Robotics
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Terrain Classification for Autonomous Robot Mobility

from Safety, Security, Rescue Robotics to Planetary Exploration

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Jacobs University Bremen
http://robotics.jacobs-university.de

Institutional Name Change

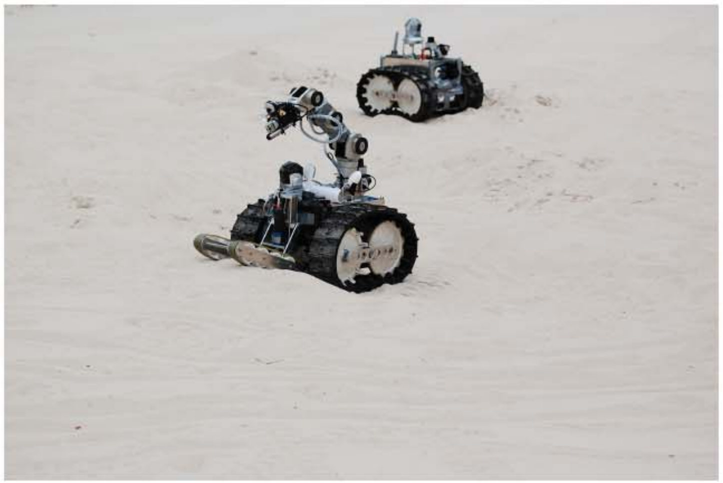
Robotics JACOBS UNIVERSITY

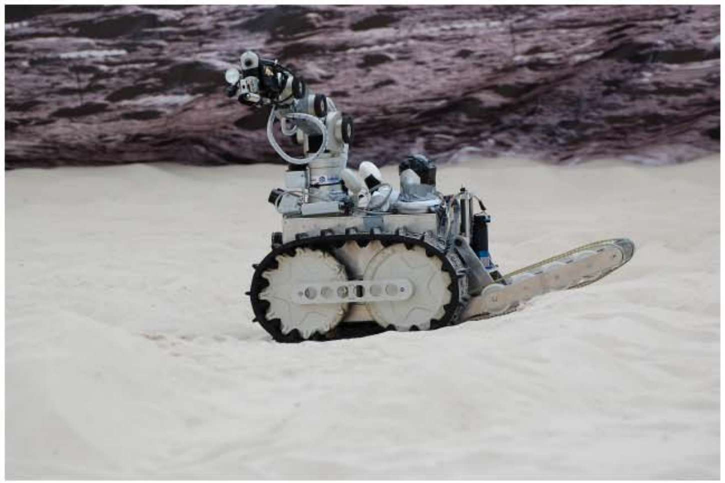
Please note the name-change of our institution.

The Swiss Jacobs Foundation invests 200 Million Euro in ***International University Bremen (IUB)***. To date this is the largest donation ever given in Europe by a private foundation to a science institution. In appreciation of the benefactors and to further promote the university's unique profile in higher education and research, the boards of IUB have decided to change the university's name to ***Jacobs University Bremen***.

Overview

- Safety, Security, Rescue Robotics (SSRR)
- Jacobs robot: locomotion for rough terrain
- Navigation on rough terrain: detection of drivable ground





Research Focus of Jacobs Robotics: Autonomous Systems

Robotics
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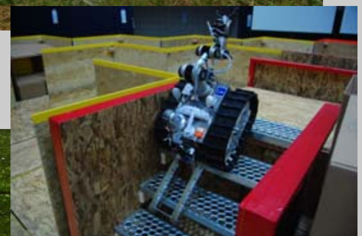
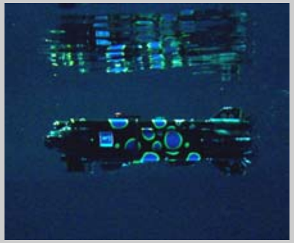
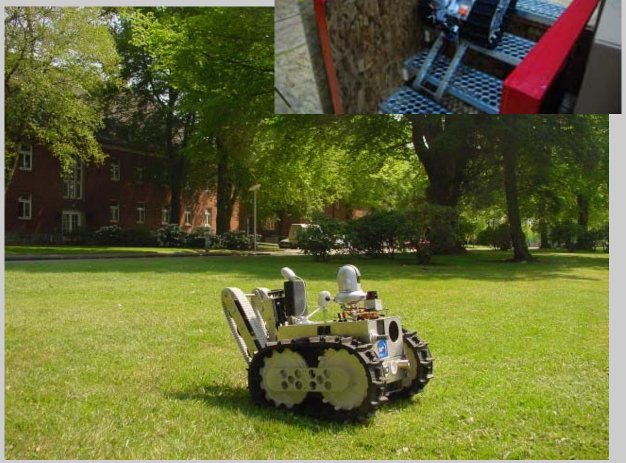
developments from
mechatronics up to high level intelligence

- ***Safety, Security, Rescue Robotics (SSRR)***
- but also
  - planetary exploration
  - underwater robotics

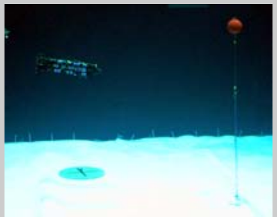










Safety, Security, Rescue Robotics (SSRR)

currently, systems mainly used for ***situation assessment***

- first deployments during real incidents
- increasing number of field trials
- large application potential

example: road accidents involving hazardous material transports

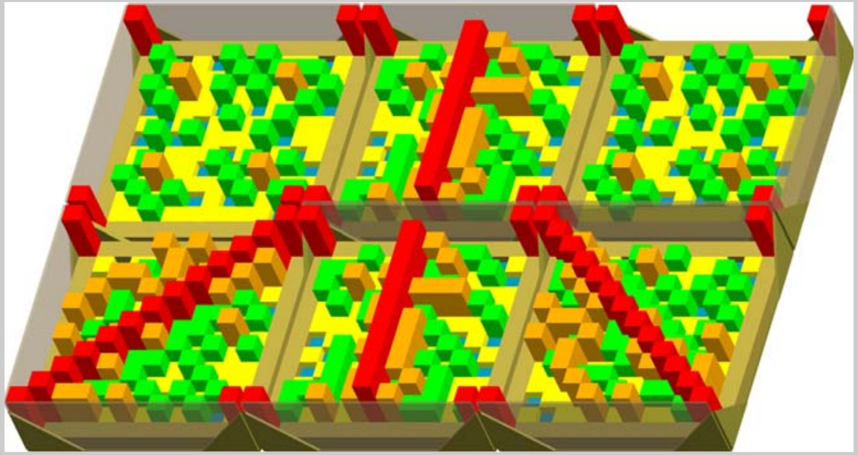
- 5 ½ such accidents per day in Germany
- first responders need protective gear
  - ⇒ limited number of balloon suits
  - ⇒ suit hinders situation assessment
  - ⇒ bad physical working conditions

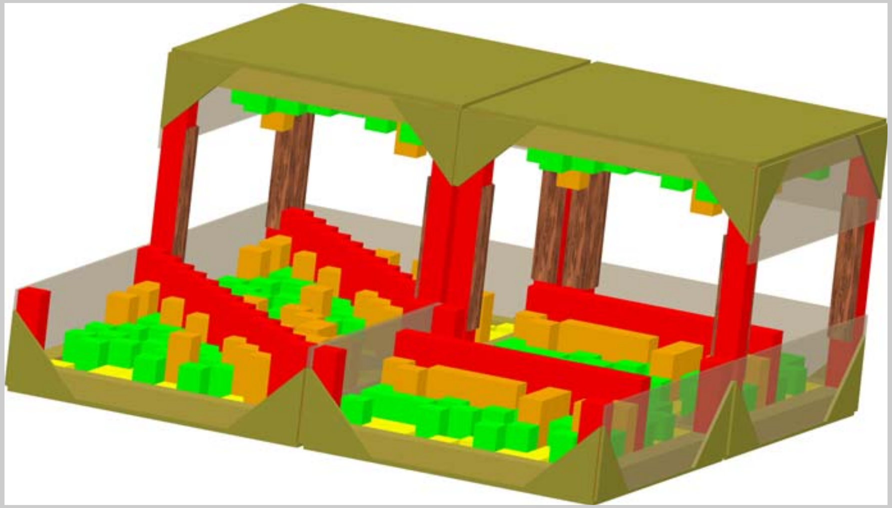
Performance Testing and Evaluation

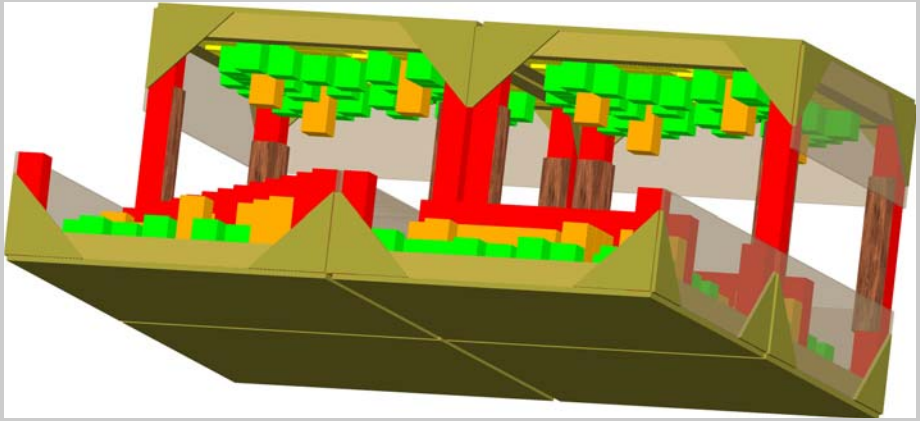
- Jacobs Test Arenas
  - one of six test sites worldwide
  - for mobile robot performance evaluation
- cooperation with US National Institute of Standards and Technologies (NIST)

Example NIST Test Element

- Random Step Field
  - wooden poles, loosely arranged
  - in different patterns (hill, diagonal, peaked)
  - with random pole length component
- good performance test for locomotion







Why working on Autonomous Systems and SSRR?

Safety, Security, Rescue Robotics

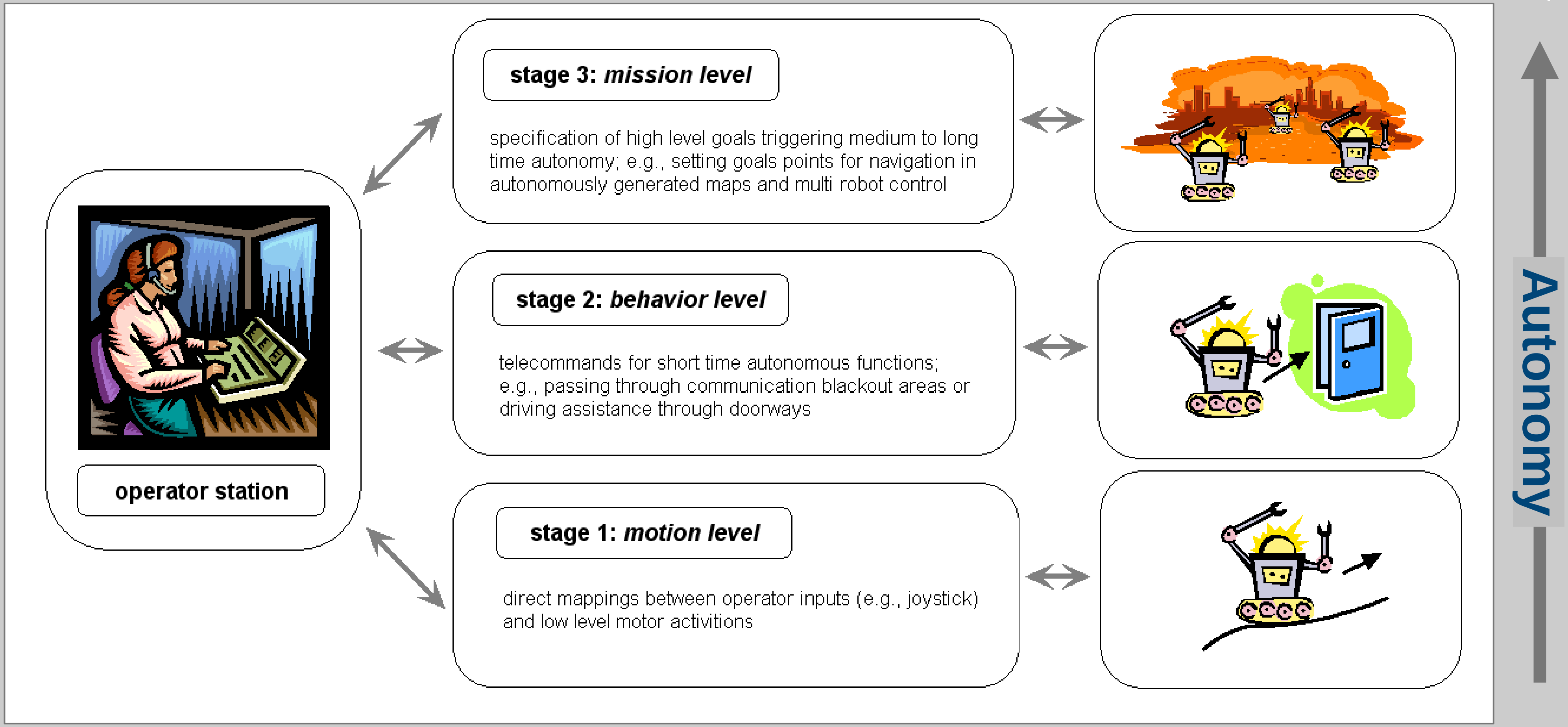
- covers the ***basic research challenges*** of robotics
  - advanced locomotion & manipulation
  - challenging perception & world modeling
- is ***application driven***
- but allows ***gradual development***
  - today's systems are already very useful
  - every further development adds benefit

Why working on Autonomous Systems and SSRR?

Autonomy to

- reuse components for user assistance
- handle communication dropout, respectively degradation
- enable single user operation of robot teams

Teleoperation Levels



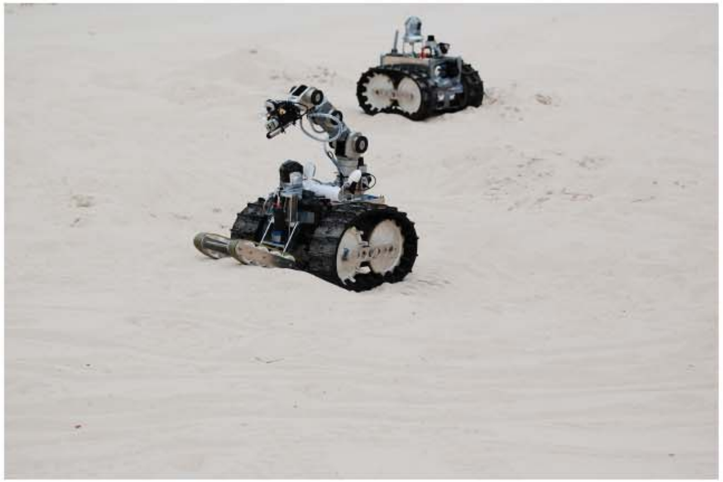
Example

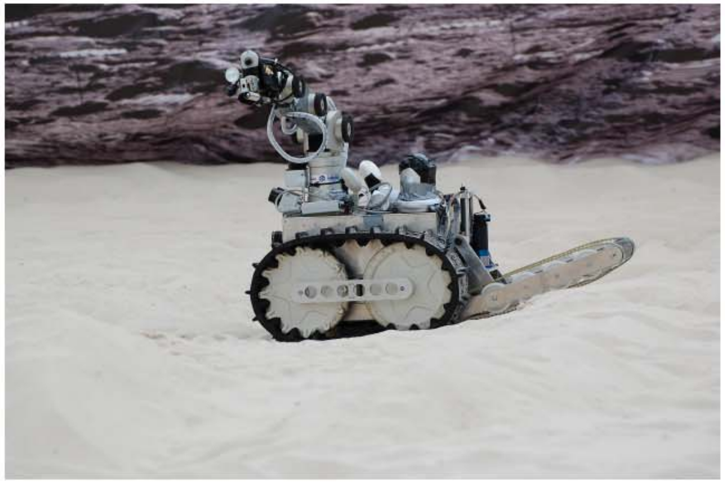
Jacobs team at
European Land Robot Trials (ELROB) 2007
Monte Ceneri, Switzerland

- urban scenario
  - ABC attack at folk festival
  - robots have to find and locate hazmat signs
  - as indicators of “interesting” spots
- Jacobs: cooperative robot team
  - two land robots, one operator
  - autonomy allowing
    - navigation by operator defined goal points
    - resp. autonomous exploration
    - in robot generated maps
  - operator
    - choosing goal points
    - taking over with joystick tele-op for locomotion challenges (stairs, curbs, etc.)

Mobility in Unstructured Environments

- locomotion
  - robots must be physically capable to handle rough terrain
- perception
  - robots must be able to detect drivable ground

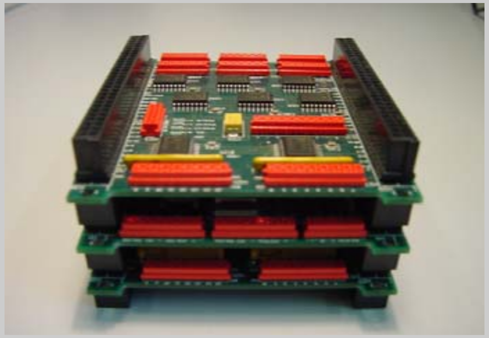




Locomotion Mechatronics

- complete in-house developments
- based on CubeSystem
  - open source
  - collection of hard- & software components
  - for rapid robot prototyping
- plus standard PC

- basic data
  - tracked drive
  - 50cm x 50cm footprint
  - 25kg weight, 15kg payload
  - 3h operation time



RoboCube
a compact
embedded controller

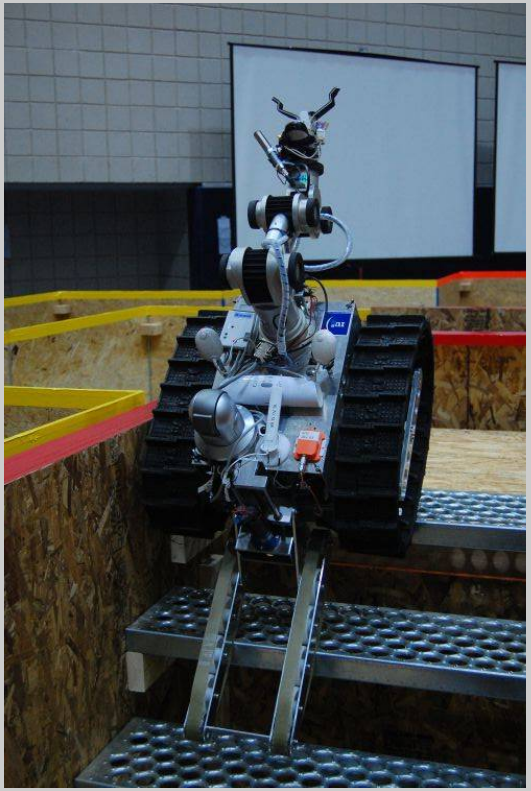
Locomotion unit: support flipper

no ideal footprint for a rescue robot

- large footprint
  - e.g. climbing up a rubble pile or stairs
  - maximize traction & prevent tilting over
- large footprint
  - negotiating narrow passages or doorways
  - prevent to get stuck.

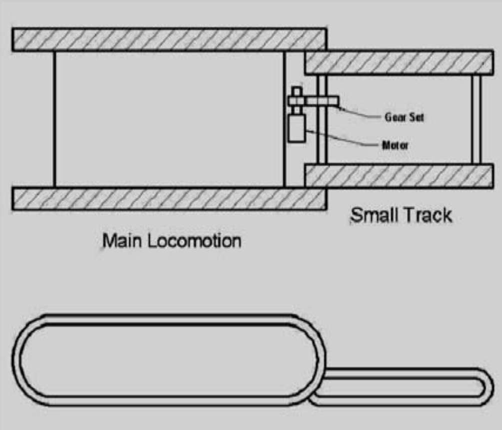
common approach: flippers

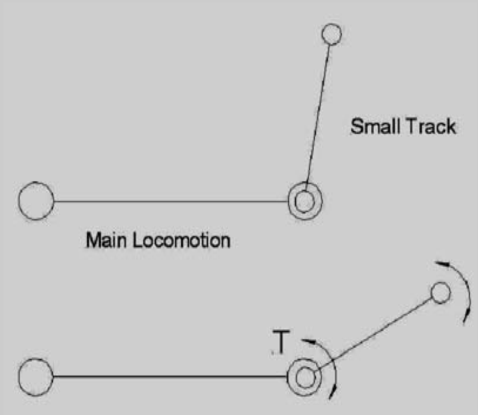
- additional support tracks
- can change their posture relative to the main locomotion tracks
- additional benefit: shift center of gravity

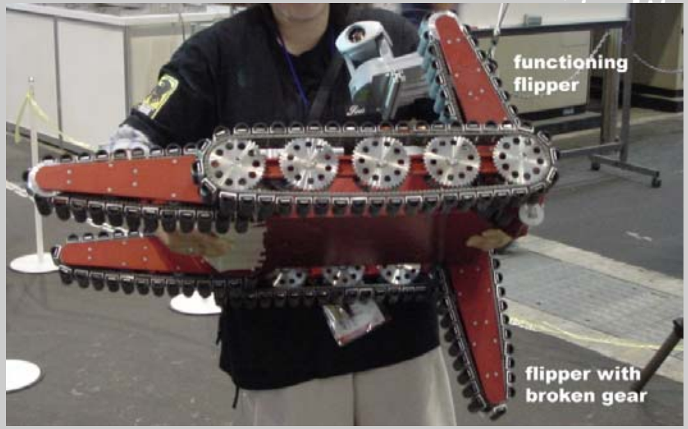


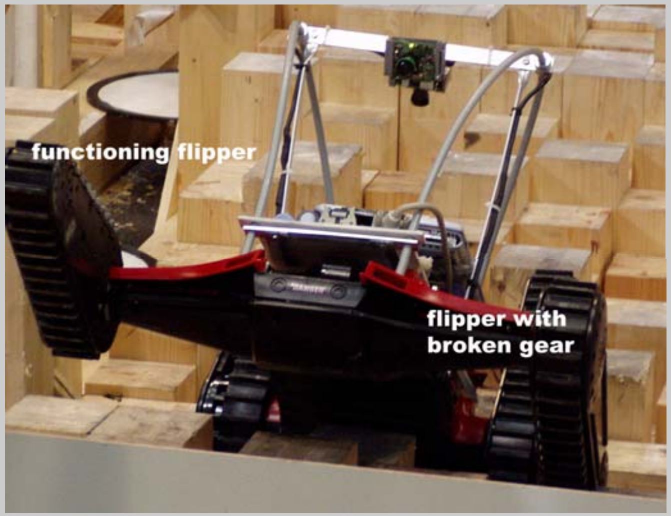
State of the art

- directly drive the joint of a flipper
  - large torque needed
  - shocks go directly to active joint
- consequences
  - high risk of broken transmissions
  - and/or overhead in weight & cost







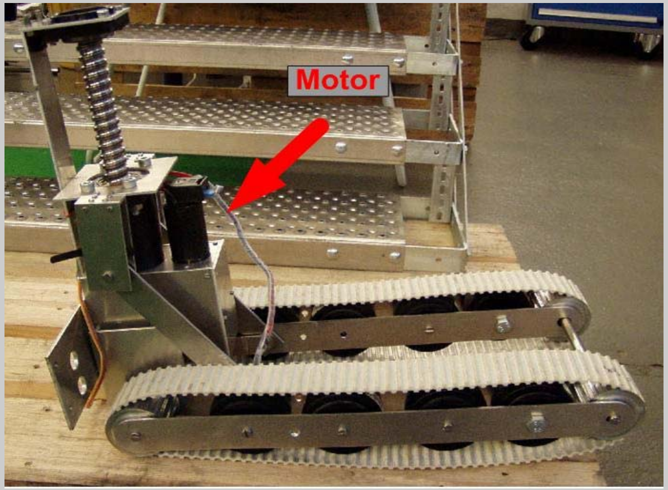


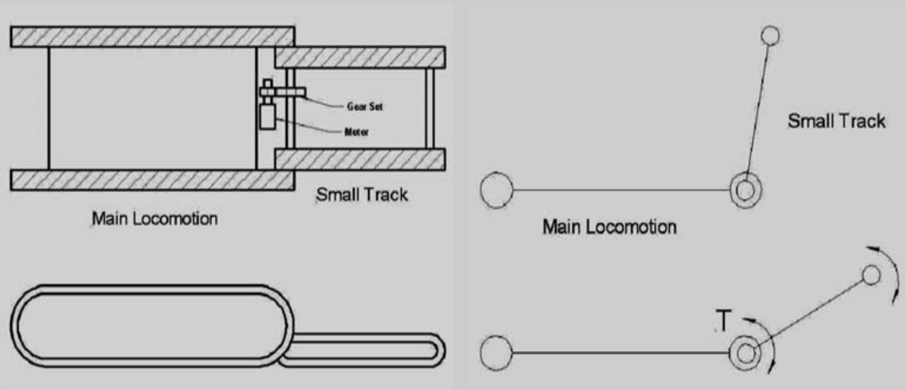
Solution

novel mechatronic design for flippers:

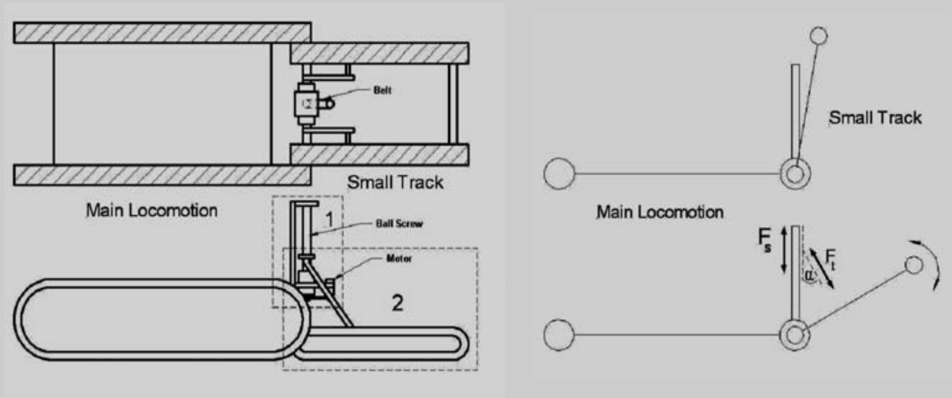
link mechanism driven by a ballscrew

- shocks are absorbed by a passive link
- much less motor torque required
    - with same flipper length, angular speed, etc. as classic design
    - an order of magnitude less force required





standard design



Jacobs Rugbot flipper

Being physically able is not enough…

European Land Robotics Trials (ELROB 2006)

- Hammelburg, Germany
- training camp for urban combat
- military organized

professional participants

- Qinetiq
- MacroSwiss
- Robowatch
- BASE 10 (RoboScout)
- Rheinmetall Land Systems
- Smith Engineering Ltd (MoonBuggy)
- Rheinmetall Defence Electronics
- Telerob
- Diehl
- Remotec
- Europ. Aeronautic Defence & Space (EADS)

results

- ***easy stairs***
  - outdoors, good visual conditions
  - ***5 out of 13*** made it
- ***hard stairs***
  - indoors, less good visual conditions
  - ***2 out of 13*** made it

Mobility in Unstructured Environments

- locomotion
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- perception
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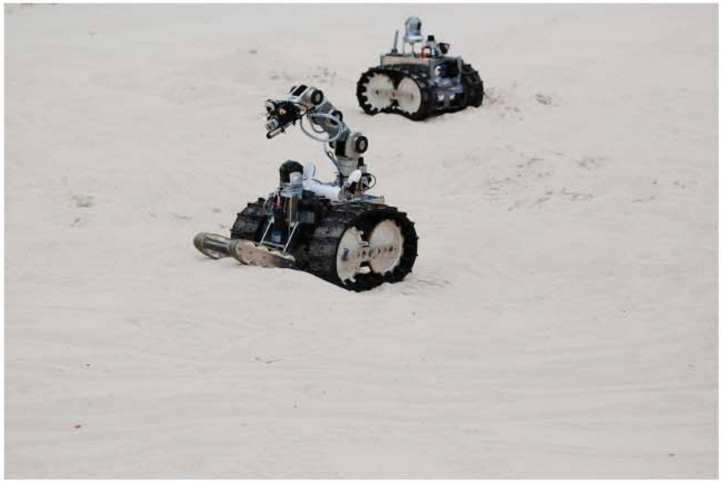
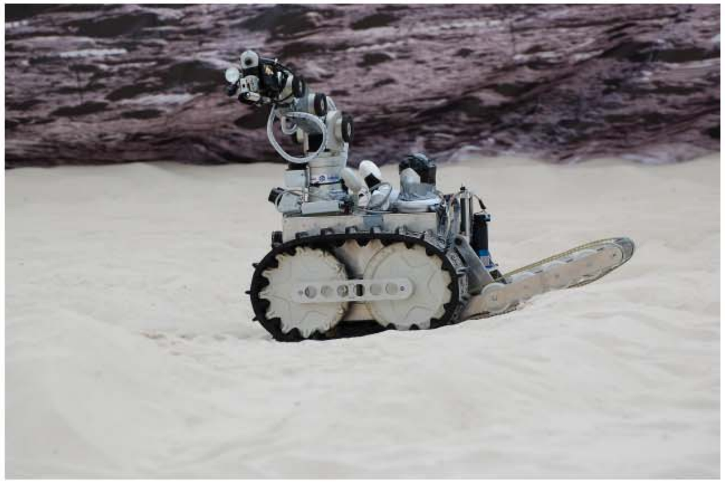
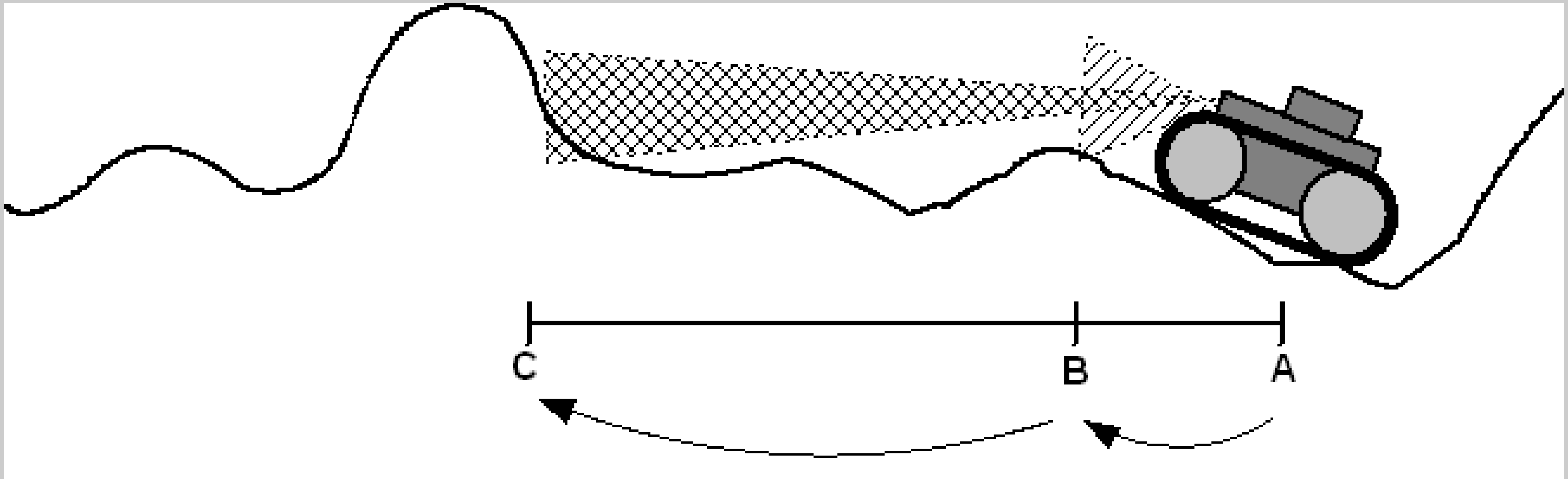




Hierarchical Navigation Behaviors

- internal system parameters (A) -> reactive “emergency” behaviors
- short range perception (B) -> reactive obstacle behaviors
- long range perception (C) -> path planning



Know where you going…

for example RoboCup Rescue:

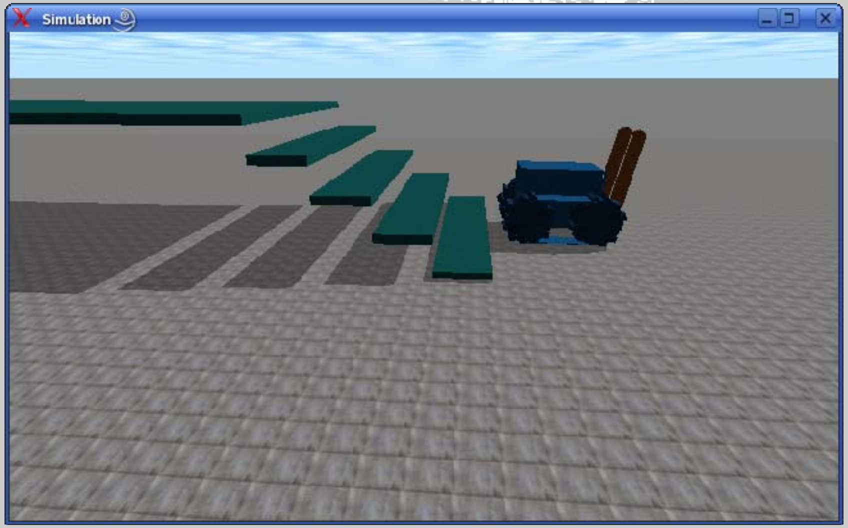
- distinction between
- inclined floor (default for autonomy)
- random step field (nobody can handle them autonomously yet)

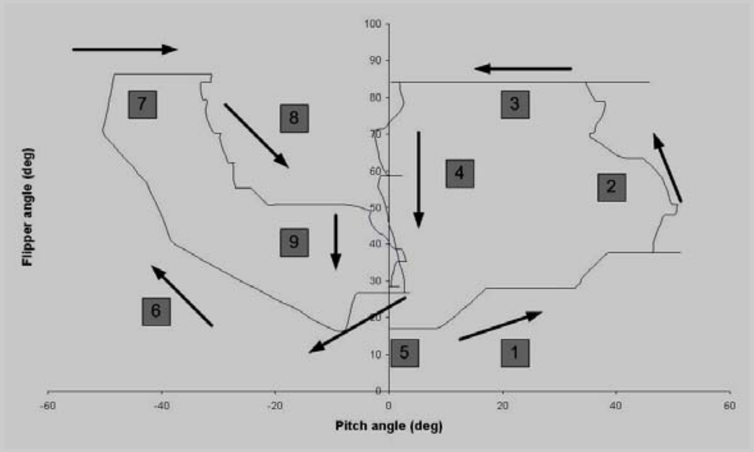
type A behaviors

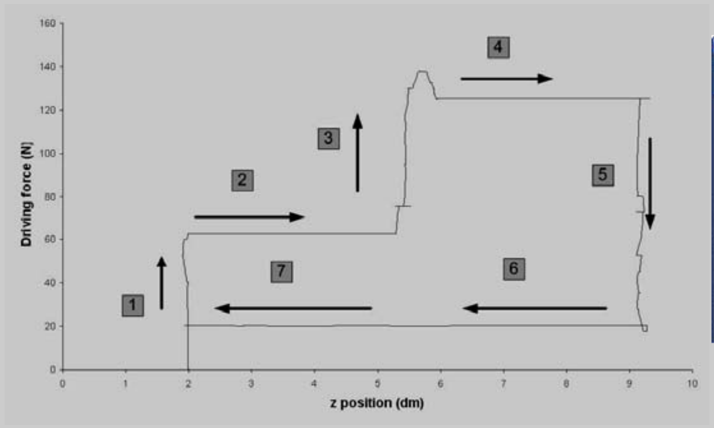
- check inclination, backoff when critical
- measure motor currents to detect stall

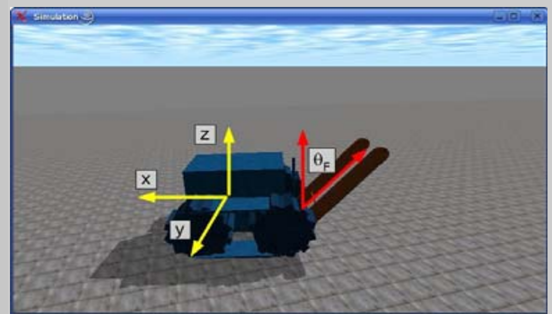
Other Type A Behaviors: Flipper Control

- determine human control strategies
  - give operator perfect viewing conditions
  - record control input / output
  - data from several users
  - extract patterns
- turn them into a fuzzy controller



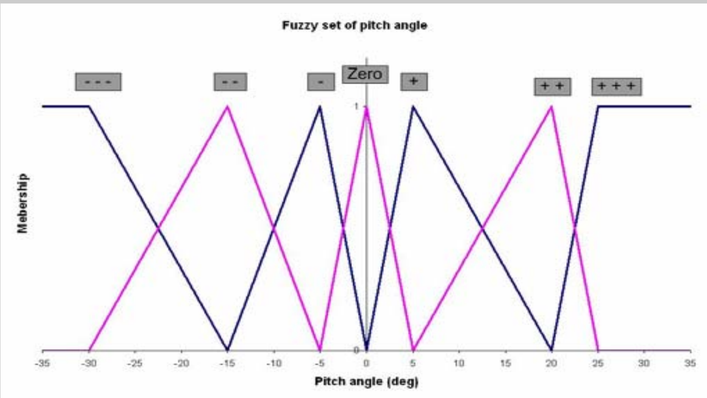


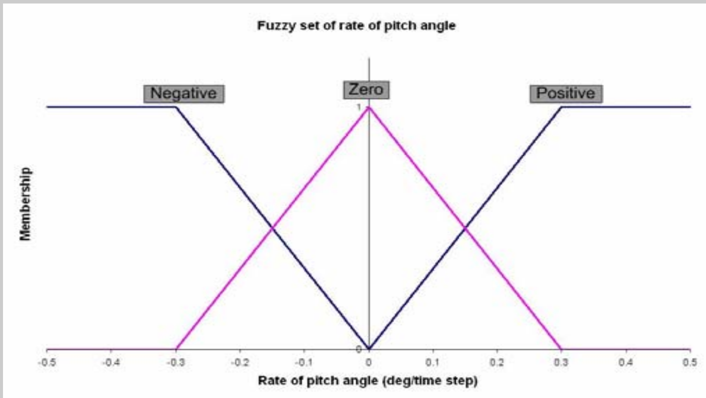




Flipper Control

- parameters
  - pitch α
  - its rate of change Δα
  - flipper angle‘s rate of change Δθ
- fuzzy rules
  - non-linear controller
  - rules as extracted from user recordings rather common sense
  - e.g., of the type „robot‘s nose pointing strongly up and fast increase in pitch => put flipper very fast down (i.e., avoid tilting over)“

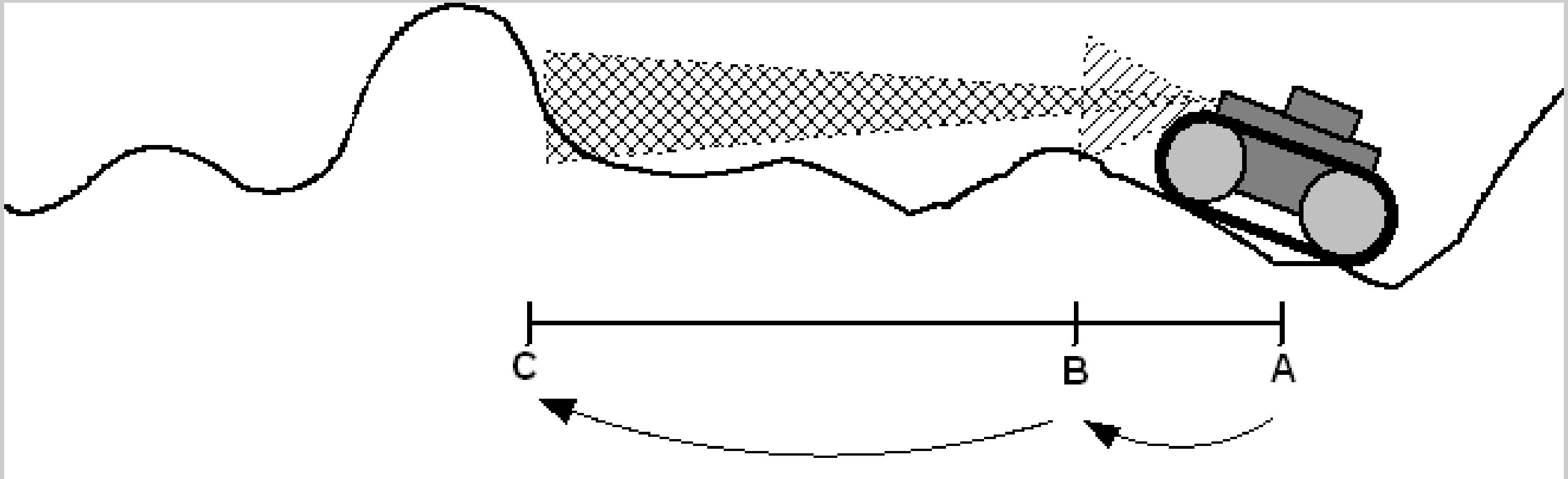




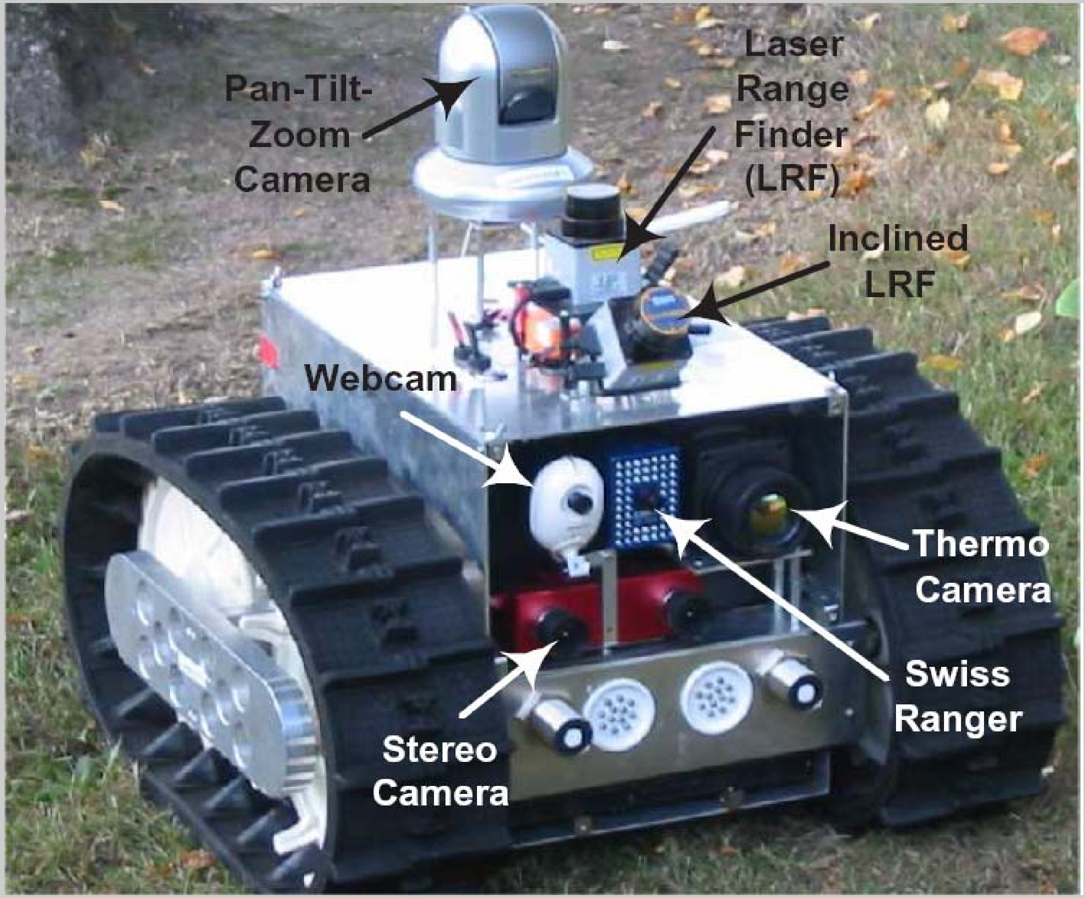
$\Delta\alpha$	α	$\Delta\theta_F$
negative	- - -	+
negative	- -	+ +
negative	-	zero
negative	zero	zero
negative	+	- - -
negative	+ +	zero
negative	+ + +	zero
zero	- - -	+
zero	- -	+ + +
zero	-	zero
zero	zero	zero
zero	+	zero
zero	+ +	+
zero	+ + +	+
positive	- - -	-
positive	- -	- - -
positive	-	zero
positive	zero	zero
positive	+	zero
positive	+ +	+ +
positive	+ + +	+ + +

Hierarchical Navigation Behaviors

- internal system parameters (A) -> reactive “emergency” behaviors
- ***short range perception (B) -> reactive obstacle behaviors***
- long range perception (C) -> path planning



3D Range Sensors for Terrain Classification



- actual LRF
  - Hokuyo URG40 + tilt servo
- stereo camera
  - Videre STOC
- TOF camera
  - Swissranger SR-3000

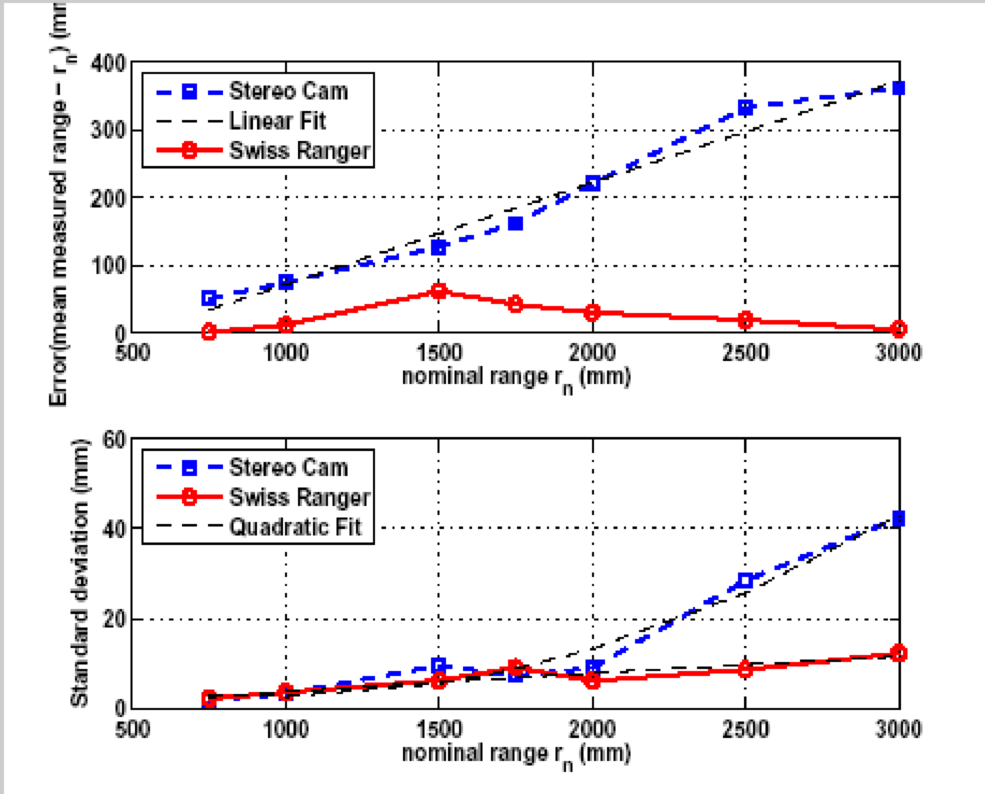
	size	weight	power
3D URG40-LX	l:50mm, w:50mm, h:70mm	425 g	2.5 W
STOC	l:132mm, w:39mm, h:44mm	261 g	2.4 W
SR-3000	l:42.3, w:50, h:67mm	162 g	12 W[1]

	number of data points	sampling rate	field of view	range
3D URG40-LX	683×90	0.3 Hz	$240^o \times 90^o$	0.2 - 4 m
STOC	640×480	30 Hz	$70^o \times 52^o$	0.75 - 3 m
SR-3000	176×144	$\leq$ 50 Hz[2]	$47^o \times 39^o$	0.6 - 8 m[3]

Fast but noise prone 3D data acquisition

time-of-flight cam:
Swissranger SR-3000

stereo camera: Videre STOC

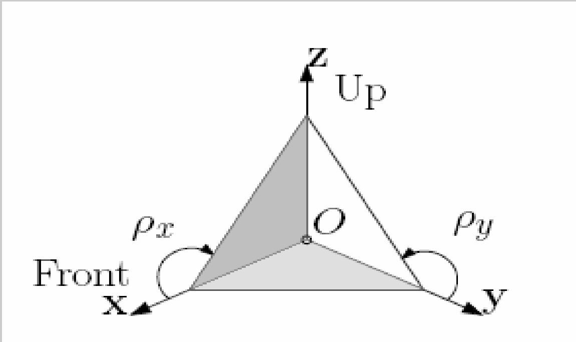


	Swissranger	**Stereo Camera**
Manufacturer	CSEM	Videre Design
Model	SR-3000	Stereo-on-Chip (STOC)
Principle	Time of Flight (TOF)	Stereo images' disparity
Range	600 – 7500 mm	686 – ∞ mm
Horiz. Field of View	47^o	65.5^o
Vert. Field of View	39^o	51.5^o
Resolution	176×144	640×480

Classification based on Planar Hough Transform

use ***Hough Transform for planes***
going from point to parameter space

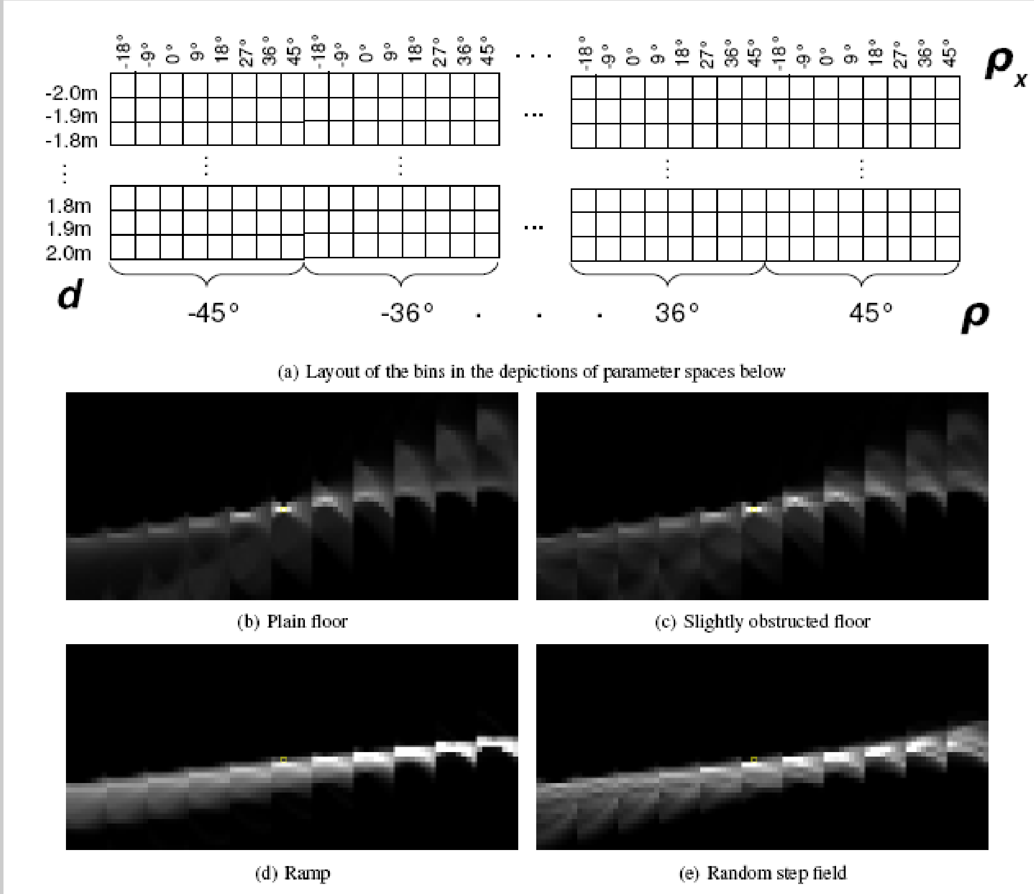
- discrete parameter space ***PS*** of bins
- bins with 3 parameters
  - two orientation angles ρ_x, ρ_y
  - plus distance ***d*** from origin
- for every range data point in point cloud ***PC***
  - put a “vote” into each bin
  - that corresponds to a plane
  - passing through that point



for all point $p \in PC$ **do**
  for all angles ρ_x **do**
    for all angles ρ_y **do**
      $\mathbf{n} \leftarrow (-sin(\rho_x)cos(\rho_y), -cos(\rho_x)sin(\rho_y), cos(\rho_x)cos(\rho_y))^T$
      $d \leftarrow \mathbf{n}p$
      $PS[\rho_x][\rho_y][d] + +$
    end for
  end for
end for

Example Hough Spaces

(a) Slightly obstructed floor (b) Grass (c) Ramp (d) Hill (e) Random step field (f) Bush



(a) Layout of the bins in the depictions of parameter spaces below

(b) Plain floor (c) Slightly obstructed floor

(d) Ramp (e) Random step field

brighter grey scale value = more hits

More Examples

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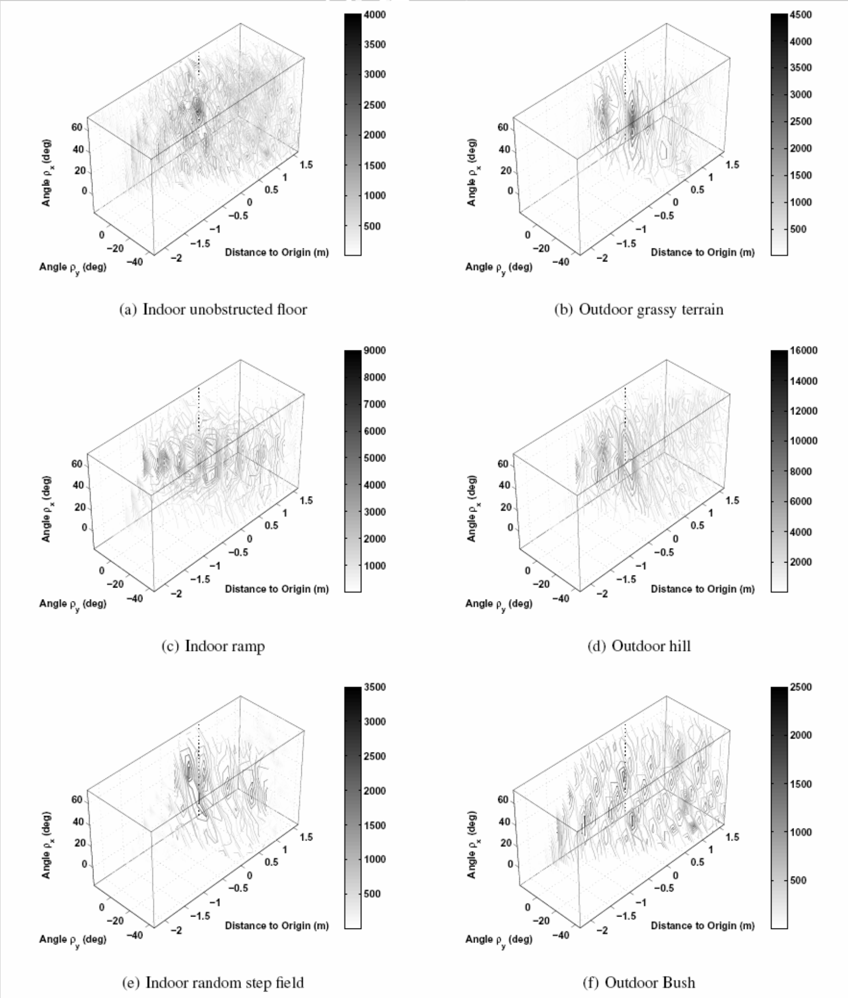
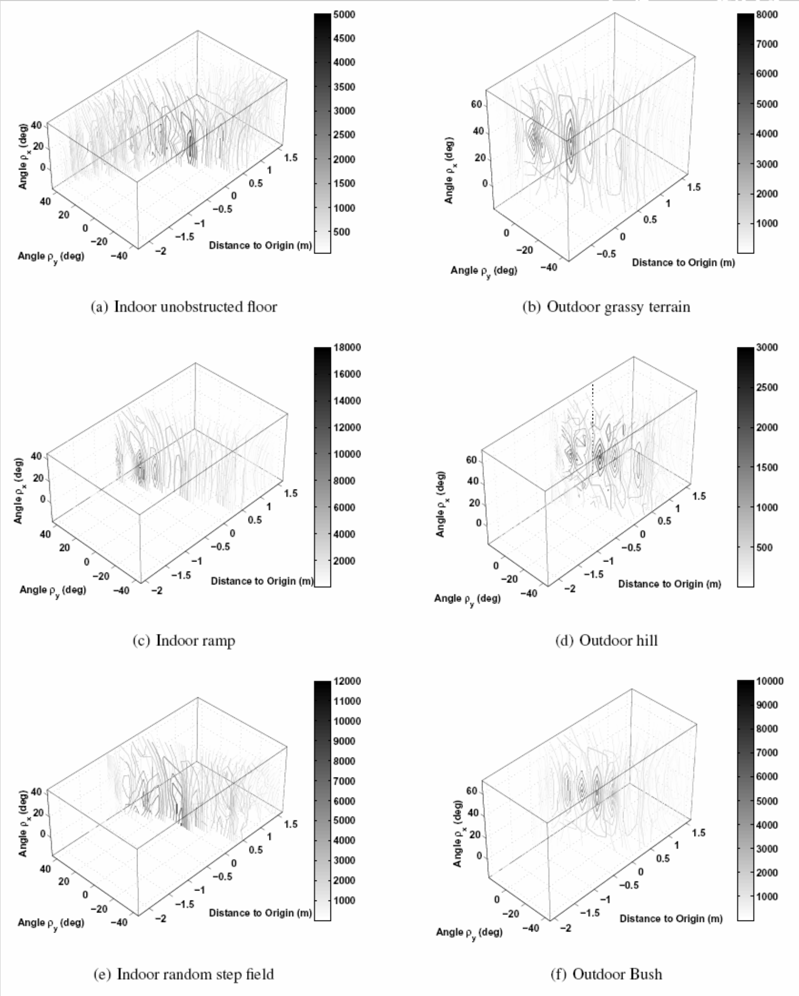
stereo cam



(a) Indoor unobstructed floor (b) Outdoor grassy terrain (c) Indoor ramp (d) Outdoor hill (e) Indoor random step field (f) Outdoor Bush

Swissranger



(a) Indoor unobstructed floor (b) Outdoor grassy terrain (c) Indoor ramp (d) Outdoor hill (e) Indoor random step field (f) Outdoor Bush

Classification by Decision Tree

- use
  - bin positions in the Hough space (i.e., plane parameters)
  - number of hits in the bins
  - and global properties (#PC, max #hits)
- to check for drivability
- and other potentially interesting terrain features
  - ramps, random step fields, stairs,…
  - rubble, hills, bushes, trees,…

if $\#\text{bin}_{\text{floor}} > t_h \cdot \#\text{PC}$ **then**
  class $\leftarrow$ floor
else
  if $(\#\{\text{bin} \mid \#\text{bin} > t_m \cdot \#\text{bin}^{\text{max}}\} < t_n)$ AND $(\#\text{bin}^{\text{max}} > t_p \cdot \#PC)$ **then**
    if $\text{bin}^{\text{max}} = \text{bin}_{\text{floor}}$ **then** class $\leftarrow$ floor
    if $\text{bin}^{\text{max}} = \text{bin}_{\text{plateau}}$ **then** class $\leftarrow$ plateau
    if $\text{bin}^{\text{max}} = \text{bin}_{\text{canyon}}$ **then** class $\leftarrow$ canyon
  else
    class $\leftarrow$ ramp
  end if
  class $\leftarrow$ obstacle
end if

current version

simply handcrafted

Experiments

more than 6800 snapshots

- indoor (850) & outdoor (5950)
- data hand labeled (based on normal camera images)

dataset	description	point-clouds (PC)	aver. points per PC
stereo			
set_1	inside, rescue arena	408	5058
set_2	outside, university campus	318	71744
set_3	outside, university campus	414	39762
TOF			
set_4	inside, rescue arena	449	23515
set_5	outside, university campus	470	16725
set_6	outside, university campus	203	25171
set_7	outside, university campus	5461	24790


(a) Slightly obstructed floor


(b) Grass


(c) Ramp


(d) Hill


(e) Random step field


(f) Bush

Sensor Drawbacks

- both sensors have flaws
  - stereo fails in featureless environments
  - Swissranger is sensitive to lighting conditions
- both indicate false range pixels

=>preprocessing of sensor data

(included in the runtimes)

- if #PC is too small
- then the data is discarded

dataset	snapshots	excluded data ratio
stereo		
set_1	408	0.92
set_2	318	0.75
set_3	414	0.70
TOF		
set_4	449	0.01
set_5	470	0.02
set_6	203	0.02
set_7	5461	0.00

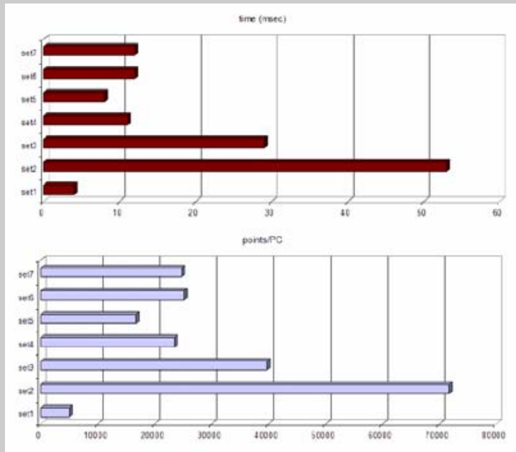
(a) The webcam image of the scene.

(b) An image of the point cloud delivered by the stereo camera. The ground does not show any features, so it does not have depth information.

Results: Fast and Robust

- processing time: 5 to 50 msec
  - mainly depends on #PC
- success rates for drivability
  - Swissranger: 83% to 100%
  - stereo cam: 98% to 100%
- notes
  - Swissranger failures mainly due to bad sensor data (outdoor light conditions)
  - more fine grain classification than drivability possible but less robust

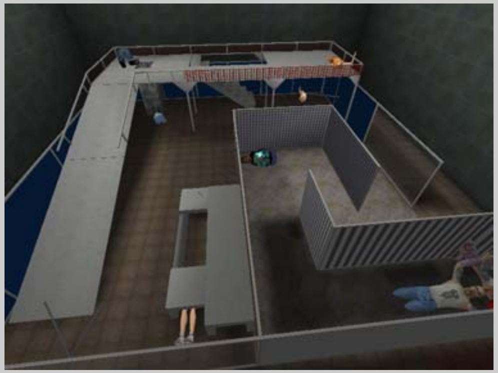
dataset	success rate	false negative	false positive	time (msec)
stereo				
set_1	1.00	0.00	0.00	4
set_2	0.99	0.00	0.01	53
set_3	0.98	0.02	0.01	29
TOF				
set_4	0.83	0.17	0.00	11
set_5	1.00	0.00	0.00	8
set_6	1.00	0.00	0.00	12
set_7	0.83	0.03	0.14	12



Virtual Test Environments

Unified System for Automation and Robotics Simulation (USARsim)

- based on Unreal Tournament game engine
- validated robot models using NIST test methods
- for prototyping, training, validation



Planetary Exploration Experiments

- planetary environments in USARsim
  - artificial landscapes
  - real world MER data
- low resolution 3D range sensor
  - plus Gaussian noise
- results with Hough Classification
  - 89% correct drivability
  - 11% false negative (conservative settings)
  - 7.1 msec computation time
  - without adaptation

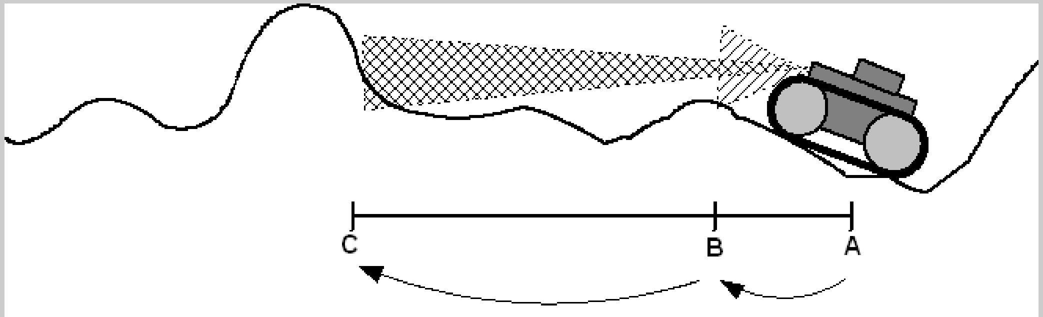
Limitations & Further Work

Hough Terrain Classification

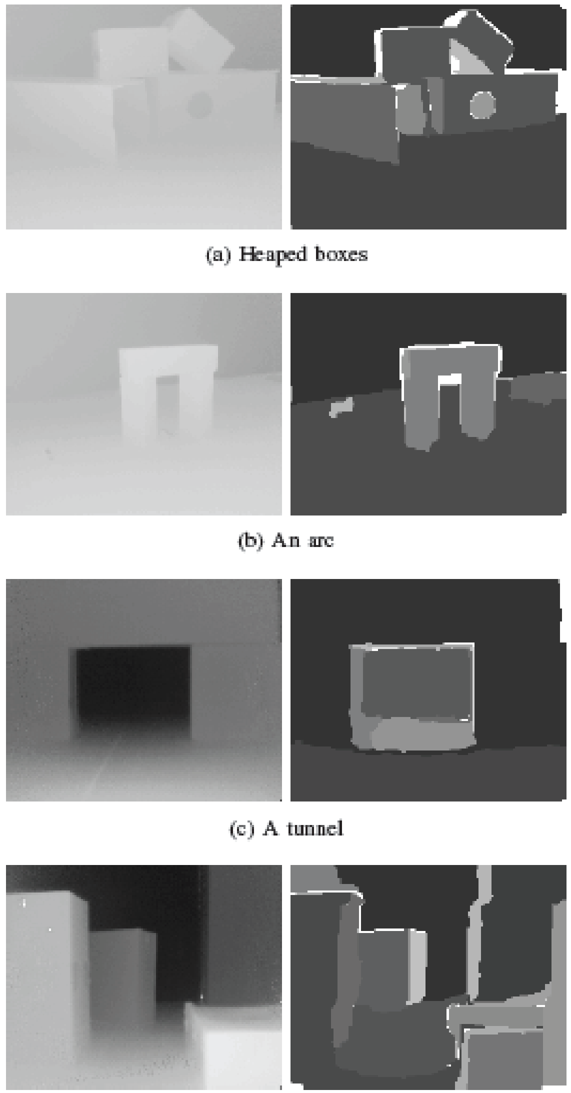
- uses number of & type of planes
- in the near field of the robot
- this has obvious limits
- e.g., thin pole on horizontal ground

better alternative (also for long range)

- consider planes & their boundaries (polyline)



SR-3000 range data   3D surface models



(a) Heaped boxes

(b) An arc

(c) A tunnel

(d) Several boxes

extraction in ~200 msec

Conclusion

Intelligent Mobile Robots in Unstructured Environments

- SSRR is a growing research and application domain
- lessons learned in this field may be of interest for planetary exploration research

Jacobs robot

- good physical locomotion capabilities
  - flipper mechatronics
- detection of negotiable ground
  - planar Hough transform & decision tree

more information: http://robotics.jacobs-university.de/

Movies


IUB
Negotiating Random Step Fields
The IUB Rescue Robot Team
RoboCup German Open 2007 at Hannover Fair


IUB
Demonstrating Stairclimbing
The IUB Rescue Robot Team
RoboCup German Open 2007 at Hannover Fair