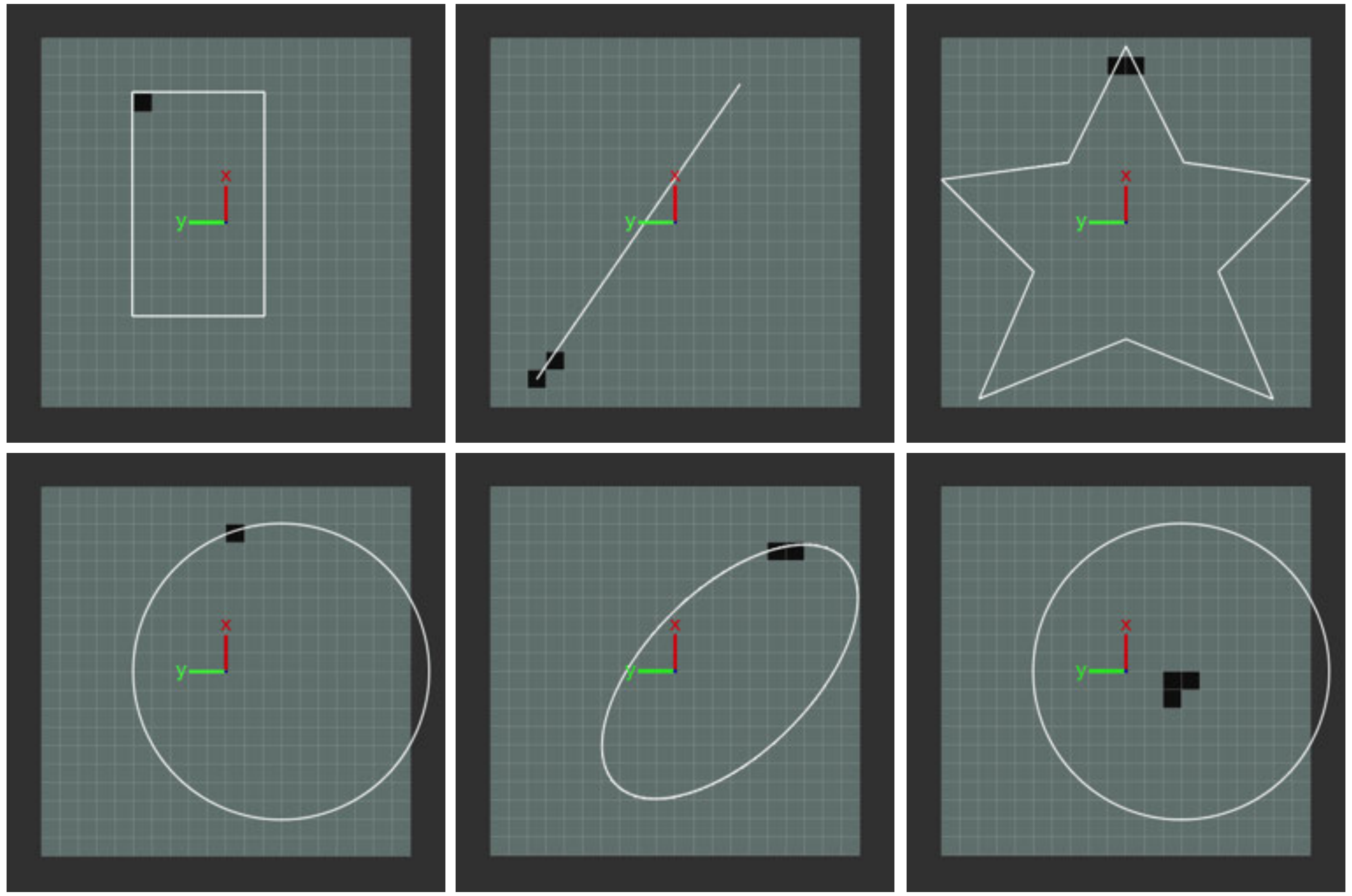

- 2D circular buffer data structure
  - ➡ Efficient map repositioning
- Based on Eigen (C++)
  - ➡ Versatile and efficient data manipulation
- Convenience functions
  - ➡ Iterators, math tools, etc.

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

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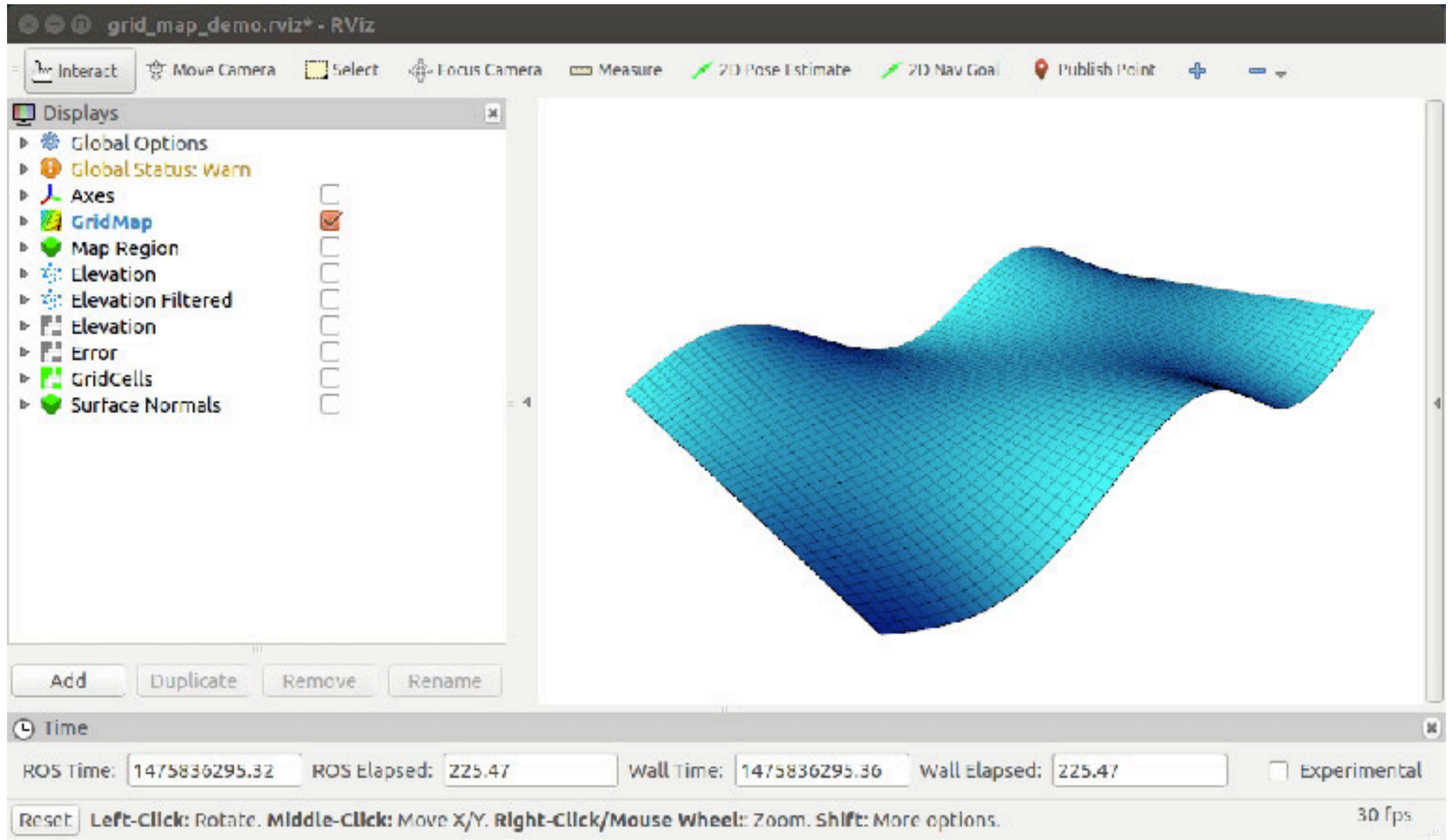
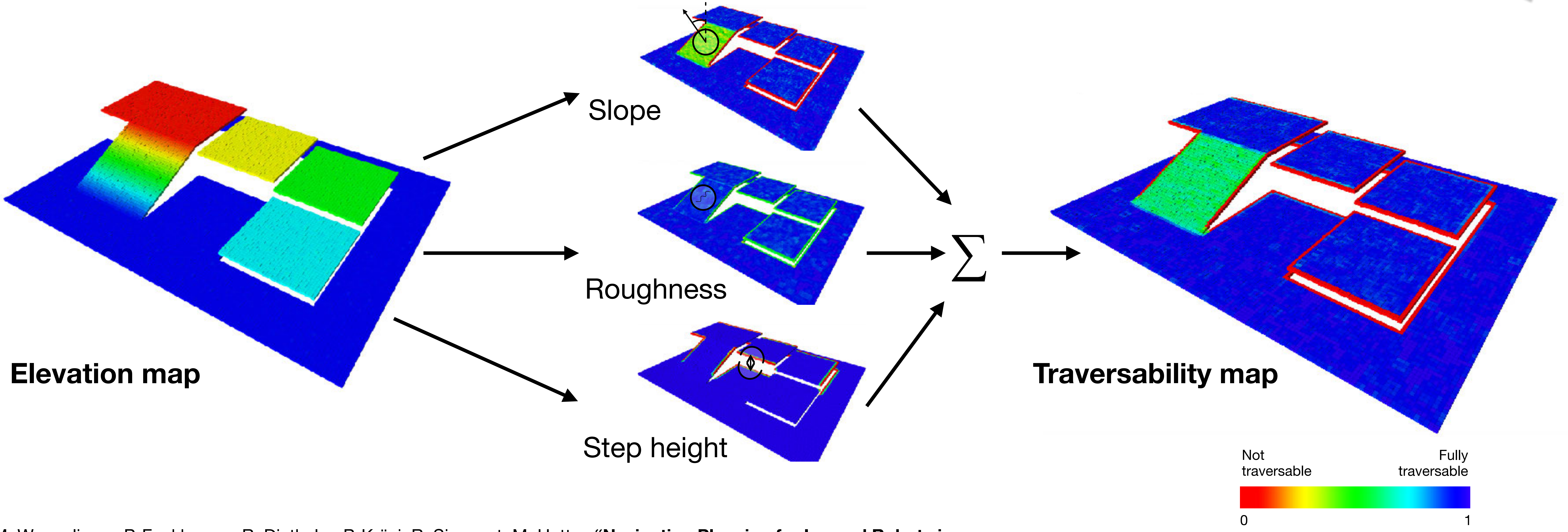


- 2D circular buffer data structure
  - ➡ Efficient map repositioning
- Based on Eigen (C++)
  - ➡ Versatile and efficient data manipulation
- Convenience functions
  - ➡ Iterators, math tools, etc.
- ROS & OpenCV interfaces
  - ➡ Conversion from/to images, point clouds, occupancy grids, grid cells

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.

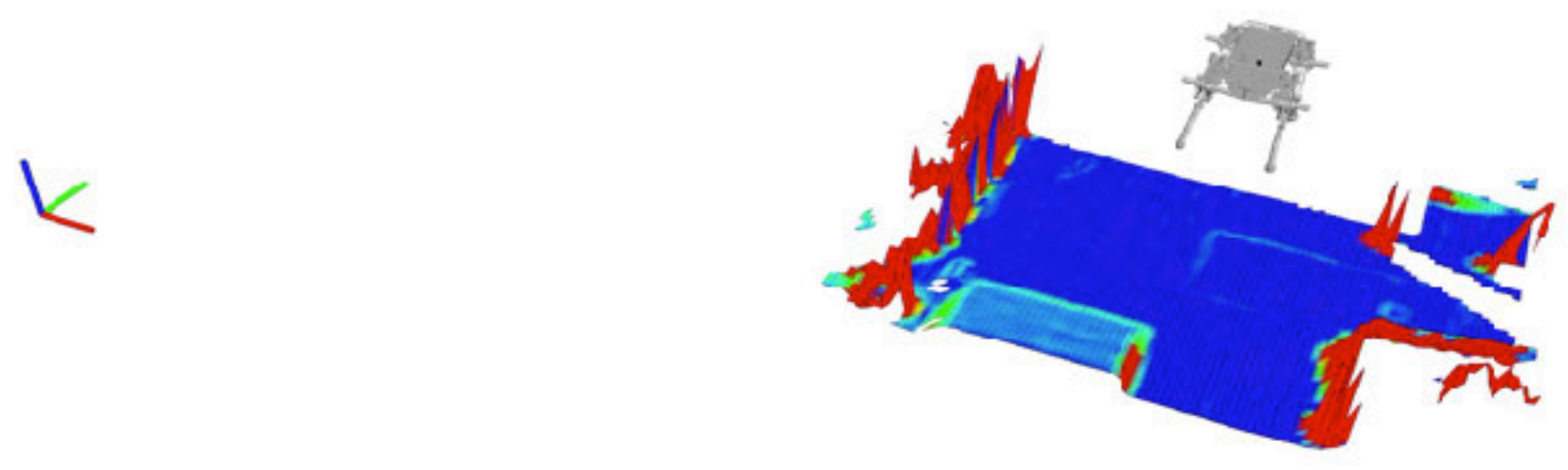
Open Source
github.com/ethz-asl/traversability_estimation

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

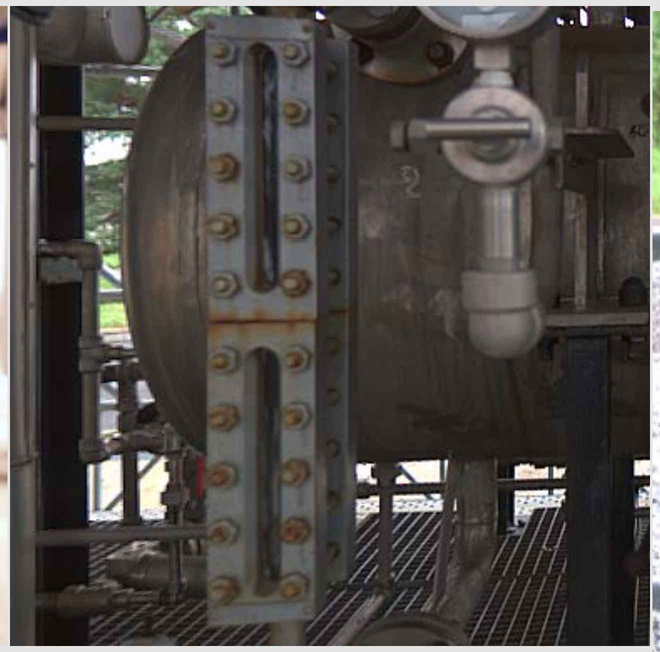


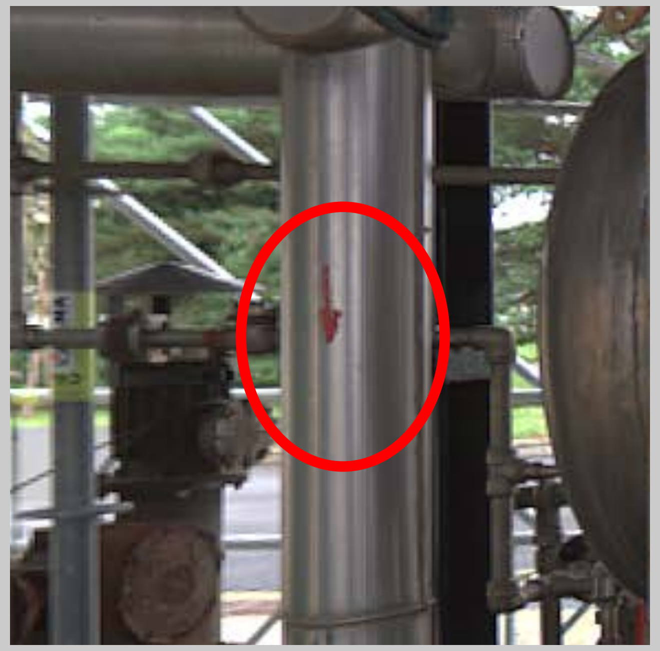
- Online navigation planning based on RRT* (OMPL)
- Works with and without initial map
- Continuous for changing environments

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

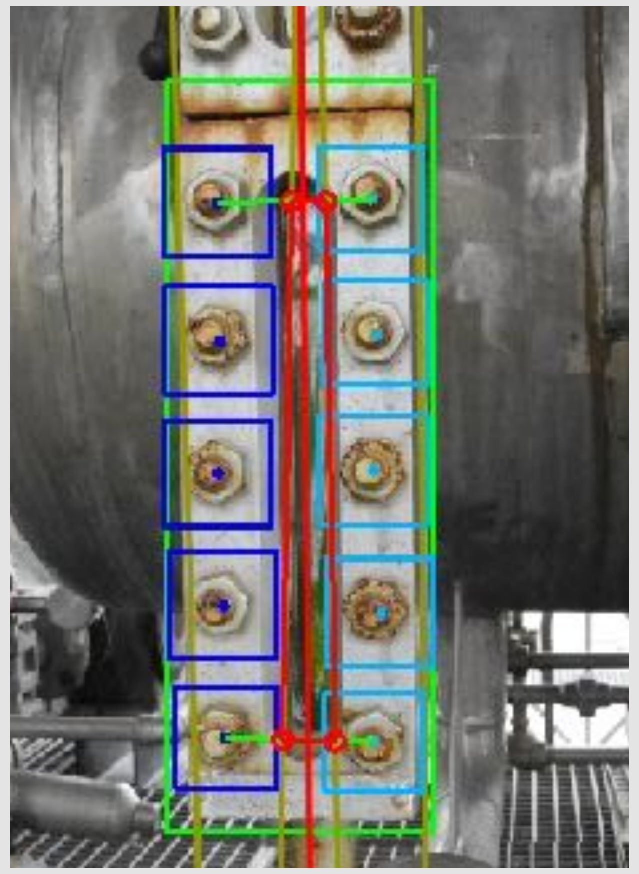
Visual inspection | **Thermal Inspection** | **Auditive Inspection**



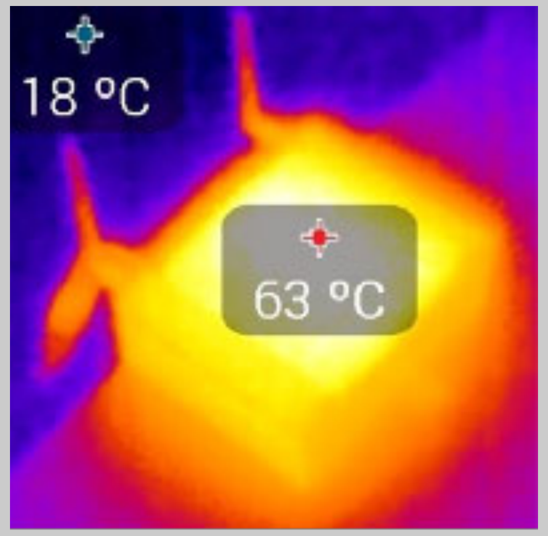


Pressure & Level gauges | **Valves** | **Thermal points** | **Pumps** | **Gas leaks** | **Platform alarm**

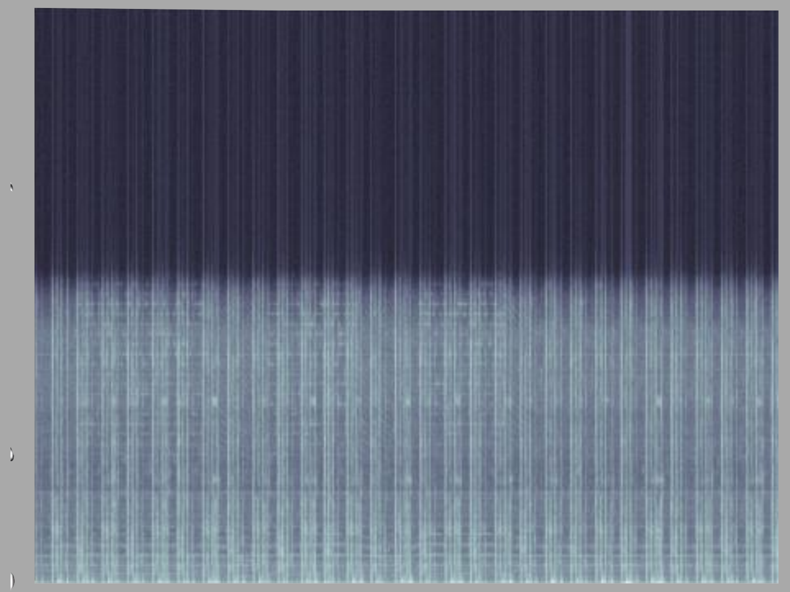
Zoom-camera



Thermal-camera

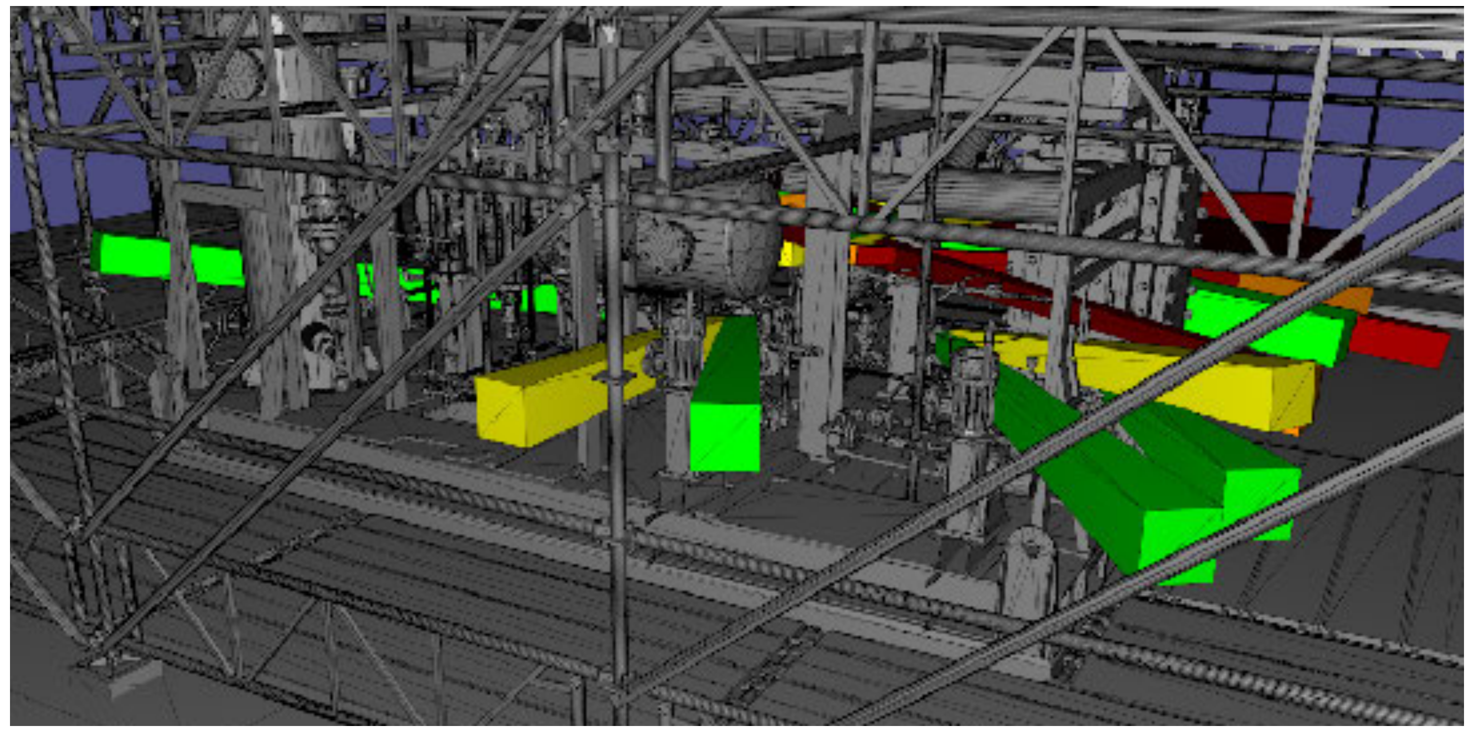


Microphones (audible and ultra-sonic)

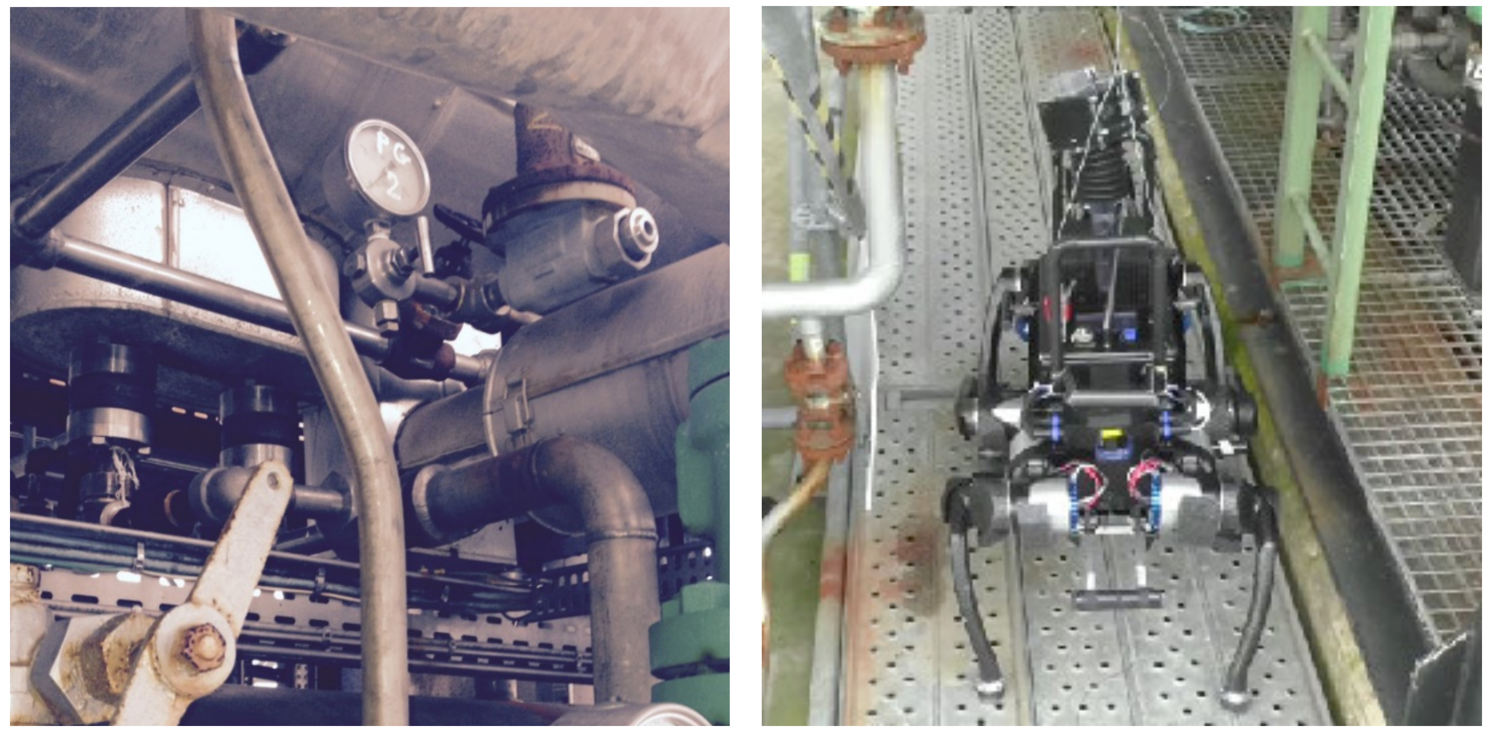


Inspection
Visual Inspection of Pressure Gauges

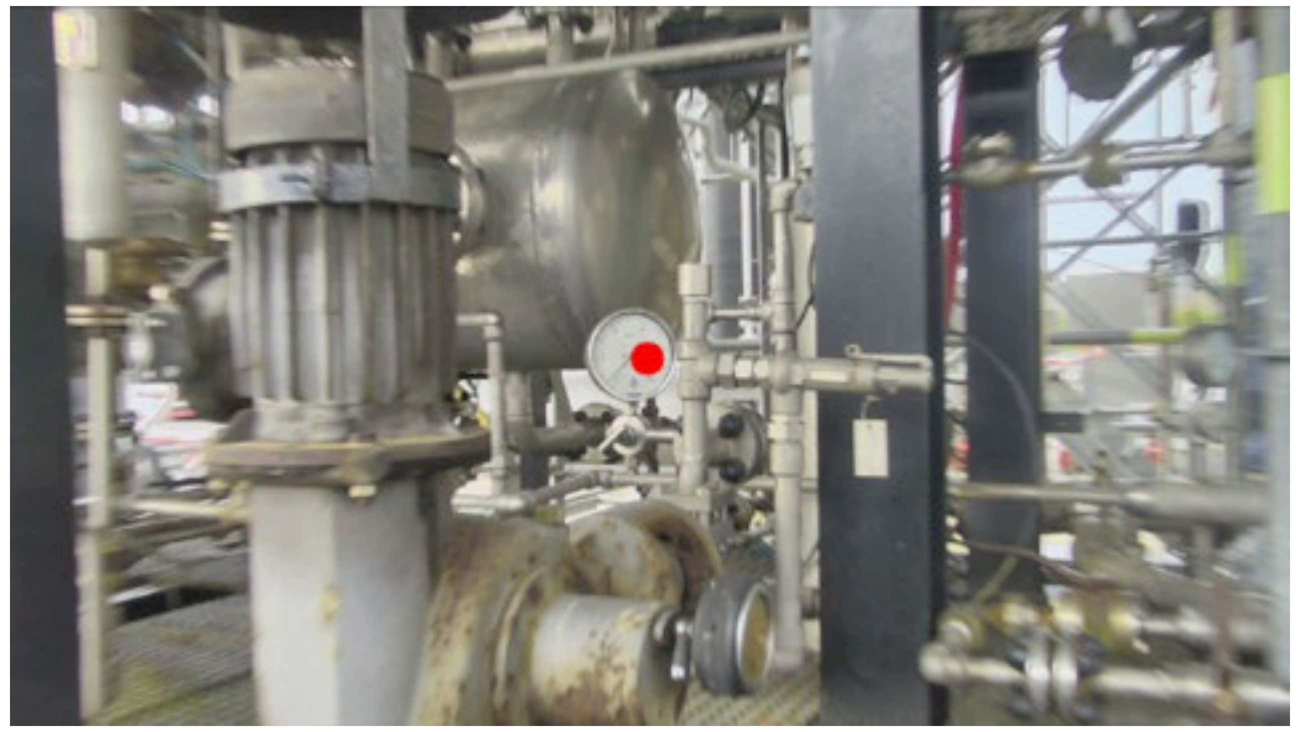
A Automatic view point generation



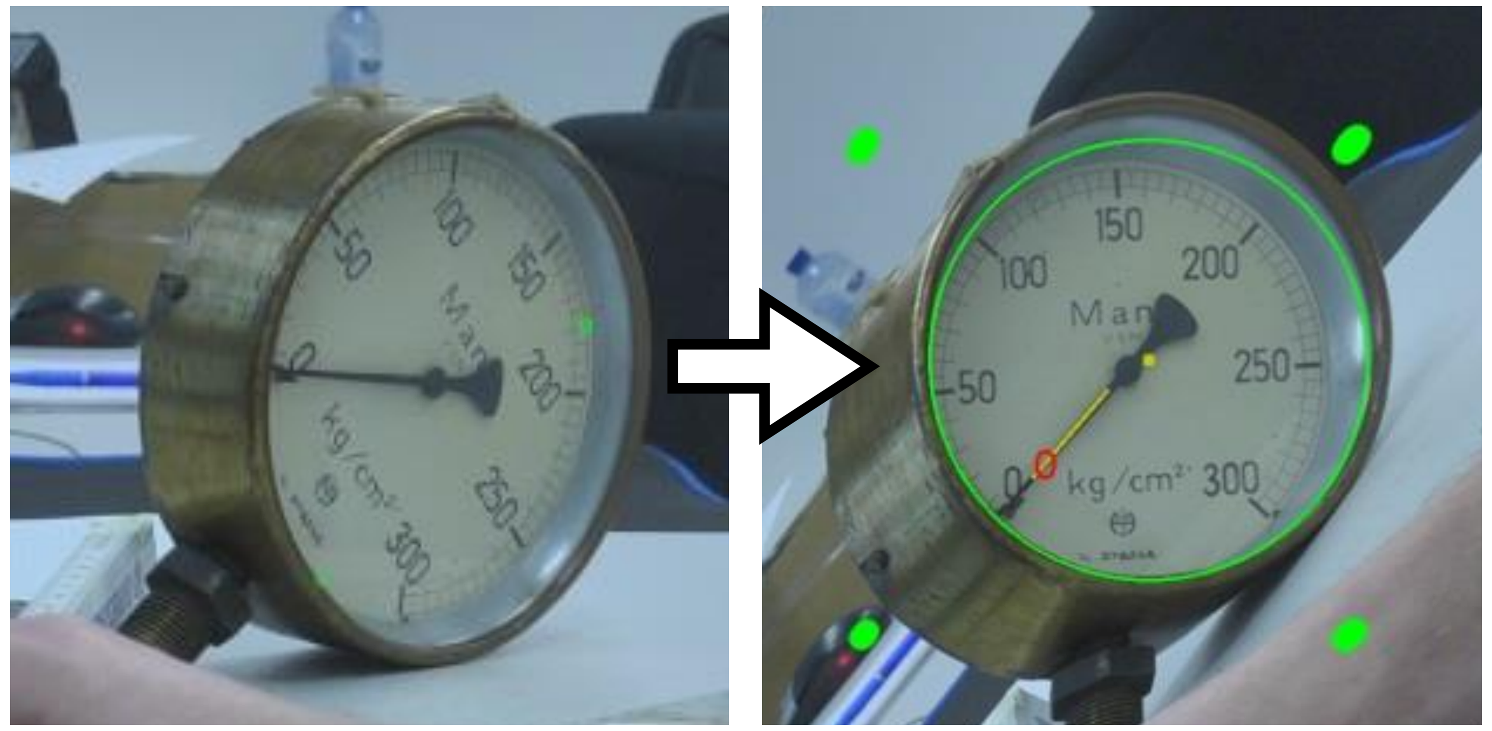
B Whole-body camera positioning



C Visual servoing

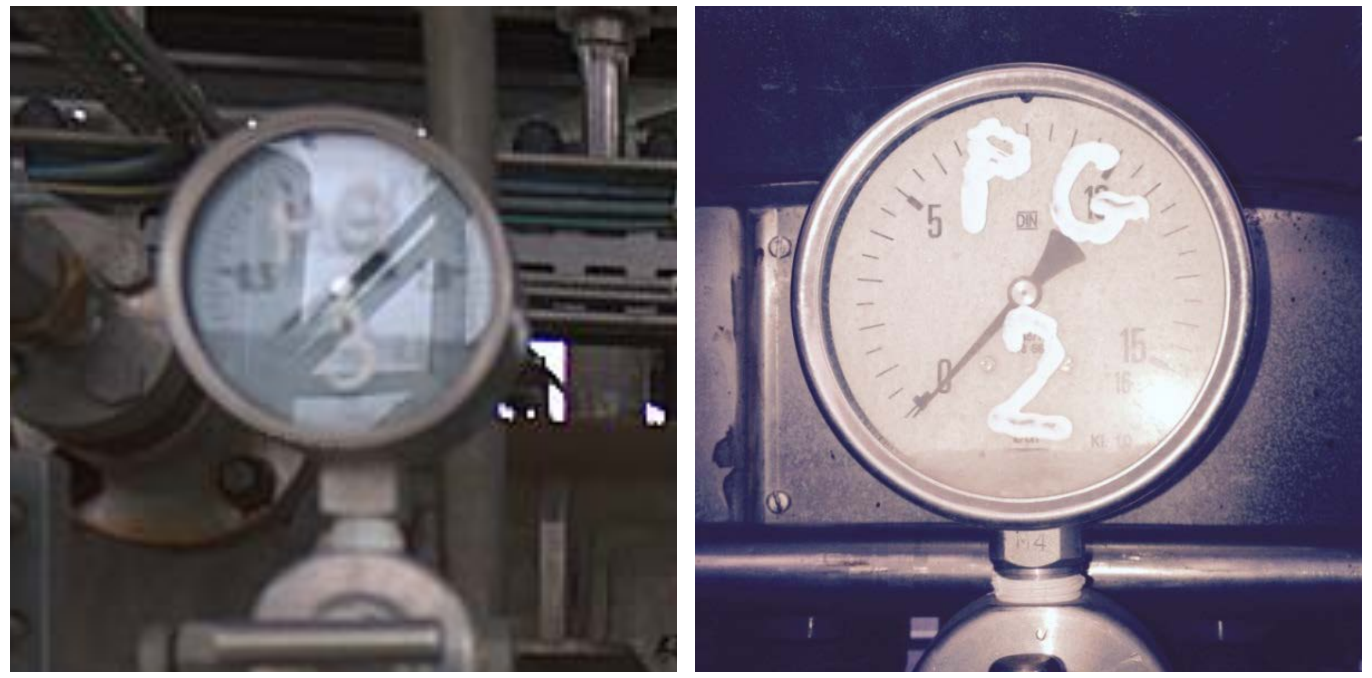


D Image de-warping



E Indicator reading

➔ Reading ok

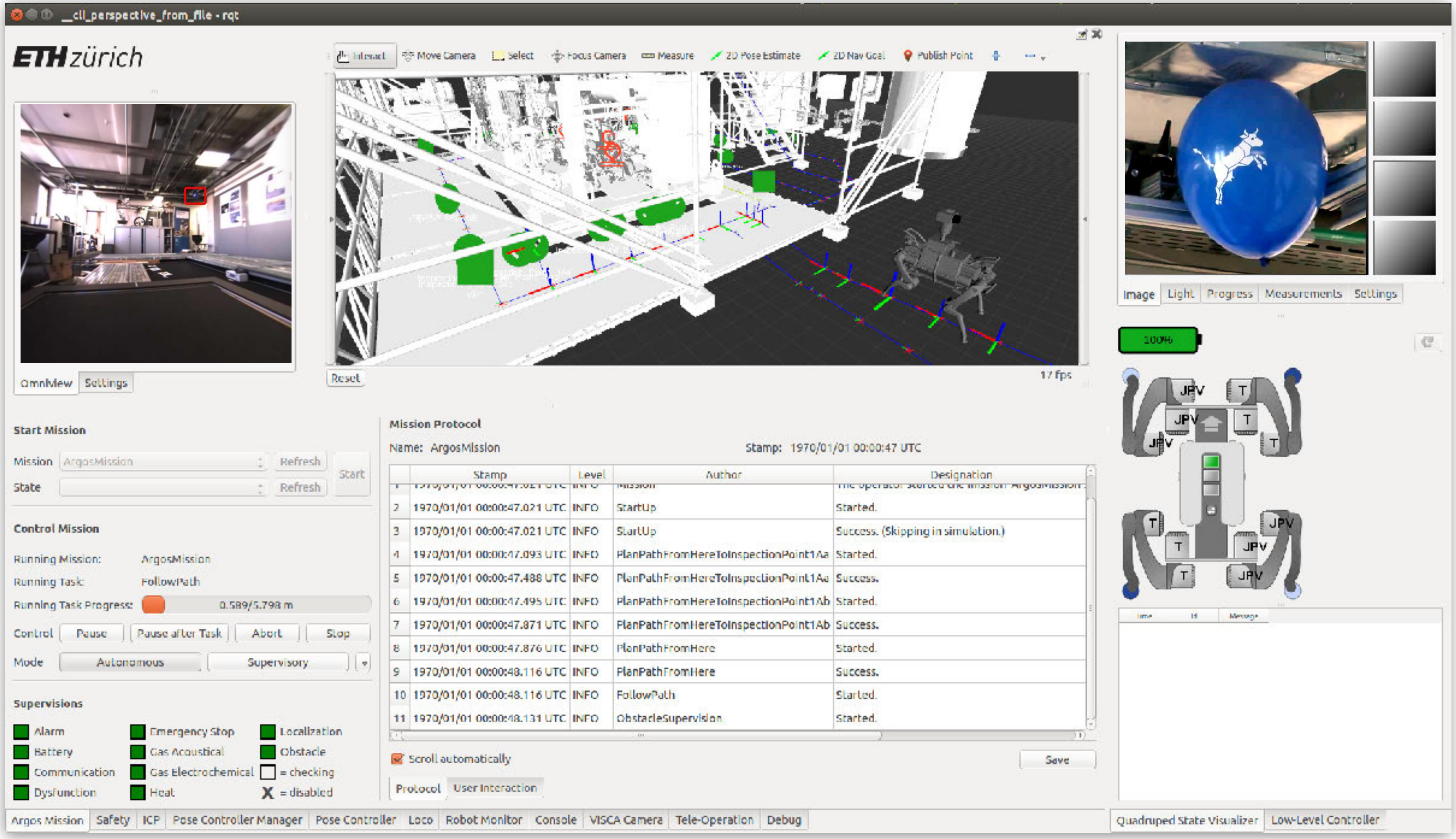


➔ Reading unsuccessful, try alternative position or report as unknown

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

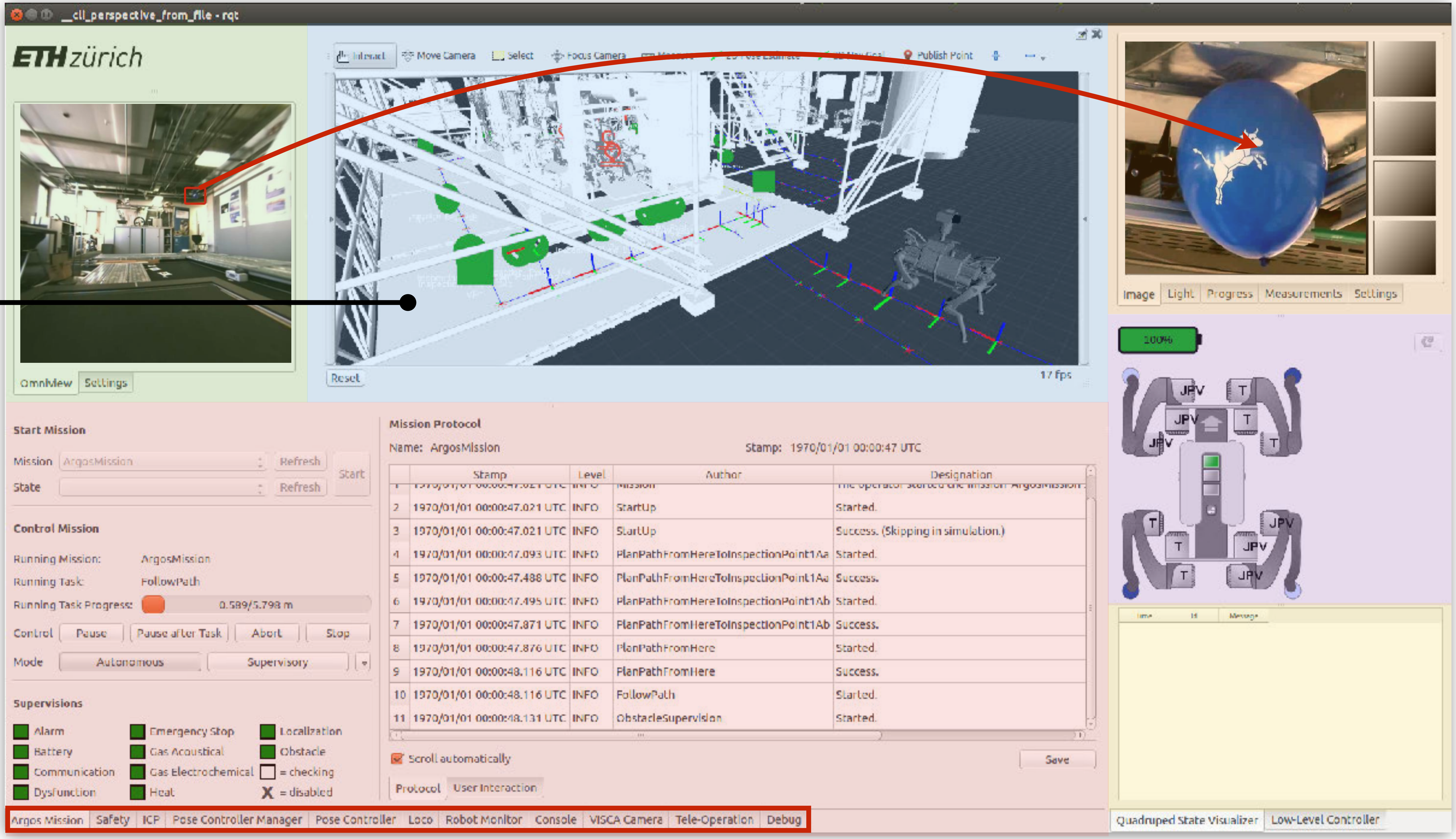
Interface for remote control, semi-, and full autonomous operation.

Situational camera

3D view (RViz)

Mission control & protocol

Other modules

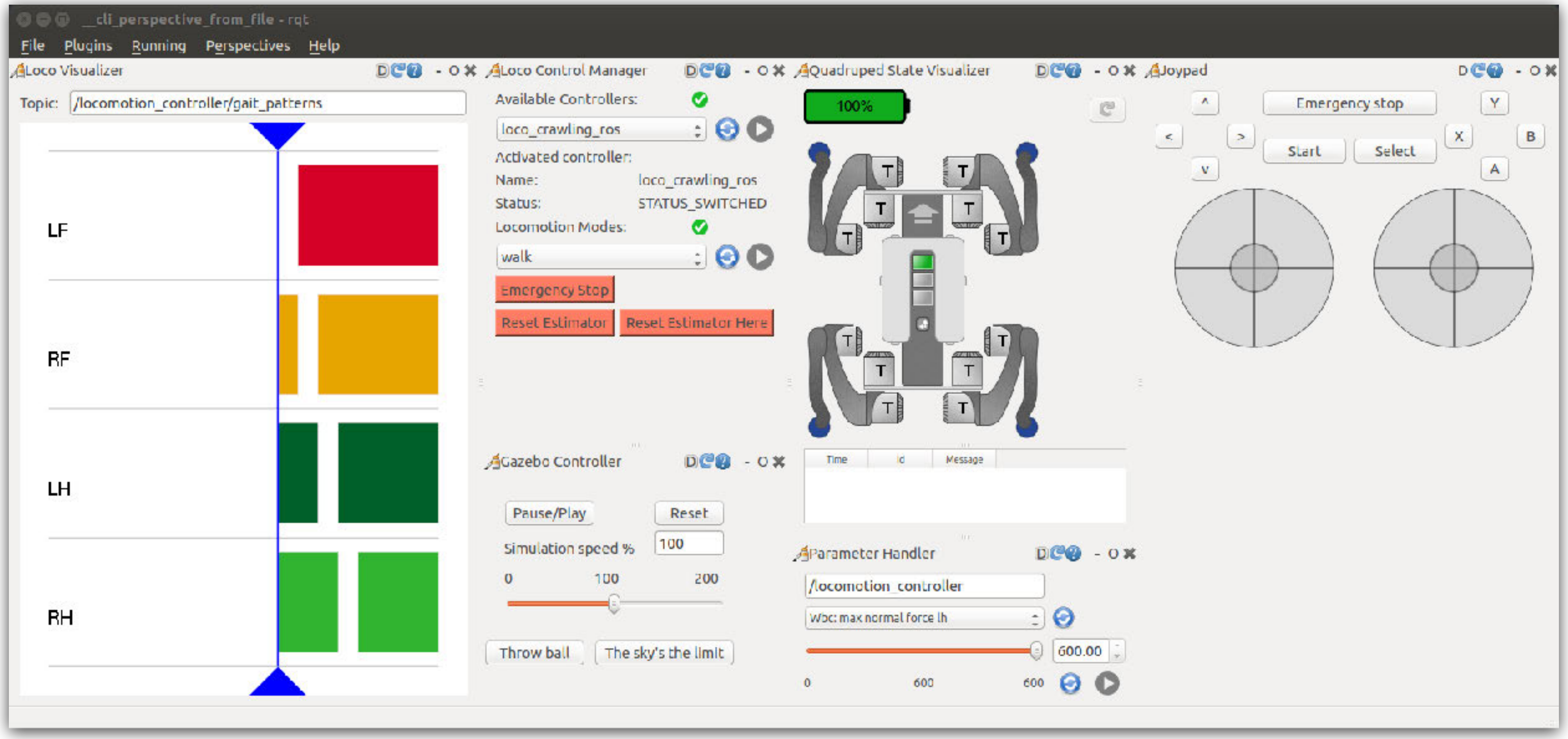


Inspection cameras

Robot actuators & sensors

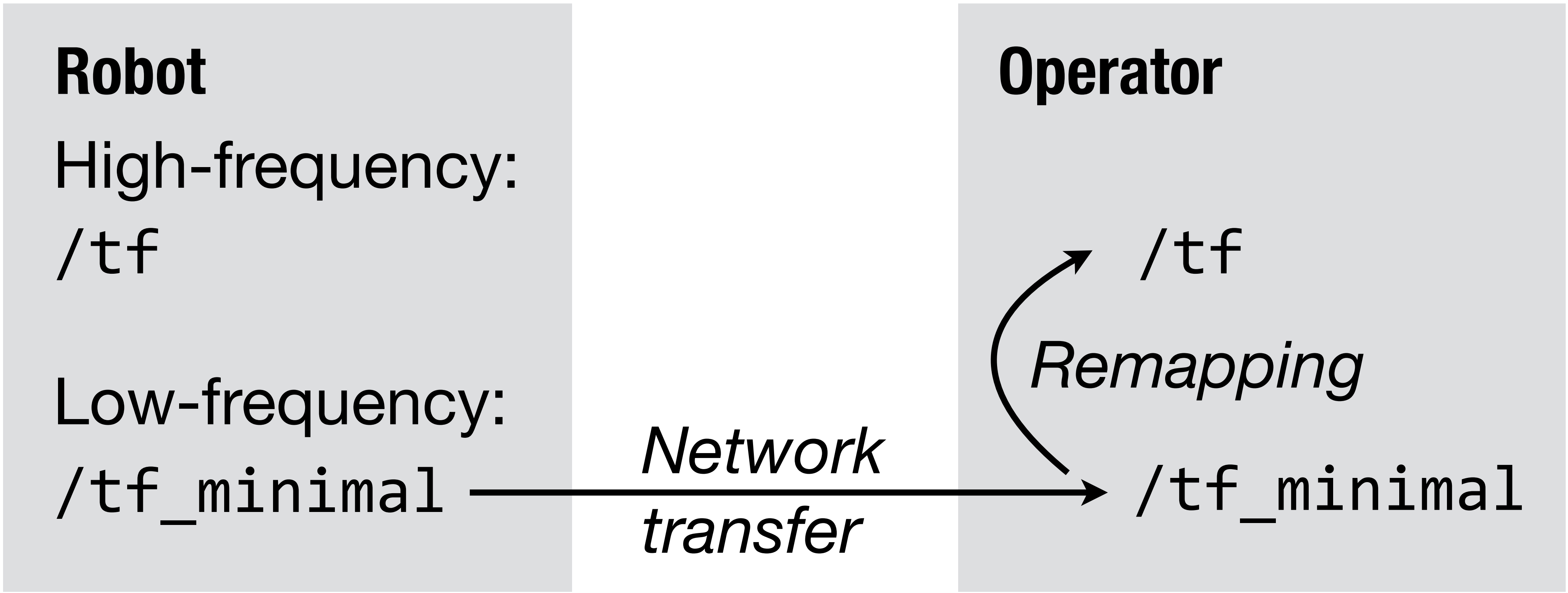
Error protocol

User Interface



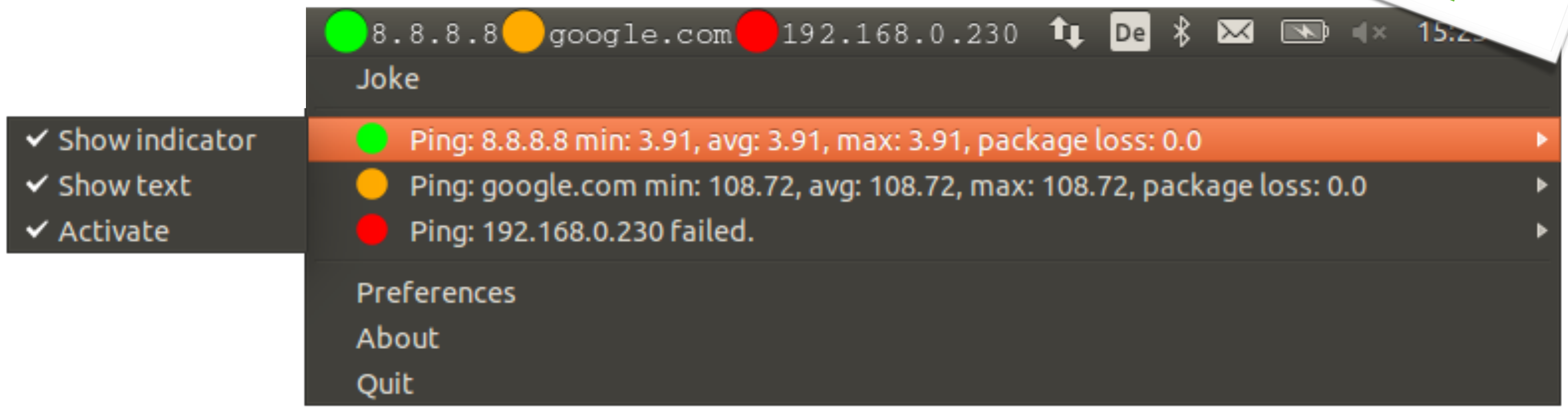
User Interface
Bandwidth Considerations

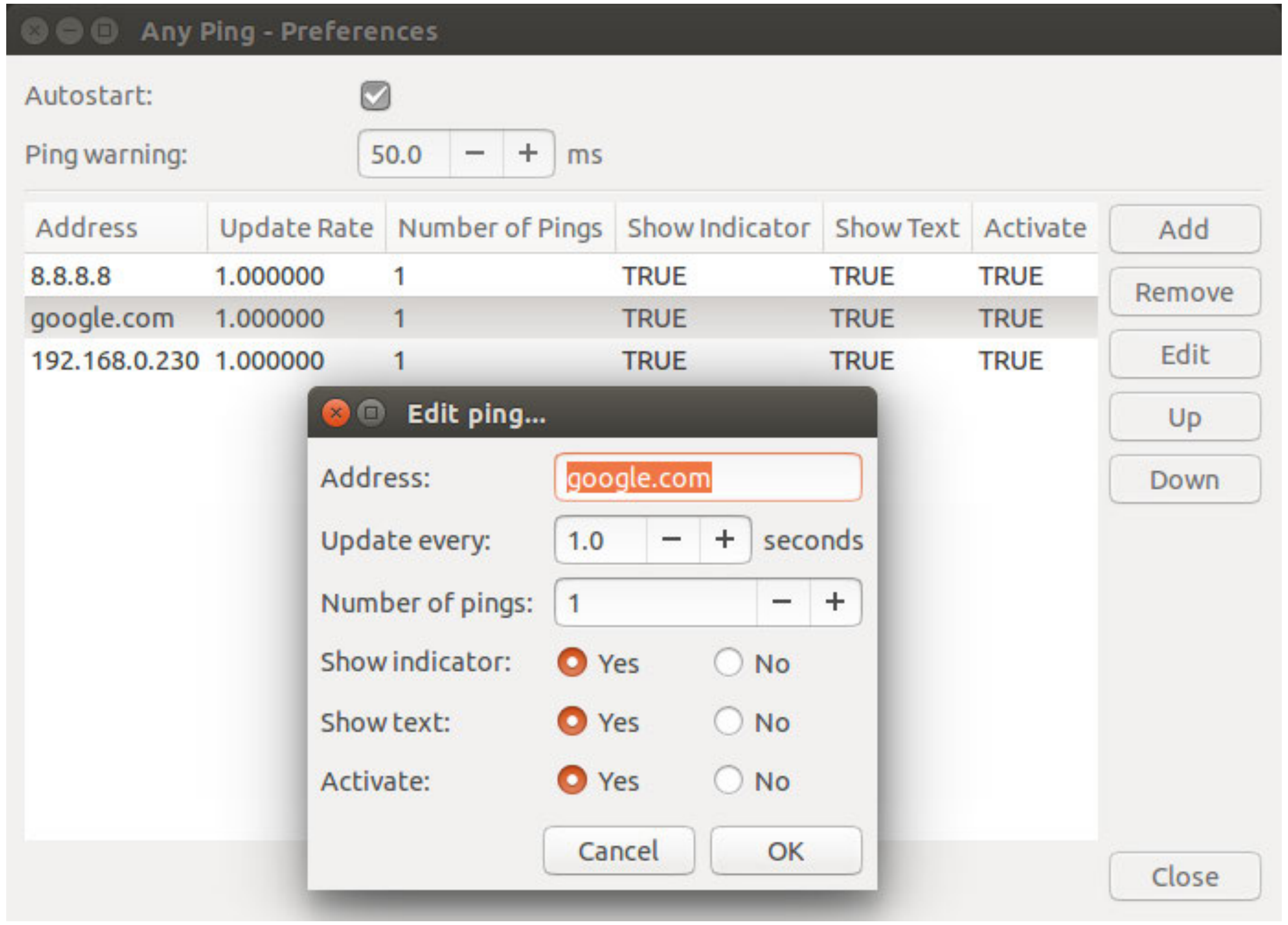
- Only critical data is transmitted by default (robot state and position)
- Other data is transmitted on demand (video, maps, etc.)
- Separation of onboard TF and operator TF
- Connection status node monitors WiFi status and triggers recovery behavior



User Interface
ANYping Indicator

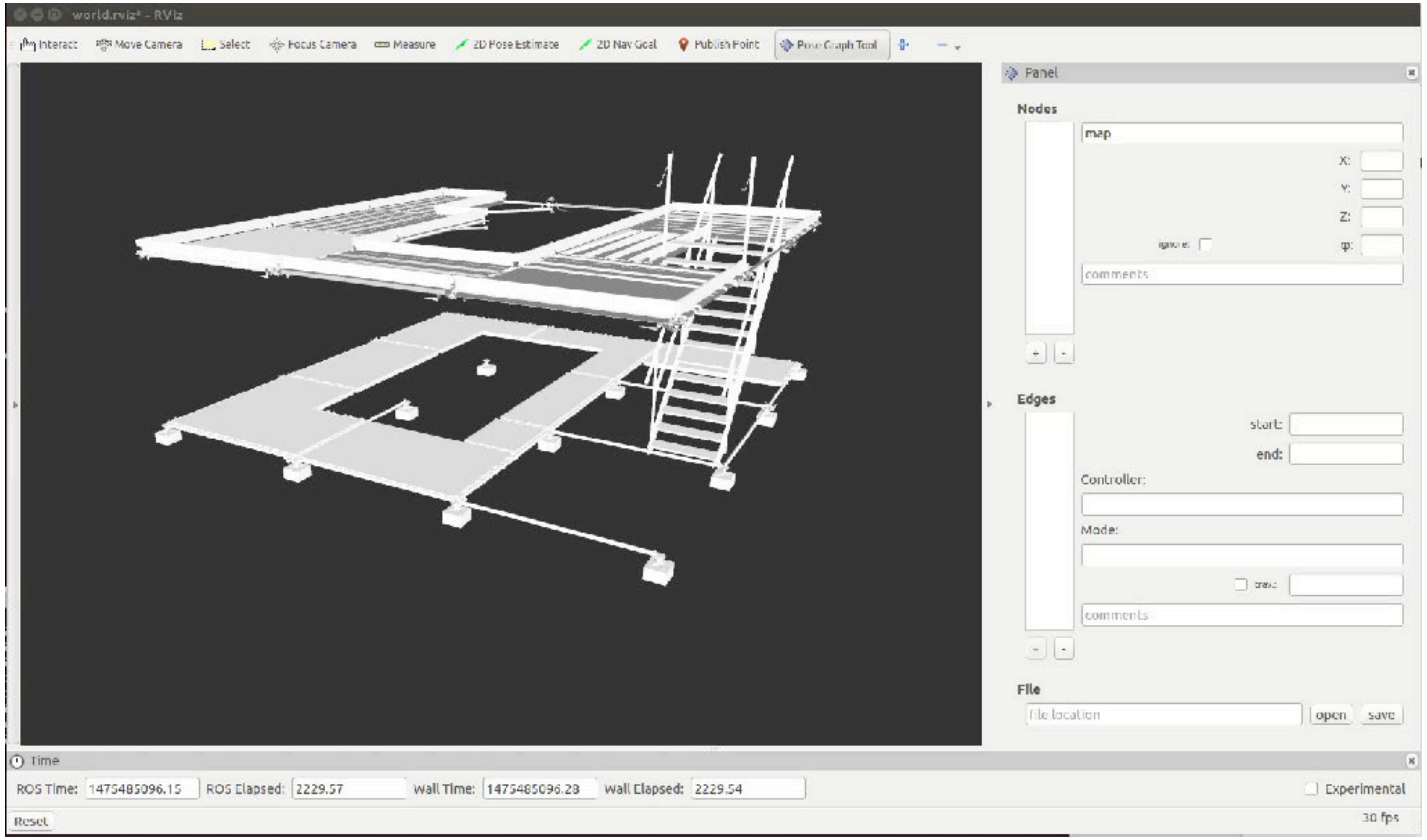
Open Source
github.com/leggedrobotics/any_ping_indicator





- Indicates PC network availability in Ubuntu menu bar

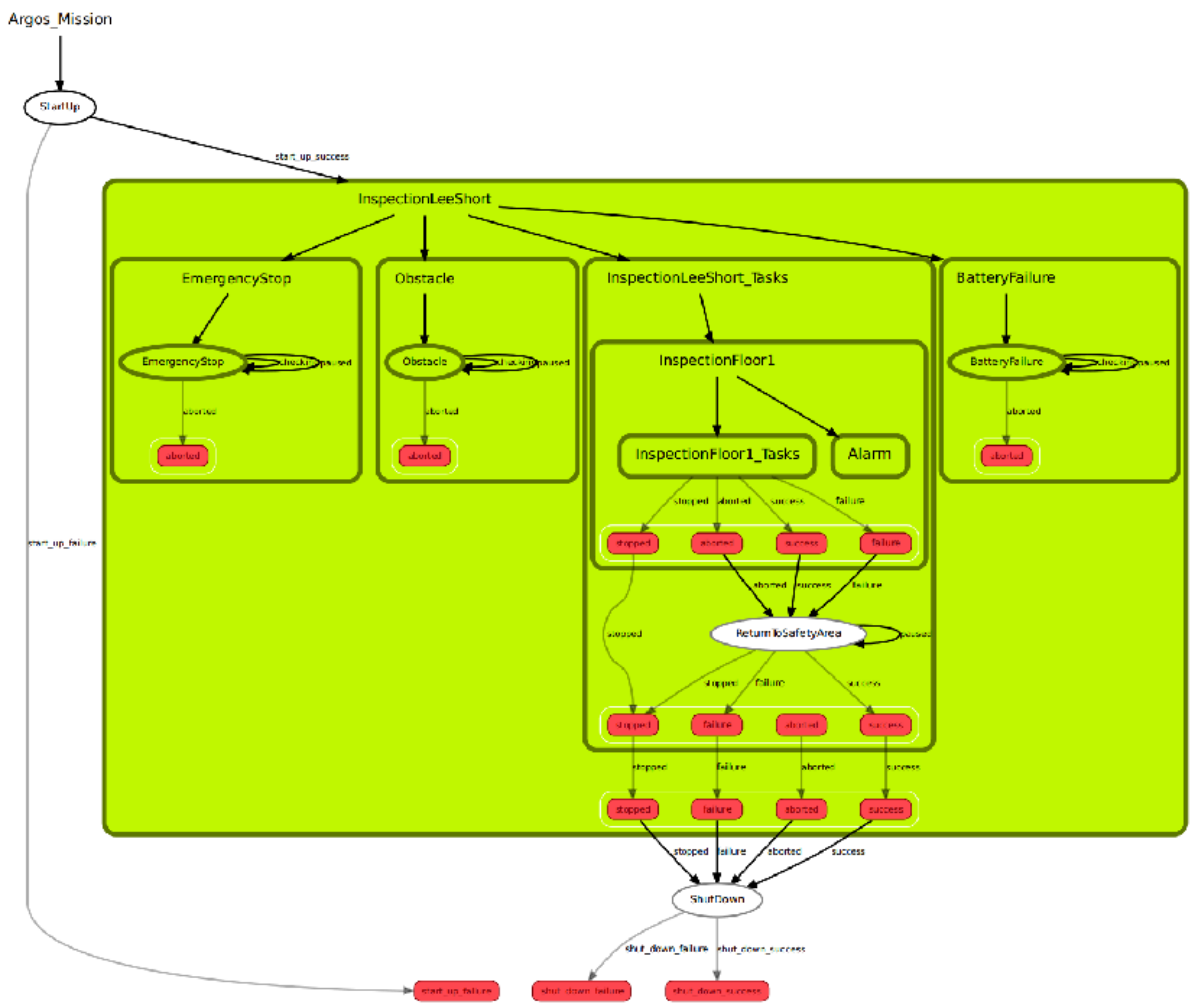
User Interface
Pose Graph



- 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)
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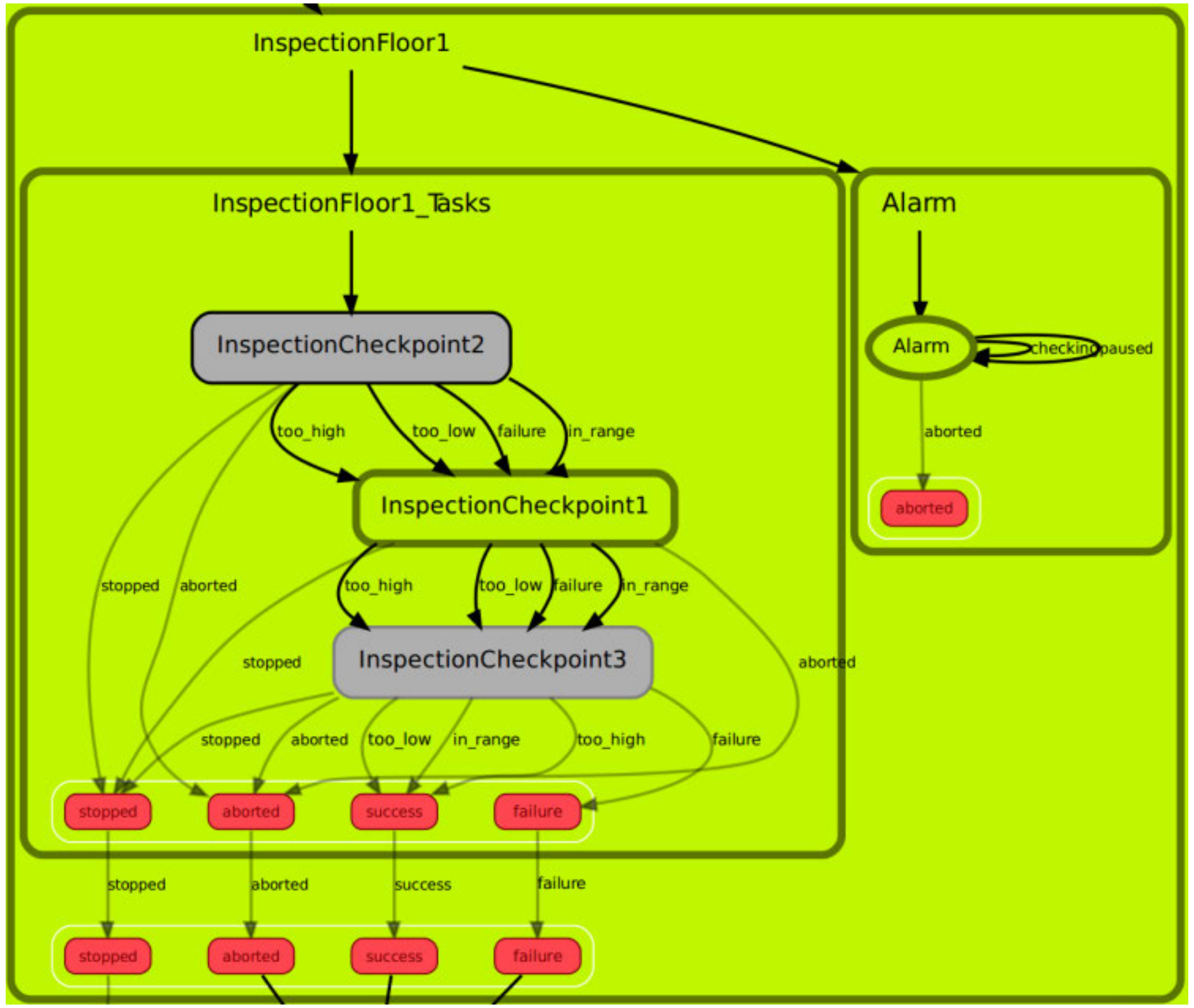
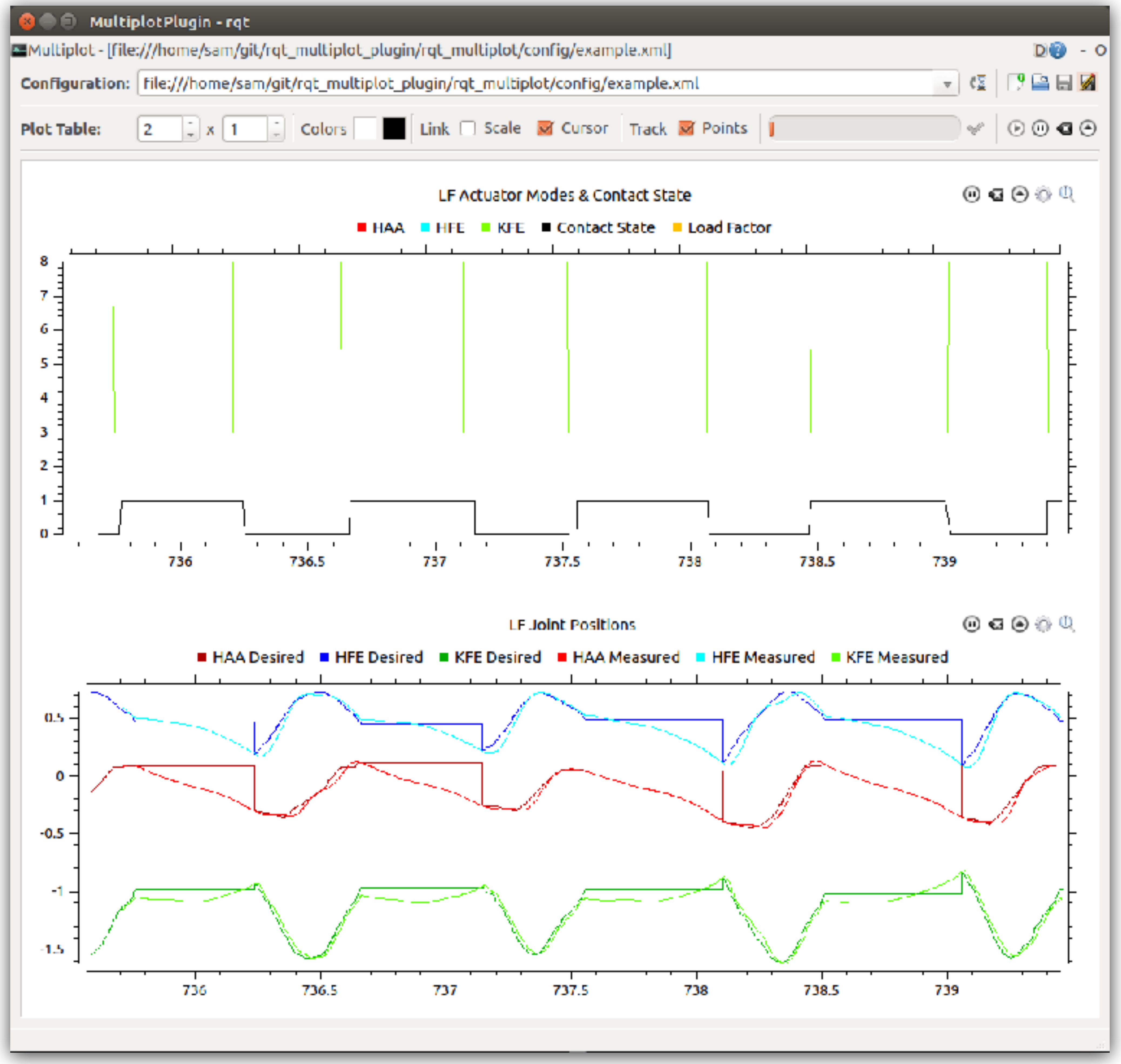
- Common building blocks to facilitate construction
- Typical missions programmed in 5–20 minutes



RQT Multiplot Plugin & Variant Topic Tools

Open Source
github.com/ethz-asl/rqt_multiplot_plugin

Open Source
github.com/ethz-asl/variant



- 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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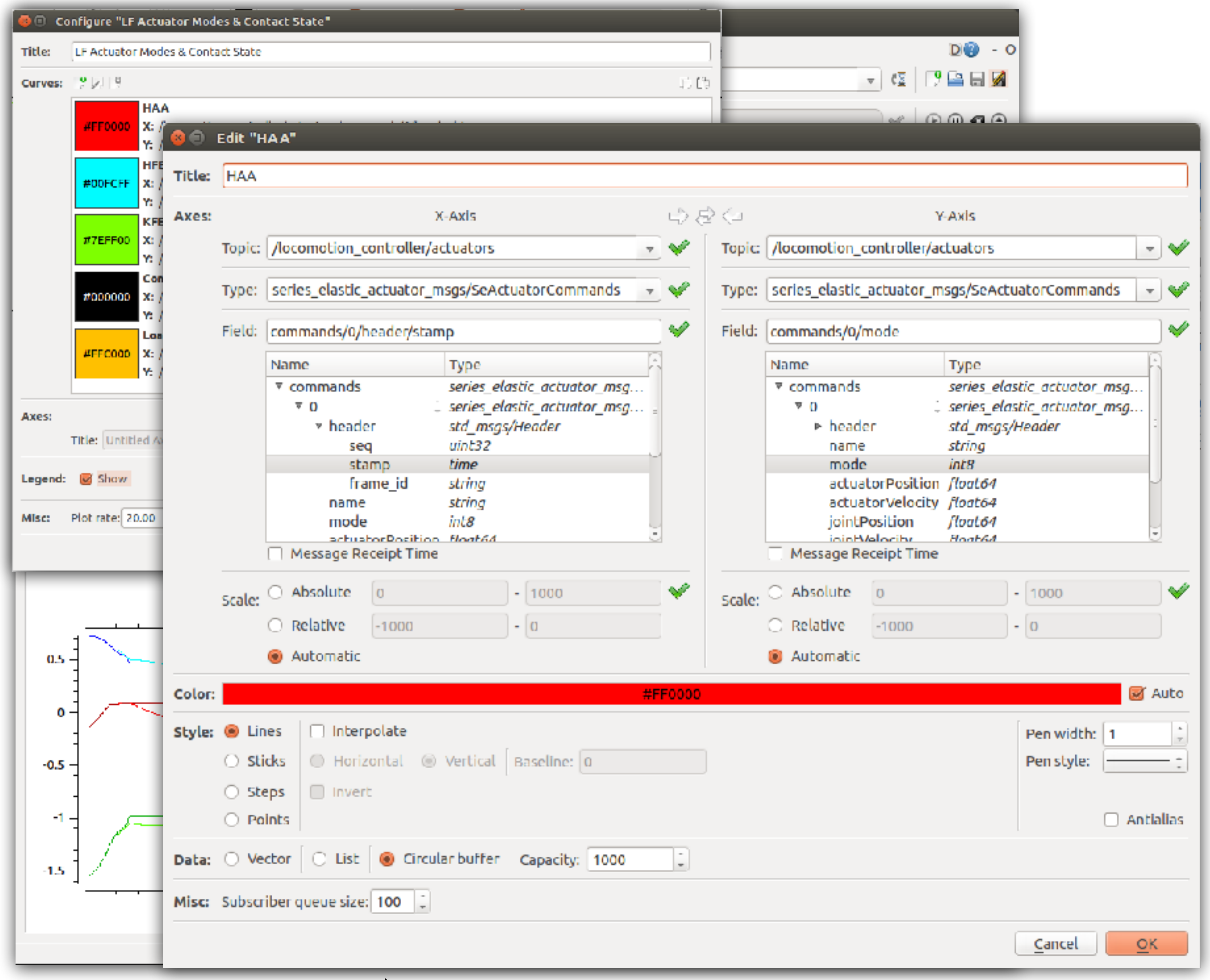

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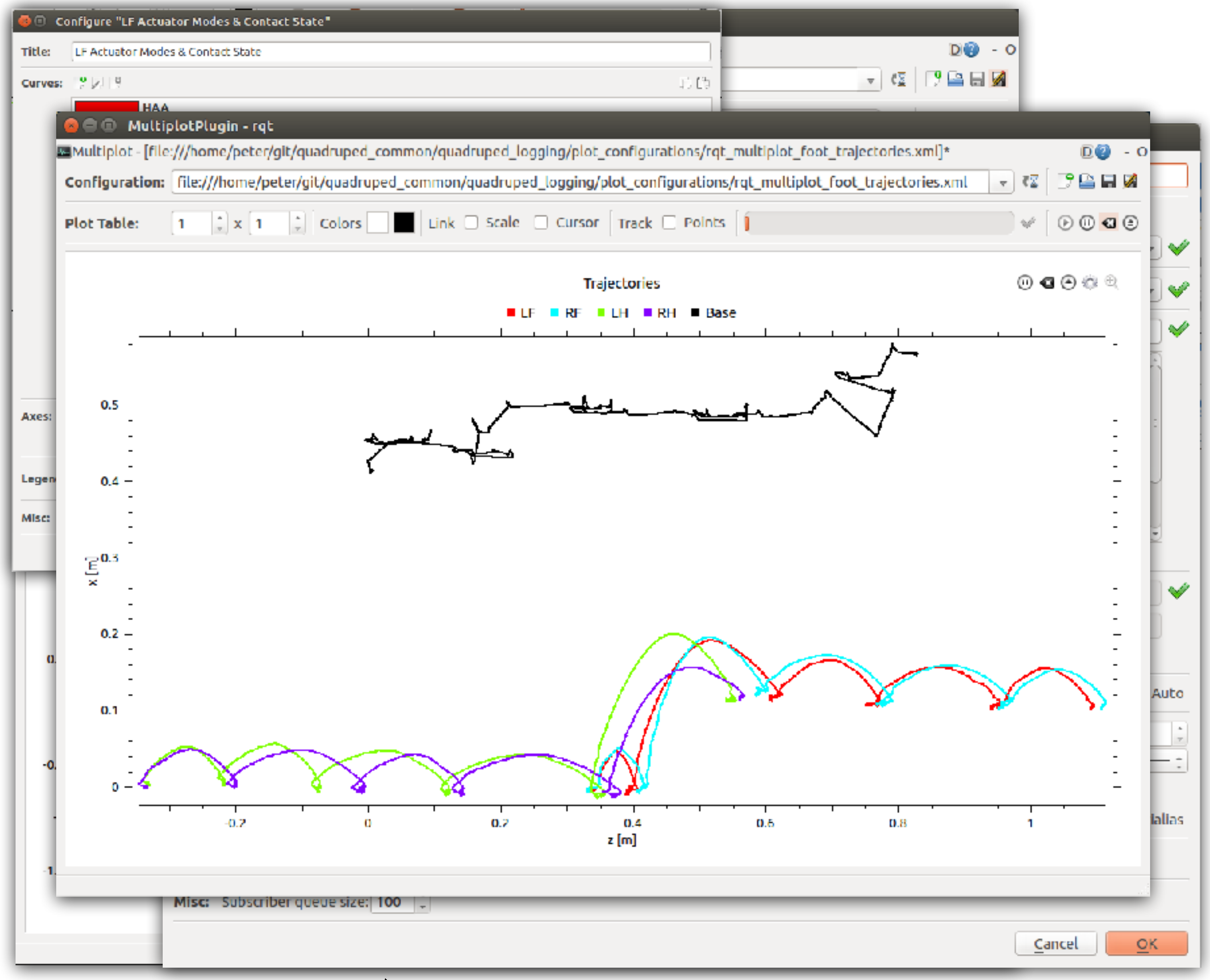

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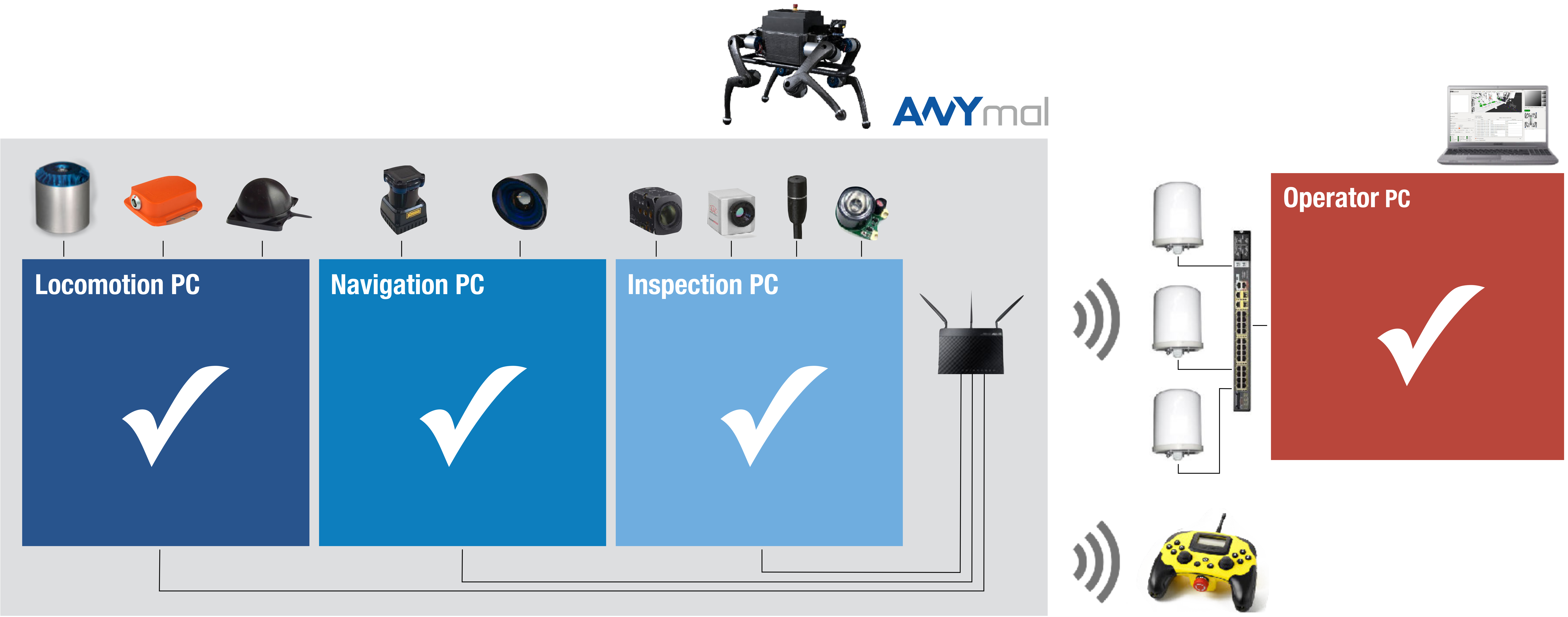
- Easy to setup configurations
- *x*- and *y*-axis freely configurable


ANYmal
Locomotion PC
Navigation PC
Inspection PC
Operator PC

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

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

ubuntu
14.04 LTS

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Atlassian Bitbucket

GitHub

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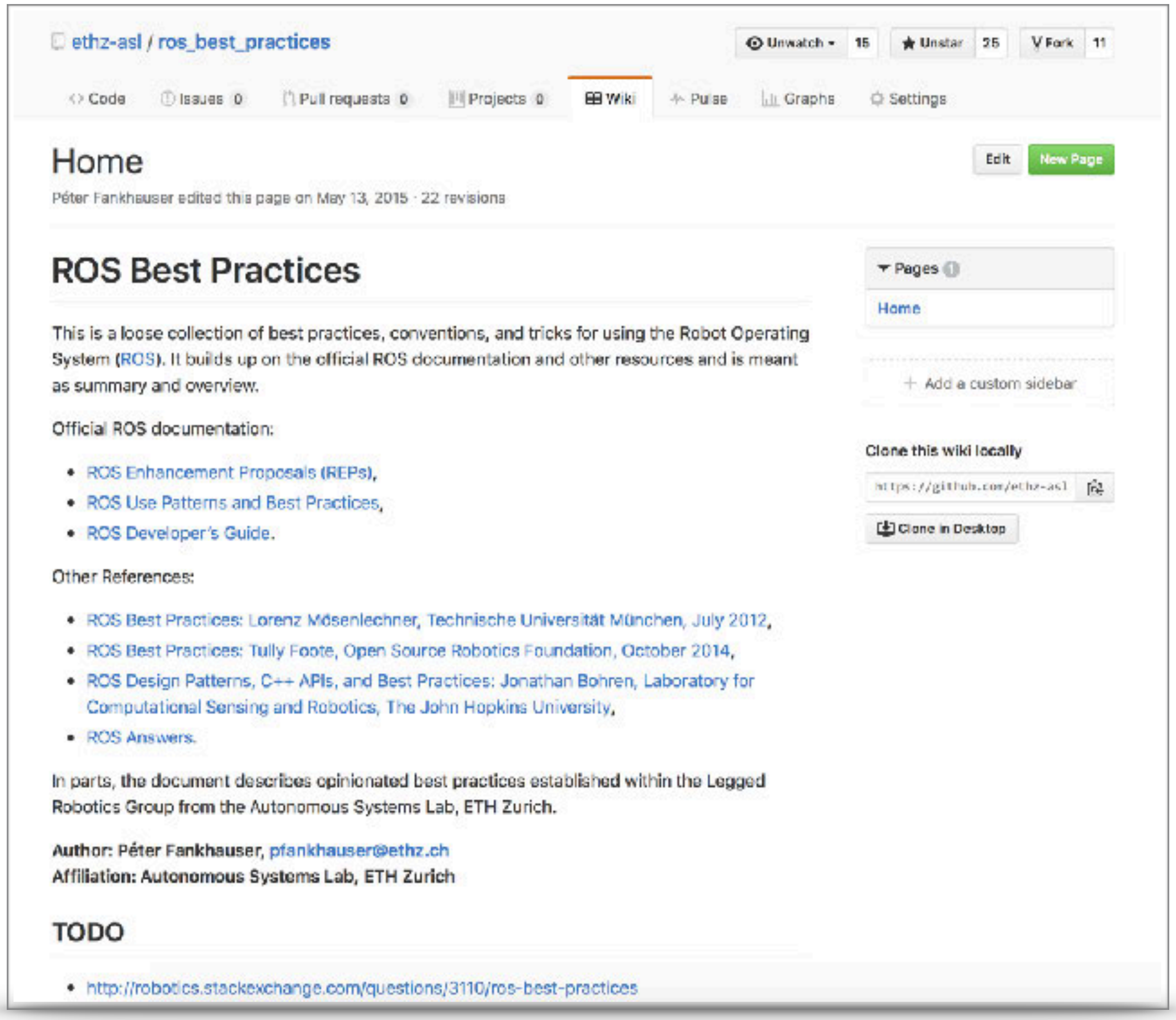

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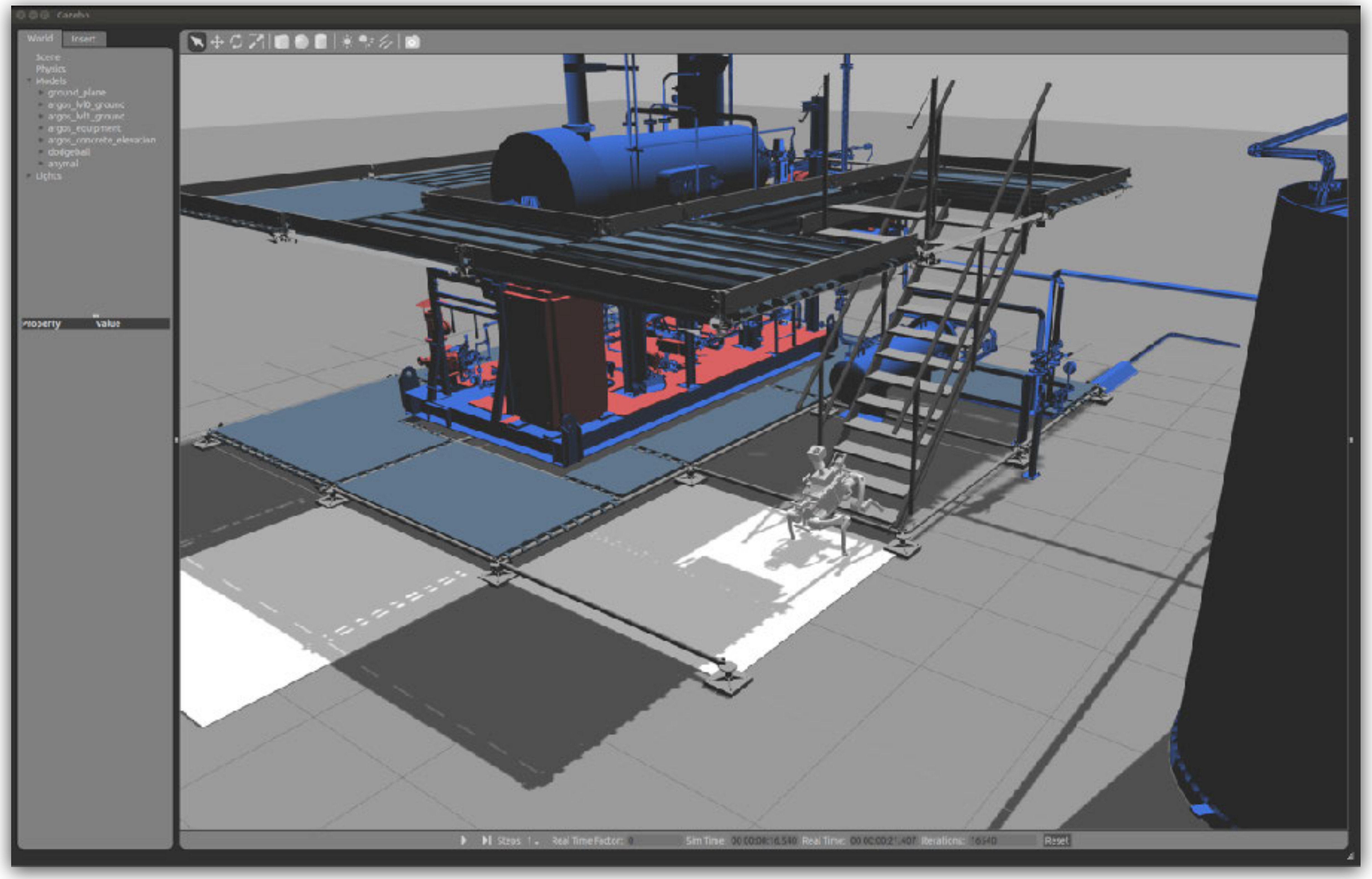

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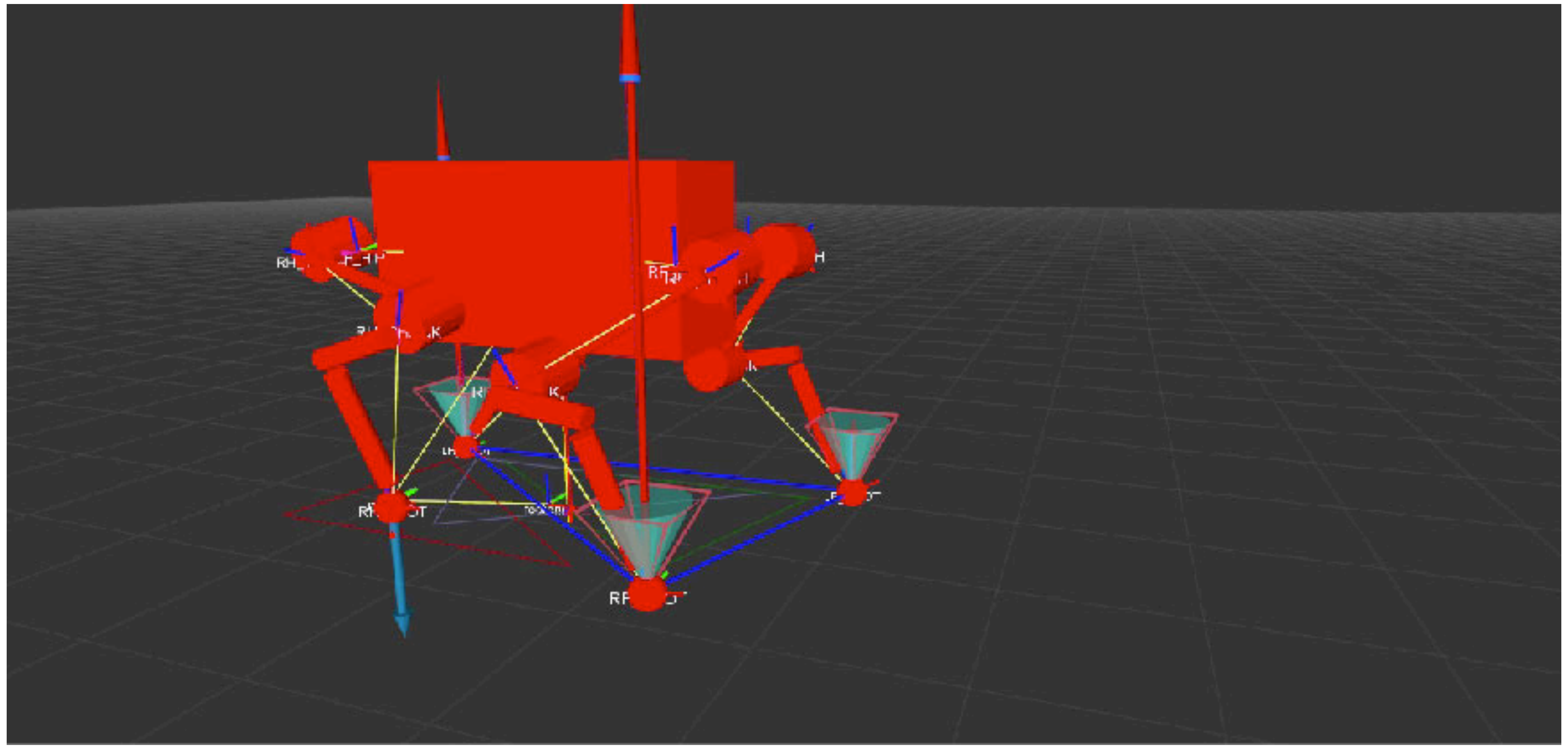
- Visualizing as much as possible



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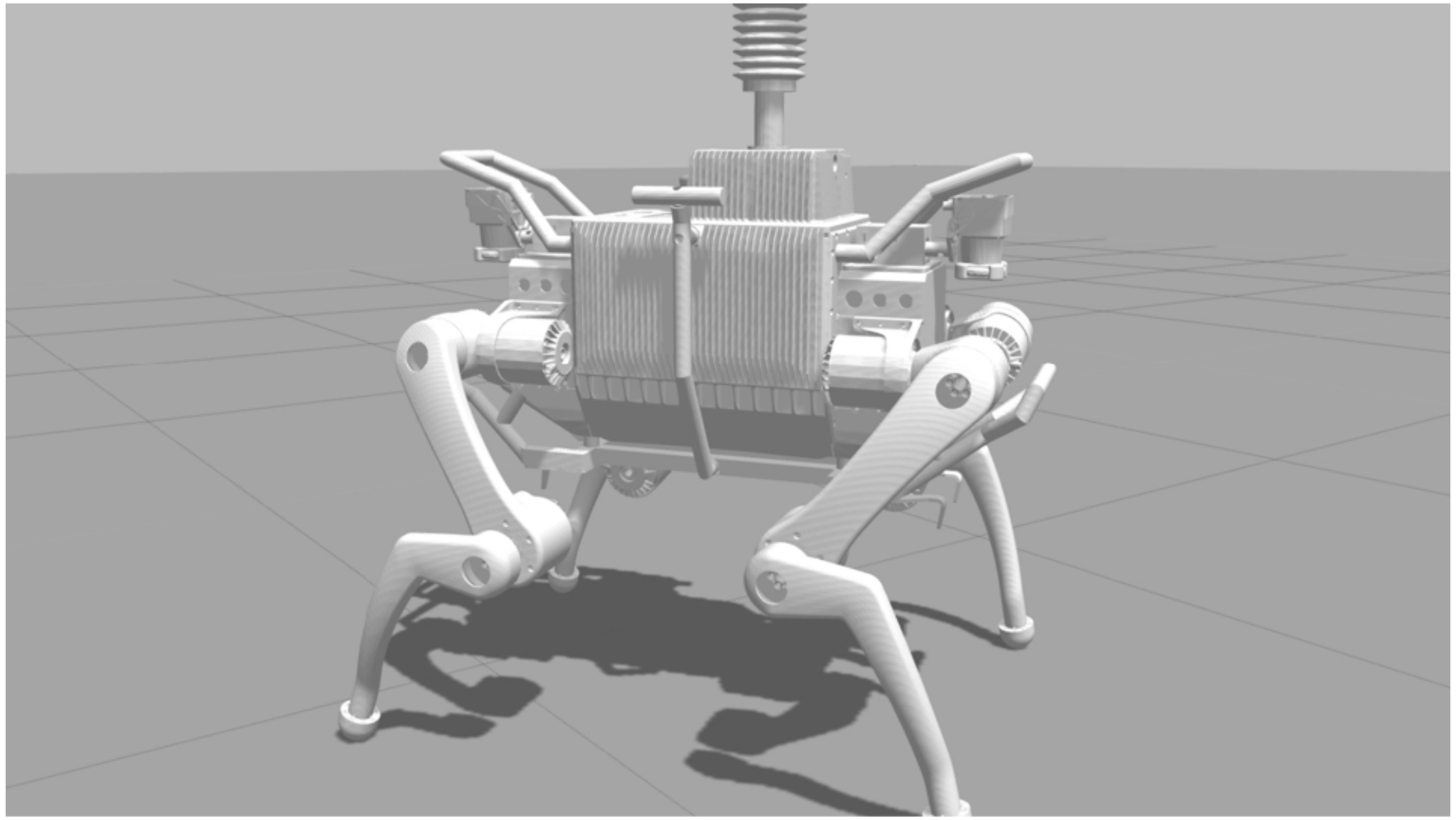

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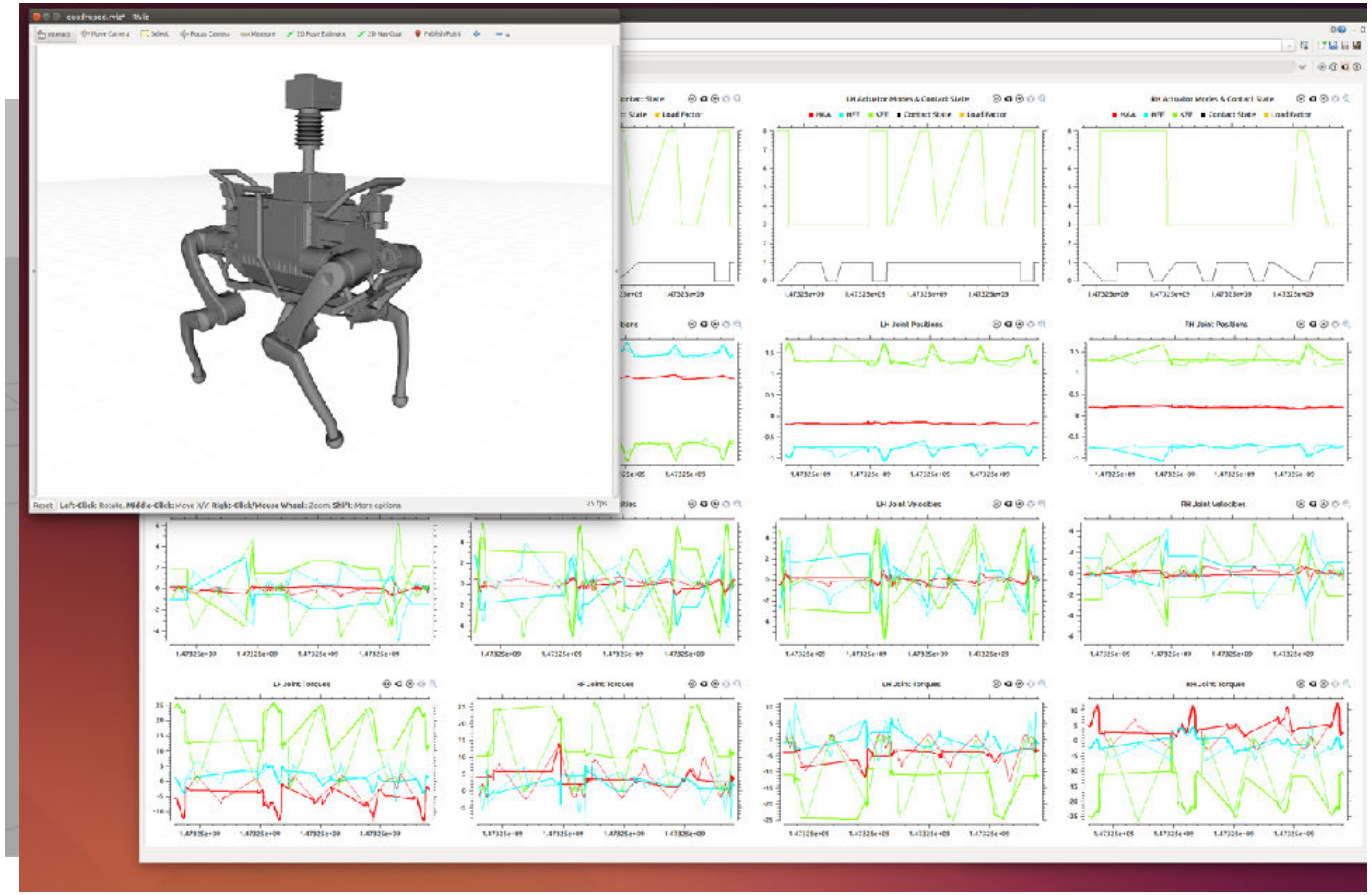
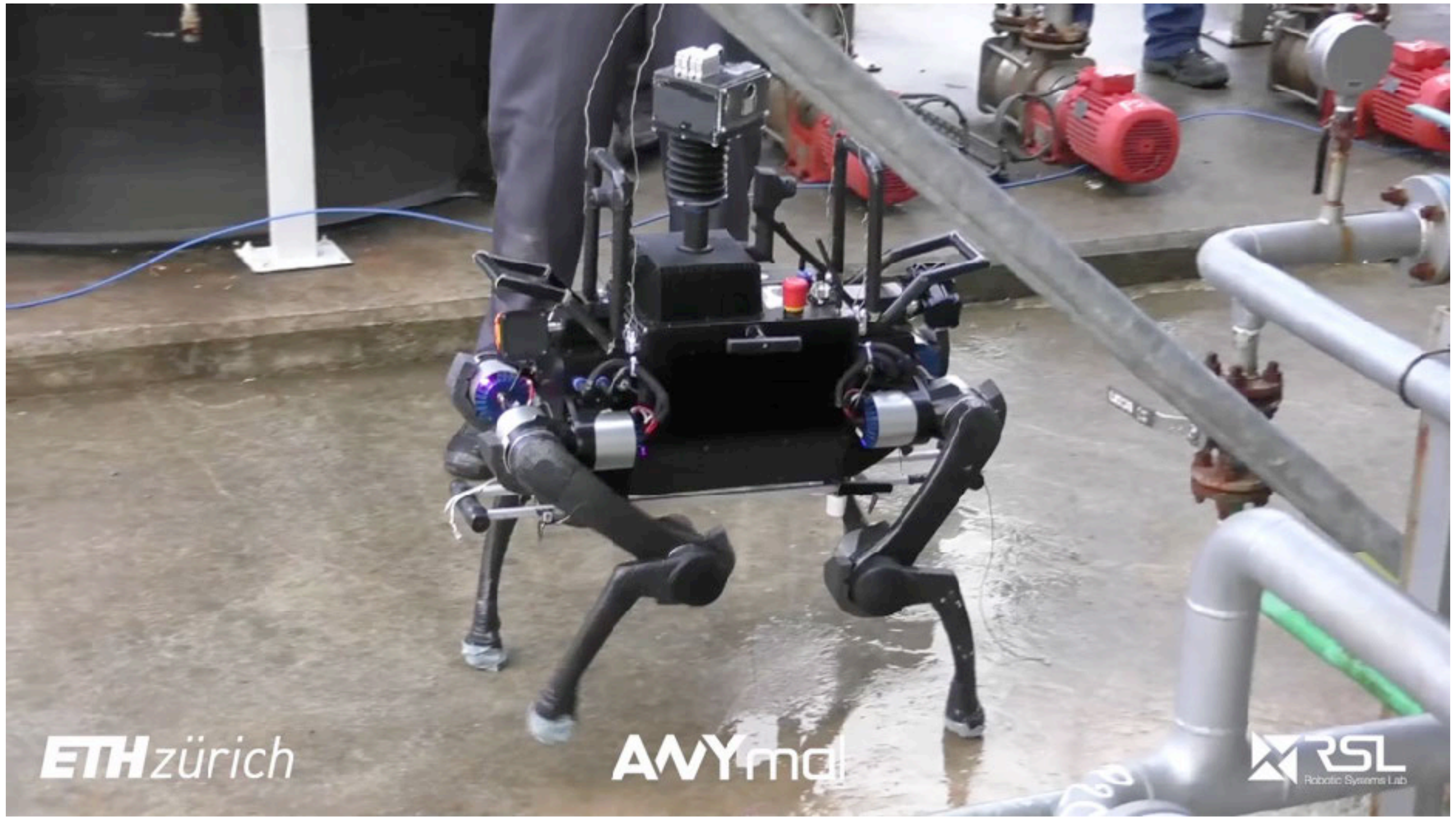
- Continuous Integration
  - ➡ Jenkins
  - ➡ Unit tests (after each change)
  - ➡ ROS integration tests (at night)
- Logging (rosbag)
  - ➡ All important information is always logged
  - ➡ Review logs with RViz and RQT Multiplot



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



RSL Robotic Systems Lab

www.rsl.ethz.ch

Autonomous Systems Lab

www.asl.ethz.ch

Open-Source Software

github.com/ethz-asl

github.com/leggedrobotics

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Dominic Jud
Ralf Kaestner
Bruno Kaufmann
Philipp Krüsi
Andreas Lauber
Philipp Leemann
Konrad Meyer
Roland Siegwart
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Martin Wermelinger