Terrain Classification for Autonomous Robot Mobility
from Safety, Security, Rescue Robotics to Planetary Exploration

Andreas Birk, Todor Stoyanov, Yashodhan Nevatia, Rares Ambrus, Jann Poppinga, and Kaustubh Pathak

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

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

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

**stage 1: motion level**
- Direct mappings between operator inputs (e.g., joystick) and low level motor activations.

**stage 2: behavior level**
- Telecommands for short time autonomous functions; e.g., passing through communication blackout areas or driving assistance through doorways.

**stage 3: mission level**
- Specification of high level goals triggering medium to long time autonomy; e.g., setting goals points for navigation in autonomously generated maps and multi-robot control.
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
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
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**
  - robots must be physically capable to handle rough terrain

- **perception**
  - robots must be able to detect drivable ground
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 $\alpha$
  - its rate of change $\Delta \alpha$
  - flipper angle’s rate of change $\Delta \theta$

- **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)“

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</table>
Hierarchical Navigation Behaviors

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- short range perception (B) -> reactive obstacle behaviors
- long range perception (C) -> path planning
3D Range Sensors for Terrain Classification

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

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<td>STOC</td>
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<tr>
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<td>30 Hz</td>
<td>70° × 52°</td>
<td>0.75 - 3 m</td>
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<tr>
<td>SR-3000</td>
<td>176×144</td>
<td>≤ 50 Hz²</td>
<td>47° × 39°</td>
<td>0.6 - 8 m³</td>
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Fast but noise prone 3D data acquisition

time-of-flight cam: Swissranger SR-3000
stereo camera: Videre STOC

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<tr>
<th>Swissranger</th>
<th>Stereo Camera</th>
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<tbody>
<tr>
<td>Manufacturer</td>
<td>CSEM</td>
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<tr>
<td>Model</td>
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<td>Principle</td>
<td>Time of Flight (TOF)</td>
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<tr>
<td>Range</td>
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<td>Horiz. Field of View</td>
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<td>Vert. Field of View</td>
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<td>Resolution</td>
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<td>Videre Design</td>
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<td>Stereo-on-Chip (STOC)</td>
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<td>Stereo images’ disparity</td>
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<tr>
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<td>640 × 480</td>
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![Graph showing error in range measurement for different systems]
use Hough Transform for planes going from point to parameter space

- discrete parameter space $PS$ of bins
- bins with 3 parameters
  - two orientation angles $\rho_x$, $\rho_y$
  - 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

```plaintext
for all point $p \in PC$ do
  for all angles $\rho_x$ do
    for all angles $\rho_y$ do
      $n \leftarrow (-\sin(\rho_x)\cos(\rho_y), -\cos(\rho_x)\sin(\rho_y), \cos(\rho_x)\cos(\rho_y))^T$
      $d \leftarrow np$
      $PS[\rho_x][\rho_y][d] ++$
    end for
  end for
end for
```
Example Hough Spaces

(b) Plain floor
(c) Slightly obstructed floor
(d) Rug
(e) Random step field

(brighter grey scale value = more hits)
More Examples

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,…

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

current version
simply handcrafted
Experiments

more than 6800 snapshots
• indoor (850) & outdoor (5950)
• data hand labeled (based on normal camera images)

<table>
<thead>
<tr>
<th>dataset</th>
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<th>point-clouds (PC)</th>
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<td>5461</td>
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</table>

(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
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

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<td>0.83</td>
<td>0.03</td>
<td>0.14</td>
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</table>
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

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

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