

Autonomous Mobile Robots
Navigation in the Real World

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Autonomous Systems Lab

ETH Zürich

Research @ www.asl.ethz.ch

- Mission
  - Create machines that know what they do

- Three Research Lines
  - The design of robotic and mechatronic systems
    - Space Rovers, Inspection-, Walking- and Micro-Robots
    - UAV – Solar Airplane, Micro-Helicopters
  - Navigation and mapping
    - Mapping and Reasoning in real world settings
    - Navigation and Planning in dynamic environments
  - Product design methodologies and innovation
    - Innovation and Creativity
    - Digital Products

Been there, done that

- Software Engineer
- Master+PhD in Imaging, Computer Vision and Robotics
- PhD: Intentional Navigation of a Mobile Robots.

- Post-Doc: CSIRO, Canberra/Brisbane, Australia: Field Robotics
  - Industrial Robots
  - Underwater Robots

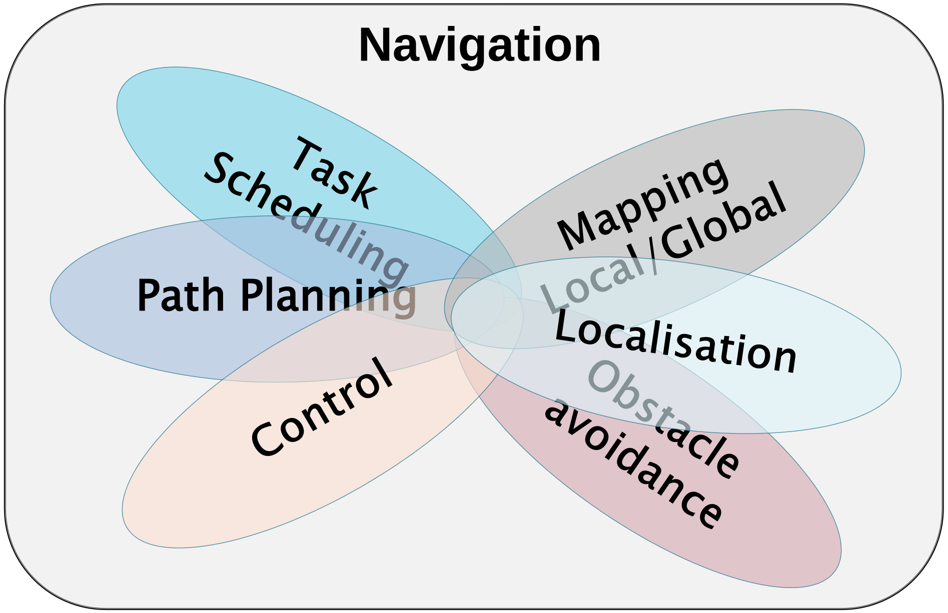
- Now: ETH Zurich, Autonomous Systems Lab (Prof. R. Siegwart)
  - Deputy Director
  - Space robotics, Home robotics, …

Navigation?

"Navigation is the art and science of reaching a destination by moving along a predefined trajectory."

- Robotic Navigation?

"Navigation is the act of reaching a given destination by moving along a controlled trajectory."



Perception: a key component

- Sensors
  - GPS
  - INS
  - Laser scanner (2D or 3D)
  - Camera
  - Depth imager (ToF cameras, Kinect)

- Characteristics
  - Accuracy
  - Field of view
  - Latency
  - Noise model
  - Jitter
  - …

Talk Outline

- Overview of navigation application from various domains developed at the ASL, from ETH Zürich and CSIRO ICT Centre.
  - Boats,
  - Ground Vehicles,
  - Micro-Helicopters…

- Identification of the characteristics as navigation tasks, and the related challenges.

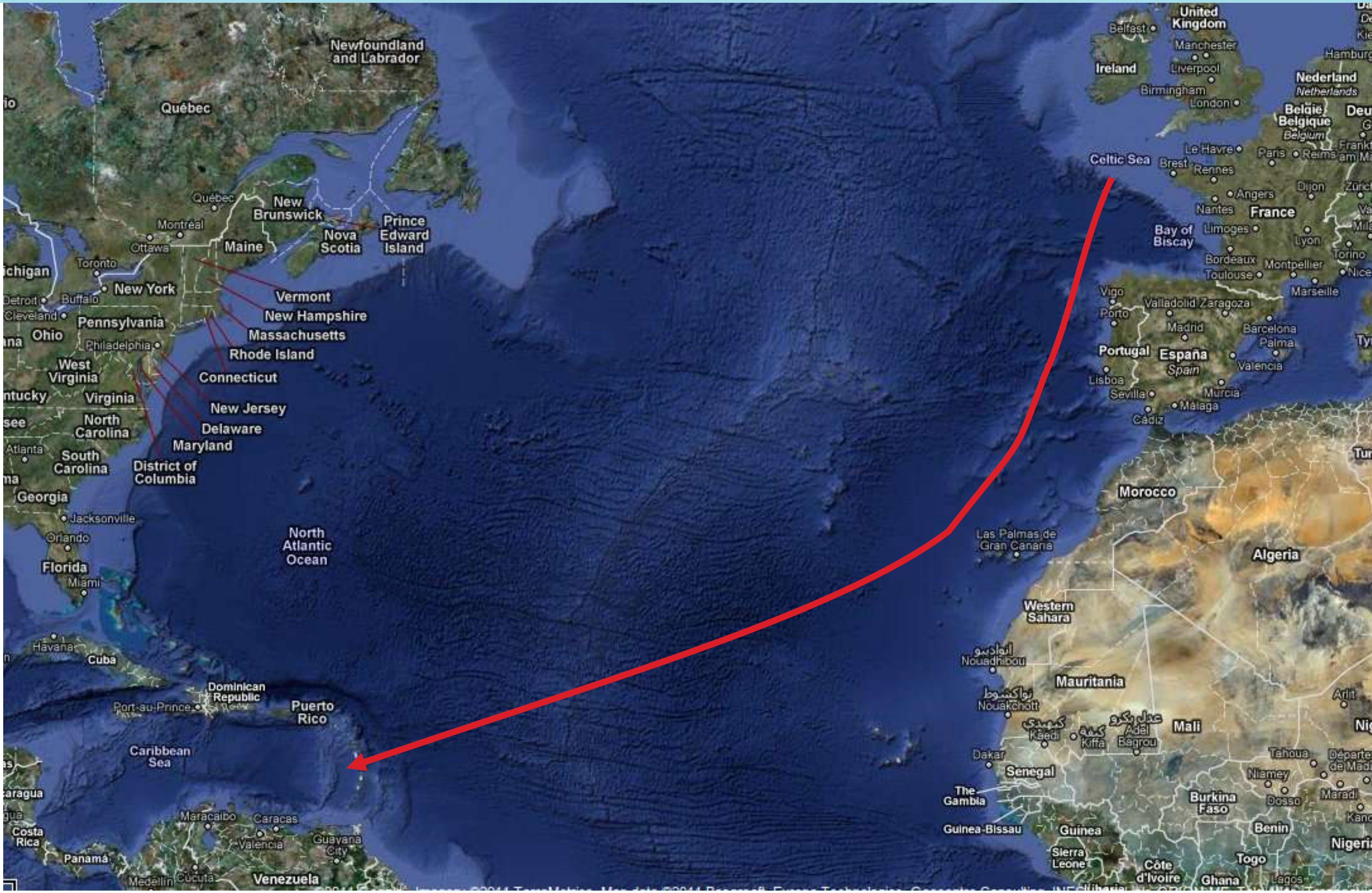
Sailing Across the Atlantic

GPS-INS

Low dynamics

Low accuracy requirements

The Original Navigation Task



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AVALON – The Autonomous Sailing Boat

www.ssa.ethz.ch

- Crossing the Atlantic
  - 4‘200 nautical Miles
  - Fully autonomous

- Technical Details
  - Very innovative design of rig
  - Length: 4m
  - Width: 1.6m
  - Over all height: 8.5m
  - Draught: 2m
  - Weight: 530kg
  - Solar power and fuel-cells

Characteristics

- Localisation:
  - GPS: Easy, enough accuracy
- Mapping:
  - Not necessary
- Path Planning:
  - Easy, Static
- Task Scheduling:
  - Easy
- Obstacle Avoidance:
  - AIS: perception of other boats
  - Local planning but very low maneuverability
- Control:
  - Path following and upwind sailing

Challenges

- Autonomy
  - Decision, Perception, Energy
  - Obtacle Avoidance
- Robustness
  - High wind, strong waves,
- Reliability
  - Mechanical, Electrical, Software
- Durability
  - Approx. 3 months of autonomous behavior

Navigation experiments

Robotic for Environment Monitoring

GPS-INS
Low dynamics
Low accuracy requirements

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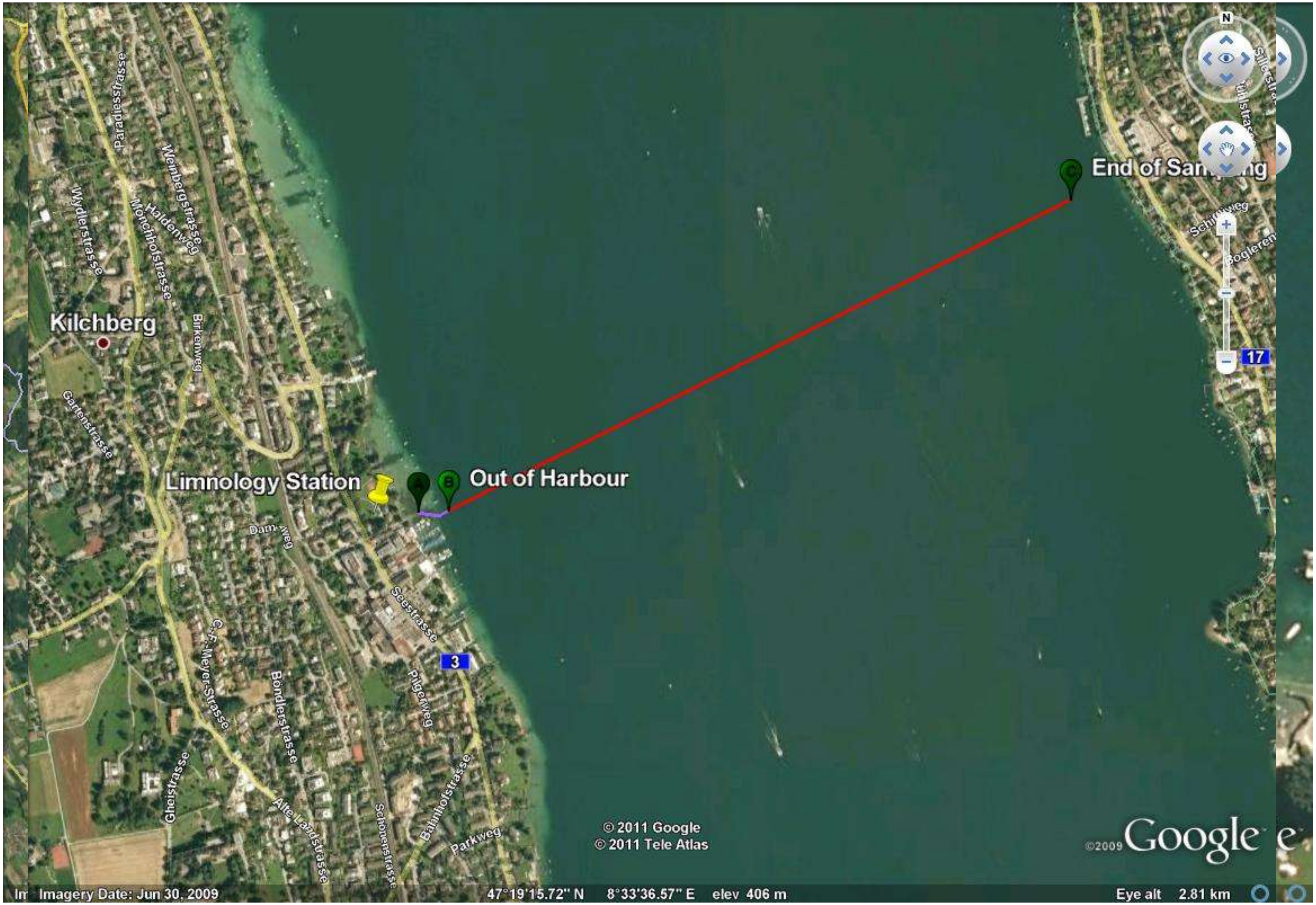
Navigation for Environment Monitoring



Limnobotic– Autonomous monitoring of lake water quality

- Regular measurement
  - Fully autonomous
  - 2-3km transects on a daily basis
  - Measurement up to 100m depth

- Technical Details
  - Custom made hull design
  - Length: 2.5m
  - Width: 1.6m
  - Weight: 120kg
  - Electric motors and marine grade batteries

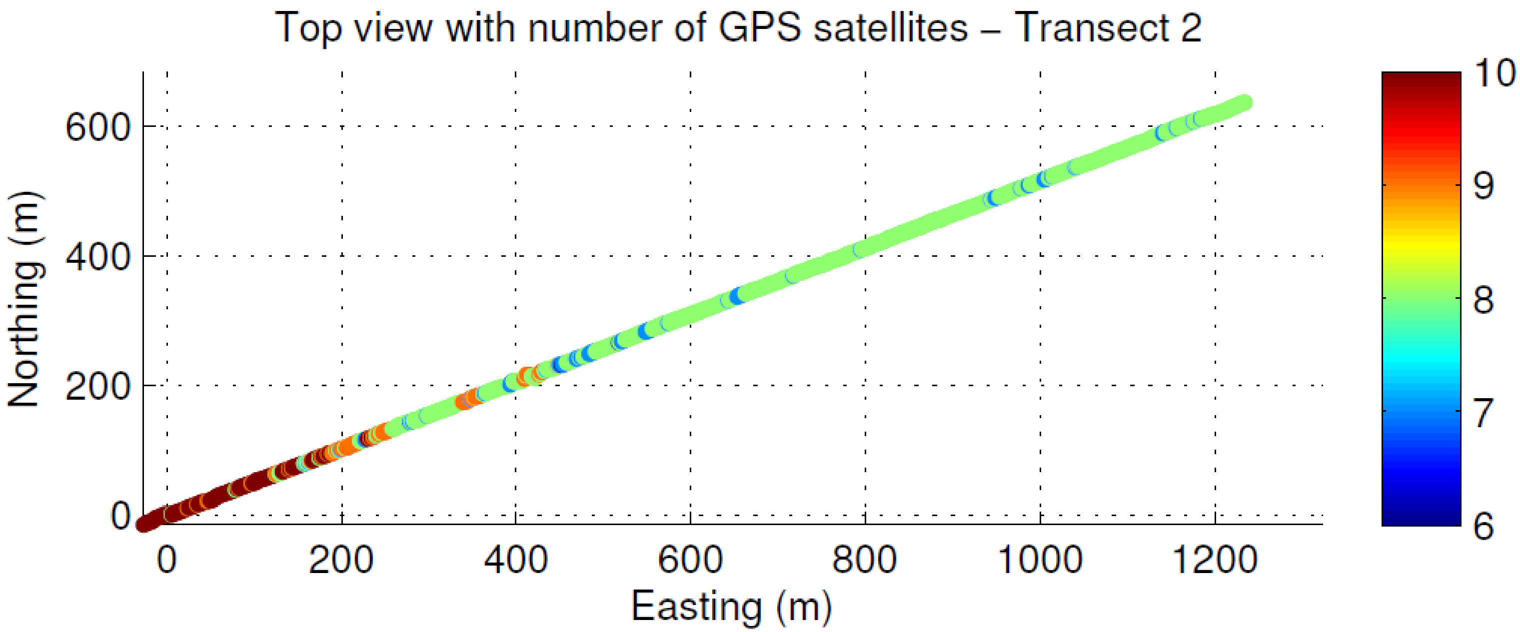
Characteristics

- Localisation:
  - GPS: Easy, enough accuracy
- Mapping:
  - Spatio-temporal mapping of a biological phenomenon
- Path Planning:
  - Easy, Static
- Task Scheduling:
  - Navigation, sampling, winch control, …
- Obstacle Avoidance:
  - Very challenging: perception and maneuverability
- Control:
  - Path following, velocity control, synchronisation with the winch

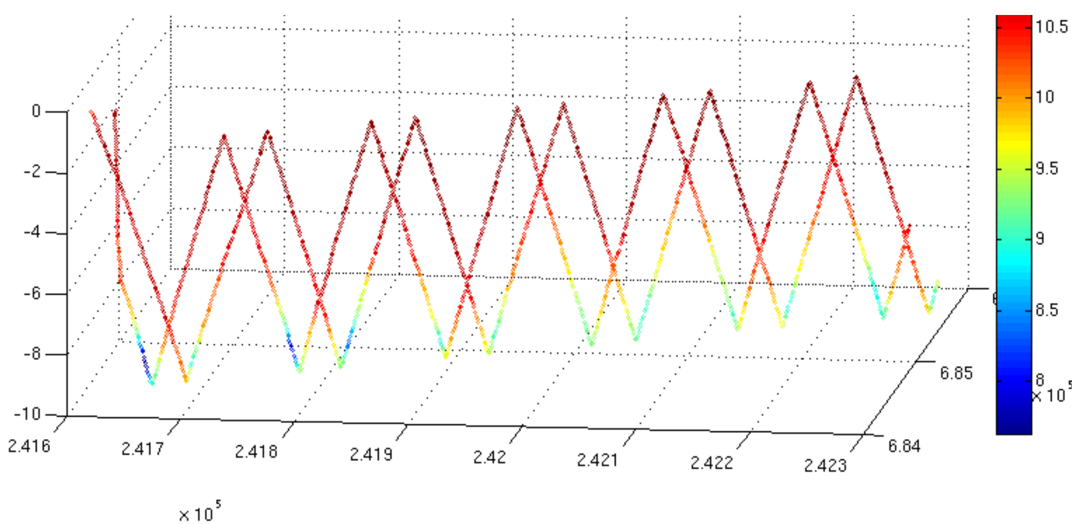
Challenges

- Autonomy
  - Vision-Based Obtacle Avoidance
  - Adaptive Sampling
- Reliability
  - Mechanical, Electrical, Software
- Validation
  - Serious experimental protocol to be able to make conclusions out of the biological data

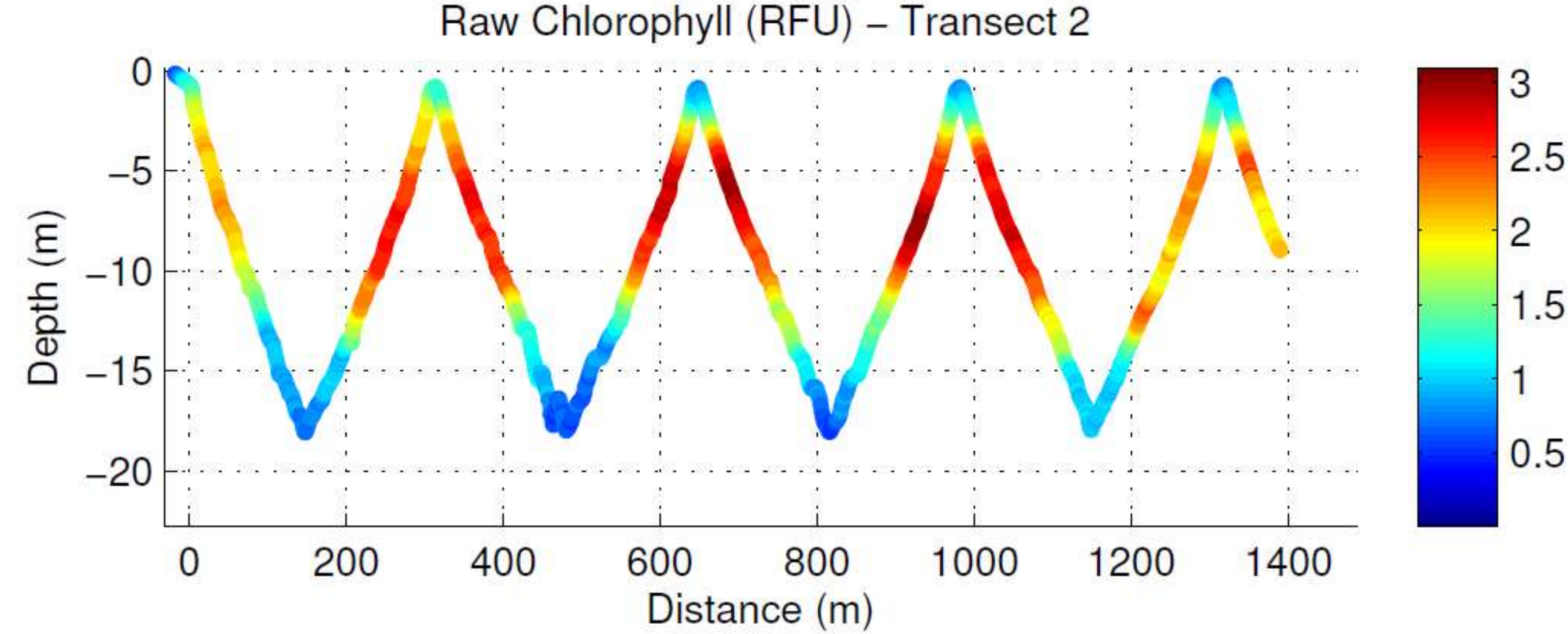
Results

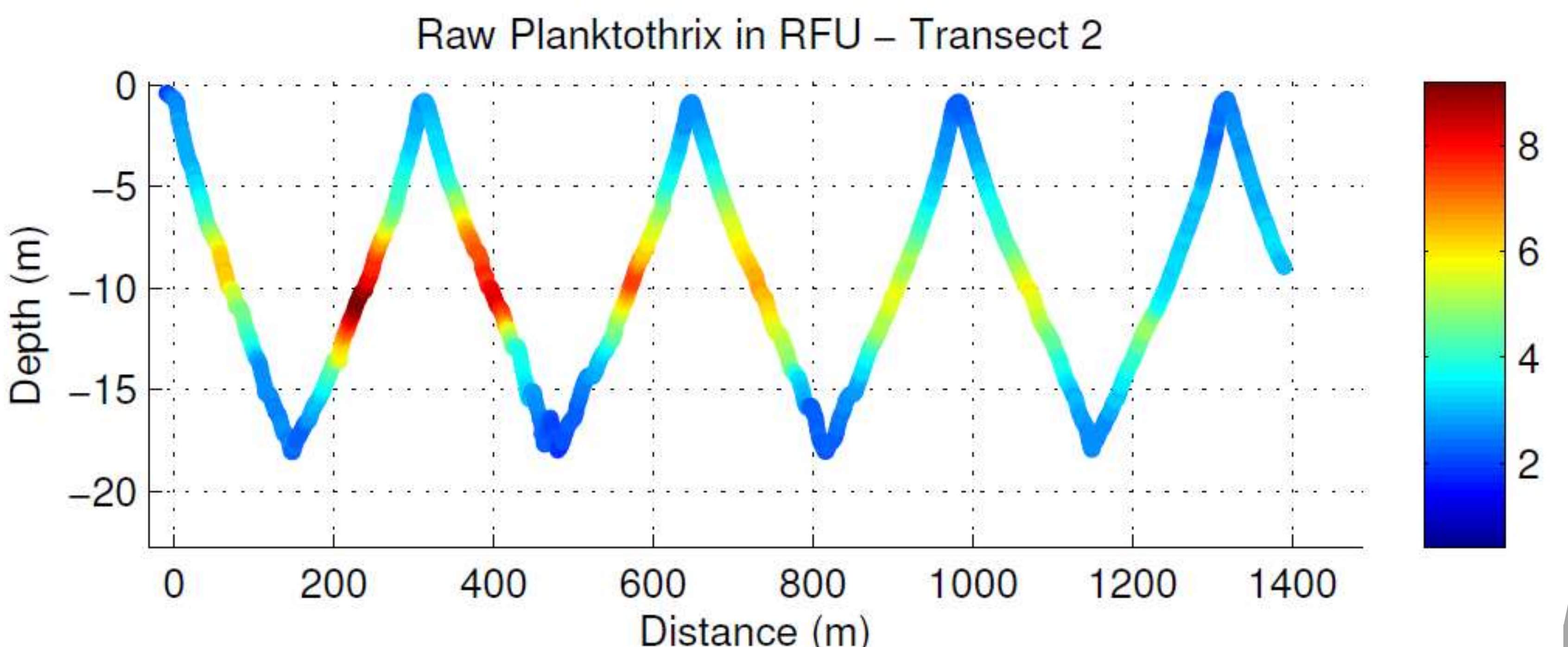


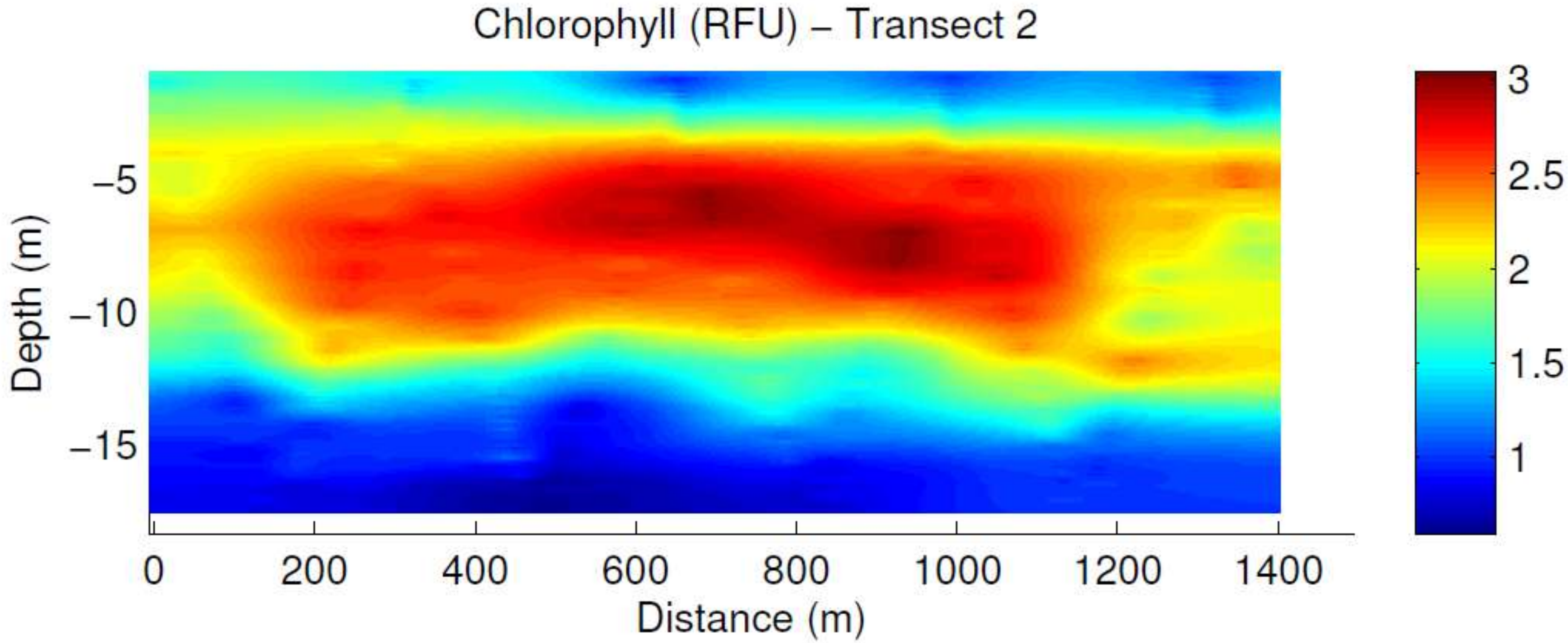
Top view with number of GPS satellites – Transect 2
Northing (m)
Easting (m)
0
200
400
600
800
1000
1200
10
9
8
7
6

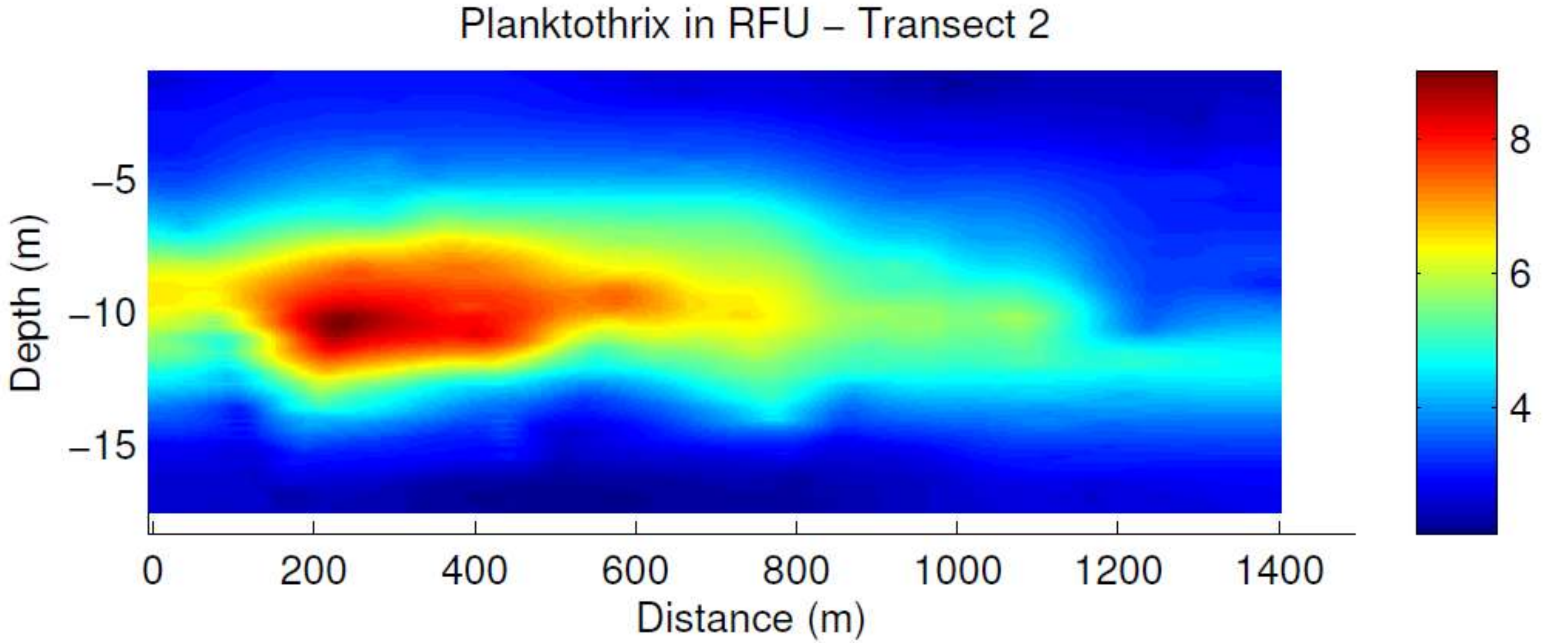


0
-2
-4
-6
-8
-10
2.416
2.417
2.418
2.419
2.42
2.421
2.422
2.423
× 10^5
6.85
6.84
10.5
10
9.5
9
8.5
8
× 10^5


Raw Chlorophyll (RFU) – Transect 2
Depth (m)
0
−5
−10
−15
−20
Distance (m)
0
200
400
600
800
1000
1200
1400
3
2.5
2
1.5
1
0.5


Raw Planktothrix in RFU – Transect 2
Depth (m)
0
−5
−10
−15
−20
Distance (m)
0
200
400
600
800
1000
1200
1400
8
6
4
2

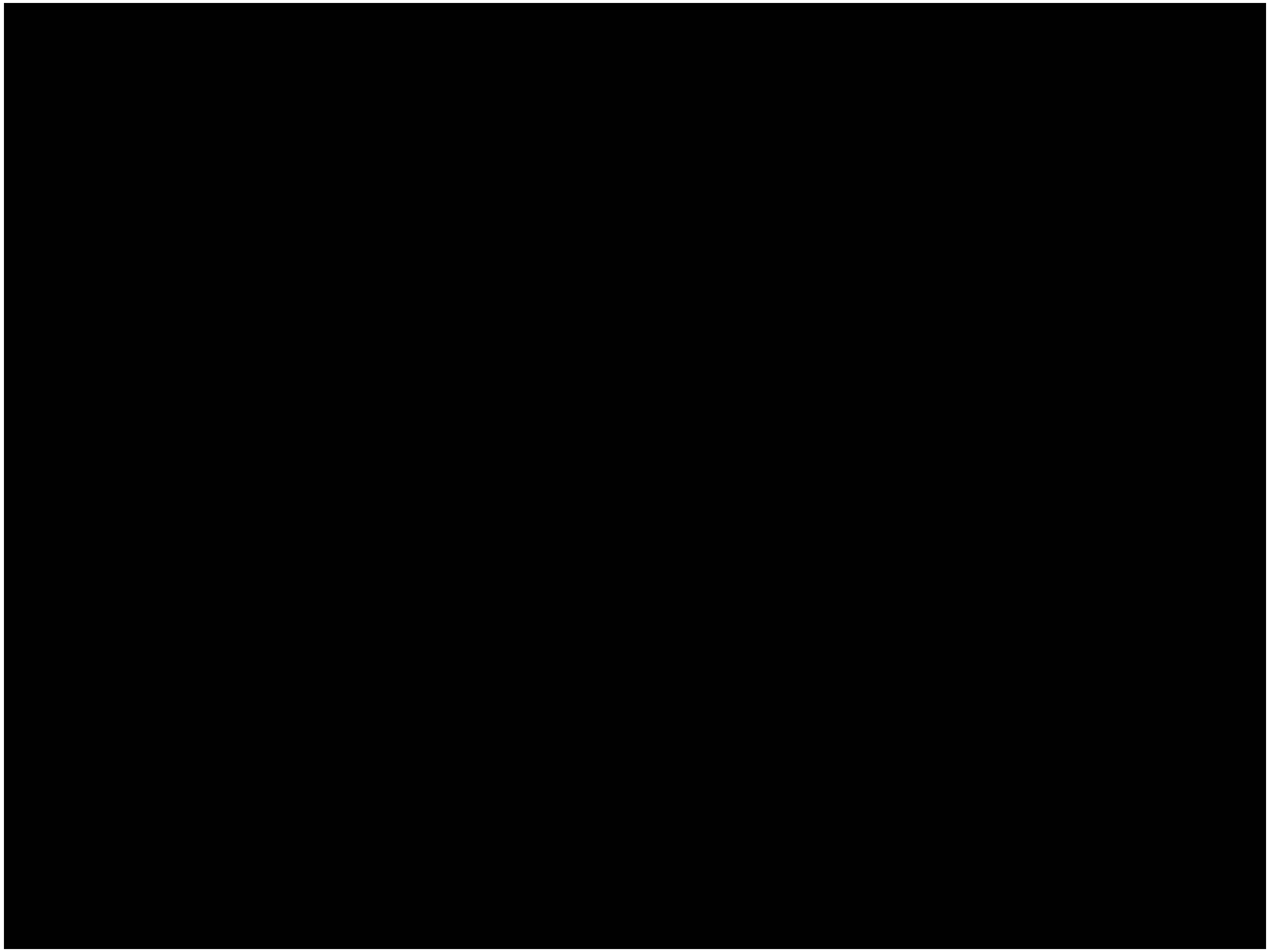

Chlorophyll (RFU) – Transect 2
Depth (m)
−5
−10
−15
0
200
400
600
800
1000
1200
1400
Distance (m)
3
2.5
2
1.5
1


Planktothrix in RFU – Transect 2
Depth (m)
−5
−10
−15
0
200
400
600
800
1000
1200
1400
Distance (m)
8
6
4

Industrial Vehicles: Load Transportation

Laser, vision, GPS-INS
High accuracy requirements
Weak energy constraints

Hot Metal Carrier Operations



Work conducted at the CSIRO ICT Centre, QLD, Australia

Characteristics

- Localisation:
  - Laser scanners: high-accuracy, low noise, reliability
- Mapping:
  - Offline, Static environment
- Path Planning:
  - Predefined path segments, driven by hand and recorded
- Task Scheduling:
  - Complex: synchronisation of mast/hook operations with movement, detection of the load, interaction with infrastructure.
- Obstacle Avoidance:
  - Laser based, collision prevention
- Control:
  - Trajectory tracking, load pick-up, speed control with gears

CSIRO

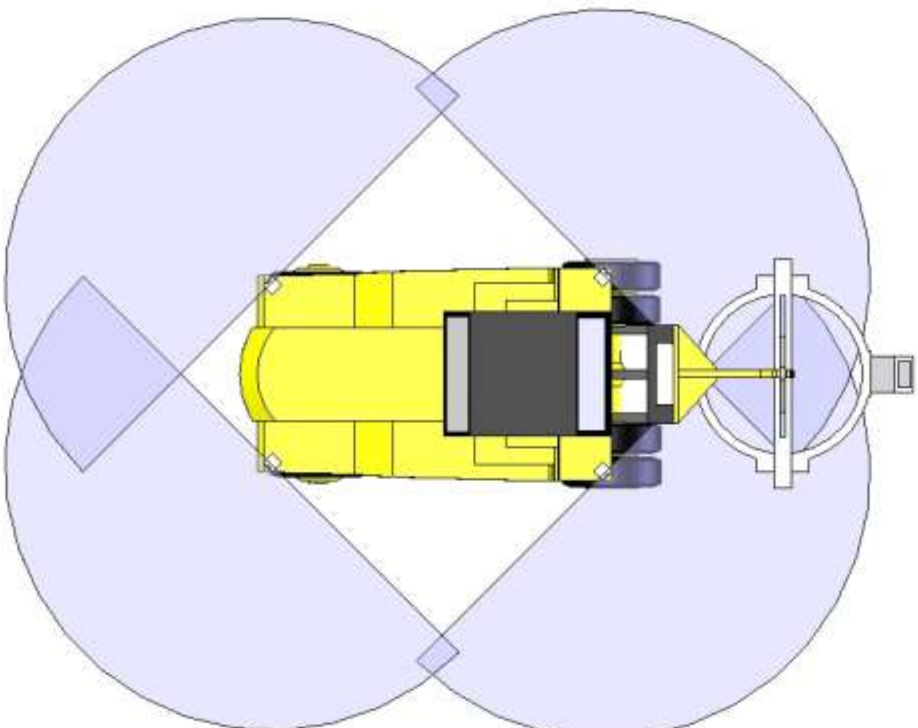
Challenges

- Load handling
  - Vision-based load handling
  - Accurate alignment for pickup (+/- 5cm tolerance)
- Long-duration Reliability
  - Mechanical, Electrical, Software
- Safety while testing
  - 20 tonnes
  - 3 m/s

CSIRO

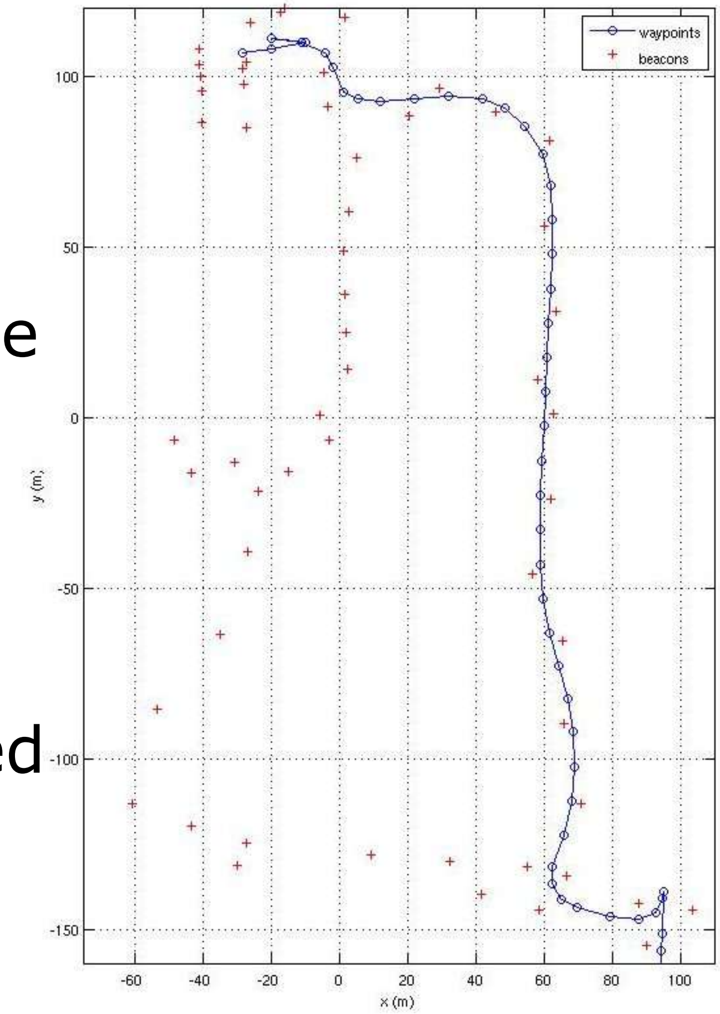
Laser Setup

- 4 Sick Laser: 30m range, 4degrees tilt, 1.2m high
- Overlapping fields for redundancy
- Also used for obstacle avoidance



Navigation and Obstacle Management

- Waypoint navigation
  - (x, y, vel) tuples
- Segments are a sequence of waypoints
- Obstacle management simply velocity controlled by object's proximity



CSIRO

Localisation technique

- Range and angle measurement to reflecting structure (GPS not suitable here)
- Probabilistic Model of Perception
- Data Association with Nearest Neighbour
  - Not the best solution for this problem but sufficient here.

Probabilistic Localisation

- Particle Filter: special instance of a Bayesian Filter:

$$Q_t = P(X_t \mid Z_0 \cdots Z_t U_0 \cdots U_t) = P(Z_t \mid X_t) \int_{X_{t-1}} P(X_t \mid X_{t-1} U_{t-1})\, Q_{t-1}$$

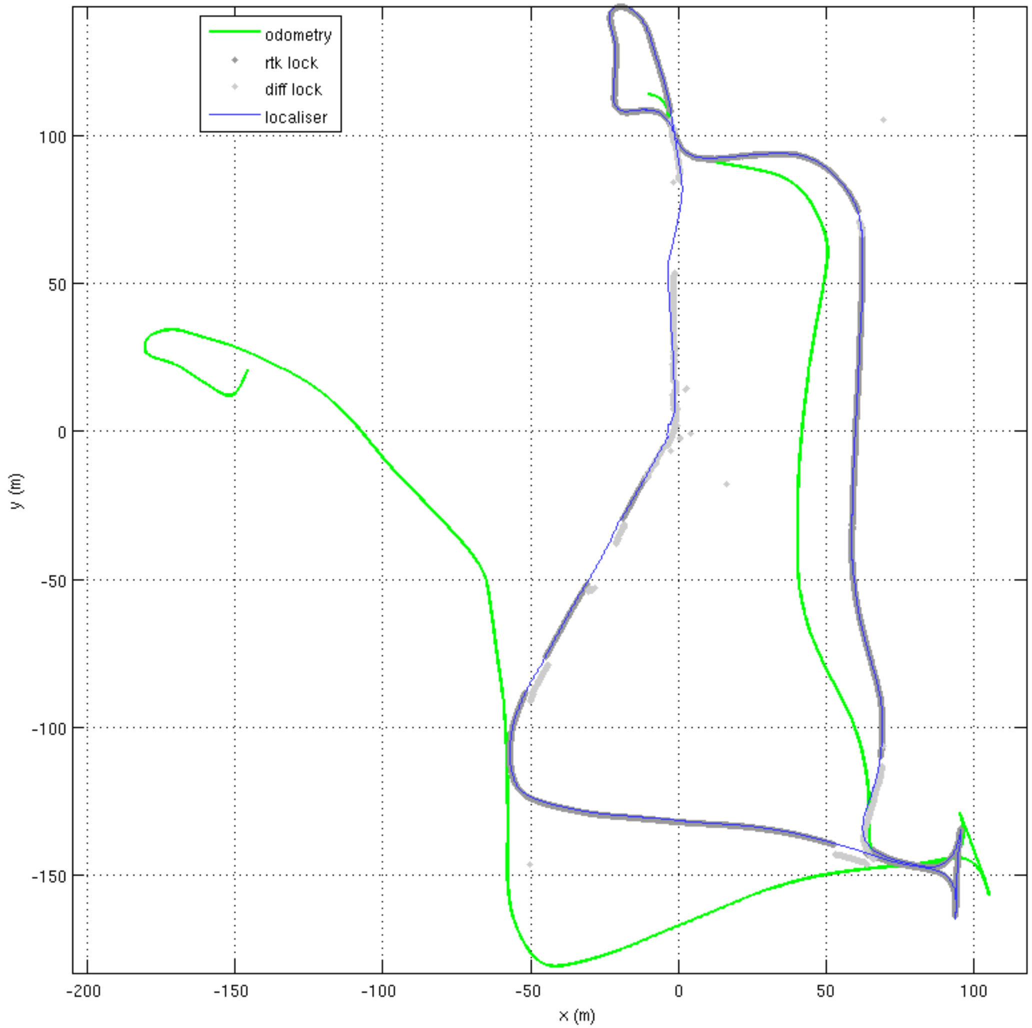
- Simple Motion Model $P(X_t \mid X_{t-1} U_{t-1})$
  - $X_t=(x_t,y_t,\theta_t)$: Robot Position -- $U_t=(V_t,\Phi_t)$: Command
  - Gaussian centered around kinematic model

- Simple Observation Model $P(Z_t \mid X_t)$
  - $Z_t=(r_t,\alpha_t)$: range and bearing to each observed landmark
  - Gaussian model centered on geometrical values

CSIRO

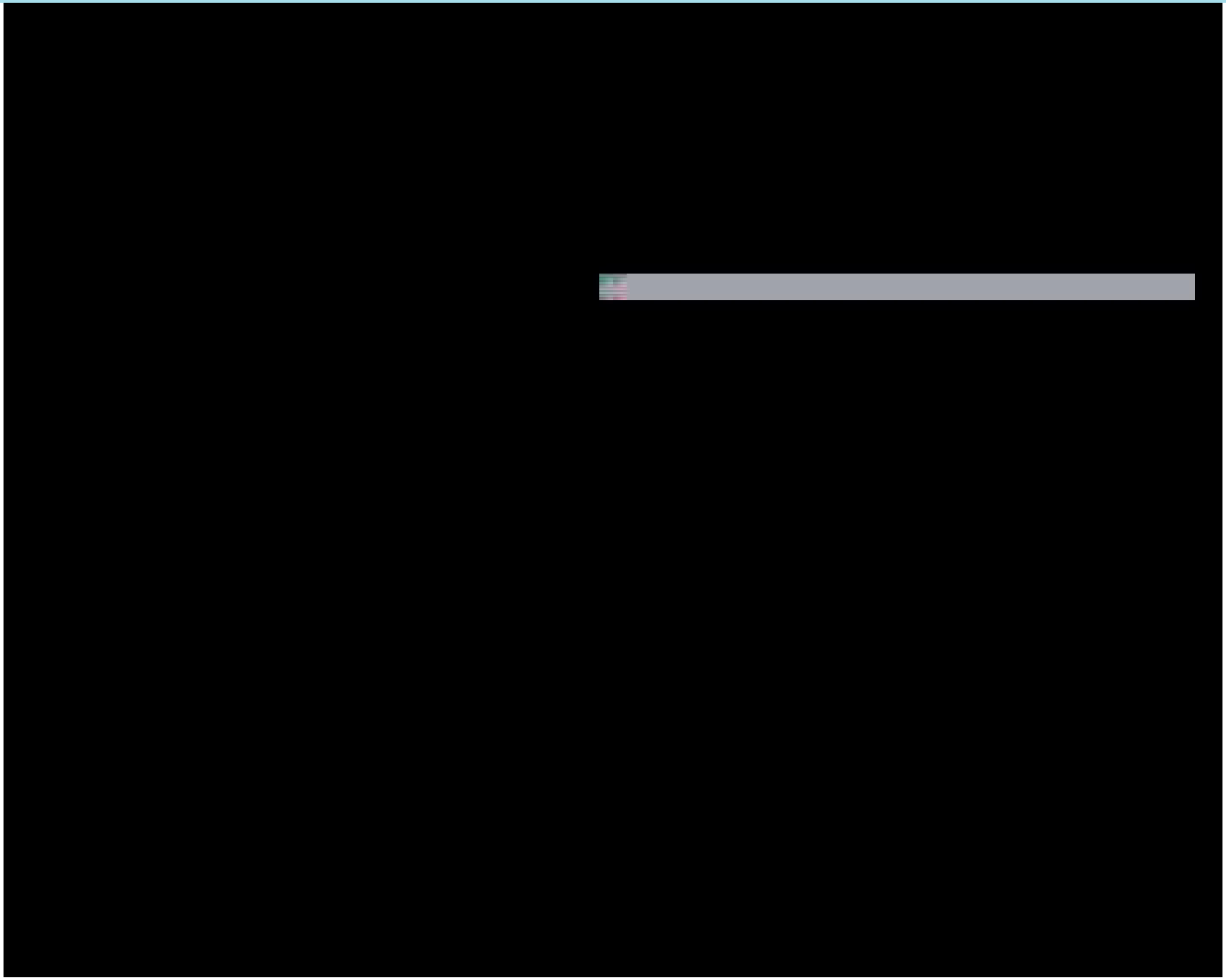
Localisation

- Accurate to within 10 cm on the HMC



5 hours experiment

2 hours experiment



Long Duration Experiments

Experiment	Distance	Cycle Dist.	Velocity	# Cruc. Ops (drop off + pick up)
5 hour	8.5 km	0.3 km	-1.1 : 1.6 m/s	58
2 hour	6.5 km	0.93 km	-1.4 : 3.0 m/s	14

CSIRO

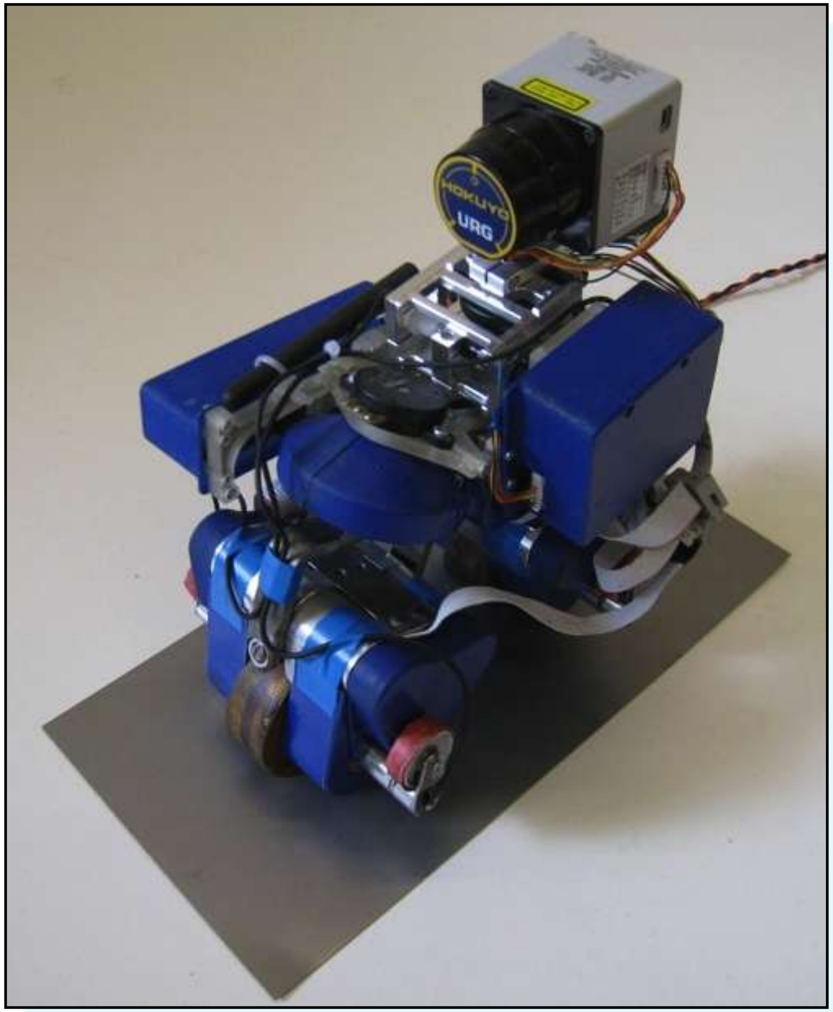
Industrial Vehicles: Pipe Inspection

Laser, vision

High accuracy requirements

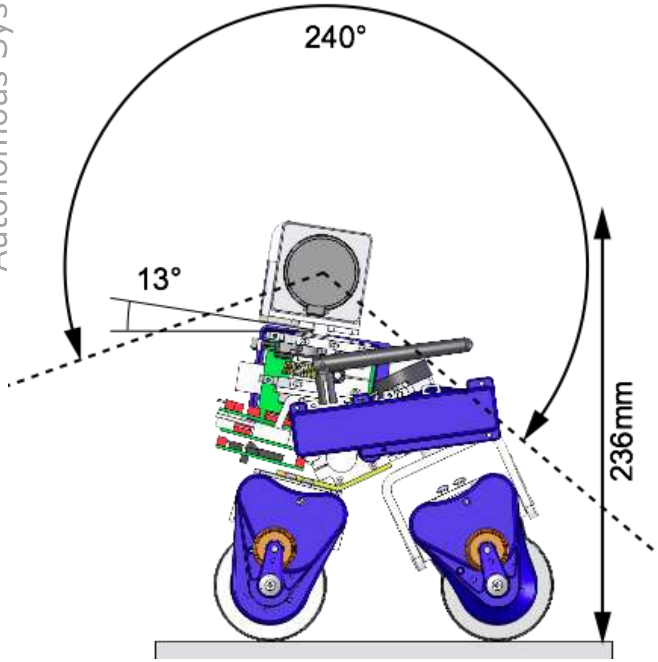
Weak energy constraints

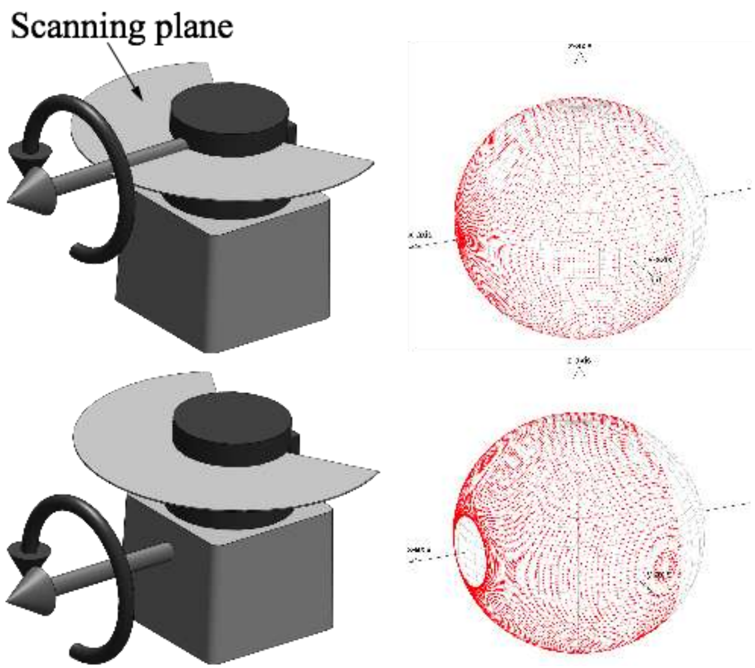
Robotic Pipe Inspection



- Robot
  - Mass: 3.3 Kg
  - Payload: 3.0 Kg
  - Max speed: 2.7mm/s
  - Size: 14.3 x 18.5 x 23.6 cm
- Rotational Laser
  - Mass: 0.19 Kg
  - Scanning time: 50 s
  - Nb points per scan: 341K
  - Angular resolution: 0.36 deg

Magnebike





Characteristics

- Localisation:
  - Rotating Laser scanners: 3D point clouds + ICP
- Mapping:
  - Online, might use CAD as input
- Path Planning:
  - Complex due to mechanical constraints of the magnetic adhesion
- Task Scheduling:
  - Segment navigation, environment scanning, edge passing
- Obstacle Avoidance:
  - Static only. Integrated in planning.
- Control:
  - Trajectory tracking, very low dynamic

Challenges

- Localisation
  - Very self-similar environments (cylinders).
  - Precise localisation of faults.
- Mapping
  - Surface extraction with the right amount of details for path planning
- Planning
  - Passing edges must be done with 90 degrees
  - Slightly less stability when driving perpendicular to gravity.

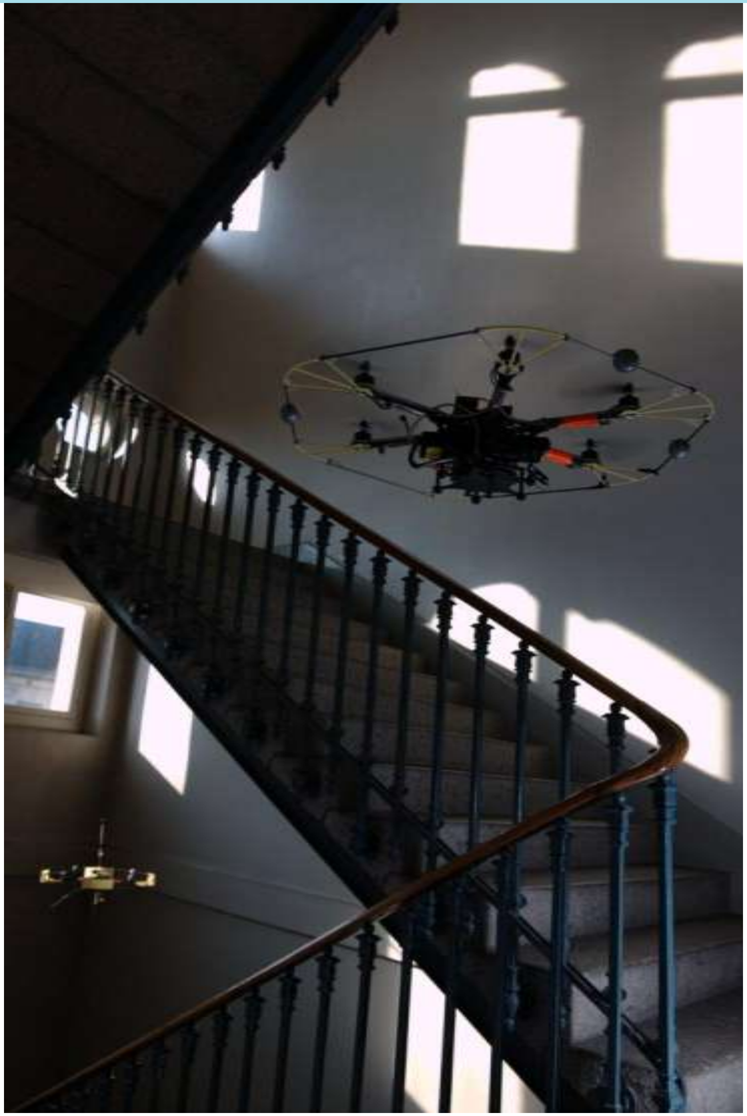
Results


MagneBike
Compact Magnetic Wheeled Robot for Power Plant Inspection
Tâche, Fabien
Pomerleau, François
Fischer, Wolfgang
Caprari, Gilles
Mondada, Francesco
Moser, Roland
Siegwart, Roland
Autonomous System Lab (ASL)
www.asl.ethz.ch

Navigation for micro-helicopters

Vision, (GPS)-INS
High dynamics
Strong energy constraints

sFly (EU FP7): Swarm of Micro Flying Robots



Characteristics

- Localisation:
  - Single camera + IMU (+GPS): computationally intense and less smooth
- Mapping:
  - Online SLAM
- Path Planning:
  - Predefined path segments (for now)
- Task Scheduling:
  - Simple: take-off, fly segments, land…
- Obstacle Avoidance:
  - From Map/Path planning
- Control:
  - Complex flight dynamic, wind gust rejection

Challenges

- 3D environment
  - Harder to map
  - Harder to monitor
- Low computational resources (weight/energy)
  - Vision-based localisation
  - Vision-based mapping
- Complex control
  - Localisation system noise, delay, low update rate
  - Wind speed and gusts

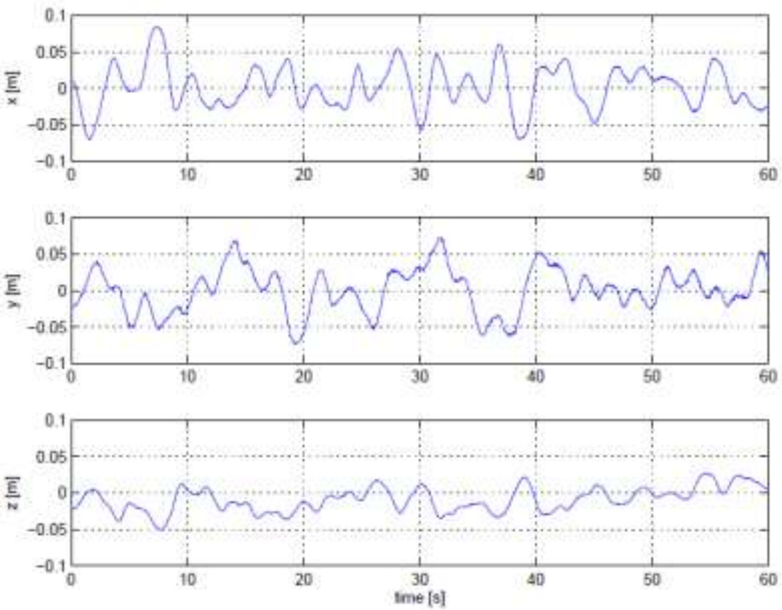
Why a single camera?

- Cheap
- Low power consumption
- Provides reach information about the environment
- Wide field of view facilitates tracking (features are tracked over longer period)
- Inspired by insects: they benefit from large field of view for take-off and landing
- Stereo-cameras do not help if the observed scene is too far (>20 times greater than the baseline)

- The camera has to move to perceive depth (up to a scale)
- With a single camera, metric depth information cannot be recovered

Controller

- Hovering performance



RMS position error = 3 cm

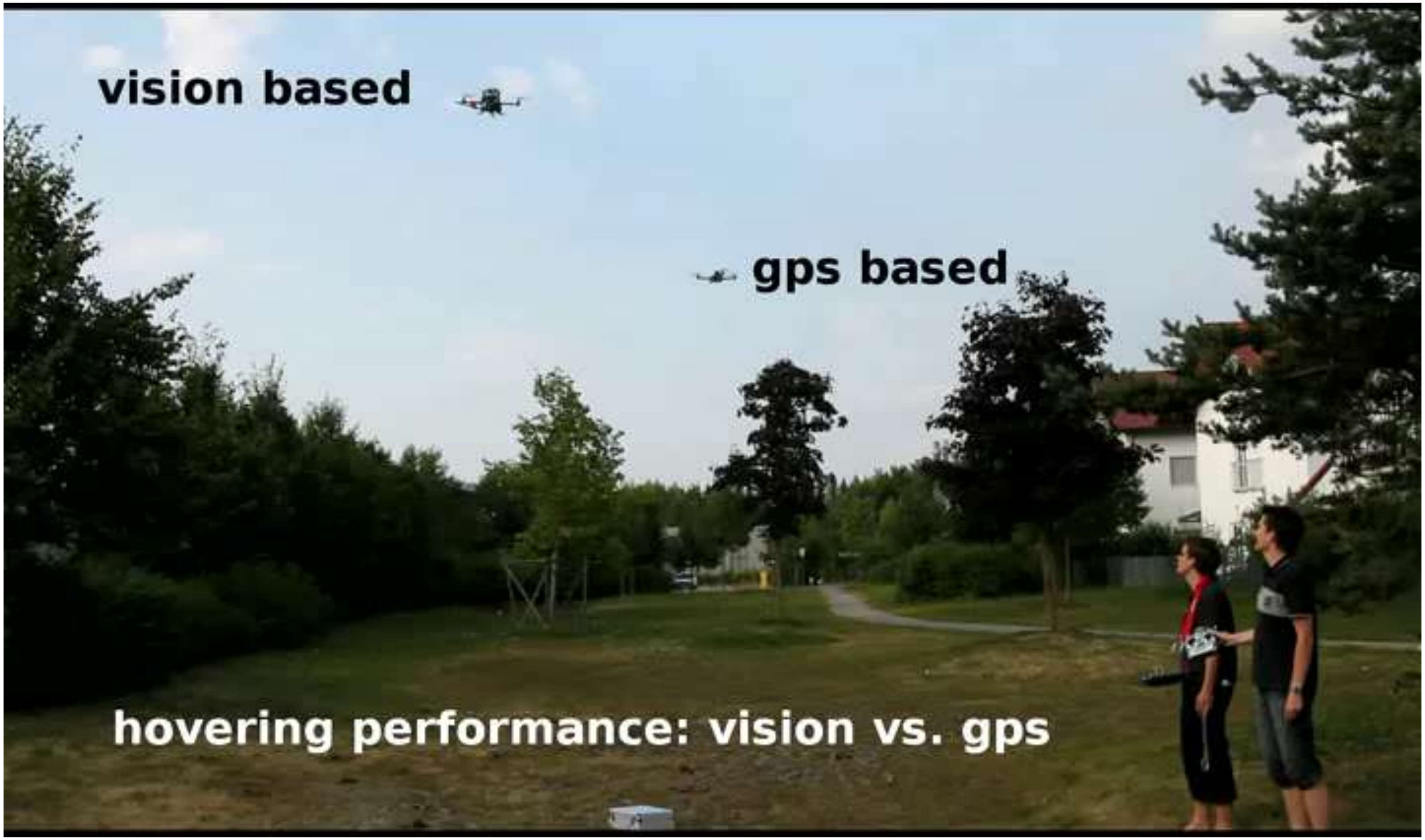
Controller

- Hovering performance above different outdoor terrains under windy conditions

Outdoor operations

Outdoor operations

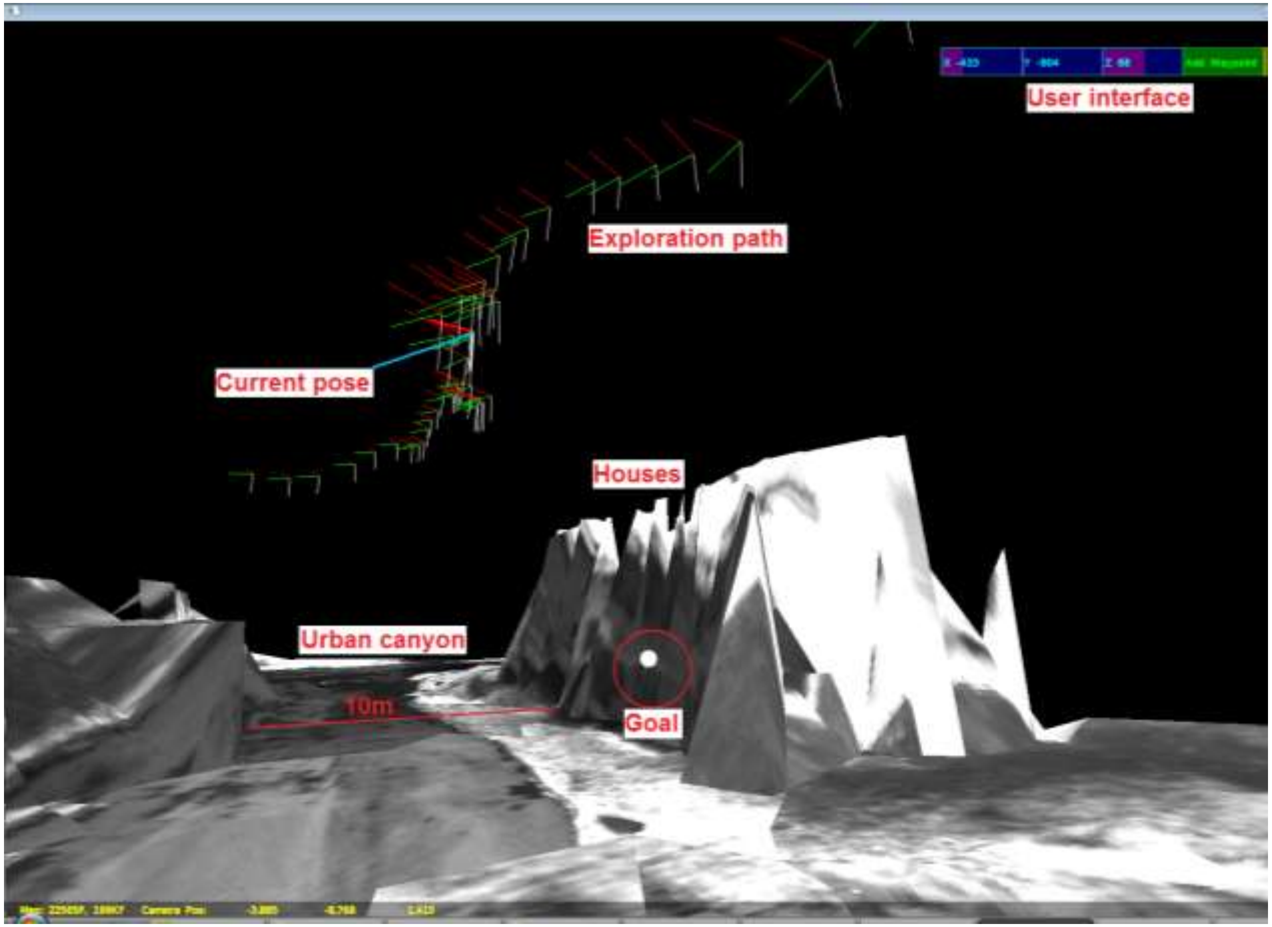
- Vision based stabilization superior to GPS stabilization (up to certain height)



Mapping

Mapping

- Generation of meshgrid from 3D map-points
- Texturing by projection of „best" keyframe to each triangle



Mapping

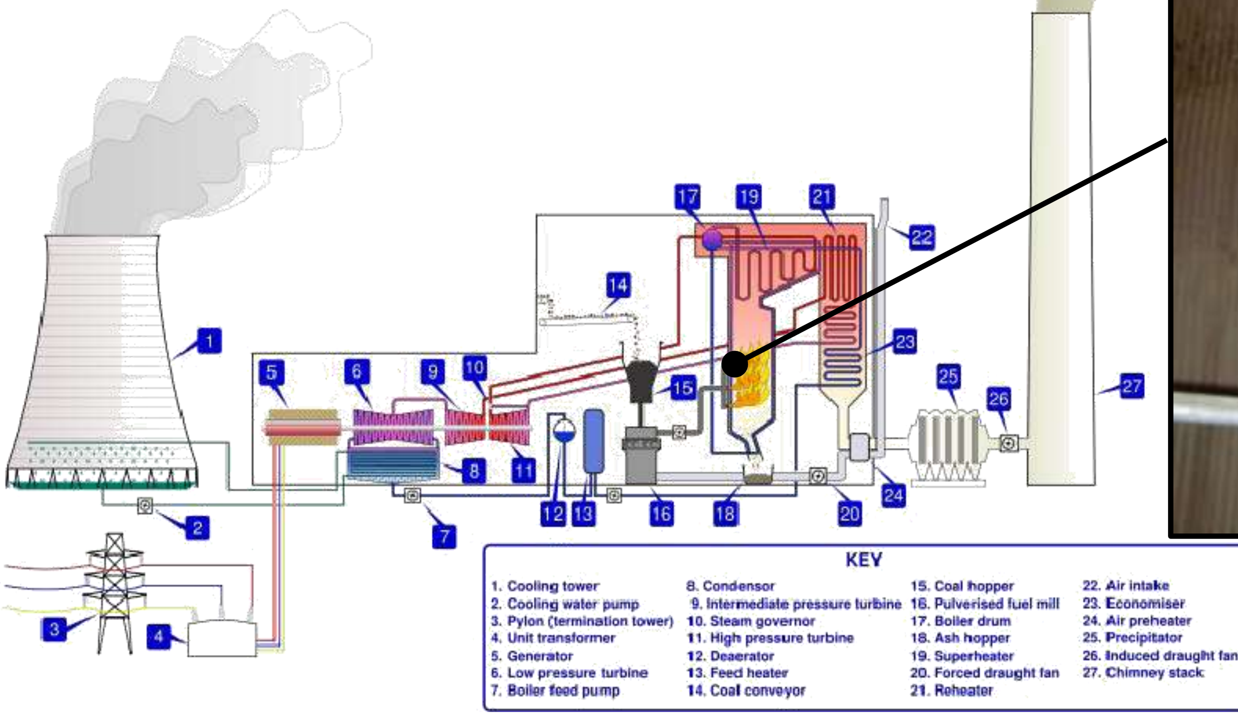

.1.2010
sfly
NEW: 14.0
us Systems Lab
H Zurich
Autonomou
ET
in a Large Outdoor Environment
Intuitive 3D Map
(remote controlled helicopter)
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

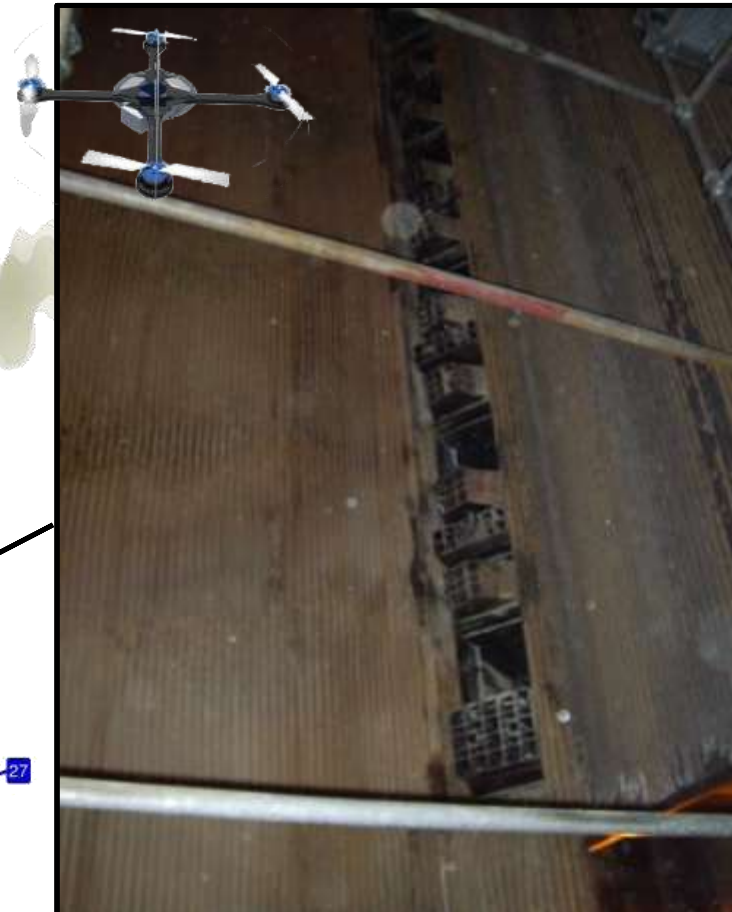
Micro-helicopters for Inspection

Vision, (GPS)-INS
High accuracy requirements
High dynamics
Strong energy constraints

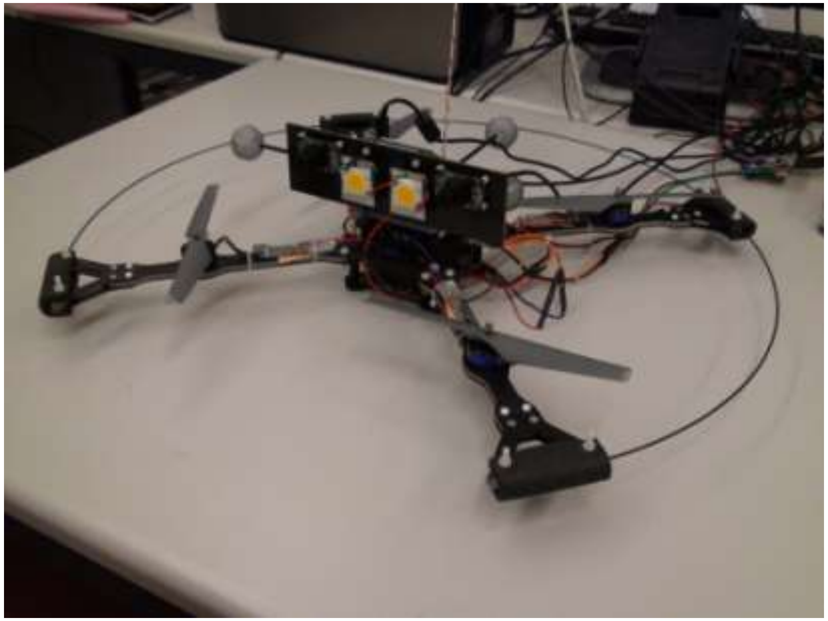
AIRobots – Navigation with Stereo

- Inspection of a coal boiler using aerial vehicles
  - Welding lines
  - Air/coal nozzles
  - Pipe wall thickness

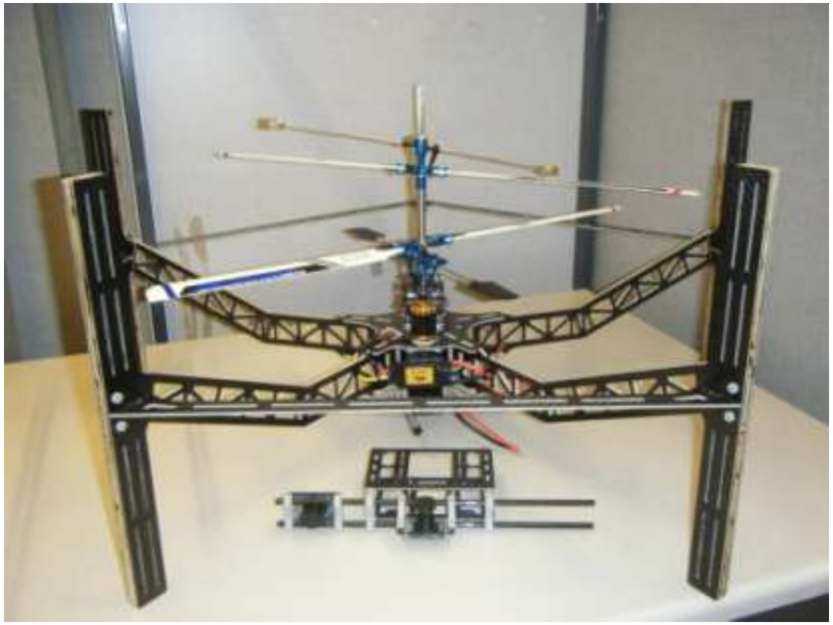




Micro-helicopters for inspection



First Prototype



Second Prototype

Characteristics

- Localisation:
  - Stereo camera + IMU (+ onboard lights): computationally and energetically expensive
- Mapping:
  - Online SLAM
- Path Planning:
  - Predefined path segments (for now)
- Task Scheduling:
  - Simple: take-off, fly segments, land…
- Obstacle Avoidance:
  - Using the Stereo Cam (not addressed yet)
- Control:
  - Complex flight dynamic + controlled contact with the wall surfaces

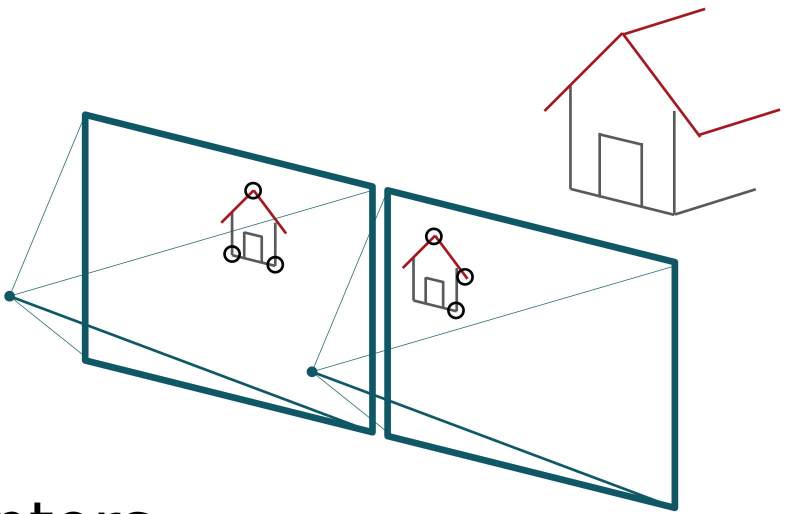
Challenges

- 3D environment
  - Dark and very self-similar
- Low computational resources (weight/energy)
- Complex control and obstacle interaction
  - Cluttered environment
  - Contact with the walls

Visual Egomotion – Keypoints, Descriptors

- Capture stereo shot

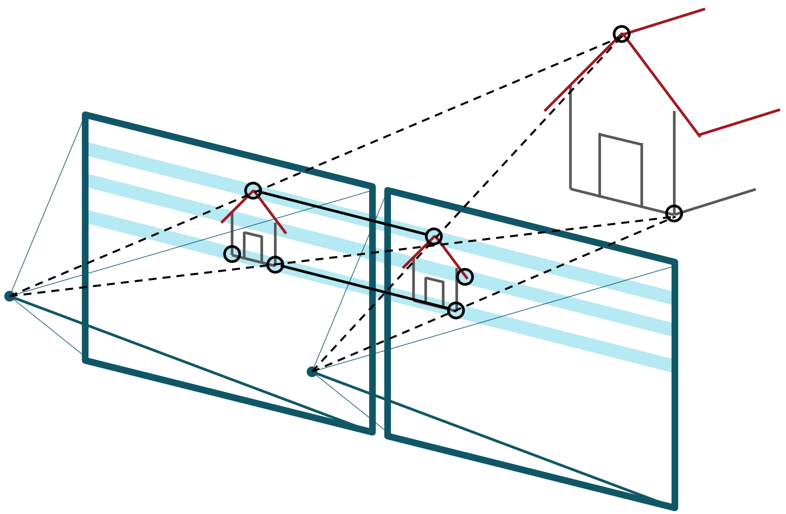
- Extract key points
  - FAST corner detector
  - Adaptive thresholding



- Compute key point descriptors
  - BRIEF feature descriptor

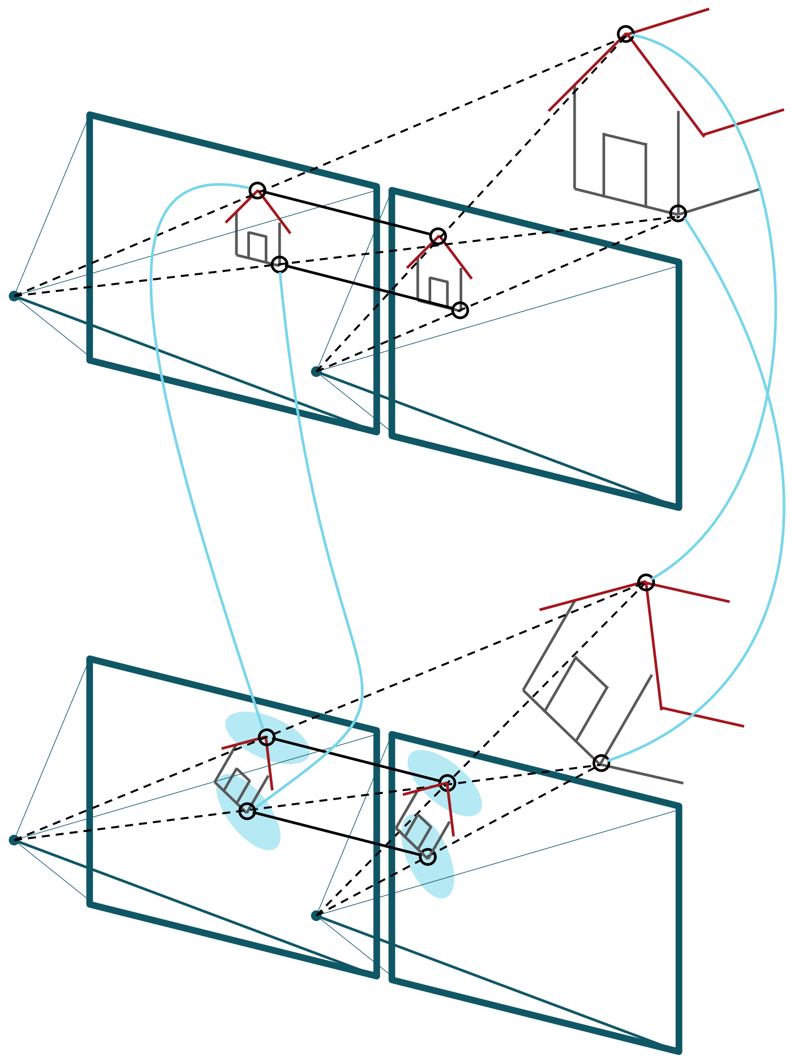
Visual Egomotion – Stereo Triangulation

- Associate features of left and right image
  - Epipolar constraint
  - Descriptor matching
- Triangulate associated features to obtain 3D points



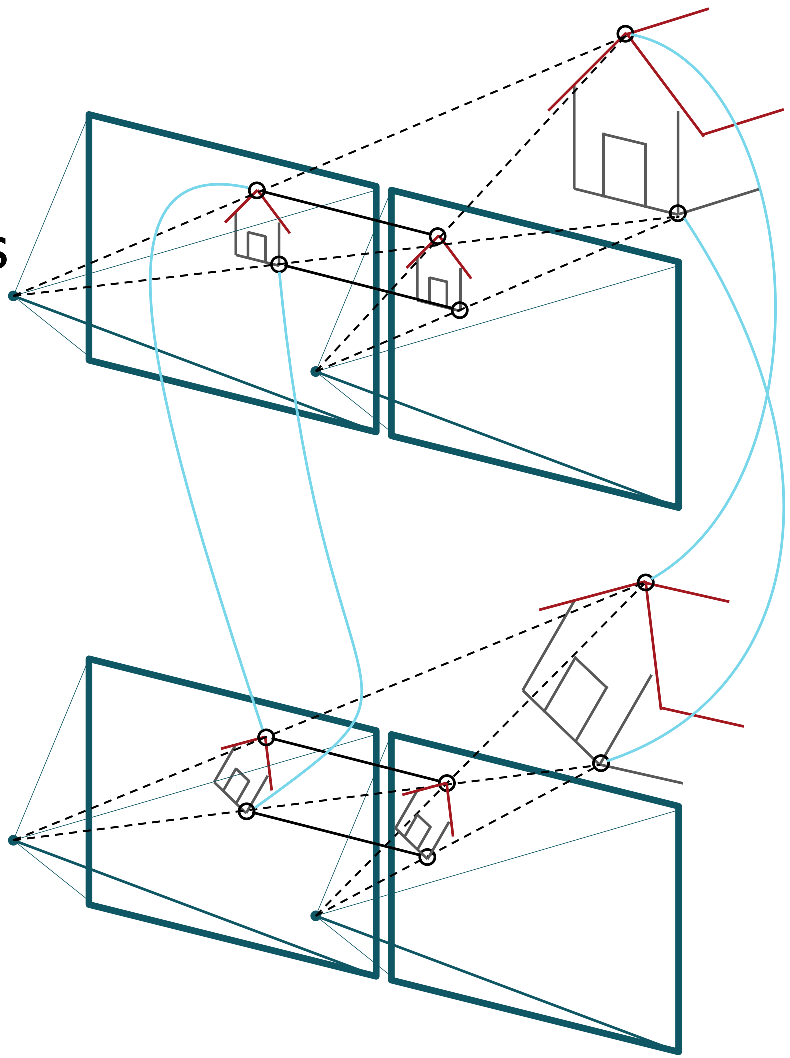
Visual Egomotion – 3D Feature Matching

- Capture next stereo shot
- Compute key points, descriptors and 3D points as before
- Associate features
  - Descriptor matching
  - IMU motion constraints



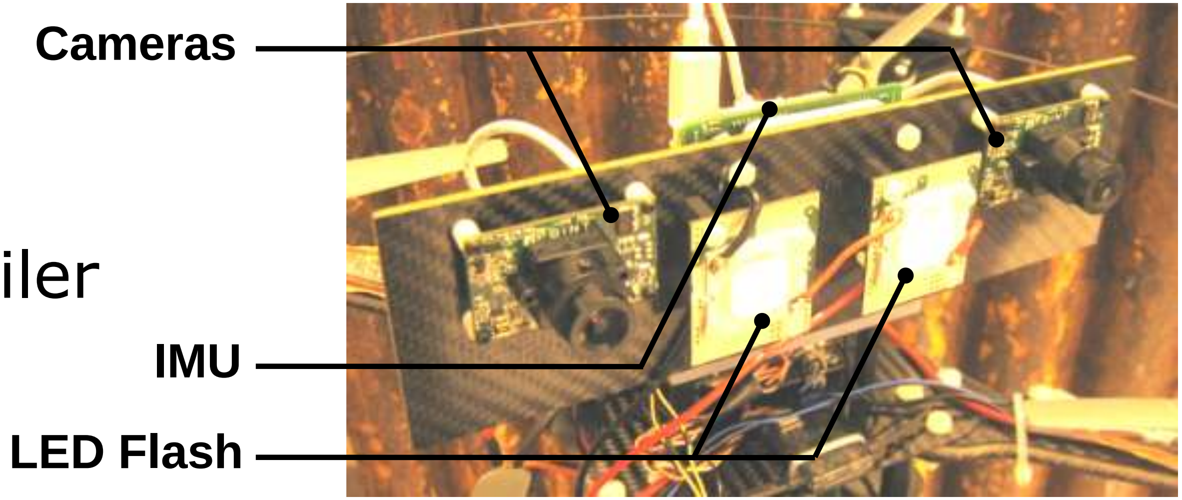
Visual Egomotion – Pose Estimation

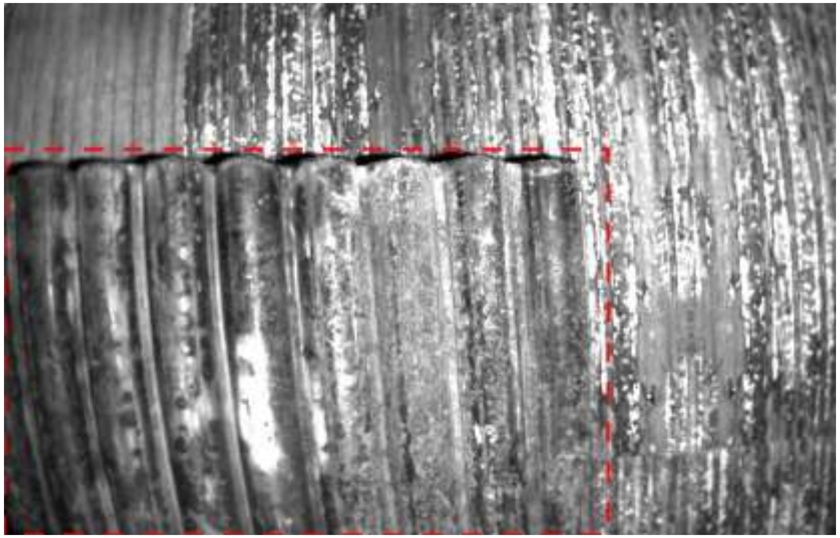
- RANSAC outlier rejection
  - P3P motion hypotheses
  - Apply density filter before counting hypothesis inliers
- Refinement via bundle adjustment

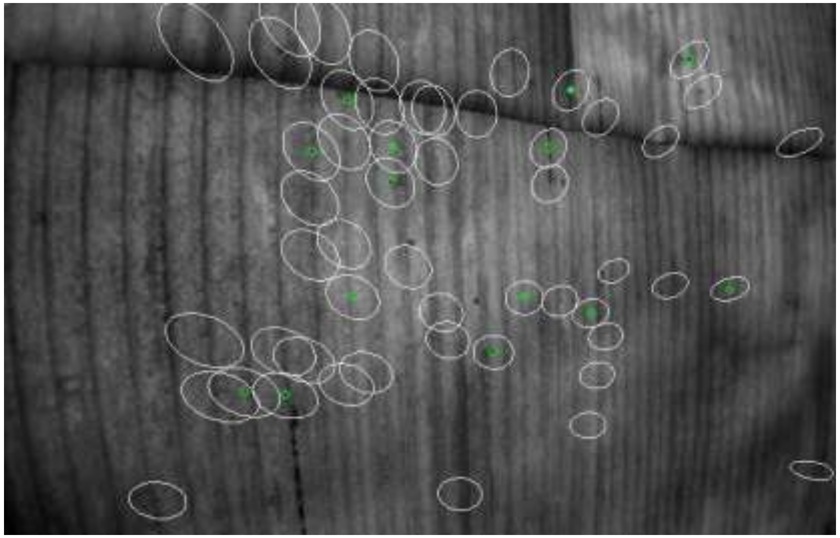


Results – Boiler Experiments

- Stereo Rig
- Mockup
- Uncleaned boiler surface

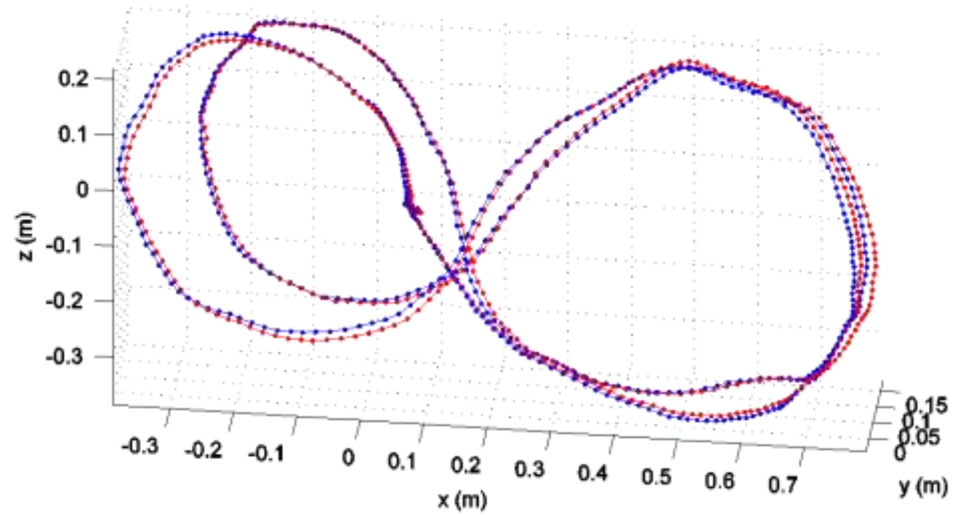




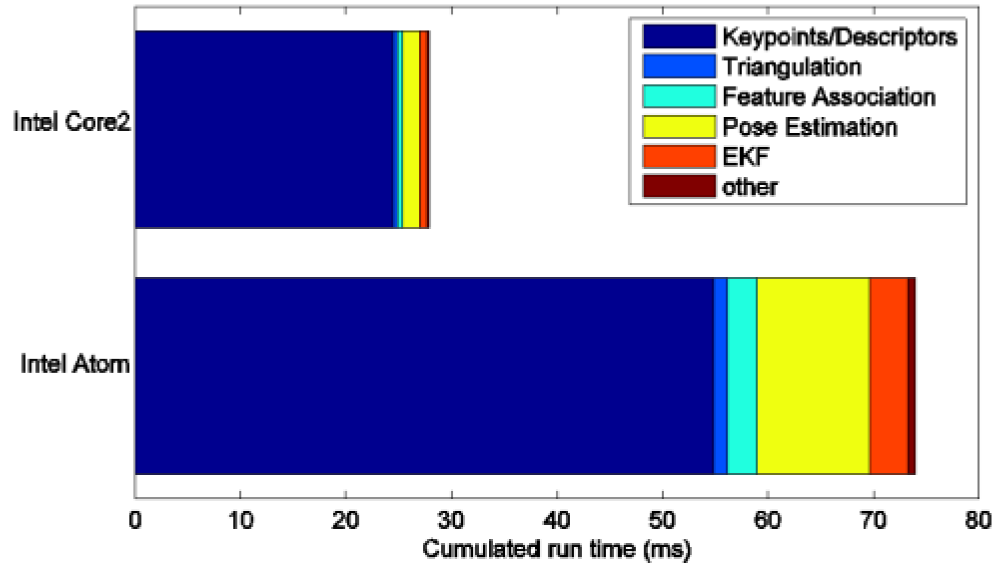


Results – Accuracy, Runtime Performance

- Final error ~0.1% to Vicon ground truth

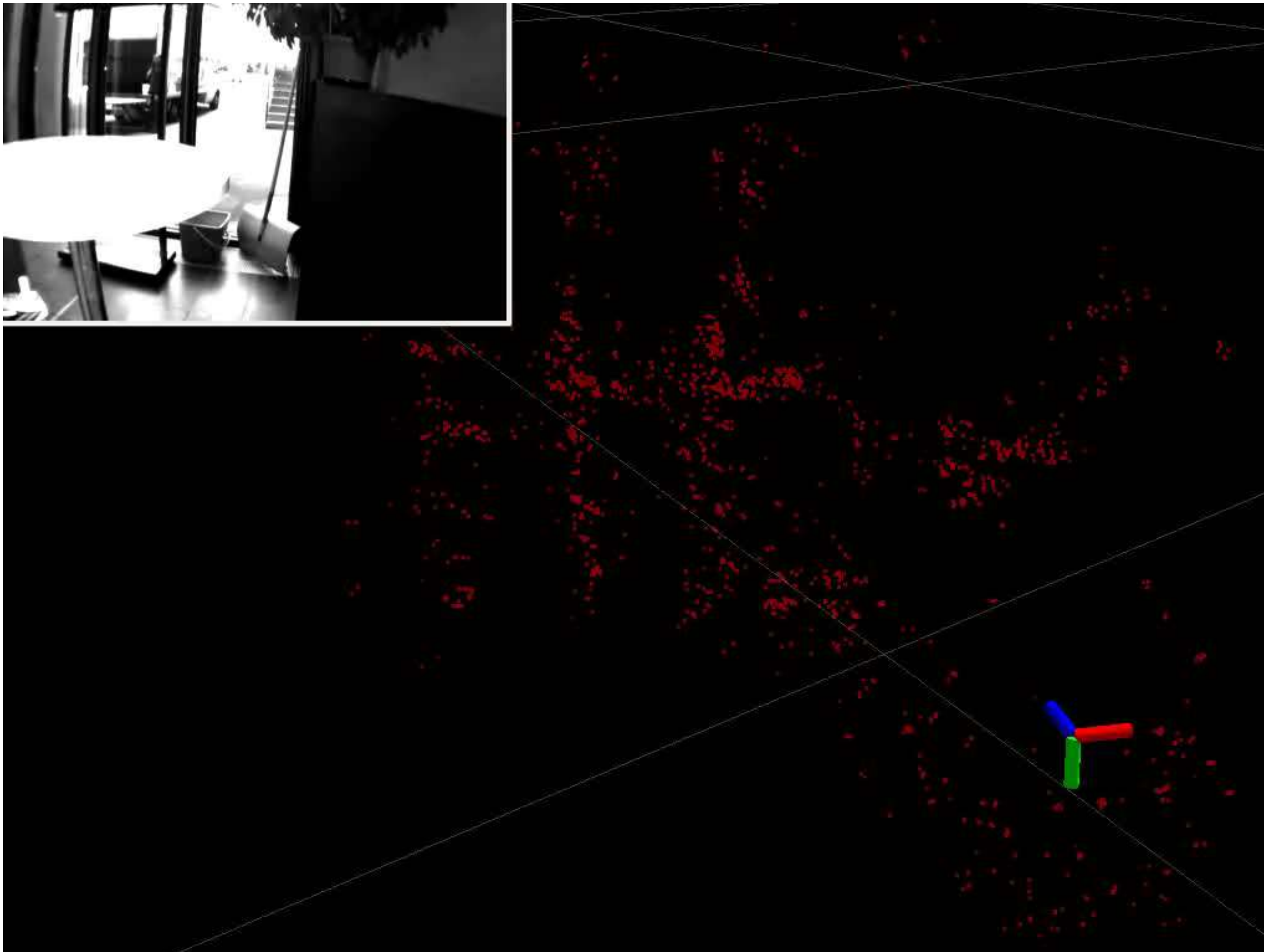


- Runs at 10Hz – 15Hz on single core Intel Atom



ETH Zürich

Results: Indoor Odometry



Navigation in rough terrain

3D Vision, INS
Strong perception constraints
Focus on planning and control

Autonomous Systems Lab

ETH Zürich

Navigation on 4 legs

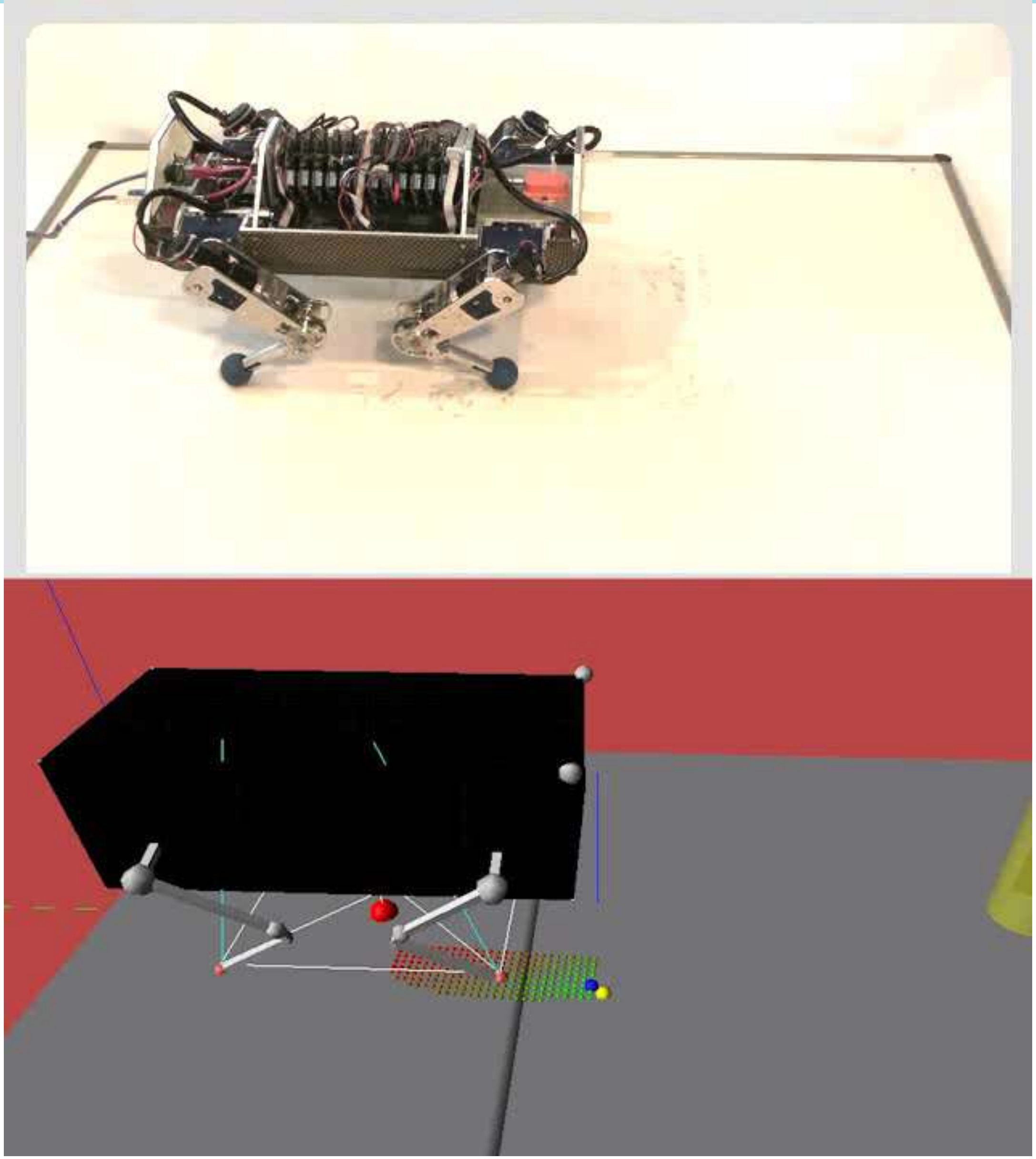
Characteristics

- Localisation:
  - 6 DoF, Foot placement
- Mapping:
  - Online terrain traversability analysis
- Path Planning:
  - Complex foot placement planning
- Task Scheduling:
  - Complex gait scheduling, in particular in rough terrain
- Obstacle Avoidance:
  - Part of the traversability analysis
- Control:
  - Complex control of the stability, 12 joints controlled in position and speed

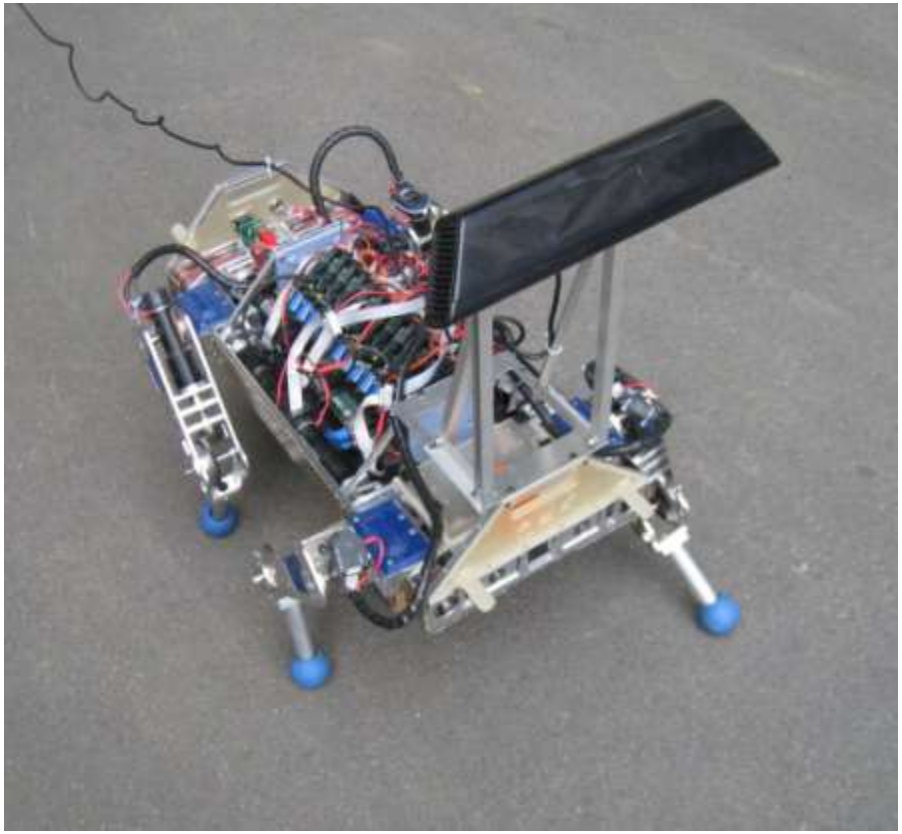
Challenges

- 3D environment mapping
  - Estimation of the surface qualities
  - Planning all foot placement to guarantee stability and account for uncertainties
  - Learning
- Energetic efficiency
  - Ongoing work on serial-elastic actuation

Planning and walking on flat ground



Ongoing works



- Terrain perception
  - Kinect, ICP
- Online integration of 3D terrain model into the path planning
- Dynamic walking & running using serial-elastic actuation

Conclusions

Where do we stand?

- A lot of work for navigation is well structured or low-clutter environments
  - Boat navigation on lakes
  - Autonomous aerial vehicles
  - Indoor or industrial robots

- A lot of challenges in complex environment
  - On the road in urban settings
  - In the presence of dynamic objects
  - In unstructured environment

The Key Challenges

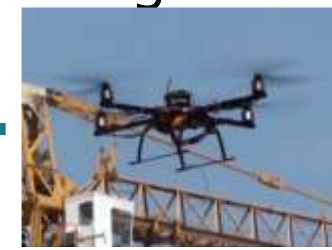
- Perception, Semantic
  - Perception in 3D
  - Understanding the world
  - Real-time Perception

- Processing power
  - Energy for sensing and processing

- Navigation in dynamic environment with highly dynamic systems
  - Urban traffic
  - Rally racing
  - Aerial acrobatics

Working together

- Leica Geosystems
  - Localisation and control of a micro-helicopter using a laser measurement system



- Crossing the atlantics

+ Google Switzerland

- Unmanned Navigation

+ RUAG

- Mapping Swiss lakes?
  - Autonomous navigation on lake is relatively easy
  - Scanning equipment is rare

Questions