Ground and Aerial Robots for Challenging Environments

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www.asl.ethz.ch & www.wysszurich.ch

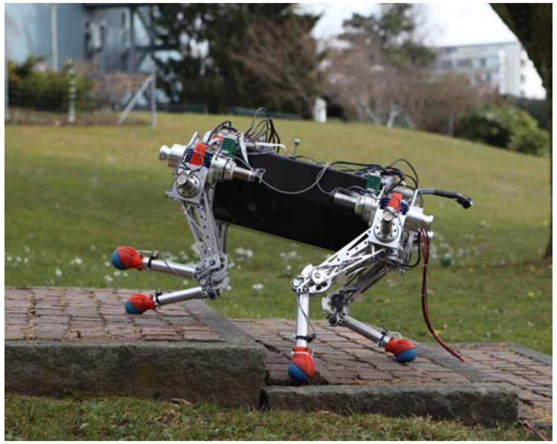
QUALCOMM

Qualcomm Augmented Reality Lecture Series
Vienna, April 21, 2016

Content

- Introduction

- Design or rolling, swimming, walking and flying robots



- Mobile robot navigation

ETH | facts and figures (2014)

- Founded in 1855 as driving force for the industrialization of Switzerland
- International flagship in research and novel technologies (no. 1 in Continental Europe)
- 21 Nobel Laureates
- 16 departments with 500 professors (69% intl.)

- 10’500 faculty & staff (incl. PhD students)
- 18’000 students
  - 9000 bachelor students (19.4% intl.)
  - 5000 master students (38.2% intl.)
  - 4000 PhD students (68.3% intl.)

- 1500 Mio CHF expenditure (incl. 370 Mio third party funds)
- Roughly 200 Mio CHF investments in buildings per year

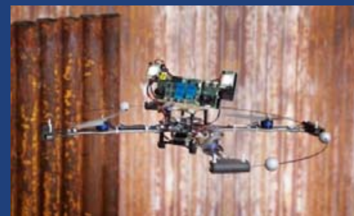
Autonomous Systems Lab

Institute of Robotics and Intelligent Systems
Prof. Dr. Roland Siegwart

- ## Mission and Dedication
  - To create intelligent robots and systems that operate autonomously in complex and dynamic environments.

- ## Research Focus
  - Novel robot concepts that are best adapted for ground, air, or water based applications.
  - New algorithms for perception, localization, abstraction, mapping, and path planning that will enable autonomous operation in challenging environments.




Research Fields

Autonomous Cars
Visual navigation and autonomous operation in city environments

Unmanned Aerial Vehicles
Design, control and fully autonomous operation in complex environments

Solar Airplanes
Continuous flight for long-term environment monitoring

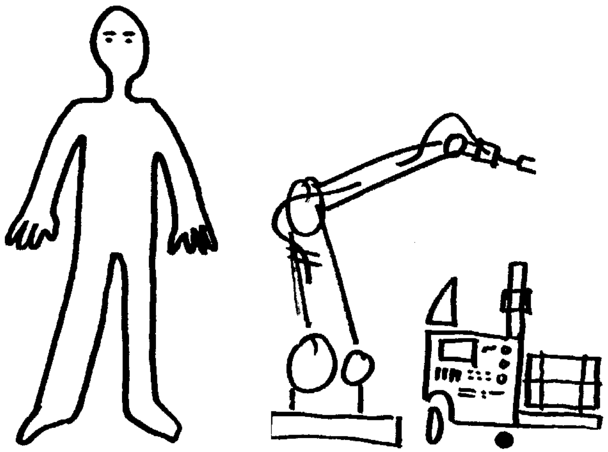
All Terrain Robots
Design and collaborative navigation of flying and ground robots

Mobile Manipulation
Object handling for manufacturing, logistics, and e-commerce

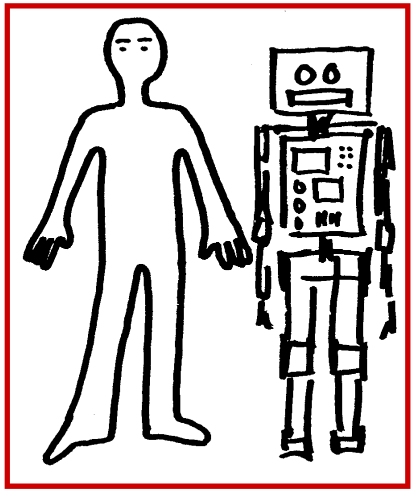
Service Robots
Navigation and transportation in our daily environment

Next generation of Robots

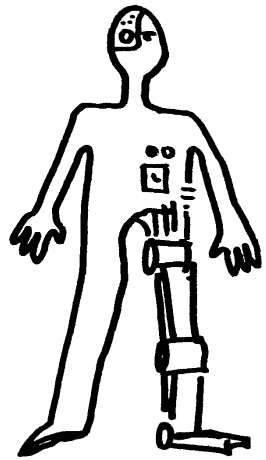
| mobile, smart, connected, adaptive and closer to humans



Industrial Robots



Service and Personal Robots



Cyborgs

Fascinating Robotics

Spot | hydraulic quadruped

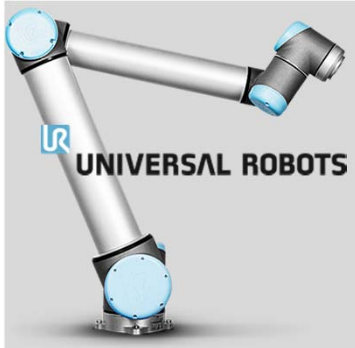
https://www.youtube.com/watch?v=M8YjvHYbZ9w

FESTO | BionicOpter https://www.youtube.com/watch?v=Vhz_UuJq7us

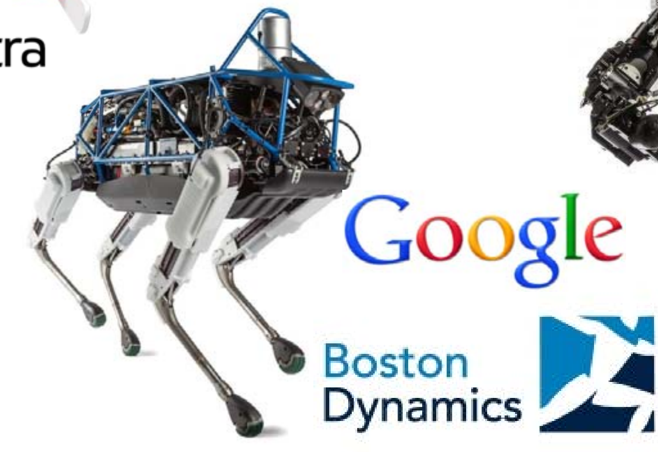
DARPA Robotics Challenge
07.06.2015,
Team NEDO-JSK, Japan
12 x original speed!!

https://www.youtube.com/watch?v=8P9geWwi9e0

“Soft Robots” | torque / force controlled robots



Mobile Platforms

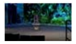


Design of

Rolling, Swimming, Walking and Flying Robots

Ultimate Rolling Robots – designed by students

rezero (2010)
| the ball balancing robot

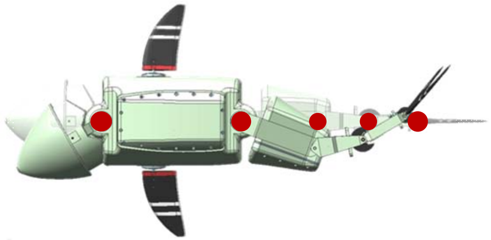


BeachBot (2014, with Disney)
| the beach artist

Vertigo (2015 with Disney)
| the ultimate wall climber

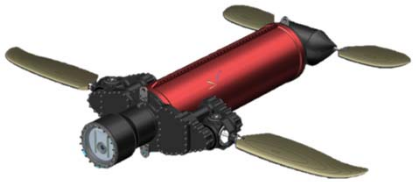
Scalevo (2015)
| the stair-climbing wheelchair

Underwater Robots – designed by students



Naro (2009)
| the tuna robot

https://www.youtube.com/watch?v=L61O2CmZCc4



Taratuga (2012)
| the turtle robot

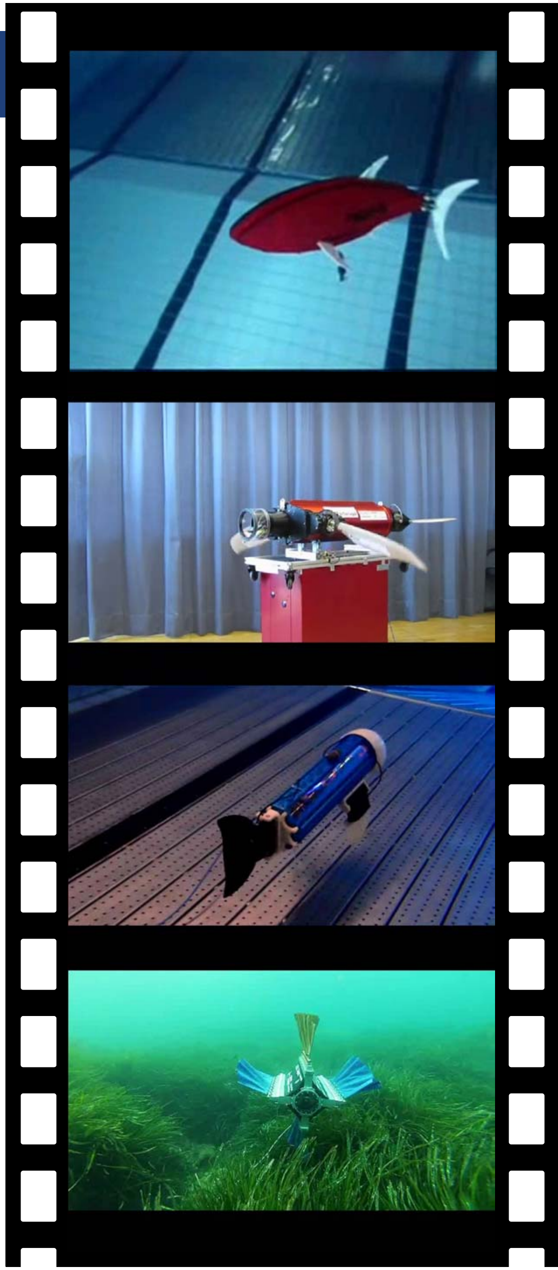
https://www.youtube.com/watch?v=pqy_NSHcGLs

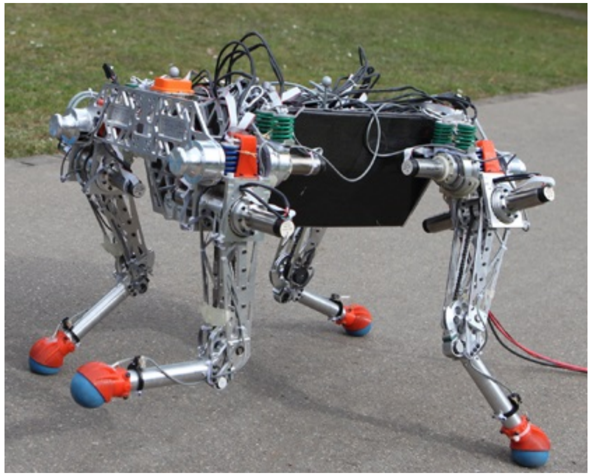
Nanins (2013)
| the modular underwater robot

https://www.youtube.com/watch?v=r5uGmWRZKGU

Sepios (2014, with Disney)
| the Kalmar robot

https://www.youtube.com/watch?v=GeCLL2RWV1c





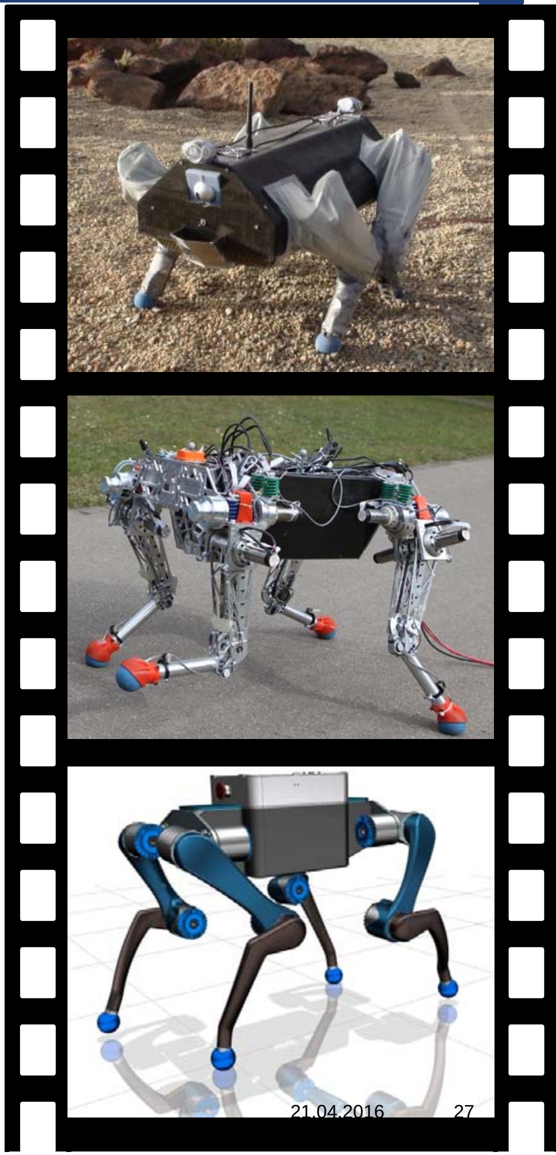
Quadruped Legged Locomotion

Walking Robots – serial elastic actuation

ALOF (2008)
| the versatile walker

StarlETH (2010)
| the quadruped with serial elastic actuation

AnyBot (2015)
| the ultimate quadruped

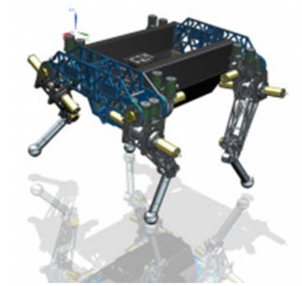


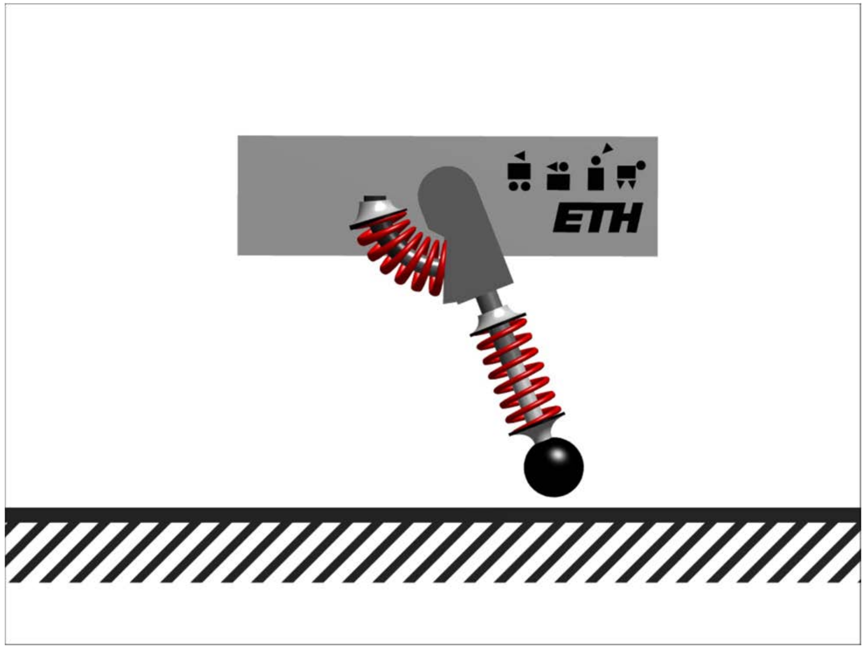


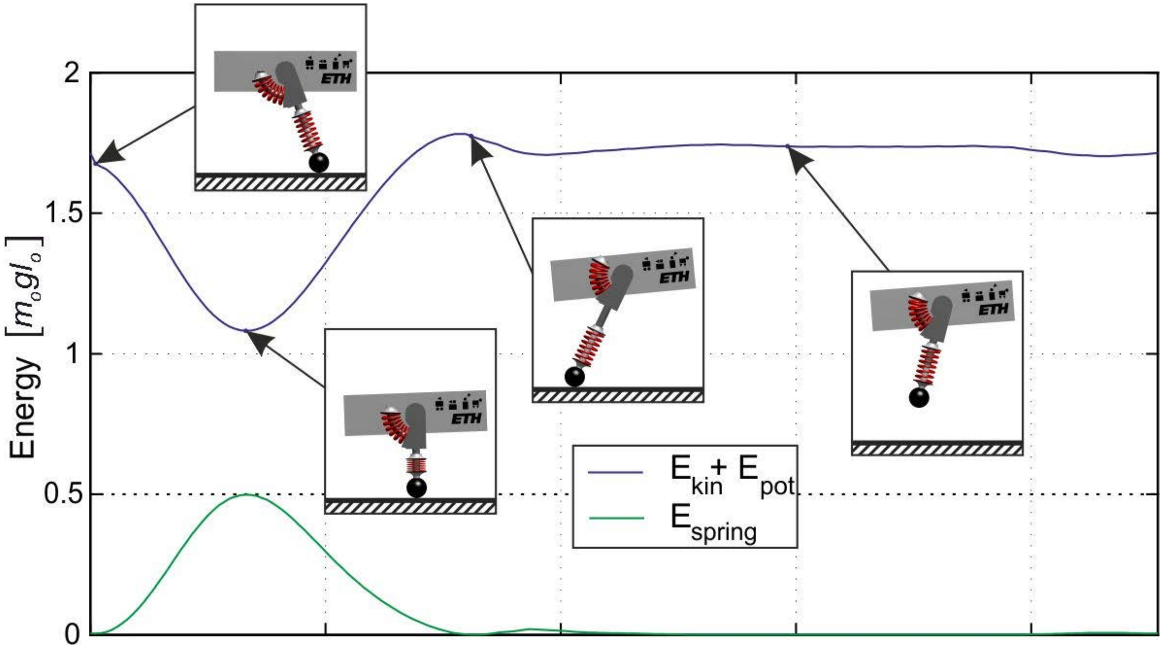
Efficient Walking and Running | what nature evolved (Extreme Jumpy Dog)

http://www.youtube.com/watch?v=Jql6TSyudFE

Efficient Walking and Running | serial elastic actuation

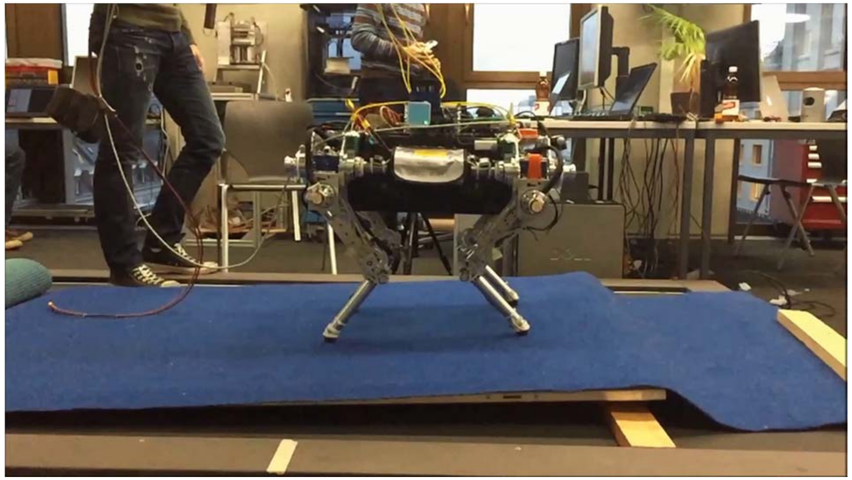


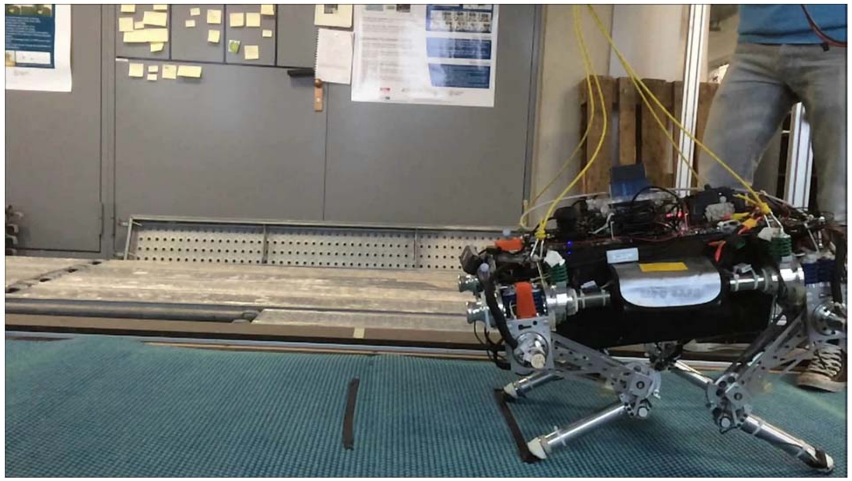




https://www.youtube.com/watch?v=6igNZiVtbxU

StarlETH – ein Laufroboter mit "elastischen Gelenken"





https://www.youtube.com/watch?v=Tj1wreifYhU

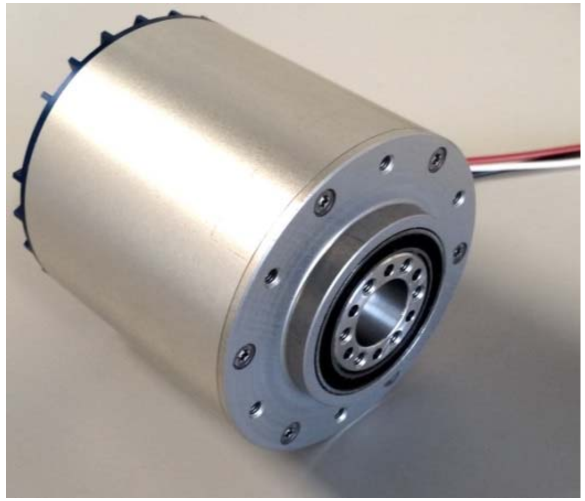
https://www.youtube.com/watch?v=IO_sZ6FBAwQ

Series Elastic Actuator | Compact robot joint

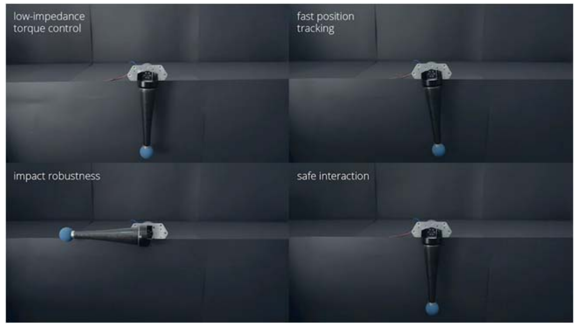
Prof. Marco Hutter

- Enclosed Series Elastic Joint
  - Combine motors, gears, springs, electronics
  - High torque and speed (40Nm, 20rad/s)
  - Low weight (<1kg)

  - **High performance torque and position control**
  - **Minimal impedance and high impact robustness**



⇒ Enables the development of various robots that are perfectly suited for interaction!

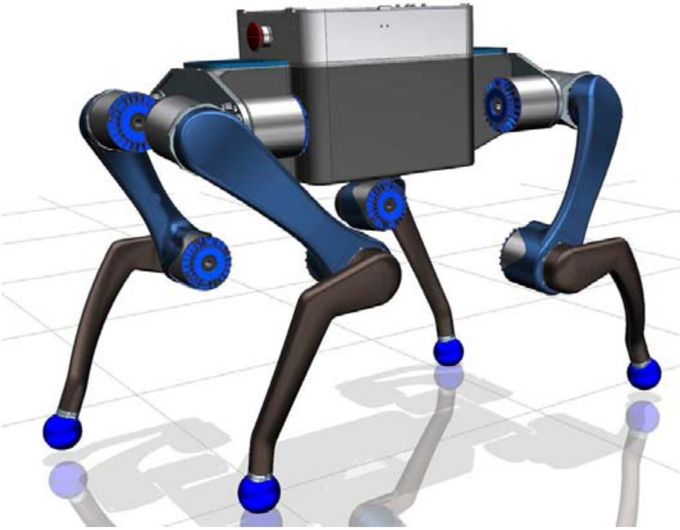


Various Types of SEA driven Robots
From locomotion to interaction

Prof. Marco Hutter

- ANYmal
  - Ruggedized & field ready
  - Full joint rotation (climbing)
  - Lightweight (running)
- ANYpulator
  - Adapter for various tools
  - Zero backlash (precision)
  - Zero impedance (impact)

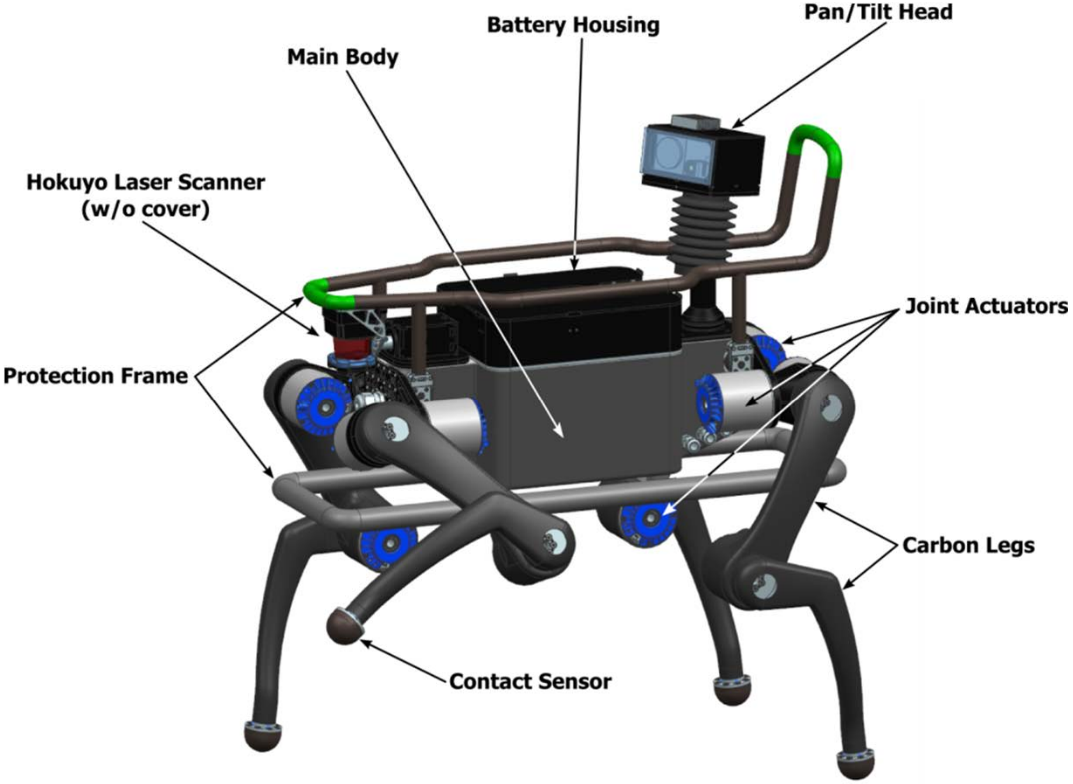
No addition encoders, bearings, or transmissions!!



ANYmal
an electrically actuated dog for real-world scenarios

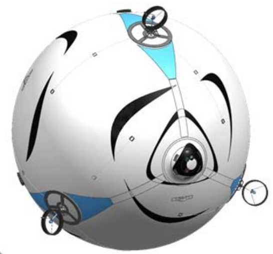
Prof. Marco Hutter

- High mobility
  - *"to go where today only humans can go"*
- 10 kg of payload
- 2 h of continuous operations



UAV (Unmanned Aerial Vehicles) | flight concepts

- Helicopters:
  - < 20 minutes
  - Highly dynamic and agility
- Fixed Wing Airplanes:
  - > some hours; continuous flights possible
  - Non-holonomic constraints
- Blimp: lighter-than-air
  - > some hours (dependent on wind conditions);
  - Sensitive to wind
  - Large size (dependent on payload)
- Flapping wings
  - < 20 minutes; gliding mode possible
  - Non-holonomic constraints
  - Very complex mechanics



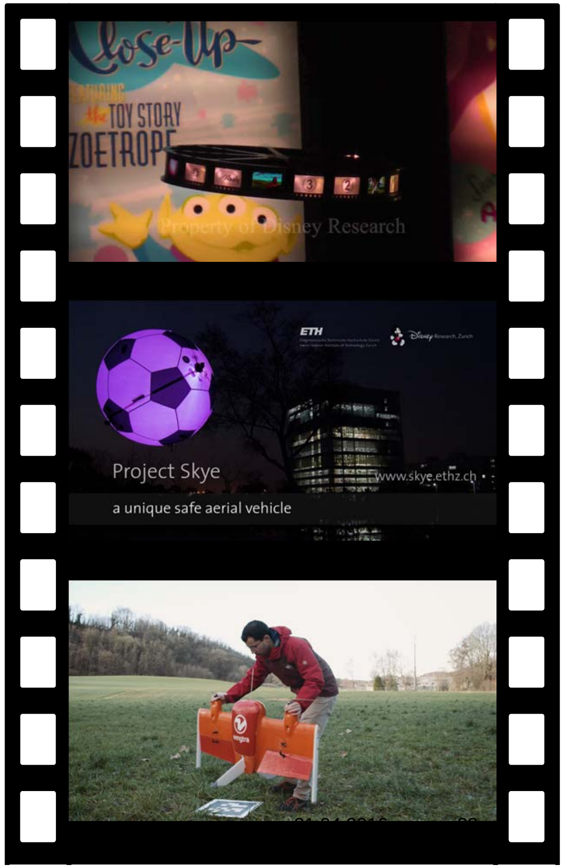
Festo BionicOpter

Flying Robots | new ways of flying

Reely (2009 – with Disney)
| the flying reel

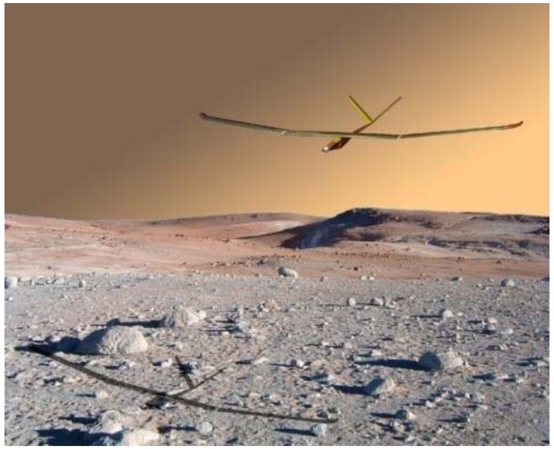
Skye (2012 – with Disney)
| the omnidirectional blimp

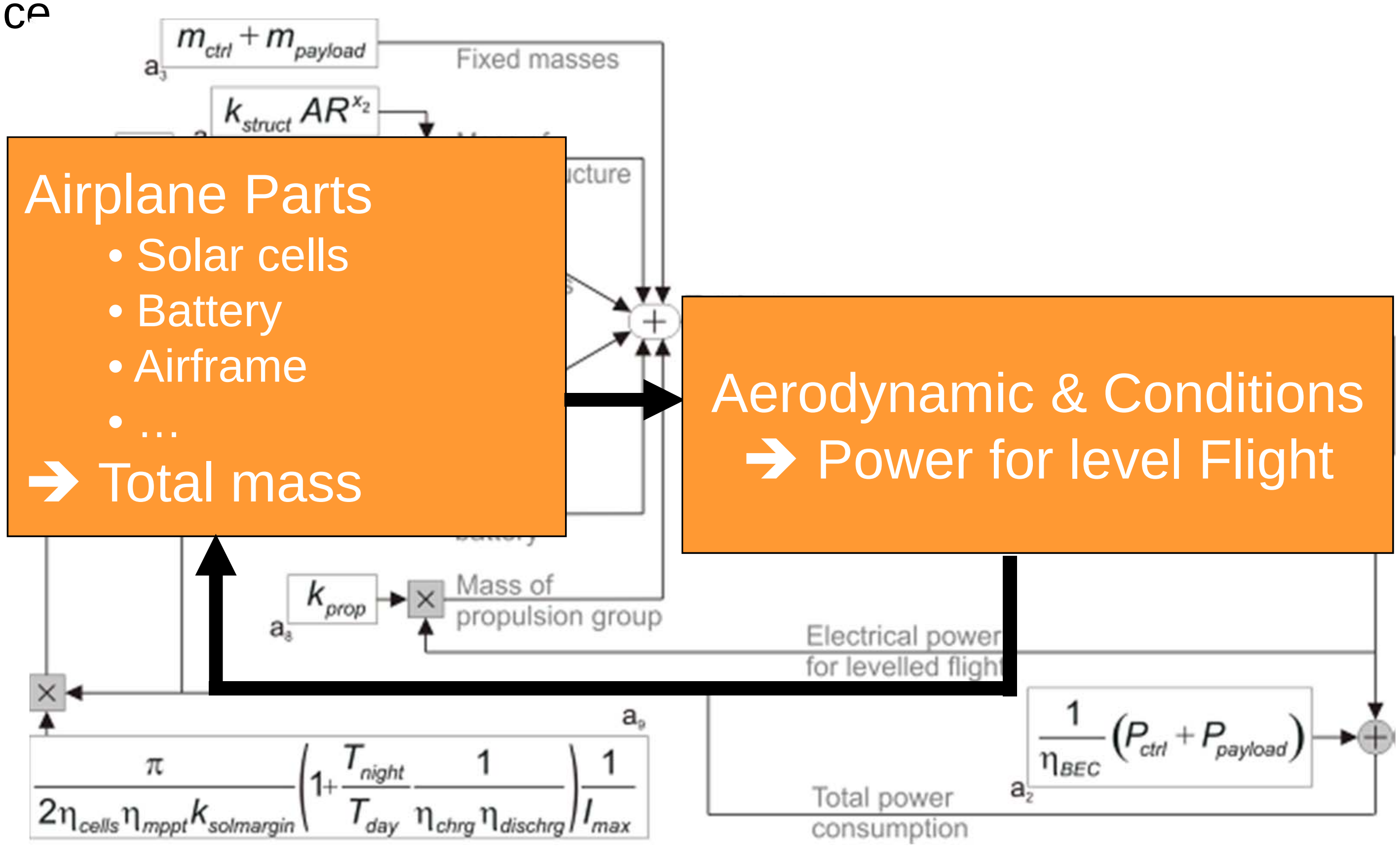
PacFlyer/wingtra (2013)
| the VTOL UAV



Solar Airplane |
design methodology for continuous flights

- Based on Mass & Power Balance
  - Need for precise scaling laws (mass models)





Flying Robots – fixed wing

Skysailor (2008)

| pioneering continuous flights

| 3.2 m, 2.3 kg

senseSoar (2012)

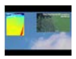
| robust and versatile solar plane

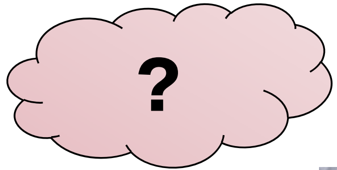
| 3 m, 3.8 kg

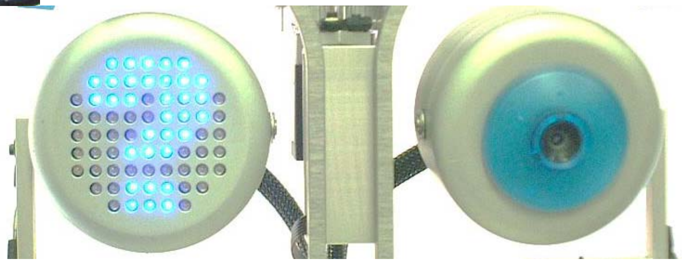
AtlantikSolar (2015)

| 81 hours non-stop in summer 2015

| 5.64 m, 6.2 kg







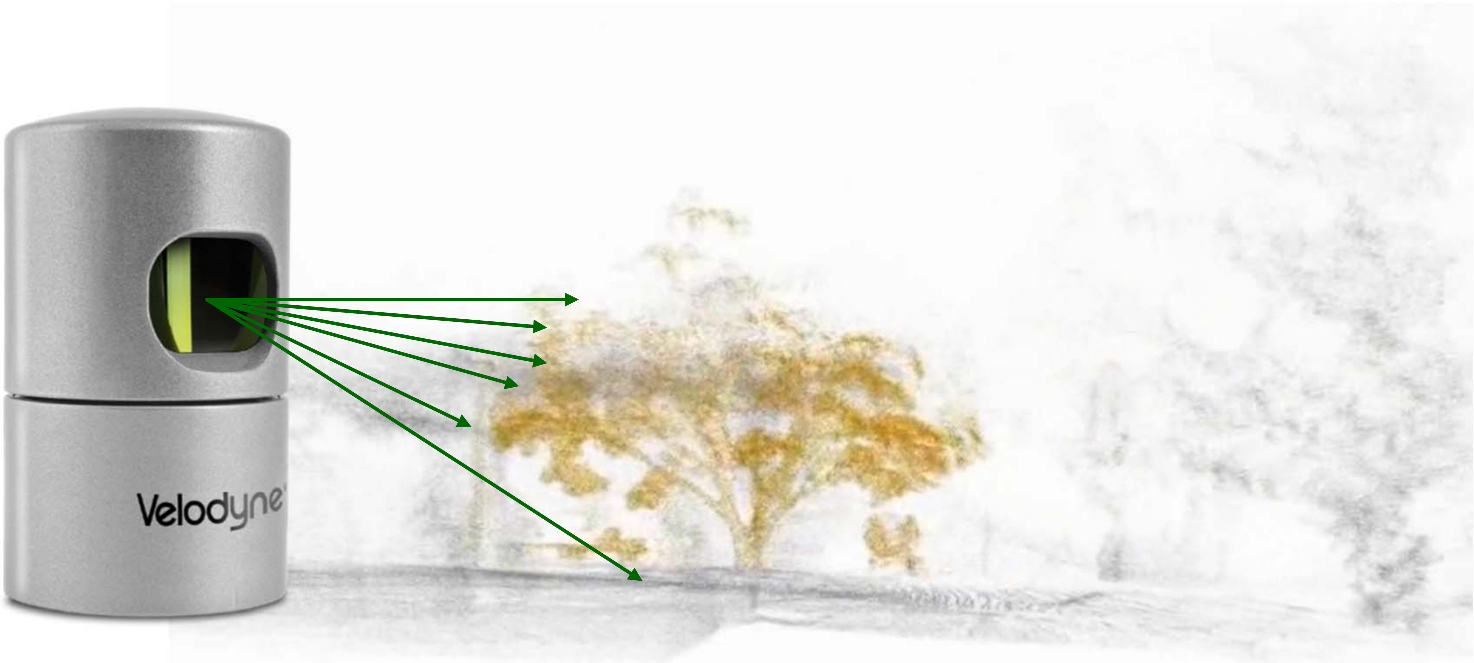
Mobile Robot Navigation

Robotics | challenges and technology drivers

- The challenges
  - ***Seeing***, ***feeling*** and ***understanding*** the world
  - Dealing with ***uncertain*** and ***partially available*** information
  - ***Act*** appropriately onto the environment

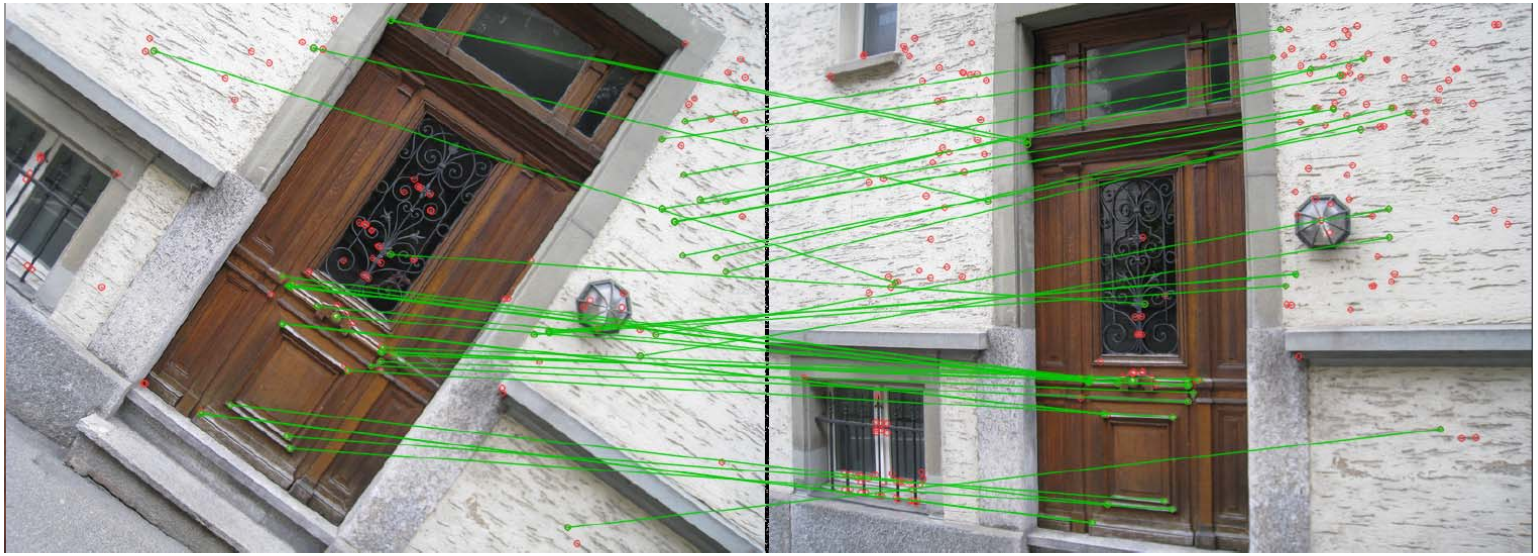
- Technology drivers
  | *technology evolutions enable robotics revolutions*
  - Laser time-of-flight sensors
  - Cameras and IMUs combined with required calculation power
  - Torque controlled motors, “soft” actuation
  - New materials

"Seeing" | Laser-based 3D mapping



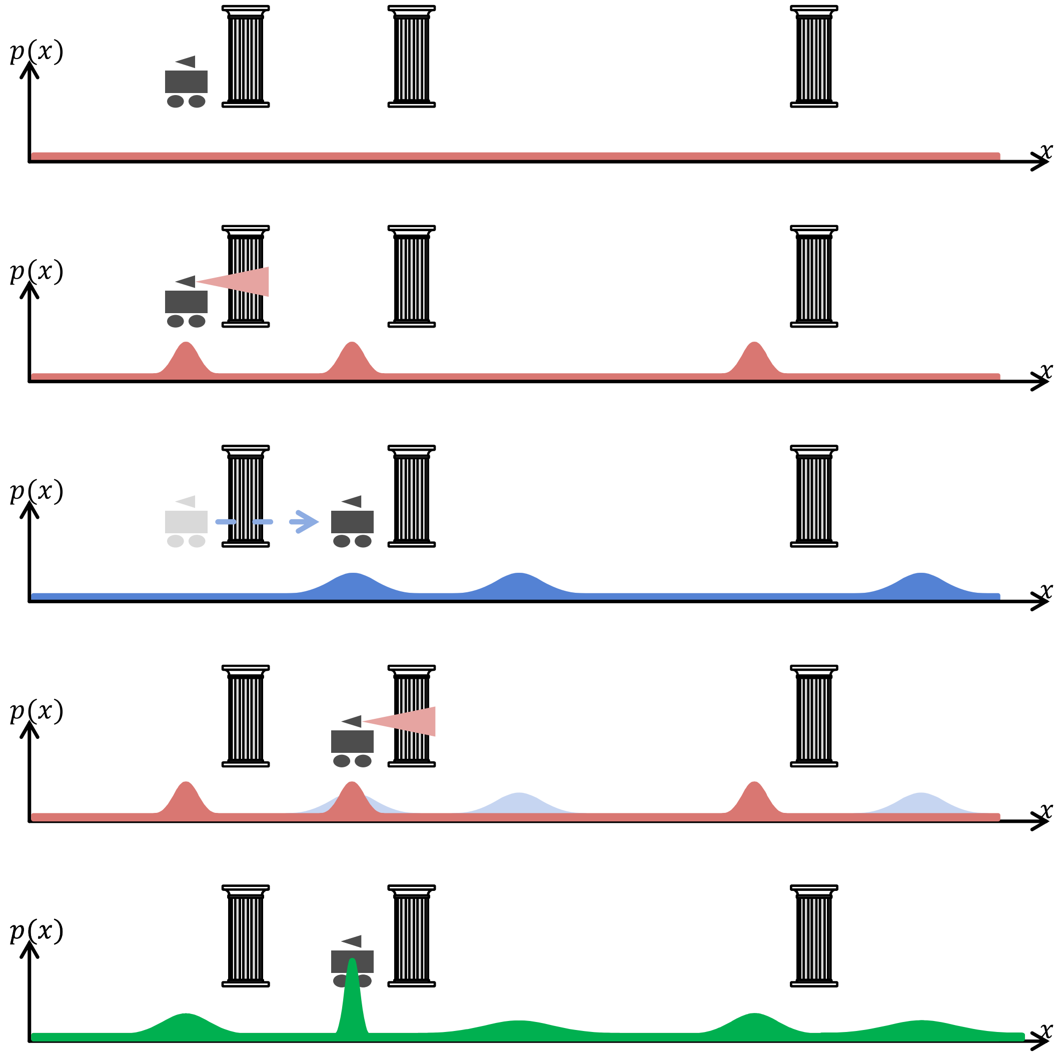
“Seeing” | Visual-Inertial Motion Estimation

Google Project Tango



"Seeing" the world | where am I?

- SEE: The robot queries its sensors → finds itself next to a pillar
- ACT: Robot moves forward
  - motion estimated by wheel encoders
  - accumulation of uncertainty
- SEE: The robot queries its sensors again → finds itself next to a pillar
- Belief update (information fusion)



"Understanding" the world

Fusing & Compressing Information

Places / Situations
A specific room, a meeting situation, …

Servicing / Reasoning

- *Functional / Contextual Relationships of Objects*
  - *imposed*
  - *learned*
  - *spatial / temporal/semantic*

Objects
Doors, Humans, Coke bottle, car , …

Interaction

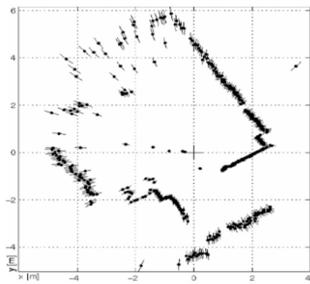
- *Models / Semantics*
  - *imposed*
  - *learned*

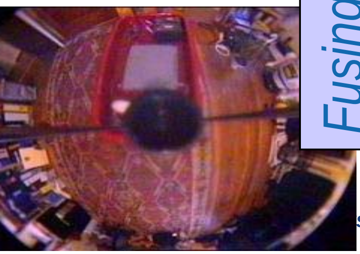
Features
Lines, Contours, Colors, Phonemes, …

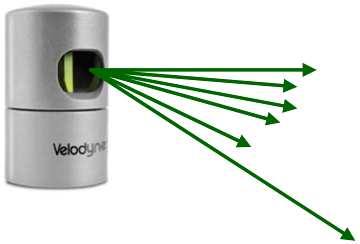
Navigation

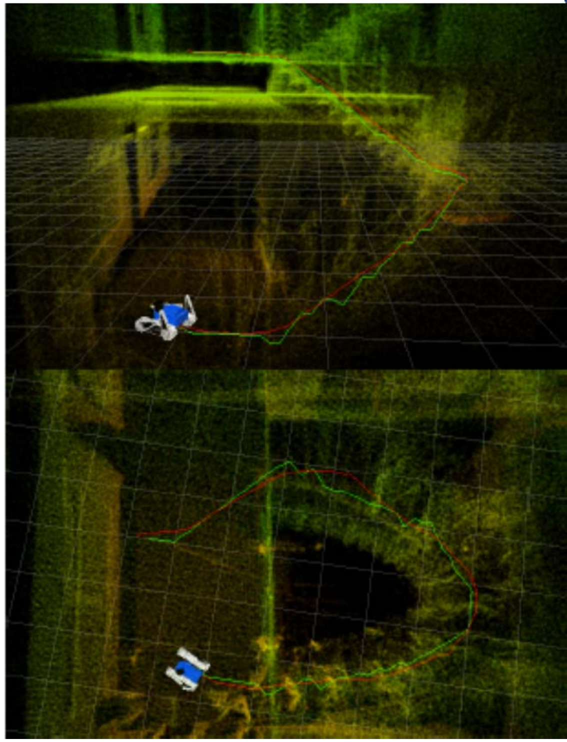
- *Models*
  - *imposed*
  - *learned*

Raw Data
Vision, Laser, Sound, Smell, …





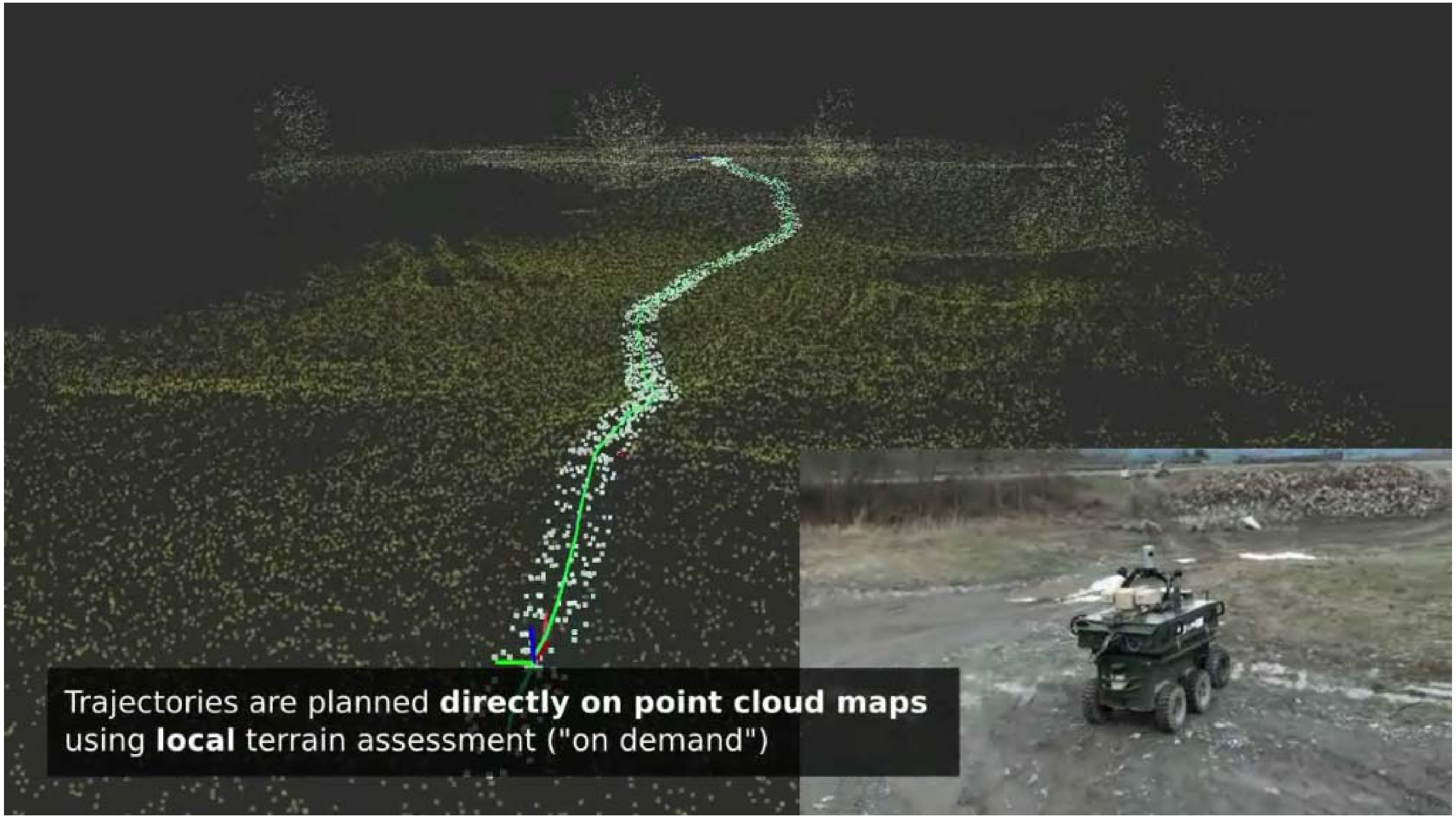




Laser-based navigation in complex terrains

3D mapping and path planning

3D mapping and path planning

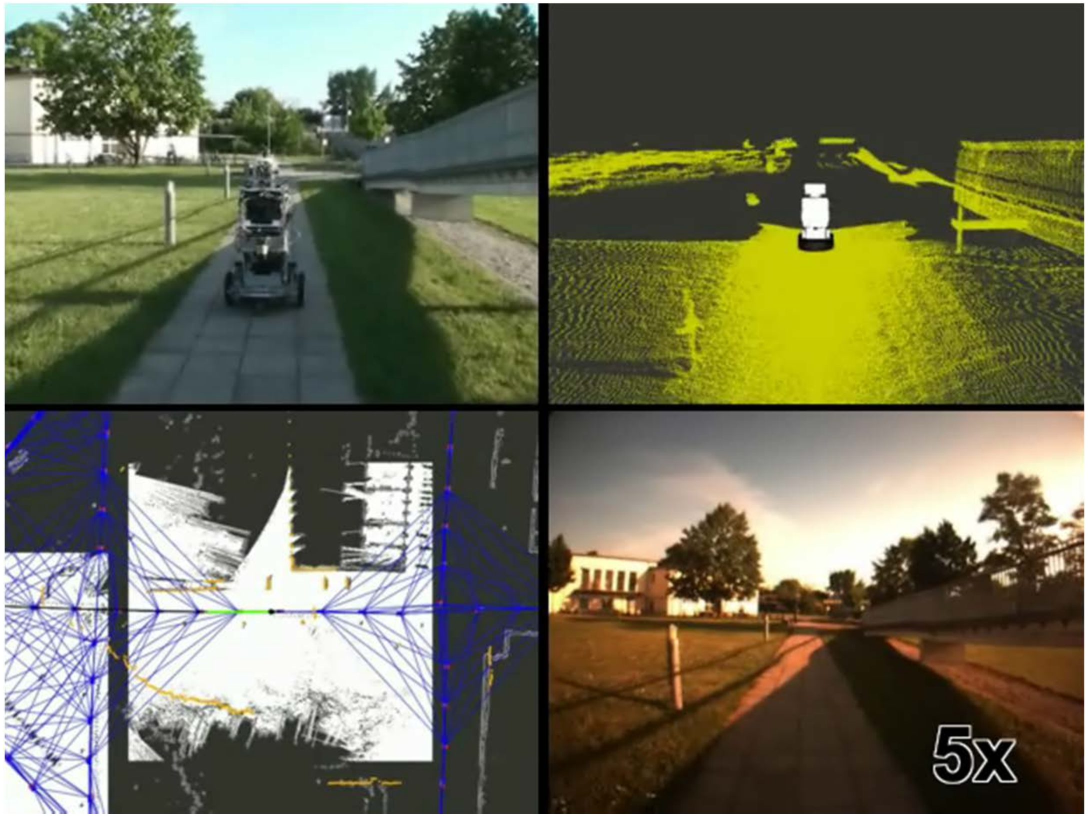


Autonomous navigation in cities

EUROPA - European Robotic Pedestrian Assistant

EUROPA

- In collaboration with
  - University of Freiburg,
  - Univ. of Oxford
  - KU Leuven
  - RWTH Aachen
  - BlueBotics

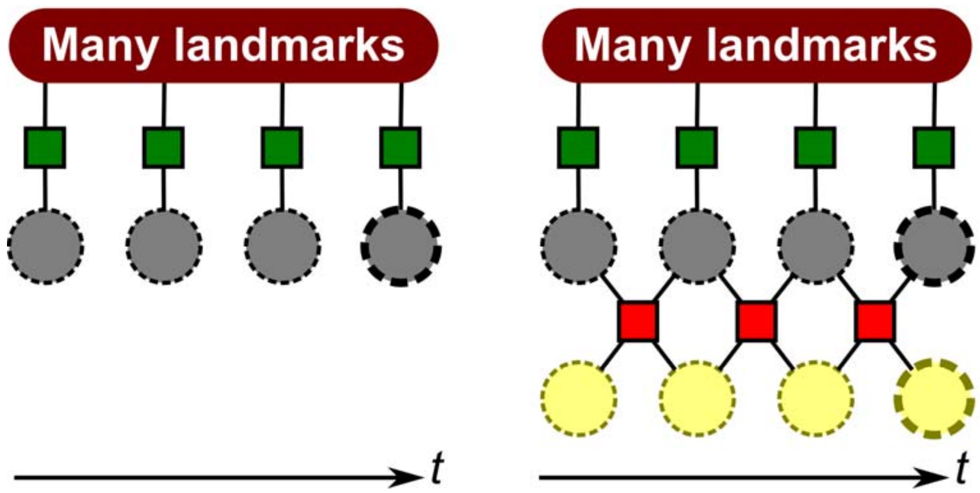


Real-time on-board **Visual-Inertial** Navigation

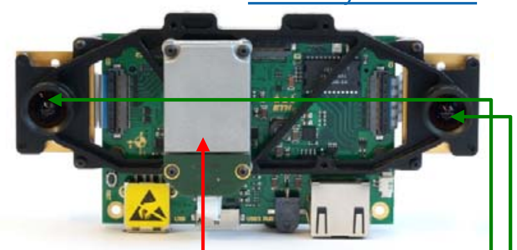
Three Approaches

- OKVIS: Open Keyframe-based Visual Inertial SLAM
- LL-VSLAM: Life-long Localization and Mapping
- ROVIO: Robust Visual Inertial Odometry

OKVIS | Vision-Only vs. Visual-Inertial in Optimization



www.skybotix.com



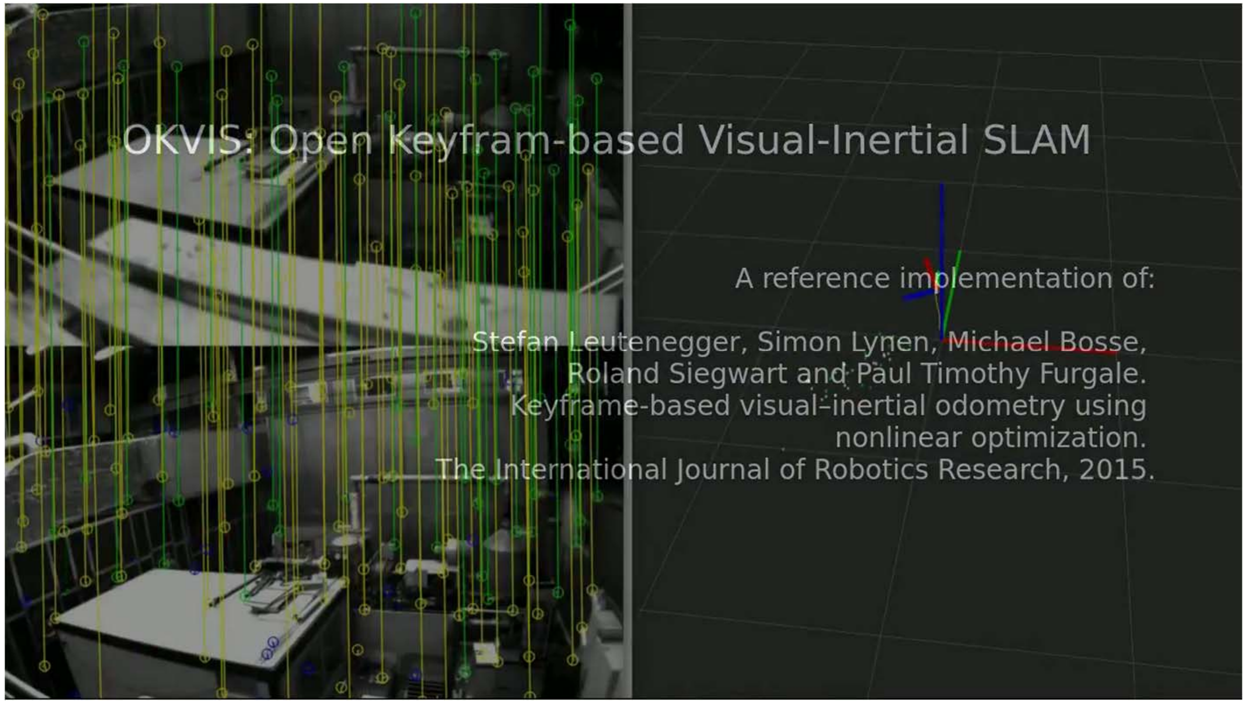
$$J(\mathbf{x}) := \sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{j\in\mathcal{J}(i,k)} {\mathbf{e}_{\mathrm{r}}^{i,j,k}}^T \mathbf{W}_{\mathrm{r}}^{i,j,k}\mathbf{e}_{\mathrm{r}}^{i,j,k} + \sum_{k=1}^{K-1} {\mathbf{e}_{\mathrm{s}}^{k}}^T \mathbf{W}_{\mathrm{s}}^{k}\mathbf{e}_{\mathrm{s}}^{k}.$$

Cost　　Reprojection errors (weighted)　　IMU terms

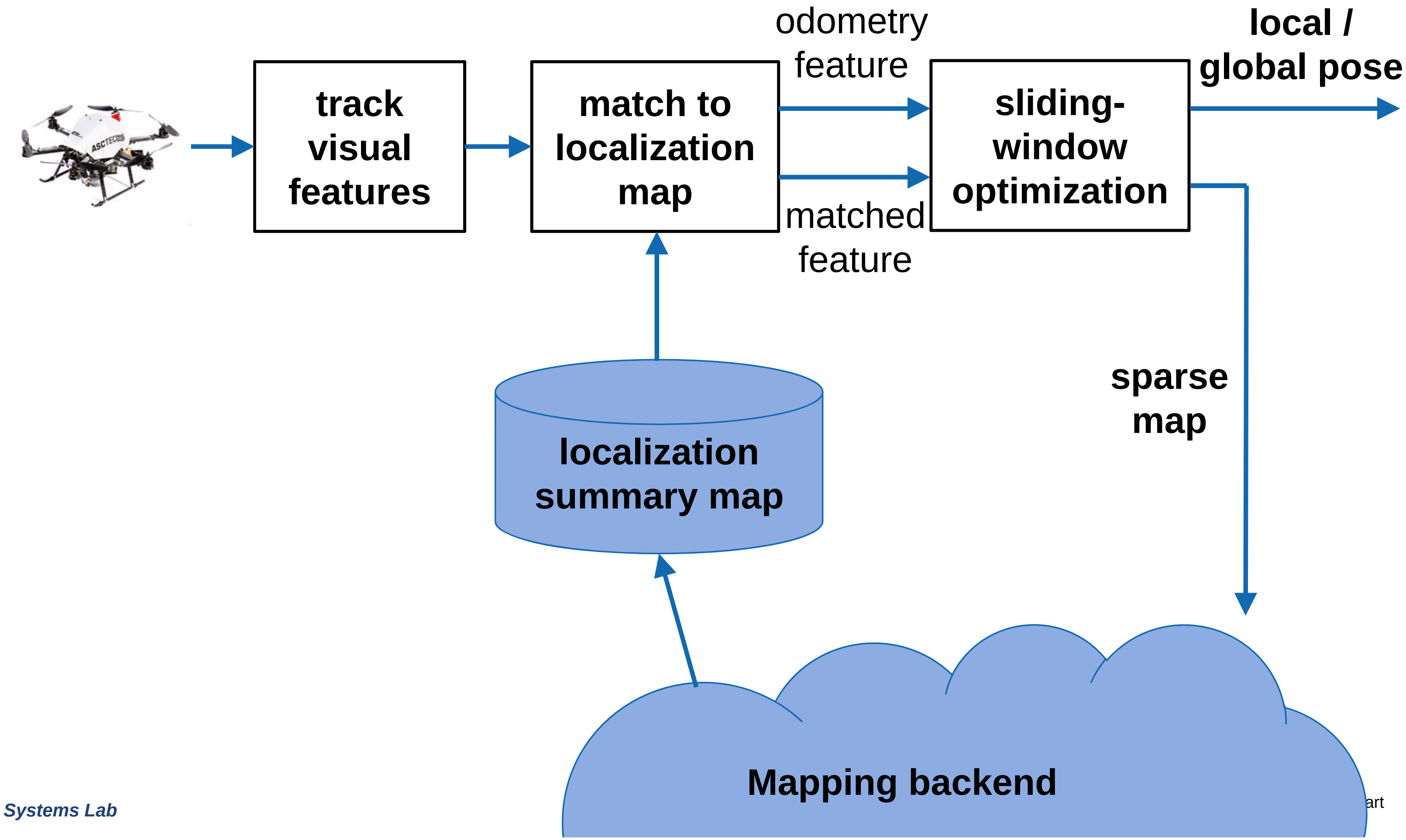
i: camera index; *k:* camera frame index; *j:* landmark index.

OKVIS: Open Keyframe-based Visual Inertial SLAM

- OKVIS tracks the motion of an assembly of an Inertial Measurement Unit (IMU) plus N cameras (tested: mono, stereo and four-camera setup) and reconstructs the scene sparsely

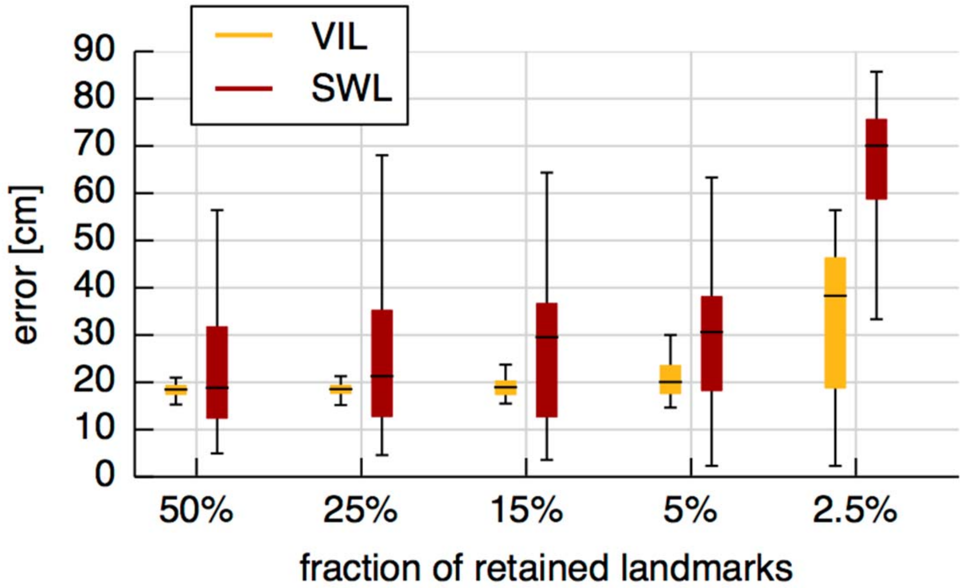


LL-VSLAM Frontend | Online visual-inertial localization



LL-VSLAM | Localization performance comparison

- Global localization error for different levels of map summarization



processing of odometry and localization landmarks:

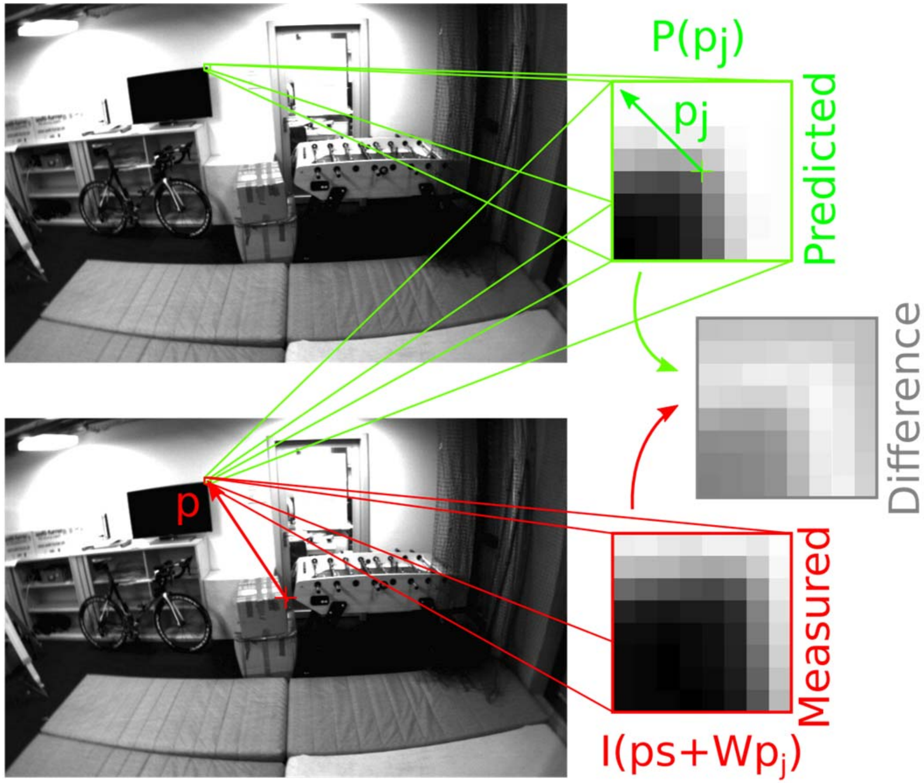
VIL	tightly coupled (proposed method)
SWL	loosely coupled approach

✓ **The proposed visual-inertial localization algorithm performs well with heavily summarized maps**

ROVIO | Robust Visual Inertial Odometry

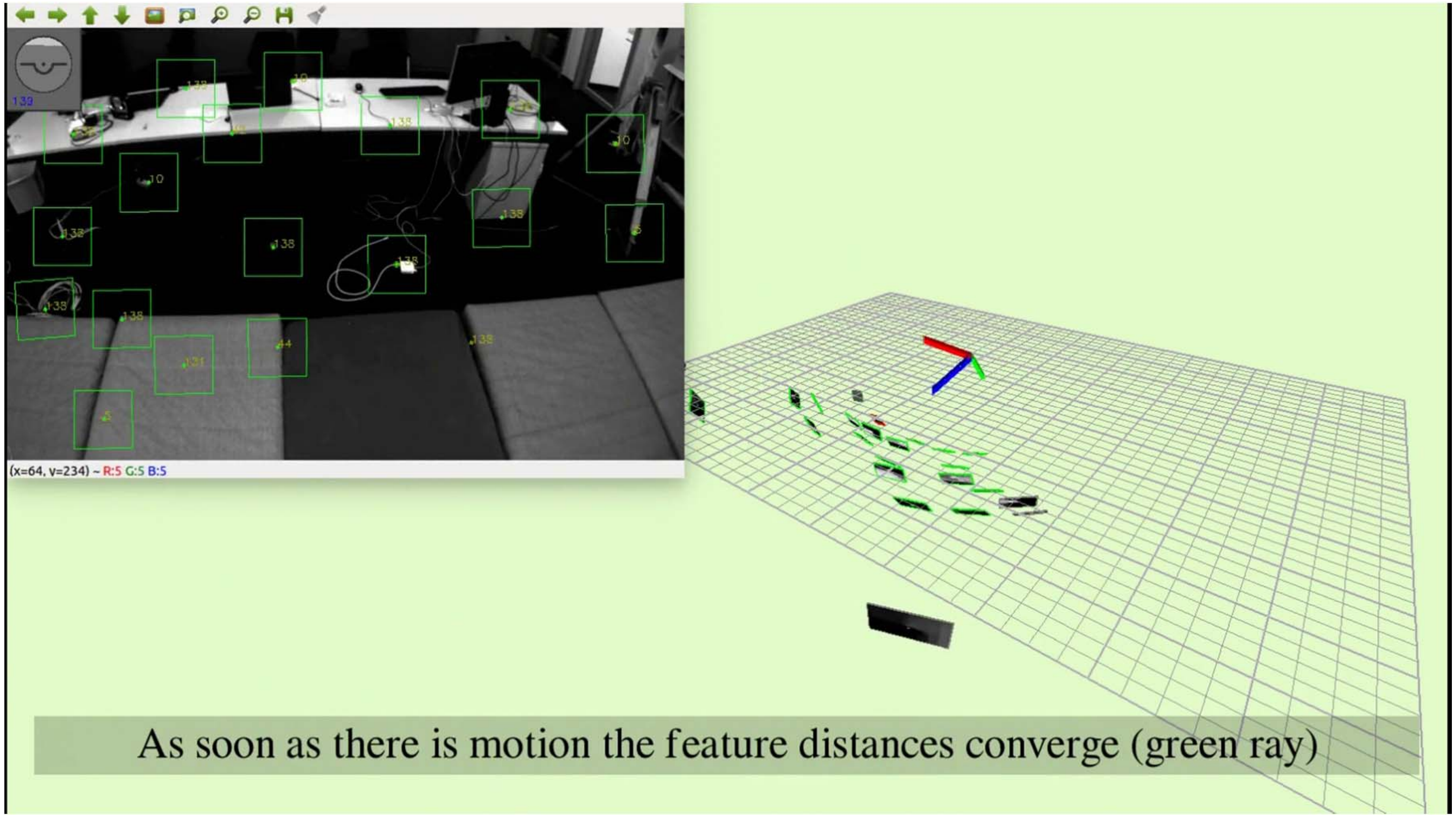
- robo-centric representation
- EKF based IMU-Vision fuses
- projected intensity errors (instead of reprojection errors)

- Procedure
  - feature detection & image patch is extracted.
  - Derivation of an intensity based error terms
  - dimension reduction of error term by QR-decomposition directly used as Kalman filter innovation



Robust Visual Inertial Odometry (ROVIO)

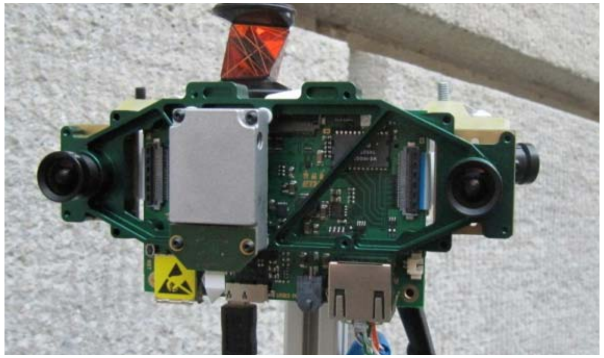
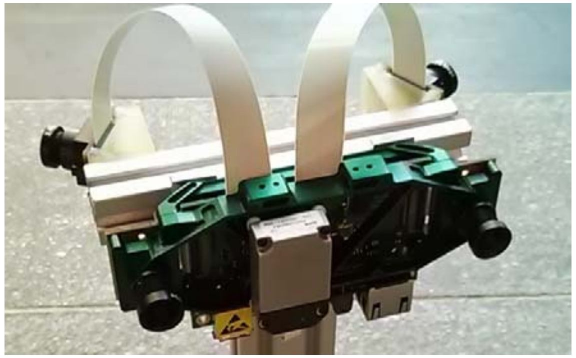
https://www.youtube.com/watch?v=ZMAISVy-6ao&list=PLJol3sa8g75RNJ0vALyl0BBfTNuhwWe1g&index=2

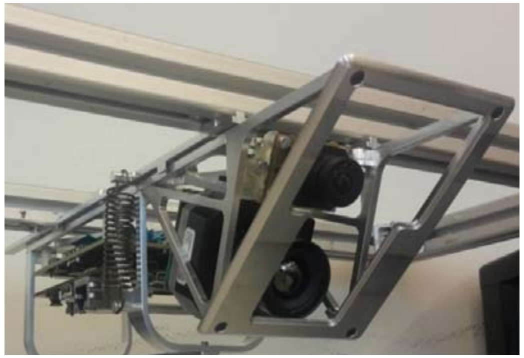


[M. Bloesch et al (2015). Robust Visual Inertial Odometry Using a Direct EKF-Based Approach, IROS]

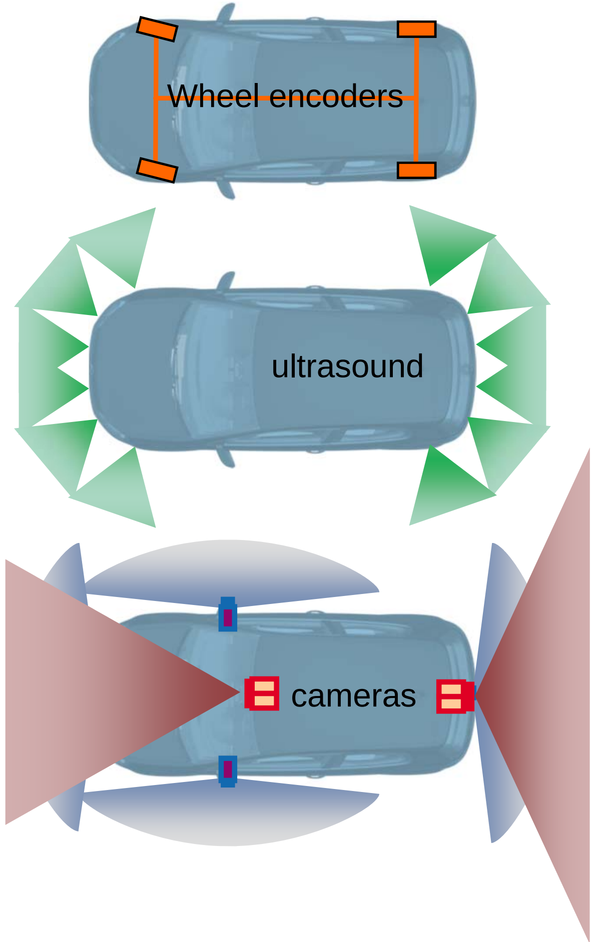
ASL Visual-Inertial Sensor
Dedicated Hardware for real-time on-board

- FPGA: XILINX Zynq 7020 SoC Dual-Core ARM Cortex A9
- Weight: 130 g (incl. 2 cams + sensor mount)



V-Charge | using close-to-market sensors



V-Charge | a typical scenario

- Scenarios can be very challenging, despite low speeds
  - Localization
  - Environment perception

- Mixed-traffic scenarios require…
  - Object classification and tracking
  - Inference of other's intentions

http://www.youtube.com/watch?v=wn2NfUH0G-Q
http://hamilton-baillie.co.uk

V-Charge | the ultimate vision

- Mixed-traffic scenarios

V-Charge | Vision and Results

Flying Robots | navigation

- Appropriate robot concept
  - Power autonomy
  - Agility
  - Robustness
- Navigation with on-board sensing ar
  processing
  - Robustness against communic s
  - “home” button
- Simple and intuitiv
  - Stable on “han
  - Collision av lization / SLAM
  - …

Teleoperation or GPS only navigation will, for most applications, not do the job

Courtesy of Ascending technologies

www.sfly.ethz.ch/

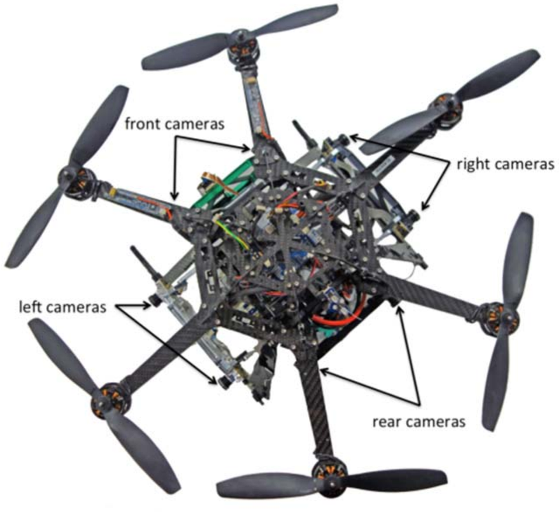
UAV | Vision only navigation

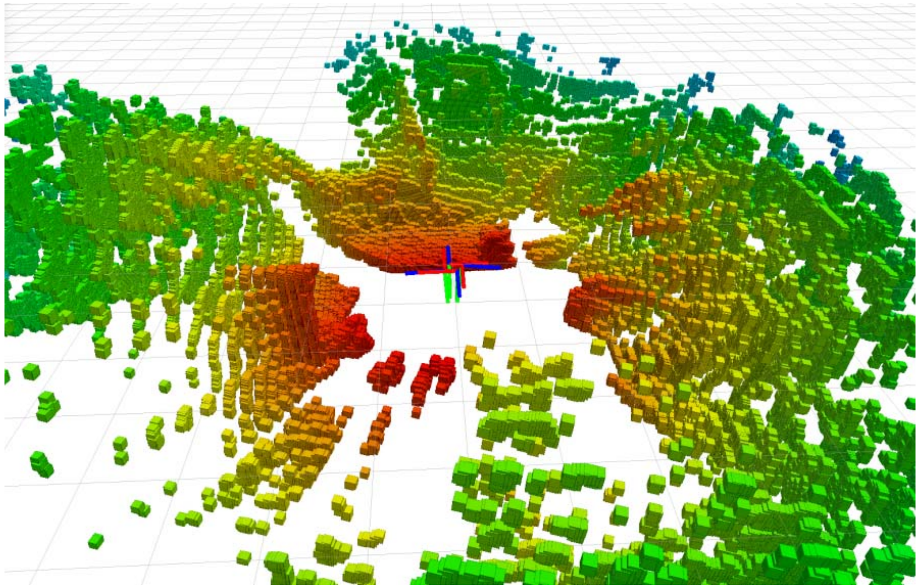
- Swarm of small helicopters
  - Vision-inertial navigation (one camera and IMU, GPS denied)
  - Fully autonomous with on-board computing
  - Feature-based visual SLAM
    - robust against lighting changes and large scale changes

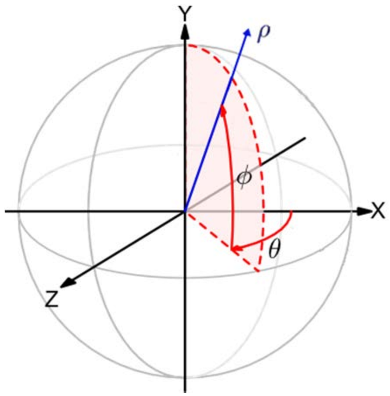
UAV | collision avoidance and path planning

- Real time 3D mapping (on-board)
- optimal path planning considering localization uncertainties

Omnidirectional Visual Obstacle Detection





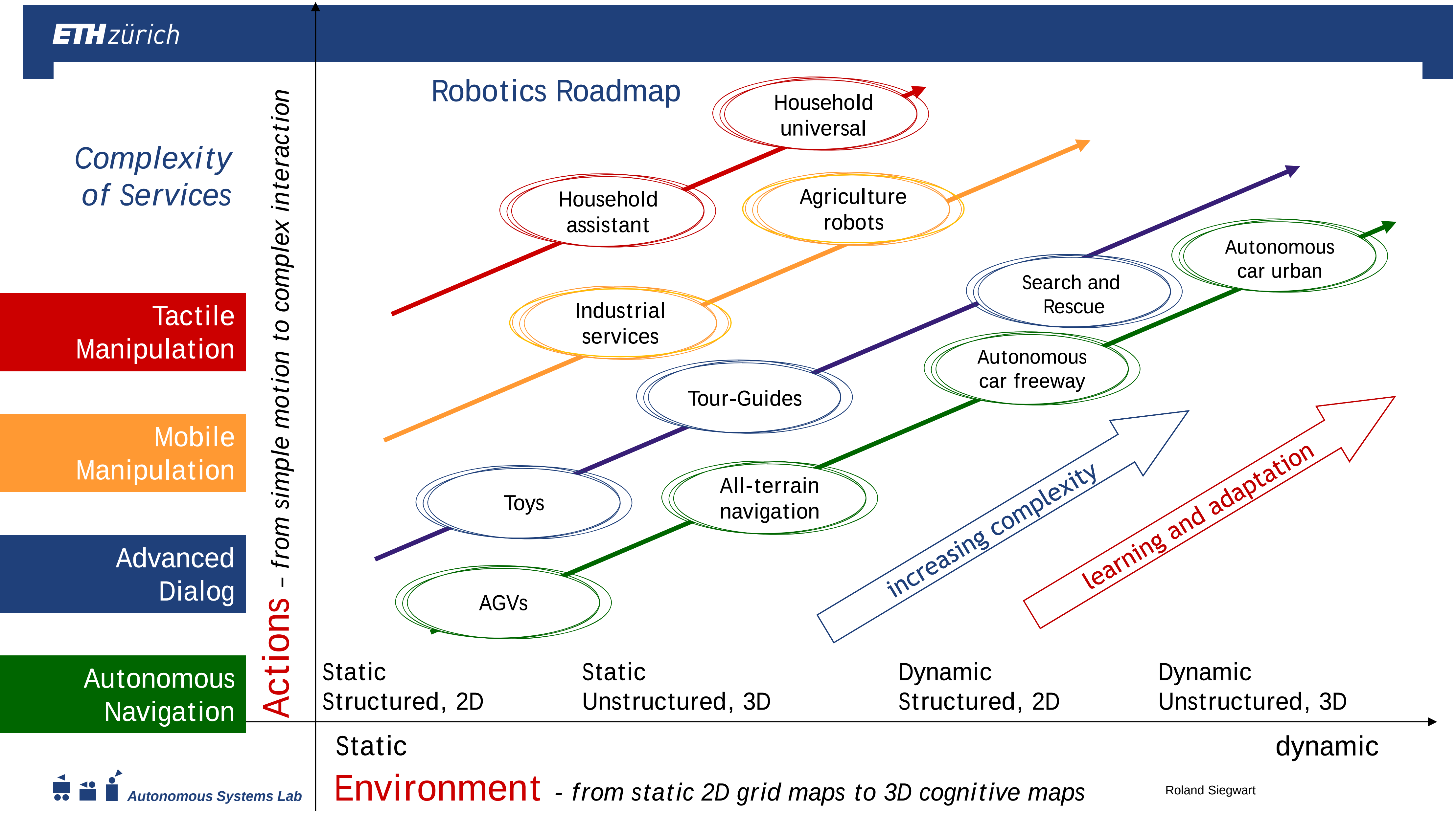


Collaborative Visual-Inertial Navigation

in collaboration with

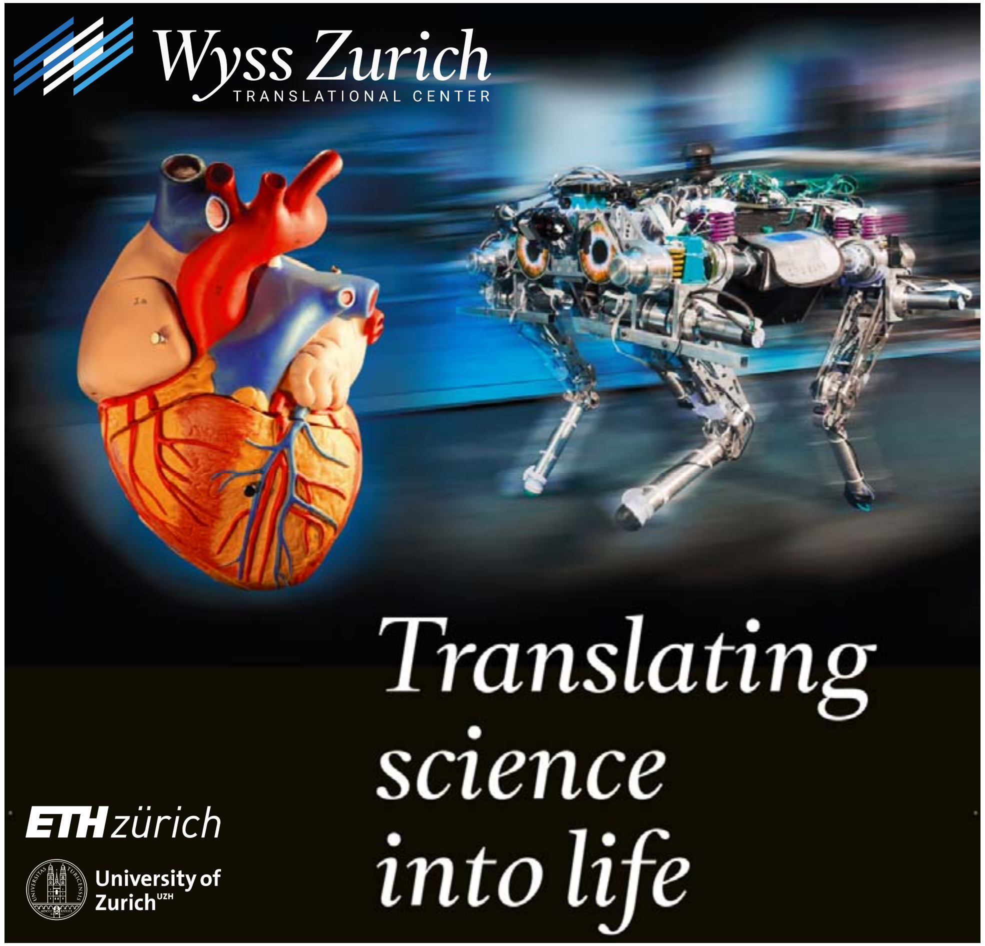
Robotic Systems Lab

Prof. Marco Hutter



ETH zürich
Robotics Roadmap
Complexity of Services
Tactile Manipulation
Mobile Manipulation
Advanced Dialog
Autonomous Navigation
Actions – from simple motion to complex interaction
Household universal
Household assistant
Agriculture robots
Industrial services
Search and Rescue
Autonomous car urban
Tour-Guides
Autonomous car freeway
Toys
All-terrain navigation
AGVs
increasing complexity
learning and adaptation
Static Structured, 2D
Static Unstructured, 3D
Dynamic Structured, 2D
Dynamic Unstructured, 3D
Static
dynamic
Environment - from static 2D grid maps to 3D cognitive maps
Autonomous Systems Lab
Roland Siegwart

Bridging the “valley of death” | The Wyss Zurich



- $120 Mio
- 6-7 years
- Focus
  - Robotics
  - Regenerative Technologies
- 8 technology transfer projects running, more in the pipeline

www.WyssZurich.uzh.ch

Switzerland, a High Density of Robotics Startups

More in the pipeline

BLUEBOTICS Mobile Robots at Your Service

senseFly

VERITY studios

GE Inspection Robotics

PIX4D simply powerful

Skybotix

FLYABILITY

wingtra

Hocoma

force dimension

MagnebotiX

aeon scientific

AEROTAIN

noonee because its wearable

Ophthorobotics AG

FEMTO TOOLS

Dacuda Scanning redefined.

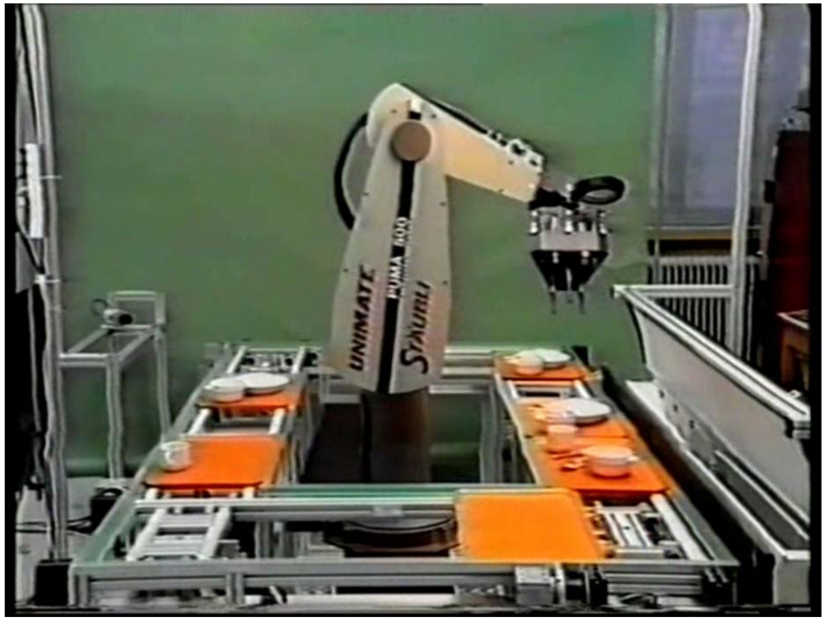
DISTRAN SWITZERLAND

YouRehab inspire motivate achieve

Rapyuta Robotics

Fotokite

"Perceiving and Handling of Objects"
– Progress is slower than we think



1992, ETH

2010
Courtesy of Willow Garage

Opportunities / Markets

- Industrial transportation
- Cleaning
- Medical robotics
- Entertainment / edutainment

- Logistics
- Autonomous Cars

- Industrial inspection
- Surveillance and rescue
- Construction and mining
- Agriculture

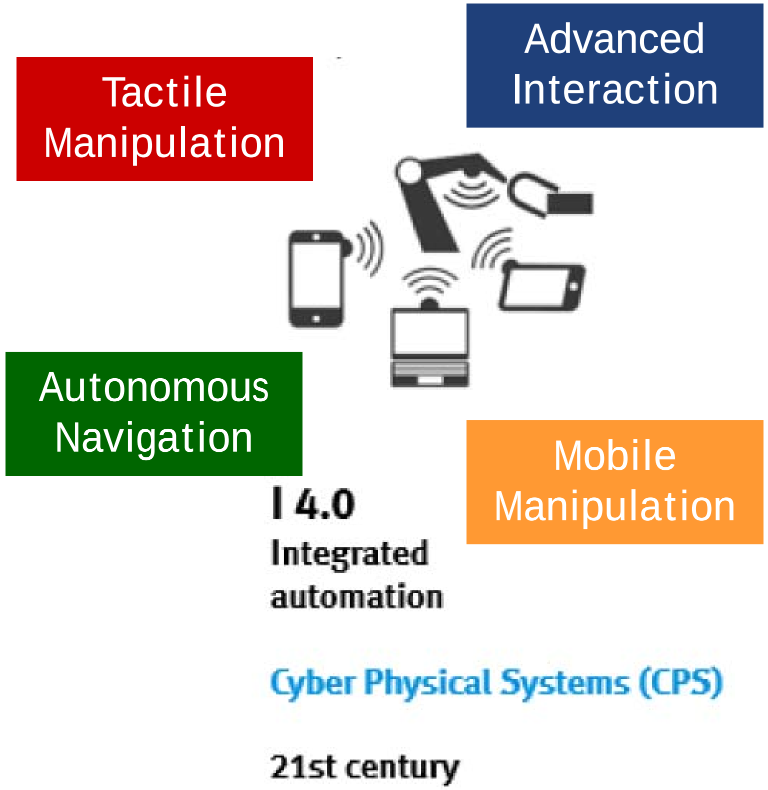
- Health and elderly care
- Personal / services robots

The coffee servant
Nesspresso / Bluebotics, Switzerland

Conclusion

- Robotics is a very fascinating engineering field
- However, robotics is a very very hard problem
  - Design and precision mechanics
  - Perception
  - Physical interaction
  - Intelligence

- The way forward
  - A single fine-tuned demonstration is not enough
  - Hype / Bobble
    - Overselling will bounce back
  - However, there are low hanging fruits



ASL Team