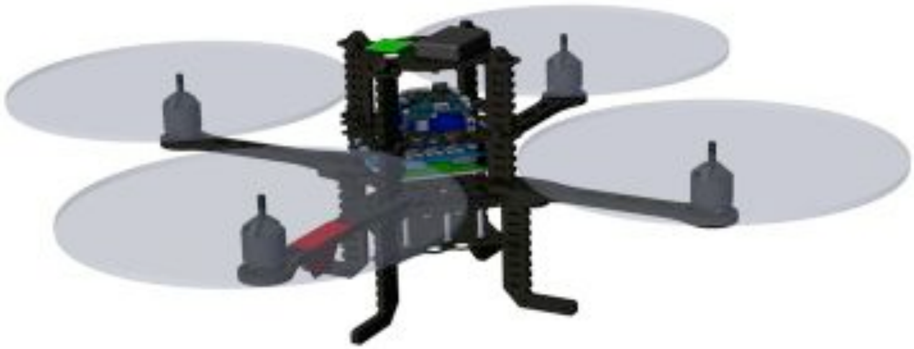
Visual-Inertial Based Navigation with MAVs in GPS Restricted Environments

Markus Achtelik, Simon Lynen, Stephan Weiss, Stefan Leutenegger, Sammy Omari, Michael Burri, Pascal Gohl, Kostas Alexis, Margarita Chli, Roland Siegwart

Micro Aerial Vehicles (MAVs)

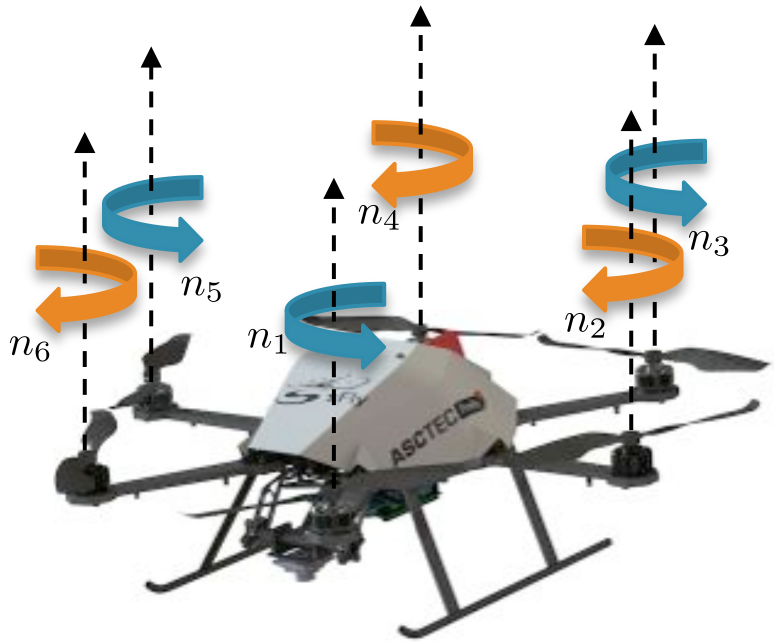
- Multi-rotor helicopters
- All rotors aligned in a plane
- Rotor axes perpendicular to that plane
- Max. take off weight ≈ 1.5 kg

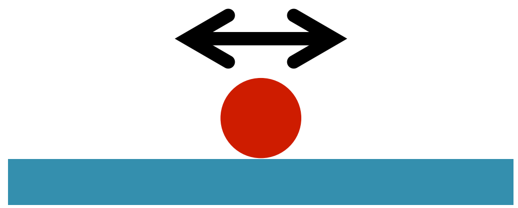


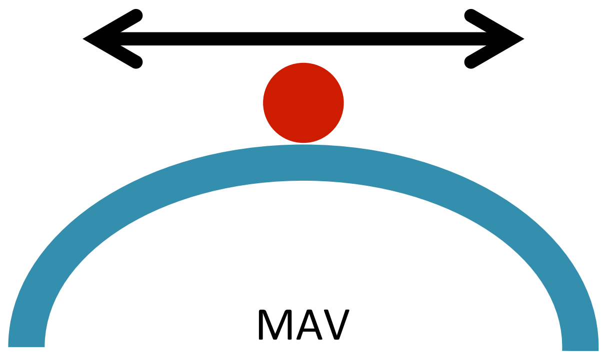
Jerome-de Bothezat Quadrotor 'Flying Octopus' in 1922

Challenges for MAVs

- Degrees of freedom
- Coupled dynamics
- Fast dynamics
- Constant motion and inherent instability





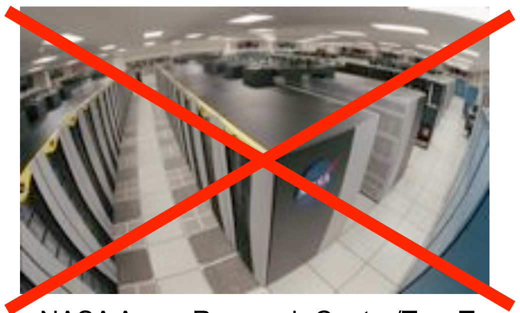


Challenges for MAVs

- Sensing payload (1g payload → ≈100 mW hovering power)




- Onboard processing power


NASA Ames Research Center/Tom Trower


Ascending Technologies

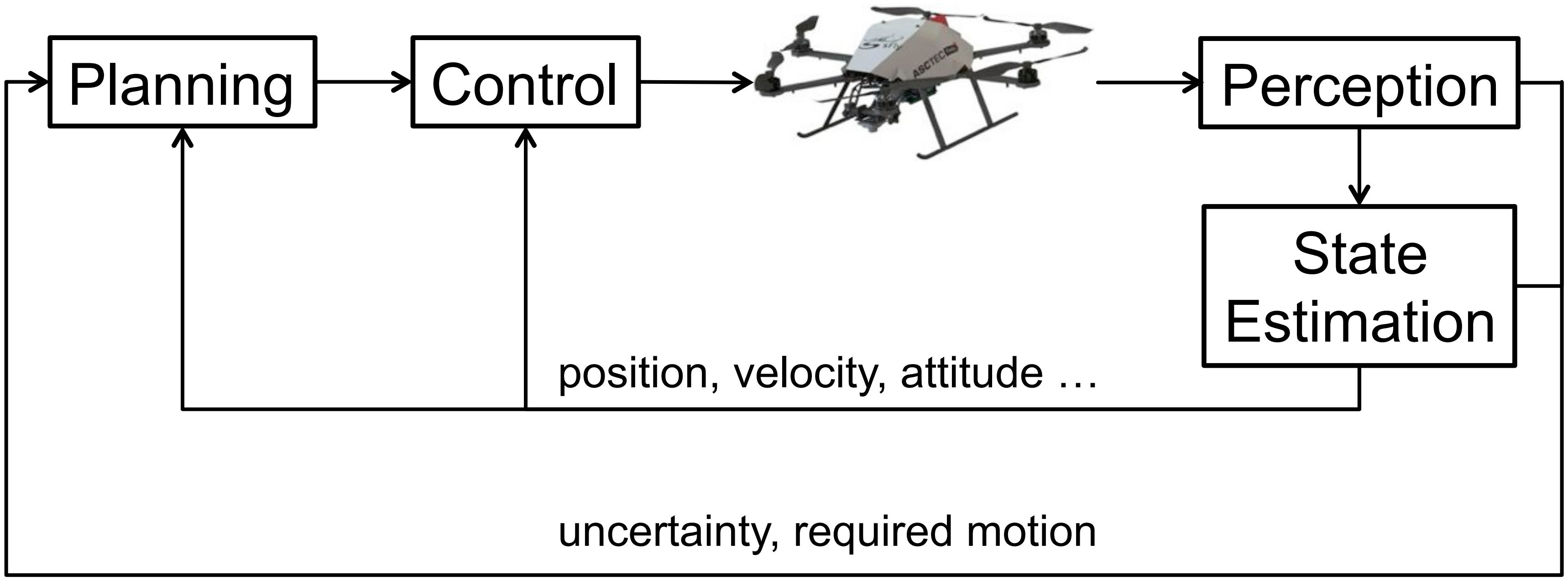
- Wireless data-links: bandwidth, delay, QoS …

Challenges Visualized

Challenges Visualized

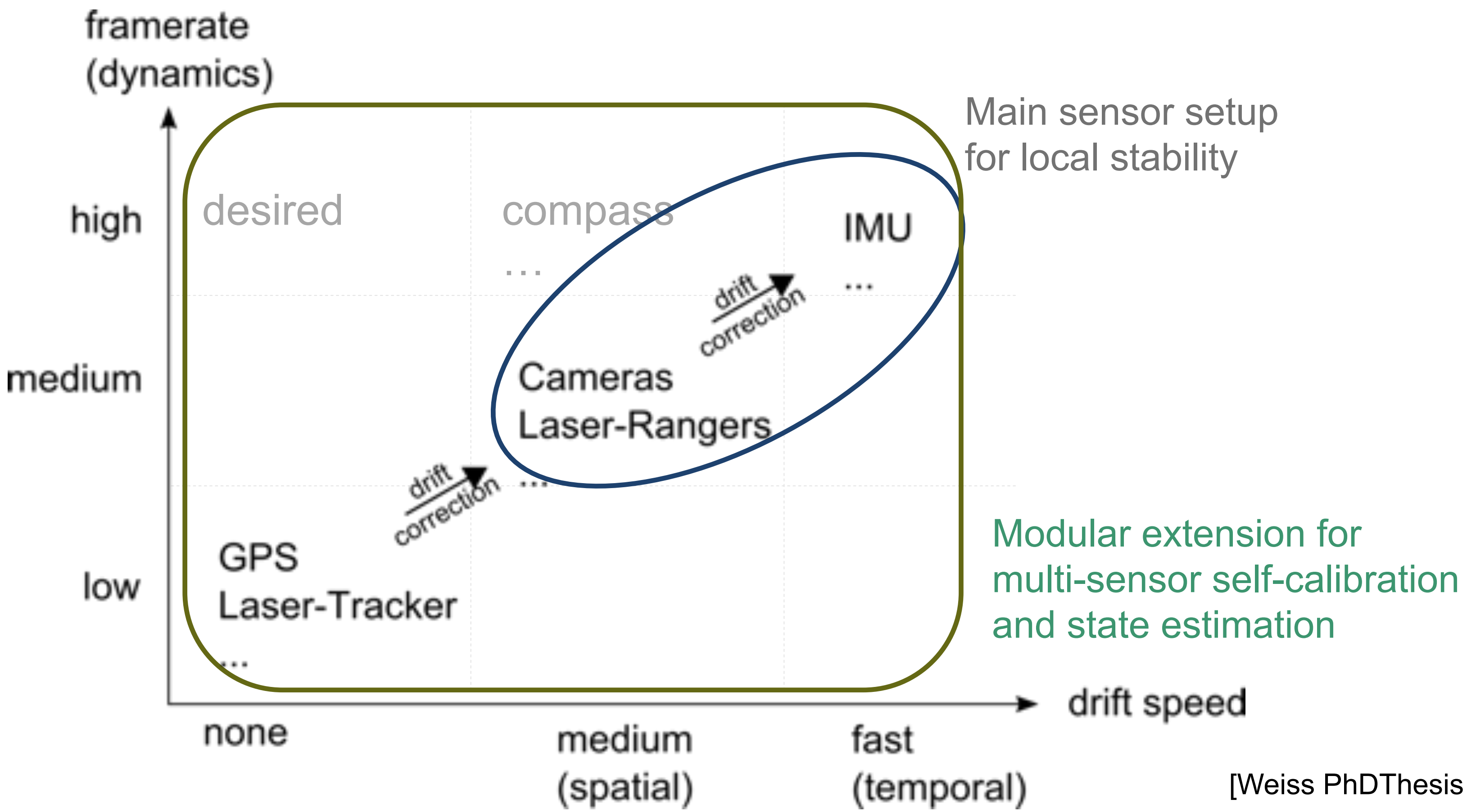
Closed Loop Visual Navigation for MAVs

Components of an Autonomous MAV



[Achtelik et al. IROS 2013]

A sensor classification attempt, considering framerate and drift

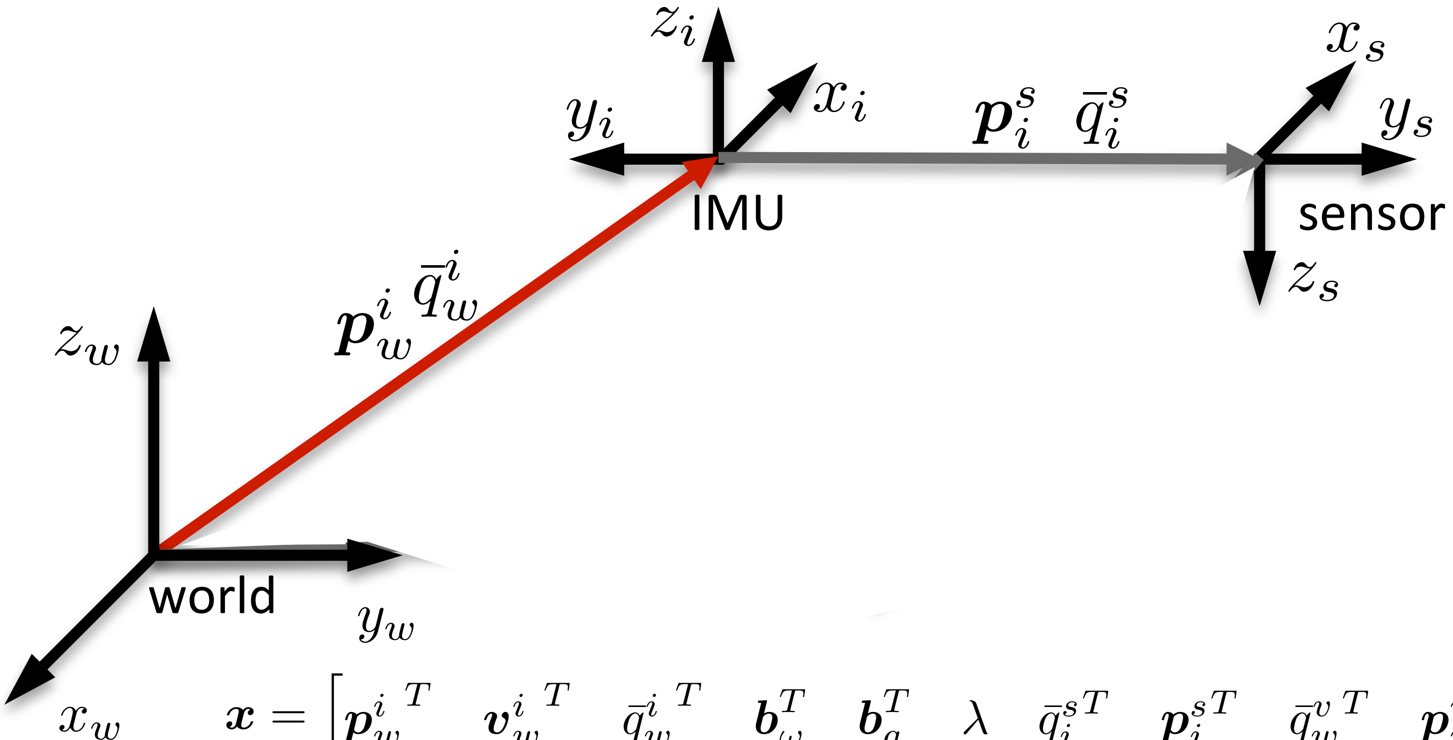


[Weiss PhDThesis 2012]

Localization: Keyframe Based Visual SLAM

- Parallel Localization And Mapping (PTAM) [Klein & Murray ISMAR07] [JFR 2011, ICRA 2012, JFR 2013]
  - Tracking and mapping in separate threads
  - Originally designed for small workspaces
  - Monocular vision approach
    → unknown, arbitrary translational scale
  - Here: used as “black box” providing a “5D” pose

State Estimation: Sensor Setup

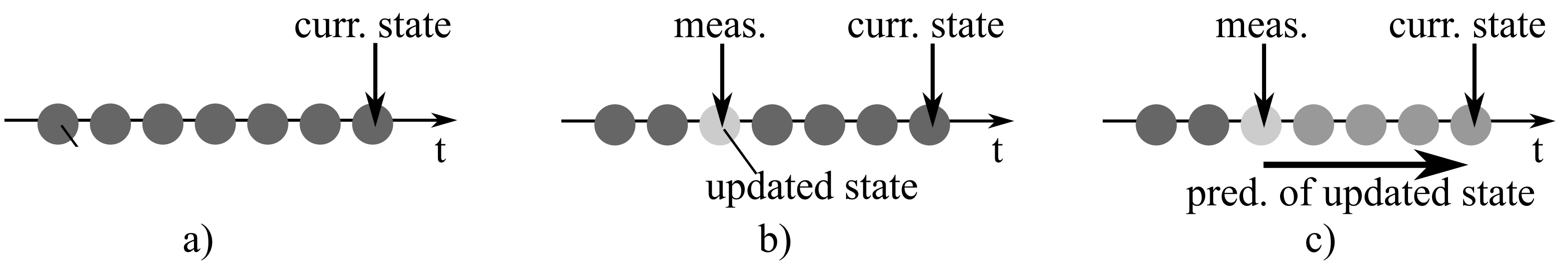


$$\boldsymbol{x} = \begin{bmatrix} \boldsymbol{p}_w^{i\,T} & \boldsymbol{v}_w^{i\,T} & \bar{q}_w^{i\,T} & \boldsymbol{b}_\omega^T & \boldsymbol{b}_a^T & \lambda & \bar{q}_i^{s\,T} & \boldsymbol{p}_i^{s\,T} & \bar{q}_w^{v\,T} & \boldsymbol{p}_w^{v\,T} \end{bmatrix}^T$$

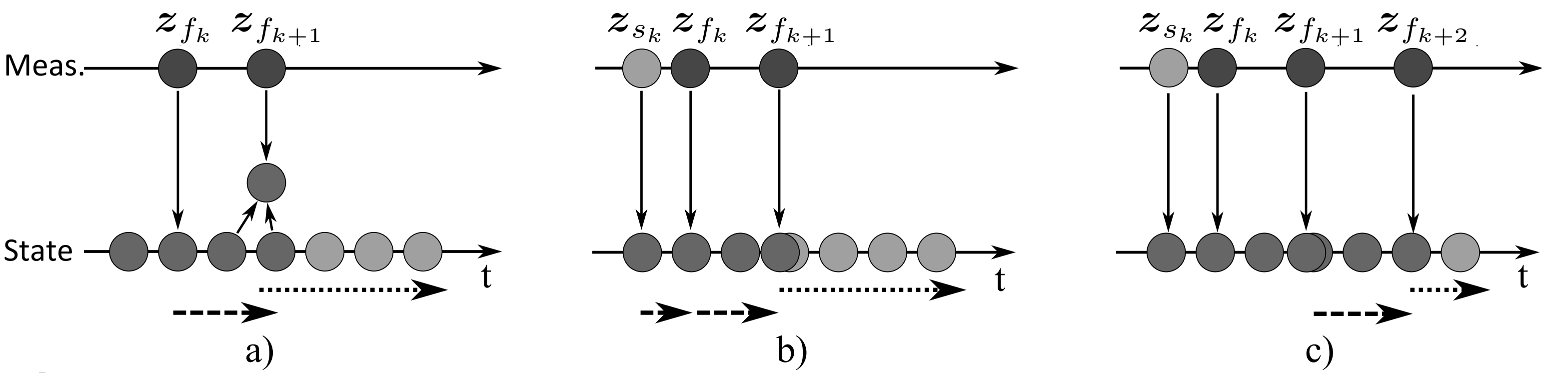
- IMU-sensor calibration and measurement scale are observable, given sufficient motion [Mirzaei, Kelly, Martinelli, Weiss]

Measurement Delay Compensation

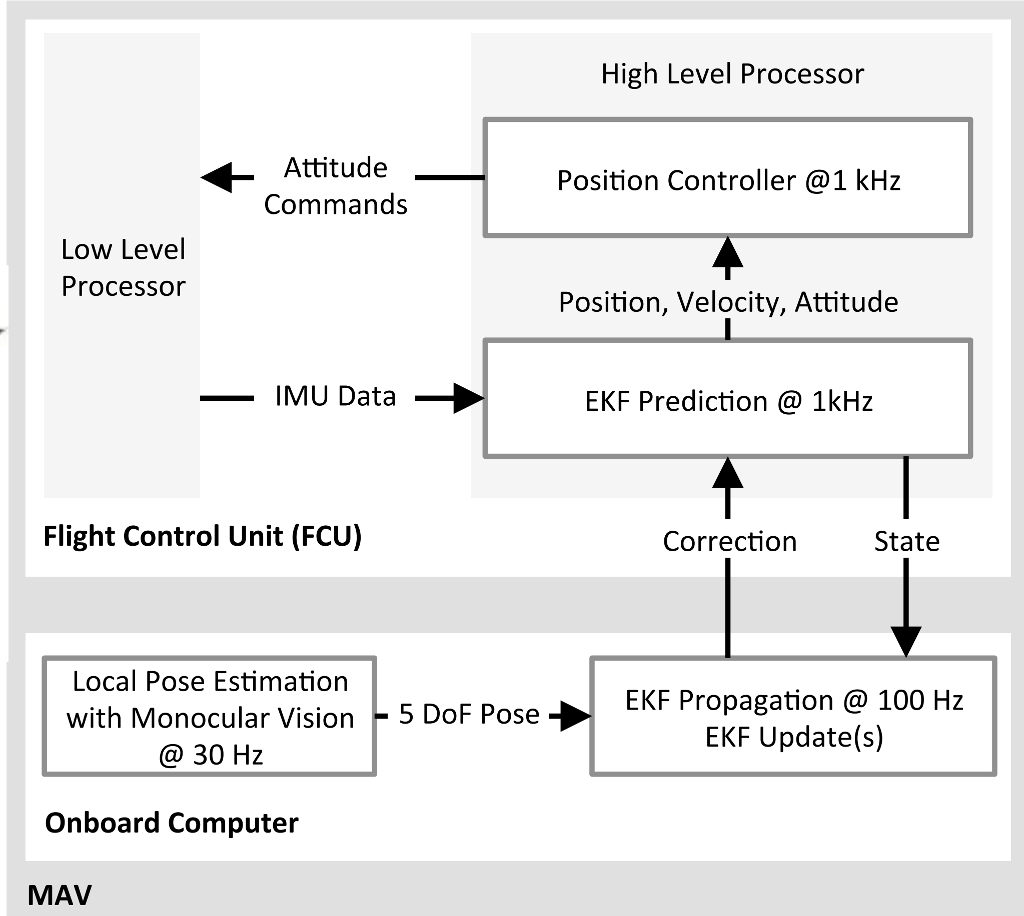
- Single sensor:



- Multiple sensors:



Sensor Fusion Integration

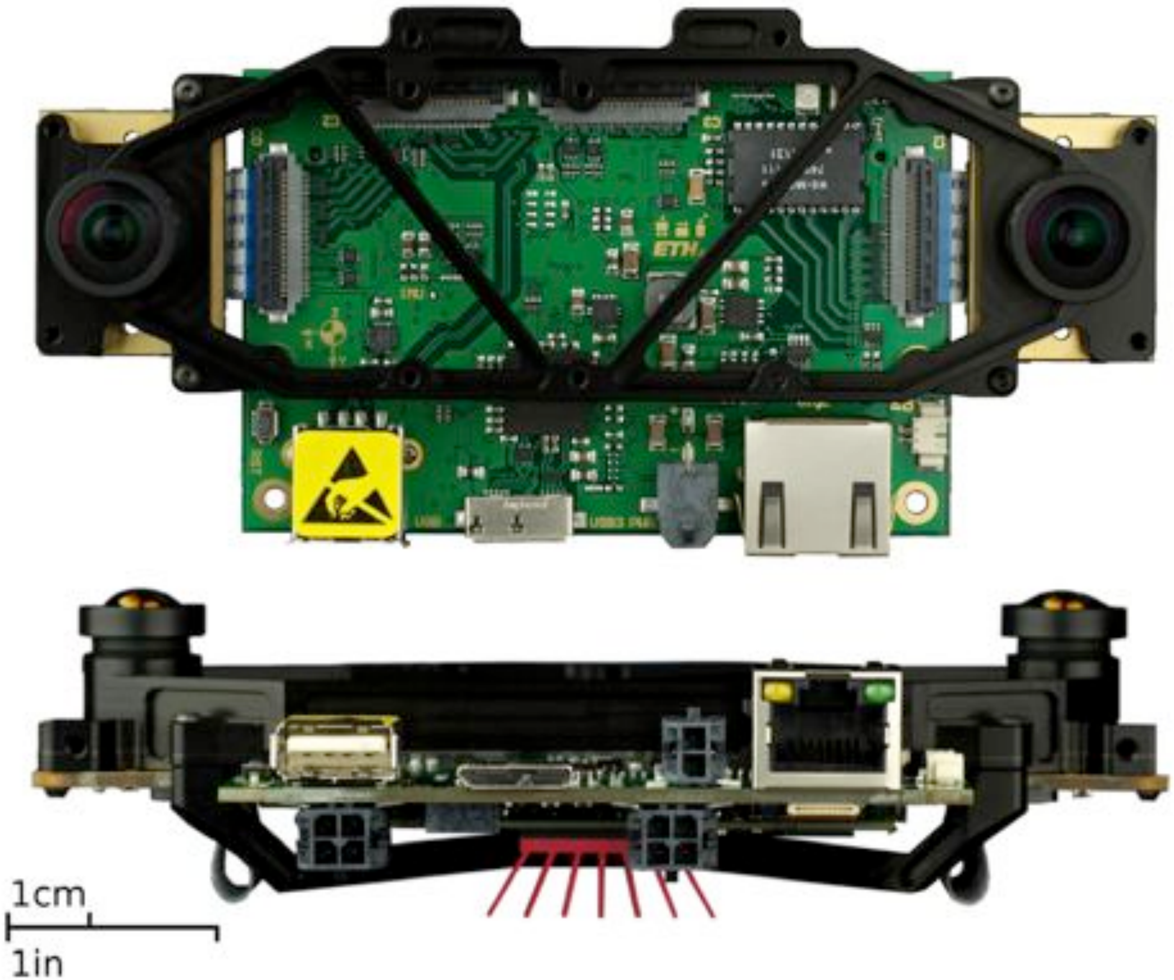


Results: Robustness to Disturbances

Results: PTAM / VSLAM -- up to 4 m/s

[Achtelik et al. IROS 2013]

Visual-Inertial SLAM sensor



Specs

- Vision: Global Shutter Aptina MT9V034 (up to four)
  Thermal Camera: FLIR Tau 640, 14 bit HDR
- IMU: Analog Devices ADIS 16488/16448
- Calibration: Camera-IMU fully calibrated & time-synchronized [1]
- FPGA: XILINX Zynq 7020
  SoC Dual-Core ARM Cortex A9

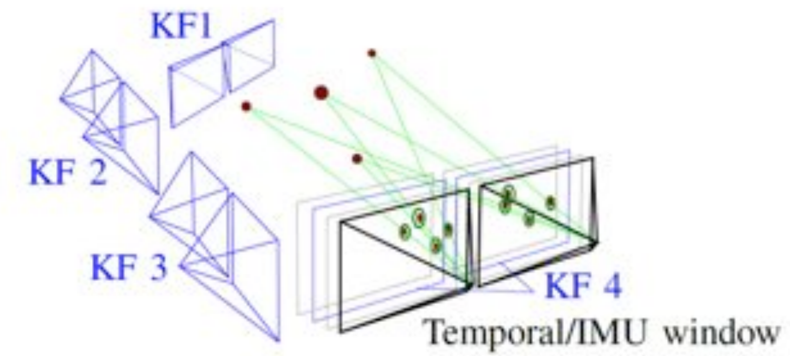
- Lighting: LED flasher
- Interface: GPS & Laser scanners

- I/O: GigE, USB-powered (<10W)
- Weight: 130 g (incl. 2 cams + sensor mount)

[1] P. Furgale et.al, "Unified Temporal and Spatial Calibration for Multi-Sensor Systems", IROS 2013

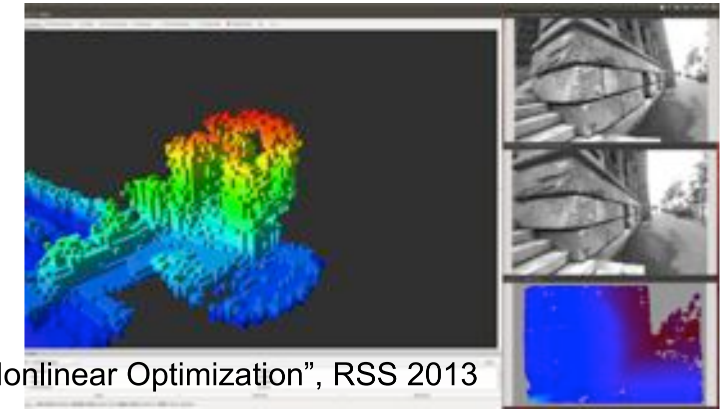
ASLam Framework

- Tightly-coupled keyframe-based visual-inertial SLAM [1]



- Tight integration of IMU allows highly dynamic motions and efficient outlier rejection.

- Realtime dense stereo-based 3D reconstruction
  - Poses: ASLam [1]
  - Stereo depth-map: ELAS [2]
  - Mapping: Octomap [3]
- Efficient outlier rejection based on photoconsistency



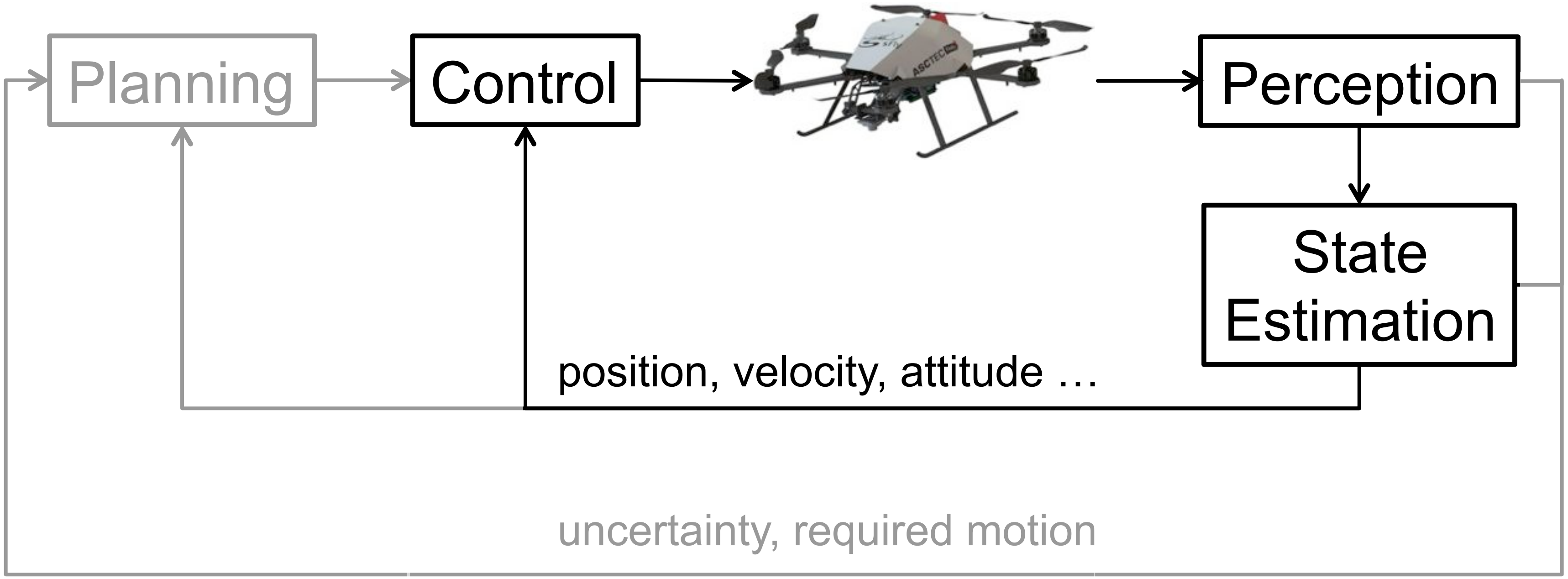
[1] S. Leutenegger et.al., "Keyframe-Based Visual-Inertial SLAM Using Nonlinear Optimization", RSS 2013
[2] A. Geiger et.al., "Efficient Large Scale Stereo Matching", ACCV 2010
[3[A. Hornung et.al, "Octomap: An Efficient Probabilistic 3D Mapping Framework Based on Octrees" ,Aut. Rob. 2013

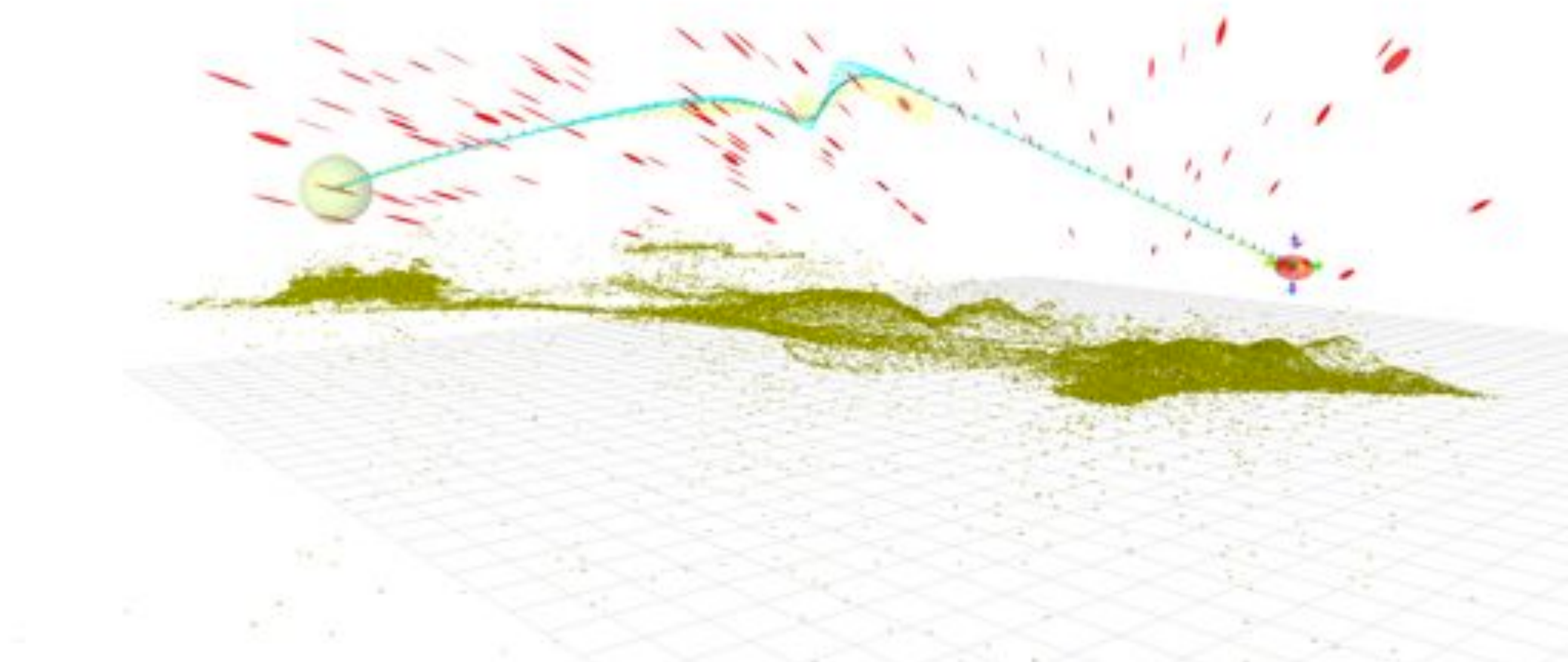
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich
Autonomous Systems Lab

Skybotix
TECHNOLOGIES

Visual-Inertial Navigation & Dense Reconstruction IROS 2013

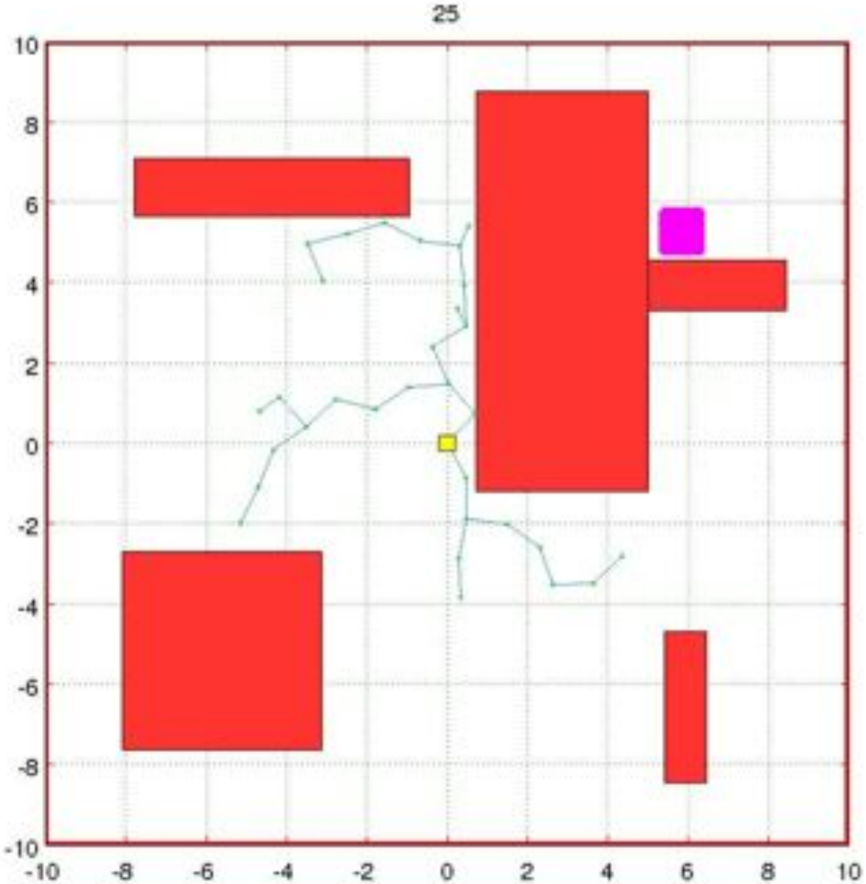
Outline


Planning
Control
Perception
State Estimation
position, velocity, attitude …
uncertainty, required motion



Motion and Uncertainty Aware Path Planning

Random Sampling Based Planning Methods

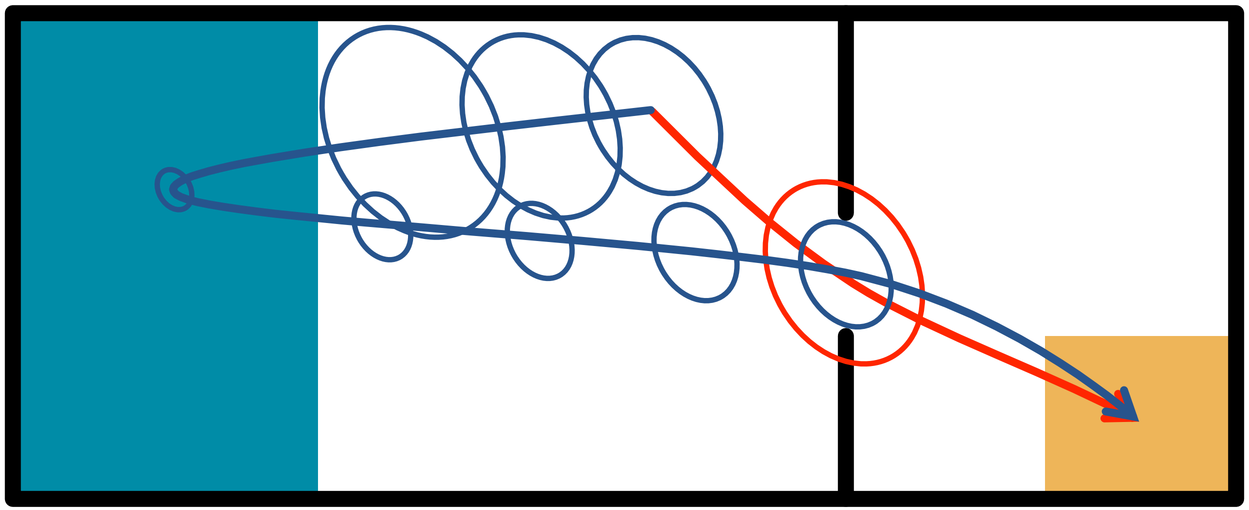


Video: S. Karaman

Rapidly-exploring Random Belief Trees (RRBT)

[Bry and Roy, ICRA 2011]

- Extends sample-based algorithms to handle measurement uncertainty
- Searches over candidate paths as an extension of the RRT* framework

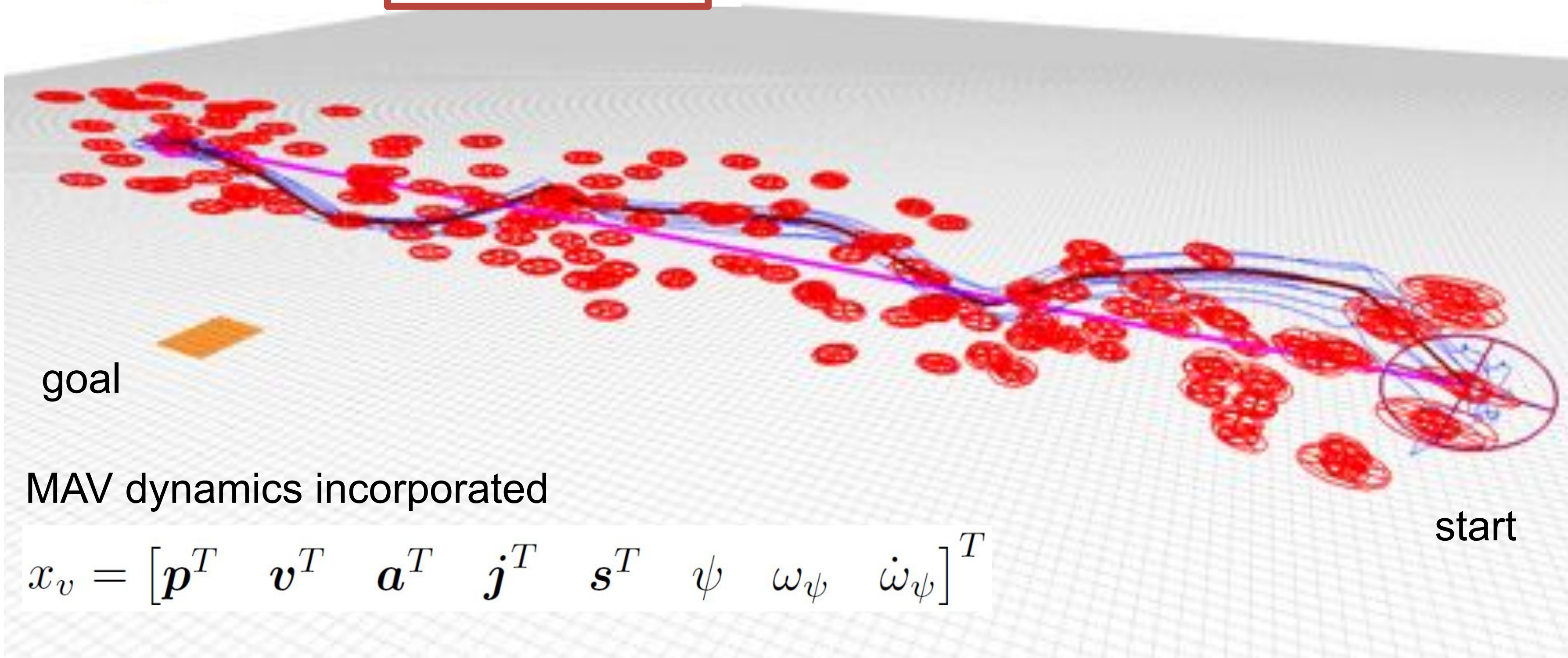


Motion Aware Path Planning

EKF state

$$x_f = \left[\boldsymbol{p}_w^{i\,T} \;\; \boldsymbol{v}_w^{i\,T} \;\; q_w^{i\,T} \;\; \boxed{\boldsymbol{b}_\omega^T \;\; \boldsymbol{b}_a^T \;\; \lambda \;\; \boldsymbol{p}_i^s \;\; q_i^s} \right]^T$$

need excitation !

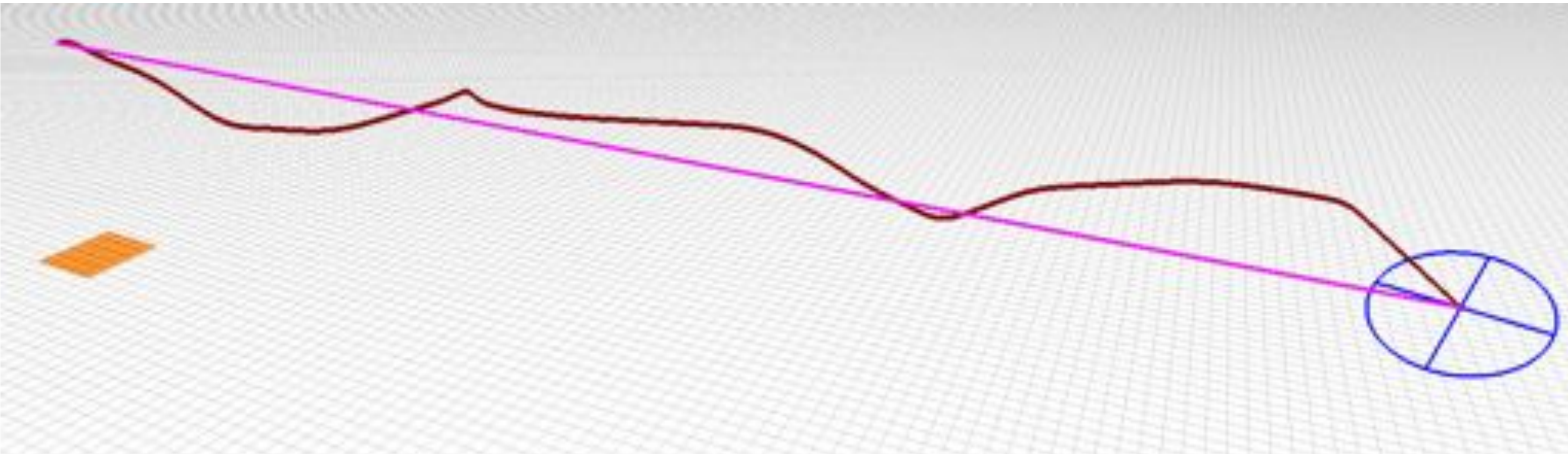


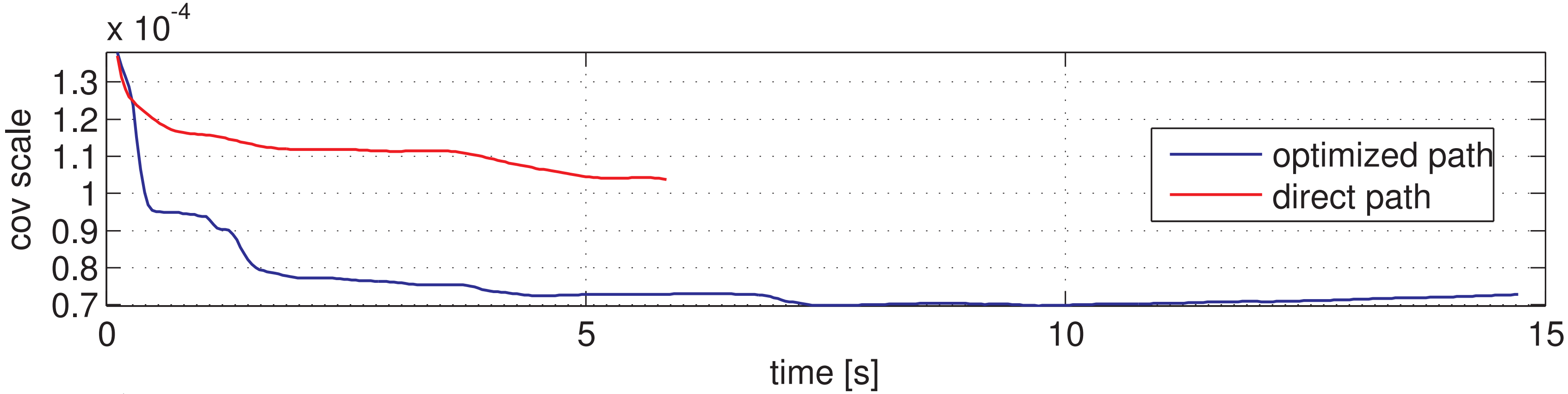
MAV dynamics incorporated

$$x_v = \left[\boldsymbol{p}^T \quad \boldsymbol{v}^T \quad \boldsymbol{a}^T \quad \boldsymbol{j}^T \quad \boldsymbol{s}^T \quad \psi \quad \omega_\psi \quad \dot{\omega}_\psi \right]^T$$

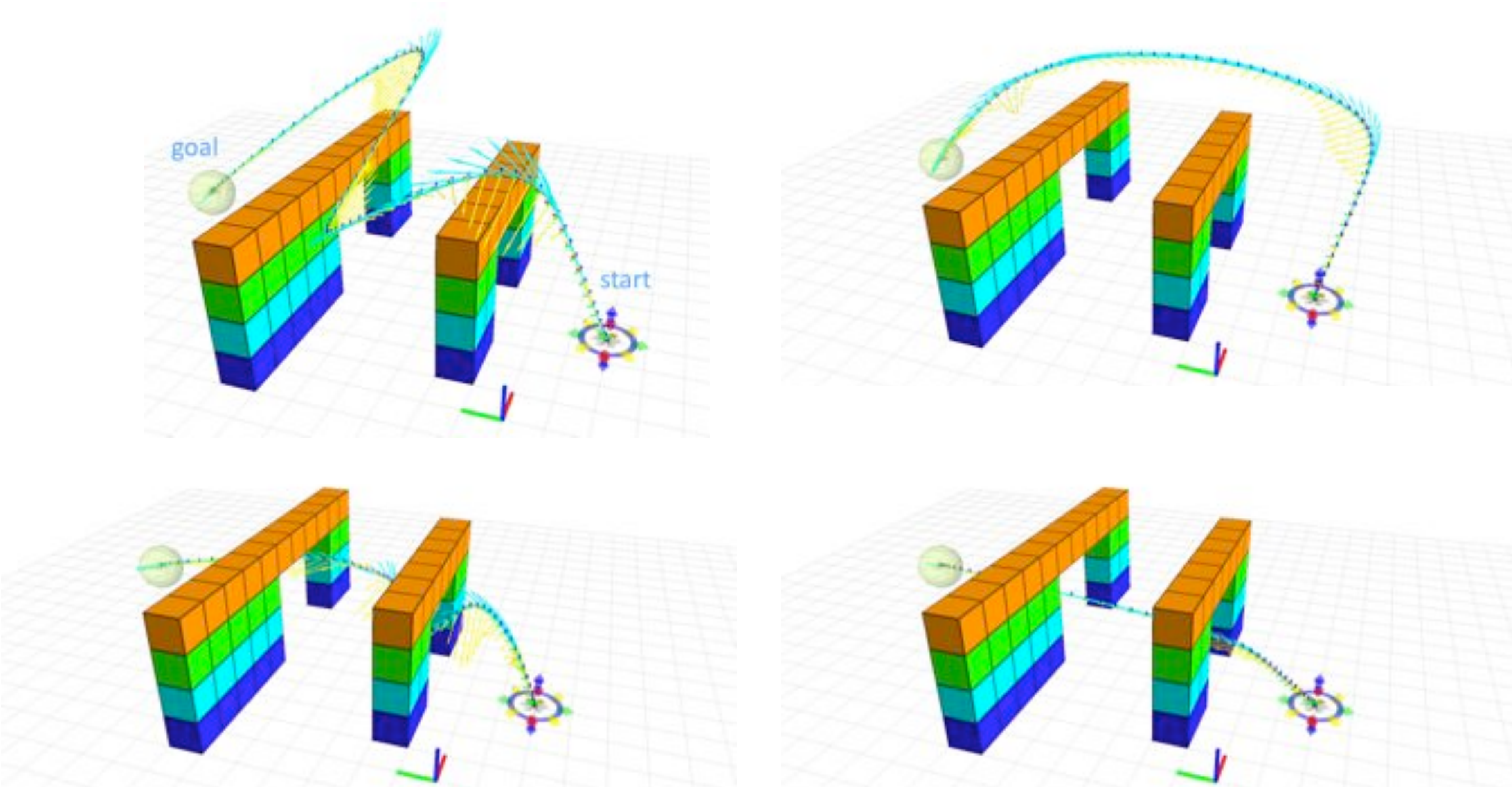
[Achtelik et al., ICRA 2013]

Results: Optimized vs. Direct Path



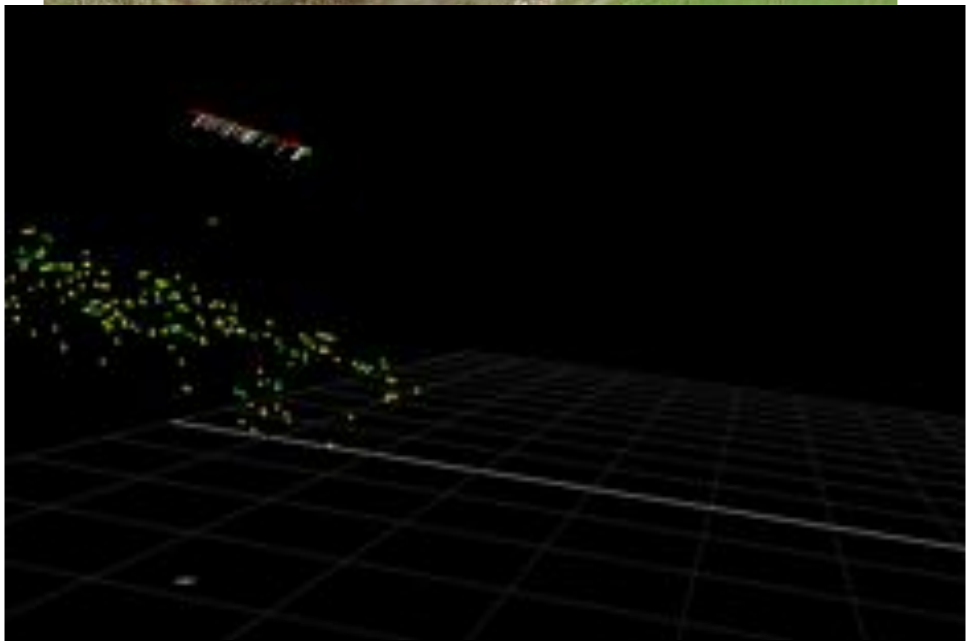


Obstacle Avoidance

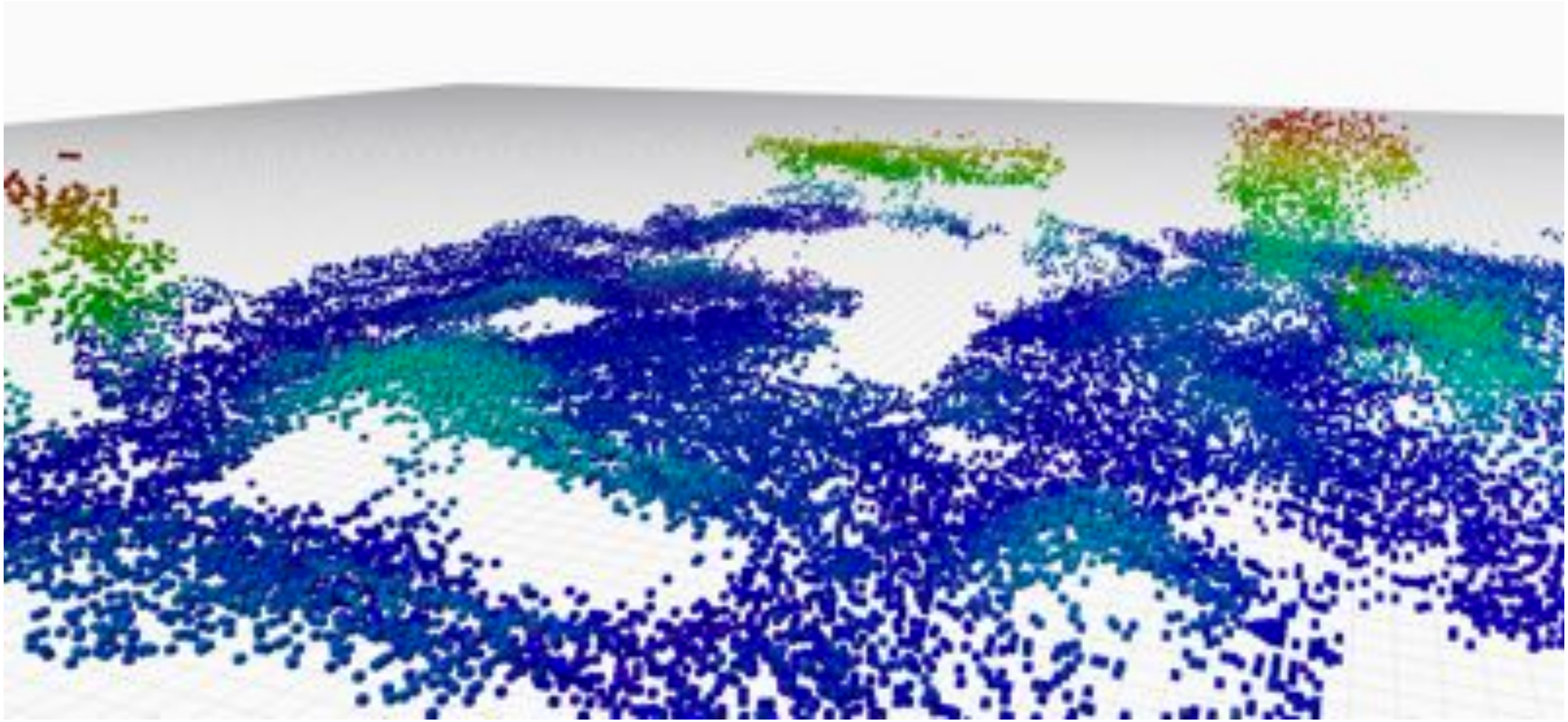


Field Tests

- Map construction from fly-over in safe altitude "approach and land"
- Point clouds from VSLAM
- Inserted as "laser-scans" into occupancy grid
- → Obstacle-lookups and covariance computation during RRBT steer- and propagation phase



Field Tests – Map Generation



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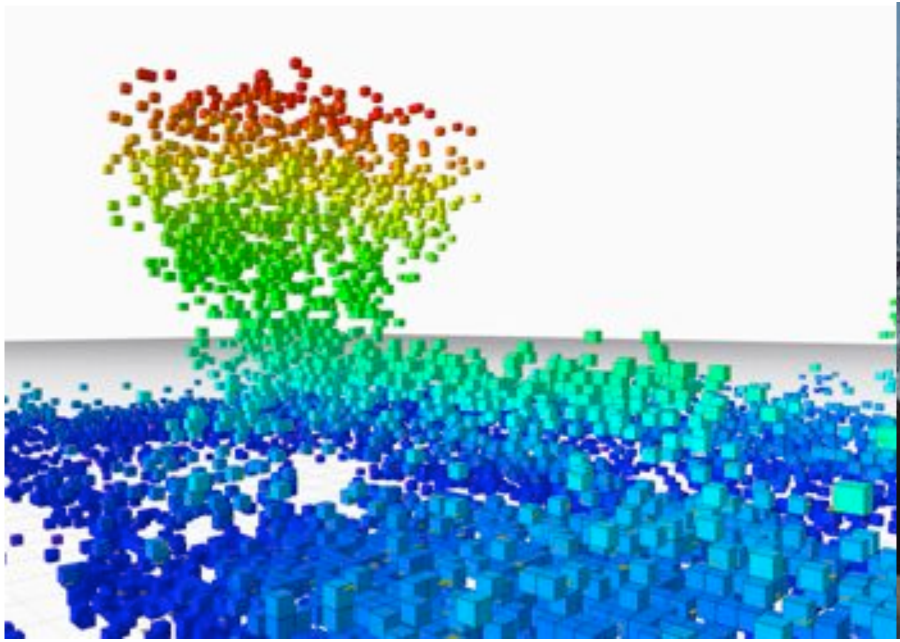
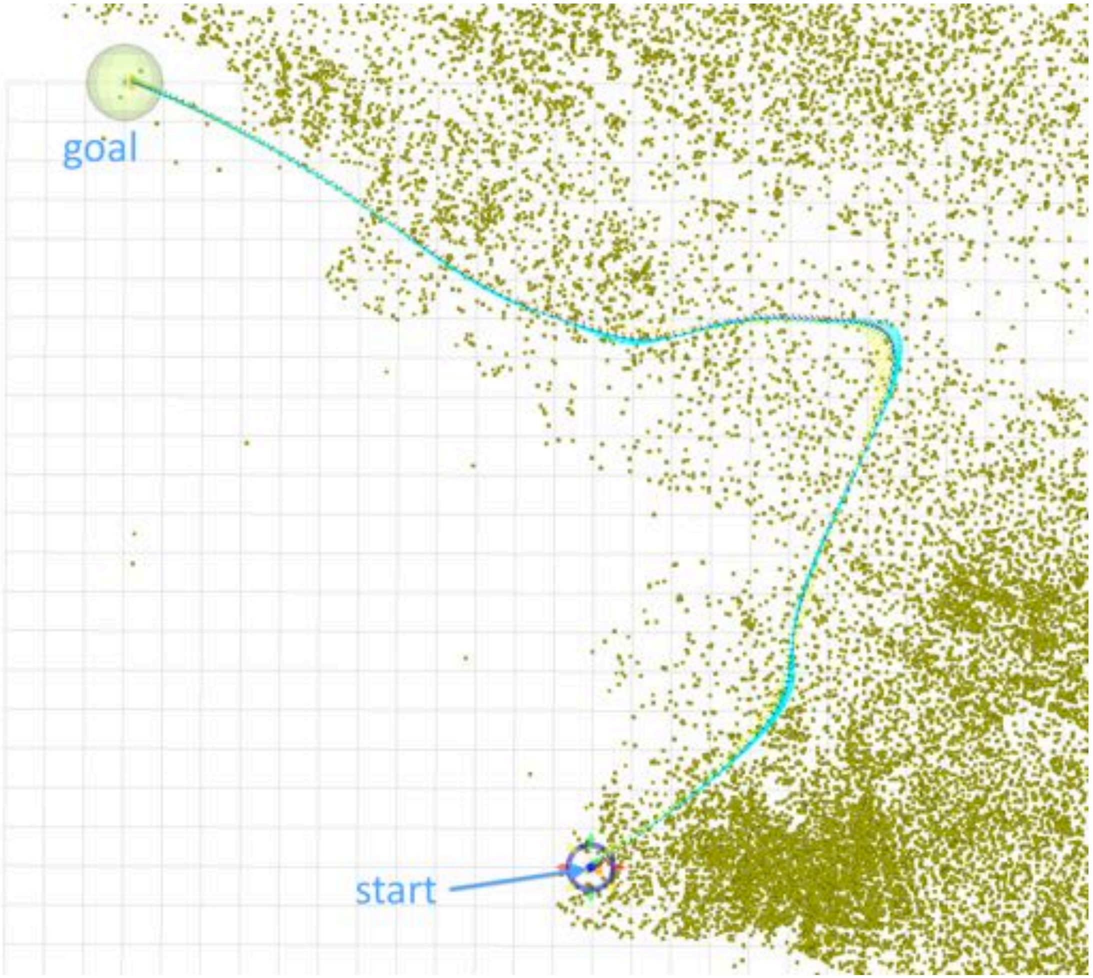


Tests with featureless areas



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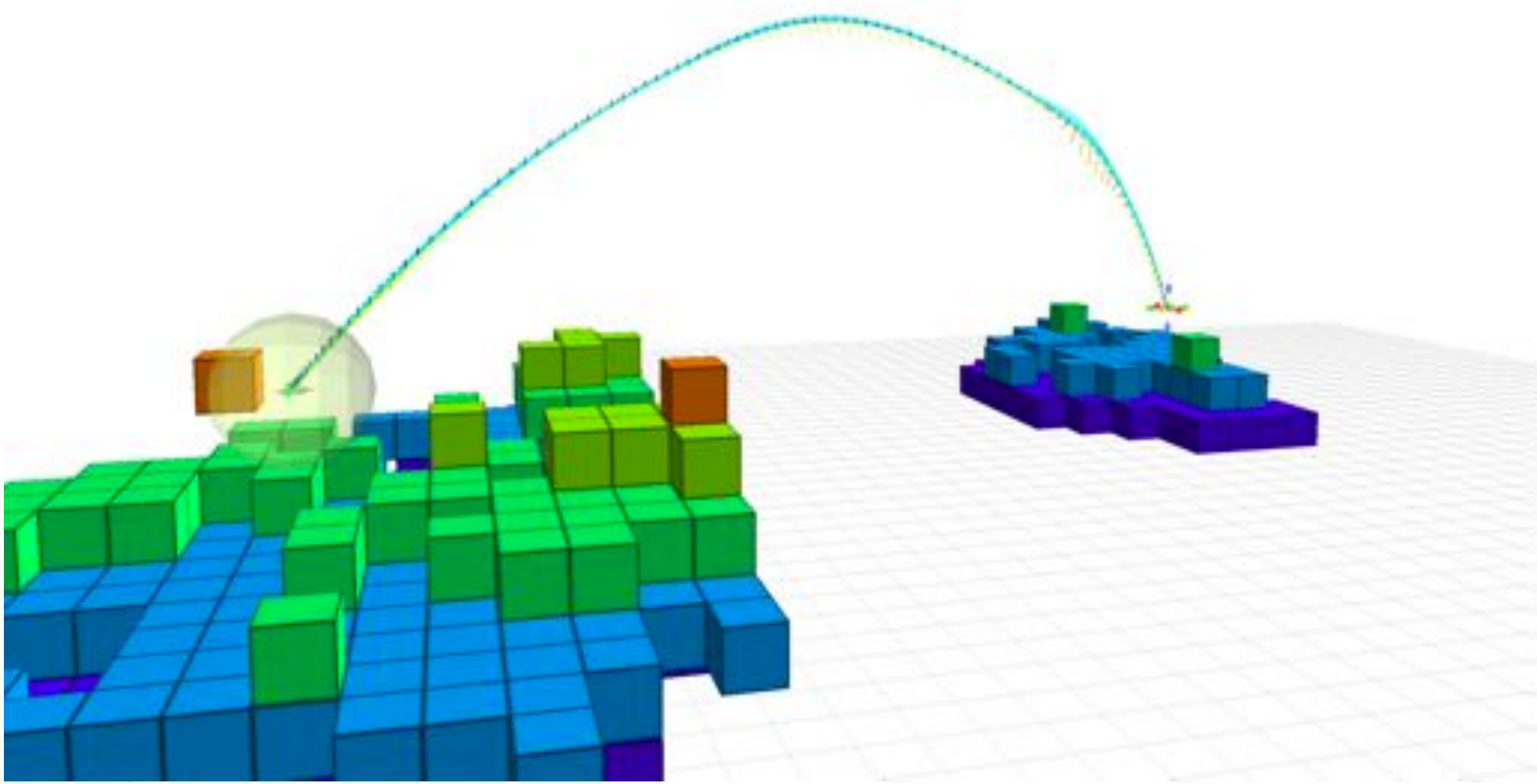
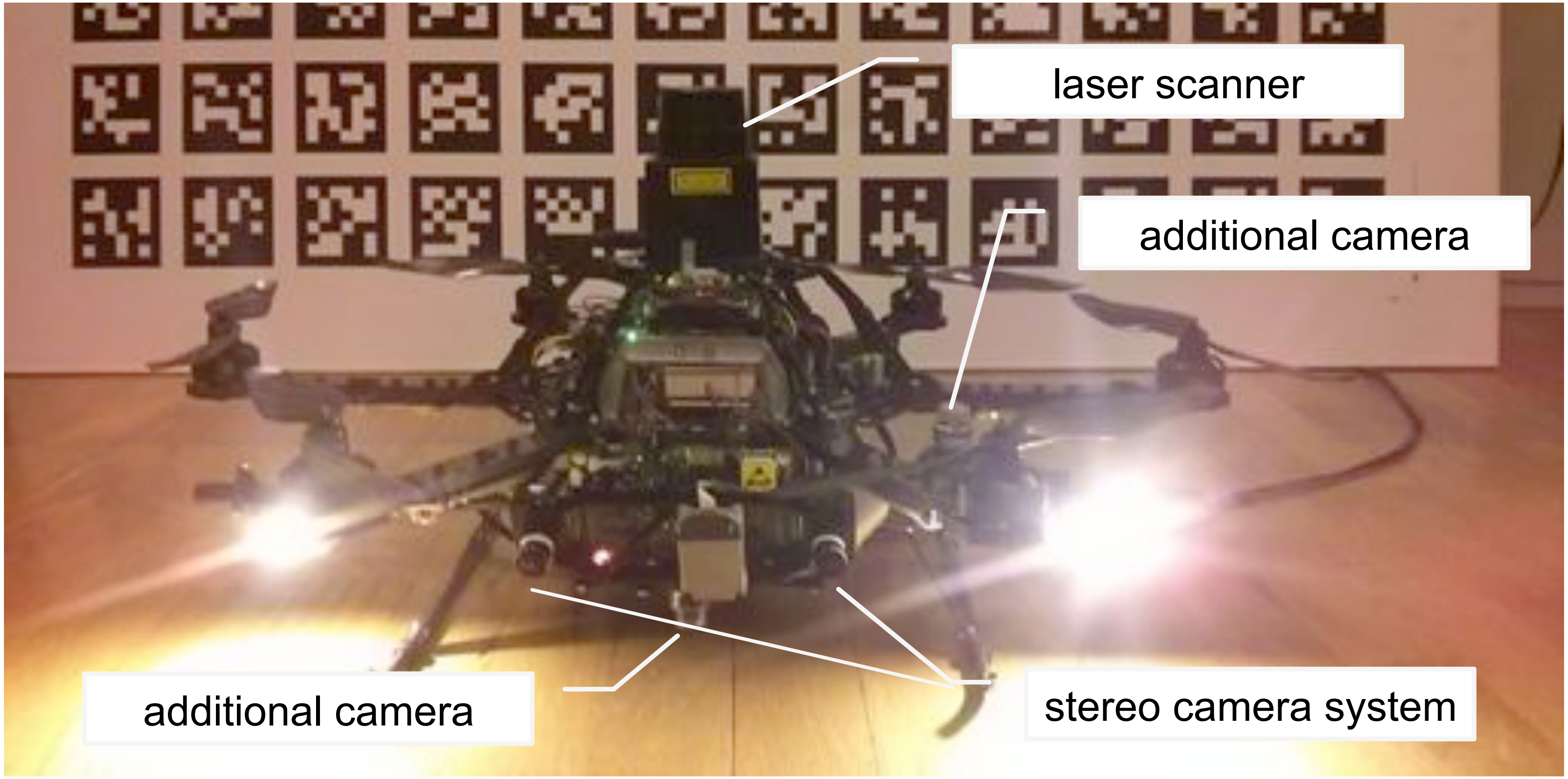


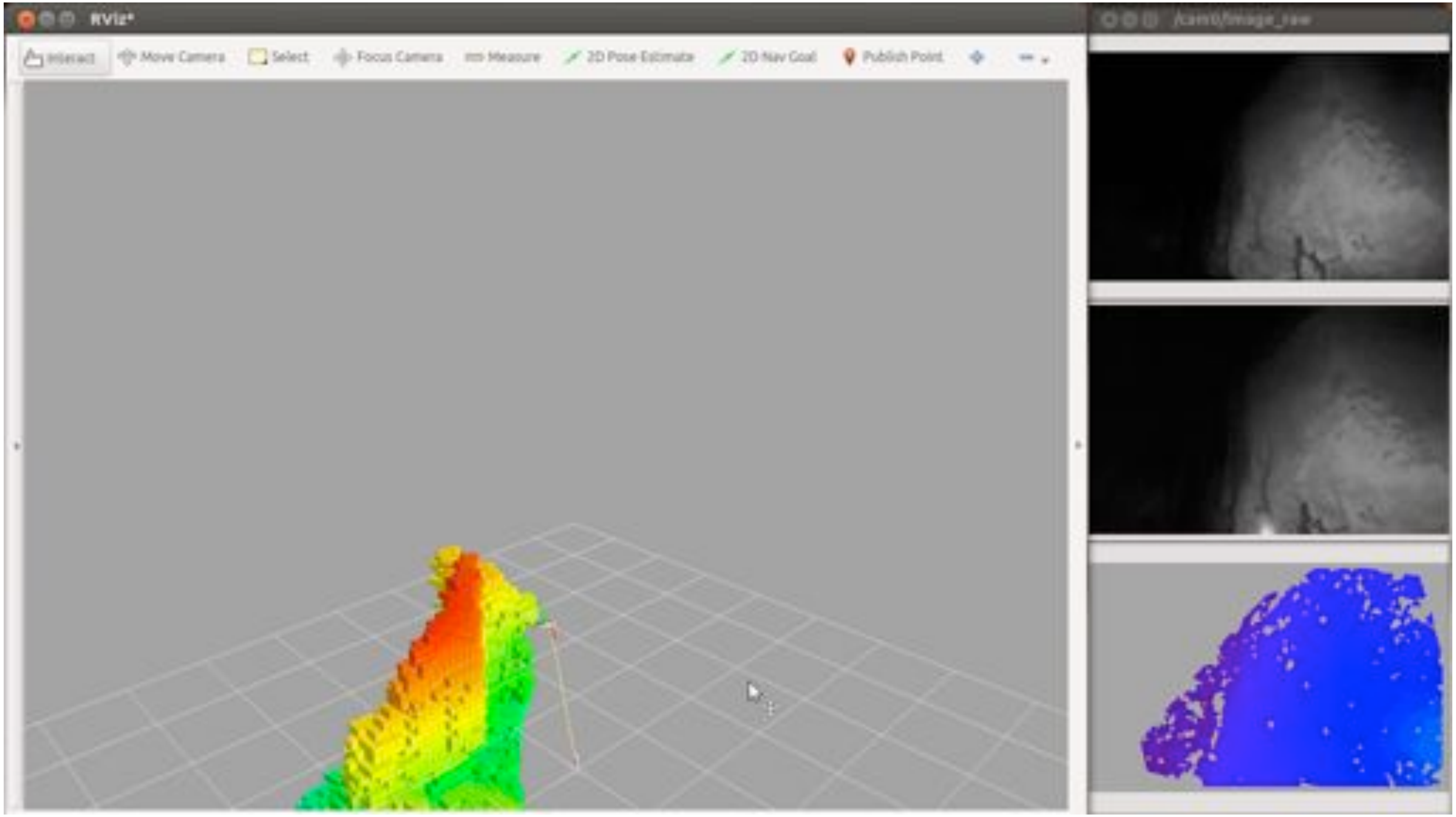
Planning and Exploration

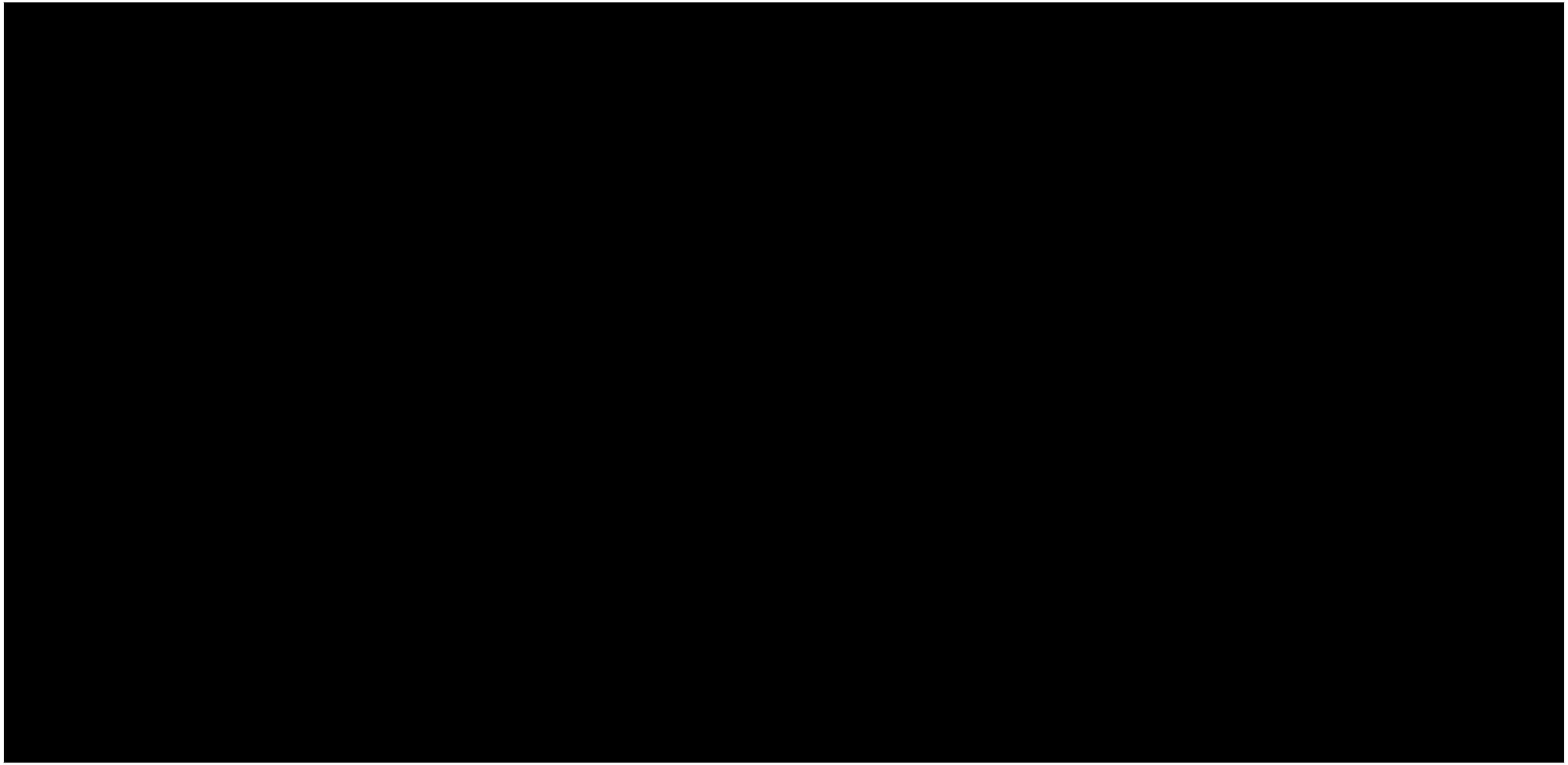
[Bircher, Alexis 2014]

Outlook – Inspection Tasks in Industry

Sensors and Illumination Integrated on Hex-Rotor




RViz*
Interact
Move Camera
Select
Focus Camera
Measure
2D Pose Estimate
2D Nav Goal
Publish Point



FP7-2013-NMP-ICT-FoF

Grant agreement no.: 608849

Funding scheme: CP-IP

EuRoC in a Nutshell

- The project proposes to launch three industry-relevant challenges aimed at sharpening the focus of European manufacturing through a number of application experiments, while adopting an innovative approach which ensures benchmarking and performance evaluation
- Within an open call framework, three stages of increasing complexity and financial support for competing teams will level the playing field for new contestants, attract new developers and new end users toward customisable robot applications, and provide sustainable solutions for future challenges

Reconfigurable Interactive Manufacturing Cell

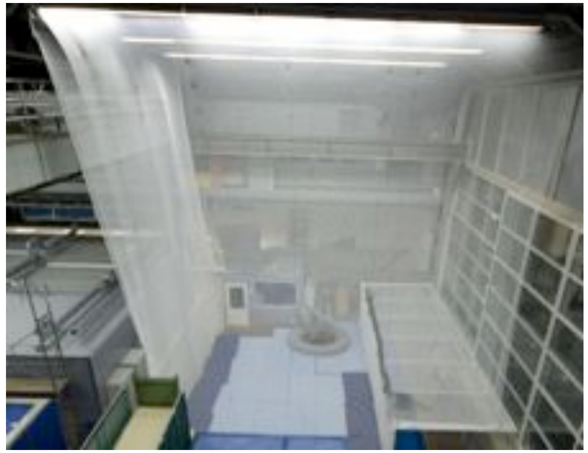
Shop Floor Logistics and Manipulation

Plant Inspection and Servicing

Challenge C3

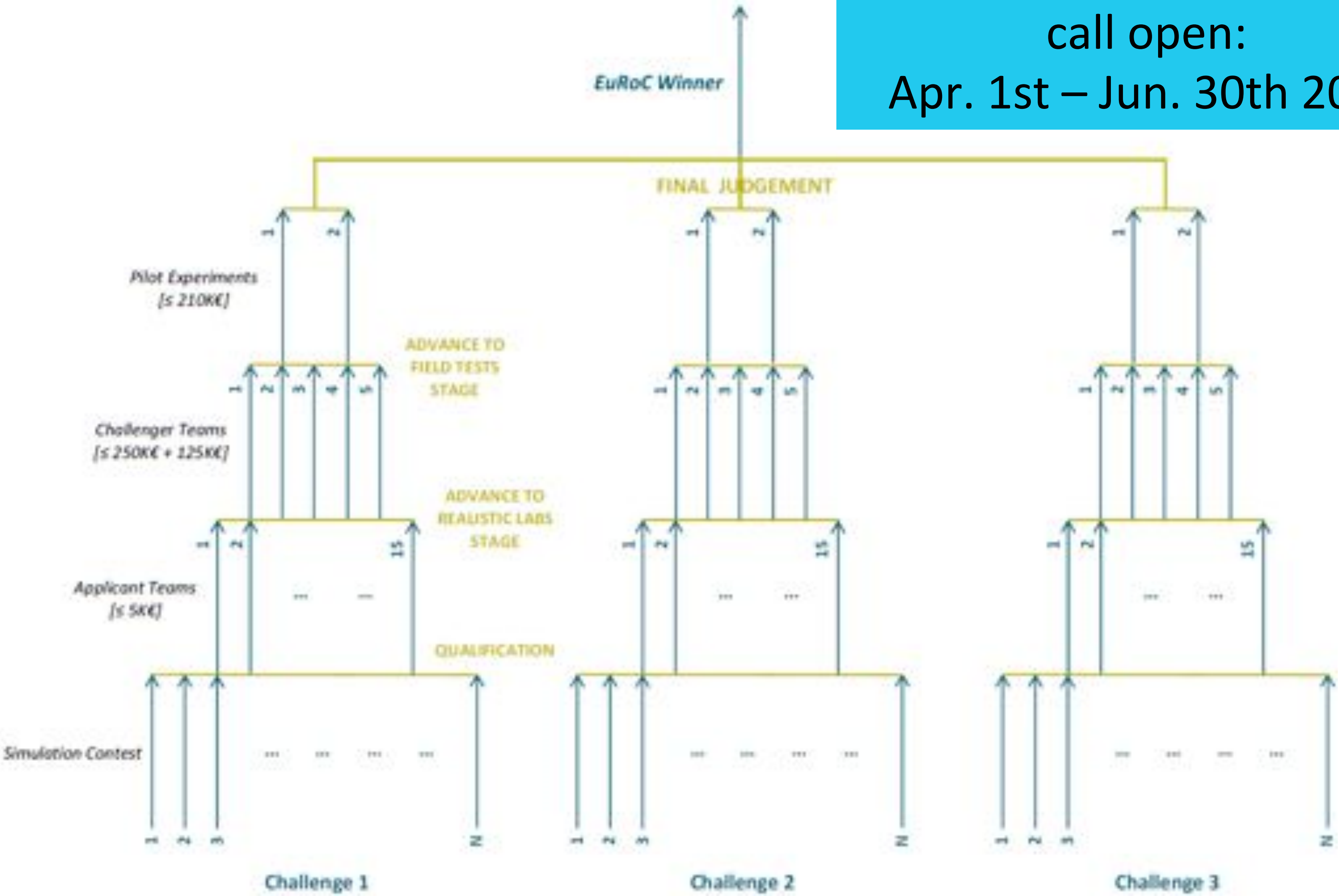
Plant Servicing and Inspection

- **Motivation**: inspection through micro aerial robots (MAV) opens absolutely new applications in servicing of large plants and infrastructures
- **RTD issues**: highly reliable vision-only navigation, dynamic control of MAVs in challenging industrial environments, high-level task allocation by mission expert, e.g. "follow this wall"
- **Research experts**: ETHZ, CREATE-PRISMA Lab, DLR
- **Technology supplier**: Ascending Technologies
- **System integrator**: Alstom Inspection Robotics
- **Platform host**: ETHZ
- **Benchmark environment**: realistic set-up on an industrial infrastructure, e.g. pipework and infrastructure for energy-/fuel-/operating material supply, tanks and storages



Challenge Chart

call open:
Apr. 1st – Jun. 30th 2014



European
Robotics
Challenges

SEVENTH FRAMEWORK
PROGRAMME

www.euroc-project.eu

Thank you for your Attention!

- Open source software frameworks: http://www.asl.ethz.ch/research/software