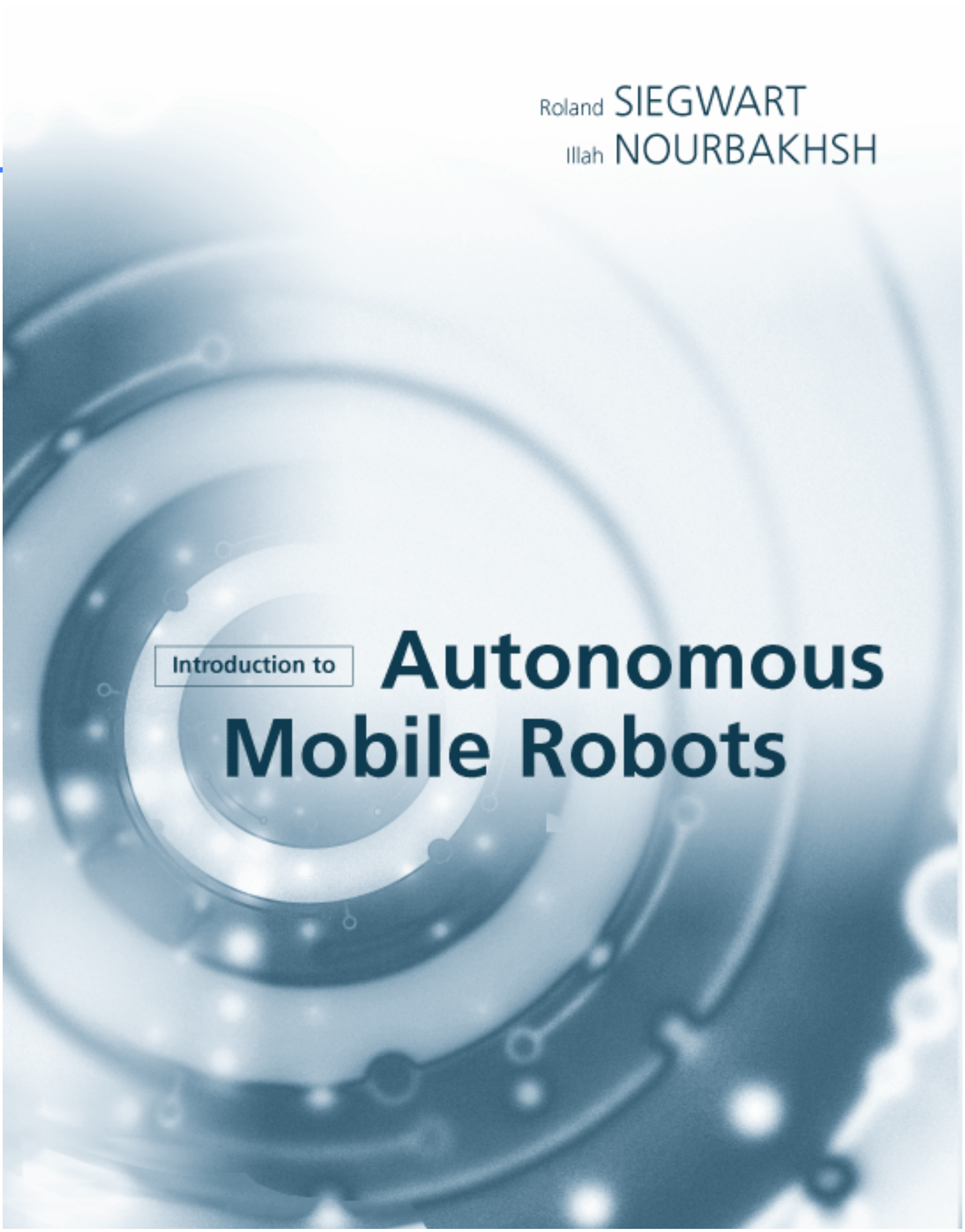


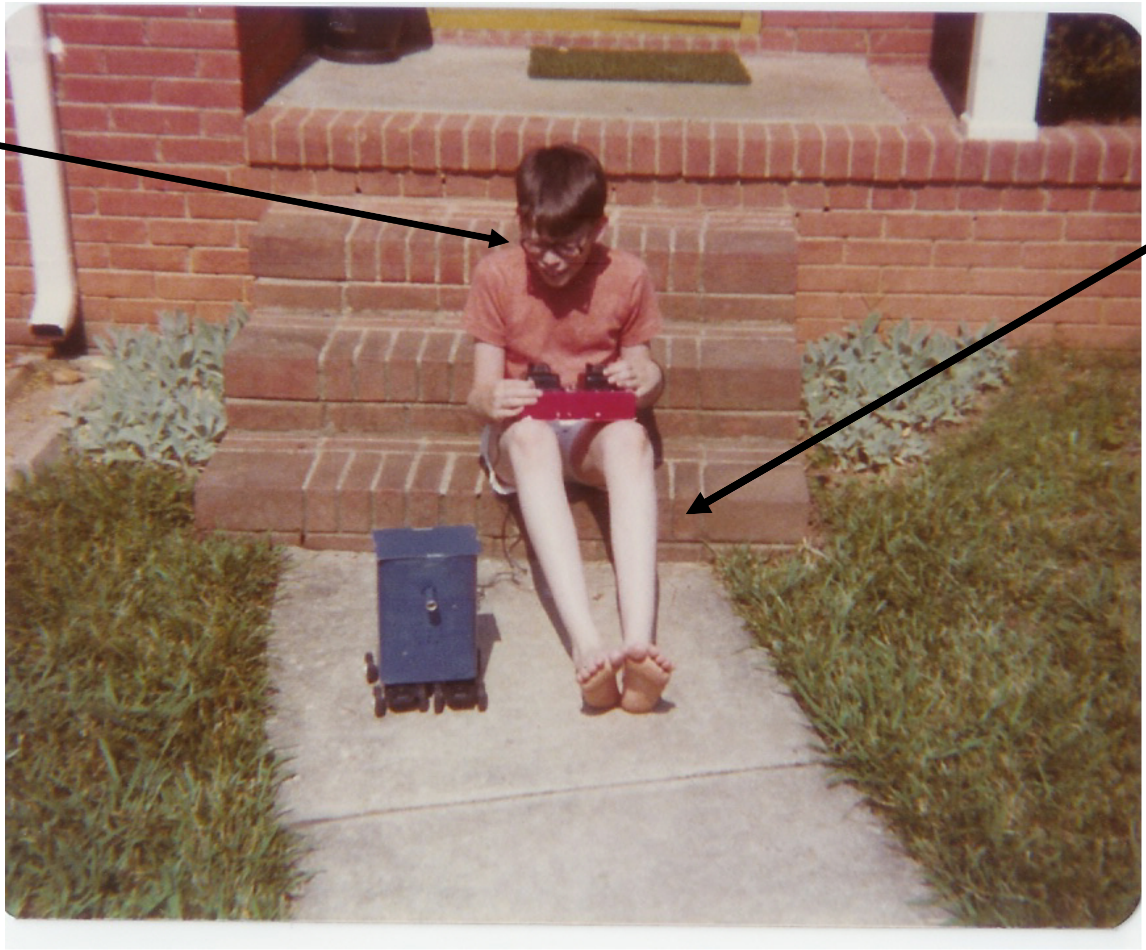
Slides

that go with the book

Intelligent Robotics and Autonomous Agents series
The MIT Press
Massachusetts Institute of Technology
Cambridge, Massachusetts 02142
ISBN 0-262-19502-X

Name this roboticist …

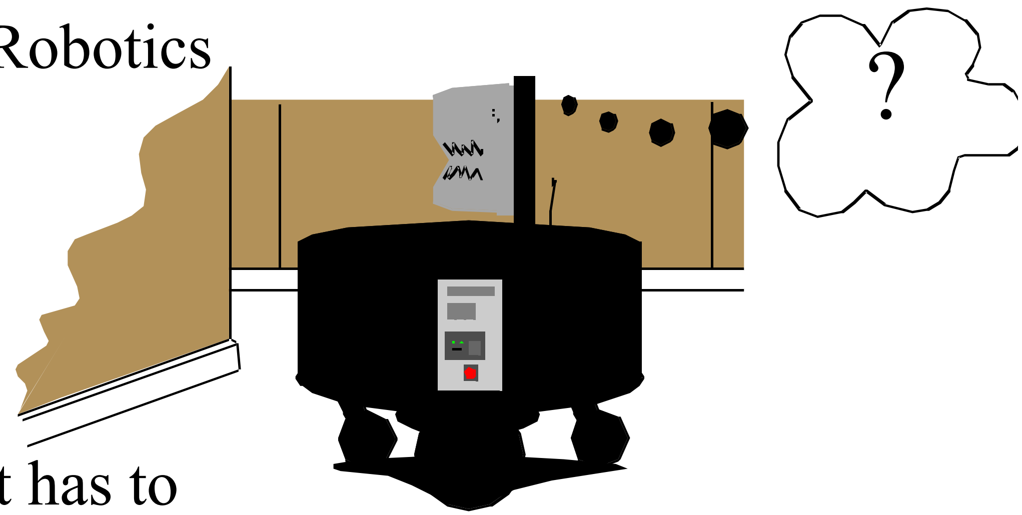
‘70s glasses



Long legs foretell tall adult

Autonomous Mobile Robots

- The three key questions in Mobile Robotics
  - *Where am I ?*
  - *Where am I going ?*
  - *How do I get there ?*



- To answer these questions the robot has to
  - *have a model of the environment (given or autonomously built)*
  - *perceive and analyze the environment*
  - *find its position within the environment*
  - *plan and execute the movement*
- This course will deal with Locomotion and Navigation (Perception, Localization, Planning and motion generation)

Content of the Course

1. Introduction
2. Locomotion
3. Mobile Robot Kinematics
4. Perception
5. Mobile Robot Localization
6. Planning and Navigation

- Other Aspects of Autonomous Mobile Systems
- Applications

Program

Date	Room/ Time	Topic	Responsible
21.10	BM 2135, 10 - 12	Introduction: problem statements, typical applications, video	R. Siegwart
28.10	BM 2135, 10 - 12	Locomotion with legs and wheels (2h)	R. Siegwart
28.10	BM 2127, 13 - 15	Exercise 1: Introduction to Matlab	Y. Piguet, A. Martinelli
4.11	BM 2135, 10 - 12	Mobile Robots Kinematics I: Kinematics model (2h)	R. Siegwart
4.11	BM 2127, 13 - 15	Exercise 2: Kinematics model and trajectory calculation of wheeled robots	R. Siegwart
11.11	BM 2135, 10 - 12	Mobile Robots Kinematics II: Motion control (1h) Perception I: Sensing and Perception(1h)	R. Siegwart
18.11	BM 2135, 10 - 12	Perception II: Sensing and Perception (2h)	R. Siegwart
18.11	BM 2127, 13 - 152	Exercise 3: Motion control of a differentially driven robot (Matlab/Khepera)	G. Caprari A. Martinelli
25.11	BM 2135, 10 - 12	Perception III: Uncertainty Representation, feature extraction (2h)	R. Siegwart
2.12	BM 2135, 10 - 12	Localization I: Introduction, odometry, belief representation (2h)	R. Siegwart
2.12	BM 2127, 13 - 15	Exercise 4: Vision and/or laser; take picture, feature extraction; uncertainty representation; belief representation	J. Weingarten B. Jensen
9.12	BM 2135, 10 - 12	Localization II: Map representation, introduction to probabilistic map- based localization, Markov localization(2h)	R. Siegwart
16.12	BM 2135, 10 - 12	Localization III: Kalman filter localization (2)	R. Siegwart
16.12	BM 2127, 13 - 15	Exercise 5: Probabilistic pose estimation with Khepera base on topological map	N. Tomatis A. Tapus
6.1	BM 2135, 10 - 12	Localization IV: Other examples of localization systems, map building (2)	R. Siegwart
13.1	BM 2135, 10 - 12	Architectures for Navigation I: Introduction, path planning (2)	R. Siegwart
13.1	BM 2127, 13 - 15	Exercise 6: Potential Field: Field generation (Matlab), implementation on Khepera	A. Martinelli Y. Piguet
20.1	BM 2135, 10 - 12	Architectures for Navigation II: Obstacle avoidance, techniques for decomposition (2)	R. Siegwart
27.1	BM 2135, 10 - 12	Architectures for Navigation III: Case Studies: architectures with behaviors (2)	R. Siegwart
27.1	BM 2127, 13 - 15	Exercise 7: Obstacle avoidance base on local grid (Matlab), implementation on Khepera	R. Philippsen G. Ramel
3.2	BM 2135, 10 - 12	Other aspects of autonomous mobile robots, applications (1h) Research in mobile robotics at ASL - EPFL, summery (1h)	R. Siegwart

Goal of today’s lecture

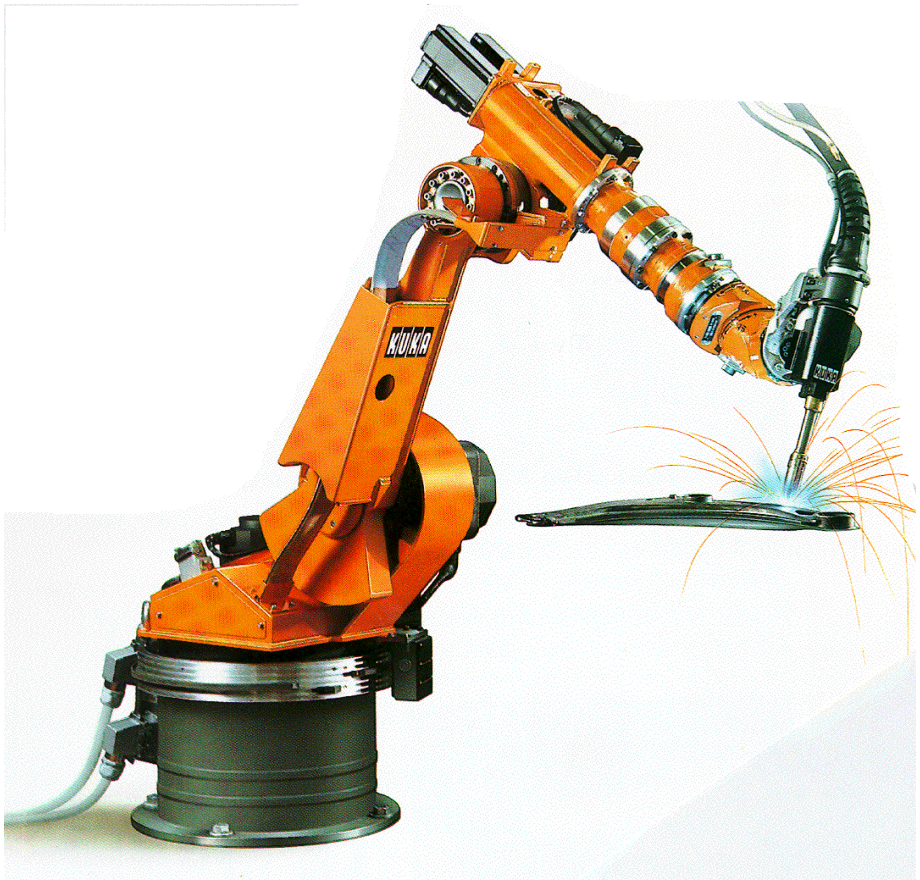
- Introduce the basic problems of mobile robotics
  - *the basic questions*
  - *examples and it’s challenges*

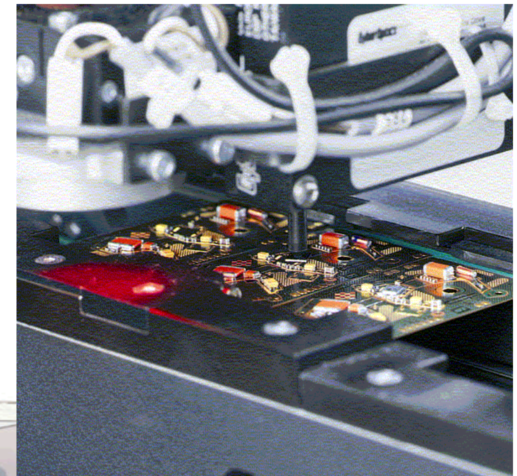
- Introduce some basic terminology
  - *Environment representation and modeling*

- Introduce the key challenges of mobile robot navigation
  - *Localization and map-building*

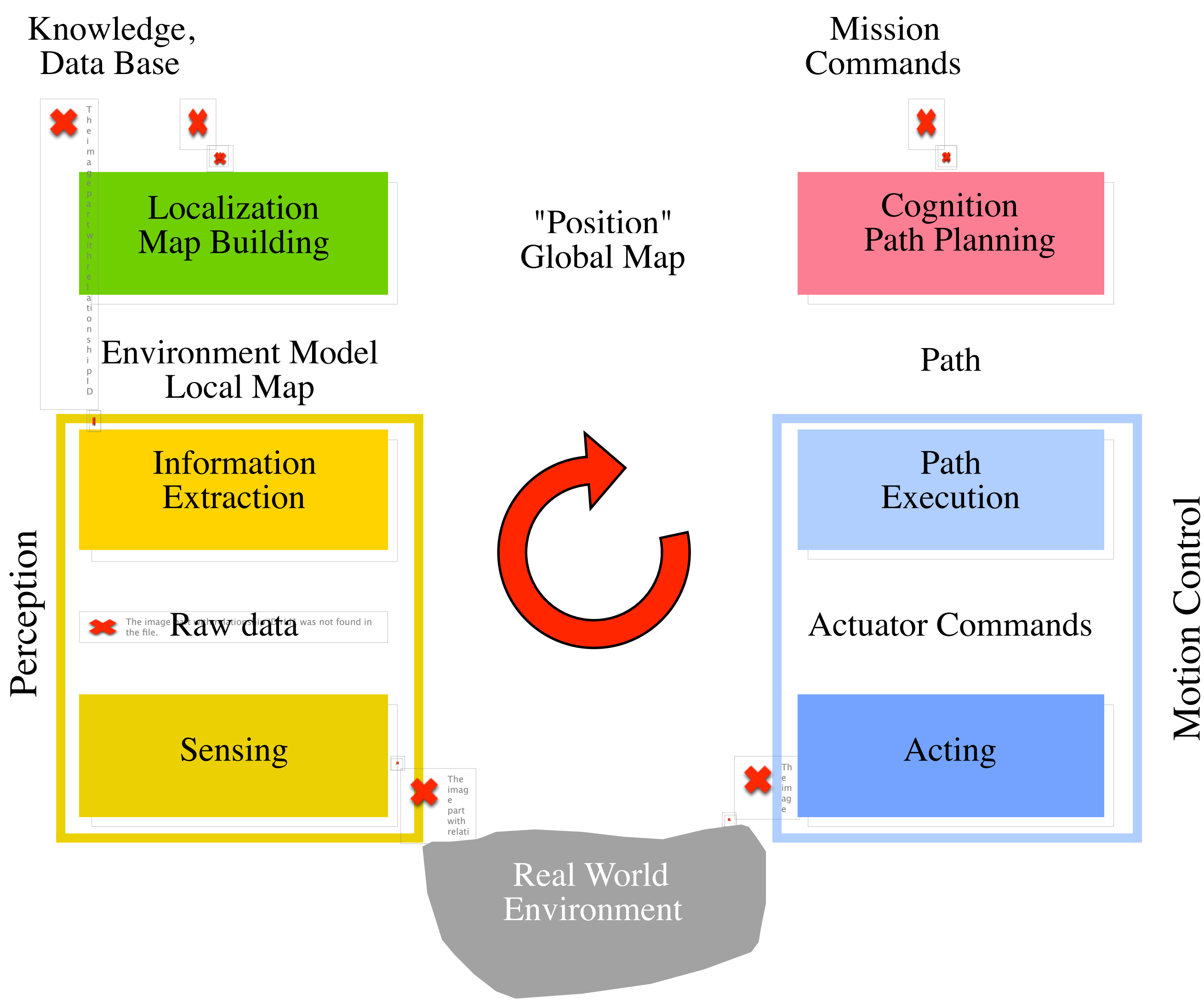
- Some examples/videos showing the state-of-the-art

From Manipulators to Mobile Robots

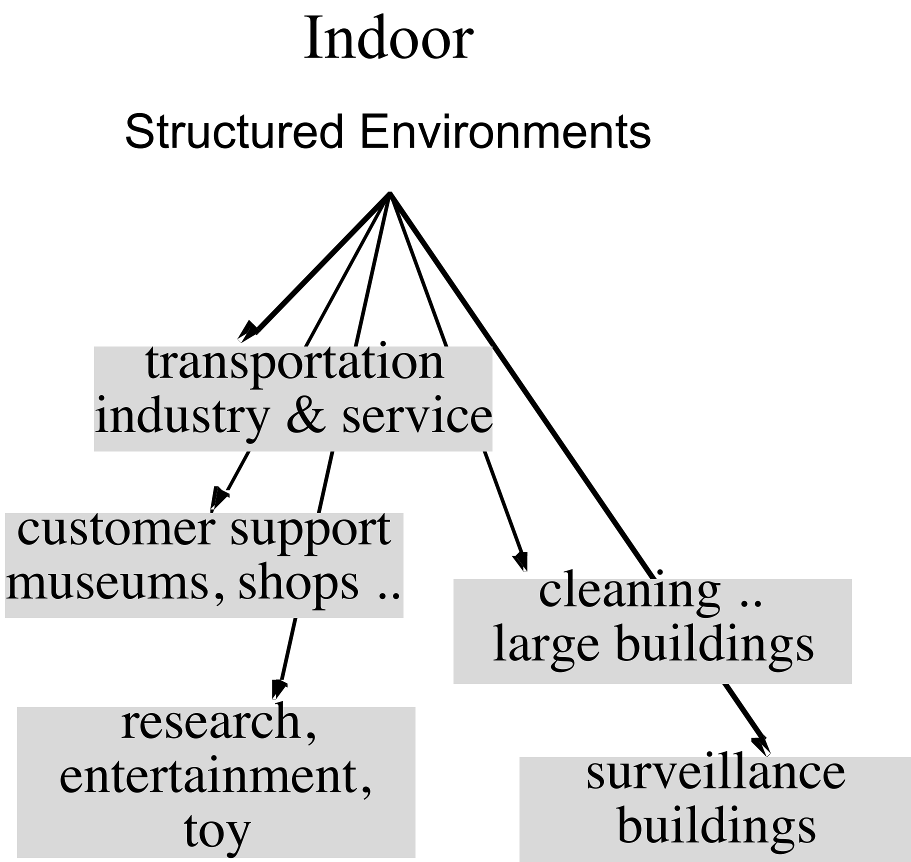


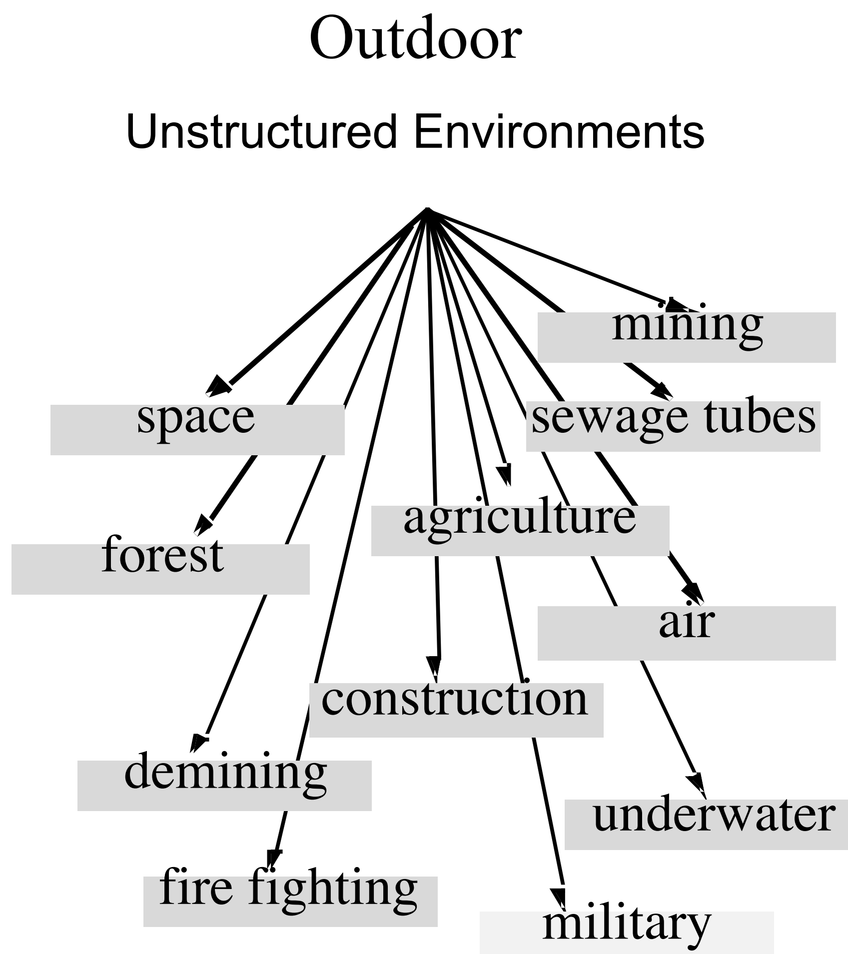


General Control Scheme for Mobile Robot Systems

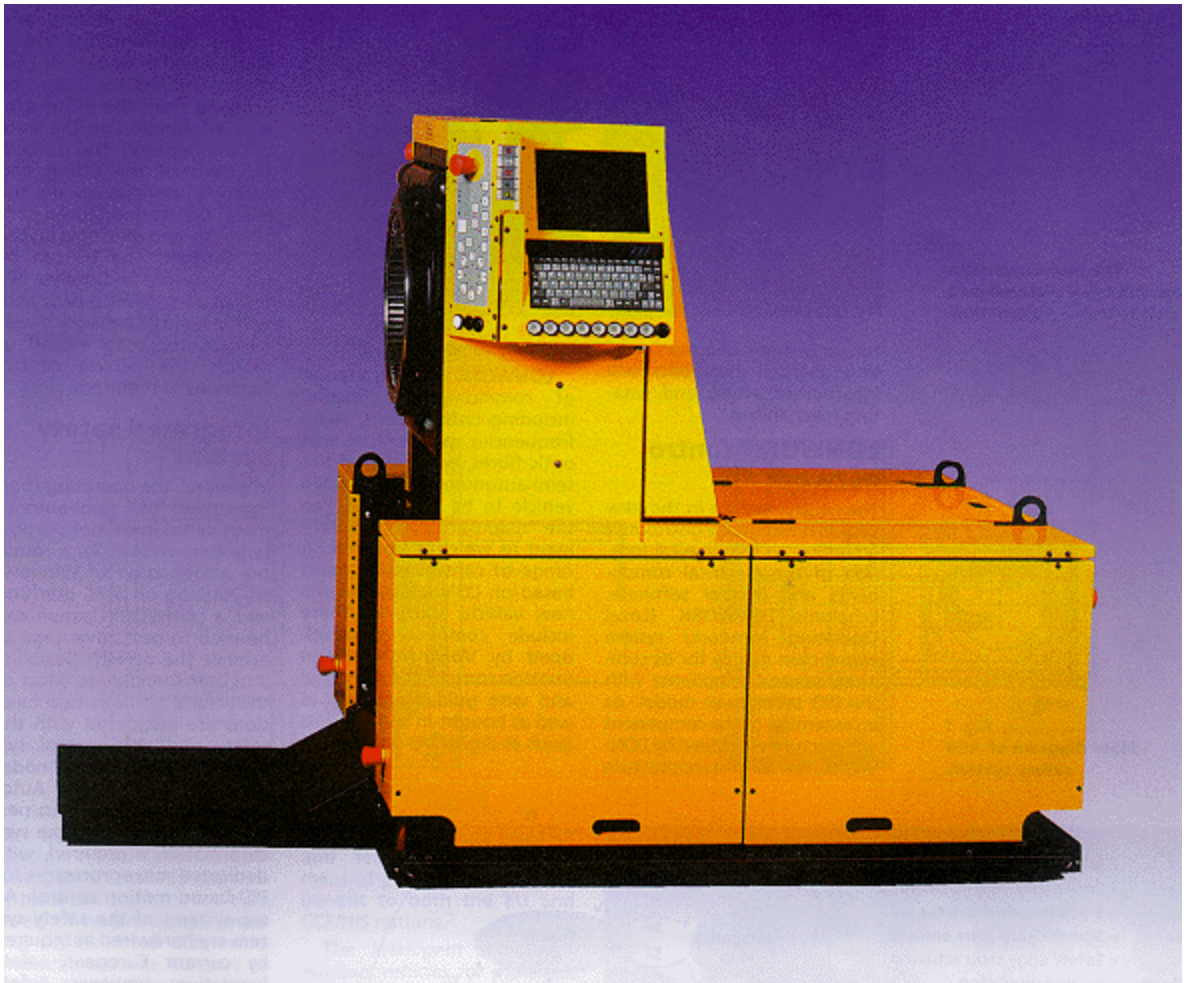


Applications of Mobile Robots



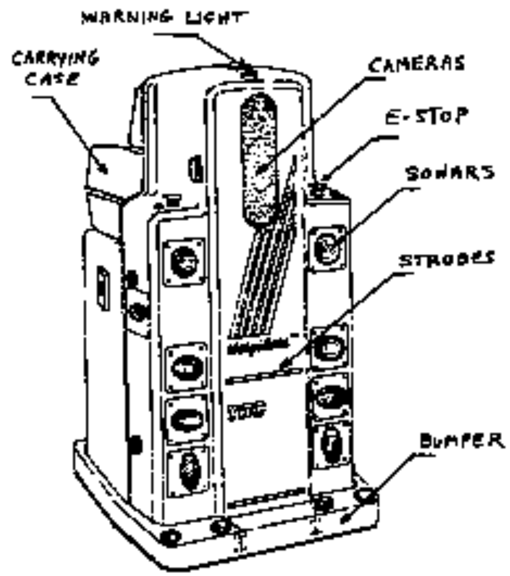


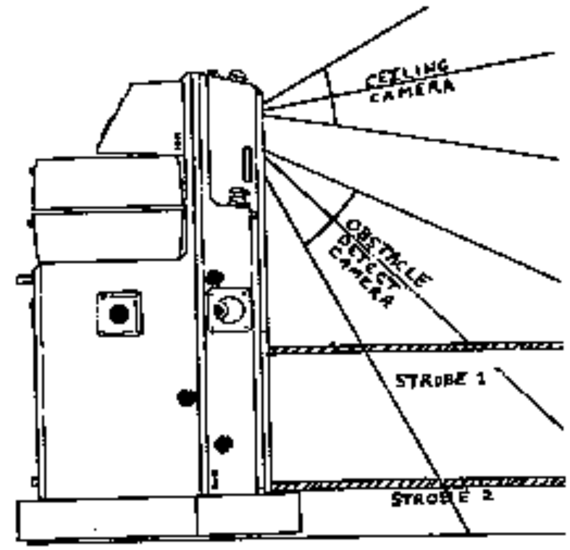
Automatic Guided Vehicles



- Newest generation of Automatic Guided Vehicle of VOLVO used to transport motor blocks from one assembly station to an other. It is guided by an electrical wire installed in the floor but it is also able to leave the wire to avoid obstacles. There are over 4000 AGVs at VOLVO's plants.

Helpmate





- HELPMATE is a mobile robot used in hospitals for transportation tasks. It has various on board sensors for autonomous navigation in the corridors. The main sensor for localization is a camera looking to the ceiling. It can detect the lamps on the ceiling as reference (landmark). http://www.ntplx.net/~helpmate/

The Cye Personal Robot

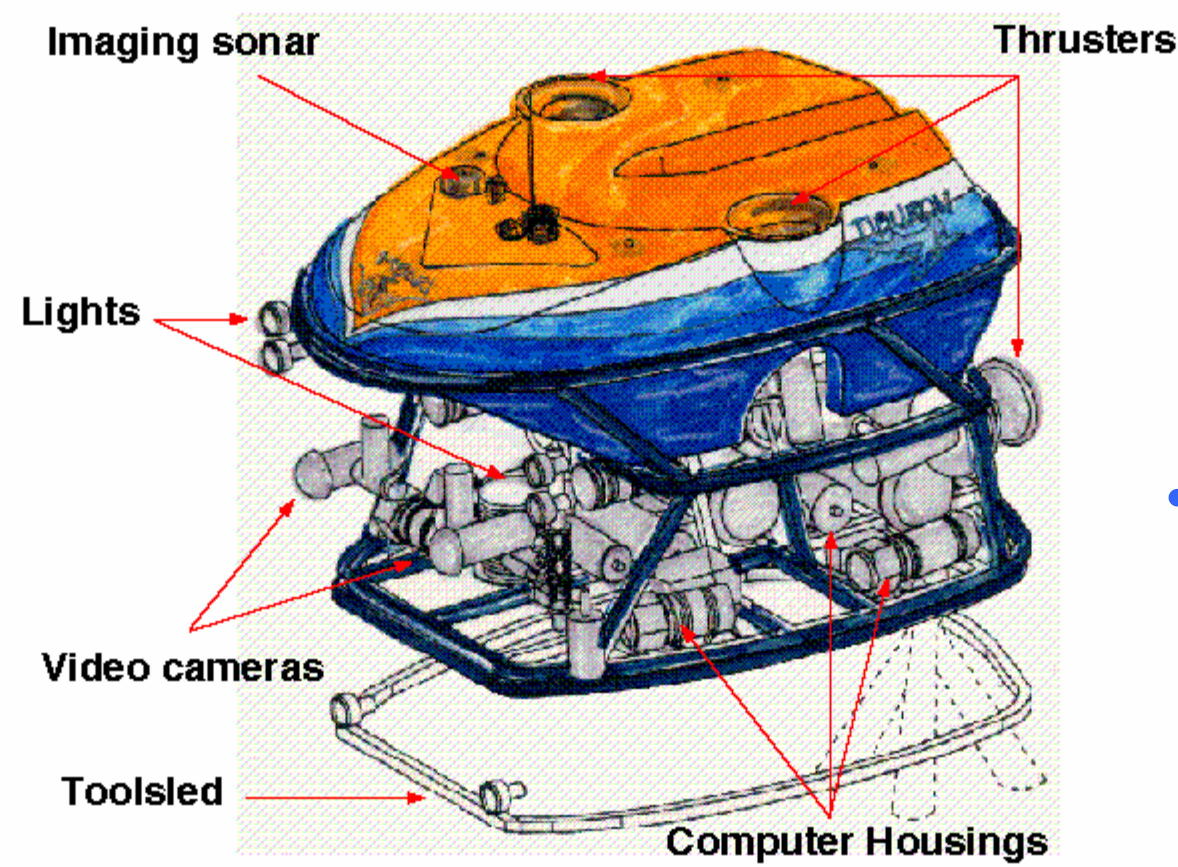
- Two-wheeled differential drive robot
- Controlled by remote PC (19.2 kb)
- Options:
  - *vacuum cleaner*
  - *trailer*

The Dyson Vacuum Cleaner Robot

BR700 Cleaning Robot

- BR 700 cleaning robot developed and sold by Kärcher Inc., Germany. Its navigation system is based on a very sophisticated sonar system and a gyro. http://www.kaercher.de

ROV Tiburon Underwater Robot



- Picture of robot ROV Tiburon for underwater archaeology (teleoperated)- used by MBARI for deep-sea research, this UAV provides autonomous hovering capabilities for the human operator.

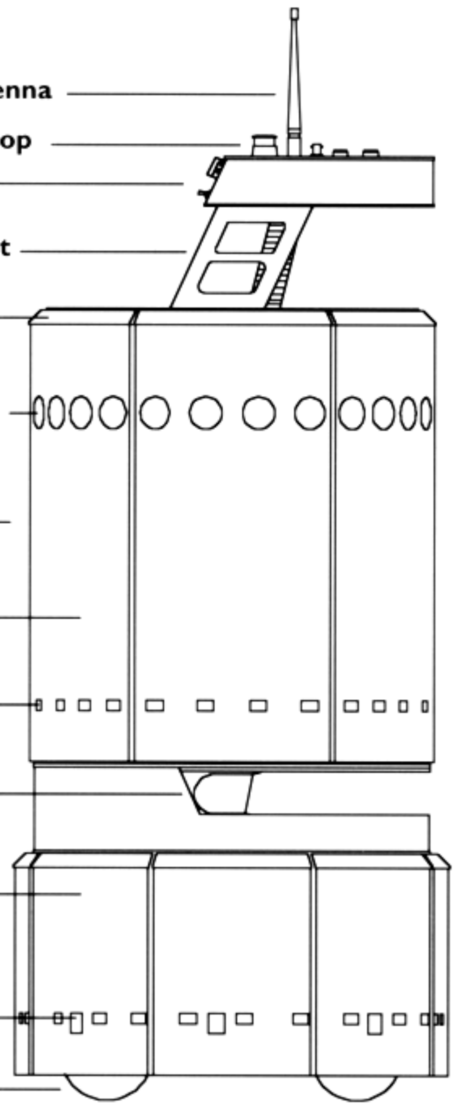
The Pioneer

- Picture of Pioneer, the teleoperated robot that is supposed to explore the Sarcophagus at Chernobyl

The Pioneer

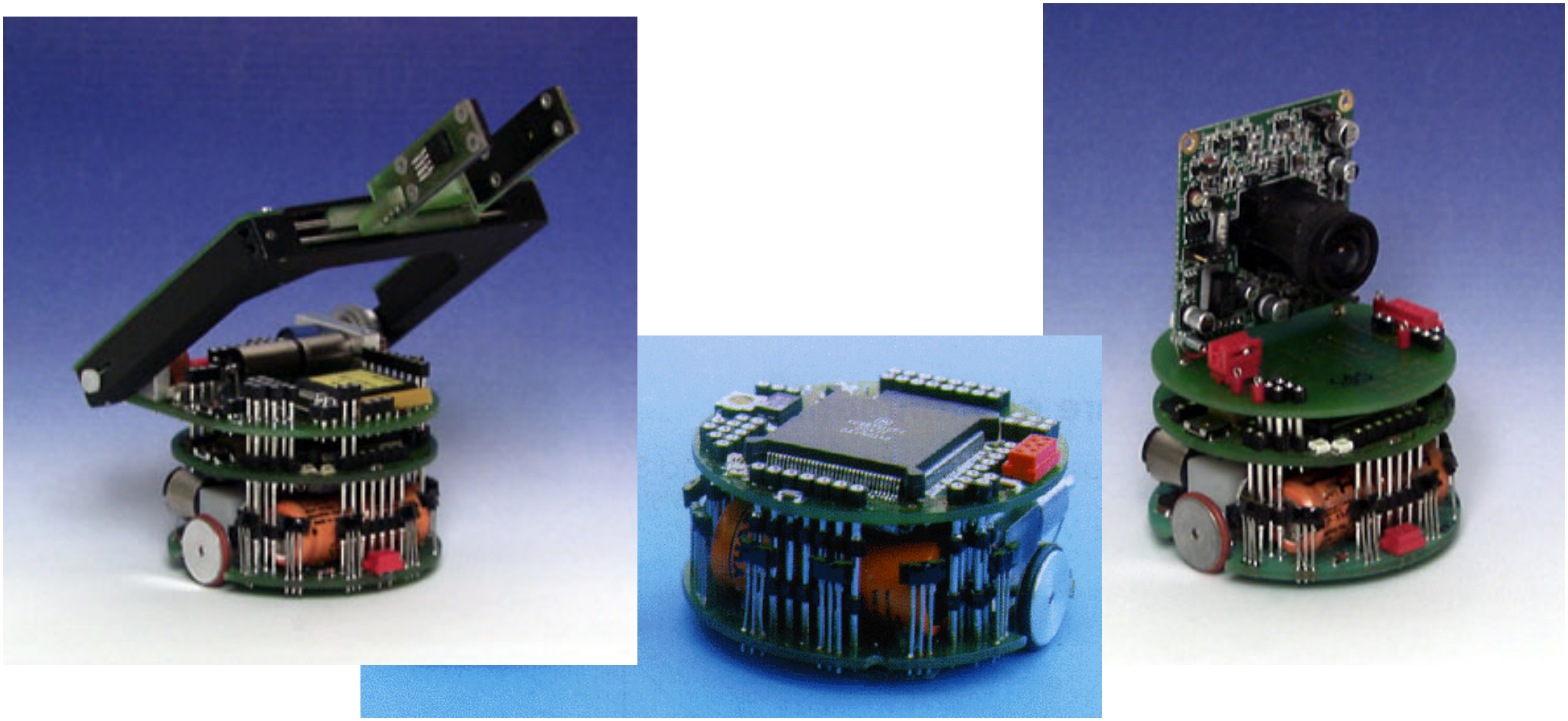
- PIONEER 1 is a modular mobile robot offering various options like a gripper or an on board camera. It is equipped with a sophisticated navigation library developed at Stanford Research Institute (SRI). http://www.activmedia.com/robots

The B21 Robot



- B21 of Real World Interface is a sophisticated mobile robot with up to three Intel Pentium processors on board. It has all different kinds of on board sensors for high performance navigation tasks. http://www.rwii.com

The Khepera Robot

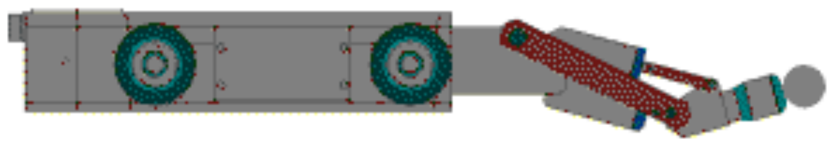


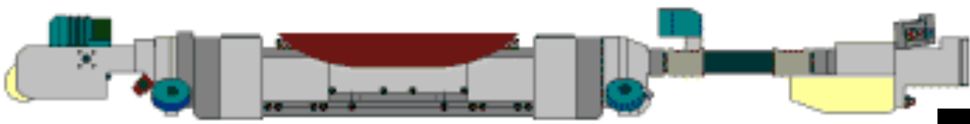
- KHEPERA is a small mobile robot for research and education. It sizes only about 60 mm in diameter. Additional modules with cameras, grippers and much more are available. More then 700 units have already been sold (end of 1998). http://diwww.epfl.ch/lami/robots/K-family/ K-Team.html

Forester Robot

- Pulstech developed the first ‘industrial like’ walking robot. It is designed moving wood out of the forest. The leg coordination is automated, but navigation is still done by the human operator on the robot. http://www.plustech.fi/

Robots for Tube Inspection

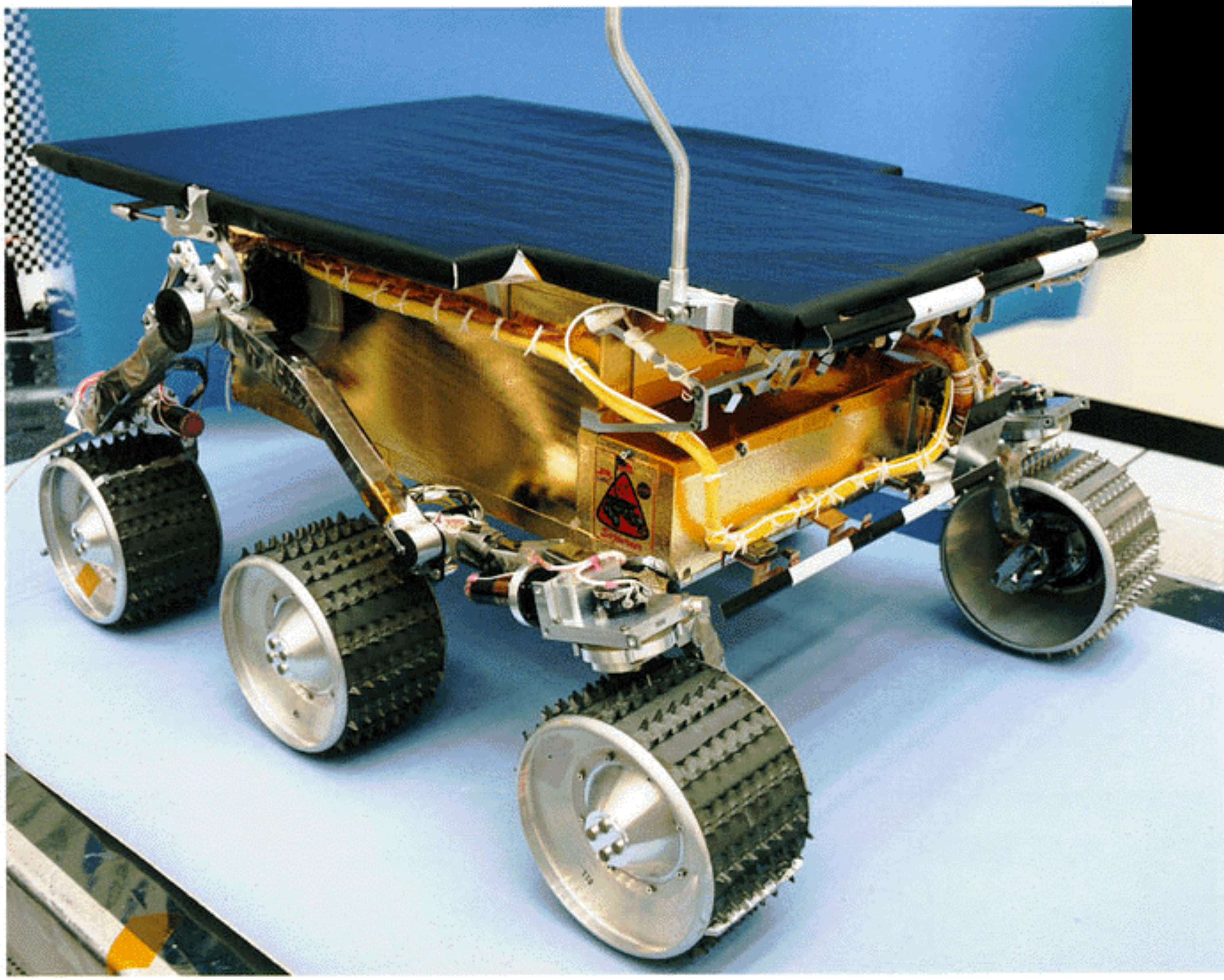




- HÄCHER robots for sewage tube inspection and reparation. These systems are still fully teleoperated. http://www.haechler.ch

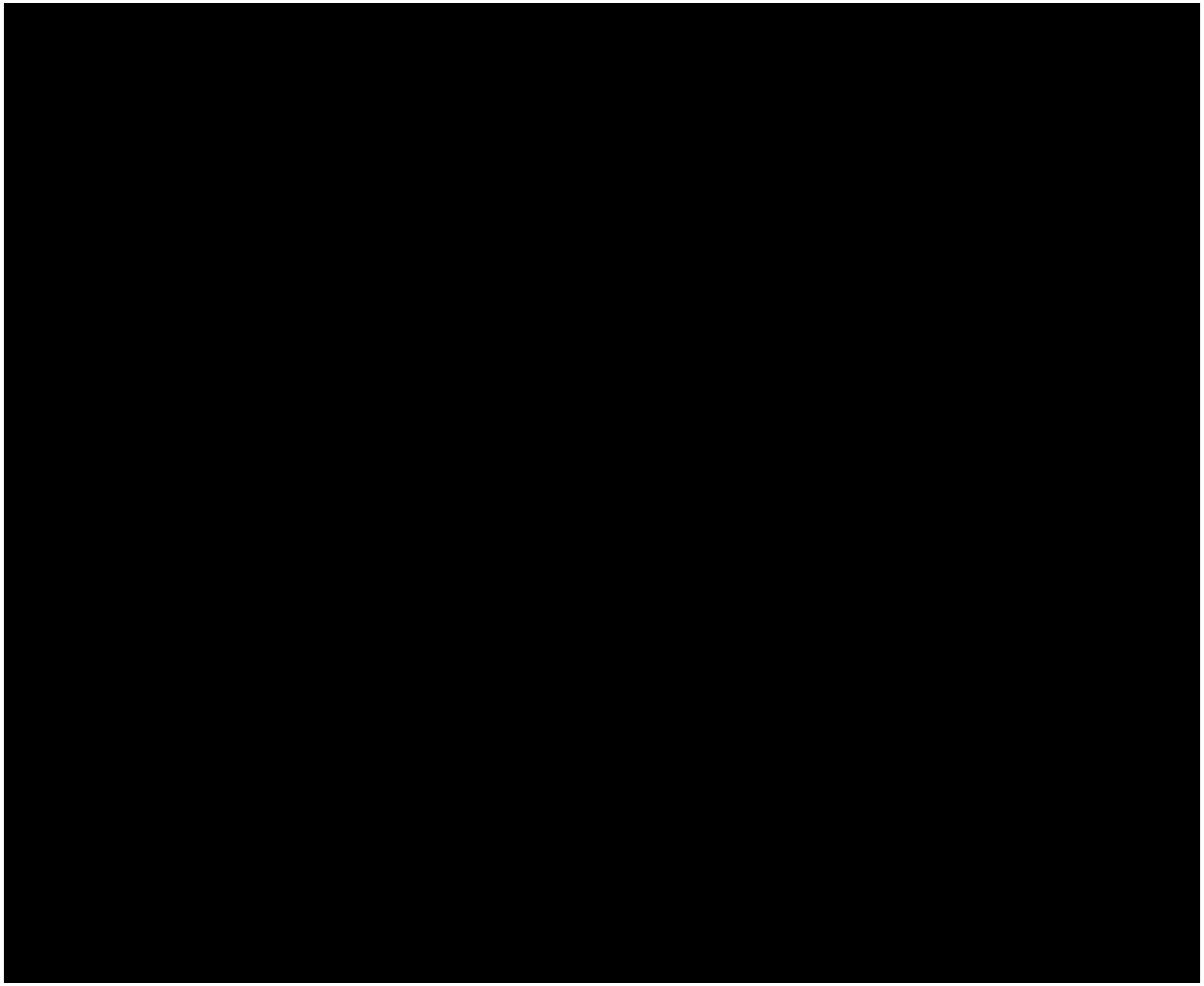
- EPFL / SEDIREP: Ventilation inspection robot

Sojourner, First Robot on Mars



Sojourner was used during the Pathfinder mission to explore the mars in summer 1997. It was nearly fully teleoperated from earth. However, some on board sensors allowed for obstacle detection. http://ranier.oact.hq.nasa.gov/telerobotics_page/telerobotics.shtm

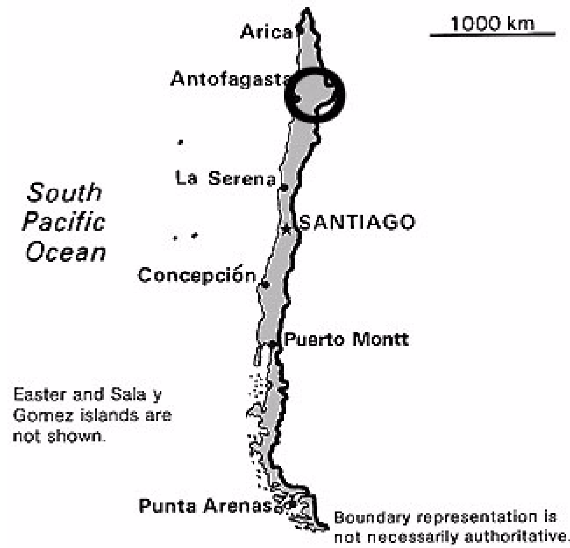
Autonomous Robot for Planetary Exploration (ASL – EPFL)

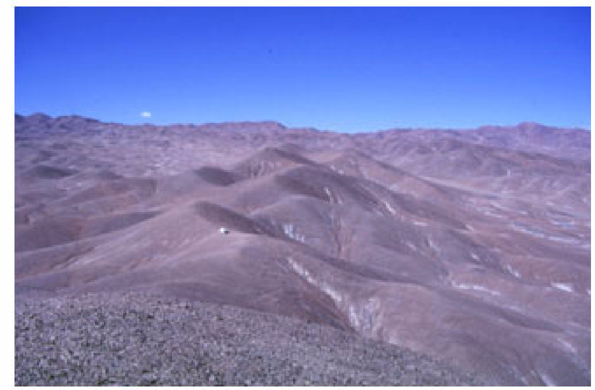


NOMAD, Carnegie Mellon / NASA

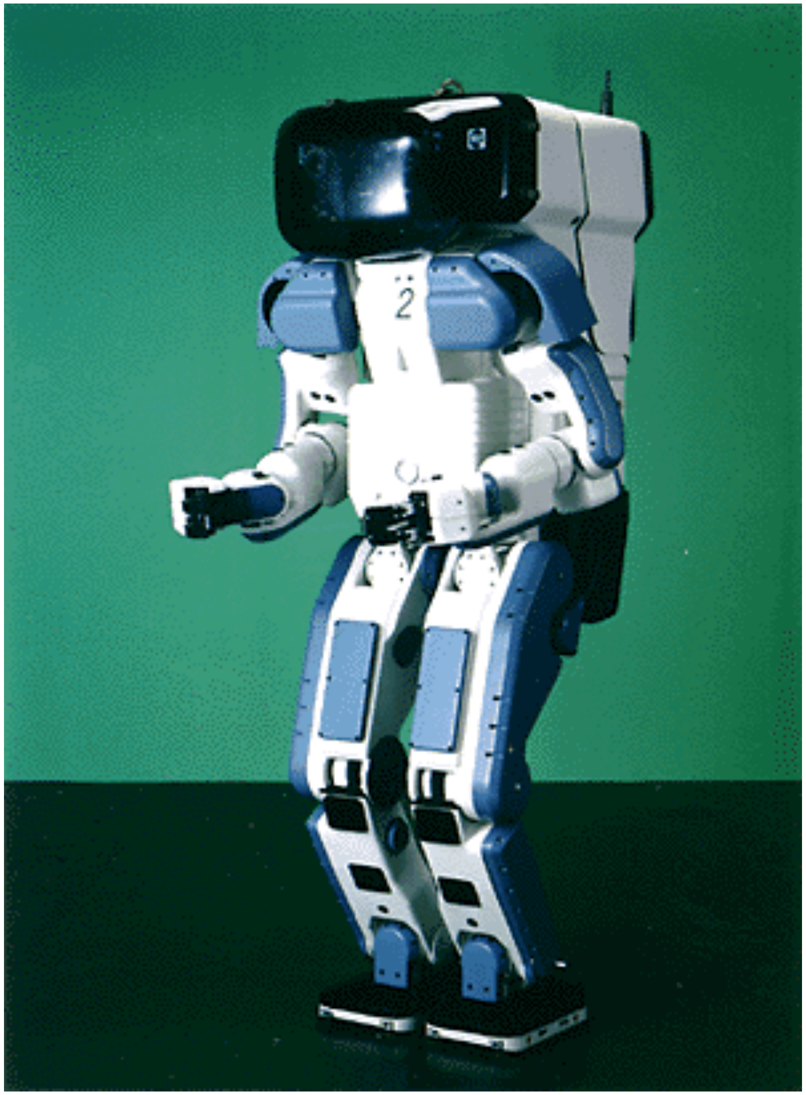
http://img.arc.nasa.gov/Nomad/

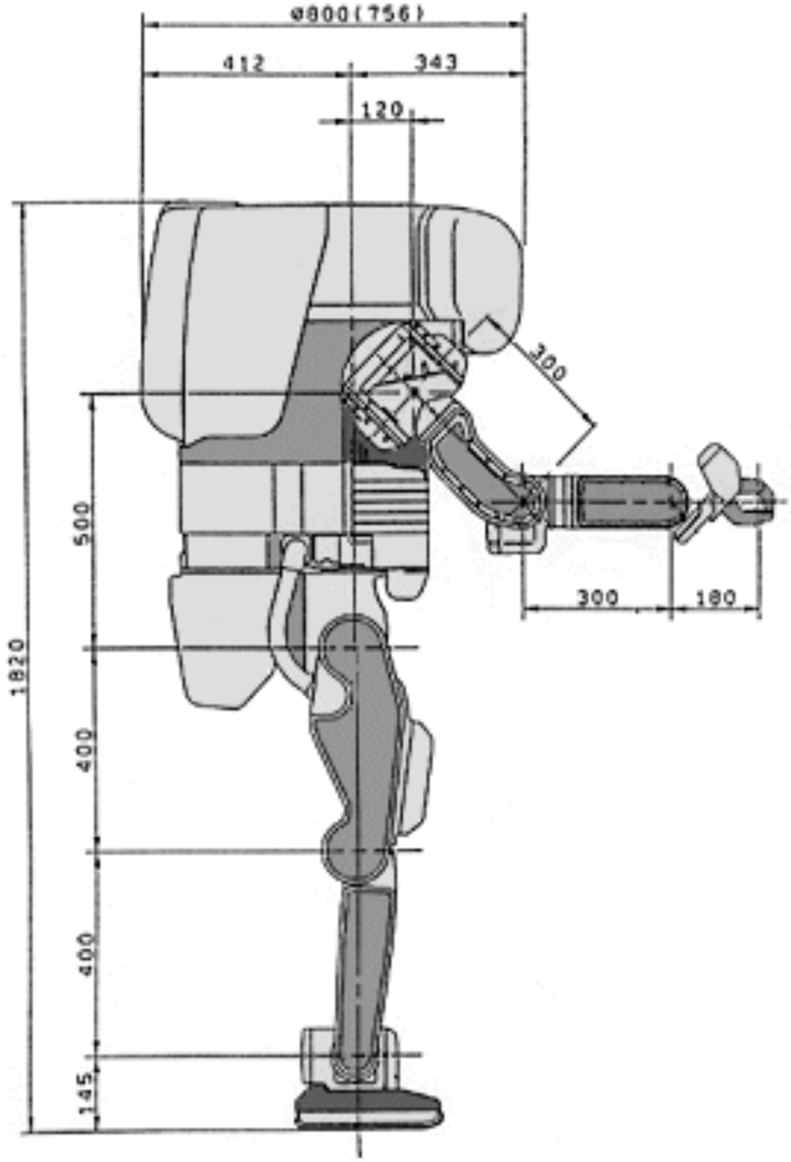
The Atacama Desert, Chile



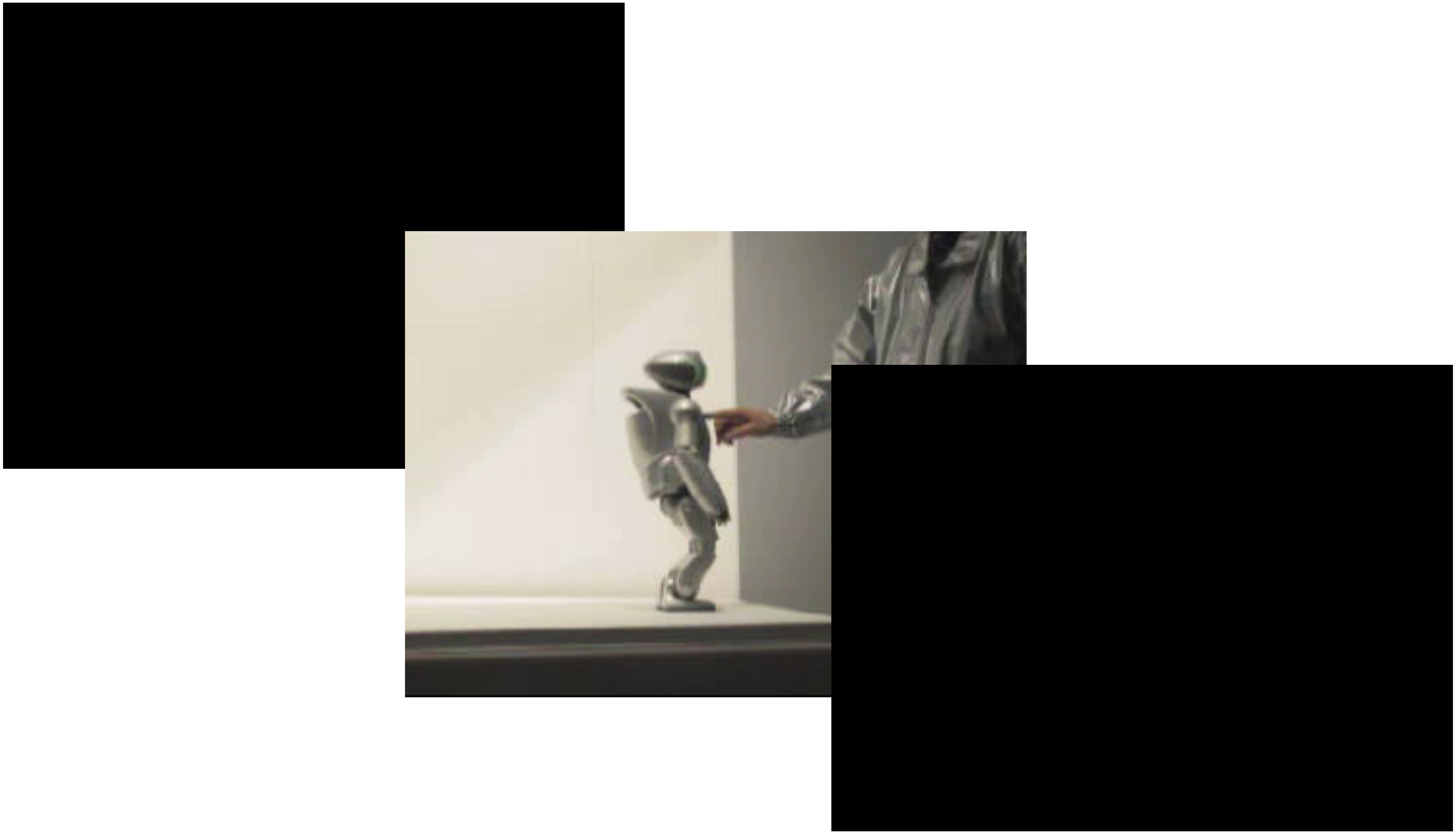


The Honda Walking Robot *http://www.honda.co.jp/tech/other/robot.html*





Humanoid Robots (Sony)



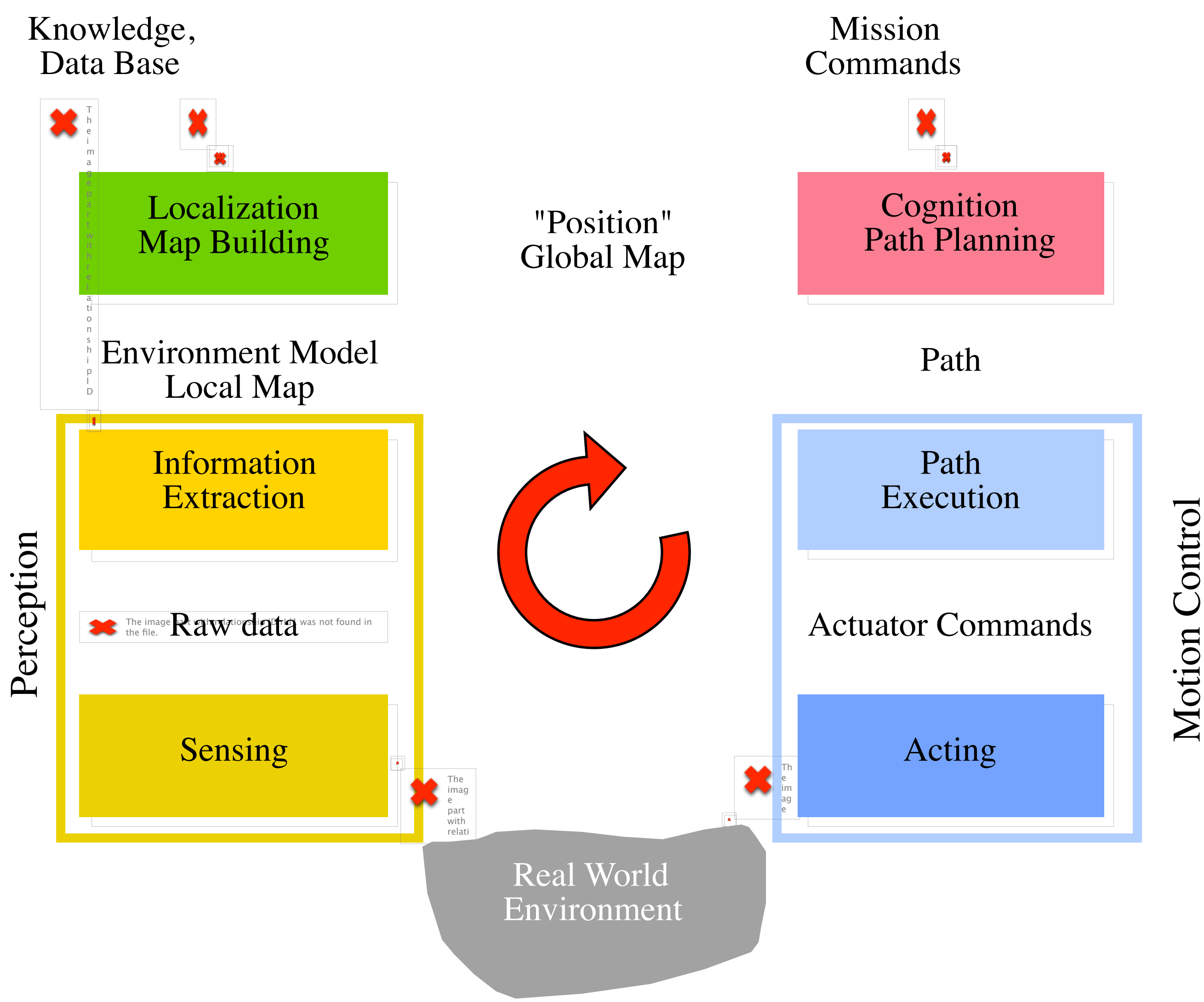
Toy Robot Aibo from Sony

- Size
  - *length about 25 cm*
- Sensors
  - *color camera*
  - *stereo microphone*


CMPack '03
vs.
Yellow Jackets
American Open 2003

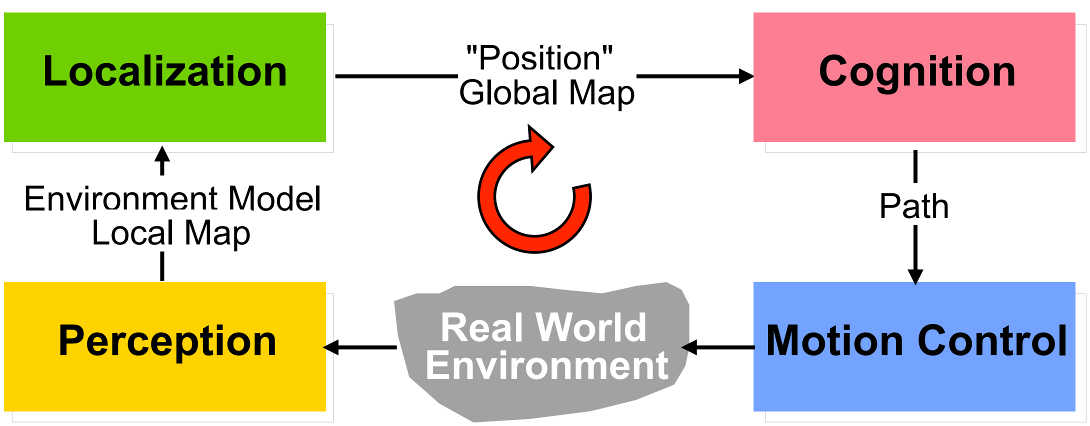

Boston Dynamics

General Control Scheme for Mobile Robot Systems

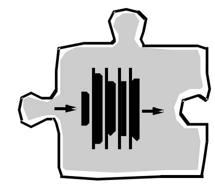


Control Architectures / Strategies

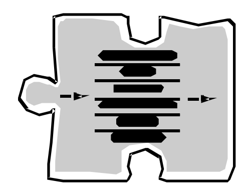
- Control Loop
  - ➢ ***dynamically changing***
  - ➢ ***no compact model available***
  - ➢ ***many sources of uncertainty***



- Two Approaches
  - ➢ *Classical AI*
    - o *complete modeling*
    - o *function based*
    - o *horizontal decomposition*

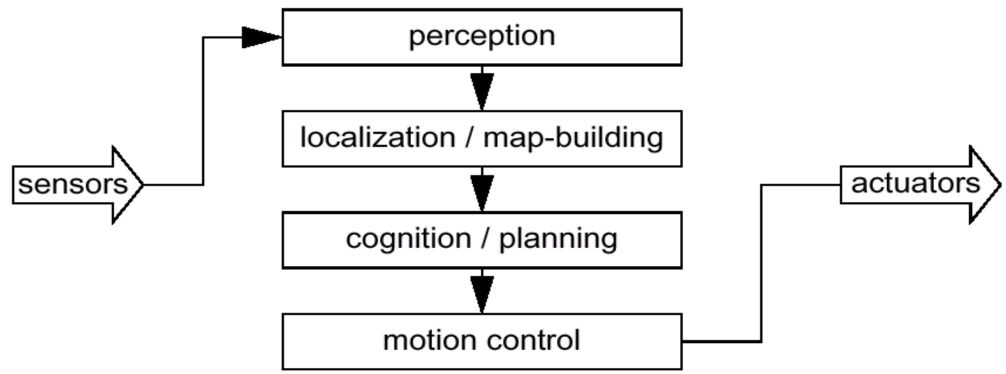


  - ➢ *New AI, AL*
    - o *sparse or no modeling*
    - o *behavior based*
    - o *vertical decomposition*
    - o *bottom up*

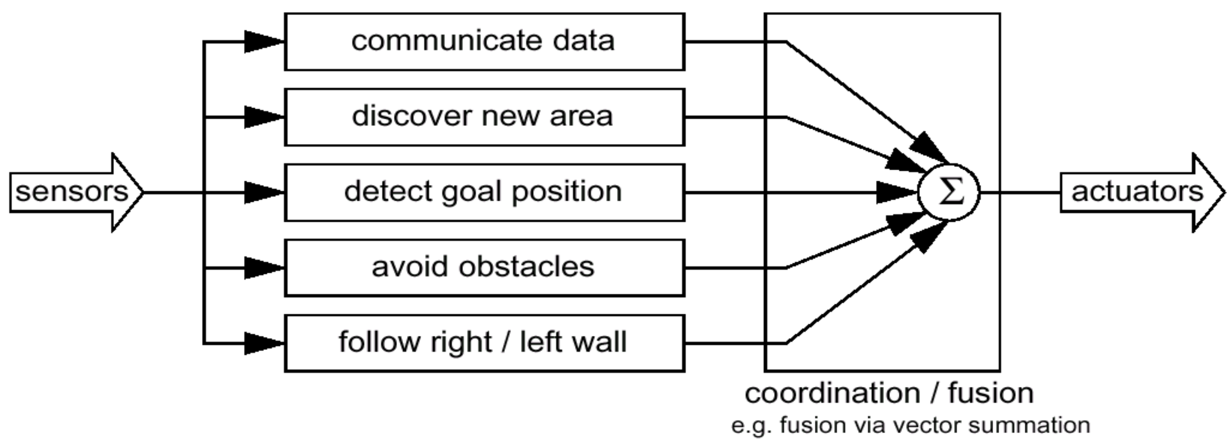


Two Approaches

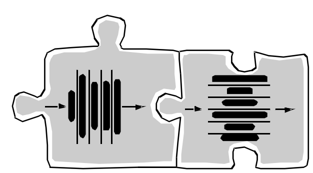
- Classical AI
  (model based navigation)
  - *complete modeling*
  - *function based*
  - *horizontal decomposition*



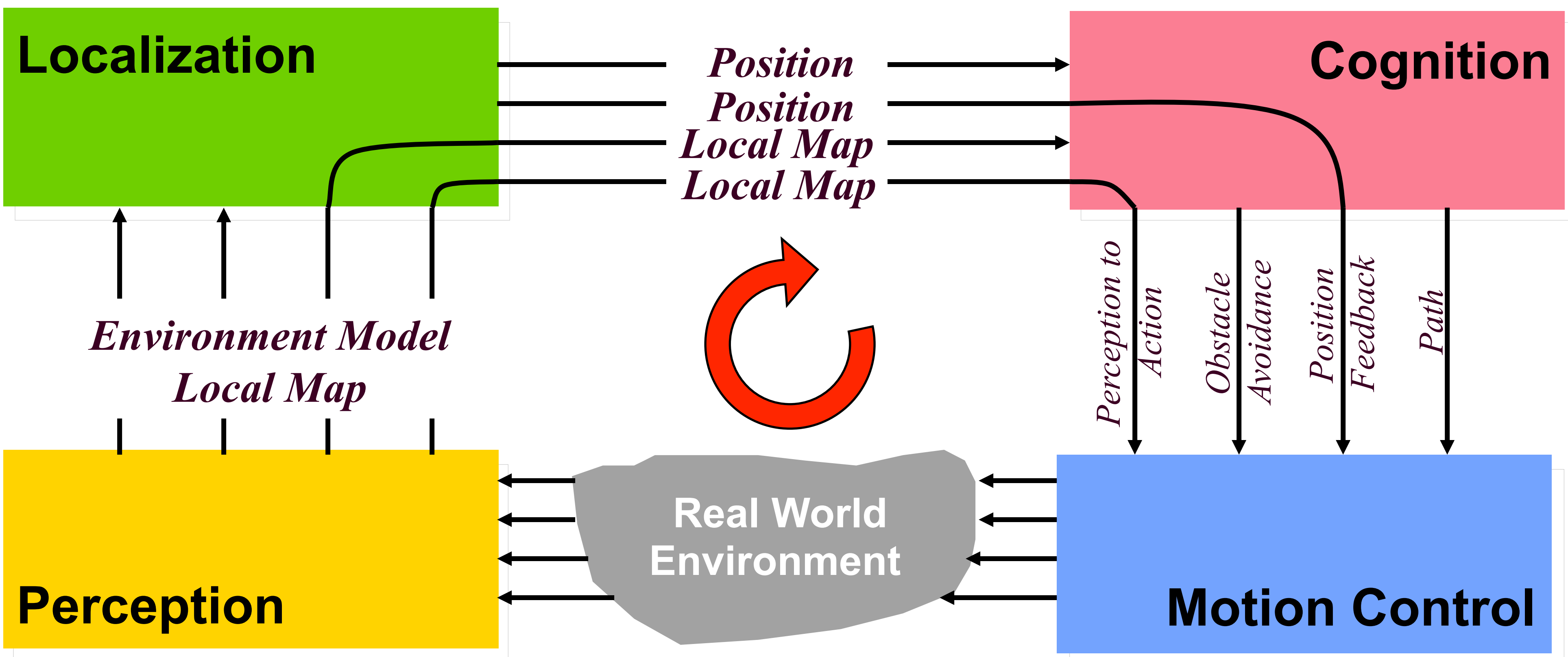
- New AI, AL
  (behavior based navigation)
  - *sparse or no modeling*
  - *behavior based*
  - *vertical decomposition*
  - *bottom up*



- Possible Solution
  - *Combine Approaches*



Mixed Approach Depicted into the General Control Scheme



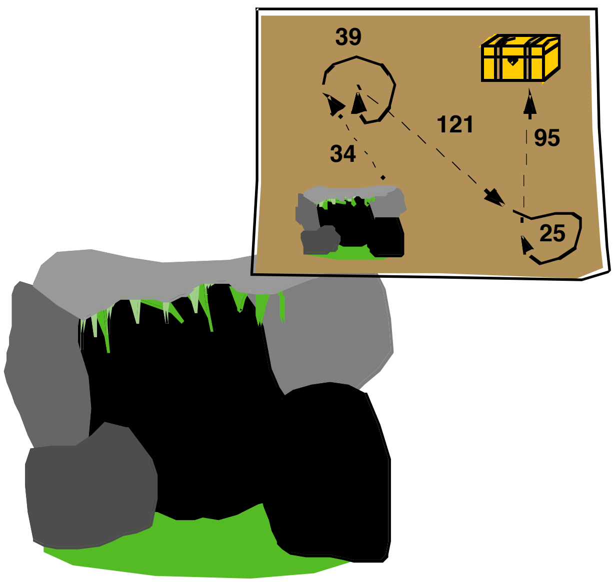
Environment Representation and Modeling:

The Key for Autonomous Navigation

- Environment Representation
  - *Continuous Metric* -> *x,y,θ*
  - *Discrete Metric* -> *metric grid*
  - *Discrete Topological* -> *topological grid*
- Environment Modeling
  - *Raw sensor data, e.g. laser range data, grayscale images*
    - *large volume of data, low distinctiveness*
    - *makes use of all acquired information*
  - *Low level features, e.g. line other geometric features*
    - *medium volume of data, average distinctiveness*
    - *filters out the useful information, still ambiguities*
  - *High level features, e.g. doors, a car, the Eiffel tower*
    - *low volume of data, high distinctiveness*
    - *filters out the useful information, few/no ambiguities, not enough information*

Environment Representation and Modeling: How we do it!

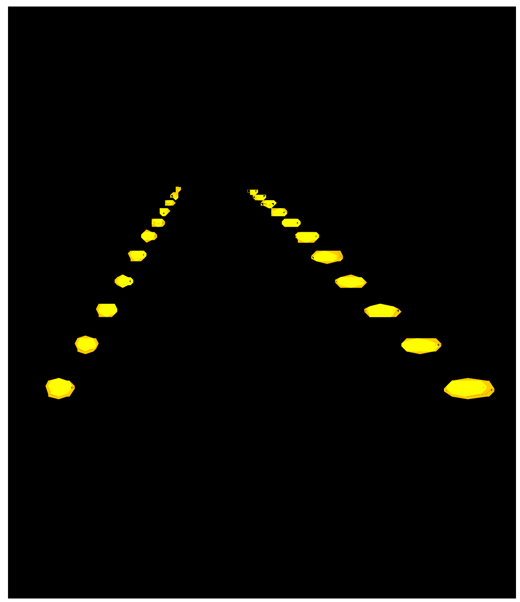
- Odometry



How to find a treasure

➢ *not applicable*

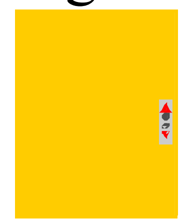
- Modified Environments



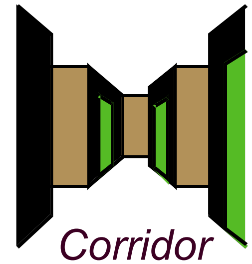
Landing at night

➢ *expensive, inflexible*

- Feature-based Navigation

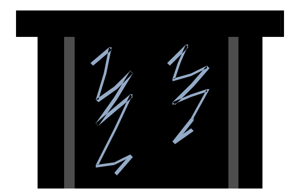


Elevator door



Corridor crossing

Eiffel Tower



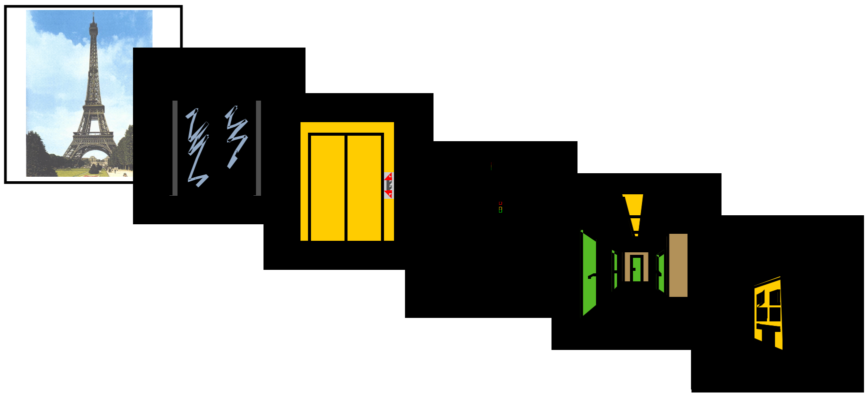
Entrance

➢ *still a challenge for artificial systems*

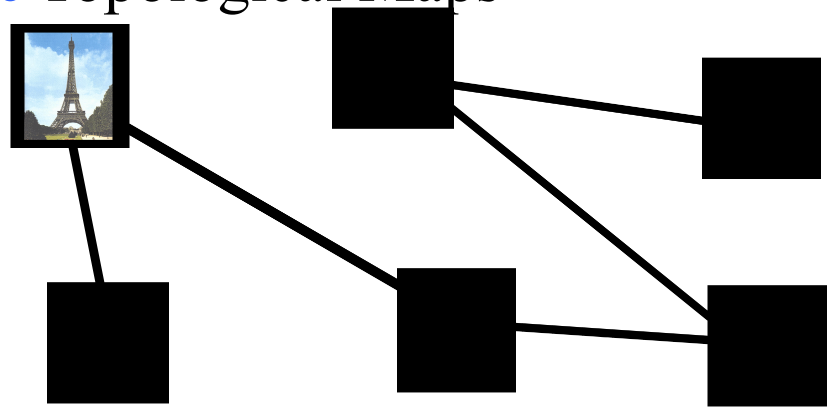
Courtesy K. Arras

Environment Representation: The Map Categories

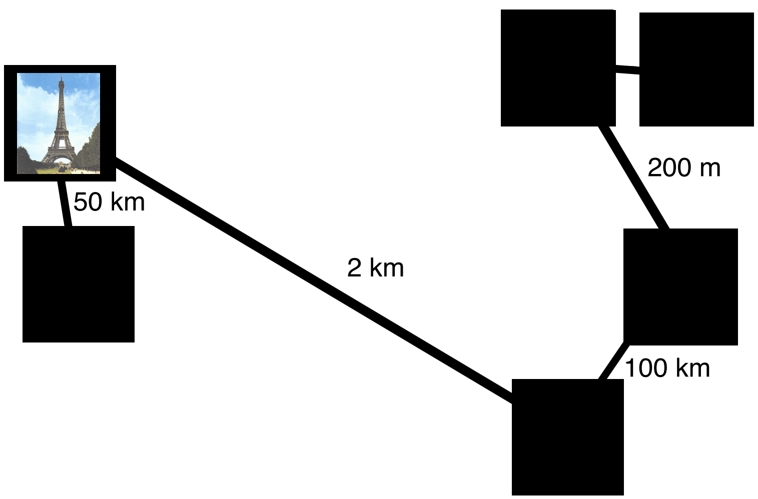
- Recognizable Locations



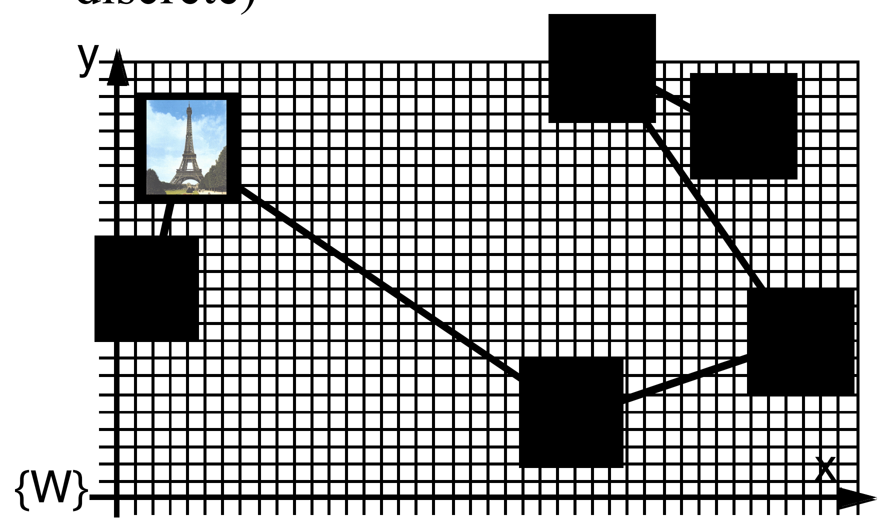
- Topological Maps



- Metric Topological Maps



- Fully Metric Maps (continuous or discrete)



Courtesy K. Arras

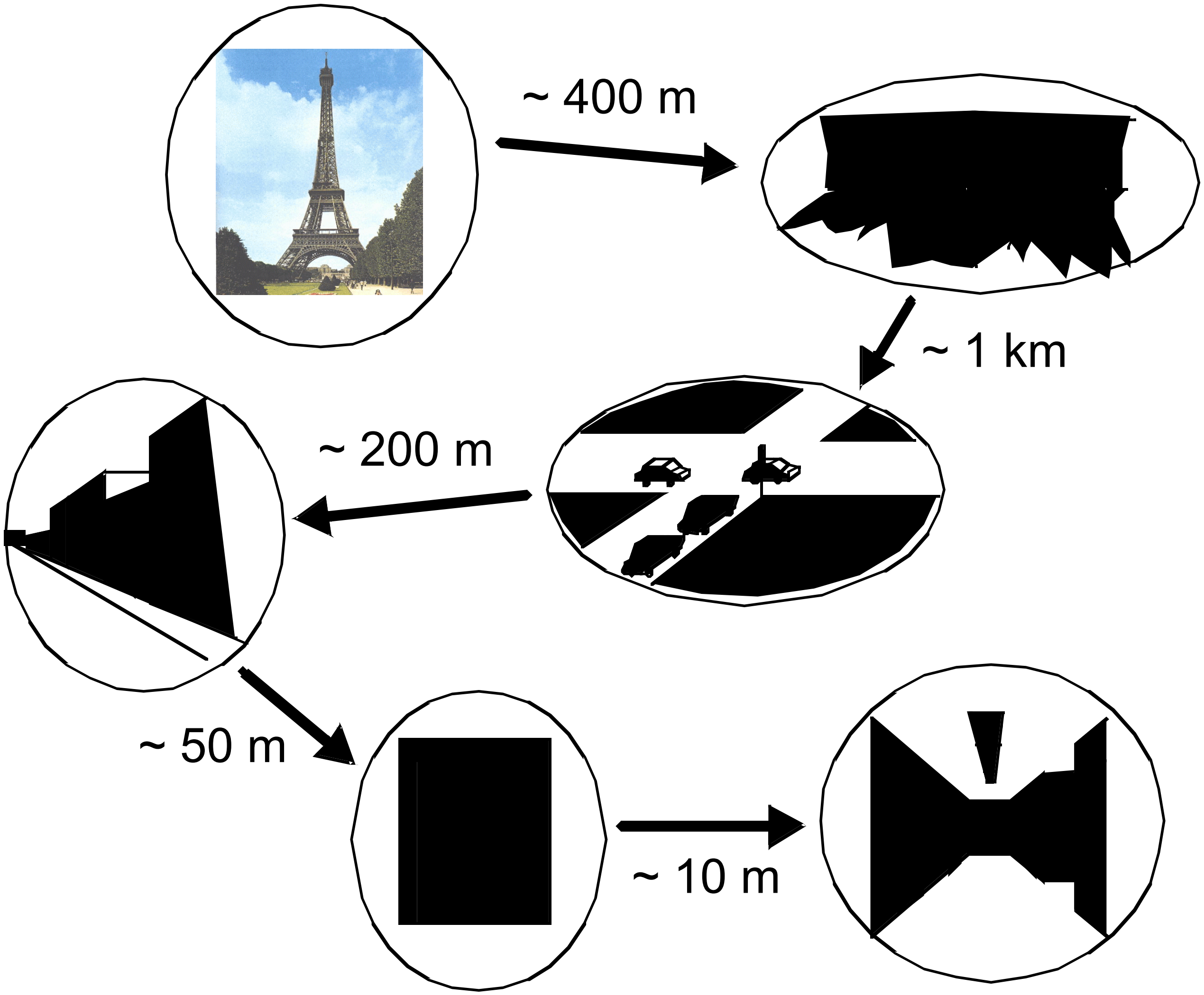
Environment Models: Continuous <-> Discrete ; Raw data <-> Features

- **Continuos**
  - *position in x,y,θ*
- **Discrete**
  - *metric grid*
  - *topological grid*
- **Raw Data**
  - *as perceived by sensor*
- **A feature** (or natural landmark) is an environmental structure which is static, always perceptible with the current sensor system and locally unique.

Examples

- *geometric elements (lines, walls, column ..)*
- a railway station
- a river
- the Eiffel Tower
- a human being
- fixed stars
- skyscraper

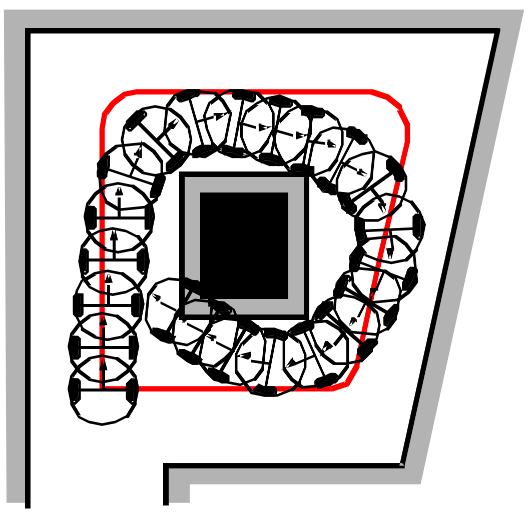
Human Navigation: Topological with imprecise metric information



Courtesy K. Arras

Methods for Navigation: Approaches with Limitations

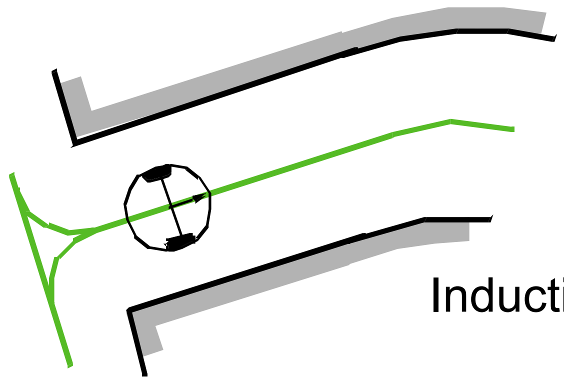
- Incrementally
  (dead reckoning)



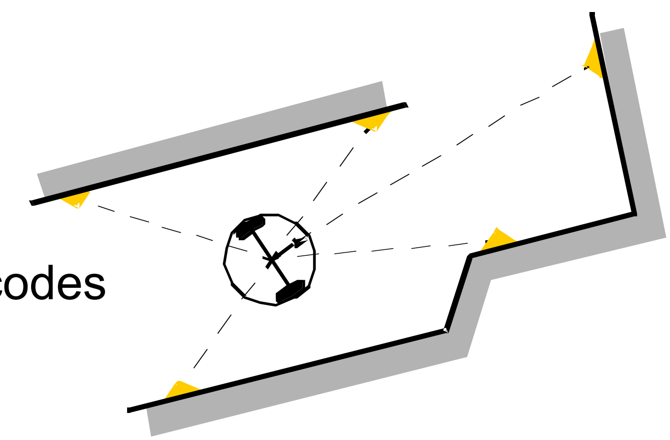
Odometric or initial sensors (gyro)

➢ ***not applicable***

- Modifying the environments
  (artificial landmarks / beacons)



Inductive or optical tracks (AGV)



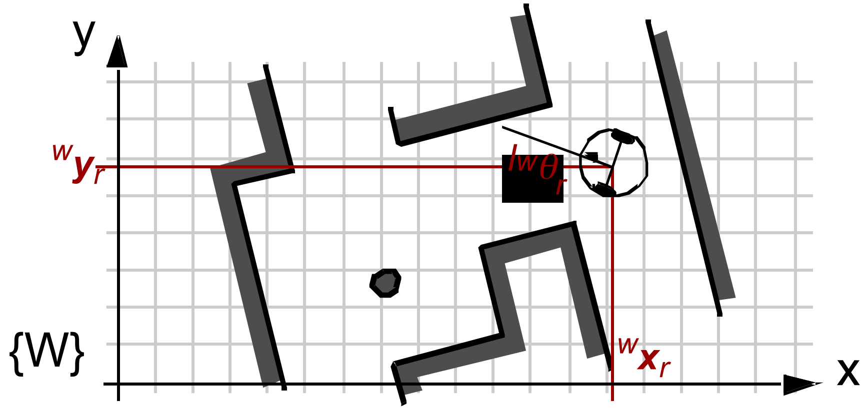
Reflectors or bar codes

➢ ***expensive, inflexible***

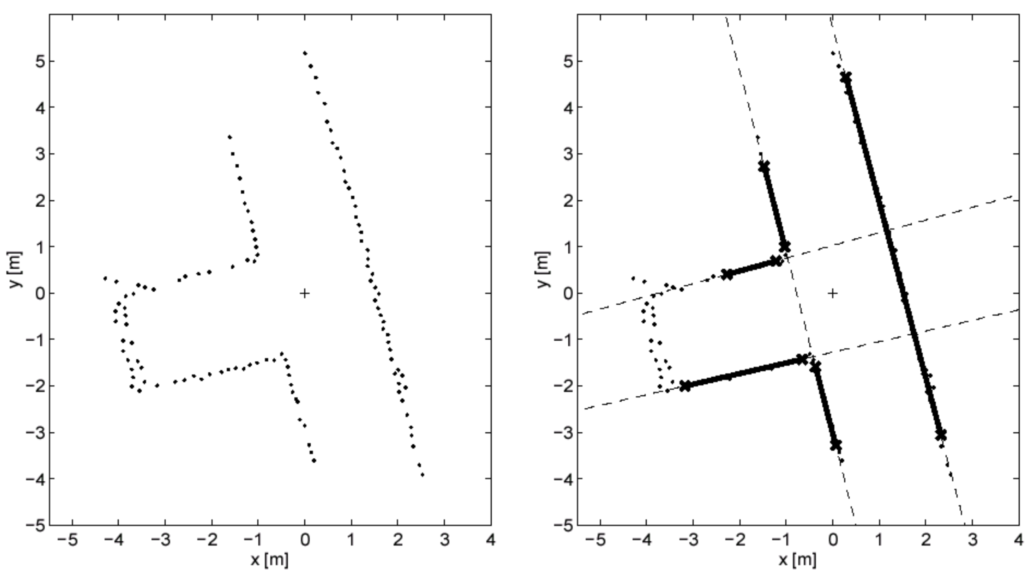
Courtesy K. Arras

Methods for Localization: The Quantitative Metric Approach

1. A priori Map: Graph, metric

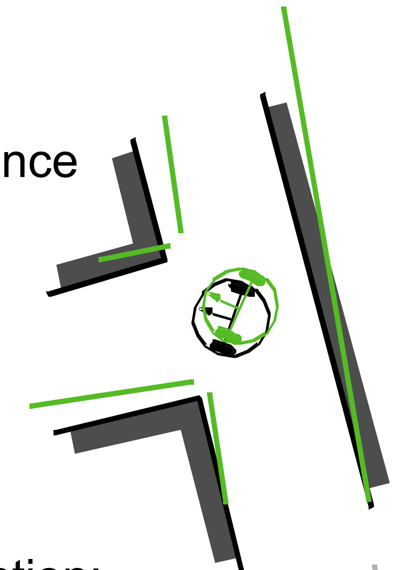


2. Feature Extraction (e.g. line segments)



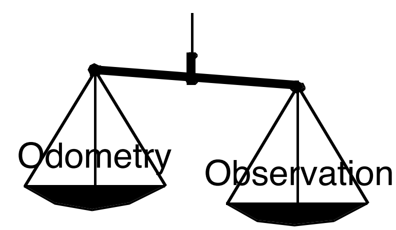
3. Matching:

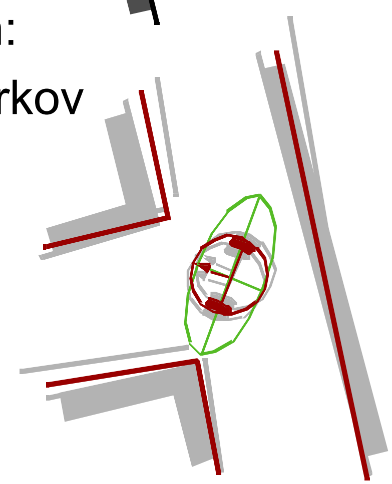
Find correspondence of features



4. Position Estimation:

e.g. Kalman filter, Markov

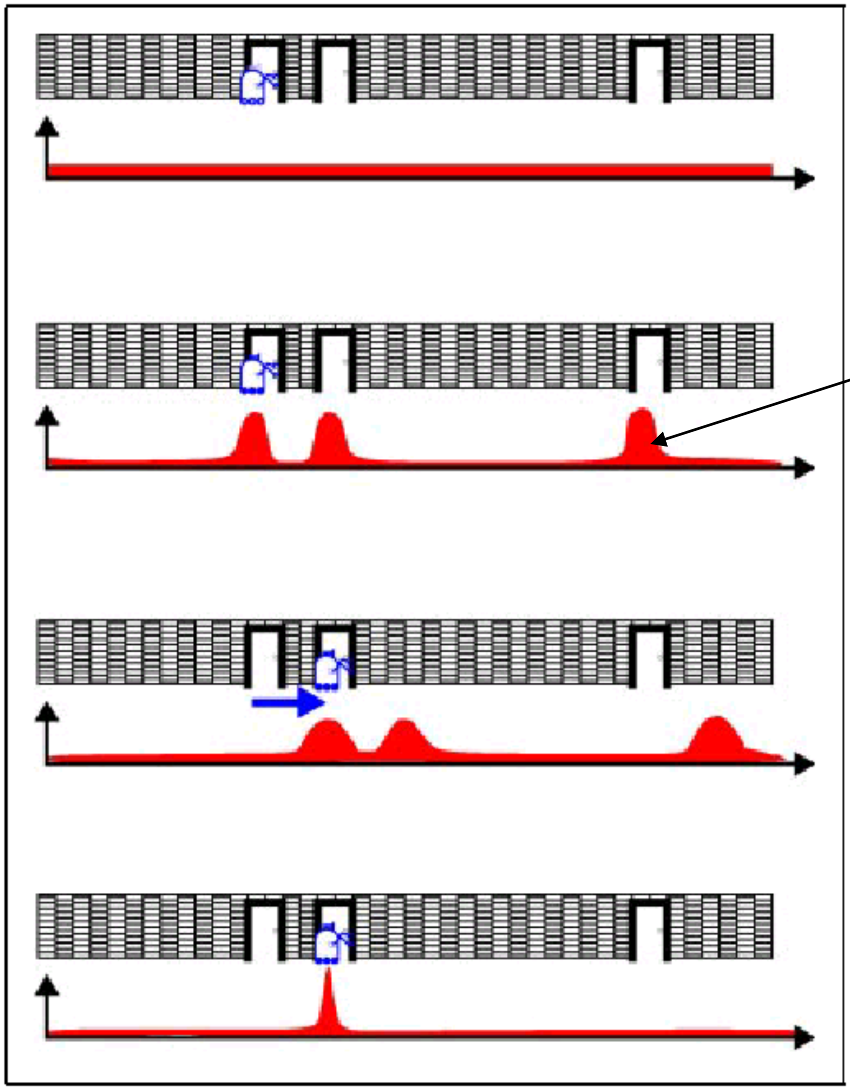




- representation of uncertainties
- optimal weighting acc. to a priori statistics

Courtesy K. Arras

Gaining Information through motion: (Multi-hypotheses tracking)



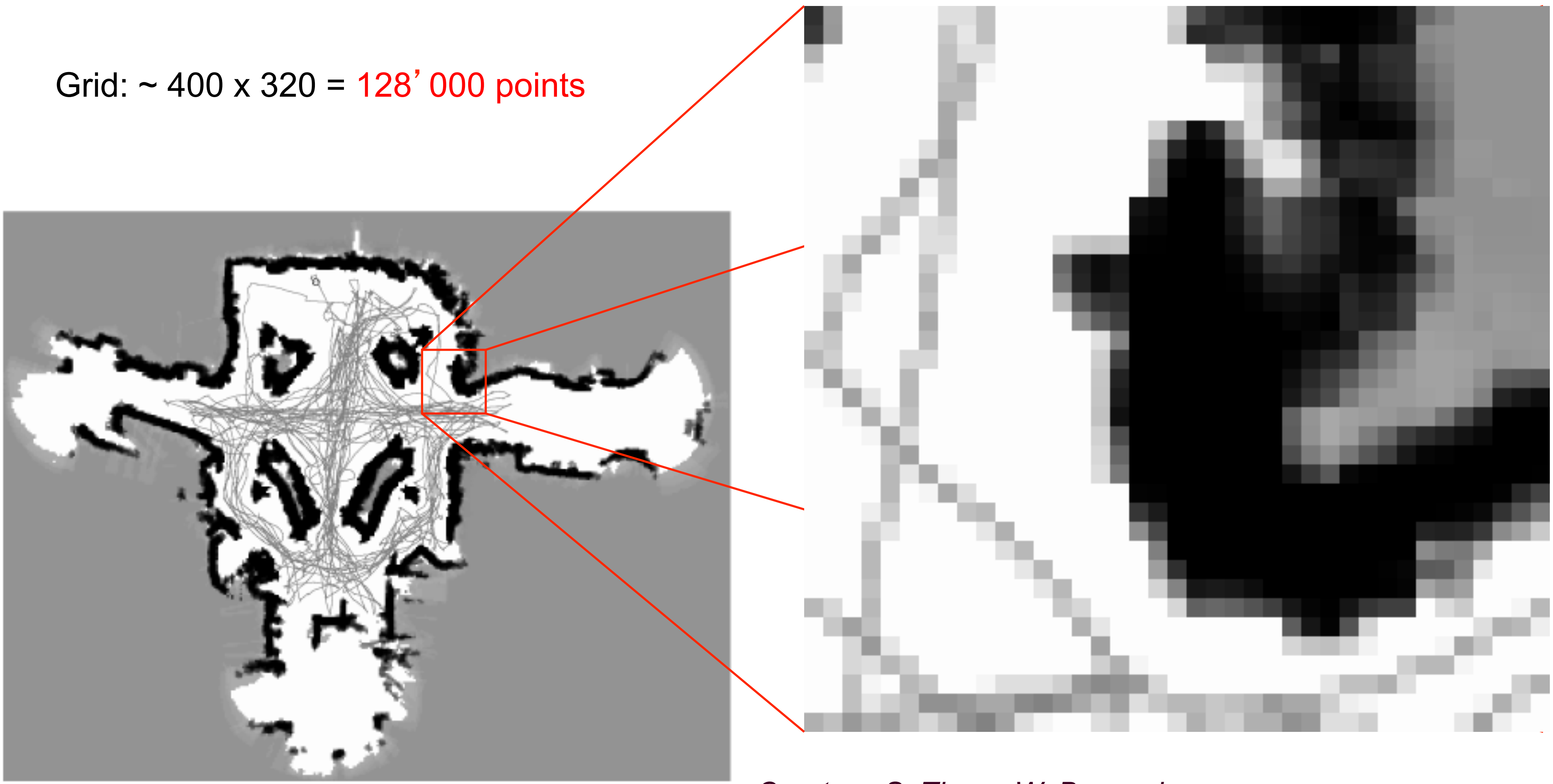
Believe state

Courtesy S. Thrun, W. Burgard

Grid-Based Metric Approach

- Grid Map of the Smithsonian's National Museum of American History in Washington DC. (Courtesy of Wolfram Burger et al.)

Grid: ~ 400 x 320 = 128'000 points



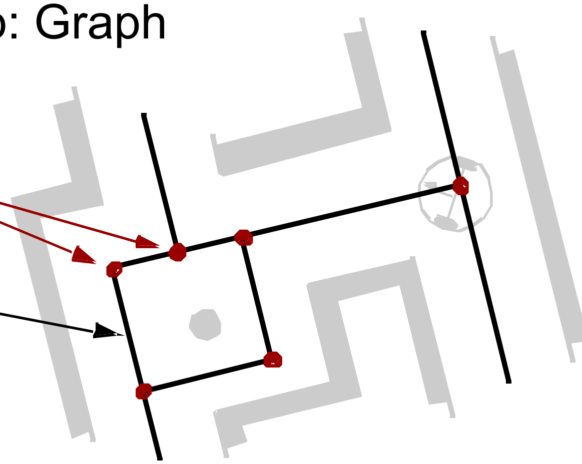
Courtesy S. Thrun, W. Burgard

Methods for Localization: The Quantitative Topological Approach

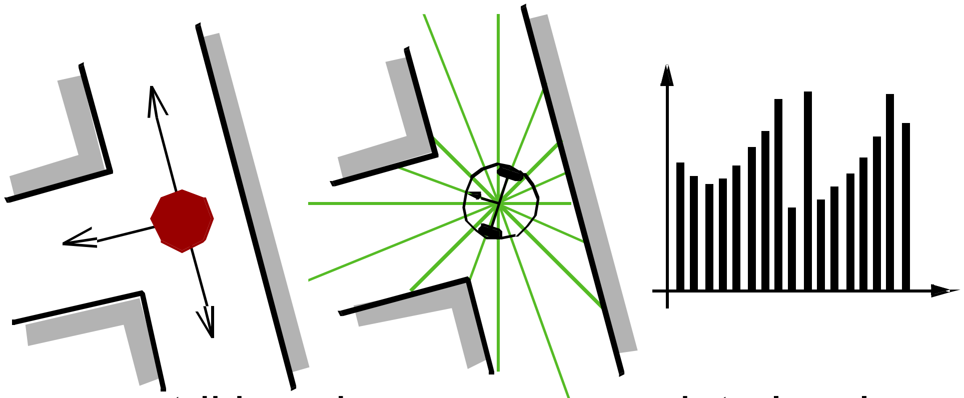
1. A priori Map: Graph

locally **unique** points

edges



2. Method for determining the **local uniqueness**

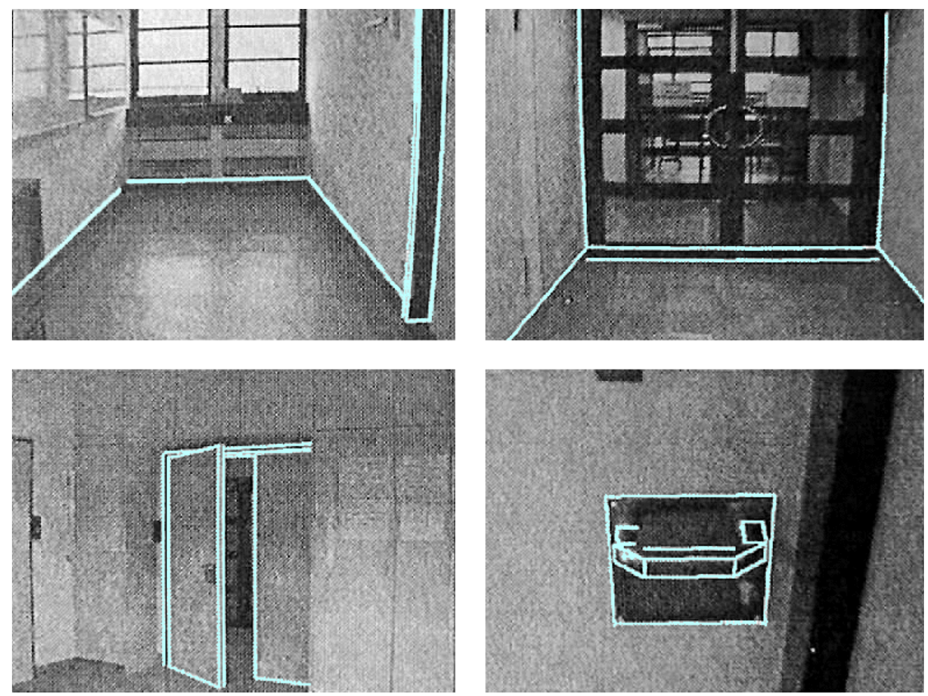


e.g. striking changes on raw data level or highly distinctive features

3. Library of **driving behaviors**

e.g. wall or midline following, blind step, enter door, application specific behaviors

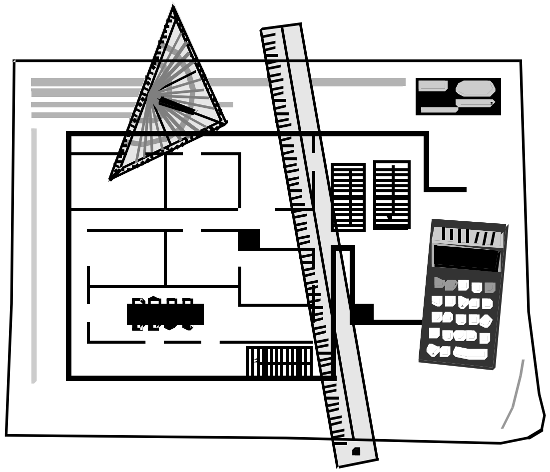
Example: Video-based navigation with natural landmarks



Courtesy of [Lanser et al. 1996]

Map Building: How to Establish a Map

1. By Hand



2. Automatically: **Map Building**

The robot **learns** its environment

Motivation:

- by hand: hard and costly
- dynamically changing environment
- different look due to different perception

3. Basic Requirements of a Map:

- *a way to incorporate newly sensed information into the existing world model*
- *information and procedures for estimating the robot's position*
- *information to do path planning and other navigation task (e.g. obstacle avoidance)*

→ *predictability*

- Measure of Quality of a map
  - *topological correctness*
  - *metrical correctness*
- But: Most environments are a mixture of predictable and unpredictable features
  → hybrid approach

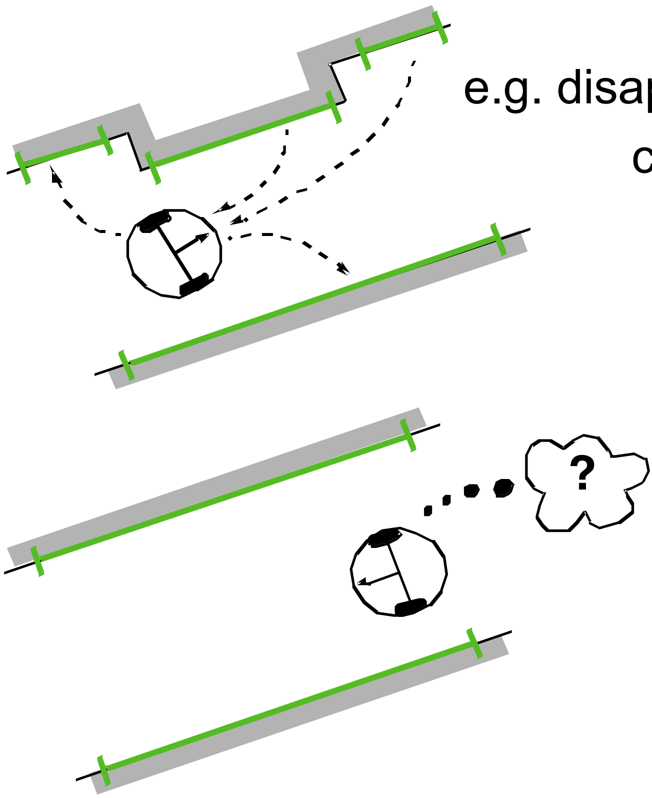
model-based vs. behaviour-based

Courtesy K. Arras

Map Building: The Problems

1. Map Maintaining: Keeping track of changes in the environment

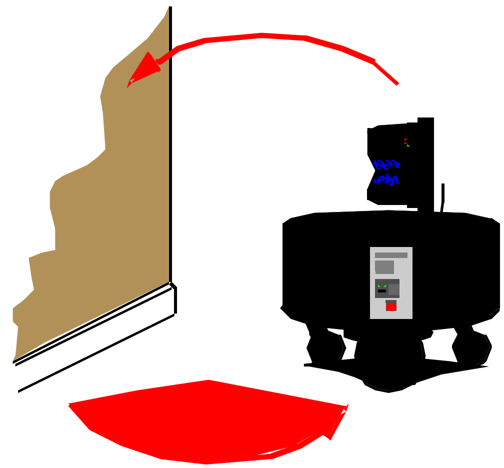
e.g. disappearing cupboard



- e.g. measure of belief of each environment feature

2. Representation and Reduction of Uncertainty

position of robot -> position of wall



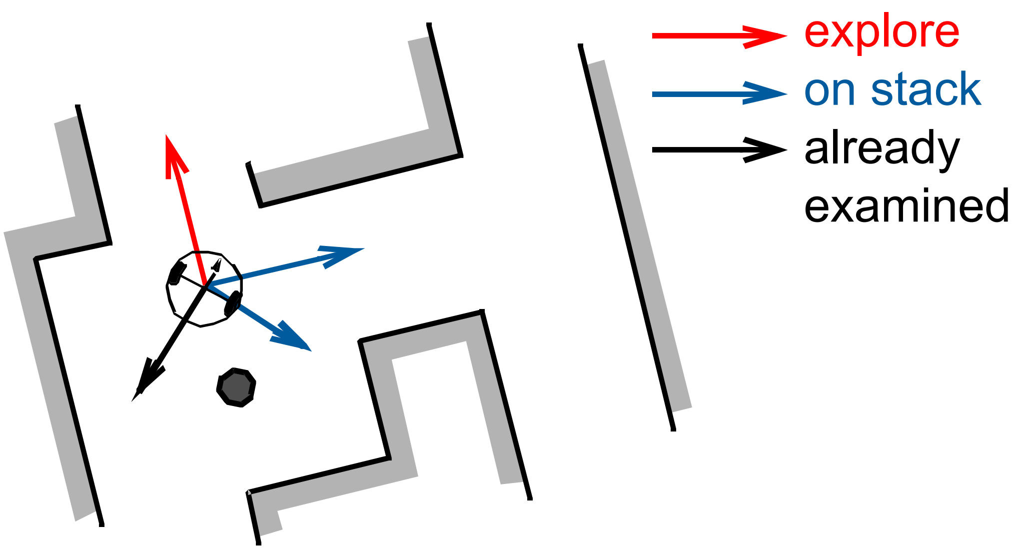
position of wall -> position of robot

- probability densities for feature positions
- additional exploration strategies

Courtesy K. Arras

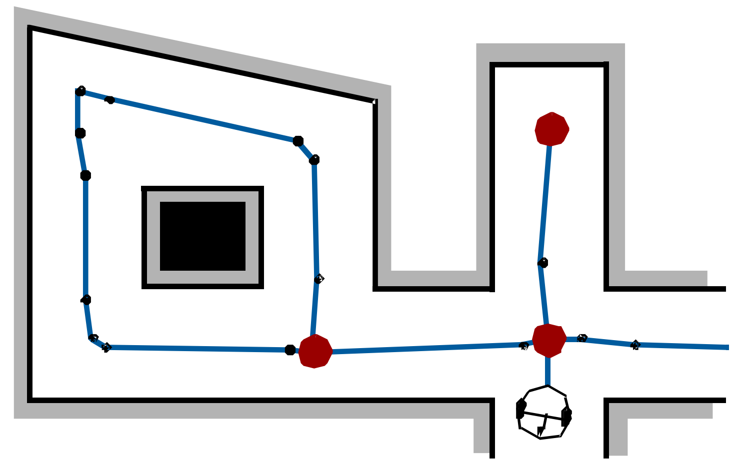
Map Building: Exploration and Graph Construction

1. Exploration



- provides correct topology
- must recognize already visited location
- backtracking for unexplored openings

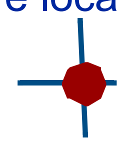
2. Graph Construction



Courtesy K. Arras

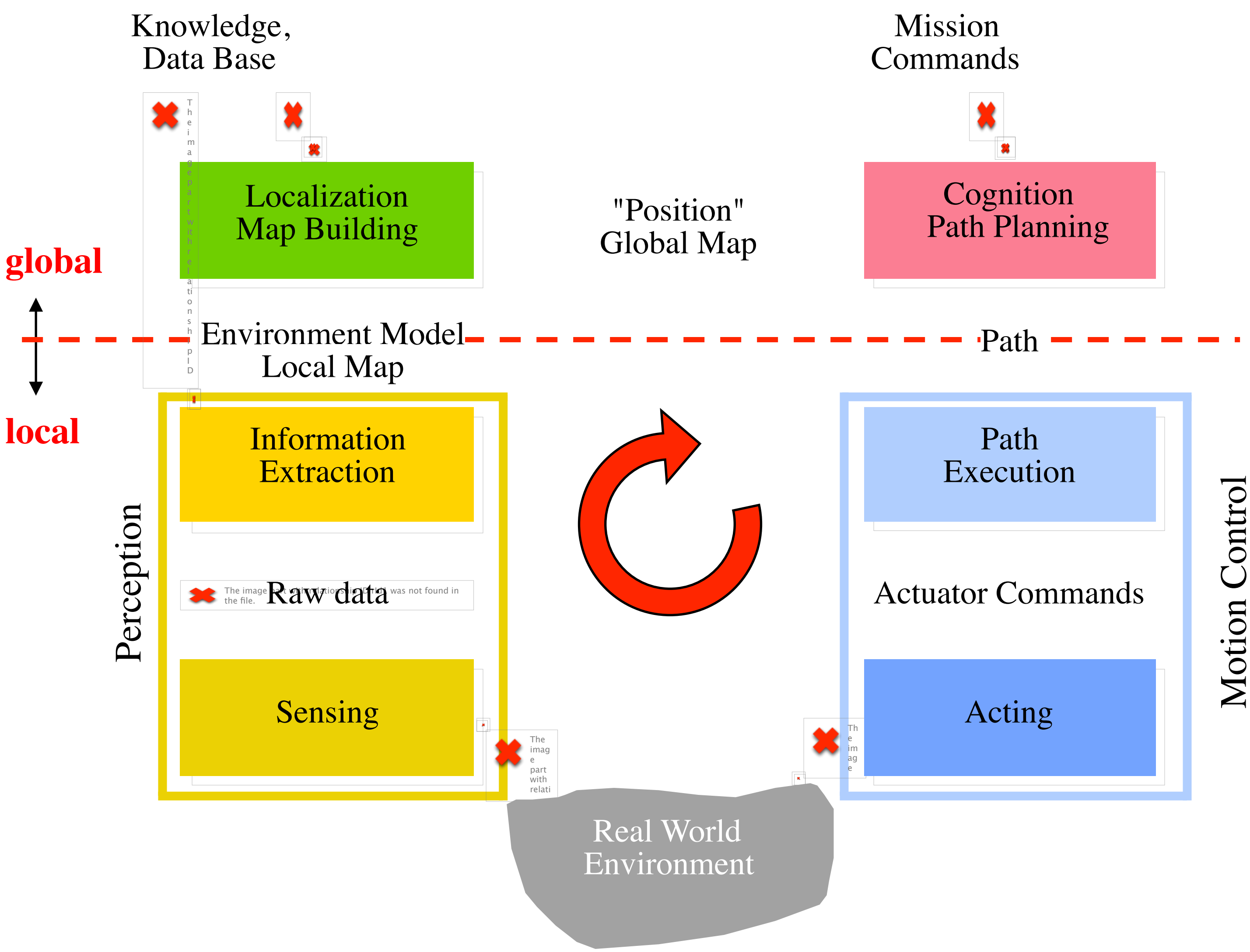
Where to put the nodes?

- Topology-based: at distinctive locations



- Metric-based: where features disappear or get visible

Control of Mobile Robots

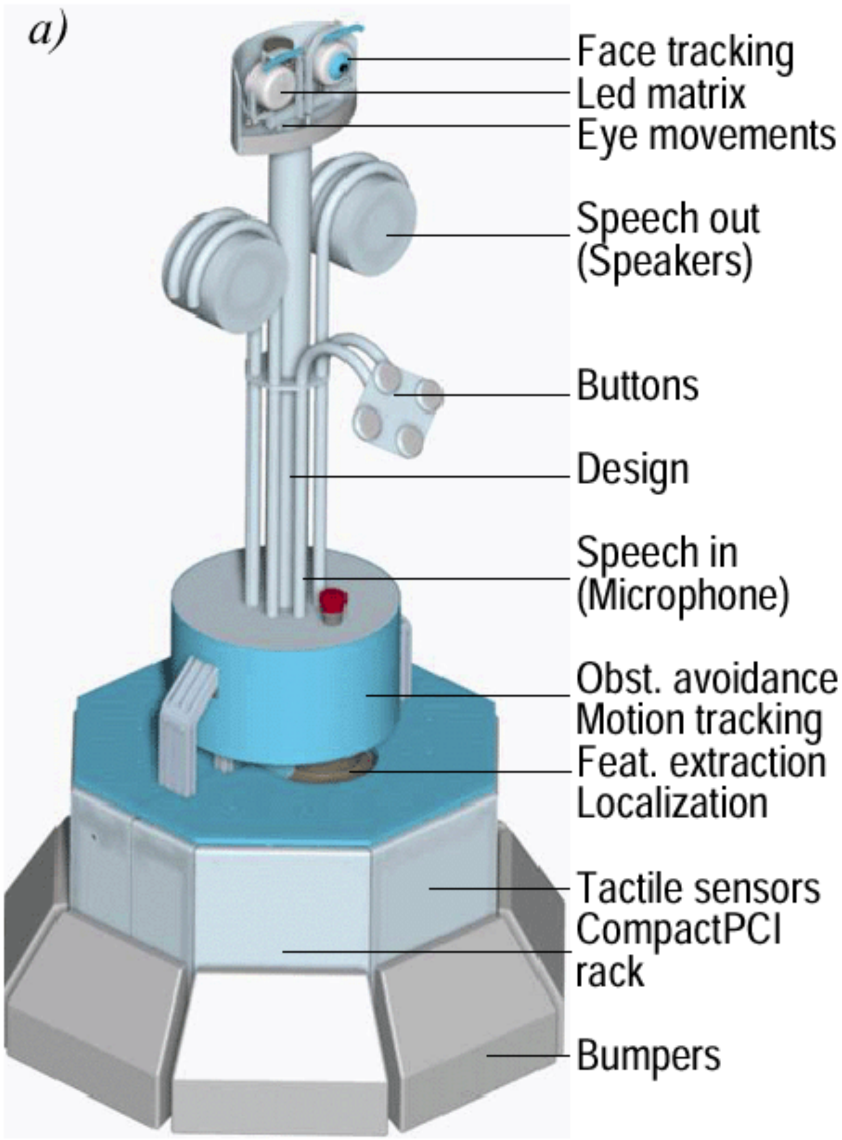


- *Most functions for* *save navigation* *are ’local’ not involving localization nor cognition*
- Localization *and* global path planning ➔ slower update rate, *only when needed*
- *This approach is pretty* *similar* *to what* *human beings do*.

Tour-Guide Robot (Nourbakhsh, CMU)

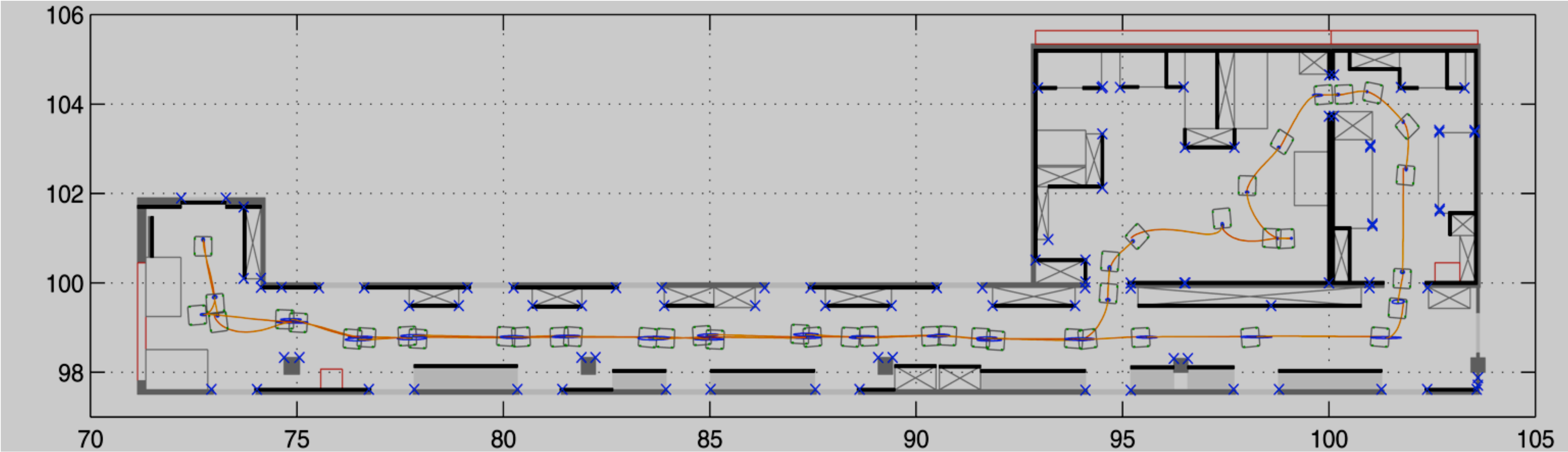
Autonomous Indoor Navigation (Thrun, CMU)

Tour-Guide Robot (EPFL @ expo.02)



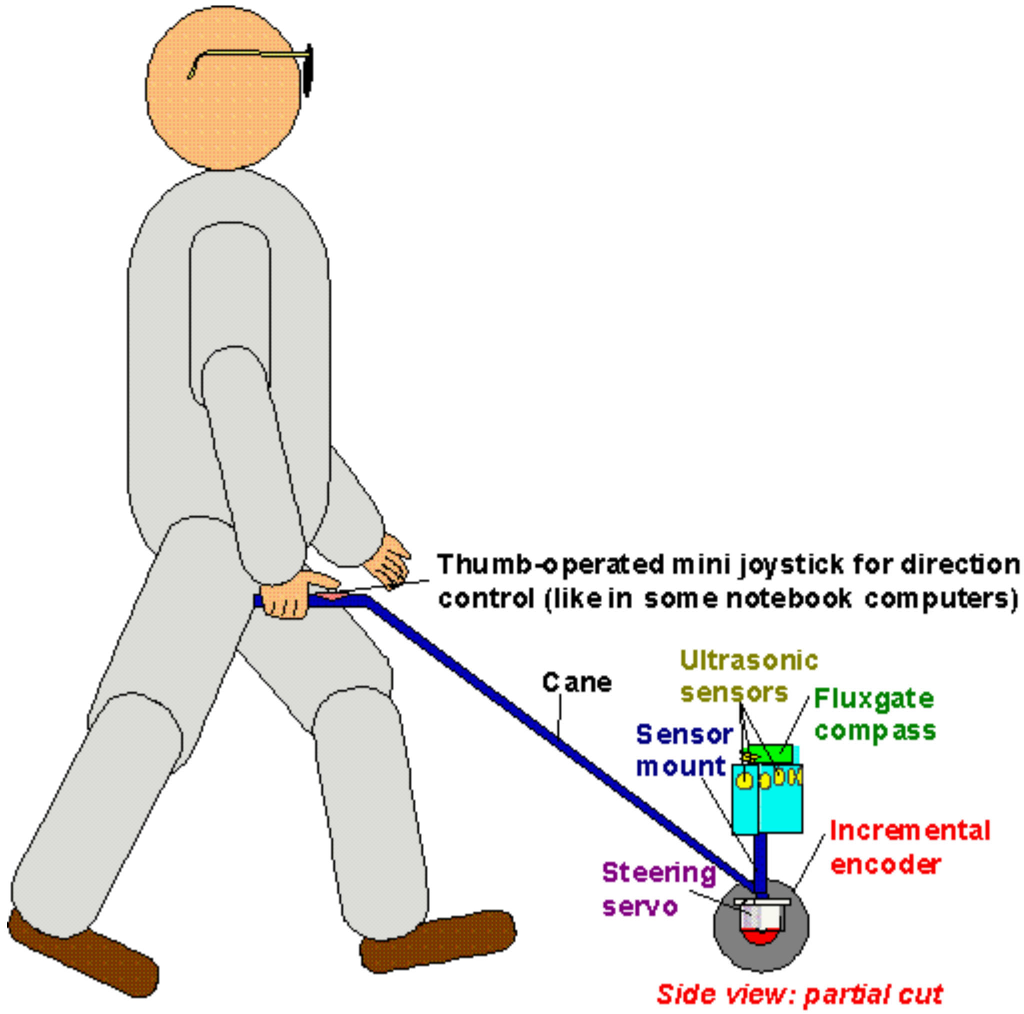
Autonomous Indoor Navigation (Pygmalion EPFL)

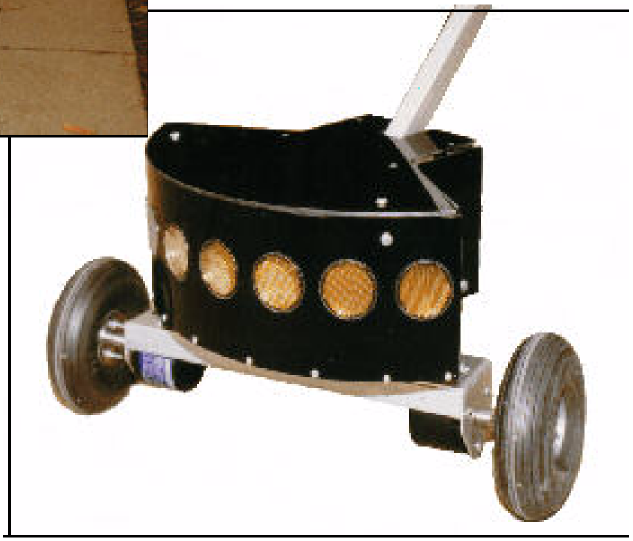
- *very robust on-the-fly localization*
- *one of the first systems with probabilistic sensor fusion*
- *47 steps,78 meter length, realistic office environment,*
- *conducted 16 times > 1km overall distance*
- *partially difficult surfaces (laser), partially few vertical edges (vision)*



GuideCane, University of Michigan

http://www.engin.umich.edu/research/mrl/

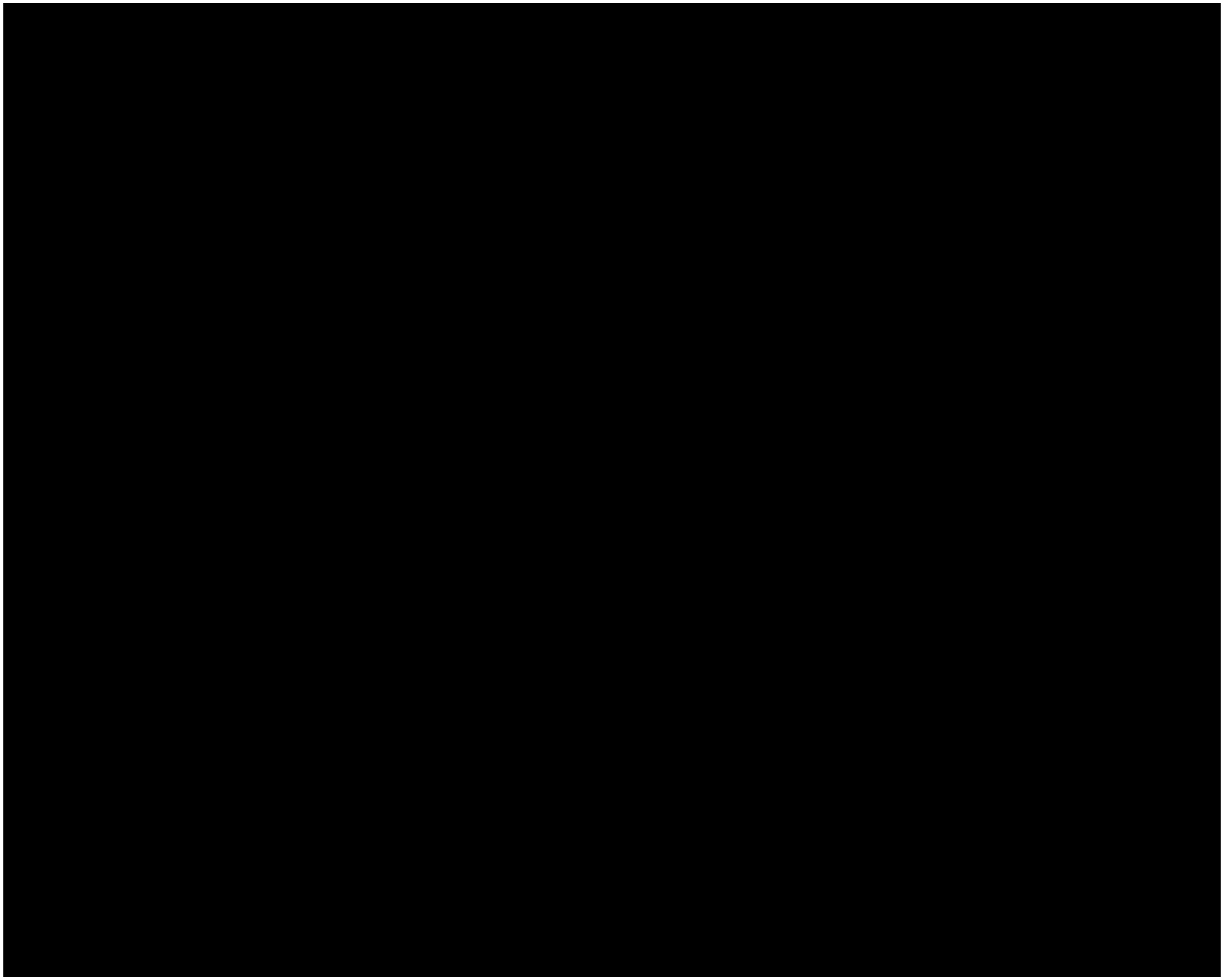




LaserPlans Architectural Tool

(ActivMedia Robotics)

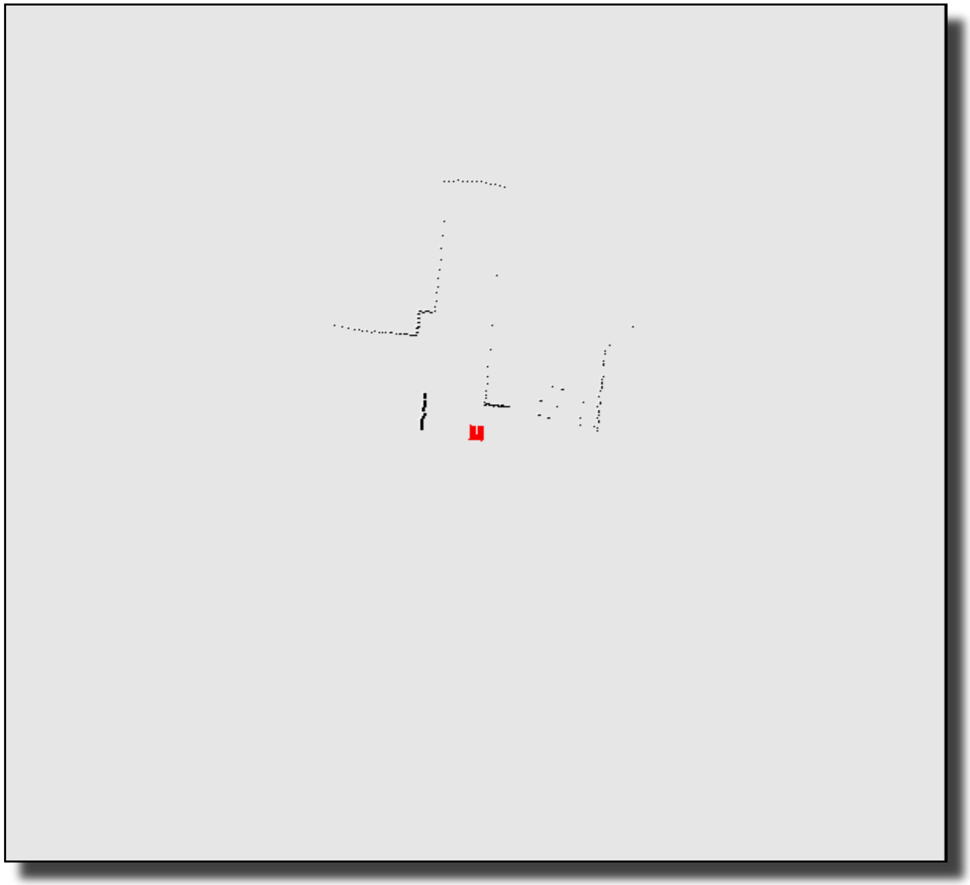
Morpha Project, Germany



Courtesy of Erwin Prassler

Autonomous Indoor Mapping

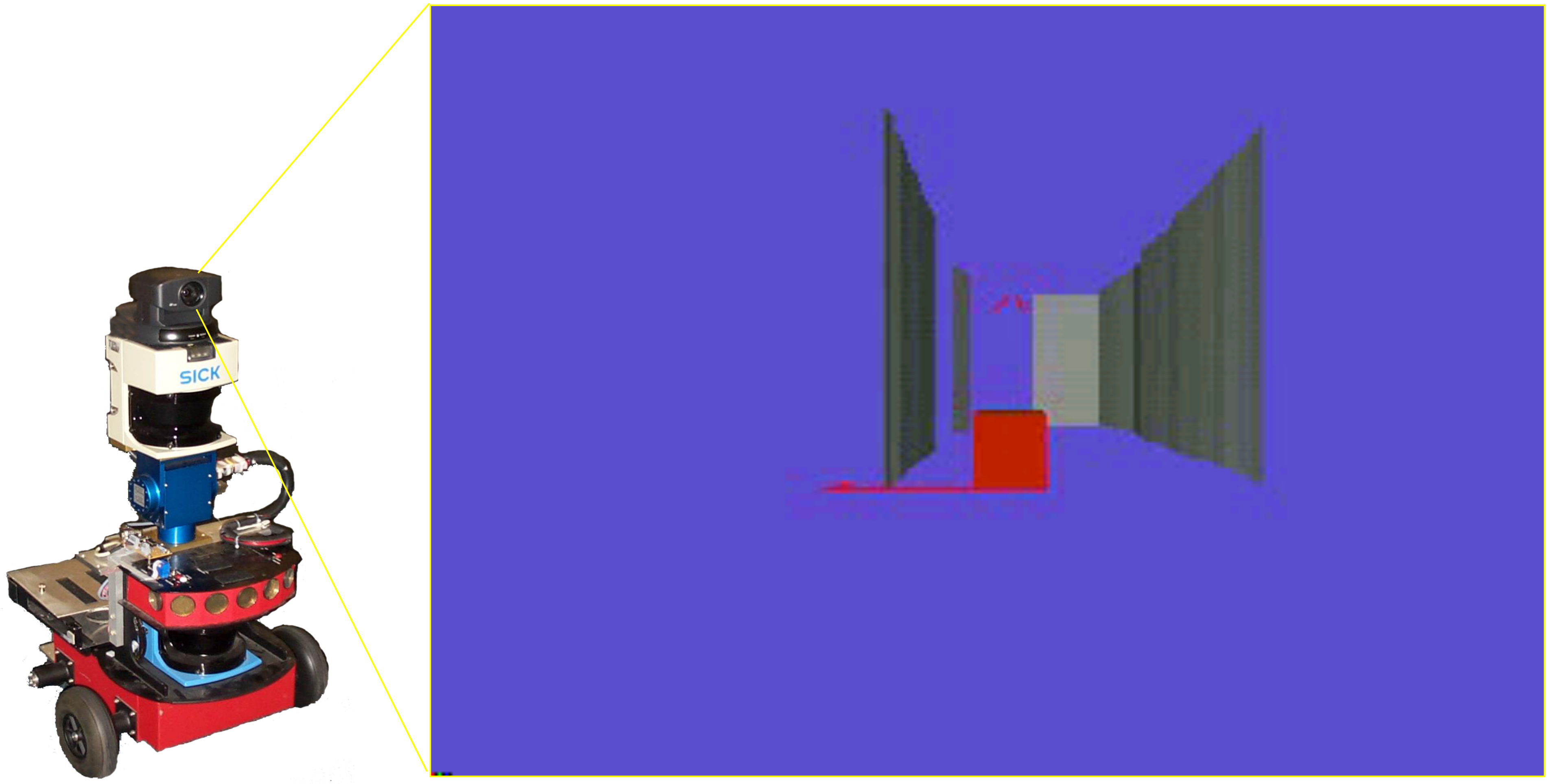
OLD



NEW

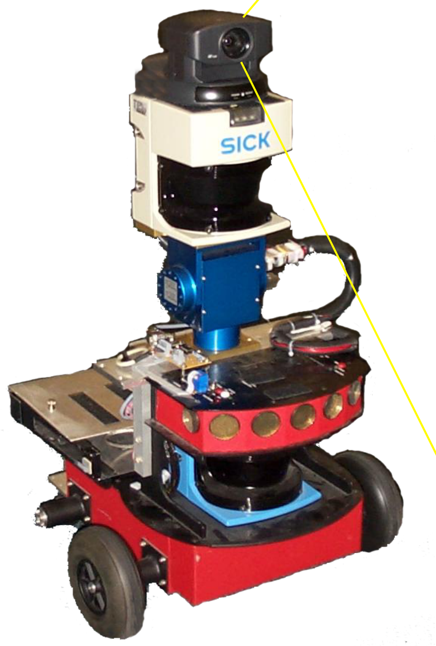
Courtesy of Sebastian Thrun

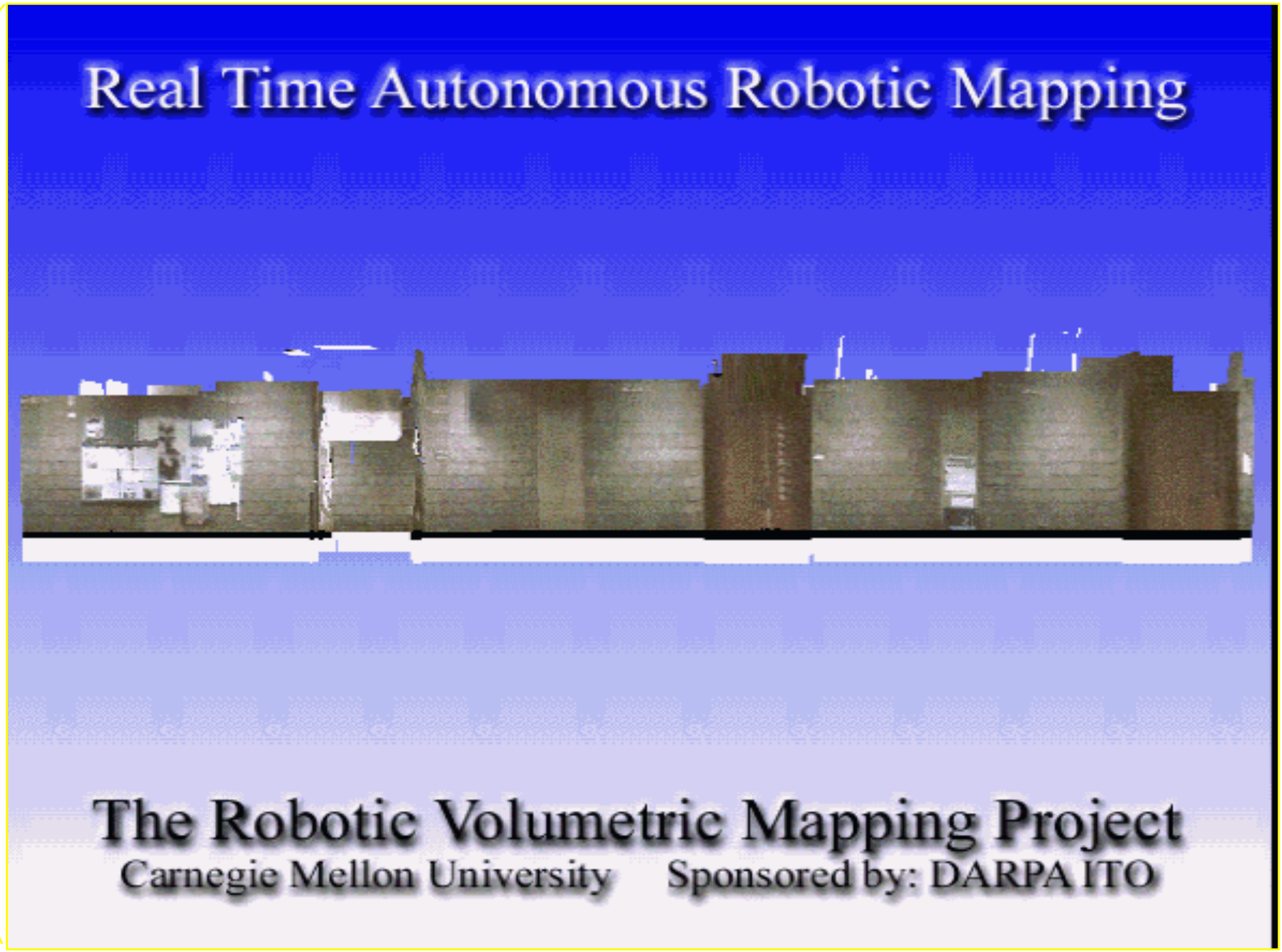
High-Speed Explotation and Mapping



Courtesy of Sebastian Thrun

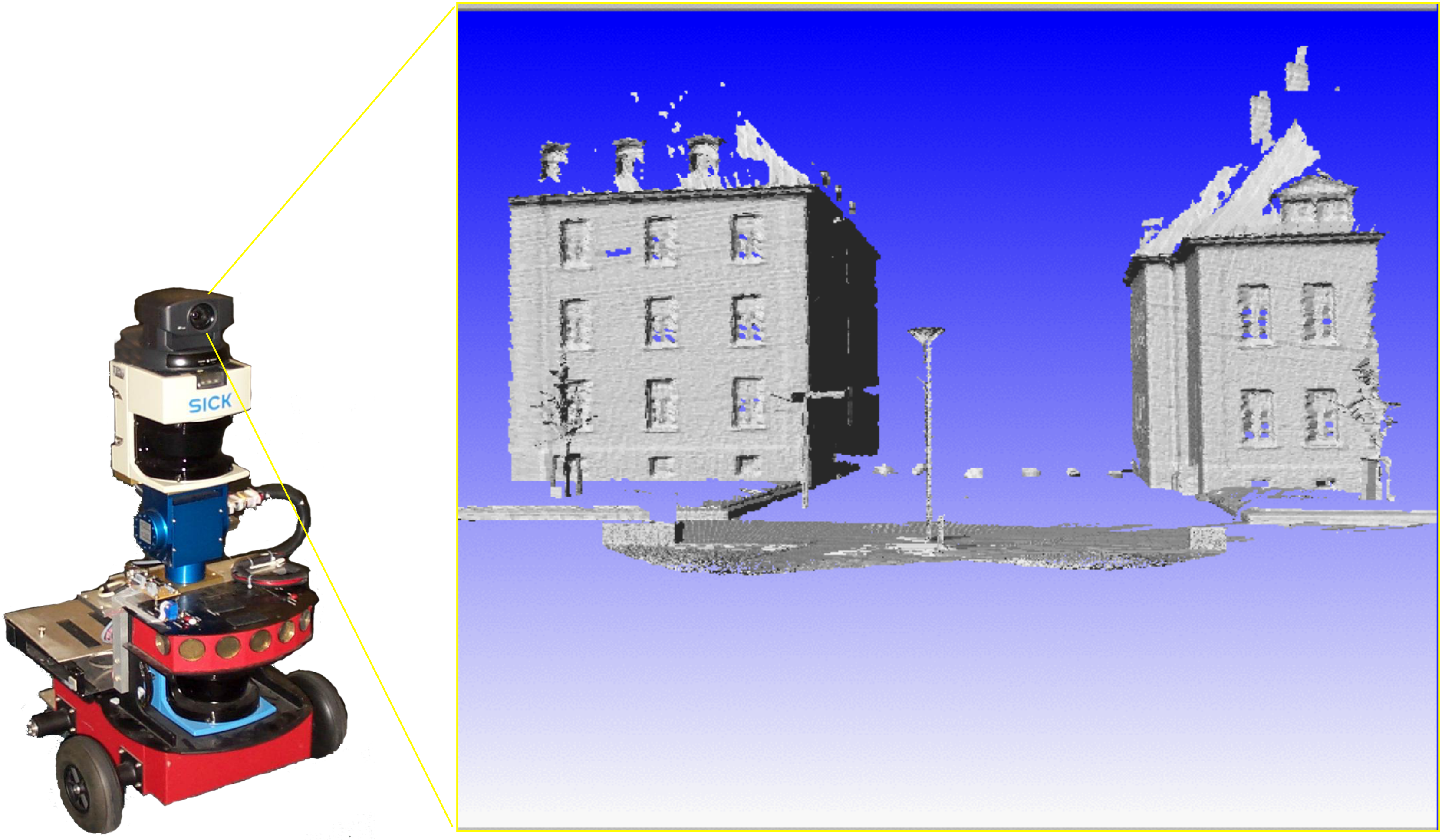
Turning Real Reality into *Virtual* Reality





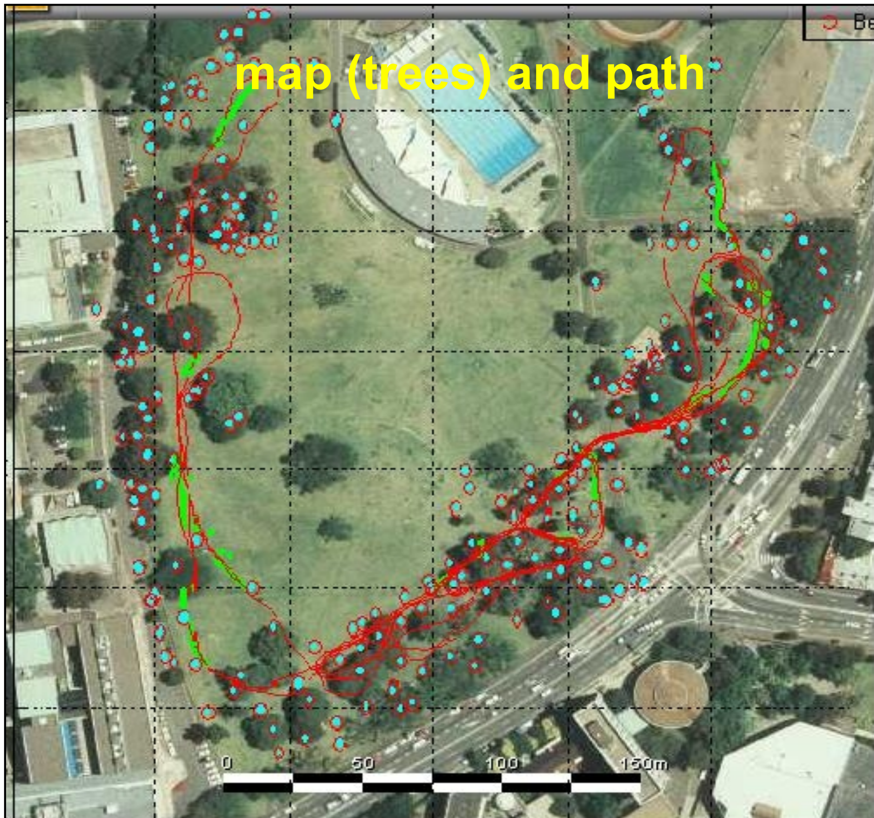
Courtesy of Sebastian Thrun

Urban Reconnaissance



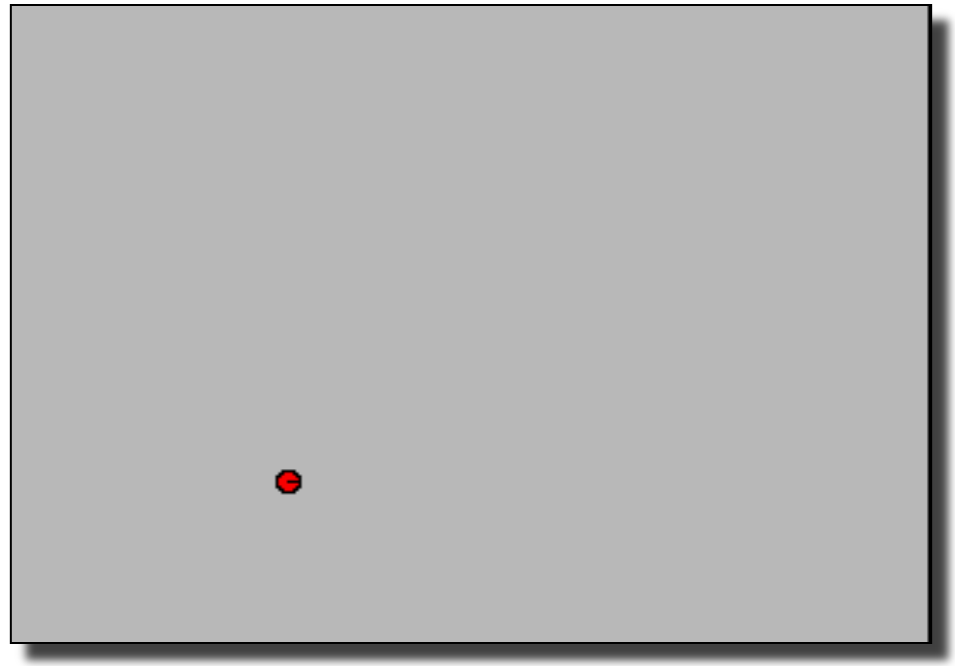
Courtesy of Sebastian Thrun

Outdoor Mapping (no GPS)



Courtesy of Eduardo Nebot

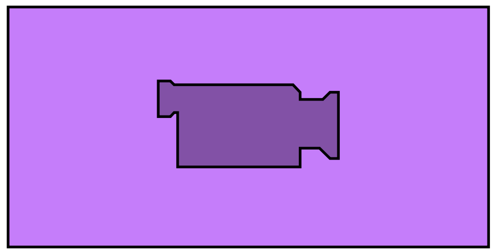
Real-Time Multi Robot Exploration



Courtesy of Sebastian Thrun

All Terrain Locomotion (Shrimp EPFL)

Human-Robot Interaction (Kismet MIT)



Cye's Navigation Concept