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ETH zürich

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

ANR ARGOS TOTAL

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. Recalling 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 50-101dB SPL).
- **Checkpoints:**
  the sensors will have to be in relation, around their expected position, and their observed response.
  - Pressure gauge (3-6)
  - Water level (3-7)
  - Valve (3-8)
  - Thermal measurement points (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 4-3 - Success of high temperatures, page 22).
- **Obstacles (3-12):**
  unexpected obstacles during the 2nd competition can be objects or parts 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):
  precise detection and localisation based on the point IR detector.
- Safety equipment - extinguishers (3-4):
  the robot has to detect whether the extinguisher are present in their expected localisation.
- 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.

21

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

Main body

Hokuyo laser scanner

Joint actuators

Contact sensors

Pan/tilt inspection head

Protection frame

Aluminium thigh and carbon shank

Battery housing

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

ANYdrive

System Overview

ANYmal

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

Open Source
github.com/ethz-asl/generalized_information_filter

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)

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.

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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

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	$\mathbf{M}$	bold capital letter
Identity matrix	$\mathbb{I}_{n\times m}$	$n \times m$-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 $\mathbf{e}$
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	$\Phi \in \mathrm{SO}(3)$	generic rotation (for all parameterizations)
Machine precision	ϵ	

Operators

Cross product/skew/unskew	$\mathbf{a}\times\mathbf{b} = \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} \times \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} = (\mathbf{a})^\wedge \mathbf{b} = \hat{\mathbf{a}}\mathbf{b} = \begin{bmatrix} 0 & -a_3 & a_2 \\ a_3 & 0 & -a_1 \\ -a_2 & a_1 & 0 \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix}$ $\mathbf{a} = \hat{\mathbf{a}}^\vee, \quad \hat{\mathbf{a}} = -\hat{\mathbf{a}}^\mathsf{T}, \quad \mathbf{a}\times\mathbf{b} = -\mathbf{b}\times\mathbf{a}$
Euclidean norm	$\lVert\mathbf{a}\rVert = \sqrt{\mathbf{a}^\mathsf{T}\mathbf{a}} = \sqrt{a_1^2 + \ldots + a_n^2}$
Exponential map for matrix	$\exp : \mathbb{R}^{3\times3} \to \mathbb{R}^{3\times3}, \mathbf{A} \mapsto e^{\mathbf{A}}, \quad \mathbf{A} \in \mathbb{R}^{3\times3}$
Logarithmic map for matrix	$\log : \mathbb{R}^{3\times3} \to \mathbb{R}^{3\times3}, \mathbf{A} \mapsto \log \mathbf{A}, \quad \mathbf{A} \in \mathbb{R}^{3\times3}$

Position & Orientation

Position

Vector	${}_I\mathbf{r}_{OP}$	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	${}_B\mathbf{r}_{OP} = \begin{bmatrix} {}_B\mathbf{r}_{OP}^\mathsf{T} & 1 \end{bmatrix}^\mathsf{T}$	from point O to point P expr. in frame B

Orientation/Rotation

1) Active Rotation: ${}_I\mathbf{r}_{OP} \mapsto {}_I\mathbf{r}_{OQ}$ (rotates the vector $\mathbf{r}_{OP}$)
2) Passive Rotation: ${}_I\mathbf{r}_{OP} \mapsto {}_B\mathbf{r}_{OP}$ (rotates the frame $(\mathbf{e}_x^I, \mathbf{e}_y^I, \mathbf{e}_z^I)$)
3) Elementary Rotations ${}_I\mathbf{r}_{OP} = \mathbf{C}_{IB}\,{}_B\mathbf{r}_{OP}$

around z-axis: $\mathbf{C}_{IB} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$

around y-axis: $\mathbf{C}_{IB} = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix}$

around x-axis: $\mathbf{C}_{IB} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix}$

4) Inversion: $\Phi^{A^{-1}}(\mathbf{r}) = \Phi^P(\mathbf{r})$
5) Concatenation: $\Phi_2^P\left(\Phi_1^P(\mathbf{r})\right) = \left(\Phi_2^A \otimes \Phi_1^A\right)(\mathbf{r}) = \left(\Phi_1^{A^{-1}} \otimes \Phi_2^{A^{-1}}\right)^{-1}(\mathbf{r})$
6) Exponential map: $\exp : \mathbb{R}^3 \to \mathrm{SO}(3), \mathbf{v} \mapsto \exp(\hat{\mathbf{v}}), \quad \mathbf{v} \in \mathbb{R}^3$
7) Logarithmic map: $\log : \mathrm{SO}(3) \to \mathbb{R}^3, \Phi \mapsto \log(\Phi)^\vee, \quad \Phi \in \mathrm{SO}(3)$
8) Box plus: $\Phi_2 = \Phi_1 \boxplus \mathbf{v} = \exp(\mathbf{v}) \otimes \Phi_1, \quad \Phi_1, \Phi_2 \in \mathrm{SO}(3), \mathbf{v} \in \mathbb{R}^3$
9) Box minus: $\mathbf{v} = \Phi_1 \boxminus \Phi_2 = \log(\Phi_1 \otimes \Phi_2^{-1}), \quad \Phi_1, \Phi_2 \in \mathrm{SO}(3), \mathbf{v} \in \mathbb{R}^3$
10) Discrete integration: $\Phi_{IB}^{k+1} = \Phi_{IB}^k \boxplus ({}_I\boldsymbol{\omega}_{IB}^k \Delta t), \quad \Phi_{BI}^{k+1} = \Phi_{BI}^k \boxplus (-{}_B\boldsymbol{\omega}_{IB}^k \Delta t)$
11) Discrete differential: ${}_I\boldsymbol{\omega}_{IB}^k = (\Phi_{IB}^{k+1} \boxminus \Phi_{IB}^k)/\Delta t, \quad {}_B\boldsymbol{\omega}_{IB}^k = -(\Phi_{BI}^{k+1} \boxminus \Phi_{BI}^k)/\Delta t$
12) (Spherical) linear interpolation $t \in [0,1]$: $\Phi_t = \Phi_0 \boxplus ((\Phi_1 \boxminus \Phi_0)\, t), \quad \Phi_t = \Phi(t), \Phi_0 = \Phi(0), \Phi_1 = \Phi(1)$
$= (\Phi_1 \otimes \Phi_0^{-1})^t \otimes \Phi_0$

Rotation Parameterizations

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

Rotation Quaternion

A rotation quaternion is a Hamiltonian unit quaternion:

$Q = q_0 + q_1 i + q_2 j + q_3 k \in \mathbb{H}, \quad q_i \in \mathbb{R}, i^2 = j^2 = k^2 = ijk = -1, \quad \lVert Q\rVert = \sqrt{q_0^2 + q_1^2 + q_2^2 + q_3^2} = 1$

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

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

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

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

Quaternion multiplication:

$Q \cdot P = (q_0, \hat{\mathbf{q}}) \cdot (p_0, \hat{\mathbf{p}}) = (q_0 p_0 - \hat{\mathbf{q}}^\mathsf{T}\hat{\mathbf{p}}, q_0\hat{\mathbf{p}} + p_0\hat{\mathbf{q}} + \hat{\mathbf{q}} \times \hat{\mathbf{p}}) \quad \Leftrightarrow$

$$\mathbf{q} \otimes \mathbf{p} = \underbrace{\mathbf{Q}(\mathbf{q})}_{\text{quaternion matrix}}\,\mathbf{p} = \begin{pmatrix} q_0 & -\hat{\mathbf{q}}^\mathsf{T} \\ \hat{\mathbf{q}} & q_0\mathbb{I}_{3\times3} + \hat{\mathbf{q}}_\times \end{pmatrix} \begin{pmatrix} p_0 \\ p_1 \\ p_2 \\ p_3 \end{pmatrix} = \begin{pmatrix} q_0 & -q_1 & -q_2 & -q_3 \\ q_1 & q_0 & -q_3 & q_2 \\ q_2 & q_3 & q_0 & -q_1 \\ q_3 & -q_2 & q_1 & q_0 \end{pmatrix} \begin{pmatrix} p_0 \\ p_1 \\ p_2 \\ p_3 \end{pmatrix}$$

$$= \underbrace{\mathbf{Q}(\mathbf{p})}_{\text{conjugate quat. matrix}}\,\mathbf{q} = \begin{pmatrix} p_0 & -\hat{\mathbf{p}}^\mathsf{T} \\ \hat{\mathbf{p}} & p_0\mathbb{I}_{3\times3} - \hat{\mathbf{p}}_\times \end{pmatrix} \begin{pmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{pmatrix} = \begin{pmatrix} p_0 & -p_1 & -p_2 & -p_3 \\ p_1 & p_0 & p_3 & -p_2 \\ p_2 & -p_3 & p_0 & p_1 \\ p_3 & p_2 & -p_1 & p_0 \end{pmatrix} \begin{pmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{pmatrix}$$

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

Rotation Quaternion ⇔ Rotation Vector

$$\mathbf{q}_{IB} = \begin{cases} \begin{bmatrix} \cos\left(\frac{1}{2}\lVert\boldsymbol{\phi}\rVert\right), \frac{\boldsymbol{\phi}^\mathsf{T}}{\lVert\boldsymbol{\phi}\rVert}\sin\left(\frac{1}{2}\lVert\boldsymbol{\phi}\rVert\right) \end{bmatrix}^\mathsf{T} & \text{if } \lVert\boldsymbol{\phi}\rVert \geq \epsilon \\ \begin{bmatrix} 1, \frac{1}{2}\boldsymbol{\phi}^\mathsf{T} \end{bmatrix}^\mathsf{T} & \text{otherwise} \end{cases} \quad \Leftrightarrow \quad \boldsymbol{\phi}_{IB} = \begin{cases} 2\,\mathrm{atan2}\left(\lVert\hat{\mathbf{q}}\rVert, q_0\right)\frac{\hat{\mathbf{q}}}{\lVert\hat{\mathbf{q}}\rVert} & \text{if } \lVert\hat{\mathbf{q}}\rVert \geq \epsilon \\ 2\,\mathrm{sign}(q_0)\hat{\mathbf{q}} & \text{otherwise} \end{cases}$$

Rotation Quat ernion ⇔ Angle-Axis

$$\mathbf{q}_{IB} = \begin{bmatrix} \cos\frac{\theta}{2} \\ \mathbf{n}\sin\frac{\theta}{2} \end{bmatrix} \quad \Leftrightarrow \quad (\theta, \mathbf{n})_{IB} = \begin{cases} \left(2\arccos(q_0), \frac{\hat{\mathbf{q}}}{\lVert\hat{\mathbf{q}}\rVert}\right) & \text{if } \lVert\hat{\mathbf{q}}\rVert \geq \epsilon \\ \left(0, \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}^\mathsf{T}\right) & \text{otherwise} \end{cases}$$

Rotation Quaternion ⇔ Rotation Matrix

$$\mathbf{C}_{IB} = \mathbb{I}_{3\times3} + 2q_0\hat{\mathbf{q}} + 2\hat{\mathbf{q}}^2 = (2q_0^2 - 1)\mathbb{I}_{3\times3} + 2q_0\hat{\mathbf{q}} + 2\hat{\mathbf{q}}\hat{\mathbf{q}}^\mathsf{T}$$

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

$$\mathbf{C}_{BI}^{-1} = \mathbf{C}_{BI} = \mathbb{I}_{3\times3} - 2q_0\hat{\mathbf{q}} + 2\hat{\mathbf{q}}^2$$

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

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.

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

`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

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

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
- 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

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
- 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

Open Source
github.com/ethz-asl/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

Zoom-camera

Thermal Inspection

Thermal points

Thermal-camera

Auditive Inspection

Pumps Gas leaks Platform alarm

Microphones (audible and ultra-sonic)

Inspection
Visual Inspection of Pressure Gauges

A Automatic view point generation

C Visual servoing

E Indicator reading

➔ Reading ok

➔ Reading unsuccessful, try alternative position or report as unknown

B Whole-body camera positioning

D Image de-warping

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)
- 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

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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- Live plotting or load rosbags
- Easy to setup configurations
- *x*- and *y*-axis freely configurable

ANYmal

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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  - ➡ github.com/ethz-asl/ros_best_practices/wiki

ethz-asl / ros_best_practices

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Péter Fankhauser edited this page on May 13, 2015 · 22 revisions

ROS Best Practices

This is a loose collection of best practices, conventions, and tricks for using the Robot Operating System (ROS). It builds up on the official ROS documentation and other resources and is meant as summary and overview.

Official ROS documentation:

- ROS Enhancement Proposals (REPs),
- ROS Use Patterns and Best Practices,
- ROS Developer's Guide.

Other References:

- ROS Best Practices: Lorenz Mösenlechner, Technische Universität München, July 2012,
- ROS Best Practices: Tully Foote, Open Source Robotics Foundation, October 2014,
- ROS Design Patterns, C++ APIs, and Best Practices: Jonathan Bohren, Laboratory for Computational Sensing and Robotics, The John Hopkins University,
- ROS Answers.

In parts, the document describes opinionated best practices established within the Legged Robotics Group from the Autonomous Systems Lab, ETH Zurich.

Author: Péter Fankhauser, pfankhauser@ethz.ch
Affiliation: Autonomous Systems Lab, ETH Zurich

TODO

- http://robotics.stackexchange.com/questions/3110/ros-best-practices

Pages

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  - ➡ github.com/ethz-asl/ros_best_practices/wiki
- Extensive use of simulation
  - ➡ Gazebo

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- Extensive use of simulation
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- 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

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

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- Continuous Integration
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  - ➡ 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

Open-Source Software

github.com/ethz-asl

github.com/leggedrobotics

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