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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









ARGOS Challenge

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











LOOKING FOR THE FIRST AUTONOMOUS ROBOT FOR GAS AND OIL SITES



http://www.argos-challenge.com



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ARGOS Challenge AARon And Gas Sites



Figure 2: UMAD map





 For the 2⁻⁴ 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. RealFusing its earlie sense. The GPA is not activated by the operator (except in simulation condition, see remarks). Accustic leak detection (3-2):
 gas leaks emittin the ultra-some range (25kHz-70kHz, dynamic range 58-10tdB SPL). Checkpoints: checkpoints will have to be detected around their espected position, and their obsence reports. Pressure gatge (3-6) Water level (3-7) Vater level (3-7) The robot will have to fee detect of the solution of the point of the solution of point (3-5): The robot of point (3-5): The robot will have to detect in the close vicinity of the point, if the solution product in matchase the expected normal sound. One spectral 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). Obstacker (3-12): unexpected obstacles during the 2nd competition can be objects or part of structs
 Obstacles (3-12): unexpected obstacles during the 2rd competition can be objects or part of structs on the ground (positive obstacles) or out of the ground (asspended obstacles), a
Accordance (negative operations), refer to requirement 2, page 24. Accordance reactions and behaviours to these stimuli detection are listed in requirement 18 [autonomous reactions].
 Takting the implementations of dataction and reaction to the following stands are get plant for the 2st competition: Gas bake 18 detection (3-3), get look detection and localization based on the point 18 detector. Safety equipment - extinguishers (3-4): the motor has to detect whether the extinguishers are present in their expected localization. Meaning of plag (3-4): monitoring the environment to identify missing plags on open pipes.
Remarks: In order to allow simulation of GPA, for testing purpose only, the operator should be able to simulate a <u>detection of a GPA</u> by the value through the control resurfs EML.



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ARGOS Challenge **5 International Teams**



AIR-K Japan



FOXIRIS Spain & Portugal







ARGONAUTS Austria & Germany



VIKINGS France



LIO Switzerland

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ARGOS Challenge **Team LIO**

ANYmal – A High-Performance & Versatile Quadrupedal Robot

"ANYmal - A Highly Mobile and Dynamic Quadrupedal Robot," IEEE/RSJ Internatio 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

Industrial Wireless

Operator PC

Remote control UI Manual, supervised control

Visualizations Sensors, robot state, environment

Mission Mission creating and protocol

- V

Radio

.

Safety operator

9

Locomotion

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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

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.

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

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.

- 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.

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

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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.

External pose measurements

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

Locomotion **Whole-Body Control**

Locomotion Controller Modules (Loco)

Trajectory optimizationWhole-Body ControlGait patterns	irtual model control	Pose optimization	Reflexes	
	Trajectory ptimization	Whole-Body Control	Gait patterns	
Point Traj. Contact force	ero-Moment Point Traj.	Contact force distribution	••••	

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.

Robot Controller Manager (Rocoma)

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.

(coming soon)

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

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.

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

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

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.

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

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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:
```


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.

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

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

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.

Matrix	Μ	bold capital letter
Identity matrix	$\mathbb{1}_{n \times m}$	$n \times m$ -matrix
Coordinate system (CS)	$\mathbf{e}_x^A, \mathbf{e}_y^A, \mathbf{e}_z^A$	Cartesian right-hand system A with basis (unit) vectors ${\bf e}$
Inertial frame	$\mathbf{e}_x^I, \mathbf{e}_y^I, \mathbf{e}_z^I$	global / inertial / world coordinate system (never moves)
Body-fixed frame	$\mathbf{e}_x^B, \mathbf{e}_y^B, \mathbf{e}_z^B$	local / body-fixed coordinate system (moves with body)
Rotation	$\Phi \in SO(3)$	generic rotation (for all parameterizations)
Machine precision	ε	
Operators		
Cross product/skew/unske	w $\mathbf{a} \times \mathbf{b} =$ $\mathbf{a} = \hat{\mathbf{a}}^{\vee},$	$\begin{bmatrix} a_1\\a_2\\a_3 \end{bmatrix} \times \begin{bmatrix} b_1\\b_2\\b_3 \end{bmatrix} = (\mathbf{a})^{\wedge} \mathbf{b} = \hat{\mathbf{a}} \mathbf{b} = \begin{bmatrix} 0 & -a_3 & a_2\\a_3 & 0 & -a_1\\-a_2 & a_1 & 0 \end{bmatrix} \begin{bmatrix} b_1\\b_2\\b_3 \end{bmatrix}$ $\hat{\mathbf{a}} = -\hat{\mathbf{a}}^{T}, \mathbf{a} \times \mathbf{b} = -\mathbf{b} \times \mathbf{a}$
Euclidean norm	$\ \mathbf{a}\ = \mathbf{v}$	$\sqrt{\mathbf{a}^T \mathbf{a}} = \sqrt{a_1^2 + \ldots + a_m^2}$
Exponential map for matri	$\mathbf{x} = \exp \left(\frac{\mathbb{R}^3}{2} \right)$	$ \begin{array}{c} & & & \\ & & & \\ \times^3 \ _ \ \mathbb{R}^{3\times3} \ \textbf{A} \ _ \ e^{\textbf{A}} \ \textbf{A} \ \subseteq \ \mathbb{R}^{3\times3} \end{array} $
Logarithmic map for matri	$\frac{1}{x} \log \cdot \mathbb{R}^{3}$	$\times^3 \rightarrow \mathbb{R}^{3\times3} \mathbf{A} \mapsto \log \mathbf{A} \mathbf{A} \in \mathbb{R}^{3\times3}$
		, , , , , , , , , , , , , , , , , , , ,
Position & Orient	ation	
Position		
Vector	rop	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	$_{B}\bar{\mathbf{r}}_{OB} = [I$	$\mathbf{p}_{\mathbf{p}}^{T} = 1$ from point <i>Q</i> to point <i>P</i> expr. in frame <i>B</i>
Drientation/Rotation	l # 4	
1) Active Rotation:	Φ^{II} : $I^{\mathbf{r}}OP \vdash \Phi^{P}$	$\rightarrow I \mathbf{r}_{OQ}$ (rotates the vector \mathbf{r}_{OP})
2) Passive Rotation: 2) Flomontary Potations	Ψ^{-} : $I^{\Gamma}OP \vdash$	$\rightarrow B^{r}OP$ (rotates the frame $(\mathbf{e}_{x}^{r}, \mathbf{e}_{y}^{r}, \mathbf{e}_{z}^{r}))$
5) Elementary Rotations	$I \Gamma_{OP} = C_{IE}$	$\begin{bmatrix} \cos \theta & -\sin \theta & 0 \end{bmatrix}$
	around z-ax	
		IS. $C_{IB} = \begin{bmatrix} \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$
	around y-ax	$ \mathbf{S} \cdot \mathbf{C}_{IB} = \begin{bmatrix} \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \\ \cos \theta & 0 & \sin \theta \\ 0 & 1 & 0 \\ -\sin \theta & 0 & \cos \theta \end{bmatrix} $
	around y-ax around x-ax	$ \mathbf{S} \cdot \mathbf{C}_{IB} = \begin{bmatrix} \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \\ \cos \theta & 0 & \sin \theta \\ -\sin \theta & 0 & \cos \theta \\ \mathbf{i} \mathbf{S} \cdot \mathbf{C}_{IB} = \begin{bmatrix} \sin \theta & \cos \theta & 0 \\ 0 & 1 & 0 \\ -\sin \theta & 0 & \cos \theta \\ 1 & 0 & 0 \\ 0 & \cos \theta & -\sin \theta \\ 0 & \sin \theta & \cos \theta \end{bmatrix} \qquad e_{x}^{I} \theta = e_{y}^{B} e_{y}^{I} e_{y}^{I$
4) Inversion:	around y-ax around x-ax $\Phi^{A^{-1}}(\mathbf{r}) =$	$\mathbf{S}. \mathbf{C}_{IB} = \begin{bmatrix} \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$ $\mathbf{is:} \mathbf{C}_{IB} = \begin{bmatrix} \cos \theta & 0 & \sin \theta \\ 0 & 1 & 0 \\ -\sin \theta & 0 & \cos \theta \end{bmatrix}$ $\mathbf{is:} \mathbf{C}_{IB} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \theta & -\sin \theta \\ 0 & \sin \theta & \cos \theta \end{bmatrix} \qquad e_x^I \xrightarrow{\theta} \begin{array}{c} e_y^B \\ e_y^P \\ e_y^$
4) Inversion:	around y-ax around x-ax $\Phi^{A^{-1}}(\mathbf{r}) = \Phi_2^A \left(\Phi_1^A (\mathbf{r}) \right)$	$\begin{aligned} \mathbf{B} \cdot \mathbf{C}_{IB} &= \begin{bmatrix} \sin \theta & \cos \theta & 0 \\ 0 & \sin \theta & \cos \theta \end{bmatrix} \\ \mathbf{B} \cdot \mathbf{C}_{IB} &= \begin{bmatrix} \cos \theta & 0 & \sin \theta \\ 0 & 0 & 0 \\ -\sin \theta & 0 & \cos \theta \\ 0 & \cos \theta & -\sin \theta \\ 0 & \sin \theta & \cos \theta \end{bmatrix} \qquad e_x^I \qquad e_y^{I} \\ e_x^{I} \qquad e_x^{I} \qquad e_x^{I} \\ e_x^{I} \qquad e_x^{I} \qquad e_x^{I} \\ e_x^{I$
 4) Inversion: 5) Concatenation: 	around y-ax around x-ax $\Phi^{A^{-1}}(\mathbf{r}) = \Phi_2^A \left(\Phi_1^A (\mathbf{r}) \right)$ $\Phi_2^P \left(\Phi_1^P (\mathbf{r}) \right)$	$\begin{aligned} \mathbf{B} \cdot \mathbf{C}_{IB} &= \begin{bmatrix} \sin\theta & \cos\theta & 0\\ 0 & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix} \qquad \mathbf{e}_{x}^{I} \mathbf{P}_{Q} \mathbf{e}_{y}^{I} e$
4) Inversion:5) Concatenation:6) Exponential map:	around y-ax around x-ax $\Phi^{A^{-1}}(\mathbf{r}) = \Phi_2^A \left(\Phi_1^A (\mathbf{r}) \right)$ $\Phi_2^P \left(\Phi_1^P (\mathbf{r}) \right)$	$\begin{array}{l} \text{is. } \mathbf{C}_{IB} = \begin{bmatrix} \sin\theta & \cos\theta & 0\\ 0 & 0 & \sin\theta \\ 0 & 1 & 0\\ -\sin\theta & 0 & \cos\theta \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix} \qquad $
 4) Inversion: 5) Concatenation: 6) Exponential map: 7) Logarithmic map: 	around y-ax around x-ax $\Phi^{A^{-1}}(\mathbf{r}) =$ $\Phi_2^A \left(\Phi_1^A (\mathbf{r}) \right)$ $\Phi_2^P \left(\Phi_1^P (\mathbf{r}) \right)$	$\begin{aligned} \mathbf{S} \cdot \mathbf{C}_{IB} &= \begin{bmatrix} \sin \theta & \cos \theta & 0 \\ 0 & 0 & \sin \theta \\ 0 & 1 & 0 \\ -\sin \theta & 0 & \cos \theta \\ 0 & \sin \theta & \cos \theta \end{bmatrix} & \mathbf{e}_{x}^{I} \mathbf{e}_{y}^{I} \mathbf{e}_{$
 4) Inversion: 5) Concatenation: 6) Exponential map: 7) Logarithmic map: 8) Box plus: 	around y-ax around x-ax $\Phi^{A^{-1}}(\mathbf{r}) = \Phi_2^A \left(\Phi_1^A (\mathbf{r}) \right)$ $\Phi_2^P \left(\Phi_1^P (\mathbf{r}) \right)$ $\Phi_2 = \Phi_1 \oplus \Phi_2$ $\Phi_2 = \Phi_1 \oplus \Phi_2$	is: $\mathbf{C}_{IB} = \begin{bmatrix} \sin \theta & \cos \theta & 0 \\ 0 & 0 & \sin \theta \\ 0 & 1 & 0 \\ -\sin \theta & 0 & \cos \theta \\ 0 & \cos \theta & -\sin \theta \\ 0 & \cos \theta & -\sin \theta \\ 0 & \cos \theta & -\sin \theta \end{bmatrix} \qquad \boldsymbol{e}_{x}^{I} \overset{\mathcal{P}}{\overset{\mathcal{P}}}{\overset{\mathcal{P}}{\overset{\mathcal{P}}{\overset{\mathcal{P}}{\overset{\mathcal{P}}{\overset{\mathcal{P}}}{\overset{\mathcal{P}}}}}}}}}}$
 4) Inversion: 5) Concatenation: 6) Exponential map: 7) Logarithmic map: 8) Box plus: 9) Box minus: 	around y-ax around x-ax $\Phi^{A^{-1}}(\mathbf{r}) = \Phi_2^A \left(\Phi_1^A (\mathbf{r}) - \Phi_2^P \left(\Phi_1^P (\mathbf{r}) - \Phi_2^P (\mathbf{r}) - \Phi$	is: $\mathbf{C}_{IB} = \begin{bmatrix} \sin \theta & \cos \theta & 0 \\ 0 & 0 & \sin \theta \\ 0 & 1 & 0 \\ -\sin \theta & 0 & \cos \theta \\ 0 & \sin \theta & -\cos \theta \end{bmatrix} \qquad \mathbf{e}_{x}^{I} \mathbf{e}_{y}^{I} \mathbf{e}_{y}^{I$
 4) Inversion: 5) Concatenation: 6) Exponential map: 7) Logarithmic map: 8) Box plus: 9) Box minus: 10) Discrete integration: 	around y-ax around x-ax $\Phi^{A^{-1}}(\mathbf{r}) = \Phi_2^A \left(\Phi_1^A(\mathbf{r}) + \Phi_2^P \left(\Phi_1^P(\mathbf{r}) + \Phi_2^P(\mathbf{r}) + \Phi_2^P(\mathbf{r})$	is: $\mathbf{C}_{IB} = \begin{bmatrix} \sin \theta & \cos \theta & 0 \\ 0 & 0 & \sin \theta \\ 0 & 1 & 0 \\ -\sin \theta & 0 & \cos \theta \\ 0 & \cos \theta & -\sin \theta \\ 0 & \cos \theta & -\sin \theta \end{bmatrix} \qquad \mathbf{e}_{x}^{I} \mathbf{e}_{y}^{P} \mathbf{Q}$ $\mathbf{e}_{x}^{I} \mathbf{e}_{y}^{I} \mathbf{e}_{y}^{I}$ $\mathbf{e}_{x}^{I} \mathbf{e}_{y}^{I} \mathbf{e}_{y}^{I}$ $\mathbf{e}_{x}^{I} \mathbf{e}_{y}^{I} \mathbf{e}_{y}^{I}$ $\mathbf{e}_{x}^{I} \mathbf{e}_{y}^{I} \mathbf{e}_{y}^{I} \mathbf{e}_{y}^{I} \mathbf{e}_{y}^{I}$ $\mathbf{e}_{x}^{I} \mathbf{e}_{y}^{I} \mathbf{e}_{y}^{I} \mathbf{e}_{y}^{I} \mathbf{e}_{y}^{I} \mathbf{e}_{y}^{I}$ $\mathbf{e}_{x}^{I} \mathbf{e}_{y}^{I} \mathbf{e}_{y}^{I} \mathbf{e}_{y}^{I} \mathbf{e}_{y}^{I} \mathbf{e}_{y}^{I} \mathbf{e}_{y}^{I}$ $\mathbf{e}_{x}^{I} \mathbf{e}_{y}^{I} \mathbf{e}_{y}^$
 4) Inversion: 5) Concatenation: 6) Exponential map: 7) Logarithmic map: 8) Box plus: 9) Box minus: 10) Discrete integration: 11) Discrete differential: 	around y-ax around x-ax $\Phi^{A^{-1}}(\mathbf{r}) = \Phi_2^A \left(\Phi_1^A (\mathbf{r}) + \Phi_2^A \left(\Phi_1^A (\mathbf{r}) + \Phi_2^A (\Phi_1^A (\mathbf{r}) + \Phi_2^A (\Phi_1^A (\Phi_1^$	is: $\mathbf{C}_{IB} = \begin{bmatrix} \sin \theta & \cos \theta & 0 \\ 0 & \sin \theta & \cos \theta \\ 0 & \sin \theta & 0 & \sin \theta \\ -\sin \theta & 0 & \cos \theta \\ 0 & \cos \theta & -\sin \theta \\ 0 & \cos \theta & -\sin \theta \end{bmatrix} \qquad \mathbf{e}_{x}^{I} \mathbf{e}_{y}^{P} \mathbf{Q}$ $\mathbf{e}_{x}^{I} \mathbf{e}_{y}^{I} \mathbf{e}_{y}^{I}$ $\mathbf{e}_{y}^{I} \mathbf{e}_{y}^{I} \mathbf{e}_{y}^{I} \mathbf{e}_{y}^{I}$ $\mathbf{e}_{x}^{I} \mathbf{e}_{y}^{I} \mathbf{e}_{y}^{I} \mathbf{e}_{y}^{I}$ $\mathbf{e}_{x}^{I} \mathbf{e}_{y}^{I} \mathbf{e}_{y}^{I} \mathbf{e}_{y}^{I}$ $\mathbf{e}_{x}^{I} \mathbf{e}_{y}^{I} \mathbf{e}_{y}^{I} \mathbf{e}_{y}^{I} \mathbf{e}_{y}^{I} \mathbf{e}_{y}^{I}$ $\mathbf{e}_{y}^{I} \mathbf{e}_{y}^{I} \mathbf{e}_{y}^{I} \mathbf{e}_{y}^{I} \mathbf{e}_{y}^{I}$ $\mathbf{e}_{y}^{I} \mathbf{e}_{y}^{I} \mathbf{e}_{y}^{$
 4) Inversion: 5) Concatenation: 6) Exponential map: 7) Logarithmic map: 8) Box plus: 9) Box minus: 10) Discrete integration: 11) Discrete differential: 	around y-ax around x-ax $\Phi^{A^{-1}}(\mathbf{r}) = \Phi_2^A \left(\Phi_1^A (1) + \Phi_2^P \left(\Phi_1^P (1) + \Phi_2^P (\Phi_1^P (1) + \Phi_2^P (\Phi_1^P (\Phi_2^P (\Phi_2^$	$\begin{aligned} \text{is. } \mathbf{C}_{IB} &= \begin{bmatrix} \sin \theta & \cos \theta & 0 \\ 0 & 0 & \sin \theta \\ 0 & 1 & 0 \\ -\sin \theta & 0 & \cos \theta \\ 0 & \cos \theta & -\sin \theta \\ 0 & \sin \theta & \cos \theta \end{bmatrix} \qquad \mathbf{e}_{x}^{I} \mathbf{e}_{y}^{P} \mathbf{e}_{y}^{I} \mathbf$
 4) Inversion: 5) Concatenation: 6) Exponential map: 7) Logarithmic map: 8) Box plus: 9) Box minus: 10) Discrete integration: 11) Discrete differential: 12) (Spherical) linear interpolation t ∈ [0, 1]: 	around y-ax around x-ax $\Phi^{A^{-1}}(\mathbf{r}) = \Phi_2^A \left(\Phi_1^A (1) \right)$ $\Phi_2^P \left(\Phi_1^P (1) \right)$ $\Phi_2 = \Phi_1 \oplus \oplus_1 \oplus \Phi_1 \oplus \oplus_1 \oplus_1$	is: $\mathbf{C}_{IB} = \begin{bmatrix} \sin\theta & \cos\theta & 0\\ 0 & 0 & \sin\theta \\ 0 & 1 & 0\\ -\sin\theta & 0 & \cos\theta \\ 0 & \cos\theta & -\sin\theta \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix} \qquad \mathbf{e}_{\mathbf{x}}^{I} \mathbf{e}_{\mathbf{y}}^{I} \mathbf{e}_{\mathbf{z}}^{I} \mathbf{e}_{$

Kindr Library – Kinematics and Dynamics for Robotics

Christian Gehring, C. Dario Bellicoso, Michael Bloesch, Hannes Sommer, Peter Fankhauser Marco Hutter, Roland Siegwart

normal capital lette

Nomenclature

vper-)complex numbe

Botation Parameterization

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

Rotation Quaternion

A rotation quaternion is a Hamiltonian unit quaternion $Q = q_0 + q_1 i + q_2 j + q_3 k \in \mathbb{H}, \quad q_i \in \mathbb{R}, i^2 = j^2 = k^2 = ijk = -1, \quad \|Q\| = \sqrt{q_0^2 + q_1^2 + q_2^2 + q_3^2} = 1$ $Q = (q_0, q_1, q_2, q_3) = (q_0, \check{\mathbf{q}}) \text{ with } \check{\mathbf{q}} := (q_1, q_2, q_3)^{\mathsf{T}}$ 4×1 -vector: $\mathbf{q} = \begin{bmatrix} q_0 & q_1 & q_2 & q_3 \end{bmatrix}$ Conjugate: $Q^* = (q_0, -\check{\mathbf{q}})$ Inverse: $Q^{-1} = Q^* = (q_0, -\check{\mathbf{q}})$ Quaternion multiplication: $Q \cdot P = (q_0, \check{\mathbf{q}}) \cdot (p_0, \check{\mathbf{p}}) = (q_0 p_0 - \check{\mathbf{q}}^{\mathsf{T}} \check{\mathbf{p}}, q_0 \check{\mathbf{p}} + p_0 \check{\mathbf{q}} + \check{\mathbf{q}} \times \check{\mathbf{p}})$ $\mathbf{q} \otimes \mathbf{p} = \underbrace{\mathbf{Q}(\mathbf{q})}_{\text{quaternion matrix}} \mathbf{p} = \begin{pmatrix} q_0 & -\tilde{\mathbf{q}}^{\mathsf{T}} \\ \tilde{\mathbf{q}} & q_0 \mathbf{1}_{3 \times 3} + \hat{\mathbf{q}} \end{pmatrix} \begin{pmatrix} p_0 \\ p_1 \\ p_2 \end{pmatrix}.$ $= \underbrace{\mathbf{\bar{Q}}(\mathbf{p})}_{\text{gate quat. matrix}} \mathbf{q} = \begin{pmatrix} p_0 & -\mathbf{\check{p}}^{\mathsf{I}} \\ \mathbf{\check{p}} & p_0 \mathbb{1}_{3 \times 3} - \mathbf{\check{p}} \end{pmatrix}$ $\Leftrightarrow \quad \phi_{IB} = \begin{cases} 2 \operatorname{atan2} \left(\|\check{\mathbf{q}}\|, q_0 \right) \frac{\check{\mathbf{q}}}{\|\check{\mathbf{q}}\|} & \text{if } \|\check{\mathbf{q}}\| \ge \epsilon \\ 2 \operatorname{sign}(q_0) \check{\mathbf{q}} & \text{otherwise} \end{cases}$ $\left|\cos\left(\frac{1}{2}\|\boldsymbol{\phi}\|\right), \frac{\boldsymbol{\phi}'}{\|\boldsymbol{\phi}\|} \sin\left(\frac{1}{2}\|\boldsymbol{\phi}\|\right)\right| \quad \text{if } \|\boldsymbol{\phi}\| \ge \epsilon$ Rotation Quat ernion \Leftrightarrow Angle-Axis $\Leftrightarrow \quad (\theta, \mathbf{n})_{IB} = \begin{cases} (2 \arccos(q_0), \frac{\check{\mathbf{q}}}{\|\check{\mathbf{q}}\|}) & \text{if } \|\check{\mathbf{q}}\| \ge \epsilon \\ (0, \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}^{\mathsf{T}}) & \text{otherwise} \end{cases}$ Rotation Quaternion \Leftrightarrow Rotation Matrix $\mathbf{C}_{IB} = \mathbb{1}_{3\times3} + 2q_0\hat{\mathbf{q}} + 2\hat{\mathbf{q}}^2 = (2q_0^2 - 1)\mathbb{1}_{3\times3} + 2q_0\hat{\mathbf{q}} + 2\check{\mathbf{q}}\check{\mathbf{q}}^\mathsf{T}$ $= \begin{bmatrix} q_0^2 + q_1^2 - q_2^2 - q_3^2 & 2q_1q_2 - 2q_0q_3 & 2q_0q_2 + 2q_1q_3 \\ 2q_0q_3 + 2q_1q_2 & q_0^2 - q_1^2 + q_2^2 - q_3^2 & 2q_2q_3 - 2q_0q_1 \\ 2q_1q_3 - 2q_0q_2 & 2q_0q_1 + 2q_2q_3 & q_0^2 - q_1^2 - q_2^2 + q_3^2 \end{bmatrix}$ $\mathbf{C}_{IB}^{-1} = \mathbf{C}_{BI} = \mathbb{1}_{3\times 3} - 2q_0\hat{\mathbf{q}} + 2\hat{\mathbf{q}}^2$ $\left[q_0^2 + q_1^2 - q_2^2 - q_3^2 - 2q_0q_3 + 2q_1q_2\right]$

<u>Cheat-sheet</u> (incl. derivations)

Navigation

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

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

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

| 16

Navigation Elevation Mapping – Dense Terrain Mapping

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.

- 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.

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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.

 (\mathcal{P})

Navigation Grid Map – Universal Multi-Layer Grid Map Library

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2D circular buffer data structure

Efficient map repositioning

Navigation Grid Map – Universal Multi-Layer Grid Map Library

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.

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Efficient map repositioning

Based on Eigen (C++)

Versatile and efficient data manipulation

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.

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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

Challenging Terrain," in IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2016.

Navigation **Navigation Planning**

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.

Online navigation planning based on RRT* (OMPL)

- Works with and without initial map
- Continuous for changing environments

Inspection

Visual inspection

Thermal Inspection Auditive Inspection

Level gauges & Pressure Valves

Zoom-camera

Thermal points

TOTAL

Pumps

Gas leaks

Platform alarm

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Inspection **Visual Inspection of Pressure Gauges**

А

Automatic view point generation

Whole-body camera positioning

(D)

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

Image de-warping

→ Reading ok

→ Reading unsuccessful, try alternative position or report as unknown

| 22

User Interface

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

0

User Interface

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

3D view (RViz)

Mission control & protocol

Other modules

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🔍 🗇 __cll_perspective_from_file - rqt

Reset

Refresh

Refresh

Abort Stop

Supervisory

Localization

X = disabled

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Mission Protocol

Name: ArgosMissior

Stamp

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6 1970/01/01 00:00:47.495 UTC INFO

7 1970/01/01 00:00:47.871 UTC INFO

8 1970/01/01 00:00:47.876 UTC INFO

9 1970/01/01 00:00:48.116 UTC INFO

10 1970/01/01 00:00:48.116 UTC INFO

Scroll automatically

Protocol User Interaction

Level

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Omniview Settings

raosMissian

ArgosMission

Pause after Task

Emergency Stop

Communication Gas Electrochemical = checking

Heat

Gas Acoustical Obstacle

FollowPath

Start Mission

Control Mission

Running Mission:

Running Task Progress:

Pause

Autonomous

Running Task:

Control

Supervisions

Battery

Dysfunction

Alarm

Mode

Mission

State

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

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User Interface **ANYping Indicator**

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Indicates PC network availability in Ubuntu menu bar

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User Interface **Pose Graph**

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) Experimental
	30 fps

- 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

27

RQT Multiplot Plugin & Variant Topic Tools

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

RQT Multiplot Plugin & Variant Topic Tools

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Autonomous Systems Lab

- 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

RQT Multiplot Plugin & Variant Topic Tools

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- 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

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

ubuntu® 14.04 LTS

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

Atlassian **Bitbucket**

GitHub

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- Conventions for package structure, format, naming, and code style
 - ➡ github.com/ethz-asl/ros_best_practices/wiki

<pre>© ethz-asl / ros_best_practices</pre>		s		O Unwatch •	15 🖈	Unstar	25	¥ Fark	11
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Péter Fankhauser edited this page on May 13, 2015 · 2	2 revisions								
ROS Best Practices					▼ Pa	ges 🕕			
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This is a loose collection of best practices, convi Surface (SOS) II head a mention of ficial SOS do	entions, and trick	s for using	the Robot C	Operating					
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ROS Best Practices: Lorenz Mösenlechner,	Technische Unive	rsität Münd	hen, July 2	012					
 ROS Best Practices: Tully Foote, Open Source 	ce Robotics Foun	dation, Oct	ober 2014,						
 ROS Design Patterns, C++ APIs, and Best Pi Generated Service and Polyating, The J 	ractices: Jonatha	n Bohren, L	aboratory f	for					
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In parts, the document describes opinionated be	est practices esta	blished with	h <mark>in the Leg</mark>	ged					
Robotics Group from the Autonomous Systems I	ab, ETH Zurich.								
Author: Péter Fankhauser, pfankhauser@ethz.	ch								
Affiliation: Autonomous Systems Lab, ETH Zur	ich								
TODO									
 http://robotics.stackexchange.com/question 	is/3110/ros-best-	practices							

- All developers and robots same setup
 Ubuntu 14.04 LTS, ROS Indigo
- Software version control with Git
 Bitbucket & GitHub
- Conventions for package structure, format, naming, and code style
 - github.com/ethz-asl/ros_best_practices/wiki
- Extensive use of simulation
 - ➡ <u>Gazebo</u>

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- Extensive use of simulation
 - Gazebo
- Visualizing as much as possible

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Lots of tests on hardware

- Weekly "shakeouts" for defined tasks
- Lots of demos

Lots of tests on hardware

- Weekly "shakeouts" for defined tasks
- Lots of demos
- Continuous Integration
 - <u>Jenkins</u>
 - Unit tests (after each change)
 - ROS integration tests (at night)

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Lots of tests on hardware

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Lots of tests on hardware

- Weekly "shakeouts" for defined tasks
- Lots of demos
- **Continuous Integration**
 - Jenkins
 - Unit tests (after each change)
 - <u>ROS integration tests</u> (at night)
- Logging (rosbag)
 - All important information is always logged
 - Review logs with RViz and <u>RQT Multiplot</u>

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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

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 Vassilios Tsounis Martin Wermelinger

